THE ESA "PLASMA LABORATORY IN SPACE" STUDY

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RESUME (Résumé français) **:** L'agence spatiale européenne a initié dans le cadre de son programme des Etudes Générales une étude sur la possibilité d'utiliser l'espace pour des expériences de physique des plasmas du type fondamental ou appliqué. Un groupe d'experts a été constitué pour passer en revue un spectre très large de la physique des plasmas traitant aussi bien des applications industrielles que de la physique fondamentale et des plasma astrophysiques ou du système solaire. Il en ressort l'identification d'expériences possibles qui permettraient l'accès à l'observation de nouveaux phénomènes et donc de faire progresser les connaissances dans de nombreux domaine de la physique des plasmas. Les expériences sélectionnées traitent en particulier de phénomènes sur des échelles spatiales (entre 10^2 et 10^4 m) intermédiaires entre celles accessibles au sol et celles classiquement observées pour les phénomènes naturels spatiaux ou astrophysique.

ABSTRACT *(English abstract)* ***:*** The European Space Agency has initiated, in the context of its General Studies Programme, a study of the possible use of space for studies in pure and applied plasma physics, in areas not traditionally covered by "space plasma physics". A team of experts has been set-up to review a broad range of area including industrial plasma physics and pure plasma physics, astrophysical and solar-terrestrial areas. A set of experiments have been identified that can potentially provide access to new phenomena and to allow advances in several fields of plasma science. These experiments concern phenomena on spatial scale (10^2 to10^4 m) intermediate between what is achievable on ground experiment and usual solar system plasma observations.

1 - INTRODUCTION

The aim of this study was to imagine new experiments to be performed in space environment involving artificial or natural plasmas in open space and based on a dedicated satellite platform. To this end a team of experts, named PlasTET for Plasma and Technology Expert Team, has been set-up to review the possible experiments that could be undertaken and the plasma phenomena they may address. A peculiar characteristic of the Plastet team with respect to analogous think tanks was the fair proportion, about 1:1, between specialists in physical plasmas (fusion, MHD, ionosphere) and chemical plasmas (molecular processes, discharges, material processing). First, a review of the key issues in plasma physics has been performed and related experimental concepts have ranked according to criteria such as relevance to space and novelty. Second, more elaborated experimental scenarii have been developped in an attempt to address as much as possible the highest ranked key issues. As a result the kind of experiments considered were at the boundary between two communities and the final experiment proposed integrated aspects of plasma dynamics, namely magnetized plasmas, in two very different regime as well as discharge physics including atomic and molecular issues. In the final stage of the project, a compromise solution has been found to actually integrate all these in a single payload, based on a strongly elliptical orbit (namely GTO) which allows the satellite to explore and to use highly different space environments in the course of a single orbit. This paper presents a summary of the work performed by the PlasTET which has been published as a final report [1]. It focuses on the review of experiment requirements, presented in section 2, and the concept study for the selected experiments (section 3).

2 - INVESTIGATION OF KEY ISSUES

The first part of this study consisted of the identification of key issues in plasma sciences and technologies that could benefit from experiments in space and the selection of experimental concepts addressing these issues. A broad review has been undertaken involving a large number of plasma experts in Europe. All the material collected has been ranked by the PlasTET according to the following priority criteria:

- Scientific and technological relevance: relevance of the proposed idea to scientific and/or technological advance;
- Relevance to space: advantages offered by the space environment with respect to experiments performed on the ground;
- Novelty: innovative aspects of the proposal;
- Objectives clarity: maturity of the proposal (in terms of scientific and technological requirements);
- Applications: range of interest and application potential;
- Feasibility: foreseen feasibility of the experiment.

The key issues and their ranking according to the criteria are summarized in the table below. Based on the this analysis, it was decided to recommend two plasma laboratory mission scenarii. One is based on the production of large scale plasma structures with or without artificial magnetic field and it combines several of the highest ranked experimental concepts dealing with fundamental aspects of plasma physics. It has been analysed further by the PlasTET and is described in the rest of this paper. The other mission type is application orientated. It is based on a tether concept to perform remote sensing of the upper atmosphere composition. It has been investigated in details by Sanmartin et al. [2] and is only briefly discussed below.

