Universidad Politécnica de Madrid
Escuela Técnica Superior de Ingenieros Industriales
Instituto de Fusión Nuclear

Effects of irradiation on plasma facing
materials in HiPER Laser Fusion Power Plant:
Silica Final Lenses and Tungsten First Wall

TESIS DOCTORAL

Ángel Rodríguez Páramo

Ingeniero Industrial por la ETSII-UPM

Dirigida por:

Antonio Rivera de Mena

Profesor-Investigador

Universidad Politécnica de Madrid

Fernando Sordo Balbín

Director del Grupo del Target y

Aplicaciones Neutrónicas ESS-Bilbao

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2017

Tribunal nombrado por el Magnífico y Excelentísimo Sr. Rector de la Universidad Politécnica de Madrid, el día de de 2017.

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Suplente:

Opta a la mención de "Doctor Internacional".

Realizado el acto de defensa y lectura de la Tesis el día de de 2017 en la Escuela Técnica Superior de Ingenieros Industriales.

CALIFICACIÓN:

EL PRESIDENTE

LOS VOCALES

EL SECRETARIO

Agradecimientos.

Primero quiero agradecer a Antonio y a Fernando por la dirección de esta tesis. A ambos por su apoyo, por los buenos consejos que ayudan a avanzar lenta pero consistentemente. Por el guiado, que ayuda a reenfocar el trabajo cuando el análisis degenera en parálisis. A Antonio, por ayudarme a descubrir el camino científico para bucear entre los papers e intentar mil hipótesis, por las mil correcciones y por la paciencia. A Fer, por Gentoo y Linux, por los scripts, las gráficas y los mil códigos, por sus buenos consejos, porque la explicación más sencilla suele ser la más posible.

A Wim y el Grupo de Mecánica de Materiales y Estructuras de la Universidad de Gante, por la acogida y porque los meses allí fueron fundamentales para completar la tesis. A David especialmente por su ayuda, sus consejos, su buena acogida y mostrarme los maravillosos entresijos de CodeAster.

A todos los compañeros del Instituto de Fusión Nuclear. Por las comidas, las discusiones, los resultados, los scripts y las pequeñas conversaciones que hacen que se aclaren las ideas y salga un mejor trabajo.

A todos mis amigos.

Finalmente a mi familia y especialmente a mis padres, a Anselmo y Nieves, por saberme educar y ser siempre el mejor apoyo.

Abstract

Due to the growing energy demand, research and development of new energy sources is a must. A possible energy alternative is the control and exploitation of nuclear fusion, which can turn into a real option for energy production in the mid-term. For the development of nuclear fusion, research on plasma physics and reactor technologies is fundamental. In this context, the European laser fusion project HiPER is devoted to the study of technologically feasible components for a laser fusion power plant. This thesis focuses on the development of the tungsten First Wall and the silica Final Lenses of a laser fusion power plant.

For the development of these components we study the irradiation effects under the expected operational conditions in a fusion reactor. We study different stages for the development of the HiPER nuclear fusion reactor: from an Experimental facility aimed to demonstrate an advanced ignition to a Demonstration reactor aimed to prove feasibility of technologies under very demanding conditions. We study the irradiation spectra of the different species: neutrons, X-rays, slow and fast ions and estimate irradiation parameters such as displacements per atom, gas production, PKA (primary knock-on atom) spectra, colour centres formation or the main thermomechanical effects.

In the case of ion irradiation of silica we carry out a more detailed study. The study includes the analysis of the results of an experimental campaign using Br ions at CMAM accelerator (Madrid). This campaign measured the silica refractive index under irradiation. The result is that it initially increases as a consequence of silica compaction by track formation and accumulation reaching a saturation level once a continuous layer is formed. Further fluence increase leads to a drop in the refractive index. The effect of the irradiation enhanced plastic flow could explain the decrease in the refractive index. We tested this assumption with a model based on Finite Element Methods (FEM) with the aid of data provided by Molecular Dynamics (MD). The study of ion irradiation allows us to conclude that full ion mitigation from the final lenses will be required in a

nuclear fusion reactor.

From the analysis of irradiation we study the behavior of silica Final Optics and tungsten First Wall under operational conditions. For the final optics we consider silica transmission final lenses and address the major issues regarding the unavoidable neutron irradiation they must withstand. We study the necessity to keep the lens operating at high temperature in order to enhance defect annealing, and study how to minimize temperature induced optical aberrations. For this purpose we have devised an active intervention system based on a heat-transfer fluid to keep the temperature profile as smooth as possible. The main characteristics of the temperature control system are defined throughout this work and enable the operation of the plant, both for the start-up procedure and for normal operation.

We study the behaviour of a tungsten First Wall, evaluate its performance under irradiation conditions and give a qualitative discussion of atomistic effects. We study the evolution of first wall temperature and the thermomechanical response of the material. During the irradiation pulse, the surface heats-up leading to a surface expansion. The results indicate that the first wall will plastically deform up to a few microns underneath the surface. Continuous operation in a power plant leads to fatigue failure with crack generation and growth. Finally, crack propagation and the minimum tungsten thickness required to fulfil the first wall protection role are studied. We conclude that a tungsten first wall can be used in experimental facilities, but alternatives should be considered for a full scale reactor.

Finally we stress the necessity of more experimental data in order to validate materials and components. For this purpose we study the possibility of using a medium sized neutron irradiation facility (such as that proposed in ESS-Bilbao) for the study of nuclear fusion materials. We compare irradiation conditions (PKA spectrum, gas formation) and conclude that damage patterns in medium sized neutron facility are similar to those expected in the final lenses of real laser fusion power plants. From the analysis we conclude that while the medium sized neutron irradiation facility may only play a minor role for the analysis of structural materials due to its low neutron fluxes, it is very relevant for studies on silica for final lenses in laser fusion power plants.

Summarizing, in this thesis we give a detailed analysis of irradiation effects on the tungsten First Wall and Silica Final Lenses of an inertial fusion reactor. We study from fundamental effects of irradiation to technological solutions for operation in a full scale reactor.

Resumen

La investigación y el desarrollo de nuevas fuentes de energía es necesaria debido al crecimiento de demanda energética a nivel global. Una de estas fuentes de energía alternativas se basa en control y la explotación de la fusión nuclear, que podría convertirse en una opción real para producción energética a medio plazo. Para el desarrollo de la fusión nuclear es fundamental las investigación en física de plasmas y tecnologías de reactor. En este contexto se desarrolla el proyecto europeo de fusión laser (HiPER), que se centra en el estudio de componentes tecnológicamente viables para el desarrollo de una planta de potencia por fusión laser. Esta tesis se centra en el desarrollo del recubrimiento de la primera pared de wolframio y de las lentes finales de silica en una planta de fusión laser.

Para el desarrollo de estos componentes, estudiamos los efectos de irradiación en las condiciones de operación esperadas en el reactor de fusión. Estudiamos diferentes fases del desarrollo de reactor de fusión nuclear HiPER: desde una instalación Experimental que pretende demostrar esquemas avanzados de ignición, hasta un reactor de Demostración dirigido a probar la viabilidad tecnología bajo condiciones altamente exigentes. Estudiamos el espectro de irradiación para diferentes especies: neutrones, rayos X, iones rápidos y lentos y estimamos los parámetros de irradiación tales como desplazamientos por átomo, producción de gases, espectro PKA (átomos primarios), formación de centros de color o los principales efectos termomecánicos.

