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**Characterization of Plasma Streams and Ion
Populations from Plasma Thrusters for Space
Propulsion**

Tesis Doctoral

Julius Damba

European Master of Science in Nuclear Fusion and
Engineering Physics (Erasmus Mundus)

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Director
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2020

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Abstract

Plasma engines for space propulsion generate plasma jets (also denominated plasma plumes) having supersonic ion groups with typical speeds in the order of tens of kilometres per second, which lies between electron and ion thermal speeds. The design and features of the alternative low power hybrid ion engine (ALPHIE), a simple plasma accelerator with DC power consumptions below 450 W and that uses moderate propellant mass flow rates of xenon or argon, are discussed. The thruster depends on only one electron source for both propellant gas ionization and ion beam neutralization, thus coupling the plasma production and space-charge neutralization processes. The operation parameters of this plasma engine are studied in the laboratory in connection to the ion energy distribution function (IEDF) obtained with a retarding-field/retarding-potential analyzer (RFEA/RPA).

The ALPHIE plasma beam expansion produces a mesothermal plasma with two-peaked ion energy spectra composed of low- and high-energy ion groups. The characteristic speeds of the fast-ion group, in the range $36.6\text{--}43.5\text{ km}\cdot\text{s}^{-1}$, are controlled by the engine's acceleration voltage. These supersonic velocities are about one order of magnitude higher than typical ion sound speeds of the background plasma. The plasma beam density is driven by the ionizing electron flow from the cathode, which influences the maximum current of both IEDF peaks. The specific impulse estimated on the basis of the experimental results and the measured thrust are also presented.

The stationary plasma expansion process is studied experimentally using a four-grid retarding-field energy analyzer (RFEA), an emissive probe and a Langmuir probe (LP) – all mounted on a multiprobe structure displaced in three dimensional (3D) space. Specifically, the plasma beam properties from the measured RFEA current–voltage ($I\text{--}V$) characteristic curves is presented. The experimental results show the ion energy spectra shapes to remain nearly unaltered over 300 mm along the plasma jet expansion axis. The measured ion energy distribution function (IEDF) results from the superposition of different ion groups and has two dominant populations: a low-energy group constituted of ions from the background plasma – is produced by the interaction of the plasma jet with the walls of the vacuum chamber, and a fast-ion population composed of ions from the plasma beam moving at supersonic speeds with respect to the low-energy ions. The decreasing current density spatial profiles of the plasma jet are compared with those of the low-energy ion group, which are not uniform along the axis of symmetry owing to the small contributions

from other ion populations with intermediate speeds (energies).

The spatial variation of the electron energy distribution functions (EEDFs) in the direction of the plasma plume expansion is also studied using the combined emissive/Langmuir probe diagnostics. The results, which are inevitably affected by the plasma wake behind the LP probe (produced by the supersonic ion flow), however, show a strong evidence of an electron energy thermalization. Contrary to the ions, the relatively lighter electrons experience important energy exchange processes along the plasma plume.

Resumen

Los motores de plasma para propulsión espacial generan chorros de plasma (también denominados penachos de plasma) que tienen grupos de iones supersónicos con velocidades típicas del orden de decenas de kilómetros por segundo, que se encuentra entre las velocidades térmicas de iones y electrones. Se discuten el diseño y las características del motor alternativo de iones híbridos de baja potencia (ALPHIE), un acelerador de plasma simple con consumos de potencia de CC por debajo de 450 W y que utiliza tasas de flujo másico de propulsor moderado de xenón o argón. El propulsor utiliza solo una fuente de electrones tanto para la ionización del gas propulsor como para la neutralización del haz de iones, acoplando así la producción de plasma y los procesos de neutralización de la carga espacial. Los parámetros de funcionamiento de este motor de plasma se estudian en el laboratorio en relación con la función de distribución de energía iónica (IEDF) obtenida con un analizador de campo retardado (retarded field energy analyzer RFEA o retarded potential analyzer RPA en inglés).

La expansión del haz de plasma de ALPHIE produce un plasma mesotérmico con espectros de energía de dos picos compuestos de grupos iónicos de baja y alta energía. Las velocidades características de los grupos de iones rápidos, en el rango de $36.6\text{--}43.5\text{ km}\cdot\text{s}^{-1}$, están controladas por un voltaje de aceleración. Estas velocidades supersónicas son aproximadamente un orden de magnitud más altas que la velocidad de sonido iónica típica del plasma de fondo. La densidad del haz de plasma es impulsada por el flujo de electrones ionizantes desde el cátodo que influye en la corriente máxima de ambos picos IEDF. El impulso específico y el empuje generado se estiman sobre la base de los resultados experimentales obtenidos que también se presentan.

El proceso de expansión de plasma estacionario se estudia experimentalmente utilizando un analizador de energía de campo de retardo de cuatro rejillas (RFEA), una sonda emisora (emissive probe, EP en inglés) y una sonda Langmuir (Langmuir probe, LP), todo montado en una estructura que las desplaza en las tres direcciones del espacio. Específicamente, se presentan las propiedades del haz de plasma de las curvas características de corriente-voltaje ($I\text{--}V$) medidas con el RFEA. Los resultados experimentales muestran que los espectros de energía iónica permanecen casi inalterados a lo largo de 300 mm a lo largo del eje de expansión del chorro de plasma. La función de distribución de energía iónica medida (ion energy distribution function, IEDF en inglés) resulta de la superposición de diferentes grupos iónicos y tiene dos poblaciones

dominantes: un grupo de baja energía constituido por iones del plasma de fondo es producido por la interacción del chorro de plasma con las paredes de la cámara de vacío, y una población de iones rápidos compuesta de iones del haz de plasma que se mueve a velocidades supersónicas con respecto a los iones de baja energía. Los perfiles espaciales decrecientes de densidad de corriente del chorro de plasma se comparan con los del grupo iónico de baja energía, que no son uniformes a lo largo del eje de simetría debido a las pequeñas contribuciones de otras poblaciones de iones con velocidades intermedias.

La distribución espacial de las funciones de distribución de energía de electrones (electron energy distribution function, EEDF en inglés) en la dirección de la expansión del plasma también se estudió utilizando el diagnóstico combinado de sondas EP/LP. Los resultados se ven inevitablemente afectados por la estela de plasma detrás de la sonda LP producida por el flujo de iones supersónicos, sin embargo, muestran una fuerte evidencia del proceso de termalización de la energía electrónica. A diferencia de los iones, los electrones de luz experimentan importantes procesos de intercambio de energía a lo largo de la columna de plasma.

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List of Symbols

V_{AC}	Acceleration potential or voltage
V_{b}	Beam potential
$f(v_{\text{b}})$	Bi-Maxwellian distribution
I_{B}	Bohm current
k_{B}	Boltzmann constant
V_{d}	Cathode potential
V_{c}	Coupling voltage
I_{CG}	Cover grid current
V_{CG}	Cover grid voltage
J_{iF}	Current density of fast ions
J_{iT}	Current density of thermal ions
I_{AC}	Current through acceleration grid
λ_{D}	Debye length
D	Diameter of plasma chamber
d_{g}	Distance of separation between the two grids
$f(v, r)$	Distribution function in velocity–position space
u_{DF}	Drift velocity of fast ion population relative to the thermal ions
g	Earth’s acceleration due to gravity
j	Electric current
J	Electric current density
E_{s}	Electric field at acceleration grid
E_{a}	Electric field at screen grid
E	Electric field intensity or Total Energy

F_i	Electric force on ions
J_{em}	Electron emission current density
$g(E)$	Electron energy distribution function
r_e	Electron gyro radius
n_e	Electron or plasma number density
T_e	Electron or plasma temperature
I_{es}	Electron saturation current
u_{Te}	Electron thermal speed
I_c	Electron-collection saturation current
m_e	Electronic mass
e	Elementary charge
I_{coll}	Emissive probe electron-saturation current
V_{probe}	Emissive probe or Langmuir probe bias voltage
erf	Error function
v_{ex}	Exhaust velocity
I_{EG}	Extraction current
V_{EG}	Extraction grid potential or voltage
E_{Fi}	Fast-ion population peak energy
T_{iF}	Fast-ion population temperature
V_f	Floating potential
p_a	Gas pressure
T_r	Grid transparency
j_θ	Hall current
F_θ	Hall current force on magnets
$M_T(t)$	Instantaneous total mass of a rocket
D_b	Ion beam cross section
q_i	Ion charge
A_{IC}	Ion collector effective beam-incident area
I_i	Ion current
J_i	Ion current density

V_{ID}	Ion discriminator/retarding voltage
$v_{\text{i,ex}}$	Ion exhaust velocity
r_{i}	Ion Larmor radius
$\dot{m}_{\text{i}}$	Ion mass flow rate
m_{ia}	Ion mass in atomic mass units (AMU)
m_{i}	Ion mass in kg
n_{i}	Ion number density
$\dot{m}_{\text{i}}$	Ion production rate
I_{is}	Ion saturation current
c_{is}	Ion sound velocity/speed
I_{E}	Ion (thruster) beam current
I_{IC}	Ion-collector current
$I_{\text{IC}}(V_{\text{ID}})$	Ion-collector current as a function of the ion discriminator voltage
$I_{\text{IC}}(E)$	Ion-collector current as a function of the ion energy
J_{IC}	Ion-collector current density
$J_{\text{IC}}(E)$	Ion-collector current density as a function of the ion energy
U_{i}	Ionization energy of a gas in joules
P_{jet}	Jet power – propulsive power due to the engine propellant
I_{e}	Langmuir probe electron current or Emissive probe emitted current
p	Linear momentum
T_{iT}	Low-energy ("thermal") ion population temperature
u_{mx}	Lowest possible speed of ions detectable by the RFEA
B	Magnetic field
M_{h}	March number (ratio of ion drift velocity to ion sound speed/velocity)
$\dot{m}$	Mass flow rate in $\text{kg}\cdot\text{s}^{-1}$

η_m	Mass utilization efficiency
I_m	Maximum RFEA current value corresponding to zero energy of an ion population
J_{im}	Maximum RFEA ion current density
V_m	Maximum V_{ID} potential for which all ions are collected by RFEA
$f_M(v)$	Maxwellian velocity distribution function
λ	Mean free path
I	Measured current
V	Measured voltage
E_1	Minimum energy of fast-ion population
v_{min}	Minimum velocity
M_R	Molecular mass
P_{NH}	Neutralizer heating power
σ_{ai}	Neutral-ion collisional cross section
λ_{ai}	Neutral-ion collisional mean free path
λ_{aa}	Neutral-neutral collisional mean free path
I_{NH}	Neutralizer cathode heating current
V_{NH}	Neutralizer cathode heating voltage
n_n	Number density of neutral atoms
$f(v_z)$	One dimensional velocity distribution function
Q	Particle/mass flow rate in particles per second
n	Particle number density
V_{sp}	Plasma potential
l_w	Plasma wake length
V_{PR}	Plasma-electron repelling grid voltage
V_{dg}	Potential difference across two grids
I_{probe}	Probe current
$I(V_{probe})$	Probe current as a function of the probe bias voltage
I_H	Probe heating current

r_{probe}	Probe radius
A	Probe surface area
T_{w}	Probe wire temperature
ϕ_{w}	Probe wire-material work function
m_{p}	Propellant mass
$\dot{m}_{\text{p}}$	Propellant mass flow rate in $\text{kg}\cdot\text{s}^{-1}$
M	Propellant particle mass in kg
R_{o}	Radius of a sphere
A_{c}	Richardson's constant
V_{SS}	Secondary-electron suppressor grid voltage
I_{sp}	Specific impulse
T	Temperature
I_{em}	Temperature-limited electron emission current
E_{Ti}	Thermal ion population peak energy
u_{Fi}	Thermal ion speed of fast-ion population
u_{Ti}	Thermal ion speed of low-energy ions
v_{th}	Thermal velocity of electrons
F_{T}	Thrust
γ	Thrust correction factor
t	Time
v	Velocity
$f(v)$	Velocity distribution function
Δv	Velocity gain
X	X -axis or distance along X direction
Y	Y -axis or distance along Y direction
v_{z}	Z velocity component
z	Z -axis coordinate
Z	Z -axis or distance along Z direction

Physics Constants

e	Elementary (electronic) charge	1.60219×10^{-19} As or coulomb (C)
g	Earth's acceleration due to gravity	$9.80665 \text{ m}\cdot\text{s}^{-2}$
k_{B}	Boltzmann constant	$1.38066 \times 10^{-23} \text{ J}\cdot\text{K}^{-1}$
m_{e}	Electron rest mass (electronic mass)	$9.10953 \times 10^{-31} \text{ kg}$
u	Atomic mass unit	$1.66057 \times 10^{-27} \text{ kg}$
eV	Electron volt	$1.16045 \times 10^4 \text{ K}$ or $1.60219 \times 10^{-19} \text{ J}$

List of Abbreviations

ALPHIE	Alternative low-power hybrid ion engine
IEDF	Ion energy distribution function
RFEA	Retarding-field energy analyzer
RPA	Retarding-potential analyzer
LP	Langmuir probe
I – V	Current–voltage characteristic
IVDF	Ion velocity distribution function
AMU	Atomic mass unit
EP	Electric spacecraft propulsion
HET	Hall Effect thruster
GIE	Gridded ion engine
MPD	Magnetoplasmadynamic thruster
HEMPT	High-efficiency multistage plasma thruster
PPT	Pulsed plasma thruster
FEET	Field-emission electric propulsion thruster
QCT	Quad confinement thrusters
GEO	Geostationary orbit or geosynchronous equatorial orbit
ECR	Electron cyclotron resonance
AF	Applied field
SF	Self field
VASIMR	Variable specific impulse magnetoplasma rocket
RF	Radiofrequency
NASA	National Aeronautics and Space Administration
SERT	Space electric rocket test
ESA	European Space Agency

AEPS	Advanced electric propulsion system
DC	Direct current
NSTAR	NASA solar technology application readiness
LEO	Low Earth orbit
MEO	Medium Earth orbit
GSO	Geosynchronous (transfer) orbit
NSSK	North-South station keeping
EWSK	East-West station keeping
MCFT	Multi-cusped field thrusters
CAD	Computer aided design
FC	Faraday cup
EVDF	Electron velocity distribution function
EEDF	Electron energy distribution function
SG	Savitzky-Golay numerical scheme
AC	Alternating current
PR	Plasma-electron repelling grid
ID	Ion discriminator/retarding grid
SS	Secondary-electron suppressor grid
FG	Entrance or plasma-facing grid
p.d	Potential difference
xcf	eXperimental Computing Facility
IVI	Interchangeable virtual instruments
I/O	Input/Output
VISA	Virtual instrument software architecture
UHV	Ultra high vacuum
sccm	Standard cubic centimetres per minute
FWHM	Full width at half maximum

Chapter 1

Introduction

1.1 Concepts of Rocket and spacecraft operation

Most rockets work by shooting fuel (the working mass or reaction mass) backwards, causing the rocket to be propelled forwards. The forward acceleration of the rocket results from the momentum transfer or exchange between the working mass and the rocket. By momentum conservation, the product of the mass of ejected propellant m_p and the velocity at which it is expelled (*exhaust velocity* v_{ex}) from the rocket balances, and thus is equal to, the product of the rocket's instantaneous total mass $M_T(t)$ and the velocity gain, Δv . The relationship between Δv and $M_T(t)$ can be summarised by the famous Tsiolkovsky rocket equation [1], given by

$$\Delta v = v_{ex} \ln \frac{M_T(t)}{M_T - m_p}, \quad (1.1)$$

where $M_T - m_p$ is the remaining or final mass delivered by the spacecraft.

From this relation, a given (constant) exhaust velocity v_{ex} results in a linear increment in the spacecraft's velocity Δv while the Δv logarithmically depends on the ejected propellant mass. The energy requirement of a given space mission is thus measured by the required velocity increment of the mission.

The working mass in a rocket is the fuel which in most cases is a light-weight substance such as kerosene, liquid hydrogen or oxygen that is accelerated to high speeds. For the reaction mass, spacecraft ion engines on the other hand often use heavier elements like xenon. These are accelerated to much higher speeds using electric fields. In ion engines the working mass is a separate entity from the energy used to accelerate it, unlike in other rockets where the propellant acts as the working mass as well as being the energy source. Acceleration of such rockets therefore stops as soon as they run out of fuel, regardless of other power sources that may be available in them. In satellites this can be a limitation to their useful life.

In the following paragraphs, the concepts of thrust, specific impulse (I_{sp})

and total efficiency of a spacecraft propulsion system are introduced. The force supplied to the spacecraft by the engine is the engine's thrust. As a spacecraft's total mass $M_T(t)$ decreases with time t , the thrust F_T imparted to the spacecraft can be derived from Newton's second (or force) law using the time rate of change of p to be

$$F_T = v_{\text{ex}} \frac{d}{dt} (m_p) = \dot{m}_p v_{\text{ex}}, \quad (1.2)$$

where the propellant mass flow rate in $\text{kg}\cdot\text{s}^{-1}$ is represented by $\dot{m}_p$. This mass flow rate is given by

$$\dot{m}_p = QM \quad (1.3)$$

for the propellant particle flow rate Q (in particles per second) and mass M [1].

Specific impulse I_{sp} gives a measure of thrust efficiency. By definition, it is the ratio of the thrust to the rate of propellant consumption, i.e.,

$$I_{\text{sp}} = \frac{F_T}{\dot{m}_p g}, \quad (1.4)$$

where $g = 9.81 \text{ m}\cdot\text{s}^{-2}$ is the Earth's acceleration due to gravity. Substituting the expression for F_T in Eq. 1.2 into Eq. 1.4 results in an alternative formula for specific impulse as the ratio of the propellant exhaust velocity v_{ex} to the gravitational acceleration g . It is measured in units of time (seconds).

$$I_{\text{sp}} = \frac{v_{\text{ex}}}{g} \quad (1.5)$$

The I_{sp} can thus be related with Δv from Eq. 1.1 as

$$\Delta v = I_{\text{sp}} g \ln \frac{M_T(t)}{M_T - m_p}. \quad (1.6)$$

The propulsive power due to the engine propellant (jet power) P_{jet} depends on $\dot{m}_p$ and v_{ex} as,

$$P_{\text{jet}} = \frac{1}{2} \dot{m}_p v_{\text{ex}}^2 = \frac{F_T^2}{2\dot{m}_p}. \quad (1.7)$$

The acceleration of heated neutral propellant gases by expansion through a nozzle [2] is the source of the jet power in chemical propulsion systems. For electric propulsion however, the source of the engine propulsive power is the acceleration of charged particles plasma engines – which is the subject of the present dissertation.

From energy conservation, the ion exhaust velocity $v_{i,\text{ex}}$ for ions accelerated through two grids across which there is an electric potential drop V_{dg} (in volts) can be given by

$$v_{i,\text{ex}} = \left(\frac{2q_i V_{\text{dg}}}{m_i} \right)^{1/2}, \quad (1.8)$$

where q_i is the ion charge in coulombs and m_i the ion mass in kg.

Using the relation between mass flow rate and beam current, the ion mass flow rate $\dot{m}_i$ and the ion beam current I_E (in amperes) is given by,

$$\dot{m}_i = \frac{m_i I_E}{q_i} \quad (1.9)$$

Combining the Eqs. 1.7, 1.8 and 1.9 enables one to calculate the thrust F_T (in newtons) for a singly charged ion where $q_i = e$, the electronic charge, as

$$F_T = I_E \left(\frac{2m_i V_{dg}}{e} \right)^{1/2}. \quad (1.10)$$

It is clear from Eq. 1.10 that the thrust varies as the product of the beam current and the square root of the acceleration voltage. In the presence of beam divergence, as in Hall thrusters, the average beam voltage can be used for V_{dg} [1].

For xenon and argon propellants the thrust from Eq. 1.10 can be simplified to $\approx 1.65 I_E \sqrt{V_{dg}}$ mN and $\approx 0.79 I_E \sqrt{V_{dg}}$ mN, respectively, for a very thin (unidirectional) singly charged monoenergetic ion beam [1]. These thrust expressions are valid for ion thrusters [1], though they are only approximately valid for Hall thrusters. Also, a correction needs to be made in case of a divergent beam or multiply ionized beams. For further details on the correction factors see Ref [1].

From these equations, Xe and Ar ions of 1 A current accelerated by grids across which a $V_{AC} = 1$ kV potential drop is applied would be ejected at exhaust speeds of $\approx 39 \text{ km}\cdot\text{s}^{-1}$ and $\approx 69 \text{ km}\cdot\text{s}^{-1}$, respectively. The corresponding thrust generated would be ≈ 52 mN for Xe and ≈ 30 mN for Ar. Tab. 1.1 shows the calculated values of Xe and Ar ion exhaust velocities $v_{i,ex}$ and the generated thrust when acceleration grid voltages $V_{AC} = 0.5 \text{ kV}$, 1.0 kV and 1.5 kV are used with thruster current I_E of 0.5 A , 1.0 A , and 1.5 A .

Using Eq. 1.2 for an ion thruster that ejects unidirectional monoenergetic ions of mass m_i and exhaust velocity $v_{i,ex}$, specific impulse can also be written as

$$I_{sp} = \frac{v_{i,ex}}{g} \frac{\dot{m}_i}{\dot{m}_p}. \quad (1.11)$$

The mass utilization efficiency η_m , which refers to the ratio of the ionized to unionized propellant, for singly charged ions is defined as

$$\eta_m = \frac{I_{sp} g}{v_{i,ex}} = \frac{I_E}{e} \frac{m_i}{\dot{m}_p}. \quad (1.12)$$

A correction needs to also be made for the mass utilization efficiency of a multiply ionized propellant. In the case of a small ratio of doubly ionized propellant to the singly ionized ones, the mass utilization correction factor is

TABLE 1.1: Calculated (ideal) thrust and velocity values from Eq. 1.10 for singly ionized xenon (Xe) and argon (Ar) ion currents I_E with exhaust speeds $v_{i,ex}$, when accelerated through potential drops of $V_{AC} = 0.5, 1.0$, and 1.5 kV voltages. These speeds are above the $5.5 \text{ km}\cdot\text{s}^{-1}$ limit shown in Fig. 1.1. (Reproduced with permission from Ref [3])

		0.5 kV		1.0 kV		1.5 kV	
	I_E (A)	$v_{i,ex}$ ($\text{km}\cdot\text{s}^{-1}$)	F_T (mN)	$v_{i,ex}$ ($\text{km}\cdot\text{s}^{-1}$)	F_T (mN)	$v_{i,ex}$ ($\text{km}\cdot\text{s}^{-1}$)	F_T (mN)
Xe	0.5	27.35	18.4	38.67	26.1	47.37	32
	1.0		36.9		52.2		63.9
	1.5		55.3		78.3		95.9
Ar	0.5	49.08	10.5	69.41	14.9	85.11	18.2
	1.0		21.0		29.7		36.4
	1.5		31.5		44.6		54.6

approximately equal to one [1]. The corrected specific impulse value can then be given by

$$\begin{aligned}
 I_{sp} &= \frac{\gamma \eta_m}{g} \left(\frac{2eV_{dg}}{m_i} \right)^{1/2} \\
 &= 1.417 \times 10^3 \gamma \eta_m \sqrt{\frac{V_{dg}}{m_{ia}}},
 \end{aligned} \tag{1.13}$$

where γ is the thrust correction factor which takes into account both the beam divergence and multiple ionization, and m_{ia} is the ion mass in atomic mass units (AMU).

1.2 Electric Spacecraft Propulsion Systems

In a broad sense, electric spacecraft propulsion (EP) refers to any propulsion technology in which electrical energy is used to increase the propellant exhaust velocity and to generate thrust that is delivered to a spacecraft. The aim is to achieve thrust by increasing the mass flow of the propellant to exhaust velocities a few orders of magnitude higher than in chemical propulsion.

Fig. 1.1 shows a scheme of a typical electric propulsion thruster. As shown in this Figure, a forward thrust F_T as given by Eq. 1.2 is imparted to a spacecraft by the exhaust propellant when the thruster's electric power P is converted to the jet power P_{jet} according to Eq. 1.7. The propellant may be a

FIGURE 1.1: Thrust generation by an electric thruster [3, 4]. On this Figure the thrust F_T is denoted by F . (Reproduced with permission from Ref [3])

liquid, as is the case in FEEP thrusters (see next section for details) or gaseous as in the case in Hall thrusters.

In conventional chemical propulsion systems, thrust is generated when the propellant (heated) gas is expanded through a nozzle. The achievable exhaust velocity v_{ex} of gases in these thrusters is thus derived from the energy per unit mass stored in the propellant. This makes chemical propulsion systems to be limited by reaction energies that can be made available to the spacecraft, with exhaust gas velocities due to thermal transfers limited to a few thousand metres per second ($v_{ex} \lesssim 5.5 \text{ km} \cdot \text{s}^{-1}$) [2, 3]. The maximum achievable gas speed in conventional chemical thrusters is thus determined by the energy stored per unit mass of the propellant [4]. Electric propulsion systems on the other hand derive such energies from an independent electric power supply. Plasma engines for space propulsion produce high-velocity streams of ions with a resulting plasma jet created when electrons are added to a fast ion beam to eliminate space charge effects [1, 5–8]. The plasma jet then imparts thrust to the spacecraft. The exhaust speed v_{ex} in electric propulsion systems thus depends less on the chemical nature of the propellant.

From Eq. 1.1 on page 1, the mass fraction that can be delivered by a spacecraft – the mass that can be delivered to the destination as a fraction of the spacecraft’s initial mass – decreases exponentially as a function of the ratio $\Delta v / v_{ex}$ (of the required velocity increment Δv compared to the exhaust velocity v_{ex} of the propellant). Thus, delivering a large proportion of a spacecraft’s initial mass necessitates that exhaust velocity v_{ex} of the system is comparable to the required velocity increment. When Δv is kept constant, the dependence of the deliverable mass fraction on the exhaust velocity v_{ex} can be predicted.

Fig. 1.2 shows the relative reduction in propellant mass m_p from Eq. 1.1 for a given delivered mass $m_T - m_T$ associated with increase in v_{ex} . In the

graph shown in this Figure, the dependence of the deliverable mass fraction on the exhaust velocity v_{ex} for velocity increments Δv of $1 \text{ km}\cdot\text{s}^{-1}$, $4.3 \text{ km}\cdot\text{s}^{-1}$, and $5.9 \text{ km}\cdot\text{s}^{-1}$ which are typically required for the different space applications are shown. The limit for chemical propulsion systems ($v_{\text{ex}} \lesssim 5.5 \text{ km}\cdot\text{s}^{-1}$) is also shown by the dotted vertical line on the graph. The exhaust speed v_{ex} in electric propulsion systems is on the other hand less dependent on the chemical nature of the propellant as in chemical propulsion, since particle acceleration powered by an external power supply or source. Electric propulsion therefore makes it possible to exceed the $\simeq 5.5 \text{ km}\cdot\text{s}^{-1}$ maximum exhaust velocity limit achievable by chemical propulsion.

FIGURE 1.2: Fraction of propellant mass compared to total delivered or dry mass, $m_p/(m_T - m_p)$, as a function of v_{ex} for typical velocity increment Δv values. (Reproduced with permission from Ref [3])

With the Δv requirements of at least an order of magnitude higher than the $5.5 \text{ km}\cdot\text{s}^{-1}$ limit desirable for future space missions [2], electric spacecraft propulsion provides a better alternative to the conventional chemical propulsion counterpart. EP systems produce supersonic plasma flows (also denominated *plasma plumes*) in which ions are accelerated to reach one to two orders-of-magnitude higher exhaust speeds than in chemical thrusters. A higher specific impulse $I_{\text{sp}} = v_{\text{ex}}/g$ (see section 1.1 on page 2) in EP can thus be achieved, which allows for longer mission times and heavier payloads as a result of the reduced amount of required propellant [1, 5–7] as compared to conventional chemical propulsion systems that produce lower I_{sp} accompanied with high thrust.

Tab. 1.2 shows a comparison of these two spacecraft propulsion technologies (electric and chemical). In this Table, the different operational and mission parameters for the European Space Agency’s (ESA’s) SMART-1 Hall Effect thruster (HET) that is based on electric propulsion technology are compared with those of the chemically propelled Fregat and a monopropellant hydrazine thruster. The SMART-1 thruster uses xenon propellant whereas Fregat can use either nitrogen tetroxide (N_2O_4) or hydrazine as propellant. As seen in

TABLE 1.2: Comparison of electric and chemical propulsion technologies. ESA's electrically propelled SMART-1 Hall Effect thruster (HET) characteristics as compared to chemically propelled prototypes – Fregat and a small monopropellant hydrazine thruster. (Source: ESA - see Ref [2])

Chemical		Electric	
	Small monopropellant thruster	Fregat Main Engine (S5.92M)	SMART-1 HET (PPS-1350)
Propellant	Hydrazine	N ₂ O ₄ /Unsymmetrical dimethyl hydrazine	Xenon
Specific impulse I_{sp} (s)	200	320	1640
Thrust (N)	1	1.96×10^4	6.80×10^{-2}
Thrust time (s)	1.66×10^5	877	1.80×10^7
Thrust time (h)	46	0.24	5000
Propellant consumed (kg)	52	5350	80
Total impulse (Ns)	1.1×10^5	1.72×10^7	1.2×10^6

the Table, the total impulse produced by the chemically propelled Fregat is almost 14 times the amount generated by SMART-1's electric engine. However, it is important to note that this significant impulse is at the expense of having to sustain more mass in the form of propellant in the Fregat engine, which is about 70 times as much as the amount consumed by the SMART-1 engine. Furthermore, the monopropellant hydrazine thruster generates about 9% of SMART-1's total impulse while consuming 65% of the propellant used by SMART-1 [2].

Thus, the electrically propelled SMART-1 thruster is able to save more available mass for useful payloads instead. This highlights electric propulsion's advantage over the conventional chemical propulsion method, in the form of a decrease in the launch mass of a spacecraft or satellite, allowing for longer mission times and more payloads and thus reduced cost. In so doing, it is possible to reduce the amount of propellant required for a given space mission. For these thrusters, there is therefore no need for the spacecraft to have large fuel reserves, allowing for more useful payload. To put this into perspective, a mission such as NASA's 2007 Dawn mission (see Dawn spacecraft in Fig. 1.3a of page 11) in which three redundant ion engines were employed – enabling the spacecraft to orbit the asteroid Vesta and the dwarf planet Ceres – would

require a chemical rocket propulsion system with almost ten times more fuel mass.

These merits of EP are however accompanied by only a limited achievable thrust [1, 5–7] due to the low mass ion production rate $\dot{m}_i$ constrained by the finite electric power that can be made available aboard a spacecraft. As shown in Tab. 1.1, to generate substantial thrust by EP systems requires high electric power (seen by the kV and A range voltage and current values used in the calculations). In Tab. 1.1, the highest value of thrust (95.9 mN) corresponds to xenon propellant with a high atomic mass, and is achieved with I_E and V_{AC} values of 1.5 A and 1.5 kV, respectively. This makes them unsuitable for use as launch vehicles to provide the boost to launch spacecraft into orbit. However, they are capable of propelling the spacecraft with these typical thrusts. When they are operated continuously over a period of time, they slowly but steadily increment the speed of the spacecraft thus enabling it to reach even greater velocities.

Since the magnitude of thrust produced by electric propulsion devices is dependent on the amount of power that can be made available on the spacecraft, it means that to drive a large thruster requires more power. This means more power supplies, the size of which may be comparable to or even outweigh the mass that could be saved due to the ion engine's fuel efficiency. The limited electric power that can be availed aboard a spacecraft throughout its mission time has, at least to date, thus remained a major limitation to the application of this promising propulsion technology in high-thrust, short duration missions or maneuvers. The permitted usability and applicability of such propulsion technologies nevertheless remain essential for orbital manoeuvres, station keeping, flight formation and/or end-of-life disposal of Earth-orbiting satellites.

With the increasing advancements in design and materials research, however, electric thrusters have shown potential for use in longer space missions. For example, the advanced high-thrust ion engine fired by NASA that lasted over 50,000 hours proved the capability of these thrusters to last for deep space missions that last years. The recent successful tests of an air-breathing ion thruster that derives its fuel directly from the atmosphere by the European Space Agency (ESA) is an elaboration of continued technological advancement in research on electric propulsion. An air-breathing engine could operate on the unlimited supply of rarefied nitrogen–oxygen mixture available just 200 km up in the upper layers of the atmosphere. It could therefore make it possible to have low-flying satellites that would operate for much longer periods of time, as there would be no concern about the satellites depleting their fuel reserve.

If the full potential of electric propulsion is to be realized, there is still the need for increased thrust generation by electric thrusters. By doing so, larger spacecraft could be easily propelled by, say, ion engines. Engineers are working very hard to achieve these goals, and the latest advancements reported so far have been in the X3 ion thruster (see Fig. 1.3b) and the Advanced Electric Propulsion System (AEPS) tested at Aerojet Rocketdyne, both consisting of

Hall Effect ion thrusters. The X3 ion thruster designed and developed by researchers from the University of Michigan, NASA and the U.S. Air Force operates at over 100 kW power, and it has been demonstrated to produce the maximum power output (5–102 kW), thrust (5.4 N) and operating current (up to 260 A) so far achieved by a Hall thruster [9–11].

With a 227 kg mass and almost one meter diameter, the X3 is over 59 times more powerful than the thruster flown on DAWN and its design comprises of three plasma channels nested around one another in concentric rings. With such power output, this ion thruster could make it possible to realize ion propulsion's grandest ambitions such as propelling manned missions to Mars. The AEPS on the other hand operates at 13.3 kW and it is expected to form the core of solar electric propulsion vehicles to be used by NASA for transportation of habitats and cargo needed for human exploration of deep space destinations beyond the low-Earth orbit. The AEPS system could therefore become an integral component of the power and propulsion element that could make it possible for the maneuverability of the planned Lunar Orbital Platform-Gateway to be built in cislunar space near the Moon.

1.3 Electric spacecraft thrusters

A majority of electric spacecraft propulsion systems electrically expel the propellant, also referred to as *reaction mass*, at very high speeds. Common examples of electric thrusters for space propulsion include Hall Effect thrusters (HET), gridded ion engines (GIE) [1, 5], magnetoplasmadynamic (MPD) thrusters, multi-cusped field thrusters (MCFTs) [5, 12–16], such as the high-efficiency multi-stage plasma thruster (HEMPT) [15, 16] developed by the Thales Electron Devices company, pulsed plasma thrusters (PPT), field-emission electric propulsion (FEED) thrusters, quad confinement thrusters (QCT), resistojet thrusters, arcjet thrusters, colloid or electrospray thrusters, electrodeless thrusters, etc. The characteristics and features of these propulsive systems have been discussed extensively in textbooks [1] and comprehensive reviews [5–8, 17].

Depending on the field or sector in which it is employed, the attractiveness of a given thruster in terms of its usability and application can vary. How attractive or unattractive it is depends on factors such as the performance specifics of the thruster, which may include characteristics such as the magnitude of the delivered thrust, the electric power demand, and so on. However, most of the thrusters spelt out above are commercially applied mainly in large telecommunication satellites operated within the geostationary orbit (GEO).

There is not a universal classification for these thrusters, as different parameters give rise to slightly varying categorizations. Various classifications have been presented in several books and review articles [1, 5–7, 18–22]. For example, one might choose to classify them according to the mechanism of propellant acceleration or thrust generation, period of firing, and so on. Tab. 1.3 shows a

TABLE 1.3: Classification of spacecraft EP thrusters. M_R , m_i , V_{AC} , T and J are, respectively, the molecular and ionic masses, the acceleration potential, the neutral gas or ion temperature, and the electric current density. The acronyms used: ECR – electron cyclotron resonance thruster; and applied field (AF) and self field (SF) for the MPD thruster variants. (Reproduced with permission from Ref [3])

Classification		Physical principles	Thruster
Electrothermal	$v_{ex} \sim \sqrt{\frac{F_T}{M_R}}$	Solid nozzle	Arcjet
			Resistojet
		Magnetic nozzle	Helicon
			VASIMR ECR
Electrostatic	$v_{ex} \sim \sqrt{\frac{2eV_{AC}}{m_i}}$	Externally applied electric field	GIE
			Colloid
			FEEP
		Self-consistent electric field	HET
			HEMPT
Electromagnetic	$v_{ex} \sim \frac{J}{\dot{m}}$		Multi-Cusp
		Steady plasma flow	AF-MPD SF-MPD
		Unsteady plasma flow	Pulsed plasma

simple summary of thruster classification in terms of the physical principle of propellant acceleration and/or thrust generation by the thruster. Under this categorization a thruster can be considered electrostatic, electromagnetic, or electrothermal [5].

1.3.1 Electrostatic thrusters

In electrostatic thrusters Coulomb forces accelerate charged (ionized) propellant particles. The thruster's operation begins with ionization of the propellant gas to produce plasma, which is achieved in part by the use of electric power. The ionized gas particles are then accelerated to very high speeds by the forces due to an electric field within. Depending on the origin of the electric field, such thrusters can be, as shown in Tab. 1.3, termed as colloid (electrospray), FEEP, HETs, or GIEs.

When biased electrodes (grids) are used then the name gridded ion engines (GIEs), or Kaufman thrusters as in most of the literature, is used. GIEs

(a) Dawn spacecraft. Source: Ref [23]

(b) A 13 kW Hall thruster. Source: Ref [24]

FIGURE 1.3: Electrostatic thrusters: photographs of the Dawn spacecraft and the 13 kW Hall thruster for spacecraft propulsion. (a) A representation of the Dawn spacecraft (b) A 13 kW Hall thruster tested at NASA's Glenn Research Center in 2016.

accelerate the thruster ions using metal plates with carefully designed and arranged apertures in them connected to high voltages, or simply wire meshes. FEEP and colloid thrusters generate very low thrust ($< 1 \text{ mN}$). In colloid thrusters conductive liquids are fed through small needles and ions or highly charged droplets are extracted from them and then electrostatically accelerated to high energies (kV-range voltages) using aligned biased apertures. On the other hand, FEEP thrusters wick liquid metals, such as indium, cesium or mercury, along needles and then extract ions from the sharp tip by field emission. Additionally, internal self-consistent electric fields can develop in non-equilibrium discharge plasmas, which can be used to accelerate ions to high enough velocities for propulsion. These velocities are also well above the chemical propulsion limit already mentioned here. This is the main ion acceleration principle used in HETs, HEMPTs, and similar thrusters that make use of multicusp designs.

Such are the thrusters that have been used in missions like Deep Space 1 and Dawn. Mostly, heavy inert gases such as xenon are used as the propellant in ion and Hall Effect thrusters. Xenon, in particular, is the most preferred owing to its physical properties: it is non-hazardous and hence easily handled or processed; it does not easily condense at cryogenic temperatures, and thus on spacecraft components. It is easily stored at high densities; and its high atomic mass means a higher thrust generation for a given input power.

1.3.2 Electromagnetic thrusters

This closely shares similarities with electrostatic propulsion in terms of the operation principles, but the electric field in electromagnetic propulsion is not in the same direction as the generated thrust. A Lorentz force due to crossed electric (E) and magnetic (B) fields causes the plasma in the propulsive device to be accelerated at an angle to the thrust.

Pulsed inductive thrusters, magnetoplasmadynamic thrusters, and electrode-

less plasma thrusters lie in this category. A PPT thruster ionizes a fraction of a solid propellant ablated into a plasma arc by use of a pulsed discharge. Electromagnetic effects in the pulse then accelerate the ions to high v_{ex} . The thrust level depends on the pulse repetition rate.

MPD thrusters make use of a very high-current arc to significantly ionize the propellant. Then $j_\theta \times B$ forces in the plasma discharge accelerate the charged propellant, where j_θ is the Hall current. Since both the current j and magnetic field B originate from the plasma discharge, MPD thrusters tend to use very high powers to generate high thrust compared to most of the other electromagnetic thrusters.