Table 1: Key issues identified by the PlasTET and their ranking.

Domain	Idea	sci and tech relevance	relevance to space	novelty	objectives clarity	applica tions	feasibili ty
Magnetic confinement fusion	set up plasma gradients; investigate transport (magnetic bubble idea)	80	70	80	70	75	60
	wave absorption processes; resonant interactions; RF heater (cycling); inan artificial bubble	70	50	60	70	75	60
	wall-plasma interactions (issues for fusion: divertor wall; energy isotropisation;hydrocarbon formation)	75	30	50	70	75	50
Fundamental Plasma.physics	Instabilities (two-stream with beams (bubble), saturation)	80	70	60	70	75	70
Inertial fusion	(energy required too big)						
Astrophysical plasmas	reconnection could be made to occur in the bubble	80	80	70	70	75	55
	wave processes accelerate particles - use wave absorption experiment to accelerate particles	80	70	60	70	75	60
	shocks (explosive devices); physics of intermediate shocks poorly understood	80	75	80	70	75	70
	bow shocks in magnetic bubble and interplanetary shocks	80	80	70	70	75	65
Surface processes	curing of polymers directly in the space environment	80	80	50	70	65	75
	in-space localised thin-film deposition (technological)	70	80	70	70	65	80
Plasma processing	diamond layer deposition (optics, high-power windows, and electronics);	70	65	60	65	75	80
	fullerenes and nanoparticles production in discharges; influences on growth characteristics; low Mach number plasma concerns; cluster formation	80	80	80	70	75	75
Plasma discharges	very large discharge (fundamental); scaling laws	65	80	70	70	60	65
	arc discharge in microgravity - very different; on-set of instabilities in discharges	70	80	60	70	70	70
Plasma	radar & RF diagnostics in	60	70	60	65	65	70

diagnostics	space;						
Coherent radiation sources	artificial generation of radiation from an e-beam;	70	80	60	70	70	75
Beams and accelerators	see other ideas; + remote sensing of EP plumes using beam diagnostics	60	80	60	65	65	65
Dusty and complex plasma	crystals; planetary rings, solar system formation; dust contamination in plasma processing	70	80	65	65	70	65
Waves, instabilities and turbulence	covered in other ideas						
Hypersonics and propulsion (incl. MHD interactions)	plasma wind tunnel tests difficult (Mach 25 in re-entry) - flow very different (Chemistry, etc.) - in-situ experiments needed to validate modelling (EXPERT mission). 2 counter-orbiting satellites (gas + ball);	75	75	70	70	75	60
Laser-plasma interactions	laser processing (as plasma processing); LIBS laser induced breakdown spectroscopy; laser ablation for micro-N thrusters (ground based experiments seem adequate for fusion-related issues); fsec laser and dynamics of plasma response	75	65	70	70	75	70
active experiments	tethers - look at EM emissions too	70	80	50	70	70	75
	magnetised plasma bubbles; theory of co-rotation (Ferraro); B direction .ne. rot. axis; Levitated dipole ground experiment (LDX) - a space counterpart? - many plasma phyics processes can be studied (Ref.: Hastings); related to Fusion ideas; (neutrals!)	85	80	80	70	75	60
Atomic physics	Rydberg (recombinant plasma); low neutral density; expanding plasma cooling allows direct visibility of near-continuum levels; also interesting for hypersonics; Zeeman splitting	75	70	80	70	75	60

3 - PLASMA LABORATORY IN SPACE CONCEPT STUDY

3.1 - SCIENTIFIC OBJECTIVES

Space plasmas provide a natural environment for large-scale, controlled experiments in collisionless plasma regimes. Active experiments aiming at investigating basic nonlinear phenomena such as magnetic field-line reconnection, magnetic field generation, magnetic vortex dynamics and particle acceleration can be performed under essentially boundary-free conditions that cannot be realized in the laboratory. A set of experiments which can be a priori integrated on the same platform and dealing with plasma physics and non equilibrium kinetics of large scale artificial plasma structures (10^1-10^4 m spatial scale) are described in the following. Furthermore, a stand alone application orientated experiment dealing with the generation of large scale electron beam by tethered spacecraft to produce artificial auroras is briefly described.