En el caso de irradiación iónica en silice realizamos un estudio más detallado. Este estudio incluye el análisis de los resultados de una campaña experimental con iones de bromo en el acelerador CMAM (Madrid). Esta campaña midió el índice de refracción en silice bajo irradiación. El resultado es un incremento inicial como consecuencia de la compactación de silice por la formación y acumulación de trazas, alcanzando un nivel de saturación cuando se forma una capa continua. A mayores fluencias de irradiación se observa un descenso en el índice de refracción. El efecto de la aparición de un

flujo inducido por irradiación podría explicar este descenso en el índice de refracción. Verificamos esta hipótesis con un modelo basado en Elementos Finitos (FEM) con la ayuda de resultados obtenidos mediante Dinámica Molecular (MD). El estudio de la irradiación iónica nos permite concluir que es necesaria una mitigación completa de iones en las lentes finales de un reactor de fusión.

A partir del análisis de irradiación, estudiamos el comportamiento en condiciones de irradiación de las ópticas finales de sílice y de la primera pared de wolframio. Para las ópticas finales, consideramos lentes de transmisión de sílice y abordamos los principales aspectos relacionados con la irradiación neutrónica que debe soportar. Estudiamos la necesidad de mantener las lentes operando a alta temperatura para incrementar la aniquilación de defectos, y estudiamos como minimizar las aberraciones ópticas inducidas por la temperatura. Para ello, hemos desarrollado un sistema de control activo de la temperatura basado en un fluido transmisor de calor que mantiene el perfil de temperatura tan homogéneo como sea posible. Las principales características del sistema de control de temperatura se definen a lo largo del trabajo, y permitirían la operación en planta, tanto durante la puesta en marcha como en operación normal.

Estudiamos también el comportamiento de la primera pared de wolframio, evaluando su respuesta bajo las condiciones de irradiación y analizando cualitativamente los efectos atomísticos. Para ello, estudiamos la evolución de la temperatura en la primera pared y la respuesta termomecánica del material. Durante los pulsos de irradiación, la superficie se calienta dando lugar a una expansión superficial. Los resultados indican que la primera pared se deformará plásticamente en las primeras micras debajo de la superficie. Lo que daría lugar a la generación y propagación de grietas bajo operación continua en una planta de potencia. Finalmente, estudiamos la propagación de grietas y el grosor de la primera pared de wolframio necesario para que se cumpla el papel protector de la primera pared. Del estudio concluimos que una primera pared de wolframio se puede utilizar en instalaciones experimentales, pero que se deben considerar alternativas en el caso de reactores a plena potencia.

Finalmente, acentuamos la necesidad de mayor experimentación para la validación de materiales y componentes. En este sentido, estudiamos la posibilidad de utilizar una fuente de neutrones de tamaño medio (similar a la propuesta para ESS-Bilbao) para el estudio de materiales para fusión nuclear. Comparamos las condiciones de irradiación (espectro de PKAs, formación de gases) y concluimos que la forma de daño en fuentes de tamaño medio de neutrones es similar a la esperada en las lentes finales de una

planta de potencia de fusión laser. De este estudio concluimos que aunque una fuente de tamaño medio de irradiación neutrónica pueda jugar únicamente un pequeño papel para el estudio de materiales estructurales debido a los bajos flujos neutrónicos, estas fuentes podrían ser relevantes en estudios para lentes finales en plantas de potencia de fusión laser.

Resumiendo, en esta tesis realizamos un análisis detallado de los efectos de irradiación en la primera pared de wolframio y en las lentes finales de sílice en un reactor de fusión inercial. Estudiando desde aspectos fundamentales de irradiación hasta soluciones tecnológicas en un reactor.

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Abbreviations

appm	Atomic Parts Per Million
ABS	Arbitrary Beam Selection
BCA	Binary Collision Approximation
CFD	Computacional Fluid Dynamics
CMAM	Centro de Micro-Análisis de Materiales
DDSSL	Diode Pumped Solid State Lasers
DPA	Displacements Per Atom
DT	Deuterium-Tritium
DTL	Drift Tube Linac
ESS	European Spallation Source
ENDF	Evaluated Nuclear Data File
FOA	Final Optical Assembly
FEM	Finite Element Method
fpv	Full Power Year
FW	First Wall
GIMM	Grazing Incident Metallic Mirrors
HAPL	High Average Power Laser
HBS	High Brilliance neutron Source
HFR	High Flux Reactor
HiPER	High Power laser Energy Research facility
ICF	Inertial Confinement Fusion
IFMIF	International Fusion Materials Irradiation Facility
ILL	Institut Laue-Langevin
ITER	International Thermonuclear Experimental Reactor
KERMA	Kinetic Energy Release on Materials
LIFE	Laser Inertial Fusion Energy
LLNL	Lawrence Livermore National Laboratory

Abbreviations

LMJ	Laser Mega-Joule
MCF	Magnetic Confinement Fusion
MCNPX	MonteCarlo N-Particle eXtended
MD	Molecular Dynamics
NIC	National Ignition Campaign
NIF	National Ignition Facility
NIST	National Institute of Standards and Technology
NRT	Norgett-Robinson-Torrens
ODC	Oxygen Deficient Centre
ODS	Oxide Dispersion-Strengthened steel
PKA	Primary Knock-on Atom
RAFM	Reduced Activation Ferritic Martensitic steel
RFQ	Radio Frequency Quadrupole
SRIM	Stopping and Range of Ions in Matter

Chapter 1

Introduction

1.1 Context

The energy solution to the ever-growing energy demand is a long standing problem that requires innovative solutions. In the near future, fusion energy can turn into a real option to fossil fuels, with the advantages of being sustainable and environmentally friendly. Two are the main approaches to fusion energy: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) by laser (laser fusion).

The most advanced projects to demonstrate the viability of laser fusion energy are LIFE (Laser Inertial Fusion Energy) in U.S.A [1–4], HiPER (High Power Laser Energy Research) in Europe [5–7], and MCF Demo in the magnetic confinement fusion community [8–10].

HiPER is the European project for the development of laser fusion. HiPER is devoted to the development of technologies for the construction of a facility for demonstration of the economic and technical feasibility of laser fusion. At the moment, the most probable scenario for a future HiPER power plant relies on the shock ignition scheme with direct drive targets in an evacuated chamber with dry walls.

As the nuclear fusion and in particular ICF develops, it is important to study the feasibility of fusion power plants in the mid-long range. Once ignition is attained and controlled, different technological problems will become the bottleneck for fusion development. These technological problems include laser efficiency and repeatability, target fabrication and injection, tritium breeding and recovery and irradiation damage

on structural components and plasma facing materials. In order to minimise risks, the HiPER project has a conservative strategy based on the identification of technological bottlenecks and the development of proven solutions before undertaking major construction efforts.

As a part of the big puzzle that must be constructed for the development of nuclear fusion, in this thesis we study the effects of irradiation in the “plasma facing materials” for ICF. This comprises the study of the behaviour of the chamber First Wall and the Final Optical components. This thesis offers a continuation to previous works carried out by the “Instituto de Fusión Nuclear” of the “Universidad Politécnica de Madrid” in the framework of the HiPER project, which covered different aspects of the reaction chamber [11–13] and the final optics [14, 15]. The work presented in this thesis has been published in Refs. [16–21].

1.2 The HiPER Project

In this section we give an overview of the HiPER project and different works regarding the development of ICF technologies. In [Chapter 3](#) we give a more detailed description of the irradiation conditions in HiPER and its effects on materials.