1.3.3 Electrothermal thrusters

Electrothermal propulsion devices on the other hand contain uncharged gaseous propellant that is heated by the ohmic mechanism whereby an electric current is used to increase the temperature of the propellant and/or electron–neutral collisions. The heated propellant molecules gain kinetic energy and undergo an expansion process when passed through a converging–diverging nozzle to generate and deliver thrust to the spacecraft. Such propulsive devices include Helicon, resistojets, arcjets, the variable specific impulse magnetoplasma rocket (VASIMR), and radiofrequency (RF) thrusters, e.g., the electron cyclotron resonance (ECR) thruster. In resistojets the propellant is passed through a resistively heated chamber or element before entering a downstream nozzle [1], whereas for arcjets the heating of the propellant is achieved by its passage through a high-current arc in line with the nozzle feed system. The propellant is weakly ionized in arcjets, making plasma effects on the exhaust velocity insignificant. The specific impulse (I_{sp}) is limited to $< 500\text{ s}$ for resistojets, compared to arcjets where the values are up to about 700 s . Tab. 1.3 shows a summary of these thruster classifications and the main physical mechanism for propellant acceleration and thrust generation.

1.4 Ion Engines

In an ion thruster, plasma is generated when a neutral gas (propellant) is ionized, and the resulting ions are accelerated through the grids at the front of the engine (on the downstream part). Direct current (DC) electron discharges and radio frequency (RF) or microwave discharges are commonly used for the primary plasma production in ion engines. Ion acceleration and electron neutralization in these engines are in general similar, but the ones that utilize RF (microwave) ionization techniques for the primary plasma production do not need a discharge hollow cathode or anode power supply. Instead, these use RF or microwave antenna structures, microwave radiation sources and compatible discharge chambers to ionize the propellant gas and then deliver ions to the accelerator structure with applied or self-generated magnetic fields

to improve the ionization efficiency [1].

In the majority of ion engines, electrons from a hollow cathode, for example, positioned within the discharge chamber are confined when they bounce around in the chamber following the magnetic field lines. This happens until they are either lost directly to the anode wall by encountering the finite loss area at the cusps, they cause an ionization or excitation collision, or are ‘thermalized’ by Coulomb interactions with the electrons of the plasma formed.

Fig. 1.4 shows a typical DC-discharge chamber in which ionization is achieved by electron bombardment and the patterns formed on a discharge chamber unit cover of the ALPHIE, the ion engine that will form a core part of this research. Details of this thruster engine will be put forward in the next section.

FIGURE 1.4: An ion engine DC-discharge electron bombardment ionization chamber and the magnetic field pattern due to electron reflecting and loss areas. (a) DC-discharge electron bombardment ionization chamber (b) Pattern due to electron reflecting boundaries and loss areas as obtained on an aluminium cover around a discharge chamber of the ALPHIE (see Section 1.8) engine.

As seen in Fig. 1.4a, a discharge chamber can be viewed as a volume with reflecting boundaries and discrete loss areas for the electrons at the cusps where the magnetic field lines are nearly perpendicular to the surface. Such boundaries are shown by the dotted curves in Fig. 1.4a, with the cusp regions represented by the points of convergence of the curves. An actual image of the same are shown in Fig. 1.4b which are due to the magnetic field created by the magnets surrounding the ALPHIE engine (to be discussed in detail in the next section).

Fig. 1.5 shows a schematic representation of the NASA solar technology application readiness (NSTAR) gridded electrostatic ion thruster that was flown aboard the Deep Space 1 and Dawn spacecraft. Its mode of operation, which is similar to the simple description above, can be summarised as follows: The propellant, which is a neutral gas such as xenon is injected from the back end of the engine into the discharge or *ionization* chamber where the neutral gas atoms are bombarded by electrons produced by a hollow cathode in the same

chamber (see Figure). The neutral gas atoms get stripped of an electron due to this interaction, resulting in positively charged ions.

FIGURE 1.5: How an ion thruster works: a schematic showing the operation principle of a gridded electrostatic ion engine. From: Ref [25]

An *extraction* grid system composed of electrically biased multi-aperture grids – in most cases a combination a negatively charged plate (extraction grid) and a positively charged plate (acceleration grid) closely aligned next to each other and through which numerous concentrically aligned apertures (tiny holes) exist – to produce the ion beam, is at the front (downstream) end of the thruster. This grid system attracts and accelerates positive ions outwards (towards it), accelerating the extracted ions to very high speeds, which are then expelled as an ion beam out of the thruster.

As seen in Fig. 1.5, a second hollow cathode positioned at the front of the thruster just after the extraction grids maintain a steady supply of electrons into the outflowing beam to neutralize the positively charged ions. This neutralization process maintains the potential of the thruster and spacecraft relative to the space plasma potential almost constant. Because of the high mobility of electrons compared to ions, a potential barrier is usually used to prevent the backflow of neutralizer electrons into the discharge chamber. Such electron backflow can have a negative effect on the thruster efficiency, as the high backflow electron current compared to outflowing ion current would result in the wastage of essentially all the electrical power [1].

In this context, a negatively biased grid is used to create the required potential barrier whose minimum (potential well) prevents all but the highest-energy electrons from flowing backwards into the discharge chamber from the beam plasma. The high-energy (“backstreaming”) electron current thus results in

parasitic power loss as it does not add to the thrust, and it can also reduce the thruster functionality by overheating the internal components of the discharge chamber. As will be shown, the design of the ALPHIE (see section 1.8) eliminates the need for an extra deceleration grid, as the backflow of neutralizer electrons is one of its key design features.

An example of a prominent ion engine that has nowadays gained a lot of interest for space missions is the Hall thruster. Fig. 1.6 [1] shows a schematic of a Hall thruster, together with its typical electrical connections and potential distribution. In this Figure, the coupling voltage $V_c = V_d - V_b$ [1] is the difference between the cathode potential V_d and the beam potential V_b . In brief, electrons in this thruster are generated, for example by a hollow cathode, downstream at the end of the thruster. A positively charged channel (the anode) is maintained at a high potential by a power supply. This channel wall (anode) attracts the electrons, which are then accelerated in the upstream direction (towards the thruster channel). In this process, the electrons encounter a magnetic field generated by powerful electromagnets in the thruster, which traps them. The trapped electrons then move perpendicularly to the electric and magnetic fields in circular rings downstream of the thruster channel, with their flow generating a Hall current.

The propellant, such as xenon, is injected into the thruster's channel at low pressure. Collisions between the propellant atoms and some of the electrons trapped in the channel produce ions. The ions experience the electric field that develops between the positively charged channel and the formed ring of electrons, which accelerates them out of the thruster creating a beam of ions. The force imparted to the electron cloud by the ions generates the thrust when it is transferred to the magnetic field, which, in turn is transmitted to the magnetic circuit of the thruster. As the electrons have a high mobility, they are attracted to the ions in the beam and hence an electrically neutral beam emerges out of the thruster.

Hall thrusters rely on the same ionized propellant acceleration mechanism as other ion engines. However, whereas thrust transfer in the other ion engines is due to the electric forces between the propellant ions and the electrostatic grids, a Lorentz force caused by transverse electric (E) and magnetic (B) fields is the origin of thrust in Hall thrusters. The thrust F_T in a gridded ion engine is the resultant force on its two electrostatic grids, which is equal and opposite to the electric forces on the ions, F_i , during their acceleration between the two grids [1], and is given by Eq. 1.14 [1], where E_a and E_s denote the electric fields at the screen and acceleration grids, respectively.

$$F_T = -F_i = -\frac{\varepsilon_o(E_a^2 - E_s^2)}{2} \quad (1.14)$$

Hall thrusters are electrostatic, though they can also be considered to be electromagnetic thrusters since the force transfer is through magnetic fields. The electrons, being confined by the transverse magnetic field, do not move axially. The force per unit area on the electrons acts inwards into the thruster

FIGURE 1.6: Hall thruster electrical schematic and potential distribution. The coupling voltage V_c is the difference between the cathode potential V_d and the beam potential V_b , i.e., $V_c = V_d - V_b$. From: Ref [1].

(upstream), balanced by the Lorentz force. The thrust F_T is equal and opposite to the force on the ions F_i , which is equal to the Hall current force on the magnets F_θ given by Eq. 1.15 [1].

$$F_T = j_\theta \times B = -F_i \quad (1.15)$$

1.5 Applications of electric propulsion

One key sector in which electron propulsion has been extensively employed is in large telecommunication satellites [3]. Electrically propelled thrusters have been used in orbital raising, i.e., to move or eliminate satellites that have outlived their useful life from the geostationary orbit GEO (or also known as the geosynchronous equatorial orbit), to maintain or adjust/correct the inclination of the orbit plane with respect to the equator [3, 5, 26], and lately in small satellite constellations intended for interactive television. HETs, and HEMPT, and GIEs [5–8, 17] have so far been the leading EP technological

concepts employed in telecommunication satellites, especially in Europe.

These thrusters operate in steady state, with typical thrust values < 500 mN; I_{sp} figures from thousands to tens of thousands of seconds – higher than resisto-jets and arcjets; and with electric power consumption in the range of hundreds of watts up to tens of kilowatts. The microwave-based engines such as Helicon and ECR are still in the early stages of development, whereas the low-power micro-propulsion technologies for precise positioning of nano satellites such as FEEP or colloid thrusters are not employed in telecommunication satellites due to their low thrust.

De-orbiting of space vehicles at the end of their lives and moving satellites to avoid collisions with other objects within the orbit can be achieved by use of electric thrusters. A satellite that has outlived its useful lifetime needs to be moved from the GEO, i.e., at orbital altitude of about 35,786 km, as the available space within this orbit is limited. Raising the orbits of such satellites to far altitudes where the possibility of their eventual return to the Earth's atmosphere is limited can be a necessary step to reduce the proliferation of debris in the lower orbits (LEO – the low Earth orbits and MEO – the medium Earth orbits) [3, 26].

Once in the geosynchronous (transfer) orbit (GSO), a velocity increment of about $\Delta v \approx 1.5 \text{ m}\cdot\text{s}^{-1}$ is needed to transfer a satellite to the quasi-circular GEO. Such a raising process requires the orbit plane with respect to the inclination of the equator to be constantly adjusted/corrected [3, 5, 26] due to effects of lunar and solar gravitational interactions and/or the irregular distribution of the Earth's mass which can affect the satellite's orbital motion. Compensation for such orbital perturbations (North-South and East-West station keeping, i.e., NSSK and EWSK, respectively [27]) throughout the mission (lasting 15–20 years) is therefore paramount. Low thrusts (about 80–100 mN) are required for such corrections and need to be supplied daily. In such cases electric thrusters are the obvious choice and Hall Effect thrusters (HETs) have played an important role in such corrections in the past decades [3]. HETs have also been used to boost geostationary communications satellites once they have run out of fuel for de-orbiting to graveyard orbits. Such in-orbit corrections also play a crucial role in ensuring that the uplink and downlink high-gain antennas of telecommunication satellites point in precise directions [5, 26].

Electric propulsion is also employed in GPS systems in the medium Earth orbits (MEO) at altitudes of 2,000–36,000 km. In the LEO (at altitudes of 160–2,000 km), constellations of interconnected small satellites intended for interactive television and planetary internet coverage are being deployed, where projects such as SpaceX, OneWeb, O3b, Starlink, and so on using groups of up to 1,000 satellites that communicate with the Earth's surface through mass-produced, low-cost terminals have emerged. Electric propulsion has provided the proven useful propulsive technology necessary for continuous operations needed to compensate for the orbital drag force in the LEO where long term interaction with the atmosphere, however small, exists. For orbital maneuvers, station keeping, flight formation and the end-of-life disposal of these

very many small constellations of satellites (weighing 50–250 kg), low-power in-space electric propulsion that requires thrust of about 0.1–10 mN and electric power < 500 W can be a necessary solution. New concepts and continued development of such low-power thrusters are emerging [28, 29] to meet this technological challenge.

For on-board propulsion from the GSO, EP has been used as the main source of thrust necessary for the maneuvers to reach the GEO. Despite the long duration required for an orbit raising maneuver (up to about six months as opposed to about a week when conventional chemical propulsion is used), the mass fraction advantage possessed by EP (about 40 % reduction in weight compared to chemical propulsion) allows for more payloads, which enables the delivery of other services to customers [3].

1.6 Scope of this Dissertation

An outstanding characteristic of plasma thrusters for space propulsion is the acceleration of ions to supersonic speeds. Since the overall thrust generated by a plasma engine depends on the momentum imparted to the outflowing ion beam [30–33], it is thus important to determine the spatial distribution of the parameters of the thruster-expelled high-velocity plasma streams. The main objective of this research is therefore to characterize the plasma streams produced by a prototype of the low-power plasma thruster – the alternative low power hybrid ion engine (ALPHIE). The ALPHIE plasma thruster is a new alternative technology of a low-power thruster that is hybrid between HET and GIE, developed within the Universidad Politécnica de Madrid plasma laboratory. This new technological concept was recently granted a patent [28, 29].

Studies will be conducted to test, and in a way evaluate the performance of this thruster. These tests will include among other things, the achievable thrust, specific impulse produced [30], power consumption, etc, of this thruster. Such tests complement the design tests that ought to be completed before a propulsion system is qualified for a space mission or application. The thrust test measurement was done, though the results have been intentionally left out in this report.

The ions in the ALPHIE are produced by electron impact inside the ionization (discharge or plasma) chamber, where electrons are strongly magnetized. The ionizing electrons remain trapped by the magnetic field (B -field) lines whereas the unmagnetized ‘massive’ ions flow out of the plasma chamber. The electrons are emitted from a thermionic cathode, forming a plasma stream that imparts the momentum to, and also neutralizes, the ion beam. The spatial structure and physical mechanisms involved in the subsequent expansion of the plasma stream are still not well understood. The interplays among different collisional processes (electron-neutral, ion-neutral, etc) produce complex phenomena. For example, this is the case with the collisionless electron cooling

reported in Ref. [31] during the neutralization and expansion of the plasma stream.

In the research work reported here, this feature has been investigated using the ion energy distribution function (IEDF) of the engine's exhaust plasma streams in connection with the modes of operation of the plasma thruster. The spatial structure and the physical mechanisms involved in the plasma stream expansion, the ion energy relaxation processes in them, as well as the interplays among different collisional processes (electron-neutral, ion-neutral, etc) in the plasma are important characteristics of a plasma plume that are investigated here.

As a first step, a retarding-field energy analyzer (RFEA), also referred to as retarding potential analyzer (RPA), that enables the characterization of the properties of the plasma plume, including the ion energy and/or velocity distribution [34,35] is designed and developed. This new diagnostic technique (together with others already available, such as the emissive and collecting Langmuir probes [31,32]) in the laboratory from where the research is conducted, are used for the physical characterization of the plasma stream. These three diagnostics used together make it possible to measure most of the important plasma parameters, such as the electron density, n_e , ion density, n_i , plasma potential, V_{sp} , and the distribution of ion and electron energies.

To have a more complete diagnostic of the plasma plume, point-wise measurements using a combination of the three diagnostics mentioned above are made in order to obtain the spatial profiles of plasma properties. A computer-controlled 3D robotic positioning or displacement system is designed for this purpose, whose details are discussed in Section 2.5 of Chapter 2. The spatial dependence of these plasma properties are therefore measured by means of a three-dimensional (3-D) positioning system that makes it possible to locate the probes within the plasma volume. The first scientific objective is the assessment of the collisionless cooling observed in the experiments reported in Ref. [31] along the axial direction of the expansion and its relation with the ion energy spectrum. Finally, the general technical aim is to optimize the velocity component of the expelled ion streams along the axial direction, as opposed to the radial components. This implies minimizing the divergence of the ion beam and thus energy losses.

In the main experimental investigations reported here, a retarding-field energy analyzer (RFEA) (which will be discussed further on page 57 of Chapter 3) is used to measure the ion energy distribution function (IEDF) of the ALPHIE plasma plume. The design and development of a four-grid RFEA and its application in IEDF measurement are described and discussed in detail in the Chapter 2. The developed RFEA is also demonstrated to provide information on the expansion of the plasma plume and the possibility of controlling the energy distribution by at least one of the beam control parameters. The measurement results from this research can serve as an important or necessary input for the assessment of the extension of the thruster plume and its eventual interaction with the spacecraft surfaces and onboard payloads.

1.7 Low-power electric thrusters

This research focuses mainly on EP systems for small and medium-sized DC-powered satellites operated in steady state, which include the low electric power versions of GIEs [1,5], HETs [1,5] and the multi-cusped field thrusters (MCFTs) [5,12–16], such as the HEMPT [15,16] (see section 1.3 on page 9).

These EP systems require electron sources (*active* cathodes) such as hollow cathodes or thermionic electron emitters [1,36,37] for the ionization of propellant and space charge neutralization. In some designs, the electrons for collisional ionization of the propellant gas atoms is produced by a cathode positioned inside the discharge or ‘plasma’ chamber with two or more grids used to extract and accelerate the ions to high speeds enhanced by the electric potentials of the accelerating grids (as is the case in GIEs, also referred to as Kaufman thrusters). An additional cathode disposed beyond the grids then provides the electrons that neutralize the outflowing ions [1,5–7].

In such cases primary plasma production, ion acceleration and space charge neutralization are independent processes. A cylindrical discharge chamber is used in gridless HETs [1,5–7], and is made of non conductive material. An annular anode is then placed at its closed end. A radial B field is created inside the discharge chamber by a pole configuration about the central axis of the system, with a second and different counter-pole magnet surrounding it on the outside. The only electron-emitting cathode in the Hall thruster design is therefore located outside the discharge chamber. The produced electrons spread in two directions; inwards to the discharge chamber and also along the direction of the plasma beam to neutralize the outflowing ion beam [1,5–7].

The radial B field generated inhibits the axial electron motions and thus confines the electrons along ring-shaped drift paths into the discharge chamber. The ions are accelerated by the electrostatic field produced by the concentration of electrons close to the open end of the discharge chamber and the high voltages applied between the anode and the electron-emitting cathode [1,5,7]. The thrust, 10–100 mN, is higher than the amounts achievable in GIEs, but with lower specific impulses $I_{sp} \sim 1500$ s. The HET configuration is simpler than that of GIEs, and requires fewer power supplies (less power) to operate in addition to only one *active* cathode [1,5,7].

As in the HETs, MCFTs [5,12–16] also have a non-conducting cylindrical discharge chamber, but with the electron source placed in front of its open side. The anode is also at the closed back end of the discharge chamber on the external surface of which ring-shaped permanent magnets with alternate polarities are mounted. One or more annular electrodes are successively distributed longitudinally on the internal surface of the chamber [5,12–16].

The plasma discharge is produced by biasing the electrodes with respect to the electron-emitting cathode. Electron confinement is by the longitudinal B field along the axis of symmetry, to increase the electron impact ionization rate in the chamber. The ions are accelerated by the multi-stage electric field established by biasing the electrodes with voltages of magnitudes that lie be-

tween the anode and the *active* cathode potentials. Specific impulse values reported for HEMPTs [5,15,16] are in the range $I_{sp} \sim 2500\text{--}3000\text{ s}$ whereas the typical thrusts are in the range $40\text{--}100\text{ mN}$ [5,12–16]. It is therefore possible to achieve very high specific impulse or propellant mass efficiency with these thrusters. However, the relatively low thrust produced by ion thrusters as compared to the other thrusters still limits their usage to only spacecraft that have already reached space, and they cannot be used to launch vehicles from the Earth into space.

1.8 The ALPHIE

As briefly mentioned in the previous section, the “alternative low power plasma ion engine” (ALPHIE) presents a new concept of a low-power thruster (ion engine) that was recently granted a patent [28,29]. It is a new alternative technology of a low-power thruster that is hybrid between HET and GIE that was developed within the Universidad Politécnica de Madrid plasma laboratory from where this research has been conducted. The experiments referred to here were conducted on the ALPHIE thruster, being an almost novel kind of ion thruster.

FIGURE 1.7: The Alternative low power hybrid ion engine (ALPHIE) electrical schematic [38]

Fig. 1.7 shows a scheme of the ALPHIE cross section along the axis of

symmetry of the small (10 cm diameter and 14 cm length) plasma engine, a CAD drawing of which is shown in Fig. 1.8. The ALPHIE primary (engine) plasma is generated within a discharge unit, using an electron beam in an argon gas medium. The electrons are produced by thermionic emission from a tungsten wire cathode at the front (*exhaust*) of the thruster engine, positioned just outside the last (cover) grid.

FIGURE 1.8: Engineering drawing of the ALPHIE plasma thruster mounted to its DN100 ISO-K vacuum flange. The front grids, neutralizer wire and the magnetic insulation casing are not shown.

Primary charge production is by collisional impact ionization in the engine. The wire cathode emits electrons when heated, which are used both for plasma production in the argon-filled discharge chamber and for neutralizing the plasma exiting the engine. The source of electrons, and indeed the only one in this thruster, is therefore thermionic emission from the thin tungsten wire supplied with a current $I_{\text{NH}} = 2\text{--}5\text{ A}$ [38]. For most of the experimental sessions, the cathode tungsten material employed was 99.95 % pure with a diameter between 0.08 and 0.25 mm.

Part of the produced electrons also serve to neutralize the out-flowing ions, whereas the rest flows back into the discharge chamber due to the electric field between the chamber anode and the plasma stream outside the exit. Unlike in other almost similar design of low-power electric thrusters such as GIEs described in Section 1.7 above, this new design makes deliberate use of the backflow of the neutralizer electrons for the primary plasma formation. While in the engine chamber, electrons are confined by the B field present in the discharge unit. Because of the high vacuum created in the chamber, the probability of successful collisional ionization of the confined electron beam increases. This is the source of the primary plasma. The ALPHIE thruster design is aimed towards achieving reasonable thrust by plasma acceleration.

The cylindrical stainless steel discharge chamber has diameter $r_c = 4\text{ cm}$ and is 10 cm long with one open end. To the front of the open end are two parallel metallic grids, which will be denominated *extraction* and *cover* grids respectively in the rest of this report. For most of the initial experimental campaigns, molybdenum wire grids were employed. The grids form meshes of 57.8 % open area, and are comprised of 0.97 mm thick wires. The grids

are kept vertically aligned, with their mesh apertures horizontally aligned to facilitate the flow of charged particles through them. These grids are separated at 2.0 mm from one another and are electrically insulated from other elements by ceramic spacers. The propellant neutral gas can be either argon or xenon, but Argon has been mainly used in the experiments referred to here. The gas is introduced into the discharge chamber through a 3 mm-diameter pipe connected to the ceramic break connector shown in Fig. 1.7 to electrically insulate the gas feed system from the thruster body.

As already mentioned, the only electron source of the scheme in Fig. 1.7 is outside the discharge chamber. This *active* cathode can be of different forms, such as hollow cathodes, dispenser cathodes, or thermionic electron emitters. It is in this case used to ionize the argon gas in the discharge chamber and for neutralization of the outflowing ion beam. The electron source is a thoriated tungsten wire of 0.25 mm thickness, which is heated to thermionic electron emission by a DC current. The plasma engine is therefore the only source of heavy ions in the experiments discussed throughout this report.

In the Fig. 1.7, the positive DC voltage V_{AC} (varied between 400 and 650 V) is used to electrically bias the *active* cathode with respect to the conductive walls of the plasma chamber [38]. This electric bias potential pulls a fraction of the emitted thermionic electrons inwards through the open spaces in the grids. When the cover-grid voltage $V_{CG} = 0$, the front grid is transparent to the counter flow of ions and electrons from the *active* cathode. However, negative V_{CG} voltages disrupt the ionizing electron inflow and thus can be used to interrupt the electric charge production.

Additionally, the current through the cover-grid I_{CG} in Fig. 1.7 is small because of the low capture of electrons and ions by the thin mesh wires. The two *passive* cathodes of the scheme in Fig. 1.7 are electrically connected: First, the *central* cathode is a metallic disc, 5 mm in diameter, electrically insulated from the discharge chamber walls by a ceramic support which keeps it concentric with the system's discharge chamber. The second is the *extraction* grid which lies in front of the open end of the discharge chamber.

The DC ion extraction voltage V_{EG} (typically 100–200 V) maintains an electric field between the two passive cathodes and the conductive walls of the plasma chamber. Electrons are thus returned back by the *ion-extraction* grid whereas the more massive ions are attracted towards its open spaces and to the small *central* cathode. The discharge current I_{EG} is a measure of the flow of charges between the metallic discharge chamber walls and the two passive cathodes. Because of the efficient electron confinement by the B field and owing to the low ion losses at the passive cathodes, the current I_{EG} is minimal.

The B field inside the plasma chamber is produced by three concentric crowns made of eight high-temperature permanent magnets each and a last ring shaped magnet placed at its closed end. The metallic discharge chamber is transparent to the B field produced by these magnets surrounding it. The magnets, with a precise circular shape, were manufactured from samarium–

cobalt alloy (SmCo 2 : 17) with a surface magnetic induction of about 350 mT. These magnets are fixed with bolts to the structure shown in Fig. 1.8 to keep them separated 0.5 mm from the external surface of the discharge chamber.

The poor thermal contact improves the thermal stability of the magnets which are maintained at minimal or no irradiation damage since they are not exposed to the plasma. As shown in Fig. 1.7, the magnets have alternate polarities along the axial and tangential directions, with the pole of each magnet opposite to that of the adjacent one. The B -field lines bend inside the plasma chamber, connecting the surfaces of the neighbour magnets placed outside.

The maximum measured B -field strength in the inner surface of the discharge chamber reaches a value of 150–250 mT at the cusps facing the magnets. This field strength decreases to 25–50 mT at the space between two successive magnets [38]. The lowest values, 1–10 mT, were measured along the centerline of the discharge chamber. For ionizing-electron energies in the range 400–600 eV, the typical gyroradii are $r_e \sim 0.2$ –0.4 mm for points close to the cusps, increasing to $r_e \sim 2.0$ –4.0 mm between two magnets. Over the centreline of the discharge chamber $r_e \sim 0.5$ –60 cm. The diameter of the plasma chamber $D \ll r_i$ is always smaller than the minimum Larmor radius $r_i \simeq 5$ cm for singly charged argon ions with these energies.

Hence, electrons are magnetized inside the discharge chamber whereas the motion of heavy ions remains predominantly driven by the electric fields. The ionization rate increases because the electron drift motion is confined by the banana-shaped B -field lines along the tangential and longitudinal directions inside the discharge chamber. Damage and sputtering produced on the inner surface of the plasma chamber is limited to the cusp B -field regions. Finally, a magnetic field proof casing encloses the thruster body to shield the nearby equipment from the intense magnetic fields.

In summary, the plasma thruster works as follows: The ionizing electrons from the *active* cathode enter the discharge chamber and are accelerated by the voltages V_{AC} and V_{EG} to high energies above the ionization threshold of the propellant neutral gas. These electrons are further confined within the discharge chamber by the intricate pattern of B -field lines. This combination of electron trapping and acceleration increments collisions with neutral atoms and the ionization rate of the neutral gas. The ions on the other hand are unmagnetized and move along the electric field lines. The configuration with two passive cathodes of the scheme shown in Fig. 1.7 focuses an important fraction of the positive ions in the discharge chamber towards the *ion-extraction* grid. For the experiments conducted during this research, the operational thruster current I_E for which plasma production can be achieved was 100–500 mA. This current results from electrons collected at the plasma chamber walls and can be used as a rough estimate for the charge production inside the plasma chamber. It is dependent on three factors: the acceleration potential V_{AC} , the propellant (argon) mass flow rate Q , and the inflow of ionizing electrons from the cathode which in turn is controlled by the cathode (neutralizer) wire temperature.

The neutral gas (argon) mass flow rates were $Q \leq 1.5$ sccm and the cathode

(neutralizer) heating power $P_{\text{NH}} = V_{\text{NH}} \times I_{\text{NH}} < 76 \text{ W}$. Finally, the thruster current $I_{\text{E}} \gg I_{\text{CG}} \simeq I_{\text{EG}} \simeq 0$ accounts for the counterflow of positive and negative charges through the grids and also for the electron flow required to neutralize the ion beam. The resulting plasma stream moves in the direction indicated by the thick arrow on the scheme in Fig. 1.7.

Chapter 2

Plasma Diagnostics and Electric Probes

2.1 The concept of plasma

Ordinarily speaking, plasma can be defined as the fourth state of matter consisting of an electrically neutral gas of charged and uncharged particles that are electrically conductive. The state is got when sufficient energy is provided to a gas, for example by heating or subjecting it to a strong electric field to which accelerates and scatters free electrons thus heating it. More scientifically, a plasma can be defined as a quasineutral gas which contains charged and neutral particles that exhibit collective behaviour [39].

In other words, the presence of charged particles in a plasma means that local concentrations of charges and their motions can lead to force fields (electric or magnetic) in the plasma which affect the motion or behaviour of other charged particles in the rest of the plasma volume (globally). These are Coulomb interactions which are long range. The force effects are thus felt even far away from the local source, hence the notion of non-local (collective) behaviour of a plasma, i.e., dependence of the plasma particle motions not only on local conditions but on the state of the plasma in even its remote regions [39]. Most of the plasma properties are therefore a result of collective properties from simultaneous interaction of many particles.

2.2 Plasma diagnostics

Plasma diagnostics thus refers simply to the determination of plasma parameters, usually with the objective of deducing information about the state of the plasma. It involves measuring a physical quantity of the plasma by expressing it as an easily observable physical variable using a suitable device or instrument – a diagnostic method. This is a very active branch of experimental plasma physics and research which focuses on the determination of plasma physical parameters such as particle number density, ionization degree, plasma frequency,

plasma potential, and so on. These parameters are inevitable in plasma studies, as a good understanding of their values is fundamental in different plasma applications like material processing and as inputs into simulation of different plasma phenomena.

The methods/techniques that provide information on the state and/or parameters of a plasma are referred to as *diagnostic techniques* whereas the process of obtaining this information is *plasma diagnostics*. This involves the devising, development of, and proof or verification of the techniques for diagnosing plasmas properties.

Due to the wide span in orders of magnitude exhibited by plasma physical properties such as electron density, n_e , and temperature, T_e , whose values can be $n_e \sim 10^0\text{--}10^{20}$ and $T_e \sim 0.1\text{--}10^7$ units respectively, different diagnostic methods are required depending on the characteristic time, length, and particle number scales considered [34]. A good knowledge or understanding of the plasma phenomena is of utmost importance in determining the techniques to apply and for correct interpretation of the results derived from them. It also forms the basis for most innovations in this field. Plasma diagnostics is therefore paramount in any study involving plasmas, such as the one we are currently involved in.

Different probes and methods have been developed and used [33, 34, 40–44] in the determination of plasma parameters in different settings of plasma conditions, ranging from low-temperature laboratory plasmas to even very high energy plasmas such as those in fusion.

The underlying physical principles of processes that enable plasma measurements can be used to classify the diagnostics into one of the following [34]: methods for plasma particle flux measurement, plasma refractive index methods, magnetic methods, those based on electromagnetic radiation from electrons, electromagnetic wave scattering, probe plasma diagnostics, optical and laser probe diagnostics, particle measurements, etc. These could also be categorised, depending on the methods of particle/radiation detection, into passive (remote sensing of incoming radiation) or active (contact as in electric probes or non-contact as is the case in scattering of electromagnetic radiation or beam particles) methods [44].

Passive methods the plasma is not perturbed by the measurement, for example the measurement of radiation emitted by a plasma, whereas active methods directly involve the plasma in the measurement, e.g., microwave transmission in a plasma [45]. Finally, the naming of the diagnostic methods may also be based on the branches of physics from which the principle of the method is derived such as: X-ray diagnostic methods, spectroscopic diagnostic methods, microwave diagnostic methods, etc.

Because of limitations associated with the nature of different plasmas, not all measurements can be achieved in all plasmas. Thus, it is not possible to use all the diagnostic methods in all plasmas. For example, the use of material probes that measure direct plasma flux may not be applied to the core of fusion plasmas. Also, the quantity to be measured should be reasonable and

not negligibly small, as this jeopardizes the quality of the information obtained from the measurement.

2.2.1 Plasmas of interest

Different kinds of plasma exist in nature, such as astronomical and astrophysical plasmas and terrestrial plasmas, whereas some plasmas can be artificially generated. Stellar interiors and atmospheres, interstellar hydrogen, the flash of a lightning bolt, polar aurorae, polar wind, the Van Allen radiation belts, solar wind, and gaseous nebulae are all made of naturally occurring plasmas, including ionospheric and magnetospheric plasmas. Within the Earth's atmosphere, plasma examples include the Aurora Borealis glow, conducting gas inside a fluorescent tube and/or neon signs.

Aside from the differences in the nature of their existence, a very important feature in characterizing plasma is the degree of ionization (or fractional ionization) in the plasma. This, for a gas in thermal equilibrium at temperature T K, is determined by the Saha equation, given by Eq. 2.1,

$$\frac{n_i}{n_n + n_i} \approx \frac{n_i}{n_n} \approx 2.4 \times 10^{21} \frac{T^{3/2}}{n_i} \exp\left(\frac{-U_i}{k_B T}\right) \quad (2.1)$$

where n_i and n_n denote the number density in m^{-3} of ionized and neutral atoms, respectively, and U_i is the minimum energy required to remove an electron from the outermost shell of an atom, i.e., ionization energy, of the gas in joules. For full ionization, and thus plasma formation, the gas temperature ought to be high enough so that $U_i > k_B T$ by a few multiples, which happens when T is very high (up to millions of degrees) [39] consequently making n_n less than n_i .

Specifically of interest to the research presented here is the plume plasma from a thruster (ALPHIE) exhaust, which is mainly applied to space research. The ALPHIE, in particular, produces low thrust (in the order of a few mN) and requires high vacuum levels for proper operation. This means that the out-flowing plume it produces consists of high-speed, low-energy plasmas. With $T_e \sim 1\text{--}5\text{ eV}$ and $n_e \sim 10^8\text{--}10^{10}\text{ cm}^{-3}$, possible diagnostic techniques used to characterize such plasma include electric probes, optical techniques (spectroscopic or fluorescence monitoring), thermal techniques, etc. We however concentrate on the use of the electric probes as opposed to the other relevant techniques, because of our limited budget and the availability within the time frame of the research.

2.2.2 Parameters to characterize thruster performance

A crucial feature of thrusters for space propulsion applications is the acceleration of ions to supersonic speeds. This means the plume plasma is a high-velocity flow stream, with the parallel component of the velocity much higher than the ion sound speed c_{is} . Also, mesothermal [41, 46, 47] plasma flow – one

in which the expelled plasma jet emerges with speeds that are intermediate between the electron and ion thermal speeds – has been of great interest in recent plasma flow studies, and are of crucial importance in electric propulsion and spacecraft–plasma interaction studies [48–50].

Characterizing the plasma jet produced in thrusters for space propulsion involves the diagnostics of such plasma streams, which is complex. An important strategy is to use different diagnostics – a multiprobe approach has been adopted to this effect. A key parameter in characterizing an ion beam is the ion energy spectrum/distribution function (IEDF).

The research presented here involves mainly the measurement of IEDFs of the exhaust jet plasma streams, with an attempt to investigate the relationship between these measurements and the operational modes of the plasma thruster. Also, plasma parameters such as plasma potential V_{sp} , electron temperature T_e , the plasma/electron density n_e , and the Debye length λ_D – of which attempts to measure are made in this research – are necessary in our attempt to fully characterize the operation of the ALPHIE thruster.

2.2.3 Electric probes for plume-plasma diagnostics and characterization

In the attempt to characterize the plasma streams from the ALPHIE, one of the main objectives of this Ph.D. research, techniques/diagnostics are developed for measuring ions from such high-velocity, low-density and energetic plasma streams. Because of the characteristics of plume plasmas (low ionization degree, low electron temperature, low density, no magnetic fields used to confine the plasma once ejected from the thruster, etc) and the presence of charged particles in plasmas generally, the use of electrostatic (particle collecting or emitting) probes/detectors for high-resolution spatial measurement of ions as they leave the thruster, and thus the energy distribution in the plume plasma, is preferred. These are electric probes and still stand out to be essential in the determination of critical plasma parameters.

A diagnostic that makes use of simple and versatile tools for the study of the plasmas – *electric probes* – is used in measurements described here. Electric probes refer to those probes that collect charged particles from or emit them to the plasma in which they are immersed or facing. These probes take advantage of plasma being composed of electric charges that are easily detected by the charged, charge-emitting, or charge-collecting probes. It is important to note that in the use of these probes a common assumption is usually that the disturbance caused by the probe’s presence remains localized and thus introduces minimal effect on the measured quantities over a wide range of conditions [51]. However, this may not necessarily be the case in the measurements described here. Such probes involve using a conducting object directly in contact with the plasma to detect the particle fluxes [44, 52–56] for carrying out the diagnostics.

For the research presented here, diagnostics for measuring the particle

(especially ion) distribution functions and densities of the cold, low density plume plasma generated by the ALPHIE thruster have been designed and constructed. A combination of mainly three electric probes has been used in the experiments: (i) a retarding-field energy analyzer (RFEA), (ii) a Langmuir probe (LP), and (iii) an emissive probe. Plans had also been made to complement the measurements, to be able to make comparisons of the results obtained, by designing a Faraday probe. However, due to time and other experimental constraints, the whole Faraday probe idea, its building/construction, and thus use in this research had to be abandoned later on. I have therefore decided not to include any further information about the Faraday probe in this report, though it may appear in some figures for example the multiprobe platform where a spot had been included for its mounting.

The three electric probes are briefly described in the sections that follow. It is important to note that for the interpretation [57] of the probe data simplified cases are used, while limiting complex theoretical considerations that would be the cases in chemically reactive, dusty, strongly magnetized, or fully ionized plasmas. Thus, the discussions involving viscous or anomalous transport processes, for example, in the calculation of probe currents are not included.

2.3 Langmuir probe

A Langmuir probe, named after its founder Irving Langmuir, was one of the earliest and is still one of the simplest and most localized plasma diagnostic tools [58]. It remains one of the most widely used plasma diagnostics probe to date, especially in the semiconductor industry where plasmas for etching and deposition are produced by radio-frequency (RF) sources [59]. The probe construction and theory need to be handled with great care and technique, as has been presented in various reviews and publications [34, 57, 60, 61].

2.3.1 Application to plasma diagnostics

Plasma measurement by a Langmuir probe involves introducing an electrode into the plasma and measuring the current that gets to it for different applied probe voltages [57]. The Langmuir probe technique of plasma diagnostics is therefore intrusive, and careful considerations have to be made during its design and application so as not to interfere with or perturb the plasma. The geometry of the probe should be such that its dimensions are smaller than the Debye length, and yet large enough to drain a measurable electric current from the plasma. The choice depends, to a great extent, on the plasma density. Also, it can be damaged by the plasma and thus, besides the design consideration, care has to be taken during its usage. Lastly but not least, the interpretation [53] of the measurement data to extract meaningful and accurate information about the plasma is not straightforward.

When the probe bias potential is varied, important plasma parameters such

as the electron temperature T_e , electron/plasma density n_e , plasma potential V_{sp} and the electron and ion beam energies can be derived from the current–voltage (I – V) characteristic obtained with it [57, 62]. It cannot however be used to measure ion temperature and hence the ion velocity distribution since the ion current is not sensitive to the ion temperature T_e [39, 57, 58].

The key challenge with these probes is in the interpretation of I – V curves. This has never been very easy and it has been a major interest area, as is evidenced by the numerous literature of theoretical papers dedicated to its analysis [57, 61–73]. During the use of Langmuir probes in measurements, care needs to be taken to measure fluctuations in the plasma potential that are in most cases faster than the possible sweep time [74]. It is therefore necessary that the bias voltage is swept over a wide range for a more accurate plasma potential V_{sp} determination [39].

2.3.2 I – V characteristics

Depending on the electric bias potential V_{probe} of the probe, a Langmuir probe drains the current $I(V_{probe})$ of ions, electrons, or both electrons and ions [72]. A Langmuir probe I – V characteristic curve is obtained when the measured currents I are plotted as a function of the probe bias voltages V_{probe} , i.e., $I(V_{probe})$. On practical grounds, the interpretation of the probe I – V characteristics usually relies on simplifying assumptions.