3.1.1 - *Nonlinear dynamics of magnetic bubble-plasma interaction in the whistler regime*

The nonlinear dynamics of a bubble of magnetized plasma (magnetic bubble) formed around the satellite and interacting with a streaming (relative to the bubble) ambient plasma is proposed to be investigated. Two different configurations and plasma bubble regimes are envisaged, depending on the density of the local ionized medium i.e. on the orbit height and on the plasma sources. The smaller scale magnetic bubble experiments are based on the confinement of artificially generated or ambient (e.g., ionospheric) plasma by a dipole field generated at the satellite. Primary objectives of the experiment are to study the physics of whistler waves and collisionless reconnection in the absence of solid boundaries. Specific experiments include the plasma dynamics in the so called electron-magnetohydrodynamic regime that corresponds to the frequency range of whistler waves. These investigations are of special interest, e.g., for the study of the current layer evolution in Hall dominated magnetic reconnection events, which is presently of great interest for space and laboratory plasmas. The relative streaming between the plasma bubble and the ambient plasma will lead e.g., to Cherenkov emission of high frequency waves and Kelvin Helmholtz induced plasma turbulence that can be detected and used to investigate the nonlinear plasma dynamics and how it is affected by the relative strength and orientation of the satellite and of the ambient magnetic fields.

It would be desirable to increase the size of the artificial perturbation, the “magnetic bubble” to lengths larger than the electron inertia skin depth in order to access electromagnetic collective effects, in particular turbulence dynamics.

3.1.2 - *Dynamics and stability of the inflation*

A larger scale magnetic bubble experiments can be based on the use of a high density plasma source on the platform, and on the ‘’freezing’’ of the magnetic field in the expanding plasma in order to investigate the possibility of inflating the magnetic bubble to larger spatial scales.

Specific experiments include the investigation of the inflated bubble expansion and stability, and the assessment of the current systems that establish when the bubble interacts with the outside plasma.

3.1.3 - *Artificial magnetosphere studies from the whistler to the MHD regime*

Depending on the magnetic bubble size that may be reached through plasma expansion, interaction between a drifting plasma and a magnetized object outside the whistler regime and possibly up to the Magnetohydrodynamic regime could be investigated. This latter regime is of direct interest to the study of the interaction between stellar winds and planetary magnetospheres (including the investigation of the reconnection processes at the magnetosphere boundaries and of Magneto-hydrodynamic turbulence).

3.1.4 - *Weakly ionized plasma phenomena: ionization, plasma heating and chemistry*

Plasma expansion in open space is an ideal environment for expanding our experiment range concerning the kinetics of weakly ionized gases. These media are of interest for the correlation between plasma physics and plasma chemistry. The dominant process here is collisional interaction between charged particles and neutrals. In these experiments ion conversion, ion reaction and dynamics can be investigated. Additional heating from a high power antenna produces an ionization scenario that can be compared to collisional models of plasma discharges, thus greatly extending the present validation range. Specific issues are: ion population ratio EEDF (electron energy distribution function), electron density and temperature, radiation losses and recombination processes, in particular recombination lines might be detectable. The deposition of sufficient energy in the expanded plasma bubble depends critically on the physics of collisional plasma wave damping in the bubble: in other terms the bubble should envelop the wave penetration sphere. Should this condition be fulfilled, the plasma energy deposition can be evaluated from estimation of the charged-to-particle collisional power loss. This is a test case of collisional, weakly ionized plasma physics which can produce useful information for vacuum science, discharge physics, aerospace technology. In particular a better knowledge of these systems is of great interest for future plasma processing in space and also for the modelling of ion thruster plumes and related perturbations on satellite communication links. It would be also possible to investigate the dynamics of negative ion production (H-) which are of interest, e.g., in propulsion system where they play a key role in the production of high energy neutral atom beams. Production of laser or maser emission from extended artificial weakly ionized molecular gases on such an unprecedented scale is also an issue open to future investigation.