The HiPER project [5–7] is the European Project for the development of Inertial Confinement Fusion (ICF). Equivalent to the HiPER project are the American LIFE project (Laser Inertial Fusion Energy) [1–4] for the development of laser fusion technologies, and MCF Demo [8–10] for the development of a magnetic confinement fusion reactor. In [Table 1.1](#) the main design parameters for the HiPER Demo reactor are shown and compared to LIFE and MCF Demo. Next we describe in detail the different

Table 1.1: Summary of main parameters of nuclear fusion reactor concepts: HiPER Demo, LIFE.2 and MCF Demo [8, 19, 22].

	HiPER Demo	LIFE.2	MCF Demo
Confinement	ICF with Direct Drive	ICF with In-direct Drive	MCF
Repetition Rate	10	16	Quasi-continuous
Thermal Power (MW_t)	1500	2200	3600
Chamber Radius (m)	6.5	6	3-10
Neutron Wall Load (MW/m^2)	2	3.6	2
Surface Heat Load (MW/m^2)	0.8	1.26	10

concepts involved in the design of the HiPER reactor.

The HiPER project began in 2008 with the aim of facing scientific and technological problems of ICF. The HiPER project began at the same time as the commissioning phase of the National Ignition Facility [23], shortly before the National Ignition Campaign (NIC) [24]. At the beginning of the HiPER project there were great expectations in attaining ignition during NIC experiments. However the campaign was unsuccessful in its final goal of attaining ignition, even considering that great advances were done for inertial fusion progress with the consecution of the so called “scientific break-even” [24]. The failure to attain ignition during the NIC has delayed all projects aimed to the development of inertial fusion technologies. The LIFE project [1, 2, 22] which was the American equivalent to HiPER was cancelled after NIC. The HiPER project continued its ongoing works but reduced the level of activity, and most European efforts are now aimed to successful experimentation in the Laser Mega Joule (LMJ) in Bordeaux, France. Even with the sour outcome from the NIC campaign, HiPER has developed fruitful works for the development of inertial fusion.

Firstly, inside the HiPER project the ignition scheme was analyzed. For commercial exploitation of inertial fusion advance ignition schemes are required [25, 26]. Basic direct or indirect drive ignition schemes will offer gains around 10, while advance ignition schemes are expected to result in gains higher than 100. The principle behind the advance ignition schemes is uncoupling the compression and heating stages for ignition. Therefore adiabatic compression would be followed by plasma heating. For the HiPER project fast ignition [27, 28] and shock ignition schemes were studied [29–31]. Fast ignition requies an additional petawatt (PW) picosecond laser. The PW laser is needed to produce a hot spot in the compressed plasma just at the end of the compression stage. The laser is used to heat a gold cone producing fast electrons that heat the plasma and ignite the hot spot. On the other side shock ignition relies on creating a spherical shock wave that converges in the centre of the compressed plasma introducint a hot spot that ignites the plasma. For shock ignition no additional laser is required, but it is necessary to synchronize the laser beams of the compression terawatt nano-second laser to procue a shock with a duration of 300-500 picoseconds at the end of the compression stage. HiPER assumes that the most promising strategy is that based on shock ignition schemes.

Therefore, HiPER power plant development is based on a shock ignition scheme with direct drive targets. For direct drive ignition the uniformity illumination of the target

is a fundamental requirement. In this context non-uniformities for different laser beam profiles in HiPER were studied in Refs. [32–35]. These works studied the geometrical distribution of the lasers as well as the beam profile defining its size and super-gaussian distribution. In order to shape super gaussian beam profiles, the inclusion of phase plates [36, 37] in the Final Optical Assembly is necessary. The phase plates define the size of the focal spot from diffraction optics. The inclusion of phase plates combined to the use of different laser beamlets would allow for an Arbitrary Beam Selection (ABS) [38] system that results in dynamic laser focusing during target ignition. This way the beam size could be reduced from the initial target size of 1-2 mm to the hot spot size of less than 100 μm [39].

Other works performed in the frame of the HiPER project include tritium breeding, laser and target technologies. Regarding tritium breeding, different concepts had been proposed for either magnetic or inertial fusion [10, 40–44]. Lithium can be introduced in the chamber blankets in different varieties: lithium metal, lead-lithium, lithium ceramics, with alternative cooling concepts: self-cooled, helium cooled, water cooled, dual cooling. For the HiPER project a Self-Cooled Lead Lithium breeding concept was proposed [45, 46]. For structural materials, in HiPER the approach includes the use of currently available steels. Current RAFM steel are expected to be able to withstand irradiation up to $\sim 10\text{--}20$ dpa [22, 47], which would imply operation for 2-3 years in a full scale reactor before replacement of irradiated modules. Due to the modular design of inertial fusion chambers [4], this initial approach seems an acceptable solution, until new materials with irradiation enhanced capacities are validated.

Regarding laser technologies, its development should allow for high efficient repetitive laser operation. Currently the focus is in the development of Diode Pumped Solid State Lasers (DDSSL) [48–50]. Target fabrication and injection is also affected by the requirement of repetitive operation. Targets require in-vacuum high velocity injection combined to, high precision tracking [51–54] and high precision target fabrication [55]. Finally HiPER also developed works related to radiological aspects [56, 57], power cycle [58] and the integration of systems [59–61].

Although there is not a definite design for the HiPER chamber, some advance concepts have been already reported [5, 45] and different scenarios for HiPER development are foreseen [14]. First, an Experimental facility aimed to demonstrate an advanced ignition scheme and repetitive laser operation; where irradiation is limited to bunches of a few shots with energies of ~ 20 MJ. Secondly, a Prototype reactor that allows for

Table 1.2: Conditions in the different HiPER scenarios studied in this work: Experimental, Prototype and Demo.

Parameter	Experimental	Prototype	Demo
Frequency	Few shots per bunch	1 Hz	10 Hz
Shot Energy (MJ)	20	50	154
Chamber radius (m)	5	6.5	6.5
Lens distance (m)	8	16	16

research on low yield targets, studying target injection, tracking, repetition mode, heat extraction or tritium production while keeping material demands low, operating with relaxed conditions of 1 Hz and 50 MJ. Finally, a Demonstration (Demo) reactor aimed to prove feasibility of technologies under very demanding conditions, operating with high repetition rates of 10 Hz and high energy gains of ~ 150 MJ. In Table 1.2 the main conditions of the different HiPER scenarios are shown.

In the different HiPER scenarios, the chamber is assumed to be spherical, having 48 openings for the laser beam lines, allowing for symmetrical target illumination. Schematic representations of the chambers are shown in Figure 1.1. The chamber inner radius depends on the facility, being 5 m for the Experimental facility and 6.5 m for the Prototype and Demo reactors.

A detailed description of the chamber design is given in Chapter 6. In all cases the chamber has an onion-like shape consisting of different layers. (i) first wall (FW), directly facing the irradiation and made of W [62]; (ii) substrate, which gives mechanical support to the FW and it is proposed to be made of ODS-RAFM steel [47]; (iii) coolant, for the Prototype and Demo scenarios, the chamber is also surrounded by a thick liquid LiPb blanket [45]; (iv) biological shielding for irradiation. For the final optics, as described in Chapter 5, biconvex transmission lenses are the base design scenario for HiPER; the lenses would be placed at 8 m from the chamber centre in the Experimental scenario and at 16 m in Prototype and Demo scenarios.

In summary the HiPER project offers a detailed study for the integration of the different aspects required for the development of nuclear fusion: from ignition physics to technological aspect. In this context this thesis develops works related to the development of the tungsten First Wall and the silica Final Lenses.

Figure 1.1: Schemes of the laser fusion reactor chambers: (a) HiPER Experimental; (b) HiPER Prototype and Demo.