From a further analysis of the resulting I – V curve, the local plasma potential V_{sp} , ion density n_i , and the electron density n_e can be obtained. The electron temperature T_e can be determined in the special case of isotropic plasma the electron velocity distribution function (EVDF) $f(v)$ whereby the voltage swept is determined by the electron temperature. This may not actually be the case in the ALPHIE plasma plume, but isotropy is assumed for simplicity so that the one-dimensional distribution of plasma electrons is taken to be Maxwellian [39], i.e., $f_M(v)$ given by Eq. 2.2.

$$f_M(v) = \left(\frac{m_e}{2\pi k_B T_e} \right) \exp \left(-\frac{m_e v^2}{2k_B T_e} \right) \quad (2.2)$$

where m_e is the electron mass, and k_B is the Boltzmann constant.

The electron density n_e (in m^{-3}) is related to $f_M(v)$ through

$$n_e = \int_{-\infty}^{+\infty} f_M(v) dv. \quad (2.3)$$

For incident electron flux in the Z -direction reaching the probe normally, the contribution to the total flux entering the probe is mostly due to the Z component of velocity, v_z . The distribution of v_z can then be given, using Eq. 2.2, as [75]

$$f(v_z) = \frac{1}{v_{th} \sqrt{\pi}} \exp \left(-\frac{v_z^2}{v_{th}^2} \right), \quad (2.4)$$

where $v_{th} = (2k_B T_e / m_e)^{1/2}$ is the electron thermal velocity.

Fig. 2.1b shows a typical characteristic I - V curve, which can be obtained from a low-pressure plasma whose electrical circuit is connected as in Fig. 2.1a.

(a) Electrical scheme for Langmuir probe measurement of glow-discharge plasma. A spherical probe is shown by letter P. [From Refs. [76–78], reproduced with permission]

(b) Langmuir probe I - V characteristic curve from a glow-discharge plasma. [76–78]

FIGURE 2.1: Langmuir probe plasma diagnostics and data analysis.

It is important to note that the I - V curve is plotted with the signs of the currents reversed, i.e., I_e positive and I_i negative.

2.3.2.1 T_e , n_e , V_{sp} and electron energy distribution EEDF from Langmuir probe I - V characteristics

Many reviews have been published on the interpretation and analysis of measured Langmuir probe I - V characteristic curves. The conventional Langmuir probe theory, which applies to thin-sheath collisionless plasmas when achieved with low pressures, is reasonably understood [61]. Plasmas with such conditions have large particle collisional mean free paths, λ , due to the low pressures such that the probe radius r_{probe} is very small compared to the mean free path, i.e., $\lambda \gg r_{\text{probe}} \gg \lambda_D$, where the Debye length λ_D is given by Eq. 2.5.

$$\lambda_D \equiv \left(\frac{\varepsilon_0 k_B T_e}{n_e e^2} \right)^{1/2}. \quad (2.5)$$

Here a spherical probe is used under very low pressures such that the plasma is collisionless and forms a thin sheath, i.e., one in which the Debye length is much shorter compared to the probe radius such that $r_{\text{probe}}/\lambda_D \gg 1$, around the probe. The Langmuir probe analysis used here is therefore based on the conventional Langmuir probe theory for a collisionless plasma under the thin sheath approximation. It is important to note that not all details have been considered in applying the conventional probe theory, such as the effects of the probe shaft illustrated in Fig. 2.6 on page 43 and the fact that we are dealing with plasma flows. To elaborate the conventional Langmuir probe theory, the measured I - V characteristic from Fig. 2.1 is used.

2.3.2.2 Plasma potential V_{sp}

The plasma potential is taken to be at the “knee” of the I - V curve [57,79,80], indicated by the point C in Fig. 2.1b. However, V_{sp} determination by this method may not be straightforward especially in plasmas with collisions and strong E fields as in magnetized plasmas (see paragraph 2.3.2.3 for details) where the “knee” is rounded. Additionally, inaccurate results would be obtained if the work function of the probe surface changed, as can be the case when it is contaminated [80], and the probe’s applicability in drifting plasma electrons fails [57,81–83].

The determination of V_{sp} then becomes difficult, and a further analysis (see Section 2.3.2.8 on page 38) is required, otherwise the use of other probes such as emissive probes (see Section 2.4 on page 44) becomes more useful. This is a limitation/shortcoming of using Langmuir probes for V_{sp} measurement. A typical I - V characteristic curve from an unmagnetized plasma can be divided into three parts I, II and III, as shown on the graph in Fig. 2.1b.

2.3.2.3 Region I/Ion collection region (V_{probe} more negative than V_{sp}):

When the probe is at a much lower potential than the plasma, i.e., $V_{\text{probe}} \ll V_{sp}$, an ion current I_i is collected by the probe, in which case the probe current is

positive (region I on curve of Fig. 2.1b).

2.3.2.4 Ion saturation current (I_{is}):

To the far left of point A on the curve, the probe has repelled all the electrons and a positive ion sheath is created around it [67, 84]. Due to the negative charge on the probe, this sheath screens the electric field from extending beyond its edge, while allowing all the positive ions reaching it to be attracted to the probe [67, 84]. The ion current I_{i} is given by

$$I_{\text{i}} = n_{\text{sh}} A e c_{\text{s}}, \quad (2.6)$$

where A is the probe surface area exposed to the plasma ($4\pi r_{\text{probe}}^2$ for a spherical probe), n_{sh} is the plasma density at the sheath edge, and $c_{\text{s}} = (k_{\text{B}} T_{\text{e}}/m_{\text{i}})^{1/2}$ is the ion acoustic speed – the minimum velocity to which the ions must be accelerated by the pre-sheath E field to form a sheath [39, 58] – for ion mass m_{i} .

Acceleration of ions to this velocity requires that the magnitude of the sheath-edge potential ϕ_{sh} relative to the plasma potential V_{sp} is at least $\frac{1}{2}k_{\text{B}}T_{\text{e}}/e$ [58, 75], i.e.,

$$\phi_{\text{sh}} \simeq -\frac{k_{\text{B}}T_{\text{e}}}{2e}. \quad (2.7)$$

The sheath plasma density n_{sh} can thus be expressed in terms of this potential, for a plasma with Maxwellian electrons, as

$$n_{\text{sh}} = n_{\text{e}} \exp\left(\frac{e\phi_{\text{sh}}}{k_{\text{B}}T_{\text{e}}}\right) = 0.61n_{\text{e}}. \quad (2.8)$$

For a probe surface large enough compared to the thickness of the sheath formed, the measured ion current is truly representative of the ion current density in the plasma. Its value remains almost constant, independent of the magnitude of the applied probe voltage V_{probe} . The probe thus collects the ion saturation current I_{is} . By the Bohm sheath criterion [58, 75], the ion saturation current I_{is} can be approximated from the Bohm current I_{B} .

$$I_{\text{B}} = 0.61n_{\text{e}}Aec_{\text{s}} \quad (2.9)$$

$$\simeq \frac{1}{2}n_{\text{e}}Ae\left(\frac{k_{\text{B}}T_{\text{e}}}{m_{\text{i}}}\right)^{1/2} \quad (2.10)$$

$$(2.11)$$

That is,

$$I_{\text{is}} \simeq \frac{1}{2}n_{\text{e}}Ae\left(\frac{k_{\text{B}}T_{\text{e}}}{m_{\text{i}}}\right)^{1/2}. \quad (2.12)$$

2.3.2.5 Floating potential V_f – Point B ($I_e = I_i$):

The floating potential V_f is where the electron and ion currents are equal, i.e., at zero net probe current (point shown by B on the I - V curve). From Eqs. 2.6 and 2.15, V_f is thus given by

$$V_f = V_{sp} - \frac{k_B T_e}{2e} \ln \left(\frac{2m_i}{\pi m_e} \right). \quad (2.13)$$

The floating potential V_f differs significantly from the potential V_{sp} of the plasma since, due to the imbalance in electron and ion flux to the probe, the probe attains a net negative potential with respect to the plasma. The result is a retarding field for the electrons, which at the same time accelerates the positive ions.

Because a plasma forms a sheath layer around the surface of a material with which it is in contact, the plasma floating potential obtained by a Langmuir probe turns out to be less than the actual plasma potential. It is therefore necessary to be able to measure the plasma potential directly without the need to post process the measured data. With planar probes, the difference in the two potentials $V_f - V_{sp}$, i.e., the retarding potential is $\simeq -5.4 T_e$ (in eV units) for argon plasma [39]. This value has been shown to be less negative ($-4T_e \leq V_f - V_{sp} \leq -5T_e$) for cylindrical probes due to the geometry [39] and to be dependent on the probe radius to Debye length ratio. The relation in Eq. 2.13 can be used to determine V_{sp} for a Maxwellian plasma if T_e is known. However, it cannot be used in our experiments where multiple electron populations are present.

2.3.2.6 Region II (Transition region):

To the right, just beyond V_f , is the transition region where I_i is negligible. Here, the negative probe potential above the plasma potential, ($V_{probe} - V_{sp}$), partially repels electrons. This is represented by the exponentially increasing part of the curve for a Maxwellian plasma, represented by region II (or BC) on the curve.

The measured current continues to grow until a point when the probe space potential is equal to the probe voltage ($V_{probe} = V_{sp}$). At this point, the negative potential difference no longer exists to repel the electrons and thus the electron current saturates to the electron saturation current I_{es} , given by Eq. 2.14.

$$I_{es} = \frac{1}{4} n_e A e \bar{v} = n_e A e \left(\frac{k_B T_e}{2\pi m_e} \right)^{1/2} \quad (2.14)$$

The I_{es} represents the random thermal current reaching the probe surface at the plasma potential V_{sp} , for the electron mass m_e .

FIGURE 2.2: Electron energy distribution function (EEDF) from the electron repelling region of the I - V characteristic curve from the Fig. 2.1b. [76–78]

2.3.2.7 Region III/Electron saturation region ($V_{\text{probe}} \gg V_{\text{sp}}$):

When $V_{\text{probe}} \gg V_{\text{sp}}$ as in region III of the curve in Fig. 2.1b, the probe collects a negative current (electron current I_e). The electron current I_e is given by the Eq. 2.15,

$$I_e = I_{\text{es}} \exp \left[\frac{e (V_{\text{probe}} - V_{\text{sp}})}{k_B T_e} \right]. \quad (2.15)$$

The electron saturation current I_{es} is > 200 [85] times the ion saturation current I_{is} in low-pressure unmagnetized Argon dc discharges which is the same case in the ALPHIE plume plasma, since the electron velocities are much larger than ion velocities.

When the probe is biased positively, an electron sheath is formed which shields the plasma from the field due to the probe positive charge. For the applied probe voltage beyond a certain range of values (point C on curve), the electron current is a measure of the true electron current density in the plasma, and the probe collects the electron saturation current I_{es} . A further increase in the probe potential beyond the electron saturation level causes no increase in the electron current. However, in practice an increase in the thickness of the sheath – and thus the collection area – resulting from a further increase in the probe potential leads to the tendency of the observed experimental curves to increase even beyond the electron saturation level, as shown in Fig. 2.3.

The shape of this part of the curve generally depends on the shape of the probe. This makes the determination or estimation of the electron saturation current I_{es} from the raw I - V characteristic curve generally difficult since no constant electron saturation is easily identifiable in such cases.

FIGURE 2.3: Example of a practical I - V characteristic curve obtained in a low-density laboratory plasma. The probe current increases beyond the electron saturation current, which makes the determination of the “knee” difficult. [76–78]

2.3.2.8 Electron temperature T_e

Assuming an ideal Maxwellian plasma, plotting the logarithm of the measured electron current $\ln(I_e)$ in the I - V characteristics from, for example, Fig. 2.1b against the probe potential V_{probe} makes it possible to overcome the difficulty discussed in the preceding paragraph. A more accurate I_e can be obtained by subtracting the ion current I_i from the total measured current I (raw data), for example by approximating a straight line along the curve in region I through I_{is} and extrapolating it to the electron region (II and III).

This procedure can be used to determine the electron temperature T_e . The reciprocal of T_e for T_e in eV, i.e., $e/k_B T_e$, is the slope of the resulting curve. This value is independent of the nature of the probe, i.e., the probe shape or area, and is unaffected by collisions – as these all serve to preserve the Maxwellian distribution.

The result is a curve similar to that shown in Fig. 2.4. This offers a more obvious way to determine V_{sp} by the method presented in Section 2.3.2.2. The curve has a more prominent “knee” or kink at a point where the probe potential V_{probe} is equal to that of the plasma surrounding it [84].

The V_{sp} and I_{es} values can thus be approximated from the intersection of the linear fits through the two increasing regions bounding the “knee”, as shown in Fig. 2.4. The value of $\ln(I_e)$ and probe voltage at the intersection of the fits correspond to, respectively, the I_{es} and V_{sp} points. This method of V_{sp} determination works very well in low-pressure unmagnetized Argon DC discharge plasmas [85] in which a sharp “knee” is observed.

Another way to obtain the plasma potential takes advantage of the fact that I_e grows exponentially with V_{probe} until $V_{\text{probe}} = V_{\text{sp}}$ – when the probe

FIGURE 2.4: Plasma potential V_{sp} determination: A semi-logarithmic plot of the I - V characteristics from the Fig. 2.1b. [76–78]

collects all the electrons approaching it. This involves taking the derivative of the I - V curve in the electron-collecting region, i.e., dI_e/dV_{probe} . The peak value occurs at $V_{probe} = V_{sp}$.

Obtaining dI_e/dV_{probe} from the experimental data is never an easy task, as noise enhancement is inevitable in the process. To obtain a noise-free derivative of the I - V curve demands the use of very efficient filters [68, 86] to eradicate the noise in such a way that the peak value in the differentiated curve is not strongly affected by the filtering process. It is however not recommended to use the corresponding current at the peak of the derivative as the input I_{es} for n_e determination described in Section 2.3.2.9 that follows. This is because the ‘knee’ can occur before V_{sp} is actually reached. Also, from Eq. 2.15 I_{es} is exponentially dependent on the assumed V_{sp} value. Thus, even a slight error in the V_{sp} value would magnify the error in the deduced n_e value. Finally, V_{sp} can also be determined by measuring V_f and using it with Eq. 2.13 once T_e is known.

2.3.2.9 Plasma density n_e

Having measured/determined the T_e and I_{es} values, the plasma/electron density n_e can then also be determined using Eq. 2.14. This works particularly for low-density plasma in low pressures where the elastic collisional, charge exchange and ionization mean free paths λ are long. However, care has to be taken in using I_{es} to determine n_e , since outside these special plasma conditions the probe collects such large amounts of current that the plasma is drained – which may alter its equilibrium properties.

In this regard, ion collection is instead a better option for determining n_e using I_{is} . In such cases the plasma is not drained by the probe to the extent of modifying its equilibrium state, since the probe does not collect

very large current as would be the case for high-density plasmas with very short λ . Quasineutrality in plasmas means the same results should be obtained. In this case the collected ion current is not large enough to cause any damage/degradation to the probe when measured for a considerable duration, unlike for I_{es} measurement. The relation in Eq. 2.12 can thus be used to determine the plasma density n_e if T_e is known. This relation however only applies accurately to planar probes, and a geometrical correction factor has to be introduced when used with other probe shapes [39].

2.3.2.10 Electron energy distribution function EEDF, $g(E)$

With the obtained T_e value, the electron energy distribution function (EEDF) can be obtained by considering the probe electron-repelling region, i.e., the region of the I - V characteristic curve in which $V_{\text{probe}} - V_{\text{sp}} < 0$ (the transition region up to the point where $V_{\text{probe}} < V_{\text{sp}}$). The current I_e of these electrons is

$$I_e = n_e A e \int_{v_{\min}}^{+\infty} v_z f(v_z) dv_z. \quad (2.16)$$

Since, also, $E = -eV_{\text{probe}}$, differentiating Eq. 2.16 with respect to the probe voltage V_{probe} yields

$$\begin{aligned} \frac{dI_e(V_{\text{probe}})}{dV_{\text{probe}}} &= -n_e A e v_z f(v_z) \frac{dv_z}{dV_{\text{probe}}} \bigg|_{v_z=v_{\min}} \\ &= \frac{n_e A e^2}{m_e} f(v_{\min}). \end{aligned} \quad (2.17)$$

This relation can be used to measure the electron velocity distribution function (EVDF), $f(v_z)$ in one dimension. For a spherical probe, the factor $4\pi v^2$ [39,75] has to be introduced, so that a 3-D distribution $g(v)$ is obtained, for the absolute value of velocity, v .

A more detailed derivation similar to that for the 3-D EEDF, $g(E)$, from a characteristic I - V curve and $f(v_z)$ is presented in Section 2.4.2.7 on page 69. The EEDF can be got by differentiating the current in the electron-repelling region (BC) of the curve in Fig. 2.1b with respect to the probe voltage twice, i.e.,

$$g(E) = -\frac{1}{\pi e^2 r_{\text{probe}}^2} \left(\frac{m_e V_{\text{probe}}}{2e} \right)^{1/2} \frac{d^2 (I_e(V_{\text{probe}}))}{dV_{\text{probe}}^2}. \quad (2.18)$$

Fig. 2.2 (on page 37) shows a typical normalized distribution $g(E)$, which can be used to obtain information about the distribution of electron densities as a function of their energy. In an ion engine, however, the contribution of plasma ions cannot be ignored due to limitations of the conventional Langmuir

probe theory when applied to drifting plasmas. The ion contribution can be also measured accurately from the Langmuir probe measurements.

The existence of different electron and/or ion populations in such plasmas generally complicates the use of a Langmuir probe in EEDF determination [79, 87, 88, 88]. This occurs due to the contribution by the different charge particle groups to the overall current, which in each case has a different energy spectrum. The measured I - V curves thus may depart considerably from the classical case.

For such a case where the Langmuir probe characteristic is different from the ideal Maxwellian case, interpretation of the I - V data thus becomes cumbersome, necessitating an independent measurement of the plasma potential V_{sp} for the determination of the EEDF $g(E)$, such as using emissive probes [79, 87, 89]. This is the main basis for the use of an emissive probe in this Ph.D. research.

The nonlinearity that exists in the semi-logarithmic I - V plot discussed in the preceding paragraphs are an influence of the contributions from such energetic ions. Such contributions can be approximated by applying a correction to the I_{is} that makes the $\ln(I)$ - V curve linear over as wide a probe voltage range as possible [39].

For the case of a Maxwellian plasma, the EVDF, $f(v)$, varies exponentially as $(\frac{1}{2}m_e v^2 + eV_{probe})/(k_B T_e)$ (see Eqs. 2.2 and 2.4 on page 32), i.e.,

$$f(v) \propto e^{-(\frac{1}{2}m_e v^2 + eV_{probe})/k_B T_e}. \quad (2.19)$$

Eq. 2.19 shows that the EVDF is Maxwellian at a given electron temperature T_e for Maxwellian electrons, but with the electron density decreasing by a factor $\exp(-e|V_{probe}|/(k_B T_e))$. Only the current of electrons with minimum velocity v_{min} and energy $E = \frac{1}{2}mv_{min}^2$ can overcome the Coulomb barrier and are collected by the probe.

2.3.3 Design features and experimental aspects

The Langmuir probe used in this research is a spherical stainless steel of diameter 4.44 mm that is biased with respect to the grounded walls [74] of the vacuum tank using a time-sweep circuit. The probe was polarized by a 200 Hz-frequency voltage ramp signal added to a DC time-independent voltage [74]. The probe currents I_{probe} and bias voltages V_{probe} were digitized [32, 57] using a Yokogawa DL9140 digital oscilloscope. The resulting current-voltage (I - V) characteristic curves were analysed on the assumption that the electron energy distribution function is Maxwellian [32, 57].

In the measurements with the LP, attempts were made to minimize the probe's effect on the plasma jet expansion process by use of a spherical probe in preference to planar or cylindrical configurations. The probe was carefully mounted on a thin support and made to face the plume plasma directly, while

the thin insulated steel support is attached on the side downstream of the oncoming plasma flow (see Fig. 2.6 on page 43).

For each single measurement, 800–900 equally spaced data points were obtained and used to plot the current–voltage (I – V) curves. For the data analysis, a Savitzky-Golay (SG) numerical scheme [68, 86] based on Fortran programming language has been developed, with which the data were numerically smoothed.

2.3.3.1 Spherical Langmuir probe in flowing unmagnetized plasma

Fig. 2.5 shows a photograph of the spherical Langmuir probe that was used in the research.

FIGURE 2.5: The spherical Langmuir probe and its insulated supporting shaft.

Because of the drifting ions that drag electrons along with them in flowing plasmas as the one we are working with, the use of Langmuir probe diagnostics is not an ideal choice. In a flowing or drifting plasma the effect of the support shaft of the probe cannot be ignored. The probe and its geometry affect the isotropy of the plasma particle flow collection on it, such that most of the collection is from the plasma-facing side of its spherical surface [90–92].

Fig. 2.6 shows the effects of the presence of such a probe on a plasma flow. The probe causes a distortion of the flow as shown in the figure whereby a region is created just after the probe surface (near-wake region [90–92]), which is void of ions due to the converging effect of the convex-shaped front of the spherical probe. The region behind the probe (downstream of the flow) tends to develop a shadow effect due to the obstruction of the plasma beam particles. Then beyond it is the region that results from the converging-diverging lens effect of the probe (mid wake region), which results in a peak or maximum density of ions. This is due to the intersection of the divergent and convergent ion trajectories.

The regions surrounding these areas of maximum and minimum or zero ion currents/densities display shock waves resulting from the passage around the probe, which are similar in properties as the far wake regions where the ion current densities decrease rapidly due to losses from their divergence. The ideal conditions under which LP analysis is done, where the thin-sheath approximation is used, are actually not met when the plasma flows with respect to the probe. However, this is what was available, at least for the experiments during this research. In the case of a flowing [54, 64] high-velocity plume plasma from a thruster with directed/collimated supersonic ions, the electron thermal velocities are still much higher than the directed ion velocity. The ion flow

does not influence the electron motion very much. This simplifies the problems with the anisotropy of the plasma which would add complex restrictions on the requirements for Langmuir probe diagnostics of such plasmas, since the electron temperature should be the same irrespective of the probe's orientation with respect to the plasma flow.

It is assumed that the probe can still collect, and thus produce, information on the electrons similar to the ideal plasma conditions owing to their high mobility. The electron Debye lengths λ_D are very small compared to the probe diameter and thus the probe disturbance can be neglected. Also, since the electrons move much faster than the drifting ions, the effect of the drifting ions on their collection by the probe will not affect so much the ideal LP measurement conditions. This therefore makes such conditions to be approximately valid or met for Langmuir probe usage in this kind of plasma.

The probe was placed as shown in Figs. 2.23 and 2.25, facing the plasma jet and its supporting shaft is oriented at its back side (on the remote side of the incident plasma beam). With this configuration the plasma wake effects on collected particles are minimized and would be the same even in non-flowing plasmas. The deviation from spherical symmetry introduced by the electrically insulated support shaft of 1.33 mm diameter can be estimated using its cross sectional area. This correction is only 9% compared with the surface area of the Langmuir probe.

Nevertheless, care was taken when taking measurements with the Langmuir probe in the ALPHIE plume plasma.

FIGURE 2.6: Spherical object in a mesothermal plasma flow [91]

In our measurements with the Langmuir probe, these effects were minimised by mounting the spherical probe on a thin insulated shaft.

2.4 Emissive probe

A second important electric probe is the emissive probe, the name given to a small electrode that thermionically emits electrons when heated beyond a certain temperature threshold [55, 57, 87, 93–95]. It can therefore be more precisely referred to as an electron-emissive probe.

2.4.1 Principle of operation

When the probe bias is swept over a range of potentials, an I – V characteristic curve is obtained. This can be done for varying (increasing or decreasing) probe heating currents I_H .

(a) Current collection and emission by an emissive probe in absence of space charge effects

(b) An actual emissive probe I – V characteristic curve obtained with cylindrical wire probe

FIGURE 2.7: Emissive probe current regimes.

The current measured by an emissive probe is composed of both the electron emission current and the electron collection current. Electron emission to the plasma is achieved when the probe is more negatively biased than the plasma's potential. It is accompanied by a collection of ions by the probe [96], making the probe to float at a higher voltage.

The emitted electrons, which move faster than the ions, can be measured as a net ion current to the probe [57], which is insensitive to the plasma flow since it has a strong dependency on only the plasma potential and zero dependency on the kinetic energy of the electrons. The probe floating potential thus tends to the plasma potential (see Fig. 2.10), as compared to the Langmuir probe. Fig. 2.7 shows theoretical characteristic curves obtained with this kind of probe.

In Fig. 2.7a, the purely electron collection (upper/pink curve) and emission (lower/red curve) regimes of the probe are shown, with a typical measured characteristic (the dark curve) being the sum of the two currents. The electron saturation (I_c) and electron emission (I_{em}) currents are indicated by the dashed lines. Fig. 2.7b on the other hand shows actual measured I - V characteristic curves obtained using this probe for increasing probe heating currents. When the probe is biased more positively than the plasma potential, there is no electron emission to the plasma. The emitted electrons are reflected back to the probe except for a small contribution from the high-energy tail of the electron distribution [57, 79].

Thus, there is always a non-zero emission current when the probe bias voltage is a few volts above the plasma potential. In the following paragraphs, some light is shed on features of the probe I - V characteristic and how they may be used for plasma potential determination.

2.4.1.0.1 Zero/low emission

Operating the probe in the low emission regime ($I_{em}/I_{coll} \simeq 1$) makes the description of the probe characteristics simpler, since space charge effects are less important. The probe's electron emission is limited by the wire temperature, hence the notion of the name *temperature-limited* regime. Since the temperature-limited emission current is much higher than the ion current, the measured current is assumed to be made up of entirely electron current. This regime will be used for the plasma potential measurement by the inflection point method [55, 57, 79]. The emission currents I_e of the characteristics in Figs. 2.7a and 2.7b, as a function of the probe voltage V_{probe} , are given by

$$I_e = \begin{cases} I_{em}, & V_{probe} < V_{sp} \\ I_{em} \exp \left[\frac{-e(V_{probe} - V_{sp})}{T_w} \right] g(V_{probe} - V_{sp}), & V_{probe} \geq V_{sp}, \end{cases} \quad (2.20)$$

where $g(V_{\text{probe}} - V_{\text{sp}})$ is a quantity that depends on the probe wire and sheath radii, which accounts for the orbital angular momentum of a charged particle at plasma potential V_{sp} far from the probe that will be collected by the probe [55, 57, 69, 79], and T_w is given in eV.

For a wire (cylindrical) probe of radius much smaller than the sheath thickness, the value of g can be given by [55, 57]

$$g = \left(1 + \frac{-e(V_f - V_{\text{sp}})}{T_w} \right)^{1/2}. \quad (2.21)$$

Assuming the plasma to be Maxwellian, the probe collects an electron current I_c given by

$$I_c = \begin{cases} I_{\text{coll}} \exp \left[\frac{-e(V_{\text{sp}} - V_{\text{probe}})}{T_e} \right], & V_{\text{probe}} \leq V_{\text{sp}} \\ I_{\text{coll}} g'(V_{\text{probe}} - V_{\text{sp}}), & V_{\text{probe}} > V_{\text{sp}}, \end{cases} \quad (2.22)$$

where the plasma electron temperature T_e is in eV and g' is the derivative of the function g that is given approximately by $(1 - e(V_f - V_{\text{sp}})/T_e)^{1/2}$.

2.4.1.0.2 Strong emission

In the strong emission regime where the temperature-limited electron emission current I_{em} is much higher than the electron saturation current I_{coll} , i.e., $I_{\text{em}}/I_{\text{coll}} \gg 1$, the current becomes space charge limited due to creation of a double sheath – a dip in the potential between the interface of the probe and the plasma – resulting from space charge build up [97]. This in effect reduces the amount of emitted current.

In the absence of this potential dip, the electron collection current is approximately equal to the sum of the ion saturation current I_{is} and the electron emission current I_{em} , which can be used as an indication of the floating potential V_f . In this case,

$$I_{\text{em}} \exp \left[\frac{-e(V_f - V_{\text{sp}})}{T_w} \right] g(V_f - V_{\text{sp}}) + I_{\text{is}} = I_{\text{coll}} g'(V_f - V_{\text{sp}}) \quad (2.23)$$

since $V_f \gg V_{\text{sp}}$. Care has to be taken to minimize operating the probe in the strong emission regime, as the results become less reliable since the plasma potential is modified by the emitted electrons.

2.4.1.0.3 Floating potential V_f

The emission of electrons from the probe can be used to measure plasma potential directly. The function g' can be approximated by $g' \approx 1$ if $e(V_f - V_{sp}) \ll T_e$. Thus, for negligible I_{is} , the Eq. 2.23 can be used to determine the floating potential of the hot probe using the relation

$$\ln \left(\frac{I_{em}}{I_{coll}} \right) = \frac{e(V_f - V_{sp})}{T_w} - \frac{1}{2} \ln \left(1 + \frac{e(V_f - V_{sp})}{T_w} \right). \quad (2.24)$$

Using this relation, different $I_{em}-I_{coll}$ ratios have been used (see Ref [57]) to show how $V_f - V_{sp}$ is several multiples of T_w/e , and hence, that the floating potential V_f is more positive than the plasma potential V_{sp} by the resulting product and its positivity increases with electron emission. The point of intersection of the $I-V$ curve traces with the load line—current-voltage curve of the electronics used to measure the current—(or approximately the horizontal axis when a high impedance resistor in the mega ohm range is used) can be taken as the probe's floating potential [79, 98, 99].

2.4.1.1 Practical aspects

It is essential to eliminate any heating-voltage offsets [96] during the measurements with emissive probes, such as when a constant DC heating is used. Pulsed heating has been used in this regard, to ensure that changes in the probe wire resistivity during the hot and cold regimes do not appreciably affect the measurements. A fast sampling rate (at least 10 kHz) is necessary in the feedback circuit of such heating mechanisms. The use of DC probe heating is however the most common, where the floating potential is approximated to be at the inflection point of the steepest part of the probe $I-V$ curve in which both electron collection and emission take place [79].

A major issue pointed out on the use of emissive probes is the lack of uniformity due to differences in emissivity on different parts of the wire resulting from possible temperature gradients on its surface. Because of the tendency by the plasma to prevent a net electron current flow towards it, and hence to reflect back part of the emitted electrons to the emitter, the floating potential obtained with an emissive probe during strong emission is $\sim 1 T_e$ less than the actual plasma potential [100]. This occurs as a result of the formation of a virtual cathode around the emitting surface due to a space charge resulting from the build-up of electrons slowed by the plasma [100–102].

The voltage drop along the wire is partly mitigated by the wire loop, whereby the potential V_f is measured along a distance of the order of the probe shaft diameter. The V_f value derived from this probe is thus the average value that is measured over such a small volume (bent area) so that the voltage drop considerations emphasised in some of the available literature is neglected or not an important issue. Emissive probes have proved to provide a better

alternative for, and thus been widely used mainly for, accurate plasma potential measurement – which is one of the most important plasma parameters [79, 93, 103, 104]. It can be used with drifting plasma electrons and still yield correct results, as no electron emission occurs above the plasma potential [80].

The determination of V_{sp} using an emissive probe is less straightforward than n_e , T_e and V_{sp} using Langmuir probes plasmas. The probe is intrusive, and a trade-off criterion is needed between the extent of plasma perturbation and the magnitude of the current drained by it from the plasma. To reduce its disturbance to the plasma to a level as low as possible means low electron emission which is achieved by small wires. This however results in low and poor signal-to-noise ratio of the measured current drained by the probe. Furthermore, since the determination of V_{sp} involves differentiating the raw experimental data curves, low electron emissions resulting from moderate probe temperatures are difficult to interpret.

The quality of the measured signal improves when the temperature of the probe wire is increased (strong emission). In this case, however, the electron current density exceeds the level of plasma electron thermal current. The surrounding plasma then becomes increasingly perturbed by this emitted electron current. Therefore, plasma density is also a very important parameter since emissive probes can give less reliable measurements plasmas with low n_e . Under certain conditions, however, the disturbance can be limited to the region around the probe by development of a virtual cathode structure. In this case, the emissive probe's floating potential in the strong emission regime can provide reliable measurement of the V_{sp} .

Additionally, several discussions have been presented and attempts made on the possibility of also adopting these probes for use in the measurement of other plasma parameters such as electron temperature [79, 105, 106] and in plasma potential and electric field fluctuation measurements [80, 81, 94, 95, 107, 108]. Most of the suggested use and measurements with this probe may still be lacking a concrete theoretical basis, or seem to be controversial because of the differences and lack of a common agreement on the arguments paused by the inventors or protagonists for their use and adoption. Despite it being controversial and not well established to date, it still stands out as the ideal probe for plasma potential measurement.

Moreover, different designs of this probe have been suggested by different authors, which may depend on, though not limited to, the type of plasma it is to be used in and the kind of measurement desired [57, 79, 107, 109–111]. In this section, the use of emissive probes in such measurements is introduced.

2.4.1.2 Structure and composition

Fig. 2.8 shows a schematic drawing of an emissive probe with its composite parts. To ensure minimal disturbance to the plasma, the ceramic tube (and the probe in general) should be as thin as possible. Matching of the wire diameter with the holes is necessary to ensure that only the exposed surface of the wire

glows.

FIGURE 2.8: Emissive probe. Exposed short length of electrode bent to form a loop/bow emits electrons when heated [78].

The probe electrode is made of a high-temperature wire of material such as Tungsten, about 0.05–0.1 mm in diameter that can be made such that the only exposed, and thus emitting surface, is a short length ($\simeq 6$ –10 mm) in form of a loop as shown in Fig. 2.8. The wire can be threaded into a ceramic tube made of alumina, for example, to keep the unexposed part insulated from the plasma.

The ceramic is in most cases of circular cross section, about 5–10 mm in diameter and $\simeq 30$ mm length, with two holes just wide enough to fit the probe wire bored longitudinally through it. This allows, in a directly heated probe where electric current is used, for the probe heating circuit to be connected from the back of the ceramic while leaving only the wire loop or bow (actual emitting part) in direct contact with the plasma.

2.4.1.3 The probe design and configuration

For the emissive probe measurements later referred to in this report, the emissive probe was a 0.08 mm diameter tungsten wire. A plasma-exposed or electron-emitting part of this wire, which formed an obovate-shaped bow, was at the front part (cross section) of a cylindrical solid made of ceramic that was 6.0–9.0 mm long. This ceramic contains two small holes bored longitudinally through it at a separation distance of 3.0 mm. Through each of these holes, a hypodermic needle is carefully fitted to provide the channel through which the probe wire can be passed.

At the back side of the ceramic solid are two male blade crimp terminals which act as electrodes to which the probe wire lengths emerging from the back side are connected. Electrical connection to the heating power circuit is made via the female blade terminals from the circuit, a design which allows for flexible replacement of the probe wires.

Fig. 2.9 shows the electric circuit used for heating the probe wire, as well as for taking the I – V measurement. The probe wire can be heated with either DC or AC current, I_H , which in these measurements were between 0.65 A

FIGURE 2.9: Electrical circuits for the emissive probe. [76–78]

and 1.50 A DC currents provided by a stable power supply. A fast-sweep polarization circuit (see Ref [74] for details) was used to digitize the I - V data values, obtaining these values respectively as I_{probe} and V_{probe} that were stored for analysis.

With a heating current I_H , the probe wire is heated to temperature $T_w = 1,700$ – $2,000$ K whereby it glows red. The Tungsten wire then undergoes thermal emission of electrons which can be measured as a current I_{em} – the temperature-limited (saturation) emission current. The current density J_{em} depends on the wire temperature T_w and is given by the Richardson–Dushman relation [36, 89] in Eq. 2.25.

$$J_{em} = A_c T_w^2 \exp \left[\frac{e\phi_w}{T_w} \right] \quad (2.25)$$

where A_c is the Richardson’s constant ($6.02 \times 10^5 \text{ A}\cdot\text{m}^{-2}\cdot\text{K}^{-2}$), and ϕ_w is the work function of the wire material, with T_w in eV.

The floating potential V_f of the plasma can be directly measured using the circuit in Fig. 2.9a. When the voltage drop V_F across R_2 is adjusted to zero, then V_F corresponds to the voltage drop across R_1 and part of the probe wire up to half way exposed to the plasma. This is expected to correspond to the plasma potential at floating point. However, this cannot be used as a reliable technique for V_f determination because of the errors that may arise from the asymmetry of the probe wire introduced by the thermal effects.

2.4.1.4 Plasma potential (V_{sp}) determination

As already mentioned on page 44, different methods have been used for plasma potential measurement in different contexts and probe applications, the details of which are not explored here. One way to recognise the plasma potential has been suggested to be at the point of separation of the I – V characteristic curves as shown in Fig. 2.10, which occurs near the plasma potential [51, 55, 112]. The probe bias voltage corresponding to this point therefore roughly indicates the plasma potential.

The I – V characteristic curves resulting from most experiments end up with the characteristic traces crossing rather than the expected superimposed one above the separation point [83, 113], and thus it has been referred to as the crossing point instead. For plasma potential measurement and determination by emissive probes presented here, the main emphasis will however be on the two most extensively used, and most investigated methods: (i) floating potential method, and (ii) inflection point method [100].

2.4.1.4.1 Floating potential method

The plasma potential can be determined by measuring the floating potential from a strong emission part of the probe I – V curve [55, 98, 114]. However, due to difficulties encountered in the use of floating emissive probes in high-density, high-temperature plasmas—in which it is difficult to emit a sufficient current required in their use—owing to the large collected electron currents that exist, other probes such as self-emissive probes have been opted for [109]. As seen in Fig. 2.10, the floating potential tends to more positive values—approaching the plasma potential—for increasing probe wire heating currents [99], and could thus be used as an indication for the plasma potential [55, 109]. The increase in probe emission however limits the reliability of this method, since the emission becomes space charge limited [97].

However, approaches have been suggested that enabled such probes to be used in ‘self-emissive’ plasmas [109], with the floating of the probe providing a good measure of the plasma potential. Increasing the probe emission leads to an increase in the floating potential, with the rise in the floating potential being rapid at first, and then saturating at the plasma potential and beyond [79, 98].

Beyond the plasma potential floating potential its value changes by very slight amounts, mainly due to space charge effects [56, 79]. The plasma potential can then be approximated to be the intersection of the linear extrapolations of the rising and almost flat (saturation) regimes, though the saturation of the floating potential has been used as a good estimate [79, 94, 98, 115, 116] for the plasma potential.

2.4.1.4.2 Inflection point method

In the limit of zero electron emission by the probe, i.e., $I_{em}/I_{coll} \simeq 1$, plasma disturbance is minimized. The inflection point plasma potential determination

FIGURE 2.10: Floating point method for determining plasma potential from emissive probe characteristics.

method makes use of this principle to a reliable V_{sp} values [114, 117, 118]. Varying the electron emission, the inflection point of the I - V characteristic curve tends to shift towards the plasma potential. The inflection point will occur at the probe bias corresponding to the plasma potential at zero emission (no space charge effects), as can be seen in Eqs. 2.20 and 2.22.