3.1.5 - *Tether based electron beam for remote sensing of the atmosphere*

An electrically floating tether comes out biased highly negative over most of its length. Ambient ions impacting it with keV energies liberate secondary electrons, which are locally accelerated by the tether voltage-bias, race down magnetic lines, and result in peak auroral emissions at about 120-160 km altitude. Since no current flows at either tether end, a bare-tether e-beam is fully free of spacecraft charging problems. Also, the beam is free of plasma interaction effects: its very large cross section (about twice electron gyroradius times tether length) results in energy flux over 1000 times weaker than in standard beam sources. In addition, emission of such a weak flux has no significant effect on the local plasma, and takes place far from any instrument Beyond auroral effects proper, a floating bare-tether could provide values of neutral density along its E-layer footprint track, of interest in full numerical simulations of the atmosphere lying below, and in orbit decay and re-entry predictions [2], [3].

3.2 - MISSION REQUIREMENTS

3.2.1 - *Active Magnetic Experiment*

This experiments deals with the interaction of a magnetic bubble with the ambient streaming plasma. Two modes are possible depending on whether a plasma source is in operation or not.

Without plasma source, the experiment must be operated on Low Earth orbit such that the magnetic bubble be larger than the plasma Debye length. The magnetic dipole moment, M, (and therefore the current) needed to achieve a given ratio of bubble size to electron Larmor radius increases as the square of the inverse of the ambient magnetic field, B_{ext}. Therefore no benefit is gained by going to higher altitudes.

The artificial magnetic field must balance the ambient field at the bubble boundary. Assuming a dipole-like field which scales as r^{-3} with the distance, the magnetic field required to obtain a magnetic obstacle with linear dimensions L~10m is B=100-200 g while the ambient LEO conditions is typically B=0.3-0.5 g.

When a plasma source is used the plasma pressure is increased and possibly the size of the bubble. This will allow to investigate stability of inflation and phenomena on the electron inertia skin depth lengthscale. Preliminary calculations indicate that the mass requirements for such density control are not a limitation. The alternative to the use of a plasma source, i.e. the use of natural photoionization of released neutral gas in order to achieve the desired plasma density must be reconsidered by a more careful modeling of the neutral gas fluid dynamics. In particular, calculations based on the diffusion approximation largely overestimate the residence times of particles expanding into vacuum. Available calculations [4] refer to the solar wind environment, outside the earth magnetosphere. Possible environments, however, include the low density, low magnetic field environment of high altitude orbits. Due to the very short times needed for the interesting dynamics to develop fully, a elliptic orbit may be acceptable. It would also be highly desirable from the experimental point of view in providing a wide range of experimental parameters.

The relevant scale of the plasma structure generated by the plasma source is of the order of 1 to 10 km and the magnetic field required is still of the order of 100 gauss (say around 600 gauss). The plasma density produced by the plasma source is such that the plasma pressure (or equivalently energy density) generated by the source must be a non-negligible fraction of the magnetic field energy. For a magnetic field of ~600 g and an electron temperaature of ~4eV, and the linear dimension of the inflated bubble L~10km, this gives a plasma density of $\sim 10^{14}$ cm^{-3} [5].

In both modes, electromagnetic emissions of particular interest are Langmuire waves, turbulent isotropic fields and Cherenkov emission. The latter one is expected to be anisotropic and not detectable on the platform. Its monitoring would therefore require an auxilliary spacecraft.

The lowest frequencies (both from Cherenkov and turbulence emission) are estimated to be around 10^4 Hz. All timescales of interest are well below 1 s. The duty cycle is therefore determined by the time required by the magnet system to reach a stationary state and should be of the order of 1 minute. The temporal resolution required is estimated to be of 10 Hz and the spatial resolution between 10^{-3} and 10^{-1} m.

The following measurement requirements are identified.

Magnetic field fluctuations: 10 Hz – 50 KHz

Electric field vector: up to 10 V/m

Electric field fluctuations: 10 Hz – 50 KHz (up to10 MHz for Langmuir waves)

Plasma density fluctuations (ambient at LEO is 10^3 to 10^6 cm^{-3} and artificial plasma is about 10^{14} cm^{-3}).

Electron and ion velocity distribution function must be monitored.

Environmental parameters to control and other requirements include:

- Payload charging
- E.M. environment
- Solar panels interference with the bubble dynamics
- The artificial magnetic field must have a fixed orientation during the experiment. The orientation must be controllable
- Cherenkov radiation cannot be measured from the platform that produces the magnetic field
- Measurements of magnetic field, electric field, plasma density, drift velocities must be correlated
- Bubble *in situ* diagnostics is possible with booms
- Wake *in situ* diagnostics is possible with separate diagnostic payload(s)
- The spacecraft systems must cope with magnetized environment.