1.3 Silica Final Lenses and Tungsten First Wall

In the frame of the HiPER project, this thesis studies the plasma facing components: the Final Optics and the tungsten First Wall. The Final Optics focuses the ICF laser onto the target. Laser focusing is critical in order to obtain good illumination conditions on the target, allowing for fuel compression and ignition. Therefore effects of irradiation on the final optics will be critical for a reactor operation. In the case of the First Wall, its role is to protect the chamber from ion irradiation. Ion irradiation from the target explosion is deposited in the first micrometers of the First Wall and induces an intense thermal shock that may destroy the chamber if not properly protected. Tungsten is proposed as First Wall material due to its high melting temperature, densities and thermal conductivities. Thus, we study the use of tungsten as a First Wall material.

Regarding the final optics, in this thesis we develop the conceptual design of transmission biconvex lenses as the final focusing component. In this thesis we continue previous works on the study of the final optics of HiPER by Rivera et al. and Garoz et al. [14, 15] and research carried out in the LLNL for neutron irradiation of silica [63–65] and system proposal for final optics [3, 66]. An alternative to transmission lenses is the use of Grazing Incidence Metallic Mirrors (GIMM). GIMM were designed and tested in the framework of the Prometheus, Sombrero and HAPL projects [67–73]. The main drawback of the metallic mirrors (apart of radiation-resistance considerations) is the large distance from target to focal point (>20 m), which makes impossible to reach the same beam pointing accuracy on target as with transmission lenses located closer to the target [54].

This positions the transmission lenses as a more technical feasible scenario.

Neutron irradiation of silica create colour centres, which absorb light in certain bands. The colour centres may be very detrimental if the absorption bands coincide with the laser wavelengths that must be transmitted. In addition, strong absorption of laser radiation in the lens may seriously affect the lens integrity. In Refs. [14, 15] it was concluded that operation at high temperatures could enhance defect annealing, minimizing the formation of colour centres. In Chapter 5, these effects are discussed and a system to keep the silica lenses at high temperature is proposed. Regarding ion irradiation, its thermomechanical effects were studied in Refs. [14, 15]. After ion irradiation the silica surface is heated and the temperature gradient induces stress fields. Analysing the surface temperatures and stresses after irradiation, it was concluded that ion irradiation should be mitigated before its arrival to the final lenses. In Ref. [74], Abbott et al. proposed a mitigation strategy based on the use of Helmholtz coils and in Section 5.4 we propose a mitigation strategy using magnetic dipoles. In order to define the effects of irradiation for species that may escape mitigation, in Chapter 4 we develop a detailed study of the effects of swift heavy ion irradiation on silica. We study the behaviour of the irradiated surface with ions of different energies at different irradiation fluences.

For the First Wall, in HiPER a tungsten dry-wall is the base line scenario. The effects of ion irradiation on the HiPER First Wall were already outlined in Refs. [11–13], characterizing the irradiation spectra and outlining the temperature evolution under irradiation. In Chapter 6, we give a more detailed analysis of irradiation effects on the HiPER First Wall, characterizing thermomechanical effects, crack propagation and outlining atomistic effects. In the scope of the HiPER project fundamental research on tungsten irradiation was also addressed. Which includes the description of irradiation effects on tungsten [62, 75–80], or characterization of nanostructured tungsten with enhanced irradiation resistance [81–83]. For the development of HiPER First Wall it is important to consider previous works on ICF First Wall design [4, 84–86] and the developments done by the magnetic fusion community in plasma facing materials, especially in the divertor [87, 88]. In order to compare First Wall irradiation in magnetic and inertial fusion, several differences should be considered. In inertial fusion, the presence of heavy debris from the target will lead to penetration depths up to $\sim 100\text{ }\mu\text{m}$ and the pulsed nature of irradiation will have effects on the rate of defect annealing [78]. Different approaches are used in ICF to reduce damage in First Wall materials for evacuated dry wall reaction chambers. Projects like LIFE, designed to operate with

indirect drive targets, propose filling the chamber with residual high-Z gas such as Xe (pressure ~ 1 mbar at room temperature) in order to mitigate both the very intense X-ray pulses and ion irradiation [4]. However, this approach is unfeasible in projects based on direct drive targets, like HiPER, because the residual gas makes impossible to maintain the DT target in solid state during injection [89]. Therefore, HiPER will use a dry wall evacuated chamber, i.e., with no mitigation gas for wall protection. An alternative to dry-wall would be the use of wetted walls [90]. However this technology is not yet mature to be implemented and much research should be done on aspects such as the evaporation of the wetted layer, possible boiling and droplet generation, injection of the wetted layer and its reestablishment after irradiation.

Due to the modular design of ICF facilities, material research for ICF material is expected to take place directly on the reactor chamber, performing periodic replacement of the irradiated components. Therefore, no experimental facility for material research is envisaged for the HiPER project. However HiPER will benefit from advances done in research in other facilities, mostly focused on magnetic fusion such as IFMIF [91]. In the context of this thesis, in [Chapter 7](#) we study how experimentation in a medium sized neutron source, such as ESS-Bilbao [92, 93] or Julich HBS [94], could be used for experimentation on fusion materials, especially in the ICF final optics.

1.4 Structure of the Thesis

This work is devoted to the analysis of irradiation effects and the proposal of feasible solutions for the development of plasma facing materials in ICF. From the study of fundamental effects of irradiation we define the operational range for the components, and finally we propose a technological solution feasible for implementation in future reactors. Therefore, in the different Chapters of this thesis we cover the different aspects of irradiation damage in the ICF Final Optics and First Wall.

In [Chapter 2](#) we present the methodology, describing the models, codes and procedures used during the thesis. In [Chapter 3](#) we describe the irradiation conditions in the HiPER project, summarize the irradiation effects and study in more detail specific aspects such as the formation of colour centres in silica. We calculate the main irradiation parameters in terms of deposited heat, PKA spectra, resulting damage (dpa), and gas formation. In [Chapter 4](#) we specifically address the densification of silica under ion irradiation. We study the densification of silica as a function of the ion fluence, developing a model that

can cover a wide range of irradiation fluences.

From a technological point of view we carry out the design of the silica final optics and the tungsten first wall. In [Chapter 5](#) we describe how irradiation affects laser focusing in the final lens. Then, we develop a conceptual design in order to operate the final optics under HiPER irradiation conditions. In the case of the final lenses, due to the formation of colour centres and the appearance of aberrations from temperature gradients, it is necessary to introduce a temperature control system. We discuss how to introduce this system and propose a conceptual design based on helium cooled channels. In [Chapter 6](#) we show the irradiation effects in a tungsten first wall for different HiPER scenarios. We centre the analysis in the study of the thermomechanical effects and crack propagation for different HiPER scenarios; finally we also give a qualitative discussion of atomistic effects. We conclude that a tungsten first wall can be used in experimental facilities, but alternatives should be considered for a full scale reactor.

This work is mostly computational, but we stress the necessity of more experimental data in order to validate materials and components. In [Chapter 7](#) we study the possibility of using a medium sized neutron source for the study of nuclear fusion materials. We stress the importance of studying irradiation damage in conditions similar to nuclear fusion. In this context, we study the possibility of using the medium sized neutron source of ESS-Bilbao for experimentation on nuclear fusion. In particular we discuss how silica in the final optics would behave under neutron irradiation in ESS-Bilbao and compare it to expected conditions in HiPER.

Finally, in [Chapter 8](#) we outline the main achievement of the thesis and give a guideline for future works.