The derivative dI_{probe}/dV_{probe} is an indication of the inflection point, which occurs at the peak of it. There is an observed shift in the dI_{probe}/dV_{probe} peak with change in electron emission. The experimentally obtained curves can be differentiated and the derivative compared with the theoretical value which can be expressed in two forms as follows:

From Eqs. 2.20 and 2.22, the total probe current I_{probe} is given by

$$I_{probe} = I_{coll} \exp \left[\frac{-e(V_{sp} - V_{probe})}{T_e} \right] - I_{em}, \quad \text{for } V_{probe} \leq V_{sp} \quad (2.26)$$

and

$$I_{\text{probe}} = I_{\text{coll}} \left(1 + \frac{-e(V_{\text{sp}} - V_{\text{probe}})}{T_e} \right)^{1/2} - I_{\text{em}} \exp \left[\frac{-e(V_{\text{probe}} - V_{\text{sp}})}{T_w} \right] \\ \times \left(1 + \frac{-e(V_{\text{sp}} - V_{\text{probe}})}{T_w} \right)^{1/2}, \quad \text{for } V_{\text{probe}} > V_{\text{sp}}. \quad (2.27)$$

Thus, the corresponding $dI_{\text{probe}}/dV_{\text{probe}}$ from Eqs. 2.26 and 2.27 are, respectively,

$$\frac{dI_{\text{probe}}}{dV_{\text{probe}}} = \frac{eI_{\text{coll}}}{T_e} \exp \left[\frac{-e(V_{\text{sp}} - V_{\text{probe}})}{T_e} \right], \quad \text{for } V_{\text{probe}} \leq V_{\text{sp}} \quad (2.28)$$

and

$$\frac{dI_{\text{probe}}}{dV_{\text{probe}}} = \frac{1}{2} \frac{eI_{\text{coll}}}{T_e} \left(1 + \frac{eV_{\text{probe}}}{T_e} \right)^{-1/2} - \frac{eI_{\text{em}}}{T_w} \exp \left[\frac{-e(V_{\text{probe}} - V_{\text{sp}})}{T_w} \right] \\ \times \left[\left(\frac{1}{2} + \frac{eV_{\text{probe}}}{T_w} \right)^{-1/2} - \left(1 + \frac{eV_{\text{probe}}}{T_w} \right)^{1/2} \right], \quad \text{for } V_{\text{probe}} > V_{\text{sp}}. \quad (2.29)$$

Measuring the inflection points for different low-emission levels results in a linear dependency on the probe voltage, which when extrapolated linearly to meets the probe voltage axis at a value equal to the plasma potential.

In this limit, however, the signal-to-noise ratio is much reduced as opposed to the case when more electron emission which occurs when the probe is heated to higher temperatures.

Fig. 2.11 illustrates this effect, where for low electron emission (at low T_w) in Fig 2.11a the signal-to-noise ratio is low, compared to a strong emission (Fig 2.11b). This loss in the signal strength may compromise the accuracy of the inflection point method for V_{sp} determination. At high heating voltages (or strong emission), this approximation is however not very accurate and results in large errors in the order of a few volts [79]. In spite of this possible shortcoming, the method is claimed to yield the most accurate plasma potential measurements [83].

The main focus in this research has thus been put on plasma potential determination by this method in the use of emissive probes, as its implementation is not very much limited by the plasma and vacuum tank parameters in the laboratory in which these experiments were conducted. It should be noted however that the actual determination of V_{sp} by this technique is very cumbersome as it is not straightforward.

FIGURE 2.11: Emissive probe characteristics at low and high electron emission.

2.4.2 Retarding-field energy analyzer (RFEA)

A retarding-field energy analyzer (RFEA), also referred to as a retarding-potential analyzer (RPA) in some of the available literature, is a kind of analyzer that makes use of electrostatic effects to measure charge. As the name suggests, such analyzers have been shown to reliably measure the energy of ions in both space and laboratory plasmas. This probe is used in this research to determine the ion energy spectra in connection with the operation parameters of a thruster, which is of utmost importance. For uniformity RFEA will be used throughout the rest of this report.

2.4.2.1 Principle and design

A RFEA for ion measurement filters out electrons and selects ions from the incident plasma using potentials applied at its grids, which are measured as a current at the collector.

It consists of grids aligned parallel to one another, typically two to four in number. The grids are biased depending on the type of charge of the particles to be measured. The fourth grid is usually optional, included when secondary electron emission at the collector is expected to occur. It is referred to as the secondary-electron suppressor grid, since it serves to prevent any secondary electrons produced from affecting the collected beam ion current.

Secondary electron emission can be induced not only by ion impact but also by photons, fast neutrals, and metastables [40]. It is therefore considered good practice to anticipate and try to minimize the effects of secondary electrons, as we demonstrate it in the results from the experimental measurements.

A four-grid type RFEA has been designed based on the recommendations in Ref. [40]. The plasma-facing (FG) grid is left to float relative to the plasma potential V_{sp} to minimize the perturbation of the plasma by the analyzer and its applied potentials. The second (plasma electron repelling) grid is biased negatively to repel the plasma-borne electrons whereas the electrical potential

FIGURE 2.12: Electrical circuit used for the RFEA grids and ion collector system implemented in the experiments. The corresponding potential distribution along the four-grid analyzer axis is also shown. The ion collector plate is at the back, plasma-facing grid floats at plasma potential $V_F = V_f$, plasma-electron repelling (PR), ion discriminator (ID), and secondary-electron suppressor (SS) grids are respectively shown.

of the third (ion retarding or discriminator) grid is varied or swept. Sweeping the ion retarding grid voltage V_{ID} ensures that ions of different energies are filtered such that only those with an energy-to-charge ratio greater than the bias voltage can pass through.

Fig. 2.12 shows a schematic diagram of the circuit used for the RFEA electrical connections implemented for the ion beam measurements described throughout this research. The connections of the plasma-electron repelling (PR), ion discriminator (ID), and secondary-electron repelling (SS) grids are shown, along with the distribution of their potentials V_{PR} , V_{ID} , and V_{SS} , respectively. The plasma-facing (or entrance) grid, FG, is left to float with respect to the plasma as shown. A collector plate, positioned behind the grids, forms the back end of the analyzer channel. It collects the flux of the beam transmitted through the analyzer system and measures it as a current. The whole system of grids and collector plate are coaxially arranged and positioned so that the plasma approaches the entrance grid normally.

2.4.2.2 Geometric considerations

Debye length λ_D , which is a function of the plasma density n_e and the electron temperature T_e (in K) as given by Eq. 2.5, is a critical parameter in RFEA design [34, 40]. During operations with RFEAs, there tends to develop a build up of additional charge density between the grids which can alter their potentials [34]. This occurs when the selected positively charged plasma ions flow into the analyzer and, depending on the potential difference (p.d) V be-

tween two close oppositely biased grids, i.e., compared with the magnitude of either of the two grid potentials (whether it is larger than the magnitude of the greater or smaller than the lesser of the two grid potentials), the change in potential due to this plasma ion flow can affect the operation of the analyzer. A repulsive potential hill higher than that formed by the grids results, which once encountered by the ions leads to a lowered collected current. This is a common limitation of RFEAs which occurs particularly in high-density plasmas. It is therefore important that the design is optimized to ensure a good analyzer resolution, while minimizing space charge effects within its ion channel.

For a space-charge-limited emission between two closely aligned grids, the dependency of the current density J_i on mainly the potential difference V between the grids and the separation d_g between the grids can be expressed using the Child–Langmuir relation, given by Eq. 2.30.

$$J_i = \frac{4}{9} \left(\frac{2e}{m_i} \right)^{1/2} \frac{\varepsilon_0 V^{3/2}}{d_g^2}, \quad (2.30)$$

where e , d_g and m_i , respectively, denote the electron charge, distance of separation between the two grids, and the ion mass. The optimum perveance (given by the $I_i/V^{3/2}$ ratio) determines the right V – d_g choice [119, 120].

In the design of a RFEA for measurements in a plasma, it is important to consider the existence of a sheath between the plasma and the entrance to the analyzer. The presence of a sheath creates an electric field which accelerates the plasma ions towards the analyzer entrance, which is one of the very few cases in which sheath formation can be viewed not as a hinderance in plasma diagnostics. To prevent the plasma from entering the analyzer while selecting only the plasma particles, the grid mesh size should be less than or equal to the Debye length λ_D . This condition also minimizes the electrostatic lens effects, thus maintaining a good analyzer resolution.

The grids must be close enough together to avoid space charge limitations whereby charge builds up between the grids—creating a potential hill as positively or negatively charged particle species are filtered from the flow. The resulting potential hill can lower the current collected when it becomes higher than the applied voltage, affecting the accuracy of the RFEA. Eq. 2.30 can be used to optimize the analyzer performance by choosing the right V and d_g so as to minimize the space charge effects. Here, the main focus will be on a four-grid type analyzer. Fig. 2.12 shows a potential distribution of such a RFEA along its channel axis.

2.4.2.3 The RFEA electrical circuitry

For the experiments conducted with the RFEA in this research, the PR and SS grids were maintained at $V_{PR} = -30.0$ V and $V_{SS} = -30$ V constant DC voltages, respectively, whereas the collector was kept at the Ground potential

of the vacuum tank. The ID grid voltages V_{ID} were swept between -500 V and 500 V at intervals of 1 V every 0.005 – 0.05 s, depending on the noise level.

With this grid configuration and potential distribution, the RFEA filters out electrons in the incident plume plasma and measures only the beam-ion flux as a current at the collector. Considerations for the analyzer resolution have been made, where the design features are aimed at minimizing space charge effects (defined by Eq. 2.30) to ensure a good analyzer resolution. The limitations encountered with higher-density plasmas discussed in section 2.4.2.2 on page 55 are not expected during this RFEA usage, considering the plasma's low density. Nevertheless, some of the design features are still aimed at combating such limitations, if any.

In the measurements, ion-collector currents I_{IC} are taken as a function of the sweep voltage V_{ID} by a computer-aided data acquisition system. A Keithley 6487 picoammeter—serving both as the ID grid voltage source and the collector current meter—(see Section 2.4.2.6 on page 68 for details) that communicates with the computer system is used to digitally measure the I – V characteristics. This instrument's FILTER ON option was activated to have an improved signal-to-noise ratio of the collected ion-current. The PR and SS grid voltages were provided/controlled by separate DC supplies.

ExceLINX software was used to display, control, and monitor the communication between the computer system and the Keithley instrument, and the measured data was stored for further analysis. This software was mainly used before a more advanced and easy-to-use interface (see Section 2.4.2.6 on page 68) was developed by one of the laboratory team members. A plot of the obtained I_{IC} against V_{ID} , also referred to in the rest of this report as the voltage–current (I – V) characteristics, is then used to obtain the ion distributions.

2.4.2.4 RFEA design

Designing, building and implementing the use of a retarding field/potential energy analyzer (RFEA) for ion energy measurements constituted part of the main objectives of this research. This is in part due to their proven reliability and suitability as one of the most accurate and valid tools for such measurements. As has already been introduced in section 2.4.2, a RFEA for ion measurements filters out any electrons that may be present in the exhaust plume plasma of the thruster such that only the ion flux to the collector is measured as a current.

In section 2.4.2.1, we saw that the right choices for V and d_g have to be established according to Eq. 2.30 as to optimize a RFEA's resolution and performance. It will be shown in section 3.1.1 that collisional effects within the ALPHIE working environment (vacuum vessel) are negligible, if not completely absent.

Any effects of elastic or charge exchange collisions within the analyzer were thus neglected since the mean free paths for these collisions within the oper-

ational density and pressure ranges are much longer than the dimensions of the plasma volume and analyzer channel. Limitations of geometric origin discussed in section 2.4.2.2 are thus not expected to be a serious concern during RFEA use in the expelled ALPHIE plasma, considering its low density. The requirements for the grid spacing due to limitations imposed by collisions, as pointed out in Ref. [40] are thus not critical in the case of this thruster’s plume plasma.

This allows for the simplicity and flexibility with which the probe can be built or fabricated; not limited to inter-grid separations, such as those in the order of microns presented in most of the available literature. This makes good analyzer resolution easily achievable, since it varies as d_g^{-1} , where d_g is the grid-to-grid separation [40].

Nevertheless, the design features of the RFEA used in the experiments reported here were still aimed at combating such limitations, if any. A fourth grid—the secondary-electron suppressor grid—to prevent any secondary electrons from affecting the collected ion current has been included. The analyzer accurately measures ion energy spectra, and is capable of achieving an energy resolution of about ± 8 eV for singly charged Argon ions with 400 eV energy [121] and about ± 4 eV for singly charged argon ions with energies just below 650 eV.

2.4.2.5 The RFEA construction

Throughout the experiments leading to the results presented in this report, at least three RFEA designs were implemented, built and used, which all yielded nearly similar results except for slight qualitative and quantitative differences as will be presented in the later parts of this report.

Fig. 2.13a shows a longitudinal cross section of the original design features for the RFEAs. The analyzer is built in modules that are assembled to form a whole – an approach which allows for easy disassembling and reassembling to carry out any necessary checks, modifications, repairs or cleaning of the analyzer components. The aperture through the RFEA (which defines the beam cross section D_b) is 4 mm in diameter – less than d_g . This condition ($D_b < d_g$) minimizes any distortion of the electric field due to the build up of space charges between the grids [122–124].

The prototype body is built from Teflon[®] material owing to its very good thermal resistance properties, so that it can withstand long periods of exposure to the high thermal energy loads and extreme vacuum conditions. It is made up of four equally spaced grids [34, 40], each within a Teflon module that has one side partially drilled into while the opposite side has part of the material removed leaving a short length which determines the inter-grid distance. Each module was built following the design details in Fig. 2.13b. A copper ring is placed right on top of the grid to hold it flat against the insulating Teflon material (and to also aid the connection to the grid by external electric wires), and the Seeger retaining ring provides the tight fit to keep the grids, copper ring and connecting conductor in place by its outward spring-like force exerted

(a) A longitudinal cross section of the four component RFEA modules stacked together, showing the different component parts.

(b) Dimensions of the modular Teflon[®] components used for the RFEA body.

FIGURE 2.13: RFEA design; (a) longitudinal section showing the four Teflon-body components stacked together, showing the different component parts, and (b) details of one module showing the dimensions.

onto the internal circumference of the cylindrical Teflon holder. The effective depth in which the grid, copper ring, Seeger ring and part of the connecting wire are fitted is about 3.5 mm.

Seeger retaining rings were specifically used in the first bulky prototype (see next Section 2.4.2.5.1), where each grid was fixed by positioning it to rest against the Teflon and then kept in position by a copper ring for electrical contact connection that is kept tightly in place by a metallic (stainless steel) Seeger retaining ring.

The analyzer's front (entrance) grid faces the incident plasma beam directly and thus floats with respect to the plasma potential. This minimizes the plasma perturbation by the probe. The second (PR) grid is biased negatively

to repel the plasma-borne electrons whereas the electric potential of the third (ion retarding or ID) grid is varied. This varied ID potential filters ions by their energies, such that only those with an energy-to-charge ratio greater than the bias voltage can pass through.

The fourth, and last, grid (SS) – the secondary electron suppressor – prevents any secondary electrons produced from affecting the collector current. This last (rear) module is stacked with a circular copper plate for the ion collection and measurement at the back of its protruding short length. The separate modules are supported together to form the analyzer by two metallic screws running through each, and are tightened by nuts.

As will be described in the proceeding Sections 2.4.2.5.1– 2.4.2.5.4, this original design was progressively modified to a final miniaturized, more robust version during the course of the research.

2.4.2.5.1 Prototype I: Bulky test version

The first prototype built was bulky (see Fig. 2.14), as the main goal was to understand how this diagnostic—used for the first time in this research laboratory—functioned. It was purposely built with the aim of being able to obtain a reasonable measure of ion current and to be sure that the measured currents were actually of ions and not electrons. As a means to achieve these goals/aim, grid potential and electric field analyses of the analyzer channel – both analytically and experimentally – had to be performed while taking into account the possible geometrical effects discussed above.

FIGURE 2.14: Photograph of the first Teflon-body RFEA prototype built: (a) During assembling with electrical connectors still exposed and visible, (b) Front view with grids and Seeger retaining ring visible, and (c) Top view.

Fig. 2.14 shows a photograph of this RFEA prototype just after assembling the modules with (a) the electric connectors still exposed, and in (b) and (c) the front and top views of the fully assembled analyzer ready for use. The two screw heads of the screws used to support all four Teflon rings with their different analyzer components together are seen in (a) and (b) whereas in (c) parts of the support screws with nuts are shown.

This first prototype strictly followed the design in Fig. 2.13 with four modules, with each module’s components electrically insulated from other modules’

by a 6.26 mm thickness of the Teflon body material that also corresponds to the grid-to-grid separation d_g . Each module is 7.02 mm long externally, leading to a total RFEA length of 31.3 mm including the collector.

Tab. 2.1 shows the characteristics of the grids used: made from molybdenum gauze, the grid meshes have an open area (transparency T_r) of 86.5% with a wire diameter of 0.0509 mm (or $59 \mu\text{m}$ thickness) and an average open width (mesh size) of 0.068 mm (or $68 \mu\text{m}$). An attempt was always made to see that the grids are carefully aligned parallel to each other while remaining perpendicular to the ion channel. This was achieved by stacking them against the insulating Teflon material, with the copper ring positioned right on top of the grid to maintain it flat (perpendicular to the ion channel axis), as shown in Fig. 2.13a. The same copper ring also serves to aid the connection of the grid by electric wires, which emerge from the sides unlike that to the collector which is from the rear end (see Fig. 2.14). No material is therefore spot welded against another in this RFEA design.

The exact value of the particle transmission rate through the ion channel is an important parameter in our studies, but we did not have the actual quantitative figures which we tried to estimate using the measurements we obtained using the RFEA.

TABLE 2.1: Grid parameters of the first RFEA prototype

Property	Value/Type
Material	Molybdenum gauze
Wire diameter	0.059 mm
Density	35 meshes
Open area	86.5%
Width of opening	0.068 mm

With the analyzer elements and arrangement as discussed above, the grids act as equipotential surfaces since the size of their open spaces are smaller than the characteristic Debye lengths. Additionally, space charge effects can be neglected because the separation between consecutive grids is less than two Debye lengths, i.e., $d_g \lesssim 2 \lambda_D$. The motion of ions through the open channel under such conditions is collisionless and only affected by the electric potentials at the grids.

2.4.2.5.1.1 Thermal shield and grid alignment modification: After a series of experiments with this first built prototype, a few modifications were made following the observed thermal effects on both the beam-facing materials and the beam optics of the grids (alignment) due to impingement by energetic ions.

FIGURE 2.15: Improved grid mounting and thermal shield (a) A wire gauze grid between two thin copper plates. (b) Front view of RFEA with heat shield.

The same analyzer structure was maintained, but with the front module replaced with a two-layer aluminium plate containing the floating/entrance grid as shown in Fig. 2.16. This is supplemented with a second parallel aluminium plate such that the set of plates act as a heat shield for the analyzer. These plates are electrically in contact with the support screws for the modules.

Also, due to curving inwards of the grids resulting in alterations of their alignment due to the ion beam optical effects, the grids were stacked between two thin copper plates with only a central open part forming part of the ion channel exposed to the ion beams during the measurements. Fig. 2.15a shows a grid wire gauze supported between two copper plates, whereas the plasma-facing aluminium plate that shields the RFEA components from direct ion beam fluxes is shown in Fig. 2.15b. This kind of reinforced alignment and positioning of the grids was found to be more reliable and effective in eliminating problems with the grid total or net transparency, and a device with a heat shield was more durable.

In the three modules of this heat-shielded version the grid, conducting wire, and copper ring are still together supported in the module's cavity (an open hollow section drilled partially through a Teflon body material) by a Seeger retaining ring as before. Multi-strand connectors used previously are replaced with single strand ones to minimize the noise resulting from electronics. Fig. 2.16 illustrates how the three modules and the copper plates are stacked so that the whole system of grids and the collector plate are coaxially arranged to have the plasma approaching the entrance grid perpendicularly. For the measurements with the first prototype, the RFEA was kept at a fixed position, 20 cm from exit (exhaust) of the plasma thruster along the vacuum tank's axis.

2.4.2.5.2 Prototype II: 3-D printed miniaturized version

A miniaturized version and modified design of the RFEA presented in Section 2.4.2.5.1 was made with the aim of having a more robust probe while minimizing its possible perturbation effect on the plasma. Fig. 2.17 shows

FIGURE 2.16: Horizontal cross sectional drawing of the modified prototype I RFEA along its channel axis showing the support structures.

a computer-aided design (CAD) drawing of this RFEA version. Five RFEA modules are used, of which four support the grids and their components and one contains the ion collector. A cylindrical aluminium support casing partially closed at the front end and fully open at the rear is also included to hold (and protect) the RFEA body and grid components. This is shown in Fig. 2.17c. Finally, a back cover module by which the setup is mounted onto the probe support in the vacuum vessel is also included. This back support is made with a central aperture through which the electric connection cables or wires from the RFEA are fitted.

FIGURE 2.17: CAD design of the improved (miniaturized) RFEA: (a) Front module with plasma-facing (floating) grid; (b) Exploded view of RFEA; (c) Assembled RFEA encased in aluminium housing. [Special credit to P. Argente for the CAD design]

This design was the basis upon which all the analyzers that followed after prototype I were built. The slight differences in the different prototypes rang from, for example, the choice of materials for the body, the grids and grid transparency, dimensions used, and how the electrical contacts are made to the grids.

In the original design, each module is 5.1 ± 0.16 mm thick and the depth of each cavity in which the grid with its connection and support accessories already described above are fitted in the modules is 2.6 ± 0.10 mm. The rear, and last, module's cavity that houses the collector is only 1.3 ± 0.01 mm deep for the copper collector of 1.0 ± 0.04 mm thickness and diameter 10.5 ± 0.12 mm to just fit in. The copper electrodes used for the electrical contact of the grids are each of diameter 10.4 ± 0.7 mm and thickness 2.0 ± 0.10 mm and they have a central aperture of diameter 6.5 ± 0.10 mm.

A specially designed Teflon is used at the rear part of the analyzer, through which the connectors are all passed. The plan was to use this back Teflon material with a spring to provide a very firm force to keep the setup intact and tight in the aluminium casing. The mounting of the analyzer on the support platform in the vacuum tank would be done using this back Teflon component. The aluminium casing would be screwed into this back Teflon support once the required tight fit of the RFEA is established in it.

Copper mesh grids with larger widths of opening are to be used with the hope to measure higher currents resulting from the improved transparency of the copper grids. However, this is in reality difficult to achieve because of the difficulty involved in aligning the open widths of the grids with those of their neighbours.

Single strand electrical wires would be preferred for the grid connections, to minimize noise resulting from current flow. These wires would be passed from the grids through holes (of size just enough for them to pass through) drilled through the side bulk of the modules to the rear. Kapton tape would be used to wrap the assembled modules with their connectors together and to also insulate the analyzer body from the aluminium casing in which it would be fitted.

The first prototype built following this design will be referred to here as prototype II of the RFEA. Figs. 2.18a and 2.18b show photographs of the component parts before assembly, whereas Fig. 2.18c shows the setup after assembly.

Thermoplastic material with relatively high temperature resistance was used, which could be easily 3-D printed to produce the prototype based on the design. However, this RFEA's usage failed at the first attempt just after a few minutes of plasma exposure and it did not last an experimental session. Despite the attempt to have it shielded from direct particle beam flux that would degrade it very fast by carefully encasing it in cylindrical aluminium, it was melted by the energetic beam due to thermal loads on it. Fig. 2.18d shows the deformed analyzer after being exposed to the plasma ions during an experiment. The thermoplastic melted leading to shorted connections which

FIGURE 2.18: Building of RFEA prototype II and after plasma exposure. (a) Copper grids attached to copper rings; (b) The assembled modules joined together by connecting cables; (c) The assembled RFEA to be inserted in aluminium casing (the 1 € coin for actual size comparison); (d) The RFEA melted after being exposed to the energetic plume beam ions for barely 15 minutes.

led to faulty measurements.

2.4.2.5.3 Prototype III: Teflon body build

Prototype III was a result of the failure due to poor choice of material for the analyzer body in prototype II. The same design specifications described in prototype II (Fig. 2.17) were used, with the exception that the body was made from Teflon. Image analysis of a photograph through all the grids in the RFEA channel was used to estimate the resultant grid transparency which was found to be $T_r \sim 27.37\%$ in the worst case. The ion channel diameter was 7.2 mm, RFEA external diameter was 16.9 mm, whereas the inter-grid separation was 5.0 mm. This prototype was successfully used for taking quite a considerable amount of measurements.

Fig. 2.19a shows the assembled RFEA modules kept together by Kapton tape and the cylindrical aluminium protective casing used to protect it from direct ion beam impingement. The electrical wires from the analyzer pass along the side of the body to the rear, in small lateral cavities drilled on the modules.

The assembled modules with connectors are then carefully stacked together using layers of Kapton tape wrapped around them. The Kapton tape also acts to insulate the assembled analyzer body both electrically and thermally from the aluminium casing in which it would be fitted. The connectors are all fitted through a specially designed Teflon at the rear, which provides a very firm force to keep the setup intact in the aluminium casing and is also used to mount the analyzer on the mobile platform in the vacuum tank. The aluminium casing is screwed into the Teflon body once the required tight fit of the RFEA is established inside it.

FIGURE 2.19: RFEA prototype III: (a) The components showing the Teflon body covered by Kapton tape, the Aluminium casing, and the back structure. (b) The aluminium casing attached to back structure.

2.4.2.5.4 Prototype IV: Macor ceramic body

The last and final prototype built was a more robust, durable RFEA built following the design in Fig. 2.17. The main features of this prototype that distinguish it from prototypes II and III are the steel gauze wires used for the grids, and that the body was of Macor ceramic material. The stainless steel gauze grids are composed of 20 meshes woven from 0.102 mm diameter 316-type steel. A single grid mesh has $T_r = 84.6\%$ (open area) with square openings of 1.17 mm width.

FIGURE 2.20: RFEA prototype IV: (a) The four modular parts with grids and connecting wires; (b) The modules assembled and secured with Kapton tape, with collector plate before mounting together; (c) The RFEA with assembly parts, ready for full assembly (the 1 € coin for comparison purposes).

The final build was made up of five ceramic modules as in prototype III, with the back cover and support module still made from Teflon. The diameter of the modules is 16.8 ± 0.07 mm with a thickness of 5.0 ± 0.15 mm. This thickness also corresponds to the inter-grid separation. The cavity depth in which the grid and its support and connection accessories are mounted in each

module is 2.9 ± 0.08 mm. A copper collector plate is soldered to a 1.99 ± 0.06 mm copper ring electrode such that the combination was 2.33 ± 0.005 mm thick, which was mounted on the last module. The four modules containing the grids formed a total length of 20.5 ± 0.05 mm when stacked together as seen in Fig. 2.20b. The SS grid is separated from the collector plate by a distance of 2.5 mm.

Because of the difficulties associated with connecting single strand connectors (breaks easily when moved or twisted), multi-strand connecting wires were used in this last prototype. Twisted thermocouple and extension (type-T) wires insulated with two-core PFA Teflon sheath were used, which are capable of withstanding operational temperatures between -75°C and 260°C .

2.4.2.5.5 Grid transparency estimation

The grid transparency (T_r) was determined optically by scanning or photocopying a known area of a well defined surface of the grids under known magnification factor. By taking into account the magnification scale factor, the actual grid area considered can be determined together with the area occupied by the mesh wires. Care has to be taken to avoid counting the area twice due to overlapping of the wires. In this way the grid transparency can be calculated as the percentage of its area void of the wires relative to its total surface considered.

FIGURE 2.21: Grid transparency (T_r) determination by image analysis with: (a) Part of original image sample of grids in one of the module parts, (b) Gray scale sample 1 and (c) sample 2.

The above procedure is clear and straightforward. However, due to challenges associated with aligning the grids in an attempt to achieve perfect transmission of the ion beam through their apertures, a different technique ought to be employed for determining the net transparency of more multiple grids aligned with respect to one another. Fig. 2.21a shows a photograph of a typical arrangement that can result for multiple grids. As shown in this figure, there is an almost unavoidable distortion that results, which diminishes the effective transparency of a grid when considered individually.

To estimate the resultant transparency of such grids, an approach that involves the binarization (collapsing all the 256 pixels of a grayscale image to

only two levels: 0 for black, and 255 for white) of an image of the section through the grids, such as the one shown in Fig. 2.21a, is used.

For this research, the GNU image manipulation program (GIMP) – a free and open-source graphics editor – was used for the binarization and image thresholding. A photograph of the section with the grids is carefully taken and, using the GIMP program, the channel or cross section containing the grids is selected and saved as an xcf file. This file can later be imported for analysis, where the Binary and Threshold options can be used to obtain a desired black and white separation of the image components. The Create Selection option from the Edit menu is used to select only the white pixels (if white is set to represent the transparent area of the grid section) whereas the Analyse and Measure options are used to measure the selection, giving the results in the Results window. Further manipulation of these results enables one to easily save them as a table in a csv file format which can later be manipulated using any spreadsheet or data analysis program.

Figs. 2.21b and 2.21c show two example samples of binary images from a photograph as in Fig. 2.21a under different thresholds. Because this method is an estimation which depends to an extent on the clarity of the originate photograph and the angle to which it was take, it is important to take several photographs and analyse them using at least three thresholds in each case so as to have a good indication of the grid transparency. The determination of the T_r provided here involved taking a total of twenty one values and the average taken.

2.4.2.6 Practical aspects: Operation and data acquisition

During the operations with the RFEA, all the analyzer voltages were maintained at a constant value except the ion discriminator grid voltage V_{ID} . The constant voltages were easily set manually using the instrument knobs. Sweeping of the V_{ID} however required a computer control platform for setting the sweep voltage values and triggering the power supply.

For the initial part of this research work, these sweep voltage controls were managed using ExcellINX, a Tektronix® Inc. Keithley software by which data acquisition can be done dynamically within Excel. This software uses a KE6485 interchangeable virtual instruments (IVI) driver and a Keithley I/O virtual instrument software architecture (VISA) runtime layer to communicate with the instrument (Keithley 6487 picoammeter/voltage source). The operation of the software is done through a Keithley Configuration Panel which enables the setting up and/or modification of the communications between the driver and the instrument. The picoammeter/voltage source was configured for Serial port COM1.

In the last half of the research, a platform was developed based on LabVIEW software, which enabled the instrument control and/or data acquisition to be managed centrally. Unlike ExcellINX which was used only for managing the data acquisition and operation of the RFEA power supplies, this new

platform was used for the management of all the three diagnostics described above (Langmuir probe, emissive probe, and the RFEA). Additionally, it was also used for managing the position control of the 3-D robotic platform (see Section 2.5.1.2 of Chapter 3 for details) for the electric probes.

The Keithley 6487 picoammeter was used to digitally measure ion collector currents as a function of the ion discriminator voltage grid V_{ID} . These were used to obtain the current–voltage (I – V) characteristics. The V_{ID} potential was swept between ± 500 V in 1000 fixed steps of 1 V with respect to the (grounded) walls of the vacuum chamber.

2.4.2.7 Ion velocity and energy distribution function determination from I – V characteristics

From the measured collector ion current as a function of the retarding (or discriminator) grid voltage $I_{IC}(V_{ID})$, a relation between the first derivative with respect to the potential, $\partial I_{IC}(V_{ID})/\partial V_{ID}$, and the ion velocity distribution function $f(v)$ can be obtained. Considering the distribution function $f(v, r)$ of particles in a six-dimensional velocity–position space where $v(x, y, z)$ and $r(x, y, z)$ are the velocity and spatial vectors, respectively.

For a simplified case in which $f(v)$ is considered to be homogeneous and constant in time in an X – Y plane perpendicular to the discharge axis Z , the spatial dependence of $f(v, r)$ is eliminated. In such a case where the velocity distribution is almost perfectly anisotropic with respect to one axis (Z), the X and Y components of $f(v)$ may be eliminated by treating them as equivalents of the Dirac delta functions [40].

Partial integration over the entire v space then reduces $f(v)$ to one dimension along the Z -axis. The X – Y plane in this case is taken to be positioned at the Z -coordinate of the entrance grid of the analyzer, which can be taken to be z_0 . The particle density n is related to $f(v)$ through

$$n = \int_0^{+\infty} f(v) dv. \quad (2.31)$$

But by definition,

$$dn = f(v).dv = g(E).dE \quad (2.32)$$

for the energy distribution function $g(E)$. Since

$$E = \frac{1}{2}m_i v^2, \quad (2.33)$$

where m_i is the ion mass; $dE = m_i v dv$ and $f(v) = m_i v g(E)$, in this considered case the total ion current density I_{IC} is given by

$$I_{IC} = e \int v f(v) dv = \frac{e}{m_i} \int f(v) dE. \quad (2.34)$$

For a known dependency of the integral value of I_{IC} on e for $0 < E < \infty$ with $\xi = \xi_1 + \xi_2$ as the integration variable for the ion energy such that

$$I_{\text{IC}}(E) = \frac{e}{m_i} \int_0^E f \left[\left(\frac{2\xi}{m_i} \right)^{1/2} \right] d\xi, \quad (2.35)$$

differentiation yields

$$d(I_{\text{IC}}(E)) = \frac{e}{m_i} f(v) dE. \quad (2.36)$$

Since all the ions that enter the analyzer and pass through the grids ideally contribute to the collected current $I_{\text{IC}}(E)$ for a retarding potential equal to the ground potential (i.e., $V_{\text{ID}} = 0$) with no charge production within the analyzer volume, sweeping the V_{ID} from zero to increasing values leads to a reduction in the measured $I_{\text{IC}}(E)$ by an amount equal to the contribution of slower ions which are repelled. Hence,

$$I_{\text{IC}}(E) = \frac{e}{m_i} \int_E^\infty f \left[\left(\frac{2\xi}{m_i} \right)^{1/2} \right] d\xi. \quad (2.37)$$

The ion velocity distribution can be derived from

$$f(v) = \frac{m_i}{e} \left(-\frac{dI_{\text{IC}}(E)}{dE} \right) = \frac{m_i}{e^2} \left(-\frac{dI_{\text{IC}}(V_{\text{ID}})}{dV_{\text{ID}}} \right), \quad (2.38)$$

where the energy E (in eV) is the product of the elementary charge e (in coulombs) and the grid potential V_{ID} in (volts), taking into account the relation $I_{\text{IC}}(E) = I_{\text{IC}}(eV_{\text{ID}} = 0) - I_{\text{IC}}(eV_{\text{ID}} = E)$. $f(v)$ needs to be divided by the T_r -value of each grid for low transparencies.

The obtained ion velocity distribution is plotted as a function of the of E – the ion energies. Since the measured ion energies are in units of potential, the values of the V_{ID} -scale can be stretched using $v = (2E/m_i)^{1/2}$ to obtain a real ion velocity distribution. The IEDF $g(E)$ can then also be derived from the same I - V measurements as follows:

The velocity distribution function $f(v, r)$ obtained as in Eq. 2.38 is used. The kinetic energy in Eq. 2.33 is due to two ion populations with $v^2 = v_1^2 + v_2^2$ for the thermal and accelerated velocities v_1 (energy ξ_1) and v_2 (energy ξ_2), respectively. Again, using the relation in Eq. 2.32, the total ion current density J_i can be given by

$$J_i = \frac{e}{m_i} \int (f(v_1) + f(v_2)) dE \quad (2.39)$$

and

$$J_i(E) = \frac{e}{m_i} \int_0^E f \left[\left(\frac{2\xi}{m_i} \right)^{1/2} \right] d\xi. \quad (2.40)$$

Differentiation yields

$$d(J_i(E)) = \frac{e}{m_i} (f(v_1) + f(v_2)) dE. \quad (2.41)$$

Assuming no charge production within the analyzer volume, sweeping the V_{ID} from zero to increasing values leads to a reduction in the measured density $J_{IC}(E)$ by an amount equal to the contribution of slower ions which are repelled. Hence, the collected current $I_{IC}(E)$ is given by

$$I_{IC}(E) = \frac{A_{IC}e}{m_i} \int_E^\infty f \left[\left(\frac{2\xi}{m_i} \right)^{1/2} \right] d\xi, \quad (2.42)$$

where A_{IC} is the collector cross-sectional area. The IEDF can then be derived using a similar equation as in Eq. 2.38.

A Bi-Maxwellian velocity distribution, which is a superposition of the $f(v_1)$ and $f(v_2)$ components is got, of the form

$$f(v_b(V_{ID})) = \frac{1}{2} A_1 \sqrt{\pi} \left(\frac{1}{\sqrt{\frac{1}{k_B T_e}}} - \sqrt{k_B T_e} \operatorname{erf} \left[\frac{V_{ID} - \phi_1}{\sqrt{k_B T_e}} \right] \right) + \frac{1}{2} A_2 \sqrt{\pi} \left(\frac{1}{\sqrt{\frac{1}{k_B T_e}}} - \sqrt{k_B T_e} \operatorname{erf} \left[\frac{V_{ID} - \phi_2}{\sqrt{k_B T_e}} \right] \right), \quad (2.43)$$

where the parameters A_1 , A_2 , ϕ_1 , ϕ_2 , and erf are the amplitudes of the thermal and accelerated peaks, the most likely thermal and accelerated ion voltages, and the error function, respectively.

The $f(v_b)$ is plotted as a function of the ion energies E .

Fig. 2.22 shows a typical simulated bi-Maxwellian distribution of Eq. 2.43. Scaling the V_{ID} -values using $v_b = (2E/m_i)^{1/2}$ leads to the real ion velocity distribution given by Eq. 2.38.

2.5 Diagnostics setup

We used the probes already described above in the plume plasma characterization. We developed a LabVIEW software platform for the diagnostics platform displacement control and data acquisition management, which controls the displacement/movement of the 3-D positioning system that in turn moves the probes within the plasma volume. These made it possible to measure the axial and radial profiles of the physical variables [48].

The results derived from the spatial measurements would then be used to also measure the beam divergence angle, which in turn provide a basis for estimating the conversion efficiency of momentum to the axial/parallel direction of the thruster.

FIGURE 2.22: Simulation of a distribution $f(v_b)$ from Eq. 2.43.

2.5.1 Multiprobe platform and the 3-D

The RFEA has been employed in this work to measure the energy/temperature and velocity, together with their respective distributions, of ions from the exhaust plume of the ALPHIE plasma thruster. Throughout the work described here, a four-grid retarding-field energy analyzer (RFEA) probe is used.

The ion energy distribution of the exhaust plume plasma provides information on the measure of the achievable thrust from the thruster. The ALPHIE thruster is designed to achieve an increased (modulated) thrust by plasma acceleration. A further advantage – control of the generated thrust achieved by changing the parameters of the thruster – has been confirmed, which conforms with the design inventions of the thruster. In electric propulsion, such analyzers are used in experimental measurements to carry out ground tests for thrusters. These form part of the motivation for the work described herein.

The energy/velocity distributions of the out-flowing exhaust plume plasma have been obtained using the developed analyzer. The obtained distributions clearly corroborate the design invention of the engine, where ions are accelerated to high (supersonic) velocities by the thruster. Details and the design features of the analyzer, the experimental setup, and the measurement results are described in the following paragraphs.

2.5.1.1 The Multiprobe Platform/Structure

For the characterization of the plume plasma, which would otherwise be difficult with only one or two probes, a multiprobe support platform was built that has slots for mounting up to four diagnostic probes to be used independently and concurrently during a given single plasma experiment. The design includes slots for a Langmuir probe, an emissive probe, an RFEA/RPA, and a Faraday cup (probe)—this was not used.

(a) Front view of the multiprobe platform. The geometrical centre is indicated by the arrow.

(b) Side view showing the LP, emissive probe (labelled as EP) and RFEA probes.

FIGURE 2.23: The multiprobe platform: The probes are mounted onto the platform with their front ends aligned and facing the plasma thruster.

Fig. 2.23 shows the multiprobe platform built for the simultaneous diagnostics of the plume plasma using different probes. As shown in Figs. 2.23a and 2.23b, the probes are carefully and precisely mounted – facing the plasma flow and aligned with a transversal plane to the platform.

The RFEA is supported by screws whereas the LP and emissive probe are mounted on D-shaped supports which can be released for maintenance and cleaning. However, calibration needs to be performed for the actual axial distances to account for the relative position of the exit section of the plasma thruster to the actual measuring range considered, e.g. in Figs. 5.15a, 5.15b and 5.19, i.e., 50–350 mm of Section 4.4. This ensures that the coordinates of each of the probes during measurements correspond to the real coordinates registered by the control software.

2.5.1.2 The 3-D Positioning/Robotic System

The scheme in Fig. 2.25 shows the 3-D coordinate frame for the mechanical system, where the centre point of Fig. 2.23a indicates the location of the Z axis, parallel to the symmetry axis of the vacuum tank. The mechanical system can displace the platform by 150 mm along both the X - and Y -directions and 300 mm along the Z -coordinate axis.

The support structure for positioning system fits exactly into our cylindrical stainless steel vacuum vessel of 80 cm length and 40 cm diameter and it has the same cylindrical symmetry as the vacuum tank. The multiprobe platform that supports the measurement probes, shown in Figs. 2.23a and 2.23b, is driven by three independent stepper motors.