3.2.2 - *LDE : Large Discharge Experiment*

This experiment is devoted to the production and the study of large scale (10-100 m) discharge plasmas in open space, including hydrodynamics and atomic physics issues. The peculiarity of these experiments towards already performed active plasma experiments is the role played by ionization processes and the stress on cold plasma physics, where the collisions of charged species with neutrals are most relevant. Because of this last circumstance, atomic physics and hydrodynamics strongly affect the system, while the variety of collective plasma phenomena is drastically reduced. The choice of composition allows to study non ambient gases, molecular physics interest (ion transport, instabilities, recombination), artificial models of extraterrestrial ionospheres. First step towards future large scale discharge-based applications in open space. Negative ion production in open space makes the way for energetic atom beam: application to neutral particle/sail propulsion.

The expected characteristics of the discharge are expected to be as follows:

Plasma density: 10^{5}-10^{7} cm^{-3}

Plasma temperature: 1 eV

Ionization degree: 10^{-6}

Neutral gas density: 10^{11}-10^{13} cm^{-3}

Neutral gas temperature: 300 K

The maximum tolerated ambient plasma density is 10^{4} cm^{-3} therefore this experiment has to be performed outside the ionospheric plasma. The power required for the discharge is about ~3kW.

The following measurement requirements are identified:

3D components of the electric and magnetic field electromagnetic field with search coil magnetometers and double probe electric field antenna.

Electric current and plasma density measurement.

Electron and ion velocity distribution function.

Density profile based on the identification of the cut-off of electrostatic, longitudinal waves at Ωpe and on the plasma-sheath resonance [6] using a frequency synthesizer and broad band amplifier (range 1-500MHz) (power: a few hundred watt).

Visible/ultraviolet sensors: imagers, spectrographic imagers

IR/Visible/UV spectroscopy: telescope, CCD, spectrometer, Lyman-a imager

Radio emission (for recombination and Rydberg states)

The environmental parameters to control include:

- Particle ionization due to solar radiation could interfere but it is relatively slow. The problem is fully solved by running the experiment when the satellite is in the Earth shade
- Gas ionization by cosmic rays is negligible
- The electron skin depth must be of the same order as the discharge dimensions in order for the antenna to couple with the discharge effectively.

3.2.3 - *Tethered experiments (artificial aurora)*

Details of the requirements for this experiment are elsewhere[2]. The most favoured mission scenario is a LEO orbiting spacecraft with a tether length of about 20 km and a Power of 40 kW for a spacecraft of about 1000 kg. A rocket based version of this experiment is planned to be performed on the Japanese S-520-25 rocket to be launched on the summer of 2009.

4 - CONCLUSION

The above described study identified several novel plasma experiments to provide improvements of understanding of plasma physics and chemistry under controlled conditions in a range of parameters not accessible on ground. They deal with plasma expansion either in magnetised or non-magnetised regime, streaming plasma interaction with plasma bubbles, and creation of auroras by a tether generated large electron beam. Besides the fundamental plasma physics and chemistry aspect, at least two of them have potential interest for application (i.e., magnetic sailing with a large magnetic bubble and upper atmosphere diagnosis by the tether experiment). Although the experiments have different requirements, combination on the same platform is feasible. The tether experiment is currently planned to be flown on the Japanese S-520-25 rocket experiment to be launched on the summer of 2009. The three other experiments could be combined on a spacecraft on a GTO orbit with preferably an auxilliary diagnosis spacecraft. Two additional experiments which have been discussed in details during the PlasTET workshops have not been finally incorporated in the final proposed platform for engineering reasons. The first one is a tether experiment to investigate Alfvèn front waves, the second one is a proposal for using the relative velocity of two counter-orbiting satellites together with a gas emission to realize a dynamic shock tunnel in earth orbit to simulate realistic conditions for extraterrestrial atmospheric entry. These concepts might be investigated in future studies.

5 - AKNOWLEDGEMENT

This work was supported by the European Space Agency, under ESTEC contract AO/1-4615/04/NL/LvH.

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