Chapter 2

Methodology

This Chapter describes the methods used in this thesis, giving a description of the codes, tools and procedures used in this work. Two are the objectives of the methodology: *a)* give the reader a better understanding of the project and how the results have been obtained, *b)* give a methodological approach valid for other works concerning irradiation effects in a wide range of facilities and materials.

The methodology is divided in *i)* description of codes, *ii)* evaluation of neutron effects, *iii)* thermomechanical effects of ion irradiation, *iv)* track densification due to ion irradiation and *v)* optical performance of the ICF Final lenses.

2.1 Description of Codes

Throughout this work several codes have been used, either nuclear codes (MCNPX, NJOY, SRIM), fluid-thermomechanical commercial codes (CodeAster, Fluent) or self-developed code.

In the following paragraphs a brief introduction to each code is given. This introduction should give the reader information about each code capabilities and why it has been used in the present work. For more detailed information it is necessary to refer to the user manuals or the source code in the case of self-developed modules.

2.1.1 MCNPX

The code MCNPX [95] is a Monte Carlo radiation transport code. MCNPX is the last generation of the transport codes designed at Los Alamos National Laboratory. MCNPX stands for MonteCarlo N-Particle eXtended. MCNPX is able to transport 34 particle types (from electrons to light ions, including photons, neutrons, hadrons, etc), in a wide energy range (from meV to GeV).

MCNPX was designed from the coupling of two previous transport codes MCNP4B and LAHET2.8. The coupling of both codes is still visible in MCNPX, at low energies (< 20 MeV) MCNP4B with nuclear libraries is used while at high energies (> 20 MeV) LHET is used with nuclear models.

With the MonteCarlo technique implemented in MCNPX, particle tracking is done through random sampling of collision events. For each source particle the probability of a collision event is calculated. Each collision event can also result in different type of reactions: elastic, inelastic, producing a third particle, etc. The collision type defines the energy and direction of the particles after the collision. All the previous processes are statistically defined through probability functions.

The probability of a collision event is calculated from the model geometry and the implemented physics, either from nuclear libraries and nuclear models. Therefore each collision is estimated through random sampling on the probability distribution of the model. The result is that for each source particle we have a description of collisions and third particles (gamma, electron, neutron, etc). Repeating this process for n -particles a full description of the fluxes and doses is obtained.

Therefore, as a Monte Carlo code, it is important to take into account the statistics of the simulations. Monte Carlo codes trace a number of histories (source particles) based on probabilistic distribution of their collisions. Each result is therefore associated with an average value and an error. Typically the error should be below 5% to have reliable results. In remote regions where the fluxes are low, the statistics are poor and variance reduction techniques may be implemented. MCNPX implements different types of variance reduction techniques: cell importance, weight windows, point detectors, DX spheres. These techniques allow for more detailed calculations of the regions of interest (cell importance, weight windows) or implement quasi-deterministic approach to the problem (DX sphere, point detector). In this work we restrict the use of variance reduction techniques to cell importance. We assign a cell importance n on the cells of interest, which

corresponds to the irradiated sample in the different models. This way every particle entering the cell of interest is divided in n tracks, weighted $1/n$, increasing the number of collisions, and thus improving the statistics for the fluxes, doses, gas production or PKA spectra estimation.

2.1.2 NJOY

The NJOY code [96] was developed in Los Alamos national Laboratory and is used for the post-processing of nuclear libraries. NJOY is used in order to produce cross section data in the ENDF format. NJOY allows operating with cross sections for different particle types: neutrons, photons, and charged particles. In the context of this work, NJOY is used for the post-processing of nuclear data in order to extract double-differential cross sections from ENDF libraries.

The NJOY code works through the use of modules called by a main module. The user interface is provided through input files that lack semantic features and are highly structured. For a better user interface the NJOY inputs have been processed through python scripts to include high level programming features.

In this work we have used several NJOY modules in order to calculate gas production, damage or the PKA spectra. The modules of NJOY used in the present work are: a) HEATR module, generates heating cross sections (KERMA factors) and damage production cross sections. Although the nuclear libraries used in MCNPX already include the postprocessing of HEATR, partial heating cross sections are interesting in order to account for the influence of specific reactions. b) GASPR module generates gas production cross section (up to ^4He). c) GROUPR module that generates multigroup cross sections, group to group scattering matrices, photon production matrices, and charged particle cross sections from pointwise input. The GROUPR module has been used in this work for the calculation of recoil matrices necessary for the calculation of the PKA spectra.

2.1.3 SRIM

SRIM (Stopping and Range of Ions in Matter) [97] is a code for the simulation of ion interaction with matter. SRIM implements MonteCarlo techniques using a binary collision approximation (BCA) in order to simulate particle track. The probability

distribution for the collision events are estimated from the stopping power of ions at different energies. These stopping power are included in SRIM through data fitting from a wide experimental database.

In this work we use SRIM in order to calculate the ion energy deposition as a function of depth, as well as the ion range. Finally damage evaluation as displacements per atoms can be done using methods based on the Kinchin-Pease model [98].

2.1.4 CodeAster

CodeAster [99] is a Finite Element Code created by EDF. In this work we use CodeAster in order to solve mechanical and thermal problems doing static and transient analysis. For this work we have used versions 10.1 and 11.6. For geometry and meshing we have used Salome-Meca [100] software. Salome-Meca creates a single interface for the CodeAster solver and the Salome platform [101], that is used for CAD design, meshing and postprocessing analysis, and

A CodeAster analysis is defined by an input file where the different commands and modules are described. The input file uses python scripting language, and the different CodeAster modules are called as python objects. The CodeAster modules perform the different parts of the FEM analysis, from mesh reading, material definition, model definition, to solver options and data postprocessing. In this work we use modules for mechanical and thermal non-linear transient analysis, postprocessing of results and calculation of stress intensity factors.

2.1.5 Fluent

Fluent [102] is a code used for Computing Fluid Dynamics (CFD) analysis. With Fluent we are able to study fluid flow, analysing the fluid pattern, pressure losses, heat transfer, etc. It is also possible to study heat transfer in solids solving the heat equation.

For the meshing we use ICEM-CFD tool, defining boundary layers near the walls. We implement 2D simulation, with a κ - ϵ turbulence model and S2S model for radiative estimations. The κ - ϵ turbulence model is based on the transport of turbulent kinetic energy (κ) and its dissipation rate (ϵ). For the formulation of the model we select the κ - ϵ -RNG variation with enhanced wall treatment. The RNG variation improves the

model behavior in low Reynolds problems, giving more accurate results on near wall treatments where the flow is laminar. Enhanced wall treatment is also used, simulating the laminar section of the boundary layer with a mesh refinement near the wall. The radiation model assumes gray and diffuse surfaces. The form factors are calculated using the S2S model, and the radiative heat exchange is calculated using Stefan-Boltzmann law.

2.1.6 Python Modules

In this work Python [103] have been used extensively. Python is a programming language that has object-oriented high-level features. It is an interpreted language that emphasizes code readability, which makes it ideal for scripting and fast development of code. In general the capabilities of Python make it an ideal programming language for data analysis. The main defect of Python is its slow executing times when tackling computing demanding problems, in which case C or Fortran languages offer a better approximation.

Python allows solving different problems through its different modules. In this work Python has been used for data analysis (numpy and scipy modules), postprocessing of results (re module) and plotting (matplotlib and mayavi module).

Different codes have been written for this work. The most relevant are the raytracing modules, double differential cross section modules for calculation of PKA spectrum, colour centre formation, or silica surface densification under irradiation. The basics of the models are described in the next sections of this Chapter.