The electric motors of the computer-controlled platform are shielded from any electromagnetic effects due to the plasma by carefully wrapping them in aluminium foils that are electrically connected to the grounded walls of

FIGURE 2.24: Front view of the multiprobe platform in the vacuum tank.

the vacuum tank. Each stepper motor drives a rubber timing belt arranged inside an aluminium rail (also electrically grounded) that protects the belt from thermal loads and damage due to plasma exposure. This enables the setup to withstand long operation periods. The geometrical centre of the platform is indicated by an arrow in Fig. 2.23a. The combined effect of the three stepper motors produces 3-D rectangular displacements of this point with a spatial resolution better than ± 1 mm along the three spatial coordinates.

FIGURE 2.25: Schematic of the mechanical system for the multiprobe platform of Figs. 2.23a and 2.23b. The probes face the plasma beam that is approximately centred at the Z-axis of symmetry. The emissive is labelled as EP.

The scheme in Fig. 2.25 shows the 3-D coordinate frame for the mechanical system, where the centre point of Fig. 2.23a indicates the location of the Z-axis, parallel to the symmetry axis of the vacuum tank. The mechanical system can displace the platform by ± 150 mm along both the X and Y directions and ± 300 mm along the Z-coordinate axis.

However, a calibration is performed for the actual axial distances to account for the relative position of the exit (exhaust) of the plasma thruster to the actual measuring range considered in Figs. 5.15a, 5.15b and 5.19,

i.e., 50–350 mm. This ensures that the coordinates of each of the probes during measurements correspond to the real coordinates registered by the control software.

The analyzer support is mounted on a movable clamp positioned within the vacuum vessel. The whole arrangement was then exposed to the out-flowing plume plasma. During the measurements with the RFEA, it was positioned such that the plasma-facing (entrance) grid was at 14.3 cm in front of, and directly facing the plume plasma. The base pressure of the vacuum vessel was typically 1.3×10^{-5} mbar.

To measure the spatial profiles of the plume plasma, serial measurements are made by displacing the probes mounted on the multiprobe platform (see Section 2.5.1.1 on page 72 for details) using the 3-D robotic system (Section 2.5.1.2 on page 73) within the plasma tank to obtain two-dimensional (2D) and three-dimensional (3D) measurements.

From the 2D and 3D measurements, an attempted to gain an insight into the physics of the plasma by making surface, waterfall, and/or contour plots of the parameters measured. The results from these measurements are used to obtain information on the radial structure of any fluctuations that may exist in the plasma since a probe immersed in plasma is sensitive to even short scale-length perturbations within the plasma [34].

Chapter 3

Experimental

The laboratory in which the experiments were carried out is divided into two main sections: an experimental room in which the actual facility is located and all the experiments conducted, and a control room (Fig. 3.1) in which remote operation and management of experiments are conducted and which also houses the computer controls and data acquisition systems, power supplies and the main electronic circuit panel for the facility. The control room is located next to the experimental laboratory room. Most of the mechanical and electrical gadgets required in the laboratory are also stored in the control room.

The experimental hall on the other hand contains the vacuum tanks and pumps, pressure meters, and the refrigeration device for cooling the diffusion pumps. Additionally, it is where most of the mechanical fabrication works done within the lab take place, as it is where the mechanical workshop tools are located (see Fig. 3.3).

3.1 Vacuum and Plasma Facility

The research work presented in this report, which is majorly for space propulsion, involves experiments with plasmas produced at low pressures that are necessary for the operation of the ion thruster ALPHIE.

Brief descriptions of the components and devices that make up the experimental facility are provided in the paragraphs that follow. A flow of neutral gas is used for the primary plasma formation when it is ionized in an almost enclosed unit called the plasma chamber by an electron beam.

3.1.1 The Vacuum Tank (Plasma Chamber)

The vacuum chamber or vacuum vessel, also referred to in this report as the vacuum tank or plasma chamber—names derived from the fact that a vacuum (required for the plasma production) is maintained in the tank during the engine operation, is the section where the plasma plume is ejected. Two vacuum tanks were used for the experiments: a large chamber that was later (last half

FIGURE 3.1: Power supplies in the control room. At the foreground are the engine power supplies (on middle and left racks), Langmuir probe and emissive probe bias and power supplies (rack on right hand side). The central electrical panel for the laboratory experiments rests on the wall to the right, and a glass window makes it possible to view what goes on in the experimental room from the control room.

FIGURE 3.2: The smaller cylindrical stainless steel vacuum tank with the ALPHIE engine mounted to it.

of 2018) prepared for plasma experiments has so far been mainly used for the thrust tests and measurements, and a smaller plasma chamber that has been functional since 1992 in which most of the experiments carried out prior to December 2018 were performed.

The small plasma chamber is made of a cylindrical stainless steel vessel of 80 cm length and 40 cm diameter, and a baseline pressure of up to 10^{-6} mbar can be achieved in it. The working pressures with the plasma and ion engine in

operation are between 10^{-5} and 10^{-4} mbar of Argon. The chamber is enlarged by connecting it to a T-shape section by a DN 250 ISO KF flange to fit the large-diameter diffusion vacuum pump. This extra section contains windows with transparent glass material through which the inside of the chamber can be viewed or observed. The ALPHIE engine was mounted and connected to this vacuum tank (see Fig. 3.2). Further details of the small vacuum tank are illustrated in the paragraphs that follow after this brief introduction.

FIGURE 3.3: The mechanical workshop tools in our experimental laboratory hall.

The larger vacuum chamber is also made of a cylindrical stainless steel vessel of 2 m length and 80 cm diameter. The same pumps and measuring gauges used with the small vacuum tank were transferred and connected to this large tank. Fig. 3.4 shows the larger vacuum tank in the experimental hall, as seen from the front and from the back.

(a) Front view of the larger tank in the experimental room. The circular coils around it are redundant.

(b) The diffusion and fore pumps connected to the larger vacuum tank (an the back end).

FIGURE 3.4: The larger vacuum tank used mainly in the last quarter of the research for direct thrust measurements.

Thus, at least for the periods during which this research was conducted, the two vacuum tanks could not be used for plasma experiments at the same time. With the same vacuum pumps pressure gauges, the baseline pressure achieved is the same as for the small tank, i.e., 10^{-6} mbar. The external coils surrounding this vacuum tank have not been used and do not serve any purpose at the moment, at least for the experiments referred to in this report.

3.1.2 Vacuum Pumps

Two pumps are available for use in our laboratory: a vacuum diffusion pump and a mechanical or forepump (see Figs. 3.5a and 3.5b). These two pumps operate at different regimes – the forepump is used as an ancillary pump to first pump out air molecules and any contaminants or particles until the vacuum diffusion chamber pressure is $\sim 10^{-3}$ mbar, the minimum required pressure for the operation of the diffusion pump.

3.1.2.1 Forepump

The forepump is a DUO 65 model manufactured by Pfeiffer Vacuum technologies. It is a positive displacement rotary vane pump, i.e., one that achieves fluid movement by trapping a fixed volume which it forces into the discharge pipe.

(a) Small vacuum tank with the pumps connected.

(b) The forepump connected to the diffusion pump.

FIGURE 3.5: The vacuum equipment used in the experiments. The vacuum tank (VC) together with some of its viewing windows (W) are shown. The forepump (P_1) and the diffusion pump (P_2) are also shown.

It moves fluid by a rotating mechanism (vanes attached to a rotor) that creates a vacuum on the suction side thereby capturing and drawing in the liquid and an increased pressure on the discharge side.

It has two DN 40 ISO-KF flanges (inlet and outlet) and can be used to attain a vacuum pressure of $\sim 10^{-3}$ mbar. The rotation speed is $1390\text{--}1660\text{ min}^{-1}$, achieved with a 1.1 kW power motor operated on a three-phase current motor circuit with 220/380 AC voltage and 4.85/2.8 A current for a 50/60 Hz frequency mains, respectively, in a delta or star connection. It can achieve a pumping speed of $65\text{ m}^3\cdot\text{h}^{-1}$. It is cooled by a synthetic diester-based (or P3 hydrocarbon) oil which can withstand high operation temperatures of up to 120°C .

Fig. 3.5b shows the rotary vane pump with a connection from the diffusion pump and the vacuum tank (not seen on the figure). For the experiments, we only connected the pump through the inlet (suction) region by the vacuum flange which allows pumping to be possible from both the diffusion pump and the vacuum tank and left the exhaust flange open.

3.1.2.2 Diffusion pump

The diffusion pump is an Agilent HS-20 model with a pumping speed of $32,000\text{ l}\cdot\text{s}^{-1}$ for air and $21,625\text{ l}\cdot\text{s}^{-1}$ for Helium and Hydrogen.

FIGURE 3.6: How a diffusion pump works. (From: Ref [125])

Tab. 3.1 [126] shows the details of its technical specifications.

The pump heater uses a silicon-based oil (DC-704 type) made of Tetramethyl tetraphenyltrisiloxane cyclosiloxane, but can also be operated on synthetic hydrocarbon oil NEOVAC SY that is also a high quality, low-cost organic compound (alkyldiphenylether) [126]. This oil has a low vapor pressure, enabling it to achieve base pressures in the low 10^{-8} mbar range untrapped while not

TABLE 3.1: Technical and operational characteristics of the Agilent HS-20 diffusion pump used in the experiments. (Source: Ref. [126])

Characteristic	value
Pumping speed @ operating range	17,000 l·s ⁻¹ air 21,625 l·s ⁻¹ He and H ₂
Pumping speed, AVS 4.1 (1963)	32,000 l·s ⁻¹ air
Maximum throughput	40 mbar·l·s ⁻¹ in operating range 45 mbar·l·s ⁻¹ @ 0.01 mbar
Operating range	2.3×10^{-3} to $< 6.5 \times 10^{-8}$ mbar
Maximum forepressure	No load: 0.65 mbar Full load: 0.45 mbar
Recommended backing pump	$\geq 510 \text{ m}^3 \cdot \text{hr}^{-1}$
Backstreaming rate, standard cold cap	$< 7 \times 10^{-4} \text{ mg} \cdot \text{cm}^{-3} \cdot \text{min}^{-1}$
Warm-up time	60 minutes
Cool-down time	180 minutes
Fluid charge	11.3 litres
Electrical requirements	3 ph, 50/60 Hz, 240/415/480 VAC
Pump power	24,000 watts
Cooling water requirements	800 l·hr ⁻¹ @ 60–80°F (15–26 °C)
Water connections	3/8 in. FTP Tee
Recommended fluid	DC-704 or equivalent

producing inorganic deposits that could cause electrostatic charge buildup on electrodes of sensitive instruments. Tab. 3.2 [126] shows the working properties of these two oil types.

The vacuum diffusion pump is only turned on after a 10^{-3} mbar vacuum level [126–130] has been attained using the forepump, and is used to achieve vacuum ranging from 10^{-3} mbar to up to 10^{-10} mbar, which is the range within which plasma is produced in our experiments. The resulting arrangement forms a shape of an upwards-pointing arrow (see Fig. 3.6). It has a heater which heats up silicon-based oil to a gaseous state, usually between 180 and 270 °C, positioned at the bottom of the chamber.

The free-moving gaseous molecules (vapour) travel upwards and exit through pressure jets elevated sideways. The downward out-flowing vapour travels at very high speeds and air molecules are trapped in it through diffusion [127–130]. The walls of the pump chamber are water-cooled so that this gas condenses to liquid state as it reaches the cooled chamber walls, releasing the trapped air molecules at a lower position and at increased pressure thus creating the vacuum. The oil then drips back to the bottom of the pump chamber where it continues to be heated and the cycle begins again.

TABLE 3.2: Working characteristics of the DC-704 and NEOVAC SY type diffusion pump oils that can be used with our Agilent HS-20 diffusion pump used in the experiments. (Source: Ref. [126])

	NEOVAC SY	DC-704
Chemical description	Synthetic hydrocarbon	Single-component silicone
Chemical composition	Mono-N alkyldiphenylether	Tetramethyhtetra-phenyltrisiloxane cyclosiloxane
Ultimate pressure		
Untrapped (mbar)	low 10^{-8} range	10^{-8} – 10^{-7} range
Trapped (mbar)	1×10^{-11} range	10^{-11} range
Vapour pressure at 25 °C (mbar)	1×10^{-8}	2×10^{-8}
Viscosity (cst) at 25 °C	25 at 40 °C	39
Boiling temperature at 0.7 mbar (°C)	220 at 1.1 mbar	215
Flash point	230	221
Ultimate pressure	Very good	Very good
Thermal stability	Good	Excellent
Oxidation resistance	Good	Excellent
System cleanliness	Very good	Very good

When working with diffusion pumps, care must be taken [126, 127, 131–133] to ensure that the pump heater is never turned on without the pump oil/fluid, otherwise the heater and pump assembly may get damaged. Also, water cooling should be turned on or circulated to prevent overheating of the pump and fluid, which can lead to unstable or improper operation of the pump due to thermal runaway [127, 134].

The vacuum in a diffusion pump therefore begins at the top of the pump chamber where air molecules are pulled and moved downwards at increased pressures. The removed air exits the pump through a nozzle at the bottom, enhanced by the ancillary forepump that provides an outlet pressure ~ 0.1 mbar.

To overcome the main limitation in diffusion pumps (backstreaming of the gaseous pump oil into, and thus contaminating, the vacuum), cold traps and baffles may be used – though with compromised pumping abilities of the equipment. Fig. 3.5b shows the diffusion pump and forepump connected to the vacuum tank. The diffusion pump (labelled P₂) is a stainless steel chamber with the outside walls fitted with aluminium cooling coils. The coolant (water in our case) is maintained by a KRA20 model chiller produced by KELVIN S.r.l (see section 3.1.2.3 below). It is made up of three cone-shaped pressure jets of

TABLE 3.3: Characteristics of the 2001 Kelvin KRA20 model chiller used to cool the diffusion.

Characteristic	value
Model	KRA20
Weight in kg	98
Refrigerant/Quantity in kg	R134a/1.1
Nominal AC voltage (V)	230
Power phase	1
Power frequency (Hz)	50
Starting current/Running current (A)	30/10
Cooling capacity (W)	2300
Power consumption (W)	1200
Sound pressure level dB(A)	69
Tank volume (l)	33
Pump available pressure (kPa)	50–380

varying sizes (largest at bottom and decreasing upwards) stacked vertically.

3.1.2.3 Cooling system for the diffusion pump

To avoid overheating of the diffusion pump, a steady supply of water coolant is maintained using a heat exchange system (chiller) manufactured by Kelvin S.r.l. It is a 3 phase, 230 V KRA20 model chiller that is operated on a 50 Hz power line. The technical details are summarised in Tab. 3.3.

Fig. 3.7 shows a photograph of the chiller in operation.

FIGURE 3.7: Photograph of the Kelvin KRA20 chiller for cooling the diffusion pump.

FIGURE 3.8: PKR Compact FullRange[®] pressure gauges used in the measurements.

3.1.3 Pressure gauges

Throughout the experiments referred to here, Pfeiffer PKR 251 Compact FullRange[®] vacuum gauges (part number PTR2600) and a high current, metal sealed Pfeiffer PKR 361 Active Pirani/Compact Cold Cathode vacuum gauge (part number PTT03140010) were used.

The PKR 251 Compact FullRange[®] gauge uses a PKR 251 vacuum sensor. It is corrosion resistant and can work with the same (a single) flange throughout the atmospheric pressure to ultra high vacuum (UHV) range.

Both gauge models measure pressure using two separate systems (the Pirani [135] and the cold cathode) whose gauge heads are in a single case as in an inverted magnetron [136, 137]. Both systems' signals are combined to generate a single and uniform signal output which is the measuring signal is output as a logarithm of the pressure [136]. They are both connected using a DN25 ISO-KF high vacuum flange, and have a display range of 1.0×10^{-9} –1000 mbar [136, 137] and a pressure measurement range of 1.0×10^{-8} –1000 mbar for air/Nitrogen gas, with an accuracy of $\pm 30\%$ of the reading for measurements < 100 mbar, which increases to $\pm 50\%$ of the reading above this value for Nitrogen gas. The maximum pressure referred to in this case is applicable to inert gases and temperatures of less than 55°C .

3.1.4 Neutral gas and the flow control gauge

The neutral gas flow through the ion engine into the vacuum tank was controlled by a Bronkhorst F201C valve and a E-7100 flow controller. The flow rates of the gas injected into the discharge chamber were maintained between 0.6–1.5 standard cubic centimetres per minute (sccm). However, corrections for the neutral gas back flow from the vacuum tank through the open spaces of the grids were also considered.

Photographs of the digital display meters for the gas mass flow rate and the

(a) A photograph of the Bronkhorst F201C valve used for the neutral gas flow control.

(b) Photograph of the meters with the E-7100 flow controller and Pfeiffer Vacuum pressure displays.

FIGURE 3.9: The flow rate and gas pressure digital display meters for the experiments. The signal controller hardware are mounted on racks to form a single meter unit.

vacuum tank pressures are shown in Fig. 3.9.

3.1.5 Power supplies

Tab. 3.5 shows the characteristics of the ALPHIE thruster DC power supplies. The magnitudes of the typical operational bias voltages and the engine currents indicated in the schematic of Fig. 1.7 summarized in Tab. 3.4.

3.1.5.1 Keithley 6487 and 6485 Picoammeters/Voltage source

These power supplies were employed mainly for providing the RFEA ion discriminator grid voltage which were dc voltages varied between -500 and 500 V. The 6487 model served both as a Picoammeter for measuring the ion collector current I_{IC} and as the voltage source for the analyzer ion discriminator grid voltage. It was chosen majorly because of its high accuracy and fast rise time (20 fA to 20 mA current range with measurement speed of $1,000$ readings per second and 200 μ V to 505 V).

This instrument's ability to measure current values with eight possible ranges that can be selected in the front panel with high speed autoranging enabled us to detect even the smallest ion currents. Calibration of the picoammeter and voltage source of this instrument were performed before its usage in the experiments.

For the calibration, I - V characteristics were measured using the picoammeter:

TABLE 3.4: Operational parameters of the scheme in Fig. 1.7 of Section 1.8 used in the experiments discussed in Section 3.1.

Parameter	Value(s)/range(s)
Gas pressure	$p_a = 4.0\text{--}10.0 \times 10^{-6}$ mbar
Argon flow rate	$Q = 0.5\text{--}1.5$ sccm
Acceleration voltage	$V_{AC} = 400\text{--}650$ V
Thruster current	$I_E = 100\text{--}500$ mA
Cover grid voltage/current	$V_{CG} = 0\text{--}350$ V, $V_{CG} \leq 2$ mA
Ion extraction grid voltage/current	$V_{EG} = 100\text{--}300$ V, $I_E \leq 2$ mA
Neutralizer heating voltage/current	$V_{NH} = 10\text{--}12$ V, $I_{NH} = 5.5\text{--}6.3$ A
Maximum power	< 450 W

TABLE 3.5: The characteristics of the DC power supplies of the electrical scheme of Fig. 1.7 employed in the experiments.

Function	Max. power characteristics	Brand model
Neutralizer heating	150 V, 10 A	Agilent N5770A
Ion extraction grid	$V_{EG} = 150$ V, $I_{EG} = 10$ A	Agilent N5770A
Acceleration	$V_{AC} = 1.5$ kV, $I_{AC} = 0.75$ A	Fug MCA 750-1500
Control	$V_{CG} = 300$ V, $V_{CG} = 5$ A	Agilent N5771A

1. Three resistors of 500 k Ω , 570 k Ω and 1000 M Ω were used.
2. Connections were made such that currents in the μ A and nA ranges could be measured using the picoammeter with a standard multimeter also connected in series with it for monitoring any significant fluctuations or deviations from the expected current range.
3. I – V Measurements were obtained for (i) an externally generated (not Keithley picoammeter and voltage source powered) dc voltage source, and (ii) the Keithley (picoammeter) dc voltage source both with and without the voltage sweep function.

Fig.3.10 shows some of the results of the calibration.

(a) nA range: with 1,000 M Ω , external V source. (b) nA range: with 1,000 M Ω , external V source.

(c) μ A range: with 578 k Ω , external V source. (d) μ A range: with 500 k Ω , picoammeter voltage source.

FIGURE 3.10: Calibration curves for the picoammeter voltage source

3.2 Experiments

3.2.1 Setting up the experiments

For all the plasma plume experiments described in this research, the engine and the vacuum tank are aligned during mounting so that they are almost axisymmetric around the same central axis. A regular experimental session begins with setting the apparatus into operation, which involves creating the right vacuum levels for plasma production and maintaining the achieved vacuum throughout the experiment. A very well defined sequence of steps is thus followed when preparing for experiments once the ALPHIE engine has been mounted and the vacuum tank closed. Attainment of the required vacuum levels and turning off of the vacuum equipment after the experiment therefore take almost 70 % of a day's experimental work.

3.2.1.1 Turning on the experimental equipment

Because of the different working regimes of the pumps described above, a well defined sequence of steps is followed to attain the required vacuum in the tank. Fig. 3.11 shows the experimental vacuum equipment, with connections of the rotary forepump to the diffusion vacuum pump and the vacuum tank made through clear PVC Hi-Vacuum KF-40 suction and delivery hoses reinforced with wire/steel spring spiral and with ISO-KF NW-40 Stainless Steel Flanges. The PVC hoses are connected to the vacuum flange of the rotary pump by a TEE NW-80 Vacuum Fitting with ISO-LF NW-40 stainless steel flanges.

Since the forepump serves to create the required starting vacuum for the diffusion pump, it is connected to the diffusion pump with the flow of molecules/air controlled by valve A and also to the vacuum tank (with valve B) for is simultaneous pumping from both the diffusion pump and the vacuum tank, or only from one of them if necessary. Each of the connections to the two components has a valve that is used to allow or prevent pumping of air and particles from it by the rotary forepump.

FIGURE 3.11: Photograph of one of the laboratory vacuum apparatus used in our experiments. The different parts are labelled.

The pumping procedure to achieve the required high vacuum therefore follows the following sequence of events:

1. With the pressure meters switched ON, valves A and B (see Fig. 3.11) are opened to allow pumping from the vacuum tank and the diffusion pump by the rotary forepump.

2. The guillotine valve is also opened. This ensures that the pumping circuit is continuous from both sides of the inlet or suction part of the rotary pump.
3. The rotary forepump is then turned ON by connecting it to a power socket.
4. This pump is left to work continuously until the pressure in the vacuum tank and the diffusion pump is lower than 5.0×10^{-2} mbar or even less, which is observed on the pressure meters.
5. The guillotine valve is closed using the lever shown in Fig. 3.11. This isolates the diffusion pump chamber from the vacuum tank. Pumping of the two chambers by the forepump is however maintained while permitting the diffusion chamber of the pump to be pumped independently from the vacuum tank.
6. The chiller (see Fig. 3.7) is turned ON. This is a very important step that MUST never be forgotten since it maintains a continuous supply/flow of coolant water in the aluminium cooling coils surrounding the diffusion pump to avoid overheating of the pump and its fluid.
7. The diffusion pump is turned ON by plugging its power cable to an electric power socket. It is left to work for a minimum of at least 30 minutes so that the diffusion pump oil warms up.
8. Valve B is then closed. The rotary forepump now only pumps from one direction – the diffusion pump chamber.
9. The guillotine valve is opened. The diffusion pump is then directly connected to the vacuum tank, which are now pumped to as high a vacuum as possible by it.
10. Once the vacuum system has stabilized at the lowest possible pressure, the vacuum is then controlled/fixed by the computer-controlled gas leak valve system.

3.2.1.2 Turning off the experimental equipment

Once the experiments have been completed, it is important that the experimental facility equipment is turned off/shut down for reasons ranging from safety to the longevity of the apparatus as maintenance steps. The continuous functioning of the vacuum pumps and heat exchanger operations for cooling the diffusion pump throughout an experimental session involve generation and emission of thermal energy which need to be reduced. As part of the turning OFF process of the experimental apparatus, some of this thermal energy accumulated by the equipment needs to be reduced/eliminated. This is where the cooling down times come in.

The cooling down of the apparatus alone consume more than 95% of the turning OFF/shutting down of the experimental apparatus/facility. Just like the case for the turning ON of the apparatus, a well defined set of procedures is followed during the shut down process. These are summarised below:

1. The computer-controlled gas leak system is cut off by closing the leak

- valve. This is done automatically using the control flow software.
2. The guillotine valve of the diffusion pump is then closed. This isolates the diffusion chamber from the main vacuum tank.
 3. The diffusion pump is turned off by unplugging the connection of its power cable from the electrical power socket.
 4. Valve B is opened. The vacuum tank in this case is pumped by only the rotary forepump.
 5. A cooling down period of at least 45 minutes is allowed for the diffusion pump oil. This is a crucial step, as it is a maintenance procedure stipulated by the pump manufacturer.
 6. Valve B is then closed and the chiller turned off.
 7. Lastly, the rotary forepump is turned off by unplugging the power cable from the power socket, and the pressure meters turned off.

3.2.2 Vacuum tank operational conditions and collisional considerations

Since the understanding of an ion beam and its parameters requires among other things taking into account the ion source and vacuum chamber characteristics, such as the characteristic dimensions and pressure which involve consideration of the pumping means (cryopumps, turbopumps, diffusion pumps, etc.), possible undesirable physical impactors of the ion beam are:

1. gas entrained into the ion discharge channel
2. particles resulting from charge exchange (affect the ion beam current and lead to beam divergence)
3. resputtering and deposition of the ion source surfaces (affect ion operation)
4. negative ion effects.

The operation of the thruster requires vacuum in order for the plasma formation in the engine. In this research, the limited pumping speed of the vacuum equipment used determines the maximum possible Argon mass flow rate for the operation of the plasma thruster, and consequently its ion production rate $\dot{m}_i$. It is however possible to produce sufficient plasma using Argon with even neutral gas flow rates as low as $Q = 0.28$ sccm. This allows for a low gas pressure of $p_a = 1.5 \times 10^{-5}$ mbar to be achieved in the plasma vacuum vessel, as shown in Figs. 3.12a.

During the experiments on the ALPHIE plume plasmas, the normal working pressures in the tank when the thruster was functioning (turned ON) were $\sim 4.0\text{--}8.0 \times 10^{-5}$ mbar. Tests on ALPHIE's performance already introduced in Chapter 1 (Section 1.8) were conducted in the cylindrical stainless steel vacuum tanks. The base pressure in the system was 5×10^{-6} mbar and the working pressures p_a were $\sim 4.0\text{--}8.0 \times 10^{-5}$ mbar for neutral gas flow rates $Q = 0.5\text{--}1.5$ standard cubic centimetres per minute (sccm) injected into the discharge chamber. The calibration curves of the vacuum tank pressures for neutral gas valve opening ratios ranging from 0.1 to 1.0 are shown in Fig. 3.12,

with 100 % being when the valve is fully open or equivalently equal to 1 sccm. These are equivalent to Argon mass flow rates $\dot{m} = 0.89\text{--}2.7\text{ mg}\cdot\text{min}^{-1}$.

FIGURE 3.12: Vacuum tank pressure calibration for different gas inlet valve opening ratios (mass flow rates)

For these pressure values the characteristic elastic and resonant charge exchange collisional cross sections for neutral atoms with Argon ions in the plasma are in the order of $\sigma_{ai} \sim 3 \times 10^{-15}\text{ cm}^2$ [89, 138]. These correspond to a mean free path $\lambda_{aa} \simeq 500\text{ cm}$ [139, 140]. Taking into account the corrections for neutral gas backflow from the vacuum tank through the open spaces of the engine grids, the mean free path for collisions among neutrals, and for ions of Argon with neutrals [139, 140] for these pressures are in the range 60–200 cm – much larger than the relevant dimensions of the experiment.

The mean free path for elastic collision between two neutral Argon atoms [89] is $\lambda_{aa} \sim 430\text{ cm}$, whereas with the cross sections for electron and ion impact ionization of Argon [138] the mean free paths also exceed the size of the vacuum tank. In line with these collisional mean free path results for the operational density and pressure ranges used, we do not expect collisional effects in the ALPHIE experiments.

Additionally, the local Ground for the plasma thruster and its power supplies in Fig. 1.7 was electrically insulated from the grounded wall of the vacuum tank. Thus, the stream of charged particles is the only connection between the plasma engine and the diagnostic equipment which were electrically isolated.

The operation of the ALPHIE plasma thruster follows three steps: First, the voltages V_{AC} , V_{EG} and the propellant gas flow rate Q are fixed to values within the ranges indicated in Tab. 3.4. Next, the control potential V_{CG} is set to null to maximize the electron inflow towards the discharge chamber. Finally, the DC heating power $P_{NH} = V_{NH} \times I_{NH}$ of the neutralizer cathode is increased to the point of thermionic electron emission [37]. This increase in the P_{NH} multiplies the high energy electrons trapped inside the plasma chamber. The thruster current I_E steadily increases with increasing ionization rate and, for $I_E \approx 100\text{ mA}$, the plasma outflow can be detected by a Langmuir probe (in our case positioned 20 cm away) within the vacuum chamber.

In these conditions, the currents I_{CT} and I_{EG} are always below 2 mA, two orders of magnitude lower than I_E . This indicates the low loss rate of charged particles. Alternatively, I_E decreases for negative voltages V_{CG} high enough because the inflow of ionizing electrons decreases or eventually gets disrupted. The thruster current I_E increases with the ion outflow and depends on three parameters, namely, the acceleration potential V_{AC} , the propellant mass flow rate Q and the inflow of ionizing electrons from the active cathode. The latter is governed by the wire heating power P_{NH} in our case [37].

Nevertheless, we restricted the operation of ALPHIE plasma engine to $I_E = 100\text{--}500\text{ mA}$ as in Tab. 3.4 to maximize the ion current outflow within the technical limits of our equipment. Specifically, the mass flow rate was $Q < 1.5\text{ sccm}$ and $P_{NH} < 76\text{ W}$ that limited the ion production rate in our experiments. In experiments with the above multiprobe diagnostics, the possible origin(s) of the energy losses (collisions or any other mechanisms (non-collisional) such as the existence of electric fields during the plume expansion) are further investigated. To study the electron and ion behaviour or properties, in addition to the neutrals, an attempt to measure the electron and ion temperatures and densities at various spatial positions within the plasma vessel in addition to the ion energy distribution function (IEDF) and the electron energy distribution function (EEDF).

Chapter 4

Plasma Diagnostics and Data Analysis

The plasma jet structure and parameters were determined using the three electric probe diagnostics described in Section 2.2.3 on page 30, but the four-grid RFEA was the main diagnostic for ion measurements. Electron characteristics have been mainly measured by the Langmuir and emissive probes. In all the measurements with the RFEA, the ion-collector currents were below $600\text{ }\mu\text{A}$, ranging from 0 to $500\text{ }\mu\text{A}$ very close to the engine exhaust section and less than this farther away from the exit section of the engine. Langmuir probe measurements showed no relevant plasma waves or oscillations.

To study the plasma plume structure and flow properties, measurements were taken both at a fixed point in front of the engine exit section and at different spatial positions, along the beam axis shown in Fig. 2.25 (page 74) or radially along the beam diameter (cross section). These were achieved with the probes mounted on the platform in Fig. 2.23 (page 73), as shown in Fig. 2.24 of page 74.

4.1 Fixed point and spatial measurements

Langmuir probe, RFEA, and emissive probe measurements were first taken with the position of the probes fixed 200 mm downstream (in front of the engine exhaust/exit section of the plasma thruster) on the axis referred to in this Chapter's introduction. From these measurements, the ion beam characteristics and dependencies on the engine operational parameters such as the acceleration voltage V_{AC} , cover grid voltage V_{CG} and the beam current of the out-flowing beam from the discharge-plasma chamber of the engine, I_E , were studied (see schematic on Fig. 1.7 of page 21).

These measurements were mainly intended for understanding how the RFEA worked given that it is a new diagnostic in the research laboratory. This involved tests carried out on the performance of different electron sources such as the dispenser cathode. Unfortunately the dispenser cathode did not yield

better results than the originally used hot wire cathode and was discarded as an electron source in this research. Later, these measurements were very fruitful in understanding the beam dependence on the ALPHIE engine parameters like the control or cover grid voltage V_{CG} , propellant mass flow rate Q , and acceleration voltage V_{AC} . The measurement data that will be presented in Figs. 4.12, 4.13, 4.14, 4.15 and 5.6 above were all obtained at this fixed position.

With the aid of the multiprobe stand (see Fig. 2.23, page 73) and the 3D robotic positioning system whose mechanism has been described in Fig. 2.25 of Section 2.5.1.2, the experimental techniques discussed in Section 2.2.3 were employed for the determination of plasma plume physical characteristics along its axis of symmetry. These enabled the measurement of both axial and cross sectional profiles of the ion beam current and IEDFs.

For the analysis of the measured data, a software tool – based on the Savitzky-Golay (SG) numerical approximation [68, 86] algorithm – that has been developed by the research group of our laboratory is used to first smooth the measured data. This turned out to be a very powerful tool, as will be shown under the various probe data post processing and analysis of the measured data in the sections that follow. Both the obtaining of, and the analysis of, data from these measurements required considerable time. To put this into perspective, obtaining the plasma potential dependence on mass flow rate at a given point by the emissive probe, for example, requires at least six profiles for each mass flow rate. With 9 mass flow rates used, this leads to at least 6×9 files to be analysed e.g. for a single acceleration voltage V_{AC} . For eight acceleration voltages, it would require at least 54×8 files, whereas it would take not less than 432×20 files for twenty axial positions. This elaborates the magnitude of work involved and the amount of time needed to enable the completion of the research activity.

Considering that also the axial variations of the plasma potential were to be studied, and also that other diagnostics (RFEA and Langmuir probes had to be used and the corresponding data files analysed), the number of data files explodes considerably, which becomes enormous when cross-sectional profiles are also obtained. Nevertheless, axial measurement of the plasma potential using the emissive probe was made, with the characterization (measurements) by the RFEA done both axially, radially along the beam diameter, and cross-sectional profiles obtained at selected axial distances from the engine. In the sections that follow the actual plasma measurement by the different diagnostic probes is discussed.

4.2 Emissive probe measurements

The emissive probe whose characteristics have been presented in Section 2.4.1.3 (page 49) was used to measure the plasma potential V_{sp} . As already discussed in Section 2.4 on page 44, this probe was operated both in the weakly emitting

($I_{\text{em}}/I_{\text{coll}} \simeq 1$) and strong emission regimes ($I_{\text{em}}/I_{\text{coll}} \gg 1$), with the floating potential method employed in the analysis of the obtained probe characteristics from the latter case. The inflection point method was used for the weak emission probe analysis.

Here, I present the obtained emissive probe I - V characteristic curves, then discuss the use of this probe in the plasma potential measurement, including the obtained V_{sp} values from the two analysis approaches which are then compared. Despite the time constraint that limited my freedom and ability to analyse all the measured experimental data as put forward at the end of the previous Section (4.1), especially resulting from the difficulties associated particularly with the inflection point method, I still felt it was useful for me to attempt to explore both approaches.

4.2.1 I - V characteristics

To obtain the plasma potential by the use of this probe (which is the main reason for its use in this research), a set of probe I - V curves are measured for a fixed parameter at a given position, e.g. fixed z . With the thruster engine parameters such as mass flow rate, beam power, or acceleration voltage maintained at constant values, the probe I - V characteristics are obtained for different emission levels determined by the probe heating current I_{H} . The plasma potential V_{sp} can then be determined using the methods and procedures already described in Section 2.4.1.4, page 51, of Chapter 2.

FIGURE 4.1: Raw emissive probe I - V characteristics in a dense plasma for different probe heating currents.

Fig. 4.1 shows an example of a set of probe I - V characteristic curves obtained from plotted raw data measured for 50 % neutral gas valve opening (0.5 sccm), 1.5×10^{-5} mbar base pressure, and acceleration voltage $V_{\text{AC}} = 500$ V. This characteristic is typical of a dense ALPHIE plasma. However,

in most of the measurements the curves are not as smoothed out but with some unavoidable oscillations and thus shapes slightly different from these ones, as shown in Fig. 4.2 are obtained. Unfortunately the actual source of such oscillations are still unknown and were difficult to deal with throughout the measurements, as sometimes they occurred as transients and in some cases were observed throughout an experimental session. It is likely that they were associated with the electronics of the power supplies used.

FIGURE 4.2: I - V curves for three probe wire heating currents $I_H = 0.87, 0.99$, and 1.05 A. The characteristic curves contained within high-frequency oscillations as shown.

4.2.2 V_{sp} measurement

4.2.2.1 Inflection point method

To measure the plasma potential by this method, the I - V characteristic curves as in Fig. 4.1 are measured for a weakly emitting probe (see Section 2.4.1.4.2 on page 51). In case of characteristic curves where the I - V signals are contained within noisy or oscillatory signals as in Fig. 4.2, the measured I - V signal data is first filtered/smoothed using the aforementioned Savitzky-Golay (SG) numerical software tool. Fig. 4.3 shows examples of smoothed I - V curves for measurements taken at $Z = 100$ mm and 80 mm. The characteristics in Fig. 4.2 are an extract of the axial measurements at $Z = 80$ mm before smoothing, which show oscillations that were occasionally observed during measurements with the emissive probe.

To determine the inflection-point potential, the original probe I - V curves are differentiated with respect to the probe bias potential V_{probe} . The inflection point corresponds to the peak of the differentiated characteristic. This is elaborated in Fig. 4.4a where both the first and second derivatives are shown, with

(a) $Z = 80$ mm (b) $Z = 100$ mmFIGURE 4.3: SG-smoothed emissive probe curves for different probe heating currents I_H at $Z = 80$ mm and $Z = 100$ mm.

the zero of the second derivative occurring at the same potential as the peak of $dI_{\text{probe}}/dV_{\text{probe}}$. The characteristics, as in Fig. 4.3, were therefore differentiated to get $dI_{\text{probe}}/dV_{\text{probe}}$ whose peak indicates the inflection point. Fig. 4.4 shows graphs of typical characteristics used in the plasma potential determination using the inflection point method.

In Fig. 4.4a a single I - V curve with oscillations (in blue) is shown together with its SG-smoothed fit (in red). The corresponding first (in pink) and second (in black colour) derivatives, also computed and smoothed using the same SG filter are also shown on the same axes, with the inflection point of the I - V curve (peak of the first derivative curve) shown.

Fig. 4.4b shows zoomed-in (magnified) SG-smoothed curves for the first

(a) SG-smoothed original low-emitting probe curve with the 1st and 2nd derivatives.

(b) Observed shift in the peaks of 1st derivative towards V_{sp} as emission gets closer to zero.

FIGURE 4.4: Inflection point method of plasma potential determination

derivatives of the characteristics in Fig. 4.3b above with the peaks marked as the inflection points. As seen on this graph, the inflection points shift to more positive probe bias voltages (towards V_{sp}) as the electron emission tends to zero.

The potential V_{sp} is then obtained by plotting the temperature-limited emission current–collected electron current ($I_{em} - I_{coll}$) ratios for the different curves against the inflection-point potential. Because of the ambiguity that still arises from the interpretations put forward by the the proponents of this technique, mainly regarding the criterion for determining the point considered

in determining the I_{coll} from the emissive probe I - V characteristics, I have laboured to explore two different interpretations which I present here.

In the first interpretation the I_{coll} is determined from the curve corresponding to each probe heating current I_{H} , whereas in the second interpretation the I_{coll} value is obtained from the curve corresponding to purely electron collection by the probe where no emission occurs, as illustrated in Fig. 2.7a on page 44. The measurements by these two interpretations are also compared in the paragraphs that follow here.

(a) $Z = 80$ mm (b) $Z = 180$ mm

FIGURE 4.5: Inflection point method for V_{sp} determination using a single I_{coll} at $Z = 80$ mm and 180 mm.

Fig. 4.5 shows typical plots obtained with the latter case, where I_{coll} is got from one curve corresponding to a purely collecting probe. The error bars for $\pm 5\%$ of the $I_{\text{em}} - I_{\text{coll}}$ values for the data are also shown. This is found to give consistent, reproducible results which can be seen from the the graphs

in Fig. 4.5a and Fig. 4.5b, obtained from measured data at $Z = 80$ mm and 180 mm, respectively.