2.2 Neutron damage evaluation

2.2.1 Overview

For the characterization of neutron damage several magnitudes have to be calculated: neutron spectrum, energy deposition, gas production, Primary Knock-on Atom (PKA) spectra or displacements per atom (dpa). For the calculation of the different magnitudes we used different tools. The irradiation neutron spectrum was obtained from the Aries project for a 154 MJ direct target [104]. In order to solve the radiation transport we

used the code MCNPX [95]. Then, the estimation of the PKA spectra was done through the development of double-differential cross sections with NJOY [96].

2.2.2 Fluxes, doses and gas production

The fusion neutron spectrum was obtained from Aries project for a 154 MJ direct target [104]. The neutron source was used as an input for our MCNPX models [95], where neutron data were obtained from nuclear libraries ENDF/B-VII.1 [105].

In MCNPX the HiPER chamber geometry was reproduced to study neutron damage at the different components (Final Lenses, First Wall, and Structural Steel). In Chapter 7 a study of irradiation damage in other facilities, in particular for ESS-Bilbao, is also presented. The ESS-Bilbao model was developed by the Target Group of ESS-Bilbao and is described in Ref. [92].

From the MCNPX model the neutron fluxes in the material were obtained. With the multiplication of the neutron flux by special cross sections it is possible to calculate energy deposition H , Equation (2.1), or gas production rates R_G , Equation (2.2), for hydrogen, deuterium, helium, etc:

$$H = N \cdot \int_{E_i} \phi(E_i) \cdot \sigma_K(E_i) \cdot dE_i \quad (2.1)$$

$$R_G = N \cdot \int_{E_i} \phi(E_i) \cdot \sigma_G(E_i) \cdot dE_i \quad (2.2)$$

Where E_i the energy of the incident neutron, ϕ the neutron flux and N the density of the material.

Therefore, the energy deposition (H) was calculated using heating or KERMA cross section (σ_K), defined in barn-eV. The gas production (R_G) rate was calculated using gas production cross sections (σ_G), defined in barns. These cross sections are available in most nuclear libraries, and can be obtained postprocessing nuclear libraries with NJOY [96].

As explained before, the material heating cross section or KERMA (Kinetic Energy Release on Materials) were used in order to obtain the energy deposition. It is important to point out that the KERMA is the energy that remains in the material as the kinetic

energy of the charged particles. The KERMA includes the energy deposited by recoil nucleus, charged particles products, as well as light charged particles (p, α). For fusion neutron of ~ 14 MeV, the maximum energies for the light charged particles are of the order of 1 MeV with deposition ranges below 100 μm . Therefore the KERMA energy deposition can be used in order to calculate the temperature of the final lens in [Chapter 5](#).

The production rate of gases, [Equation \(2.2\)](#), is especially interesting in order to evaluate damage. Therefore, the production of different light species (H, D, T, He) was calculated. The light species are likely to remain as interstitial in the material, increasing material brittleness or inducing swelling. Typically the magnitude of gas production is compared to damage with H/dpa as or He/dpa ratios. The gas production to damage ratio is a widely used magnitude to compare irradiation effects in different facilities.

2.2.3 Displacements per Atom (dpa)

In order to estimate the irradiation damage in terms of displacements per atom (dpa), damage cross sections (σ_D) can be calculated for each material. The damage cross section (σ_D) in eV-barn, [Equation \(2.3\)](#), defines the energy that is available for defect formation. This energy is estimated through the use of the partition function (η), which calculates the fraction of PKA energy (E_{PKA}) that goes into defect formation.

$$\sigma_D(E_i) = \int_{E_{PKA}} \sigma(E_i \rightarrow E_{PKA}) \cdot \eta(E_{PKA}) \cdot dE_{PKA} \quad (2.3)$$

$$H_D = N \cdot \int_{E_i} \phi(E_i) \cdot \sigma_D(E_i) \cdot dE_i \quad (2.4)$$

Therefore, H_D is the energy that goes into defect formation from neutron irradiation. In order to calculate the number of defects (N_D), the defect energy (H_D) is divided by the energy necessary for an atom displacement ($2 \cdot E_D$), and corrected by a recombination factor (k):

$$N_D = k \frac{H_D}{2 \cdot E_D} \quad (2.5)$$

The determination of the partition function η can be done with different models, such as NRT [\[106\]](#), Kinchin-Pease [\[98\]](#) or MD (Molecular Dynamics) simulations. In all

cases the determination of η is complicated and has to be evaluated for each material.

In this work, the NRT model [106] was used in order to calculate the partition function (η) and the displacements per atom (dpa). In the NRT model, the partition function η_{NRT} is calculated as:

$$\eta_{NRT} = \frac{1}{1 + F_L \cdot (3.4008 \cdot \epsilon^{1/6} + 0.40244 \cdot \epsilon^{3/4} + \epsilon)} \quad (2.6)$$

$$\eta = 0 \quad E_R < E_d \quad \epsilon = E_R/E_L$$

$$E_L = 30.724 \cdot Z_R \cdot Z_L \left(Z_R^{2/3} + Z_L^{1/3} \right)^{1/2} \cdot (A_R + A_L) / A_L$$

$$F_L = \frac{0.0793 \cdot Z_R^{2/3} \cdot Z_L^{1/2} \cdot (A_R + A_L)^{1/2}}{\left(Z_R^{2/3} + Z_L^{2/3} \right) \cdot A_R^{3/2} \cdot A_L^{1/2}}$$

Where η_{NRT} is the partition function calculated with the NRT model, E_R is the recoil energy, E_d the energy necessary for a displacement, Z_R , A_R are the atomic and mass number of the recoil and Z_L , A_L the atomic and mass number of the lattice atoms.

Damage cross sections (σ_D) using the NRT model are directly available in ENDF nuclear libraries [105]. For the implementation of the NRT model, we calculated the number of defects, N_d , using Equation (2.5). We used a recombination factor (k) of 0.8 and a displacement energy (E_D) of 40 eV in the case of iron, 90 eV in the case of tungsten [96]. In the case of silica E_D is between 105 and 133 eV [64, 65], for the calculation we took a value of $E_D=120$ eV.

Although very simple, the NRT model is useful for the purpose of studying damage, providing a standard way to estimate the number of displacements per atom (dpa) stemming from PKAs of different energies. In Figure 2.1 we show the partition function using the NRT model, η_{NRT} , for different materials. We observe how the partition function, and the energy that goes to defect production depends on the on the PKA energy.

In the next section we describe the calculation method for the PKA spectrum.

Figure 2.1: NRT partition function (η_{NRT}) values for different materials.

2.2.4 PKA Spectrum

As explained in the previous paragraphs, the NRT model is used in this work as a tool for damage estimation. However, for a more realistic approach it is necessary to study defect formation using Molecular Dynamics [64, 107], having a detailed estimation of the partition function as a function of the PKA energies, $\eta_{MD}(E_{PKA})$. For this purpose a full description of the PKA spectrum has to be calculated.

For the calculation of the PKA spectrum double-differential cross sections, $\sigma(E_i \rightarrow E_{PKD})$ are used. The PKA energy depends on the scattering angle and energy loss (non-elastic reactions) from the neutron reaction. Therefore, each incident energy (E_i) gives a spectrum with different PKA energies (E_{PKA}). Figure 2.2 shows $\sigma(E_i \rightarrow E_{PKA})$ for incident neutrons in ${}^{16}\text{O}$. Finally, the full PKA spectrum (R_{PKA}) is obtained multiplying the cross section, $\sigma(E_i \rightarrow E_{PKA})$, by the incident neutron flux:

$$R_{PKA}(E_{PKA}) = N \cdot \int_{E_i} \sigma(E_i \rightarrow E_{PKA}) \cdot \phi(E_i) \cdot dE_i \quad (2.7)$$

The double differential cross sections are available in nuclear libraries only for neutron energies up to 20 MeV. We extracted them from the ENDF/B-VII.1 [105] nuclear library

Figure 2.2: Double differential cross section, $\sigma(E_i \rightarrow E_{PKA})$, section for ^{16}O .

using the NJOY code.

Although maximum neutron energy in nuclear fusion is 14 MeV, in this work we also study irradiation in other neutron facilities, see [Chapter 7](#), with neutron energies exceeding 20 MeV. For energies exceeding 20 MeV no tabulated data is available and computational models are used. In this work the simulations are run with Bertini/Dresner model [108–110] using the module HTAPE3X of MCNPX. Through these simulations we created double differential cross sections for neutrons energies >20 MeV.

2.3 Thermomechanical effects of ion irradiation

2.3.1 Overview

In order to evaluate the thermomechanical effects of irradiation on the tungsten FW material, we used an approach involving different fields and codes, from the irradiation spectra to the effects of irradiation.

The neutron irradiation spectrum was obtained from the Aries project for a 154 MJ

direct target [104]. From the spectrum the heat deposition was calculated. The heat deposition was used as an input for the FEM solver, Codeaster [99], in order to calculate temperatures, stress and strains evolution. Finally we did fatigue estimations and studied crack propagation in the material.

The presented methodology is valid for the assessment of FW materials in nuclear fusion or other irradiation facilities. In Chapter 6 we study the irradiation effects on tungsten.

2.3.2 From irradiation fluxes to power density

In order to fully describe the irradiation load, we need the temporal and spatial distribution of the irradiation. From the Aries project [104], we have the irradiation spectra corresponding to the different species (X-rays, burn ions, debris ions) generated during the target explosions. As described next, with the irradiation spectra we calculate the power density deposited on different components as a function of time and depth.

The irradiation spectra are given as ions per energy bin ($\#/\text{keV}$). As the thermo-mechanical effects depend on the heat deposition, we estimated the energy spectra (J/keV). For the different facilities studied in this work we scaled the heat load to the chamber radius and target energy. Therefore, for each facility we obtained an energy fluence spectrum ($\text{J}/\text{cm}^2\text{-keV}$).

In order to obtain the temporal evolution we transform the energy spectrum ($\text{J}/\text{cm}^2\text{-keV}$) to a power spectrum ($\text{J}/\text{cm}^2\text{-}\mu\text{s}$). For this purpose we need the irradiation time of flight. For ions, the time of flight is $t_{TOF} = r\sqrt{m/2E}$, i.e. the arrival time for ions of energy E , mass m , in a chamber of radius r . For the case of X-ray irradiation $t_{TOF} = r/c$, being c the speed of light.

The spatial distribution was calculated in the case of ions from the stopping power using SRIM [97] and for X-ray with attenuation coefficients obtained from NIST data [111]. Multiplying the temporal spectrum by the stopping power we obtained the power density ($\text{J cm}^{-2} \mu\text{s}^{-1} \mu\text{m}^{-1}$), which can also be expressed in W m^{-3} .

The spatial-temporal spectrum were discretized in bins, forming an irradiation matrix. In this work we used a temporal discretization of 250 bins of 32.5 ns, which reproduced the first 8 μs of irradiation, where all the energy is deposited ¹. For the spatial discreti-

¹This is for a chamber radius of 6.5 m (HiPER Demo), for other radius the time bins are scaled.

Figure 2.3: Power density as a function of time and depth. The figure shows the results for Helium irradiation the tungsten First Wall in the HiPER Demo facility.

zation we distinguished short range irradiation ($<1\text{MeV}$) and long range penetration ($>1\text{MeV}$). For short range we calculated 300 bins of 25 nm, characterizing the first 7.5 μm of the material. For long range irradiation we calculated 100 bins of 1 μm , up to a depth of 100 μm .

Therefore, as shown in Figure 2.3, we obtained an irradiation matrix describing the power density as a temporal and spatial term. We used this matrix as an input for the FEM model.

2.3.3 Code Aster simulations

The irradiation matrix (power density as a function of time) was used as the source term in the finite elements model developed for the First Wall. The finite elements solver Code Aster [99] was used for the calculations. The thermomechanical effects appear as a consequence of the deposition of energy in the first wall. For the calculation of the mechanical response a bilinear elasto-plastic material model, under the quasi-static deformation approach was used. The quasi-static approach is justified regarding the

natural period of tungsten (τ). The natural period (τ) depends on the irradiation depth (L), and tungsten elastic modulus (E), and density (ρ), resulting in $\tau = 2\pi L \cdot \sqrt{\rho/E}$. Which for irradiation depths of $\sim 4 \mu\text{m}$ is of the order of nanoseconds, much lower than the irradiation times of microseconds.

In the model, the physical parameters and mechanical properties are implemented as a function of temperature. In our case the values reported in the ITER material handbook [112, 113] were used for the tungsten FW. The wall geometry was modelled with a 2D mesh developed under the Salome Platform [101]. A plane strain condition was applied in the model ($\epsilon_z = 0$), which stems from the symmetry of the problem. In order to achieve a detailed estimation of the temperature gradients and local stresses, the mesh was refined near the FW surface and at the FW-surface interface.

The tungsten FW was simulated as a uniform, isotropic material. Therefore, the bulk averaged properties were evaluated, regardless of local discontinuities caused by material microstructure. In this context, in the FW surface the mesh was refined with elements of 25 nm, which coincide with the size of the irradiation matrix. The reactor wall is adiabatic except at the surface in contact with the coolant. The mechanical boundary conditions were fixed allowing for axial displacement of the surface. For the time evolution of the FW we adapted the solution time to the irradiation time, with time steps of nanoseconds during the irradiation and increasing time steps up to ms when the material cools down. Finally we studied different cases of irradiation, such as first pulse irradiation, steady state regime and pulse evolution in steady state.

In Figure 2.4 we show a schematic overview of the model used for the thermomechanical calculations. In this model the irradiation pulse reaches the FW, heat is transferred through FW and substrate and is finally removed by the coolant.

Figure 2.4: Sketch of the reactor wall. The tungsten first wall is attached to the substrate. The substrate is in contact with the biological shielding in HIPER Experimental or with the coolant in HIPER Prototype and Demo.

2.3.4 Crack Propagation

The appearance of cracks is a stochastic phenomenon, dependent on material impurities or discontinuities. These factors lead to stress concentration and the initialization of a crack. Typically, crack appearance is predicted through fatigue curves that makes possible the estimation of the number of allowable load cycles (N_f) as a function of the load, typically the plastic deformation (ϵ_p). These curves are usually experimental and depend on the material, in our case for tungsten we use the following formula [84, 112]:

$$\epsilon_p = 34 \cdot N_f^{-0.46} \quad (2.8)$$

Once the crack is initiated, we study the crack propagation. For this purpose, the model described in the previous section is modified adding a crack in the mid-plane of the mesh (see Figure 2.5). In this case, we are only interested in the behavior of the FW near the surface, and the cooling step is simplified with a fixed temperature as boundary condition. As mechanical boundary conditions we impose free displacement in the irradiated surface, null axial displacement in the rear part of the FW, and symmetry condition in the sides of the model (null transverse displacement). In order to study the crack, contact elements are used, avoiding that the nodes of the two sides of the crack overlap when the crack closes.