(a) $Z = 80$ mm

(b) $Z = 180$ mm

FIGURE 4.6: Inflection point V_{sp} determination using separate I_{coll} for each curve at $Z = 80$ mm and $Z = 180$ mm.

On the other hand, the attempt to find the I_{coll} from each curve with this method results in inconsistent (and most likely unreliable) results, as shown in Fig. 4.6. As seen on the graph in Fig. 4.6a, this interpretation fails to produce consistent results because of the divergent behaviour that occurs for I_{coll} values very close to zero. Such points appear as outliers and have not been considered in the determination of V_{sp} in the presented results. Some of them are however shown on the graph in Fig. 4.6b. An example of a case where outliers can seriously affect the measurement data due to this issue is further illustrated in Fig. 4.7, for probe data measured at $Z = 140$ mm. This means

that the approach does not work well for characteristics such as that shown in Fig. 4.4, which may sometimes be inevitable in plume plasma flows.

FIGURE 4.7: Outliers resulting from divergent behaviour around I_{coll} values close to zero can be very prominent, when this value is uniquely determined for each curve.

However, both approaches or interpretations may agree for the case of characteristics as in Fig. 4.1 where the I_{coll} value is the same for all the curves. Fig. 4.8 shows axial measurements of V_{sp} obtained by the inflection point method using the two approaches.

FIGURE 4.8: Axial measurements of the plasma potential V_{sp} by the inflection point method compared for the two approaches: with, and without a unique I_{coll} value for different characteristic curves.

As seen in the Figure, V_{sp} values do not change appreciably over the length

of the plasma plume. The values remain almost constant downstream of the exhaust plasma plume. The two approaches provide an almost similar general trend, but with a constant deviation above or below a certain mean value. This leaves many questions still to be answered regarding the exact procedure followed when implementing the inflection point method. It however offers quite consistent measurements of the plasma potential.

4.2.2.2 Floating potential method

A second and somewhat less involving method used to measure V_{sp} requires measurement of the floating potential V_f as the magnitude of the emission current increases.

This is the floating potential method in strong emission. As pointed out in Section 2.4.1.4.1. The theoretical considerations assume probe operation in the strong emission regime. In this case the current becomes space charge limited. However, in the absence of space-charge effects the floating potential V_f is approximately equal to the probe potential corresponding to zero probe current, as electron collection is balanced by the sum of the ion saturation current I_{is} and the electron emission current I_{em} [55, 109]. This should correspond to the point of intersection of the I - V curve traces with the load line (approximately the horizontal axis since a high impedance resistor has been used) [79, 98, 99].

During the implementation of this method, all the ten obtained curves corresponding to different I_H were utilized in each case. The V_f values are determined as the probe potential for $I_{probe} = 0$, which are plotted against the temperature-limited emission currents I_{em} [94, 96, 98, 115, 141].

Fig. 4.9 shows plasma potential determination by this method for $Z = 100$ and 200 mm along the axis of the vacuum tank. The extrapolation of the floating potential at large values of I_{em} magnitudes is approximately equal to the plasma potential V_{sp} . This is got by extrapolating the two linear parts of the curves obtained as shown.

This method yielded consistent results of V_{sp} , which showed a more significant variation with distance from the engine exit section as shown in Fig. 4.10. A comparison of the V_{sp} determination methods used here is made, and the results show mainly two striking differences. First, there appears to be a general trend in the axial values of V_{sp} obtained by the floating potential method, whereas the variation in values got by the two approaches to the inflection point method is insignificant. As shown in Figs. 4.10 and 4.11, the plasma potential V_{sp} increases with distance from the engine. Secondly, the values obtained by the floating potential method are generally higher than those obtained by the inflection point method.

These differences leave a lot of questions still to be answered as to which of the two methods' values should be considered as more accurate. For the calculations where these values will be required as input in the proceeding parts of this research report, the mean of the values obtained by the two inflection point method approaches will be used. This is because this method is seen

(a) $Z = 100$ mm (b) $Z = 200$ mm

FIGURE 4.9: Floating potential method for V_{sp} determination: floating potential V_f as a function of the temperature-limited electron emission current for $Z = 100$ mm and $Z = 200$ mm.

to be more reliable since in the limit of zero or almost no electron emission in which it is employed there is minimal disturbance caused, and thus no alteration in the V_{sp} values obtained. On the other hand, it is most likely that the values obtained by the floating point method are altered by the space charge effects which are inevitable in the strong emission limit in which the method is employed.

All in all, these results of plasma potential variations along the axial direction are in the order of a few volts. These values are well below the characteristic kinetic energy of the ions. Such small variations in potential cannot cause axial electric field variations significant enough to to appreciably change or influence the energy of heavy particles in the plasma. Despite the advan-

FIGURE 4.10: Axial V_{sp} measurements by the floating potential method. FIGURE 4.11: The results of the two approaches to the inflection point method compared with the floating potential method for V_{sp} determination.

tage associated with the use of the computer-controlled 3D positioning system and data acquisition platform developed during the course of this research, with which enormous amounts of measurement data could be obtained using the three probes owing to the automated measurements capable of generating numerous measurement files for a given experimental event, only a few measurements from the emissive probe are presented here.

This is majorly because the determination of the plasma potential using this probe is very involving, especially the inflection point method. To measure the plasma potential V_{sp} , e.g., at a given axial point, requires I - V characteristic curves measured for at least five different probe heating currents I_H as shown

in Figs. 4.1 and 4.3 to obtain a single V_{sp} value, as shown in Figs. 4.5, 4.6, 4.7, and 4.9.

It is for this reason that the plasma potential profile is only measured along the axial direction, moreover at only a few points of 10 mm separation. Additionally, the measurement of cross-sectional profiles as has been achieved with the RFEA which will be described in Section 4.4 to follow, requires a 9 by 9 grid square plane to produce one cross-sectional profile perpendicular to the engine axis. This implies 81 data files are required for the emissive probe alone to generate a cross sectional plasma potential profile. This would mean determining the inflection point or floating potential and the $I_{em}-I_c$ ratio for each of the five probe heating currents which is cumbersome. In other words, to generate a cross-sectional V_{sp} profile would need about 405 analysis files to be accurately analysed when radial measurements are made at 10 mm intervals.

This explains why only few planes have been considered for the cross sectional beam profiles for the RFEA measurements that have been conducted and no such profile has been presented here for the plasma potential. Additionally, the thin hot wire cathode used to supply the electrons that sustain the operation of the thruster engine is limited in terms of durability due to degradation that accompanies the electron emission and also the energetic ion impact on it when emerging from the thruster. This means that only a limited number of measurements can be made during with a given cathode. Therefore, to obtain measurements for a full characterization of the beam plume was not an easy task.

4.3 Langmuir probe measurements

The plasma/electron temperatures T_e , plasma/electron densities n_e , and the Debye length in addition to other parameters were measured using the Langmuir probe. With the assumption of a Maxwellian energy distribution of electrons for distant background plasma [32, 57], the typical electron densities n_e are $0.1-8.0 \times 10^8 \text{ cm}^{-3}$ with electron temperatures T_e of 1–2 eV. These values give electron Debye lengths λ_D between 0.2 and 3.3 mm. This LP probe was also employed to monitor the eventual presence of plasma waves and oscillations during the measurements with the RFEA. Most important to this research, the Langmuir probe was used to measured the electron energy distribution (EEDF). This will be explained and discussed in Section 5.2 of Chapter 5.

4.4 RFEA/RPA

This probe was mainly used to measure the ion energy distribution functions (IEDFs) in the plasma plume. The ion currents I_{IC} collected at its back plate are measured with respect to the grounded walls of the vacuum chamber, as

shown in the schematic of Fig. 2.12 on page 55. These currents are measured as a function of the ion-discriminator grid voltage V_{ID} to give the I – V characteristics. As already described on page 54, the analyzer is equipped with grids (PR and SS grids) whose negative bias potentials repel the plasma electrons passing through the electrically floating RFEA front grid and suppress the secondary-electron emission current produced by high-energy ions impacting the collector plate, respectively. A Keithley 6487 digital picoammeter and its computer-controlled voltage source connected to the ion-discriminator grid were used to record the measured I – V data.

With the said RFEA electrical circuit configuration, the secondary electron suppressor (SS) and plasma-electron repelling (PR) grid [34, 40] potentials were typically $V_{SS} \simeq V_{PR} = 25\text{--}30\text{ V}$. I – V characteristics were obtained with the RFEA for measurements at both a fixed point (in which the IEDF measurements were made in addition to conducting studies on the engine operational characteristics), and for various spatial positions (axial and along the ion beam diameter) to study the plasma plume expansion and flow characteristics. These measurements are detailed in the sections that follow.

4.4.1 I – V characteristics

With the RFEA connected as in the schematic of Fig. 2.12 (see page 55), the probe current–voltage (I – V) characteristics are obtained. This involves sweeping the ion discriminator voltages V_{ID} between -500 and 500 V while recording the current I_{IC} that reaches the ion collector.

This being a completely new diagnostic in the research laboratory, different trials were made to affirm the functionality of the probe once built. As an initial step, the first built prototype was installed into the vacuum tank and tests were conducted to ascertain that it could detect charges. This was done with different combinations of the RFEA grid potentials to observe any changes in the characteristics of the measured signals. Fig. 4.12a shows an example of a measurement obtained with the first RFEA prototype during the testing phase in which its working parameters such as V_{PR} were established. The graph shows measurements obtained for different plasma electron-repelling grid voltages [34, 40] V_{PR} at a constant acceleration voltage V_{AC} of 400 V .

The plasma-electron repelling (PR) grid in particular required great care in establishing the right voltage to which it would be biased during the experiments, as it would serve to eliminate electrons from the beam to be measured by the analyzer. As there is no published information available in the literature, where a similar analyzer (at least with regards to the dimensions) as the one built and used in this research has been used, there is equally no information on the grid bias voltages to be used with this analyzer. The bias voltages used here were therefore determined experimentally by testing with various possibilities so as to obtain reliable measurements.

Fig. 4.12b shows actual voltage–current (I – V) plots for different acceleration potentials V_{AC} , also obtained during the testing phase, with constant DC

(a) Some of the I - V characteristic curves from determination the optimal plasma-electron repelling (PR) grid bias voltage for the experiments.

(b) I - V characteristic curves as a function of V_{AC} , obtained with the first RFEA prototype.

FIGURE 4.12: RFEA plasma-electron repelling (PR) grid bias potential determination and first I - V characteristics measurement.

voltages $V_{PR} = -7.73$ V and $V_{SS} = -20$ V. These characteristics were obtained with the thruster under a working pressure of 8.3×10^{-5} mbar, with $V_{CG} = 0$ V, and thruster ion beam current $I_E = 310$ mA. The Argon mass flow rate was constant at 0.15 sccm. The curves show an increase in the ion current densities (which are proportional to the measured ion currents) for increasing V_{AC} , shown by the marked increase in the measured ion current from 400 nA to just above 1700 nA.

For different acceleration voltages (V_{AC}), the curves are displaced – with an observed shift in the onset of the “knees” of the curves (representative of the shift in energy of the collected ion beam) to lower energies for increasing V_{AC} values, unlike in Fig. 4.12a. This graph’s curves, and the majority of the results

from the initial tests, suggested a possible existence of two ion populations. The ions could thus be described by a bi-Maxwellian distribution introduced in Section 2.4.2.7 on page 69.

It is probable that because of the different grid potentials used at distances within close proximity to each other, the interplays among the grid potentials create a complex net electric field which is responsible for this energy shift. After observing this consistent behaviour in a series of measurements, one important deduction drawn and learnt from these measurements is the need to compensate the I - V characteristic curves for these shifts in any further analysis of the data. This will be elaborated in the next section.

A simulation of the I - V characteristic curves produced a curve similar to those obtained by the RFEA, from which a bi-Maxwellian distribution (see graph on page 72) could be derived. This results in two ion populations that represent *thermal* and *fast* ion groups. This latter result is an evidence of ion energy enhancement by V_{AC} as a control parameter, in good agreement with the design expectations of the thruster. A great deal of the research experiments were therefore dedicated to verifying this hypothesis.

The optimal RFEA PR-grid voltage was found to be -30.0 V which was used for the majority of the experiments since it suppresses the electrons which would enter into the analyzer channel while at the same time having minimal effect on the ion beam current measured. Additionally, as seen in Fig. 4.12a, the characteristics obtained with this value of V_{PR} were stable and less noisy than the same signal when measured with this grid subjected to other bias voltages.

Fig. 4.13 shows typical I - V characteristics measured with the built RFEA (of Figs. 2.19 and 2.20 in Section 2.4.2.4) for different acceleration voltages V_{AC} . Such were the measurements got directly by this probe, which were further analysed to obtain the ion energy distribution functions (IEDFs). In this Figure, unlike in Fig. 4.12 where part of the left hand side of the graph has been left out, a start ramp is shown to the left of the characteristic curves. This ramp was unavoidable throughout the measurements with this probe, as it is inherent in the voltage power supplies used. The top/flat top of the current ramp forms the first flat region of the I - V characteristics, as per the calculations shown on page 2.43.

These measurements taken for both increasing and decreasing V_{AC} values show a reproduced similar trend for the variation with V_{AC} . Waterfall plots for the same measurements are shown in Fig. 4.14. As shown in both Fig. 4.13 and Fig. 4.14, the characteristics generally show two almost constant ion currents, each followed by a steady fall for increasing (more positive) discriminator grid voltages. The two falls/decreasing parts represent the retarding effect of the retarding/discriminator potentials V_{ID} that filter low- and high-energy ion populations, as it will be further shown in Section 4.4.3. Thus, the two main slopes in the I - V curves give rise to two peaks in the IEDF, which can be interpreted as a superposition of two ion populations.

In the rest of this report, for clarity, these two ion populations are referred

(a) RFEA I - V curves represented against V_{ID} at $Z = 200$ mm for increasing V_{AC} values.

(b) Measurements in Fig. 4.13a, for decreasing V_{AC} .

FIGURE 4.13: RFEA I - V curves for increasing and decreasing acceleration voltages V_{AC}

to as “thermalized” (low-energy group) and suprathermal [142–146] (or supersonic) – the high energy or fast groups, with the onsets of the fall or decrease in the measured ion current signifying the retardation or blocking of two groups of ions by the discriminator voltages. The points at which the retarding effect of the discriminator voltages start to be noticeable shift to less positive voltages for increasing V_{AC} . This highlights the throttling effect of the V_{AC} in the engine operation. In other words, these voltages act as a control for the driving energy of the exiting ion beam. This behaviour will be discussed further in Section 4.4.2.

(a) Waterfall representation of the I - V curves from Fig. 4.13a.

(b) Waterfall plot of RFEA-measured I - V characteristics Fig. 4.13b.

FIGURE 4.14: Waterfall plots for characteristics in Fig. 4.13

4.4.2 Ion energy (IEDF) and velocity (IVDF) distributions

The I - V characteristics measured with the RFEA can be used to derive the beam plume's one-dimensional ion energy (IEDF) and velocity (IVDF) distributions, as has been explained in Section 2.4.2.7 on page 69. The measurements obtained with the different RFEA prototypes are presented here, though with no particular regard to a specific one. Where necessary the parameters of the probe will be stated for clarity.

The IEDF is obtained when the measured I - V curves are differentiated once to give curves proportional to the one-dimensional ion energy distribution

which, from Eqs. 2.37 and 2.42, can be expressed as

$$J_{\text{IC}}(\mathbf{r}, V_{\text{ID}}) = e \int_0^\infty u_z f(\mathbf{r}, u_z) du_z = \frac{e}{m_i} \int_{eV_{\text{m}}}^\infty f(\mathbf{r}, E) dE \quad (4.1)$$

where the maximum ion current density $J_{\text{im}}(\mathbf{r}) = J_{\text{IC}}(\mathbf{r}, V_{\text{ID}} = V_{\text{m}})$ measured when $V_{\text{ID}} = V_{\text{m}}$ is calculated for each spatial position $\mathbf{r}$ as

$$J_{\text{im}}(\mathbf{r}) = \frac{I_{\text{m}}(\mathbf{r})}{T_{\text{r}} \times A_{\text{IC}}}. \quad (4.2)$$

Here, T_{r} is the transparency of the four-grid analyzer, A_{IC} is the effective ion-impinging area of the copper ion collector plate and $I_{\text{m}}(\mathbf{r})$ is the maximum current of an RFEA I - V curve.

FIGURE 4.15: RFEA data processing: Oscillating experimental I - V data plots (as blue dots) accurately approximated/smoothed numerically (red solid curve) by the tool based on Savitzky-Golay algorithm. The derived IEDF (blue solid curve) – right axis – is represented against the common V_{ID} axis for the measured data at $Z = 200$ mm.

The Savitzky-Golay (SG) numerical approximation [68,86] algorithm software tool introduced in Section 4.1 of this Chapter is however used to first smooth the measured data to facilitate the process of obtaining meaningful derivatives, as shown in Fig. 4.15. This Figure highlights the power of this software tool in accurately approximating even very noisy data, one of the motivations for its use in the computation of required derivatives and in the smoothing of noisy data for the other probes' data analysis.

Fig. 4.15 shows a graph with one of the analyses leading to IEDF determination for measurements at this position. In this Figure, both the original RFEA-measured current data (shown as blue dots) and its corresponding fit (indicated as a red solid curve) approximated using the SG numerical software tool, together with the obtained one-dimensional IEDF (blue solid curve), are

represented against the bias potential of the ion-discriminator grid. The one-dimensional distribution of ion energies is obtained using Eq. 2.38 where the derivative $dJ_{\text{IC}}/dV_{\text{ID}}$ is expressed as

$$\frac{dJ_{\text{IC}}}{dV_{\text{ID}}} = -\frac{e^2 f(\mathbf{r}, V_{\text{ID}})}{m_i}. \quad (4.3)$$

Thus, differentiating the measured ion current with respect to the bias potential of the ion-discriminator grid thus yields the one-dimensional IEDF $f(\mathbf{r}, V_{\text{ID}})$.

In the analyzer channel, the ion beam experiences an electric field that has contributions from more than one electric potential due to the multiple grids used. Thus, the minimum energy of the ions does not correspond to zero volts of the discriminator grid voltage, but it corresponds to some non-zero voltage. In Fig. 4.15 this voltage is about -347 V . The ion discriminator voltages (V_{ID}), corresponding to the ion energies, are corrected for offsets due to the RFEA grids' electric field (floating potential V_f). This has been done by subtracting the V_f (which is different for each V_{AC} value) from the actual V_{ID} values applied to the ion discriminator grid. Multiplying the result by -1 may be necessary in case of voltages measured in the reversed sense, which can be implemented directly in the electrical circuit.

The discriminator voltages of the graph in Fig. 4.15 are therefore adjusted so that the maximum ion energy corresponds to zero volts. The transformed electric potentials, $V_m - V_{\text{ID}}$, and thus modified ion energies,

$$e(V_m - V_{\text{ID}}) = \frac{1}{2}m_i u_z^2, \quad (4.4)$$

for $V_{\text{ID}} > V_m$ are used such that $u_z \simeq 0$ for the maximum measured current $I_m(\mathbf{r})$ of the RFEA current-voltage curve.

4.4.3 Beam dependence on ALPHIE parameters

The study of the ALPHIE thruster also involved understanding the way this thruster could be controlled by its operational parameters. This requires being able to know how its operation can be affected by changes in parameters such as the control or cover grid voltage V_{CG} which plays a key role in the transport of electrons for the primary plasma production in the engine, propellant mass flow rate Q which is important in determining the ionization rate in the thruster engine, and acceleration voltage V_{AC} which by design is meant to provide the necessary driving energy for the expelled ions.

Additionally, the generation of the plasma jet in the thruster being studied depends critically on the electron flow from the only source in the engine – the active cathode. This supplies the electrons that control both the ion production within the discharge chamber and the space charge neutralization. This feature makes the ALPHIE IEDFs free of possible distortions that would occur when ions from other sources rather than the plasma engine existed, as may be

the case when hollow cathode plasmas are employed for ion beam neutralization. The thruster's operation strongly relies on the rate of thermionic electron emission by this electron source/cathode, which in turn depends on its temperature [37]. The effectiveness with which the cathode-generated electrons travel to the engine plasma-generation section (discharge chamber) relies on the electric field between the cover grid and the cathode region, due to the electrons cloud created. The electron transport is thus controlled by the electric potential at the cover grid, V_{CG} .

To study the effect of V_{CG} as this engine's control parameter, the engine parameters are set to points such that plume-plasma production into the vacuum vessel is as much as possible. Once the desired plasma production has been achieved, the engine is left for some time so that all physical processes attain an almost equilibrium state. In this case the only parameter controlled is the cover grid voltage V_{CG} , which is usually set to zero during plasma experiments. The level of plasma production is measured by the ion beam current I_E , which is displayed digitally on a meter and so can be recorded.

Changing (increasing) the V_{CG} values slowly, and thus the plasma production while measuring I_E is done to study its effect on the engine operation. The same procedure is then repeated to study the V_{AC} and Q effects, in each case, on the engine operation by taking measurements for a set of values. The results from these studies will be presented in Section 5.3.2.

Chapter 5

Plasma flow measurements

The first measurements were taken at a fixed point 200 mm in front of the engine exit section into the vacuum chamber. These were mainly aimed at the determination of plasma beam properties from the RFEA current–voltage (I – V) characteristics obtained. Specifically, the ion energy distribution I EDF or spectra were measured using the designed and built retarding-field energy analyzers (RFEA) introduced in Section 2.4.2. The results show the ion energy spectra (IEDFs) to be composed of a superposition of different ion groups of which two are dominant: low-energy group (*thermal ions*) constituted of ions from the background plasma produced by the interaction of the plasma jet with the walls of the vacuum chamber, and a fast-ion population composed of ions from the plasma beam moving at much higher speeds relative to the low-energy ions. The operation parameters of the plasma engine in connection with the ion energy distribution functions obtained were experimentally studied using these measurements.

These studies show the ALPHIE plasma beam expansion to produce mesothermal plasma jets, with two ion groups (low and high energy, and thus speed, ion groups) dominating the plasma jet expansion along the axial direction. The estimated characteristic drift velocities of the fast-ion groups, which are in the range 36.6 – $43.5 \text{ km}\cdot\text{s}^{-1}$, are controlled by the thruster’s acceleration voltage V_{AC} . These are supersonic speeds, and are higher than the typical ion sound velocities of the low-energy ion group produced by the expansion of the plasma jet.

Additionally, plasma properties were determined using the Langmuir probe (LP) whose operation has been introduced in Section 2.3 and features described on page 41, and the emissive probe. Monitoring of the any eventual presence of plasma waves and oscillations during the measurements with the RFEA was also done using the LP probe. The plasma (electron) densities n_e were measured with the collecting Langmuir probe at a distant point where assumption of a Maxwellian electron distribution exists [32, 57]. Electron densities measured at distant points from the plasma thruster where the LP I – V curves approximately correspond to a Maxwellian plasma were $n_e = 0.1$ – $8.0 \times 10^8 \text{ cm}^{-3}$, with the electron temperatures T_e of 1 – 2 eV .

Then, spatial measurements were made with the aid of the 3D displacement system described in Section 2.5.1. These measurements were made either along the axis of symmetry (see Fig. 2.25 of page 74) of the vacuum tank or along the cross sections (perpendicular to the symmetry axis) of the plasma plume beam flow. Measurements along the plasma plume (beam) diameter were taken to provide insight into the 2D profile of the ion beam currents using the RFEA and the Langmuir probe. The cross sectional measurements of the ion currents obtained with the RFEA are used to study the distribution of ions along the beam cross section, whose variation with axial distance from the engine exit section is also presented. These are aimed at providing important information on the flow properties and expansion structure of the ALPHIE plasma plume.

For the cross-sectional measurements, approximate values of the ion current density are used since, unfortunately, it is not possible to determine precisely the actual ion current densities J_{im} of the plasma streams whose value could be got using Eq. 4.2 (on page 113). This is because of the difficulties associated with aligning the four grids of the RFEA to such an accuracy that all their apertures are in line with one another for a continuous undisturbed transmission of the incident ions. Thus, determination of the accurate value of the transparency T_r of the four-grid analyzer in addition to the effective ion-impinging area A_{IC} of collector, which is a necessary input into Eq. 4.2 is not possible. However, the IEDFs can be used to qualitatively assess or approximate the plasma beam ion current density and were therefore used for this purpose.

The electron distribution function (EEDF) measurements show an energy relaxation with increasing distances parallel to the direction of the plasma plume flow. A flow of fast supersonic ion beams is observed along the z -axis for both sets of IEDF measurements, which reaffirm the mesothermal nature of the plasma flows produced by the ALPHIE. An attempt to analyze the individual flow characteristics/properties of the two ion groups (thermal and fast ion groups) shown in the RFEA curves is made using the approximate measures of the ion current densities, as not enough information on all parameters needed for the accurate measurement of the ion density is available as has been explained before.

Decreasing spatial profiles of the plasma-jet ion currents are obtained, which can provide a picture of the ion current densities are compared with those of the low-energy ion group which are not uniform along the axis of symmetry. These are related with small contributions from other ion populations with intermediate speeds. An attempt is made to explain the physical origin of the additional low peaks at intermediate energies, mostly between 100–200 eV that appear in some IEDF distributions, but unfortunately not a satisfactory explanation or conclusion can be reached with the obtained measurements. The ion energy losses by collisional energy exchange would be an acceptable explanation in this case, but are excluded because of the long mean free paths required.

The detailed results are presented in the following order: the spatial plasma

potential and electron distribution function measurements are discussed first. As already mentioned, these are mainly axial measurements, as the measurement of cross-sectional variations of these parameters require a great deal of measurement and analysis time as already explain earlier. Then, fixed point measurements will be presented, with emphasis on how to obtain the one-dimensional IEDF and on the study of the ALPHIE control parameters. Finally, the outcomes of the IEDF spatial measurements will be discussed, starting with the fixed point IEDF measurements and concluding with the measurements with the probes moved to different positions along the z -axis (axial and cross-sectional plasma flow measurements).

5.1 Plasma potential distribution

The emissive probe was used to measure the plasma potential (V_{sp}) variation along the axial direction. Fig. 5.1 shows the experimentally measured V_{sp} values along the direction parallel to the axis of expansion of the plasma plume. The plasma potential is higher closer to the engine exhaust and decreases with distance away from the engine, becoming almost zero at far axial distances from the exhaust. So, plasma plume expansion seems to be extended to 30–40 cm from the origin.

FIGURE 5.1: Plasma potential profile along the axial direction. The experimental parameters were as in Figs. 5.16, 5.15, and 5.16.

5.2 Electron energy distribution (EEDF)

These obtained V_{sp} values were then used to determine the electron energy distribution function (EEDF). The EEDF was measured with a collecting Langmuir probe already described in the previous chapters, with the axial variation as shown in Fig. 5.2. The electron distributions show complex two-peaked energy spectra for axial distances close to the exit section of the engine. An electron energy thermalization process along Z is observed whereby a single peak is formed far from the plasma thruster.

FIGURE 5.2: Electron energy distribution function (EEDF) along the Z axis (EEDF axial profile)

The electron temperature T_e and density n_e were measured with the Langmuir probe as described in Section 2.3.2.1 by using the second derivative of the probe I - V curve with respect to the probe bias potential V_{probe} . With these measured T_e values and the plasma potentials in Fig. 5.1 obtained with the emissive probe, the electron energies were measured and values up to about 50 eV were obtained. Electron energy distribution functions (EEDFs) were then measured as already described, based on Eq. 2.18 on page 40, using the transition region just beyond V_f (see Fig. 2.2 on page 37) where I_i is negligible and the negative probe potential above the plasma potential ($V_{probe} - V_{sp}$) partially repels electrons.

Fig. 5.1 shows the measured EEDF. The distribution shows a possible electron energy thermalization process whereby a double-humped distribution is obtained close to the engine, the peaks of which then merge into one (wider peak) with increasing Z distances away from the thruster exit section. This seems to imply that the light electrons experience energy exchange along the plasma plume by a possible collision.

Using the full width at half maximum (FWHM) values of the peaks for the distributions obtained at the different axial distances, the temperatures corresponding to the electron populations (low-energy and high-energy populations) were estimated. Fig. 5.3 shows the measured T_e values for both the low-energy (blue diamond markers) and fast-energy (red dots) electrons along the axis of symmetry of the vacuum tank.

FIGURE 5.3: Electron temperatures measured by the Langmuir probe along the Z axis

As seen in the Figure, the variation of the electron temperature does not have a very clear pattern as compared with the ion temperature (to be shown later in Section 5.5.1). Instead, it appears like there is an increase in the electron temperature T_e farther away from the engine exit section, which does not look to be correct. The low-energy electron temperatures ranged between 2 and 6 eV, whereas they were 4–8 eV for the fast electrons.

However, from the temperature variation shown in Fig. 5.3 above, not a conclusive deduction can be made to support the thermalization process shown by the EEDF variation. It contradicts the observation from the EEDF, suggesting a possible lack of correctness in the measured EEDF. Though not very correct results may be obtained by the Langmuir probe for such measurements (as will be explained at the end of this section), this measured EEDF gives a good indication of electron thermalization process.

As will be shown in the next sections, this response of electrons is different from that of ions, whose IEDF remains essentially unchanged (always two peaks) along the axial coordinate. For ions (see Figs. 5.15b and 5.18), the heights of both peaks decrease, unlike for the electrons. Fig. 5.4 shows the variation of the peak heights of the two electron populations from the EEDF represented in both linear scale (a) and a semi-logarithmic scale (b). As seen in Fig. 5.4a, the heights of the peaks seem to decrease with the Z distance away from the thruster exit section.

(a) Axial variation of the peak heights of the EEDFs from Fig. 5.1 above.

(b) Semi-logarithmic plot of the peak heights in Fig. 5.4a.

FIGURE 5.4: EEDF peak heights as a function of the distance from the engine exit section (Z)

In this case not a very obvious or clear power law exponent could be obtained for the decrease in the energy corresponding to the peak maxima of the two electron populations as was the case for ions, as seen in Fig: 5.5.

As explained in Section 2.3.3.1, the measurements obtained with a Langmuir probe are subjected to possible errors, especially when used in plasma flows as in the case studied here. The wake effects [90–92] when spherical Langmuir probes are used in such plasmas introduce anisotropies in the measured electrons by the the probe, which can affect the obtained results. The electrons, being lighter and thus much faster than the ions, easily fill the void

FIGURE 5.5: Z variation of the energies corresponding to the energy distribution function (EEDF) peaks

region making the electrostatic potential in the wake near the probe surface negative [92]. The result is the convergence of ions immediately downstream of the near wake [90] (see Fig. 2.6 on page 43) due to the negative potential. Considering the near-wake region to be the space between the probe surface and the ion convergence region, a length scale l_w of the plasma wake behind a sphere of radius R_o can be estimated as

$$l_w \sim M_h \times R_o, \quad (5.1)$$

where $M_h = u_{DF}/c_{is}$ is the ratio of the ion drift velocity u_{DF} to the ion sound velocity c_{is} . The ion speeds c_{is} of the background plasma under study or consideration are $\sim 1.5\text{--}2.7\text{ km}\cdot\text{s}^{-1}$ which give M_h ratios between ~ 13.3 and 27.5 .

The wake length l_w behind the spherical Langmuir probe used, which is of $R_o = 2.22\text{ mm}$, is therefore $\simeq 8.8\text{--}61.0\text{ mm}$. Hence, the collected-electron current density on the Langmuir probe surface facing the thruster is not equal to that on the opposite side of the probe. In this case, the probe is used outside the limits of simplified theory for a Maxwellian plasma. Despite the accuracy of the plasma potential V_{sp} measurements by the emissive probe being unaffected by this flow, this can have an overall effect on the EEDF measurements, as explained here. There is need to handle carefully the results from these measurements.

The imperfections of the measurement result obtained with this probe is therefore subject to criticism, but with careful interpretation and analysis of the results as explained above it can be used to give a good indication of the thermalization of electrons. From these measurements, it can be concluded that electrons in the plasma plume flow undergo collisions with a resulting thermalization during the expansion process. The electron cooling previously

observed in similar studies put forward by Ref [31] can therefore be explained in terms of a complex thermalization process undergone by electrons and not necessarily a cooling of electrons.

5.3 Fixed point measurements

5.3.1 One-dimensional IEDF of ion populations

Fig. 5.6a shows the ion energy distribution function (IEDF) measured as in Fig. 4.15 on page 113. In this case, re-scaled ion energies are used such that the IEDF is plotted against the one-dimensional kinetic energy of the ions. Similar plots are shown in Fig. 5.6b, where IEDFs from characteristics as in Fig. 4.14 are displayed with the zero-energy offsets compensated.

The IEDF, as in Fig. 5.6a, has two main peaks so it can be considered to be a superposition of two dominant populations in the ion beam. The third peak observed is so small and is essentially the overlap of the two main peaks, thus its contribution to the total ion energy can be neglected. The shape of the one-dimensional IEDF thus indicates the presence of two different ion groups or populations, with maximum ion energies corresponding to RFEA bias voltages for which the maxima (peaks) of Eq. 2.38 occur. This corroborates the theoretical prediction suggested in Section 2.4.2.7, page 71. The temperatures of the two ion groups from the two-peaked IEDFs above can be evaluated using the calculated full width at half maximum (FWHM) values obtained when two Gaussian model functions are used to fit the peaks as in Fig. 5.7.

In graphs (a), (b), and (c) of Fig. 5.7, the sample plots from which ion temperatures were derived for IEDFs corresponding to three acceleration voltages V_{AC} of 550 V, 600 V, and 650 V, respectively, are shown. Taking the thermal population temperature to be T_{iT} and that of the fast ion population peaks as T_{iF} , for these energies of 550, 600, and 650 eV the FWHM values obtained from these graphs give $T_{iT} = 239, 257, \text{ and } 200 \text{ eV}$. The corresponding T_{iF} are, in the same order, equal to 216, 251, and 192 eV. Such were the typical values of ion temperatures obtained for the two ion populations generated in the ALPHIE plasma plume.

5.3.2 ALPHIE exhaust plasma control parameters

The results obtained when only the engine cover grid voltage V_{CG} values were varied while measuring I_E to study its effect on the engine operation and also the effects that the acceleration voltage V_{AC} and Argon gas mass flow rate Q may have on the engine operation are discussed here.

It is evident that the engine exhaust plasma is controlled by the voltage V_{CG} in the ALPHIE thruster. Fig. 5.8 shows the obtained $I-V$ (I_E-V_{CG}) characteristic curves from such measurements for constant thermionic electron emission rate (or equivalently a fixed power P_{NH}).

(a) The IEDF (open symbols) of Fig. 4.15 and the two main peaks approximated by Gaussian functions (solid curves).

(b) Waterfall plot of IEDFs as a function of V_{AC} , the beam acceleration voltages.

FIGURE 5.6: Superposition of two ion populations seen in the two-peaked IEDFs

In Fig. 5.8a the thruster current I_E is shown as a function of the cover grid voltage V_{CG} , for varied Argon gas mass flow rates Q injected into the discharge chamber. In this case the potential V_{AC} is held constant at 400 V. As seen on the graph, there is a slight increase in the current I_E for increasing neutral gas (propellant) mass flow rates Q .

An important feature is the sudden or abrupt fall in the current I_E by more than one order of magnitude when the cover grid voltage V_{CG} reaches a certain threshold value. This is in fact a shutdown, as I_E falls to zero, which remains the case for all I_E values above the threshold value. The same effect is seen in Fig. 5.8b whereby the same measurements are taken but for changing

(a) $V_{AC} = 550$ V (b) $V_{AC} = 600$ V (c) $V_{AC} = 650$ V

FIGURE 5.7: Two-peaked Gaussian fits to the IEDF for acceleration voltages V_{AC} of (a) $V_{AC} = 550$ V, (b) $V_{AC} = 600$ V, and (c) $V_{AC} = 650$ V. The corresponding ion population temperatures are estimated from the FWHM of the two peaks.

acceleration voltages.

FIGURE 5.8: I_E and V_{AC} as thruster control parameters. Thruster current I_E as a function of the cover grid voltage V_{CG} for (a) different gas flow rates Q while holding the acceleration voltage constant, and (b) changing acceleration voltages V_{AC} , holding the gas flow rate Q constant.

This fall or shutdown occurs because the control grid now repels a large fraction of the thermionic electrons from the cathode when the potential V_{CG} hinders the inflow of ionizing electrons and, in effect, both the ion production rate and I_E abruptly fall. In experiments with plasma the cover grid voltage V_{CG} , as a must, is thus set to zero by biasing the cover grid to the local ground of Fig. 1.7 to maximize the ion outflow.

Almost similar to the measurements of the graph of Fig. 5.8a, the graph in Fig. 5.8b shows—in addition to the voltage V_{CG} effect as an engine control parameter—the acceleration voltage V_{AC} effect on the measured I_E . Here, the measurements are taken for a fixed propellant gas mass flow rate Q . The thruster current I_E measured as a function of the cover grid voltage V_{CG} for various V_{AC} show the current I_E to increase when the acceleration potential V_{AC} is increased.

5.4 The plasma plume IEDF at a fixed point

In this section the plasma plume properties determined with the diagnostics at a fixed point along the axis of the ion flow are discussed. As already introduced in Sections 4.1 and 4.4.3, measurements with the probes at a fixed point were used to study the ion beam characteristics and dependencies on the engine operational parameters.

The driving effect of V_{AC} can be seen on the measured IEDFs, whose determination/calculation for $V_{AC} = 450$ and 650 V was as in Fig. 4.15, when V_{AC} is varied while maintaining the other parameters and conditions constant. Fig. 5.9 on the other hand shows the energy spectra for two different accelera-

tion voltages V_{AC} , which stresses the heavy-particle (suprathermal ion group) driving/acceleration effect of V_{AC} . The graphs in (a) and (b) of this Figure show an energy-enhancement effect of the thruster V_{AC} parameter.

FIGURE 5.9: Driving effect of V_{AC} seen on the IEDFs: SG-smoothed I - V curves and their corresponding IEDFs for acceleration voltages V_{AC} of (a) 450 V, and (b) 650 V measured 20 cm from the engine exit section.

This effect is confirmed by the 3-D waterfall plots in Figs. 5.10 and 5.11 where the two-peaked IEDFs for different V_{AC} values are shown, for constant thruster currents $I_E = 0.288$ and 0.296 A . The ion energy spectra in the graphs in Figs. 5.10 and 5.11 show the energies (and correspondingly speeds) of the expelled supersonic plasma stream to be governed by the acceleration potential V_{AC} .

The IEDFs, measured at the fixed point, represented for varied (increasing or decreasing) voltages V_{AC} in these Figures show the low-energy peaks that correspond to ‘thermalized’ ions of the ion energy distributions to be centred around $E_{Ti} \simeq 100 \text{ eV}$. These are due to the heavy particles that have lost a large fraction of their initial energies in the plasma-expansion process.

FIGURE 5.10: Waterfall representation of the IEDFs against acceleration voltages at constant $I_E = 288$ mA, for $V_{AC} = 450, 500, 525, 550, 575, 600, 625$, and 650 V.

The peak energies E_{Fi} of the fast-ion groups are in the range 350–550 eV, which linearly depend on the acceleration voltage in Figs. 5.10 and 5.11. Therefore, the kinetic energy of the suprathermal ion population is controlled by the voltage V_{AC} .

As has already been shown, the effective temperatures of both ion groups in each case were estimated by approximating the IEDFs as in Figs. 5.10 and 5.11 by a sum of two analytical Gaussian functions. The calculation of the full width at half maximum (FWHM) of the peaks gives $T_{iT} \simeq 80$ – 90 eV for the low-energy population and $T_{iF} \simeq 50$ eV for the fast ion group.

Then, the typical ion thermal speeds for the low-energy population are $u_{Ti} \simeq 20$ – 21 km·s^{−1} and $u_{Fi} \simeq 16$ km·s^{−1} for high-energy ions. The characteristic electron thermal speeds are $u_{Te} \sim 593$ – 863 km·s^{−1}, much higher than the thermal speeds u_{Ti} of low-energy ions, u_{Fi} of the fast-ion population, and the fast-ion drift speed u_{DF} .

From the IEDF spectra, the drift velocity u_{DF} of the fast ions with respect to the low-energy ones can be determined using the energies corresponding to the two peaks as $u_{DF} = \sqrt{2\Delta E/m_i}$, where ΔE is the difference between the two peaks' energies, i.e., $\Delta E = E_{Fi} - E_{Ti}$, for the energy of the peak maximum

FIGURE 5.11: Waterfall representation of the IEDFs against acceleration voltages at constant $I_E = 296 \text{ mA}$ for $V_{AC} = 450, 475, 500, 550, 575, 600, 625$, and 650 V .

corresponding to the fast ion group E_{Fi} and to the low-energy ion group E_{Ti} . Fig. 5.14a shows the energies corresponding to the two peaks plotted against the acceleration voltages V_{AC} (left axis) for the two ion groups (solid markers), with the corresponding drift speeds u_{DF} (hollow markers) on the right axis. These supersonic ion drift speeds u_{DF} (open symbols) are in the range $36.6\text{--}43.5 \text{ km}\cdot\text{s}^{-1}$, about one order of magnitude higher than the ion sound speed c_{is} and more than three times the ion thermal speed u_{Ti} .

Furthermore, the relative weight of high energy ions in the IEDF also increases with V_{AC} (also seen in Fig. 5.9). The thermalized ion group maxima in Figs. 5.10 and 5.11 reduce with V_{AC} , whereas the high energy peaks grow. In Fig. 5.10 about 65.2% of ions have energies below that corresponding to the IEDF minimum, whereas 34.8% have higher energies for $V_{AC} = 450 \text{ V}$. These figures change to 59.5% and 40.5% when $V_{AC} = 650 \text{ V}$. The number of fast ions reaching the distant RFEA thus grows with V_{AC} .

The DC heating power P_{NH} controls the temperature of the neutralizer wire of Fig. 1.7 which regulates the thermionic electron emission and therefore the electron inflow towards the plasma chamber [37]. When raising P_{NH} at a

FIGURE 5.12: A 3D-waterfall plot of I - V curves for changing ion beam current I_E (corresponding IEDFs displayed in Fig. 5.13). Measurements taken for $V_{AC} = 550$ V and 20 % gas valve opening and $I_E = 241, 255, 274, 291, 321, 340, 380$ mA.

fixed V_{AC} , the plasma engine produces a denser ion beam that increases the thruster current I_E . This effect of incrementing the ionizing electron flow is shown in Figs. 5.13.

From the experimental results in this section, the ALPHIE plasma engine is shown to possess a very fundamental feature as a plasma thruster – the acceleration potential V_{AC} (indicated in Fig. 1.7) drives the kinetic energy of out-flowing ions, and can thus be used as a control parameter for the axial velocity of the supersonic plasma streams.

This feature is clearly seen in Fig. 5.14a, where the energies corresponding to the IEDF maxima in Figs. 5.10 and 5.11 are represented against the acceleration voltage. The peak energy of the thermalized ion population corresponding to $E_{Ti} \simeq 100$ eV is insensitive to V_{AC} . However, the energies E_{Fi} corresponding to the peaks of the fast ion groups linearly increase with this acceleration potential. At the distant point where the RFEA is located, the high energy ion population still retains its original energy proportional to V_{AC} .

Fig. 5.12 shows the increase in the ion-collector current I_{IC} for increasing values of the thruster current I_E , whereas Fig. 5.13 shows the waterfall plot of these I_{IC} values for the varied I_E . As discussed in Section 4.4.1, the “knees” of the I - V curves tend to be shifted with change in the thruster current I_E . The IEDFs in Fig. 5.13 can be used to provide a qualitative assessment of the relation between the increase in the thruster current I_E and the increase in the plasma beam ion current density due to the ionizing electron inflow which is

FIGURE 5.13: Waterfall representation of the IEDFs (in arbitrary units) for the plots in Fig. 5.12 as a function of the current I_E for constant the plasma acceleration voltage $V_{AC} = 550$ V. I_E values considered are 241, 255, 274, 291, 321, 340, and 380 mA.

controlled by the DC heating power P_{NH} .

The ion densities tend to generally increase with V_{CG} . The behaviour of the energy distributions, as just explained above, is also seen from the slight changes in the position of the “knees” as explained earlier on in Section 4.4.1. It is therefore possible to control both the plasma plume ion densities and energies using V_{CG} and V_{AC} as control parameters. As seen in the figure, both the ion densities and the ion energy distributions can be controlled using V_{CG} as a control parameter. Without the cover grid voltage ($V_{CG} = 0$ V) the ion density is highest, with a wider energy distribution.

However, on imposing the V_{CG} as a control parameter, there is a clear observed decrease in the ion density and also changes in the energy distribution of the ions. The ion densities tend to generally decrease with increase in the V_{CG} . It is therefore possible to control both the plasma plume ion densities and energies using V_{CG} as shown in Figs. 5.8 (a) and (b).

(a) The energies E_{Ti} and E_{Fi} of IEDF maxima (solid symbols) of Figs. 5.10 and 5.11 against the acceleration voltage V_{AC} with their best linear fits. The speeds u_F of the fast ion group (open symbols) refer to the right axis.

(b) The IEDF maxima in Fig. 5.13 (open symbols) and the thruster current I_E (solid squares) with their best linear fits represented against the heating power P_{NH} of the neutralizer wire of Fig. 1.7.

FIGURE 5.14: Driving effect of V_{AC} on ion group velocities

5.5 The plasma plume IEDF spatial profiles

The plasma-jet properties were characterized using the diagnostics described in Sections 2.2.3 and 4. The properties of the plasma plume flow that were mea-

sured with the aid of the 3-D positioning system described in Section 2.5.1.2 are presented here. Two- and three-dimensional profiles along the radial directions (see scheme in Fig. 2.25 for details) of the ion beam structure/distribution measured at planes perpendicular to the axis of the engine were taken at different axial positions to understand the beam flow and expansion characteristics. The average maximum current values were used in these measurements, as they are a good measure of the ion current density. Such profiles provide a more conceivable picture of the distribution of the fast and thermal ions and/or electrons during the beam expansion away from the thruster.

5.5.1 Along the axial direction

One-dimensional IEDF spatial profiles have been obtained with the RFEA to study the IEDF spatial dependencies. Fig. 5.15a shows Savitzky-Golay approximations of the RFEA-measured ion I - V curves along the Z -axis (see Fig. 2.25 for details) of the vacuum tank.

The FWHM estimates of ion temperatures for the two main peaks in Fig. 5.6a give $k_B T_{iT} = 23$ eV for the low-energy ion group whereas $k_B T_{iF} = 62$ eV for the fast-ion population. Both ion temperatures are higher than the typical electron temperatures of the distant background plasma. The kinetic energy range 200–400 eV of the fast-ion group peaks in Fig. 5.15b leads to ion velocities of 22 – 44 km·s⁻¹, which are much higher than the ion sound speed $c_{is} = \sqrt{k_B(T_i + T_e)/m_i} \sim 7.5$ km·s⁻¹.

The average supersonic drift speed $u_D = u_{df} - u_{dl} \simeq 38.6$ km·s⁻¹ of the fast-ion group was estimated by the difference between the average peak velocities $u_{dl} \simeq 11.4$ km·s⁻¹ and $u_{df} \simeq 40.2$ km·s⁻¹ of the slow and fast ion groups, respectively. This shows the ALPHIE to produce mesothermal [38, 41, 46, 47] plasma flows.

The RFEA ion energy resolution was about ± 4 eV, equivalent to axial speeds of ± 4.4 km·s⁻¹ for singly charged argon ions with energies below 650 eV. This minimum axial velocity is similar to typical ion sound speeds of the background plasma. The fast ion groups in Figs. 5.10– 5.13 have peak energies between 300 eV and 550 eV, resulting in speeds of $u_{DF} \simeq 36.6$ – 43.5 km·s⁻¹, which are similar to other plasma thrusters [14, 46, 48–50, 147–150] and more than three times the typical ion thermal speed. This last velocity depends on the energy thermalization processes of the plasma beam.

A waterfall plot of the fast-ion beam currents is shown in Fig. 5.15a, for which the IEDF variation along the Z axis is shown in Fig. 5.15b. In Fig. 5.15a the zero point of the $V_m - V_{ID}$ axis corresponds to the maximum V_{ID} voltage that gives rise to the maximum of the total ion current.

These general characteristics are confirmed by the waterfall representation of the I - V characteristics that give rise to the two-peaked IEDFs of the plasma jet along Z (that is approximately aligned with the centreline of the scheme of Fig. 2.25) in Fig. 5.15a. The IEDFs are plotted against the ion kinetic energy $E = e(V_m - V_{ID})$, as shown in Fig. 5.15b. Here V_m is the potential

(a) A waterfall representation of the SG approximations of RFEA current–voltage characteristic curves along the Z -axis of the scheme in Figure 2.25; the ion energy is $E = e(V_m - V_{ID})$ (see text).

(b) Waterfall representation of the two-peaked IEDFs, calculated from the I – V curves of Fig. 5.15a, along the Z -axis against the ion kinetic energies.

FIGURE 5.15: Axial distribution of the RFEA I – V characteristic curves and IEDFs

corresponding to the maximum value of I_{IC} and V_{ID} is the electric potential of the ion discriminator grid.

The maxima of the fast-ion group occur at about 350 eV and at about 50 eV for the low-energy populations. The energies corresponding to the low-energy ion group peaks remain essentially independent of the operational parameters of the ALPHIE thruster, whereas the those of the fast ions depend on the

acceleration voltage [38, 121] (which was fixed to $V_{AC} = 500$ V in this case). The shape of the energy spectra in Fig. 5.15b remain essentially constant over a 300 mm length along the axial direction. This is shown in Fig. 5.16 where the energies corresponding to the IEDF peaks from Fig. 5.15b are plotted against Z . From the graph in this Figure, the energy-axis position of the peaks are almost constant for both ion populations.

FIGURE 5.16: Axial variation of the IEDF peak energies. The blue solid markers at low energies represent the low-energy peaks whereas the red solid markers correspond to the fast ion peaks in Fig. 5.15b.

Additionally, the shape of the ion energy distribution functions remains essentially unchanged as seen in Fig. 5.15b.

From these observations, it can be concluded that there is no ion energy loss during the plasma plume expansion in the ALPHIE. This is confirmed by the variation of the ion temperature along the plasma plume flow axis, which is shown in Fig. 5.17. As shown in this Figure, the ion temperature is seen to remain almost constant along Z , which is in accord with the conclusion that no short range collisional effects could play a role or have remarkable effects on the IEDF (and thus the plasma plume expansion process) along the Z direction.

On the contrary, the electron energy spectra in Fig. 5.2 experience important changes along the axial direction of the plasma flow. The exception is the decrease in the height of the peaks, which are due to the plasma expansion process. This will be further shown in Section 5.5.3 to follow on page 141. But the characteristic cross sections for collisions (elastic and resonant charge exchange) of neutral atoms with Argon ions are in the order of $\sigma_{ai} \sim 3 \times 10^{-15} \text{ cm}^2$ [89, 138], which give a mean free path of $\lambda_{ai} \simeq 500 \text{ cm}$ for our working pressures.

The mean free path for elastic collisions between two neutral Argon atoms [89]

FIGURE 5.17: Axial variation of the ion temperature. The red solid dots represent the fast-ion temperatures, whereas the blue diamond markers show the low-energy ion temperatures.

$\lambda_{aa} \simeq 430$ cm. The cross sections for electron and ion impact ionization of Argon also lead to mean free paths exceeding the size of our vacuum tank [138]. Ion energy losses by collisional energy exchange are therefore excluded because of the long mean free paths required as compared to the existing dimensions of the vacuum tank.

Since the plasma thruster is the only source of ions in our experiment, the low-energy ion groups in Figs. 4.15 and 5.15b are therefore due to the interaction of fast positively charged particles with the vacuum chamber walls. A number of ions from the plasma beam recombine after colliding with the walls, but a more significant proportion is reflected back towards the plasma chamber after losing a large fraction of its initial energy. The resulting heavy particles, with reduced speeds, must be responsible for the formation of the low-energy peak in the IEDF. Hence, the speeds of ions in this low-energy group must be in random direction directions yet the ion velocity distributions in Fig. 5.15b only account for those with $v_z > 0$ present at the point where the RFEA is located. On the contrary, fast ions have a very important proportion of velocity components along the direction of the plasma jet expansion, parallel to the Z -axis in Fig. 2.25.

As shown in the Fig. 5.18, an inverse square dependence is obtained for the decrease in the low-energy group peak height whereas the power for the fast ion group is smaller. This suggests that low-energy ions undergo a free expansion naturally determined by geometrical factors, unlike the fast ion population that has a directed energy and velocity component in the beam axis of expansion.

FIGURE 5.18: The peaks' heights from Fig. 5.15b represented against Z . The best fit to $1/Z^{-b}$ is shown.

5.5.2 Ion current density J_i axial variation

To understand the expansion process of the plasma plume it is important to isolate the contribution of the thermal ions from the fast-ion beam. In this section I show how the separation of the contributions to the total measured ion current I_{IC} by the low-energy and the fast ion groups is achieved. This separation makes it possible to determine the current densities of these two ion populations, and was used in this research to study separately the axial variations of these ion groups in addition to the total ion current.

I determined the maximum current I_{IC} due to the contribution of all ions and due to the fast ions independently. These I_{IC} values were then used to eliminate the contribution of the thermal ions by subtracting it from the total current so as to examine the physics governing its expansion properties. The axial profile of the stationary plasma jet expansion along the axis of symmetry (Z) is shown in Fig. 5.19, where the maximum RFEA ion current densities $J_{im}(z)$ are referred to. A background of the theoretical basis upon which these measurements were made, together with a discussion of the obtained results are presented here.

These values are calculated from the current maxima $I_m(z)$ in Fig. 5.15a and they account for the contribution to the RFEA ion current of all ion populations in the energy spectra of Fig. 5.15b. Unfortunately, the charged particle densities in the plasma beam cannot be estimated from the current densities in Fig. 5.19 because of the broad ion energy range in Fig. 5.15b as explained before. The ions with speeds $u_z > 0$ parallel to the axis of symmetry of the vacuum tank are collected and measured by the RFEA back plate. This is equivalent to radial speeds of $\pm 6 \text{ km s}^{-1}$ for ions with axial speeds of 44 km s^{-1} .

The current density at the ion collector plate is $dJ_{\text{IC}} = e u_z, dn_i$ where $e > 0$ is the electronic charge, $dn_i = f(u_z) du_z$ is the number of ions with axial speeds between u_z and $u_z + du_z$, whereas $f(\mathbf{r}, u_z)$ is the stationary one-dimensional ion velocity distribution function at the point $\mathbf{r}$ where the RFEA is located. The ions reaching the collector plate have kinetic energies $E = m_i u_z^2/2 \geq eV_{\text{ID}}$ to overcome the repelling potential V_{ID} of the ion-discriminator grid. Hence, the ion current density collected by the RFEA copper plate is in terms of E , as from Eq. 4.1, given by

$$J_{\text{IC}}(\mathbf{r}, V_{\text{ID}}) = \frac{e}{m_i} \int_{eV_{\text{ID}}}^{\infty} f(\mathbf{r}, E) dE \quad (5.2)$$

For a fixed position $\mathbf{r}$ the current density $J_{\text{IC}}(\mathbf{r}, eV_{\text{ID}})$ is a monotonically decreasing function of the discriminator voltage V_{ID} . It falls from the maximum value when $V_{\text{ID}} = V_m$, in which case all the ions can pass thorough the RFEA channel to impact the collector plate. The maximum current density $J_{\text{IC}}(\mathbf{r}, eV_m)$ contains the contribution from all groups of ions in $f(\mathbf{r}, E)$ to the RFEA current-voltage curve. Then, $J_{\text{IC}}(\mathbf{r}, eV_{\text{ID}})$ in Eq. (5.2) decreases for $V_{\text{ID}} > V_m$ because ions with low energies are rejected by the ion-discriminator grid and do not contribute to the total (integrated) current density.

The discriminator electric potential V_m that results in the maximum ion current density $J_{\text{IC}}(\mathbf{r}, V_m)$ corresponds to the lowest possible ion speed $u_{\text{mx}} \simeq 0$ detected by the RFEA. The voltage V_m can be different from zero because the discriminator potentials V_{ID} are not measured with respect to the local plasma potential but to the electric ground of the system. Thus, with $V_{\text{ID}} = V_m$ in the lower limit of the integral in Eq. (5.2),

$$J_{\text{IC}}(\mathbf{r}, V_m) = \frac{e}{m_i} \int_{eV_m}^{\infty} f(\mathbf{r}, E) dE \quad (5.3)$$

The axial profile of the stationary plasma jet expansion along the Z axis of symmetry is studied from Fig. 5.19 where maximum RFEA ion current densities $J_{\text{im}}(z)$ are represented against Z . These values are calculated from the current maxima, I_m , of Fig. 5.15a and account for the contribution to the RFEA ion current due to all ion populations in the energy spectra of Fig. 5.15b.

Unfortunately, the charged particle densities in the plasma beam could not be estimated from the current densities in Fig. 5.19 because of the broad ion energy range in Fig. 5.15b. However, the current density $J_{\text{IC}}(z, V_m)$ in Eq. 5.3 is due to the contribution of ions with energies $E \geq V_m$ to the RFEA ion current. This fact is used to estimate the axial current density of ions in the plasma jet.

In Fig. 5.15b, the two main IEDF peaks are separated at energy $E_1 \simeq 200$ eV which is the minimum energy for the fast-ion group. Therefore, for $E \geq E_1$, $J_{\text{IC}}(z, V_m) = J_{\text{iF}}$ is approximately the current density J_{iF} of the plasma beam fast-ions whereas $J_{\text{iT}} = J_{\text{im}} - J_{\text{iF}}$ is the contribution of low-energy ions in the IEDF to the RFEA maximum current. These approximate current densities are shown to vary along the plasma plume axis (Z) as shown in Fig. 5.19. The

values of $J_{iF}(z)$ (open circles) and $J_{iT}(z)$ (open squares) are also represented together with $J_{im}(z)$ (blue solid diamonds), the sum of the two ion current densities, in Fig. 5.19.

FIGURE 5.19: Current densities along the Z -axis of Fig. 2.25, calculated from the RFEA I - V curves in Fig. 5.15a. The open circles and squares show, respectively, the current densities of the fast ions $J_{iF}(z)$ and of the low-energy ions $J_{iT}(z)$, i.e., of the ions with kinetic energies above and below 200 eV, respectively. The solid diamond shapes represent the sum of both contributions.

The plasma beam fast-ion current density $J_{iF}(z)$ decreases by a factor 2.7 over 300 mm along the axial direction Z that is collinear with the axial direction of propagation of the plasma jet. The flow of supersonic ions is maximum close to the exit section of the plasma thruster and decreases along the axial direction as seen in Fig. 5.19. As seen in the $J_{iT}(z)$ profile of Fig. 5.19, the flow due to low-energy ions is spatially irregular – always below that of fast ions – and is maximum around 150 mm. The increase in both $J_{iF}(z)$ and $J_{iT}(z)$ around $Z = 150$ mm results from the contribution of the small peak between 100–200 eV to the total ion current, which have been observed in Figs. 5.15b and 5.6a.

The estimation of $J_{iF}(z)$ and $J_{iT}(z)$ was made by setting $E_1 = 200$ eV which distributes the contribution of the third (small peak) ion group between both current densities.

For a fixed position $\mathbf{r}$ the current density $J_{IC}(\mathbf{r}, V_{ID})$ is a monotonically decreasing function of the discriminator voltage V_{ID} . It falls from the maximum value when $V_{ID} = V_m$, in which case all the ions can pass thorough the RFEA channel to impact the collector plate. The maximum current density $J_{IC}(\mathbf{r}, V_m)$ contains the contribution from all groups of ions in $f(\mathbf{r}, s)$ to the RFEA current-voltage curve. Then, $J_{IC}(\mathbf{r}, V_{ID})$ in Eq. 4.1 decreases for $V_{ID} > V_m$ because ions with low energies are repelled by the ion-discriminator

grid and do not contribute to the total (integrated) current density.

The discriminator grid potential V_m that results in the maximum $J_{IC}(\mathbf{r}, V_m)$ corresponds to the lowest possible ion speed $u_{mx} \simeq 0$ detected by the RFEA. The V_m can be different from zero because the discriminator potentials V_{ID} are not measured with respect to the local plasma potential but to the electric ground of the system.

5.5.3 Transversal or cross sectional measurements

Similar to the procedure already described in Section 5.5.2 (page 138), which led to the qualitative estimates of the ion current density variations along the axial direction discussed above, the maximum ion currents from the measured RFEA I - V curves were used to study the ion beam expansion properties. These were obtained for the contributions due to all ions (total ion contributions) and fast ions. Using the measurements taken at different coordinate points, these transversal measurements were taken either along a line through the beam centre (measurements along the beam diameter) or a mapping in an 8 mm by 8 mm two-dimensional (2-D) imaginary plane perpendicular to the beam axis (of the scheme in Fig. 2.25 referred to earlier in the previous sections) was made to obtain a cross-sectional ion current profile.

To have a picture on the beam expansion or plasma plume flow, such cross-sectional profiles were measured from at least three fixed distances from the engine exit section along its axis. The cross-sectional (or transversal) ion beam profiles, which show the ions to undergo a free expansion, are presented here.

5.5.4 Along a line through the beam centre (along beam diameter)

These measurements provide a 2-D ion current profile which can reflect the shape of the ion beam of the plasma plume, and can be used to provide useful information on the distribution or spread of the beam ions with respect to the beam centre. When the obtained profile is approximated by a mathematical function model such as the Gaussian function, the obtained parameters of such a model, e.g., the full width at half maximum (FWHM) can be used to estimate the beam divergence when two such profiles are measured at different axial positions along the plasma plume expansion axis.

Fig. 5.20 shows 2-D current profiles along two perpendicular directions (X and Y) normal to the Z axis measured using an RFEA at $Z = 130$ mm (see Fig. 2.25 on page 74 for details) from the exit of the thruster. The X direction measurements are lead to a horizontal profile as shown in (a) and a vertical profile is got from the Y measurements as in (b).

The graphs in both Figs. 5.20 and 5.21 show a beam that can be approximated by a Gaussian function model, with a central peak located about 15 mm from the Z axis of the vacuum chamber or engine axis. The diameter of the

(a) Along X , at $Z = 130$ mm (of Fig. 2.25). (b) Along the Y -axis at the same axial distance.

FIGURE 5.20: Plasma plume ion beam current profiles along the beam diameter: Profiles measured by the RFEA through the beam centre along X and Y directions at $Z = 130$ mm. The fit parameters of a Gaussian function model approximation of the profile: Centre = 14.7 mm and FWHM = 15.8 mm. The 5 % error bars are also displayed.

profile in graph b (measured along Y) can be estimated by the full width at half maximum of the profile fit, which is equal to 15.8 mm.

In both the two profiles, an appreciably measurable ion beam current is only obtained within a cross section of about 30 mm diameter which corresponds to the diameter of the engine grids at the exhaust of the thruster. The slight difference in the magnitude of the current is due to the deterioration of the neutralizer cathode wire which takes place when the thruster has been in

FIGURE 5.21: Comparison of the RFEA (red coloured star shapes) and LP (blue triangles) current profiles along Y of the scheme in Fig. 2.25, at $Z = 130$ mm. Currents corresponding to the maximum total ion current collected (first plateau of I - V characteristics) of the RFEA and the estimation of the ion saturation current obtained with the Langmuir probe were used for the two probes. Gaussian function model fit parameters for the LP-measured profile are: Centre = 1.2 mm and FWHM = 12.4 mm.

operation for some time.

FIGURE 5.22: RFEA-measured ion current profile along beam diameter at $Z = 200$ mm. Measured data (red solid markers) with the 5% error bar is shown. A Gaussian model function fit to the current data is shown (blue solid line). Characteristics derived from the fit data: Centre is 8.1 mm and FWHM = 20.7 mm.

The slight difference in the beam profile shape when the measurements are taken along the two orthogonal axes (X and Y) is due to the hot wire cathode that is positioned along the cross section of the beam just at the section from where it is ejected out of the thruster. This is seen in Fig. 5.20a where the beam's side that is adjacent to the cathode has the current distorted due to the negatively charged cathode's presence. This effect makes the beam to appear narrower on one side when displayed in 3-D, as will be shown in Figs. 5.25 and 5.28.

A similar profile as in Fig. 5.20b was obtained for the ion saturation currents (see Fig. 2.1 on page 33 and Section 2.3.2.4 on page 35) of a Langmuir probe, which represents (even though not accurately) the ion current density collected by the probe. The FWHM of this profile is 12.4 mm, almost the same as for the RFEA-measured data profile. Fig. 5.21 shows the LP- and RFEA-measured profiles along Y plotted on the same axes, with the LP profile represented by the blue triangles (left current axis) and the RFEA profile by the star-shaped markers (right axis).

The LP ion saturation currents trace out the same shape of profile as the RFEA, except for their displaced centres. The LP profile shows the beam centre to be at the Z axis of Fig. 2.25, whereas the RFEA profile – because of its very directional nature – shows the beam centre to be pointing slightly upwards. This is dependent on the alignment of the engine, and could result from defects during the engine's mounting process into the vacuum tank. Considering the directional nature of the RFEA where only ions with velocities directed along Z get to the collector, since the RFEA's axis is aligned and fixed parallel to the axis of the vacuum chamber, the comparison shown in Fig. 5.21 show that the LP ion current measurements are reliable in this case, and that the plasma plume ejected by the thruster is approximately a Gaussian-shaped beam. Using the FWHM values for the two RFEA-measured ion beam profiles at $Z = 130$ mm and $Z = 200$ mm above, the beam divergence angle can be estimated to be about 4° or 70 milliradians.

5.5.5 Cross sectional profiles

The separation of the fast ion group contribution to the total ion current from that of the low-energy group allowed for the measurement or study of the profiles due to both the total ion population and the fast ion group as presented in this section.

Figs. 5.23 and 5.24 show cross-sectional ion current profiles measured at a distance $Z = 150$ mm from the engine exit section. In both Figures, the thruster current I_E was kept at a constant value of $I_E = 200$ mA but different acceleration voltages V_{AC} of 650 V and 550 V, respectively, were used. The profiles of the total ion current and only the current due to the fast ion group are shown in the two Figures 5.23 and 5.24.

The profiles corresponding to $V_{AC} = 650$ V are shown in Fig. 5.23, whereas those corresponding to $V_{AC} = 550$ V are shown in Fig. 5.24. In both cases,

(a) Total ion current profile, $Z = 150$ mm and acceleration voltage $V_{AC} = 650$ V.

(b) Fast ion current profile at $Z = 150$ mm and acceleration voltage $V_{AC} = 650$ V

FIGURE 5.23: Cross sectional ion current profiles for total ion current and the fast ion-group population at $Z = 150$ mm. These were measured along the transversal direction to Z , for 650 V acceleration voltage and 200 mA beam current.

the profiles show a beam that is peaked close to the axis of the plasma plume flow, which is in agreement with the results of the 2-D profiles in the previous section (Section 5.5.4). However, smaller or relatively lower amplitude other peaks are seen around the main peak when the total ion population currents are considered. These smaller peaks tend to disappear when only the fast ion population currents are used, as seen in Figs. 5.23b and 5.24b. This shows how collimated or more directed the fast ions are with respect to the low-energy

(a) Total ion current profile at $Z = 150$ mm and acceleration voltage $V_{AC} = 550$ V.

(b) Fast ion group current profile at $Z = 150$ mm and acceleration voltage $V_{AC} = 550$ V.

FIGURE 5.24: Surface plots of the ion beam radial profile at $Z = 150$ mm for 550 V acceleration volts and 200 mA beam current.

ones in the plasma plume of the ALPHIE thruster.

Also, from the measurements at the fixed distance from the engine, a reduction in the measured ion current is observed in the profiles of the two Figures (5.23 and 5.24) which occurs for both the total ion current and the fast ion currents. This is in agreement with the IEDF and ion current density studies shown in Figs. 5.15b and 5.19 of the previous sections.

Fig. 5.25 shows a comparison of the fast ion group current profiles from Figs. 5.23 and 5.24 above. The profile in Fig. 5.25a is the measurement with

(a) Fast ion current profile at $Z = 150$ mm for 550 V acceleration voltage and thruster current $I_E = 200$ mA.

(b) Fast ion current profile at $Z = 150$ mm for 650 V acceleration voltage and thruster current $I_E = 200$ mA.

FIGURE 5.25: Fast-ion beam cross-sectional profiles at $Z = 150$ mm for two different acceleration voltages V_{AC} of 550 V 650 V. The thruster current I_E was constant at 200 mA for both measurements.

$V_{AC} = 550$ V and that for $V_{AC} = 650$ V is shown in Fig. 5.25b. The peaked profiles of these two fast ion current measurements are very comparable with the results in Figs. 5.20 and 5.21 in terms of the similarities. The profiles in both Figures show the plasma plume's fast-ion currents to be concentrated around a narrow cone as the beam is ejected by the thruster. This is shown by the sharp peaks around the centre of the profile in Figs. 5.25a and Fig. 5.25b.

The peaks in these profiles are around the same coordinates and the intensity increases when more driving energy is added to the ions by increasing the acceleration voltage. This is shown by the sharper peak in Fig. 5.25b as compared to that in Fig. 5.25a where a slightly lower acceleration voltage is used. The multiple peaks around the main peak in Fig. 5.25b are also absent in the profile of Fig. 5.25b due to the relative intensity of the measured ion current relative to the associated peaks. The smaller peaks are thus suppressed by the presence of the intense peak for the fast ion group with a higher driving energy provided by the acceleration voltage V_{AC} .

Similarly, the profiles were measured at $Z = 300$ which is 15 cm farther from the engine than the measurements whose profiles have been discussed above. In this case any changes on the shape of the profiles of the measured ion currents can help in understanding the behaviour of the plasma plume ions far away from the engine exhaust within a certain radius from the axis of the plasma plume flow.

Figs. 5.26 and 5.27 show the ion current cross-sectional profiles from these measurements (at $Z = 300$ mm from the engine exit section). As in Figs. 5.23 and 5.24, the profiles corresponding to both the total ion current and the fast-ion group current for the same parameters are presented in Figs. 5.26 and 5.27, with the former being the measurements with $V_{AC} = 650$ V and the latter with $V_{AC} = 550$ V. A slight difference though is in the thruster current I_E that is attempted to be kept constant but increased for the case with $V_{AC} = 550$ V for the purpose of being able to measure an appreciable amount of current to enable any comparisons or studies to be made. This increase in I_E to 300 mA is expected to have a negligible effect on the V_{AC} effect desired here.

From both Figs. 5.26 and 5.27, a decrease in the measured ion current is evident as the maximum total current falls from about $260 \mu\text{A}$ to about $120 \mu\text{A}$ and from about $240 \mu\text{A}$ to just less than $40 \mu\text{A}$ for $V_{AC} = 650$ V and 550 V, respectively, for measurements at $Z = 150$ and 300 mm. A proportional fall in the measured current occurs for the fast-ion group where the values fall from about $130 \mu\text{A}$ to $63 \mu\text{A}$ for $V_{AC} = 650$ V and from about $118 \mu\text{A}$ to $24 \mu\text{A}$ for $V_{AC} = 550$ V.

These measurements show a proportional decrease in the reduction in the fast-ion group currents from about 80% for $V_{AC} = 550$ V to 52% when the acceleration voltage is increased to $V_{AC} = 650$ V. The higher proportional decrease in the current of fast-ion currents for lower acceleration voltages can be seen in Fig. 5.27. In this Figure, more ions are detected at the beam periphery which could be an indication of the beam expansion resulting in the majority of the ions to be lost when they either diffuse to the walls of the vacuum tank or they lose their energy to electrons thereby resulting in the EEDF profile shown earlier in Fig. 5.2 on page 120. The tendency for the more currents to be detected closer to the beam periphery can also be seen in the colour map contour profiles in Figs. 5.28, 5.29, and 5.30.

In Figs. 5.28, 5.29, and 5.30, the behaviour or tendency of the total ion beam current for the profiles measured at axial positions of $Z = 150$, 250 , and

(a) Total ion current profile, $Z = 300$ mm and acceleration voltage $V_{\text{AC}} = 650$ V.

(b) Fast ion group current profile at $Z = 300$ mm and acceleration voltage $V_{\text{AC}} = 650$ V

FIGURE 5.26: Cross sectional ion current profiles for total ion current and the fast ion-group population measured at $Z = 300$ mm with acceleration voltage $V_{\text{AC}} = 650$ V and thruster current $I_{\text{E}} = 200$ mA.

300 mm, respectively, are shown. The thruster current $I_{\text{E}} = 200$ mA is the same for the three cross sectional measurements, but the acceleration voltage V_{AC} is changed. The contour maps show a more evenly or almost uniformly distributed ion current measured around the beam cross section at $Z = 150$ mm from the exit section from the engine.

Thus, with the measurements based on the separation of the low-energy and the fast ion groups initiated in this research, a few conclusions can be made

(a) Total ion population current profile at $Z = 300$ mm and acceleration voltage $V_{AC} = 550$ V.

(b) Fast ion group current profile at $Z = 300$ mm and acceleration voltage $V_{AC} = 550$ V.

FIGURE 5.27: Cross-sectional profiles at $Z = 300$ mm for $V_{AC} = 550$ V and $I_E = 300$ mA.

from the results of the findings: First, that the sharp peak of the ion beam is more centred closer to the engine exhaust section, and spreads outwards with distance Z , as seen in Figs. 5.25a and 5.25b. This is because closer to the engine the ion current density is higher, resulting in a more focused beam.

Secondly, the beam focus or collimation deteriorates very slightly with distance away from the beam origin or source since the density also decreases with axial distance, as seen by the very small height of the profile in Fig. 5.25b in the centre except from the periphery of the beam cross section. This ob-

(a) $V_{AC} = 650 \text{ V}$, $I_E = 200 \text{ mA}$ (b) $V_{AC} = 550 \text{ V}$, $I_E = 200 \text{ mA}$ (c) $V_{AC} = 450 \text{ V}$, $I_E = 200 \text{ mA}$ FIGURE 5.28: Total ion current colour maps at $Z = 150 \text{ mm}$.

served beam deviation from the centre would be explained in terms of a loss

(a) $V_{AC} = 650 \text{ V}$, $I_E = 200 \text{ mA}$ (b) $V_{AC} = 550 \text{ V}$, $I_E = 200 \text{ mA}$ (c) $V_{AC} = 450 \text{ V}$, $I_E = 200 \text{ mA}$ FIGURE 5.29: Total ion current colour maps at $Z = 250 \text{ mm}$.

or deterioration of the beam focus of geometric origin, where sometimes the

beam does not come out as centred as expected. This was a serious issue that was identified or discovered after some tests on the RFEA collected current intensity.

Thirdly, the measured ion beam current decreases/falls with the distance Z away from the engine exit section, which is in agreement with the ion current density estimates presented in Fig. 5.19. As seen in Fig. 5.25a, the highest current measured at $Z = 150$ mm is about $118 \mu\text{A}$, almost five times the amount measured at a farther distance $Z = 300$ mm.

The ion beam divergence could be measured from the Gaussian fits as in Fig. 5.21 when measured at two axial positions, which gave rise to a divergence angle of 4 degrees as pointed out earlier here.

As already shown in Section 5.3.2, the potential V_{AC} plays a key driving role to the ions. The intensity of the ions is higher for higher V_{AC} potentials, which explains the more focused beam profile in Figs. 5.28a and 5.28b compared to the case in Fig. 5.28c.

(a) $V_{AC} = 650 \text{ V}$, $I_E = 300 \text{ mA}$ (b) $V_{AC} = 550 \text{ V}$, $I_E = 300 \text{ mA}$ (c) $V_{AC} = 450 \text{ V}$, $I_E = 300 \text{ mA}$ FIGURE 5.30: Total ion current colour maps at $Z = 300 \text{ mm}$.

(a) $Z = 150$ mm, $V_{AC} = 550$ V, $I_E = 200$ mA

(b) $Z = 250$ mm, $V_{AC} = 550$ V, $I_E = 200$ mA

(c) $Z = 300$ mm, $V_{AC} = 650$ V, $I_E = 200$ mA

FIGURE 5.31: Contour plots for the fast-ion currents.

(a) $Z = 300$ mm, $V_{AC} = 550$ V, and $I_E = 300$ mA

(b) $Z = 300$ mm, $V_{AC} = 650$ V, and $I_E = 300$ mA

FIGURE 5.32: Fast-ion current dependence on I_E

Summary and Conclusions

Conclusions

The measurements from the experiments have enabled the study of the ALPHIE thruster key control parameters, which include the acceleration voltage V_{AC} and the cover grid potential V_{CG} . The measurements obtained with the RFEA have shown the ALPHIE thruster configuration discussed in section 1.8, simple as it is, to possess the essential performance characteristics of a plasma thruster, i.e., the acceleration potential V_{AC} controls the energies of the supersonic plasma streams (see Figs. 5.10 and 5.11), and the shutdown or turning ON/OFF mechanism can be achieved by setting the V_{CG} voltages to high values (as shown in Figs. 5.8b and 5.8a) which inhibit the ion production. The V_{AC} and V_{CG} voltages, used in such ways could be used together to permit the precise control of the plasma stream.

During the course of the experiments, it became paramount that more than one diagnostic was necessary for the plasma plume characterization, as had been established in the research goals. In this regard, a retarding-field energy analyzer (RFEA) was designed and built for ion energy spectrum (IEDF) measurement. This diagnostic was used alongside Langmuir probe and emissive probe diagnostics which were mainly relevant for the determination of the plasma electron temperature and potential, respectively. The basis of the use of electric probes in the determination of the ALPHIE exhaust plasma flow physical parameters has been discussed in the previous chapters.

This Dissertation is specifically concerned with the design and building of a RFEA and its use with a computer-driven 3D platform to investigate the spatial distribution of the ion energy distribution function (IEDF). Langmuir and emissive probes had been used in related works within the experimental laboratory, and their designs had already been implemented. These two probes that have been employed as auxiliary probes were already available, but their building/replacement whenever they broke down (especially the emissive probe) went on throughout the research. They have been used to obtain information on the spatial structure of the electron energy distribution functions (EEDF).

Simple and quite readily available material components were used to build the probes needed for the plasma plume characterization. The RFEA was designed in modular components to ensure flexibility with regard to mainte-

nance and checks. As a result, different prototypes were built and used for the measurements during the research. Additionally, the 3-D robotic platform and system that enabled the probing of a large part of the vacuum tank volume for various measurements was also made from simple inexpensive materials. The 3-D robotic system was designed in the laboratory and built with the help of partners from the mechanical and electrical engineering departments. A multiprobe platform was designed and built for use with the robotic platform. It has slots for the RFEA, emissive probe, and Langmuir probe side by side. A combination of the multiprobe platform and the robotic positioning or displacement system enabled a more complete characterization of the thruster plasma plume.

Most of the emphasis has been put on the determination of plasma properties at three key spatial positions: at a fixed point 200 mm in front of the thruster exit section along the Z -axis shown in the scheme of Fig. 2.25, along the beam or plasma plume flow cross section which was either along the beam diameter or cross-sectional measurements in a plane perpendicular to the beam flow, and axially along the Z -axis.

Chapter 2 analyzes the RFEA technique that is limited since it only provides the one-dimensional IEDF along the direction parallel to its axis of symmetry. In addition, the sliding system is only capable of displacing the probes in rectangular motions along the spatial coordinates (x , y , z), as discussed in the same Chapter. Only groups of ions with velocities parallel to the axis of symmetry of the thruster could be measured within an error of $\Delta E = \pm 4$ eV.

From the experimental results, two ion groups have been shown to dominate the expansion of ALPHIE plasma jet along the axial direction. The supersonic (fast) ion group remains essentially unchanged in distribution parallel to the axial direction and is only likely to be modified by the interaction with the vacuum chamber walls. This is evidenced by the almost uniform or unchanged ion velocity distribution functions along the Z -axis, as shown in Fig. 5.15b.

In spite of this limitation, the designed RFEA has made it possible to measure the axial drift speeds and temperatures of the fast and low-energy ion groups. These properties were measured in steady state along the axial and cross-sectional directions of the plasma plume and the obtained experimental results have been discussed in Chapter 5. The measurements have shown the ALPHIE exhaust-plasma to be a mesothermal plasma flow, whereby the fast ion group emerges at drift speeds $u_{\text{DF}} \sim 36\text{--}44 \text{ km}\cdot\text{s}^{-1}$, which is 3–4 times higher than the thermal ion velocities u_{Ti} of $\sim 20\text{--}21 \text{ km}\cdot\text{s}^{-1}$. The electron thermal velocities $v_{\text{th}} \sim 593\text{--}863 \text{ km}\cdot\text{s}^{-1}$ ($T_e \sim 1\text{--}3$ eV) are higher.

In Fig. 5.16, the energies corresponding to the IEDF maxima from Fig. 5.15b have been shown, which remain essentially constant along the axial direction of the plasma plume flow. Presently, there is no clear explanation for the high ion temperatures observed in the IEDF of fast and slow (low-energy) ion groups. Energy transfer by ions in the plasma plume is excluded due to the long mean free paths for neutral and ion encounters along the plasma plume. Thus, the origin of the wide energy spectra would be the ion production processes inside

the ALPHIE ionization chamber where collisions between confined electrons and heavy particles play a significant role.

The ALPHIE's fast ion groups move at supersonic velocities with respect to the background plasma in all cases studied. This feature is crucial, as thrust $F_T \sim \dot{m}_i u_{DF}$ is controlled by the ion exhaust velocity u_{DF} . A direct measurement of the ALPHIE thrust using argon propellant recently yielded $F_T \sim 1\text{--}3.5\text{ mN}$ [151], which confirmed the momentum delivered by fast ion groups observed in the vacuum chamber tests.

The Langmuir probe (LP) has been used to measure the electron energy distribution function (EEDF), making use of the plasma potential measurements obtained with the emissive probe. However, the measurement technique of the LP is limited in a supersonic plasma flow, as the prevailing conditions do not satisfy (and thus deviate from) the limits of the probe's simplified theory which is commonly used. This is due to wake creation on the side of the probe downstream of the plasma flow, which distorts the electric field symmetry around a spherical (or cylindrical) probe in fast mesothermal plasma flows [90, 92]. A rarefied plasma region develops past the probe (downstream side of plume flow) since ions cannot fill the space just behind the probe. This ion flow prevents the 'lighter' electrons from filling the void region (see Fig. 2.6 on page 2.6 for details), which would otherwise result in the development of an intense electric field due to electric charge imbalance [92].

As discussed in Section 5.2, the electron current density collected on the probe surface facing the thruster is then not equal to the amount collected on the opposite side of the probe. Thus, as the extension of the wake in the direction of the ion flow increases compared to the probe radius, i.e., $l_w/R_o \gg 1$, it then becomes necessary that the EEDFs in Fig. 5.2 derived from the Langmuir probe I - V curves are be interpreted with great care and precaution. The double-humped distributions in Fig. 5.2 mostly correspond to electron populations in front of the LP because the contribution of electrons collected from the back side is much smaller.

In total contrast to the ion energy distributions, further analysis of the electron energy distributions shows these particles to undergo a complex thermalization process along Z parallel to the plasma plume flow, whereby the two peaks formed close to the engine exit section merge into a single peak far from the plasma thruster. From this observation, it can be concluded that electrons in the plasma plume flow might be undergoing collisions with a resulting thermalization during the expansion process. The electron cooling previously observed in similar studies put forward by Ref [31] can therefore be explained in terms of a complex thermalization process undergone by electrons and not necessarily a cooling of electrons.

The emissive probe technique for the determination of plasma potential V_{sp} makes use of the transition from electron collection by the probe to its electron emission to the surroundings. This technique, discussed in Chapter 2, is essentially independent of the ion kinetic energy. Hence, the emissive probe measurements obtained and presented here are less influenced by the plasma

wake than those of Langmuir probes.

The axial plasma potential profile in Fig. 5.1 decreases from more than 25 V close to the ALPHIE exit section to only a few volts at a 35 cm distance along the direction parallel to the plasma plume flow. Hence, the local electric potential at this distant point is similar to that of the grounded walls of the vacuum tank where the probes were electrically biased. Fig. 5.1 suggests an abrupt fall in the electric charge concentration along the plasma plume axis of symmetry. These values were employed in the evaluation of the EEDF in Fig. 5.2 as discussed in Chapter 4.

The extension of the plasma plume shown in the above referred to Figures is confirmed by the peak heights of IEDFs measured over the ~ 35 cm distance along the axial direction in Fig. 5.17. In Fig. 5.17 the heights of the peak maxima for the slow or low-energy ions decrease as $\sim 1/Z^2$, which suggests a free expansion from the exit section of the ALPHIE thruster. The slower rate of decrease proportional to $\sim 1/Z^{1.5}$ for fast-ion peaks shows the high-energy ions to be distributed over a narrow angle.

Reflection of ions (mostly with lower energies) by the walls is a likely occurrence in the vacuum tank, which could account for the low-energy peak or population of the IEDF. In most of the measurements with the RFEA, an almost systematic additional small peak was observed in the obtained IEDFs. Possible ion energy losses by collisions (elastic and resonant charge exchange) cannot be plausible because of the long mean free paths required compared to the mean free path associated with the dimensions of the vacuum tank and the particle number densities present for such collisions to occur.

Furthermore, the cross sectional distribution of fast and slow/low-energy ion groups in Figs. 5.25–5.30 confirm that an important fraction of fast ions preserves its collimation along the plasma plume. It would be important for future experiments to try to optimize the Langmuir probe geometry by using plane probes and/or cylindrical probes pointing along the axis of the plasma flow to eliminate the shortcomings that could be associated with using a spherical probe in such flowing plasmas.

Bibliography

- [1] D. M. Goebel and I. Katz, *Fundamentals of electric propulsion. Ion and Hall thrusters*. Hoboken, New Jersey, USA: John Wiley & Sons, 2008.
- [2] “Electric spacecraft propulsion.” <https://sci.esa.int/web/smart-1/-/34201-electric-spacecraft-propulsion>, September 2019. Accessed: 06-02-2020.
- [3] L. Conde, “Plasma propulsion for telecommunication satellites,” *Journal of Physics: Conference Series*, vol. 1326, p. 012001, oct 2019.
- [4] O. B. George P. Sutton, *Rocket Propulsion Elements*. John Wiley & Sons, 7th ed., 2001.
- [5] S. Mazouffre, “Electric propulsion for satellites and spacecraft: established technologies and novel approaches,” *Plasma Sources Science and Technology*, vol. 25, p. 033002, Apr 2016.
- [6] C. Charles, “Plasmas for spacecraft propulsion,” *Journal of Physics D: Applied Physics*, vol. 42, p. 163001, jul 2009.
- [7] E. Ahedo, “Plasmas for space propulsion,” *Plasma Physics and Controlled Fusion*, vol. 53, p. 124037, Nov 2011.
- [8] M. Keidar, T. Zhuang, A. Shashurin, G. Teel, D. Chiu, J. Lukas, S. Haque, and L. Brieda, “Electric propulsion for small satellites,” *Plasma Physics and Controlled Fusion*, vol. 57, no. 1, p. 014005, 2015.

- [9] R. E. Florenz, “The X3 100-kW Class Nested-Channel Hall Thruster: Motivation, Implementation, and Initial Performance,” 2014.
- [10] S. J. Hall, R. E. Florenz, A. Gallimore, H. Kamhawi, D. L. Brown, J. E. Polk, D. M. Goebel, and R. R. Hofer, “Implementation and Initial Validation of a 100-kW Class Nested-channel Hall Thruster,” in *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA Propulsion and Energy Forum, American Institute of Aeronautics and Astronautics, 2014.
- [11] S. Hall, “Characterization of a 100-kW Class Nested-Channel Hall Thruster,” 2018.
- [12] H. Liu, P. B. Chen, Q. Q. Sun, P. Hu, Y. C. Meng, W. Mao, and D. R. Yu, “Design of a cusped field thruster for drag-free flight,” *Acta Astronautica*, vol. 126, pp. 35–39, 2016. Space Flight Safety.
- [13] D. Yu, P. Hu, H. Liu, and Y. Shen, “Experimental study on the ionization regions in a multi-cusped field thruster,” *Plasma Sources Science and Technology*, vol. 27, no. 7, p. 075012, 2018.
- [14] N. A. MacDonald, C. V. Young, M. A. Cappelli, and W. A. Hargus, “Ion velocity and plasma potential measurements of a cylindrical cusped field thruster,” *Journal of Applied Physics*, vol. 111, no. 9, p. 093303, 2012.
- [15] *Physics and evolution of HEMP Thrusters*, vol. IEPC-2007-108, (Florence, Italy), Proceedings of the 30th International Electric Propulsion Conference, September 17–20 2007.
- [16] *The HEMPT concept. A survey on theoretical considerations and experimental evidences*, vol. IEPC-2011-236, (Wiesbaden, Germany), Proceedings of the 32nd International Electric Propulsion Conference, September 11–15 2011.

- [17] F. F. Chen, “Helicon discharges and sources: a review,” *Plasma Sources Science and Technology*, vol. 24, p. 014001, Jan 2015.
- [18] E. Y. Choueiri, “A Critical History of Electric Propulsion: The First Fifty Years (1906-1956),” *Journal of Propulsion and Power*, vol. 20, pp. 193–203, April 2004.
- [19] R. H. Frisbee, “Advanced Space Propulsion for the 21st Century,” *Journal of Propulsion and Power*, vol. 19, no. 6, pp. 1129–1154, 2003.
- [20] M. J. L. Turner, *Rocket and spacecraft propulsion: principles, practice and new developments*. Springer Praxis Books / Astronautical Engineering, Springer published in association with Praxis Pub., 3rd ed., 2009.
- [21] R. Boswell, C. Charles, P. Alexander, J. Dedrick, and K. Takahashi, “Plasma Expansion From a Radio Frequency Microdischarge,” *IEEE Transactions on Plasma Science*, vol. 39, pp. 2512–2513, Nov 2011.
- [22] O. B. George P. Sutton, *Rocket Propulsion Elements*. Wiley, 8th ed., 2010.
- [23] E. Olson, “Ion thrusters: Ultra-efficient, high-speed spacecraft propulsion.” Image source: NASA <https://insights.globalspec.com/article/10010/ion-thrusters-ultra-efficient-high-speed-spacecraft-propulsion>, September 2018. Accessed: 24-01-2019.
- [24] “Electric propulsion capabilities demonstrated for future nasa missions.” Source: NASA <https://insights.globalspec.com/article/9778/electric-propulsion-capabilities-demonstrated-for-future-nasa-missions>, September 2018. Accessed: 30-01-2019.
- [25] E. Olson, “Electric spacecraft propulsion: How do ion thrusters work?.” Image source: NASA <https://insights.globalspec.com/article/10145/electric-spacecraft-propulsion-how-do-ion-thrusters-work>, October 2018. Accessed: 21-01-2019.

- [26] M. Dudeck, F. Doveil, N. Arcis, and S. Zurbach, “Plasma propulsion for geostationary satellites for telecommunication and interplanetary missions,” *IOP Conference Series: Materials Science and Engineering*, vol. 29, p. 012010, feb 2012.
- [27] S. Shimada, K. Sato, H. Takegahara, and K. Kajiwara, “20 mN class xenon ion thruster for ETS-VI,” in *19th International Electric Propulsion Conference*, 05 1987.
- [28] L. Conde, J. L. Domenech-Garret, J. M. Donoso, E. E. Del Río, and M. A. Castillo, “Plasma accelerator with modulated thrust.,” May 04 2017. Patent application PCT/EP2015/074879. European Patent Office (2015).
- [29] L. Conde, J. L. Domenech-Garret, J. M. Donoso, E. E. Del Río, and M. A. Castillo, “Plasma accelerator with modulated thrust.,” January 2019. United States Patent 10172227.
- [30] D. M. Goebel and I. Katz, *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*. JPL Space Science and Technology Series, Wiley, 2008.
- [31] E. Criado, E. Roibàs, S. P. Tierno, P. R. D. Francisco, J. L. Domènech-Garret, J. M. Donoso, and L. Conde, “Ion beam neutralization and properties of plasmas from low power ring cusp ion thrusters,” *Physics of Plasmas*, vol. 19, no. 2, p. 023505, 2012.
- [32] S. P. Tierno, J. L. Domènech-Garret, J. M. Donoso, D. Jennewein, G. Herdrich, S. Fasoulas, and L. Conde, “Emissive Langmuir Probes in the Strong Emission Regime for the Determination of the Plasma Properties.,” *IEEE Trans. on Plasma Sci.*, vol. 41, no. 4, pp. 695–700, 2013.
- [33] E. Roibàs, S. P. Tierno, E. Criado, J. L. Domenech-Garret, J. M. Donoso, and L. Conde, “Characterization of the Ion Beam Neutralization of

- Plasma Thrusters Using Collecting and Emissive Langmuir Probes,” *Contributions to Plasma Physics*, vol. 53, pp. 57–62, January 09 2013.
- [34] I. H. Hutchinson, *Principles of Plasma Diagnostics*. Cambridge: Cambridge University Press, 2nd ed., 2002.
- [35] M. Ya-li, T. Fu-jun, X. Yu-xiong, C. Yi-feng, G. Xin, W. Yi, T. Kai, and Y. Ze-dong, “Retarding Potential Analyzer Design and Result Analysis for Ion Energy Distribution Measurement of the Thruster Plume in the Laboratory,” *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, vol. 6, no. 11, pp. 2539–2542, 2012.
- [36] V. V. Zhurin, *Ion and Plasma Sources for Science and Technology*. Weinheim, Germany: Wiley-VCH, 2011.
- [37] J. L. Domenech-Garret, S. P. Tierno, and L. Conde, “Non-equilibrium thermionic electron emission for metals at high temperatures,” *Journal of Applied Physics*, vol. 118, no. 7, p. 074904, 2015.
- [38] L. Conde, J. L. Domènech-Garret, J. M. Donoso, J. Damba, S. P. Tierno, E. Alamillo-Gamboa, and M. A. Castillo, “Supersonic plasma beams with controlled speed generated by the alternative low power hybrid ion engine (ALPHIE) for space propulsion,” *Physics of Plasmas*, vol. 24, no. 12, p. 123514, 2017.
- [39] F. F. Chen, J. D. Evans, and D. Arnush, “A floating potential method for measuring ion density,” *Physics of Plasmas*, vol. 9, no. 4, pp. 1449–1455, 2002.
- [40] C. Böhm and J. Perrin, “Retarding-field analyzer for measurements of ion energy distributions and secondary electron emission coefficients in low-pressure radio frequency discharges,” *Review of Scientific Instruments*, vol. 64, no. 1, pp. 31–44, 1993.

- [41] M. Merino and E. Ahedo, “Influence of electron and ion thermodynamics on the magnetic nozzle plasma expansion,” *IEEE Transactions on Plasma Science*, vol. 43, pp. 244–251, Jan 2015.
- [42] K. Miyamoto and R. L. Dewar, “Plasma Physics for Nuclear Fusion,” *Physics Today*, vol. 33, 1980.
- [43] I. Langmuir and K. G. Blodgett, “Currents Limited by Space Charge between Concentric Spheres,” *Phys. Rev.*, vol. 24, pp. 49–59, Jul 1924.
- [44] V. I. Demidov, S. V. Ratynskaia, and K. Rypdal, “Electric probes for plasmas: The link between theory and instrument,” *Review of Scientific Instruments*, vol. 73, no. 10, pp. 3409–3439, 2002.
- [45] N. A. Krall and A. W. Trivelpiece, “Principles of Plasma Physics,” *American Journal of Physics*, vol. 41, no. 12, pp. 1380–1381, 1973.
- [46] Z. Zhang, H. Tang, Z. Zhang, J. Wang, and S. Cao, “A retarding potential analyzer design for keV-level ion thruster beams,” *Review of Scientific Instruments*, vol. 87, no. 12, p. 123510, 2016.
- [47] Y. Hu and J. Wang, “Electron Properties in Collisionless Mesothermal Plasma Expansion: Fully Kinetic Simulations,” *IEEE Transactions on Plasma Science*, vol. 43, no. 9, pp. 2832–2838, 2015.
- [48] C. Charles and R. W. Boswell, “Laboratory evidence of a supersonic ion beam generated by a current-free “helicon” double layer,” *Phys. Plasmas*, vol. 11, no. 4, pp. 1706–1714, 2004.
- [49] C. Charles, B. W. Boswell, and M. A. Lieberman, “Xenon ion beam characterization in a helicon double layer thruster,” *Appl. Phys. Lett.*, vol. 89, no. 26, pp. 261503–1,3, 2006.
- [50] C. S. Corr, J. Zanger, B. W. Boswell, and C. Charles, “Ion beam formation in a low-pressure geometrically expanding argon plasma,” *Appl. Phys. Lett.*, vol. 91, no. 24, pp. 241501–1,3, 2007.

- [51] F. F. Chen, ““Universal” Overstability of a Resistive, Inhomogeneous Plasma,” *The Physics of Fluids*, vol. 8, no. 7, pp. 1323–1333, 1965.
- [52] V. A. Godyak and V. I. Demidov, “Probe measurements of electron-energy distributions in plasmas: what can we measure and how can we achieve reliable results?,” *Journal of Physics D: Applied Physics*, vol. 44, p. 233001, may 2011.
- [53] K. J. T. a. Paul M. Chung, Lawrence Talbot, *Electric Probes in Stationary and Flowing Plasmas: Theory and Application*, vol. 11 of *Applied Physics and Engineering* 11. Springer-Verlag Berlin Heidelberg, 1st ed., 1975.
- [54] R. M. Clements, “Plasma diagnostics with electric probes,” *Journal of Vacuum Science & Technology*, vol. 15, no. 2, p. 193, 1978.
- [55] O. Auciello and D. L. F. (Eds.), *Plasma Diagnostics. Discharge parameters and chemistry*. Plasma Diagnostics, Academic Press, 1989.
- [56] L. Dorf, Y. Raitses, and N. J. Fisch, “Electrostatic probe apparatus for measurements in the near-anode region of Hall thrusters,” *Review of Scientific Instruments*, vol. 75, no. 5, pp. 1255–1260, 2004.
- [57] N. Hershkowitz, “How Langmuir probes work.,” in *Plasma Diagnostics. Discharge Parameters and Chemistry*. (O. Auciello and D. L. Flamm, eds.), vol. 1, ch. 3, pp. 113–182, San Diego, CA, USA: Academic Press, 1989.
- [58] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion*. Springer, 3rd ed., 2015.
- [59] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*. Wiley, 2nd ed., 2005.

- [60] R. L. Ferrari, “Plasma Diagnostic Techniques. Edited by R. H. Huddleston and S. L. Leonard. Academic Press, 1965, pp. 627,” *Journal of Plasma Physics*, vol. 1, 2 1967.
- [61] B. E. Cherrington, “The use of electrostatic probes for plasma diagnostics—A review,” *Plasma Chemistry and Plasma Processing*, vol. 2, pp. 113–140, Jun 1982.
- [62] E. V. Shun’ko, *Langmuir Probe in Theory and Practice*. Universal Publishers. Boca Raton, Florida, USA, 2009.
- [63] R. Clements and P. Smy, “Langmuir-probe measurement of electron temperature in a flowing high-density plasma,” *Electronics Letters*, vol. 6, pp. 538–539, 02 1970.
- [64] R. M. Clements and P. R. Smy, “Ion current to a spherical probe in a flowing high-pressure plasma under thin-sheath conditions,” *Proceedings of the Institution of Electrical Engineers*, vol. 117, pp. 1721–1724, August 1970.
- [65] R. M. Clements and P. R. Smy, “Langmuir probe measurement of electron temperature in high-pressure plasmas,” *Journal of Applied Physics*, vol. 44, pp. 3550–3556, 09 1973.
- [66] B.-W. Koo, N. Hershkowitz, and M. Sarfaty, “Langmuir probe in low temperature, magnetized plasmas: Theory and experimental verification,” *Journal of Applied Physics*, vol. 86, pp. 1213–1220, 08 1999.
- [67] I. Langmuir, “POSITIVE ION CURRENTS FROM THE POSITIVE COLUMN OF MERCURY ARCS,” *Science*, vol. 58, pp. 290–291, 10 1923.
- [68] F. Magnus and J. T. Gudmundsson, “Digital smoothing of the Langmuir probe I–V characteristic,” *Review of Scientific Instruments*, vol. 79, no. 7, p. 073503, 2008.

- [69] H. M. Mott-Smith and I. Langmuir, “The Theory of Collectors in Gaseous Discharges,” *Physical Review (Series I)*, vol. 28, pp. 727–763, Oct 1926.
- [70] M. J. M. Parrot, “Theory of cylindrical and spherical Langmuir probes in the limit of vanishing Debye number,” *Physics of Fluids*, vol. 25, 1982.
- [71] T. K. Popov, M. Dimitrova, P. Ivanova, J. Kovačič, T. Gyergyek, R. Dejarnac, J. Stöckel, M. A. Pedrosa, D. López-Bruna, and C. Hidalgo, “Advances in Langmuir probe diagnostics of the plasma potential and electron-energy distribution function in magnetized plasma,” *Plasma Sources Science and Technology*, vol. 25, p. 033001, mar 2016.
- [72] G. Sánchez-Arriaga and J. R. Sanmartín, “Relativistic current collection by a cylindrical Langmuir probe,” *Physics of Plasmas*, vol. 19, p. 063506, June 2012.
- [73] E. V. Shun’ko, “V–A characteristic of a cylindrical probe in a plasma with electron flow,” *Physics Letters A*, vol. 147, no. 1, pp. 37 – 42, 1990.
- [74] O. Troll, L. Conde, E. Criado, J. M. Donoso, and G. Herdrich, “Measurements of Plasma Properties Using Fast Sweep Langmuir Probes in Unmagnetized Weakly Ionized Plasmas,” *Contributions to Plasma Physics*, vol. 50, no. 9, pp. 819–823, 2010.
- [75] F. Chen, *Introduction to Plasma Physics and Controlled Fusion: Volume 1: Plasma Physics*, vol. 1 of *Introduction to plasma physics and controlled fusion*. Plenum Press, 2nd ed., 1984.
- [76] M. A. Ochando and L. Conde, “Langmuir probes for low temperature plasma diagnostics: Laboratory instructions (lab. project).” <http://plasmalab.aero.upm.es/~lcl/PlasmaProbes/LabProjectLangmuirProbesSlides.pdf>, 2010. Accessed: 17-09-2014.

- [77] M. A. Ochando and L. Conde, “Langmuir probes for low temperature plasma diagnostics: An analysis of laboratory results.” <http://plasma.lab.aero.upm.es/~lcl/PlasmaProbes/ResultsLangmuirProbes.pdf>, 2010. Accessed: 17-09-2014.
- [78] L. Conde, “An introduction to langmuir probe diagnostics of plasmas.” <http://plasmalab.aero.upm.es/~lcl/PlasmaProbes/Probes-2010-2.pdf>, 2010. Accessed: 17-09-2014.
- [79] J. P. Sheehan and N. Hershkowitz, “Emissive probes,” *Plasma Sources Science and Technology*, vol. 20, p. 063001, nov 2011.
- [80] S. Iizuka, P. Michelsen, J. J. Rasmussen, R. Schrittwieser, R. Hatakeyama, K. Saeki, and N. Sato, “A method for measuring fast time evolutions of the plasma potential by means of a simple emissive probe,” *Journal of Physics E: Scientific Instruments*, vol. 14, pp. 1291–1295, nov 1981.
- [81] P. Balan, R. Schrittwieser, C. Ioniță, J. A. Cabral, H. F. C. Figueiredo, H. Fernandes, C. Varandas, J. Adámek, M. Hron, J. Stöckel, E. Martines, M. Tichý, and G. Van Oost, “Emissive probe measurements of plasma potential fluctuations in the edge plasma regions of tokamaks,” *Review of Scientific Instruments*, vol. 74, no. 3, pp. 1583–1587, 2003.
- [82] T. Gyergyek, J. Kovačič, and M. Čerček, “A Fluid Model of the Sheath Formation in Front of an Electron Emitting Electrode with Space Charge Limited Emission Immersed in a Plasma that Contains a One-Dimensional Mono-Energetic Electron Beam,” *Contributions to Plasma Physics*, vol. 50, no. 2, pp. 121–134, 2010.
- [83] J. P. Sheehan, Y. Raitses, N. Hershkowitz, I. Kaganovich, and N. J. Fisch, “A comparison of emissive probe techniques for electric potential measurements in a complex plasma,” *Physics of Plasmas*, vol. 18, no. 7, p. 073501, 2011.

- [84] I. Langmuir, “The pressure effect and other phenomena in gaseous discharges,” *Journal of the Franklin Institute*, vol. 196, no. 6, pp. 751–762, 1923.
- [85] I. D. Sudit and R. C. Woods, “A workstation based Langmuir probe system for low-pressure dc plasmas,” *Review of Scientific Instruments*, vol. 64, no. 9, pp. 2440–2448, 1993.
- [86] A. Savitzky and M. J. E. Golay, “Smoothing and Differentiation of Data by Simplified Least Squares Procedures,” *Analytical Chemistry*, vol. 36, no. 8, pp. 1627–1639, 1964.
- [87] S. Tierno, E. Roibàs, J. Domènech-Garret, J. Donoso, and L. Condo, “Measurements of Plasma Properties Using the Floating Potential of Emissive Langmuir Probes,” *Contributions to Plasma Physics*, vol. 53, no. 1, pp. 16–21, 2013.
- [88] N. Hershkowitz, *How Langmuir Probes Work*. 12 1989.
- [89] Y. P. Raizer, *Gas Discharge Physics*. Berlin, Germany: Springer Verlag, 1991.
- [90] N. Stone, U. Samir, and W. Oran, “Laboratory simulation of the structure of disturbed zones around bodies in space,” *Journal of Atmospheric and Terrestrial Physics*, vol. 36, no. 2, pp. 253 – 260, 1974.
- [91] N. H. Stone, “The aerodynamics of bodies in a rarefied ionized gas with applications to spacecraft environmental dynamics,” No. NASA-TP-1933, M-361, p. 319, November 1981.
- [92] K. Endo, A. Kumamoto, and Y. Katoh, “Observation of wake-induced plasma waves around an ionospheric sounding rocket,” *Journal of Geophysical Research: Space Physics*, vol. 120, no. 6, pp. 5160–5175, 2015.

- [93] R. Schrittwieser, C. Ionita, P. C Balan, C. Varandas, C. Silva, J. Stockel, M. Tichy, E. Martines, G. Van Oost, T. Klinger, R. Madani, and R. Galvao, “Emissive Probes, Principles and Recent Developments,” *Proceedings of the 2nd German-Polish Conference on Diagnostics of Plasmas*, nov 2014.
- [94] H. Fujita and S. Yagura, “Measurements of Fast Time Evolutions of Plasma Potential Using Emissive Probe,” *Japanese Journal of Applied Physics*, vol. 22, pp. 148–151, jan 1983.
- [95] N. Mahdizadeh, F. Greiner, M. Ramisch, U. Stroth, W. Guttenfelder, C. Lechte, and K. Rahbarnia, “Comparison of Langmuir and emissive probes as diagnostics for turbulence studies in the low-temperature plasma of the torsatron TJ-K,” *Plasma Physics and Controlled Fusion*, vol. 47, pp. 569–579, Mar 2005.
- [96] H. Fujita, S. Yagura, and E. Yamada, “An Influence of a Heating Voltage on an Emissive Probe Characteristic in a Plasma,” *Journal of the Physical Society of Japan*, vol. 50, pp. 3759–3761, 11 1981.
- [97] I. Langmuir, “The Interaction of Electron and Positive Ion Space Charges in Cathode Sheaths,” *Phys. Rev.*, vol. 33, pp. 954–989, Jun 1929.
- [98] R. F. Kemp and J. M. Sellen, “Plasma Potential Measurements by Electron Emissive Probes,” *Review of Scientific Instruments*, vol. 37, no. 4, pp. 455–461, 1966.
- [99] M. A. Makowski and G. A. Emmert, “New method to measure plasma potential with emissive probes,” *Review of Scientific Instruments*, vol. 54, no. 7, pp. 830–836, 1983.
- [100] M. Y. Ye and S. Takamura, “Effect of space-charge limited emission on measurements of plasma potential using emissive probes,” *Physics of Plasmas*, vol. 7, no. 8, pp. 3457–3463, 2000.

- [101] S. P. Tierno, J. M. Donoso, J. L. Domenech-Garret, and L. Conde, “Existence of a virtual cathode close to a strongly electron emissive wall in low density plasmas,” *Physics of Plasmas*, vol. 23, no. 1, p. 013503, 2016.
- [102] S. Takamura, N. Ohno, M. Y. Ye, and T. Kuwabara, “Space-Charge Limited Current from Plasma-Facing Material Surface,” *Contributions to Plasma Physics*, vol. 44, no. 1-3, pp. 126–137, 2004.
- [103] Y. Raitses, D. Staack, A. Smirnov, and N. J. Fisch, “Space charge saturated sheath regime and electron temperature saturation in Hall thrusters,” *Physics of Plasmas*, vol. 12, no. 7, p. 073507, 2005.
- [104] P. Coakley, N. Hershkowitz, R. Hubbard, and G. Joyce, “Experimental Observations of Strong Double Layers,” *Phys. Rev. Lett.*, vol. 40, pp. 230–233, Jan 1978.
- [105] A. Matsubara, T. Sugimoto, T. Shibuya, K. Kawamura, S. Sudo, and K. Sato, “Emissive probe measurement of electron temperature in recombining plasma produced in the linear divertor simulator TPD-II,” *Journal of Nuclear Materials*, vol. 313-316, pp. 720–724, 2003. Plasma-Surface Interactions in Controlled Fusion Devices 15.
- [106] K. Kusaba and H. Shindo, “A new emissive-probe method for electron temperature measurement in radio-frequency plasmas,” *Review of Scientific Instruments*, vol. 78, no. 12, p. 123503, 2007.
- [107] E. Y. Wang, N. Hershkowitz, T. Intrator, and C. Forest, “Techniques for using emitting probes for potential measurement in rf plasmas,” *Review of Scientific Instruments*, vol. 57, no. 10, pp. 2425–2431, 1986.
- [108] D. Diebold, N. Hershkowitz, A. D. Bailey, M. H. Cho, and T. Intrator, “Emissive probe current bias method of measuring dc vacuum potential,” *Review of Scientific Instruments*, vol. 59, no. 2, pp. 270–275, 1988.

- [109] N. Hershkowitz, B. Nelson, J. Pew, and D. Gates, "Self-emissive probes," *Review of Scientific Instruments*, vol. 54, no. 1, pp. 29–34, 1983.
- [110] W. E. Yao, T. Intrator, and N. Hershkowitz, "Direct indication technique of plasma potential with differential emissive probe," *Review of Scientific Instruments*, vol. 56, no. 4, pp. 519–524, 1985.
- [111] E. Y. Wang, D. Diebold, P. Nonn, J. Pew, W. Q. Li, P. Probert, R. Breun, R. Majeski, S. L. Yan, and N. Hershkowitz, "An improved capacitive divider probe for plasma potential measurements in the Phaedrus tokamak," *Review of Scientific Instruments*, vol. 62, no. 6, pp. 1494–1497, 1991.
- [112] Y. Hagino, N. Ohno, S. Takamura, and M. Ye, "Experimental evaluation of space charge limited emission current from tungsten surface in high density helium plasma," *Journal of Nuclear Materials*, vol. 313–316, pp. 675 – 678, 2003. Plasma-Surface Interactions in Controlled Fusion Devices 15.
- [113] A. Marek, I. Picková, P. Kudrna, M. Tichý, R. P. Apetrei, S. B. Olenici, R. Gstrein, R. Schrittwieser, and C. Ionița, "Experimental investigation of the change of the electron saturation current of a dc-heated emissive probe," *Czechoslovak Journal of Physics*, vol. 56, pp. B932–B937, 2006.
- [114] J. R. Smith, N. Hershkowitz, and P. Coakley, "Inflection-point method of interpreting emissive probe characteristics," *Review of Scientific Instruments*, vol. 50, no. 2, pp. 210–218, 1979.
- [115] J. M. Haas and A. D. Gallimore, "Internal plasma potential profiles in a laboratory-model Hall thruster," *Physics of Plasmas*, vol. 8, no. 2, pp. 652–660, 2001.
- [116] J. W. Bradley, S. Thompson, and Y. A. Gonzalvo, "Measurement of the plasma potential in a magnetron discharge and the prediction of the

- electron drift speeds,” *Plasma Sources Science and Technology*, vol. 10, pp. 490–501, jul 2001.
- [117] N. Hershkowitz and M. H. Cho, “Measurement of plasma potential using collecting and emitting probes,” *Journal of Vacuum Science & Technology A*, vol. 6, no. 3, pp. 2054–2059, 1988.
- [118] M. H. Cho, C. Chan, N. Hershkowitz, and T. Intrator, “Measurement of vacuum space potential by an emissive probe,” *Review of Scientific Instruments*, vol. 55, no. 4, pp. 631–632, 1984.
- [119] E. Speth, “Neutral beam heating of fusion plasmas,” *Reports on Progress in Physics*, vol. 52, pp. 57–121, Jan 1989.
- [120] M. Liniers, J. Damba, J. Guasp, J. A. Sebastià, F. Martí, B. Rojo, R. Carrasco, E. Sànchez, F. Miguel, G. Wolfers, A. Soleto, and E. Ascasibar, “Beam transmission dependence on beam parameters for TJ-II Neutral Beam Injectors,” *Fusion Engineering and Design*, vol. 123, pp. 259–262, 2017. Proceedings of the 29th Symposium on Fusion Technology (SOFT-29) Prague, Czech Republic, September 5–9, 2016.
- [121] J. Damba, P. Argente, P. E. Maldonado, A. Cervone, J. L. Domenech-Garret, and L. Conde, “Multiprobe characterization of plasma flows for space propulsion,” *Journal of Physics: Conference Series*, vol. 958, p. 012002, Feb 2018.
- [122] T. S. Green, “Space charge effects in plasma particle analyzers,” *Plasma Physics*, vol. 12, no. 11, p. 877, 1970.
- [123] T. S. Green, “Intense ion beams,” *Reports on Progress in Physics*, vol. 37, pp. 1257–1344, October 1974.
- [124] T. S. Green, “Beam optics for ion extraction with a high-voltage-ratio acceleration-deceleration systems,” *Journal of Physics D: Applied Physics*, vol. 9, pp. 1165–1171, May 1976.

- [125] “Diffusion pump working principle.” [https://static.mimaterials.com/apiezon/small_images/diffusion-pump\[1\].jpg](https://static.mimaterials.com/apiezon/small_images/diffusion-pump[1].jpg). Accessed: 04-11-2018.
- [126] Agilent Technologies, *High Throughput Diffusion Pumps Instruction Manual*, Jan 2005.
- [127] Agilent Technologies, “Maintenance and Troubleshooting of Oil Diffusion Pumps,” December 2013.
- [128] M. H. Hablanian, “Diffusion Pump Technology,” *Japanese Journal of Applied Physics*, vol. 13, pp. 25–31, jan 1974.
- [129] M. H. Hablanian and A. V. S. E. Committee, *Diffusion Pumps: Performance and Operation*, vol. 5 of *AVS monograph series*. Education Committee, American Vacuum Society, 1994.
- [130] M. H. Hablanian, *High-vacuum technology: a practical guide*. Marcel Dekker, 2nd ed., 1997.
- [131] Varian Technologies, *VARIAN VHS-10,400 Diffusion Pumps*. Vacuum Technologies, 2004.
- [132] Varian Technologies, *VARIAN HS-16,20,32 and NHS-35 High-Throughput Diffusion Pumps*. Vacuum Technologies, 2005.
- [133] Varian Technologies, *VARIAN VHS-4,6,250 Diffusion Pumps*. Vacuum Technologies, 2005.
- [134] J. F. O’Hanlon, *A User’s Guide to Vacuum Technology*. Wiley-Interscience, 3rd ed., 2003.
- [135] A. Ellett and R. M. Zabel, “The Pirani Gauge for the Measurement of Small Changes of Pressure,” *Phys. Rev.*, vol. 37, pp. 1102–1111, May 1931.

- [136] Pfeiffer Vacuum, *IKR 360, IKR 361 Compact Cold Cathode Gauges and PKR 360, PKR 361 Compact FullRange[®] Gauges Instruction Manual*, Jan 2016.
- [137] Pfeiffer Vacuum, *Compact FullRange[®] Gauge FPM sealed PKR 251 Instruction Manual*, Aug 2005.
- [138] L. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*. Wiley, 1st ed., 1994.
- [139] A. V. Phelps, “Excitation and ionization coefficients,” in *Gaseous Dielectrics V* (L. G. Christophorou and D. W. Bouldin, eds.), pp. 1–9, Knoxville, Tennessee: Pergamon, 1987.
- [140] A. V. Phelps, “Cross Sections and Swarm Coefficients for Nitrogen Ions and Neutrals in N_2 and Argon Ions and Neutrals in Ar for Energies from 0.1 eV to 10 keV,” *Journal of Physical and Chemical Reference Data*, vol. 20, no. 3, pp. 557–573, 1991.
- [141] H. Fujita, S. Nowak, B. Hoegger, and H. Schneider, “Potential measurements by an emissive probe in a magnetized plasma,” *Physics Letters A*, vol. 78, 1980.
- [142] M. I. Desai, M. A. Dayeh, and R. W. Ebert, “Origin and acceleration of suprathermal particles,” *AIP Conference Proceedings*, vol. 1720, no. 1, p. 060002, 2016.
- [143] E. R. Harrison, “Runaway and suprathermal particles,” *Journal of Nuclear Energy. Part C, Plasma Physics, Accelerators, Thermonuclear Research*, vol. 1, pp. 105–115, jan 1960.
- [144] W. C. Knudsen, “Finite grid radius and thickness effects on retarding potential analyzer measured suprathermal electron density and temperature,” *Journal of Geophysical Research*, vol. 97, 1992.

- [145] Lazar, M., Poedts, S., and Fichtner, H., “Destabilizing effects of the suprathermal populations in the solar wind,” *Astronomy & Astrophysics (A&A)*, vol. 582, p. A124, August 2015.
- [146] E. N. Parker and D. A. Tidman, “Suprathermal particles,” *Phys. Rev.*, vol. 111, pp. 1206–1211, Sep 1958.
- [147] P. Hu, H. Liu, Y. Gao, and D. Yu, “Study on the structure and transition of the hollow plume in a multi-cusped field thruster,” *Physics of Plasmas*, vol. 23, no. 10, p. 103517, 2016.
- [148] N. Gulbrandsen, Å. Fredriksen, J. Carr, and E. Scime, “A comparison of ion beam measurements by retarding field energy analyzer and laser induced fluorescence in helicon plasma devices,” *Physics of Plasmas*, vol. 22, no. 3, p. 033505, 2015.
- [149] M. Wiebold, Y.-T. Sung, and J. E. Scharer, “Experimental observation of ion beams in the Madison Helicon experiment,” *Physics of Plasmas*, vol. 18, no. 6, p. 063501, 2011.
- [150] L. T. Williams and M. L. R. Walker, “Plume Structure and Ion Acceleration of a Helicon Plasma Source,” *IEEE Transactions on Plasma Science*, vol. 43, pp. 1694–1705, May 2015.
- [151] L. Conde, M. D. Lahoz, J. Grabulosa, R. Hernández, J. González, M. Delgado, and J. Damba, “Thrust stand based on a single point load cell for impulse measurements from plasma thrusters,” *Review of Scientific Instruments*, vol. 91, no. 2, p. 023308, 2020.