The height of the model greatly affects the results, in fact the height of the model is the parameter used to define the distance between cracks or crack density in the material. Modifying the height of the model we are able to estimate when the formation of cracks attains a saturation state (these results are discussed in Chapter 6).

When the crack opens, an accumulation of stresses takes place near the crack tip. This leads to plasticization in the crack tip and to crack growth. According to fracture mechanics [114], the crack can open in opening mode (Mode I), in plane shear (Mode II) and out of plane shear (Mode III). Due to symmetry conditions of the heat load and crack model, only Mode I will appear in our case. Therefore, cracks propagate in the axial direction under the transverse tensile stress. Assuming an ideal elastic material, the transverse stress σ_{yy} would be:

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \quad (2.9)$$

Where σ_{yy} are the transverse stress, K_I the stress intensity factor and r the distance to the tip. It is observed that the stress would increase to infinite near the tip ($r \ll$). As this is not physically possible, a plastic region will form near the crack tip. This plastic region depends on K_I and the yield strength (Y_s), with the plastic radius, r_p :

$$r_p = \frac{1}{\pi} \left(\frac{K_I}{Y_s} \right)^2 \quad (2.10)$$

Once the crack is characterized it is important to estimate how it propagates. The crack will propagate if K_I in the crack tip is higher than the fracture toughness (K_{IC}) of the material. The final length of the crack is therefore attained when $K_I = K_{IC}$.

For fracture analysis the stress intensity factors (K) are calculated using the singular displacements method implemented in the CALC_G module of CodeAster [115, 116]. From the stress intensity factor K_I the energy release (G) can be calculated using the Irwing formulas, $G = K_I^2 \cdot (1 - \nu^2)/E$. Direct calculation of the strain energy release using the J-integral [117] can also be used in CodeAster [118] with similar results. In order to have good numerical stability, we avoid the particularity near the crack tip, performing the analysis out of the plastic radius.

Figure 2.5: Left) Mesh of the crack model, showing the mesh refinement in the crack region, the contact elements and boundary conditions. Right) Diagram representing the stress intensity distribution near the crack pit.

2.4 Track densification by means of ion irradiation

2.4.1 Overview

In order to characterize silica densification under swift ion irradiation we use a methodology that includes atomistic simulations using Molecular Dynamics (MD), effects of track inclusion using Finite Element Methods (FEM), a parametrical model and experimental results.

The experimental results measure the refractive index under irradiation, which is correlated to the surface density. The MD simulations are used to describe the local densification generated by the incoming swift ion. The FEM simulations are employed to explain track inclusion at high irradiation fluences leading to plastic effects.

In this section we describe the experimental methods and the MD and FEM models. In [Chapter 4](#) the simulations are compared to the experimental results and a parametrical model is developed in order to describe the evolution of silica surface densification at the different fluences.

2.4.2 Experimental

Irradiation experiments of amorphous silica were performed at the 5 MV tandem accelerator in Centro de Micro-Análisis de Materiales (CMAM) [119], using bromine ions with energies in the 5-40 MeV range. The samples contained low-OH concentration (below 10 ppm) and were provided by Momenitive Ltd. In situ optical reflectance measurements were carried out using an in-house setup mounted on the irradiation chamber, which is described schematically in [Figure 2.6](#). Two mirrors were used to illuminate the samples with the white light produced by a halogen lamp at nearly-normal incidence, which simplifies the subsequent analysis. The reflected light was collected and focused with a 25-mm-diameter, 4-cm-focal-length silica lens and guided to a compact spectrometer, QE6500 (Ocean Optics Inc.), using a silica optical fibre of 1-mm diameter. The spectrometer is configured with a multichannel array detector for measuring simultaneously the whole spectrum in the range 400-1000 nm with a spectral resolution better than 2 nm. Further details about the experimental setup and the irradiation campaign can be found in Ref. [120].

Figure 2.6: Schematic representation of the setup for in situ reflectance measurements. A sample can be irradiated with ions (black line) and at the same time illuminated with white light (blue arrows). The reflected light is detected by a CCD spectrometer.

2.4.3 Atomistic Simulations

Ion irradiation on virgin silica leads to track compaction. Atomistic simulations based on molecular dynamics (MD) were carried out to simulate the thermal evolution of the track region upon ion arrival. These MD simulations were done by A. Prada using MDCask [121]. The MD simulations use the Feuston-Garofalini interatomic potential [122], modified by the Ziegler, Biersack and Littmark (ZBL) potential to account for close interactions. Amorphous silica boxes have dimensions of $30 \times 30 \times 14 \text{ nm}^3$ and were obtained as described in Ref. [123]. The simulation box includes $> 8 \times 10^5$ atoms in a time domain that exceeds 100 ps. MDCASK run in 256-512 cores at supercomputer CESVIMA-MAGERIT (UPM) [124] was used for the simulations.

The initial total kinetic energy of the atoms in a central hot cylinder of radius ($a = 3$ to 5 keV/nm) was set equal to the electronic stopping power (S_e) of the ion. The region surrounding the hot cylinder (radius 14.3 nm) turns out affected by the thermal evolution of the system. The velocity of the remaining (outer) atoms is rescaled to 300 K every 10 steps (5 fs) to act as a thermal bath. Despite the simple way to account for the energy deposition in the electronic stopping regime, reliable quantitative results are obtained with this method. For more details see Ref. [125].

These simulations allow us to study the compaction of the track, analysing the

formation of complex shapes, such a core-halo structure. The thermal evolution is studied and the final state shows the effects of ion irradiation in silica.

With MD we obtain the track compaction (ρ) as a function of the stopping power (S_e) and distance to the axis (r), see Figure 2.7 (a). If we interpolate the different simulations we obtain $\rho = \rho(S_e, r)$. This way we characterize local irradiation on cells with sizes of nanometers for different stopping powers.

However ion irradiation penetrates up to microns. In order to fully characterize the ion track, we calculate the ion stopping power as a function of its depth, $S_e = S_e(x)$, with SRIM [97], see Figure 2.7 (b). Finally coupling the results from MD and SRIM we are able to reconstruct the tracks, $\rho = \rho(r, x)$, as observed in Figure 2.7 (c).

Figure 2.7: a) MD: atoms displacements in the background and density variation as a function of the distance to the ion trajectory in the foreground graphic. b) SRIM: ion trajectory in the top and stopping power as a function of the ion depth in silica in the bottom graphic. c) MD + SRIM: Track density variation for different ions, reconstruction of the track from density variations from MD and stopping powers as a function of depth from SRIM.

2.4.4 Elasto-Plastic track inclusion

FEM Model Description

As we explain in more detail in [Chapter 4](#), at high fluences a surface density expansion is observed.

We simulate the mechanical effects of track inclusion in the plastic regime with FEM simulations using Codeaster [99]. The model simulates the track inclusion with a bilinear elasto-plastic model assuming isotropic hardening and using axisymmetric conditions. We use the elasto-plastic model as a simplification for track inclusion. With this simple model we characterize a sample track, and show how residual stresses may appear after track inclusion leading to surface expansion.

For the characterization of the sample track we use the values obtained from single track characterization using Molecular Dynamics (see [Chapter 4](#)). The geometry of the model and the track morphology are represented in [Figure 2.8](#). The sample track is defined with a conical shape of radius ($r = 3 \text{ nm}$) and depth ($x = 5 \text{ }\mu\text{m}$). The track inclusion is characterized through a thermal expansion, which we take as $\alpha \cdot \Delta T \sim 1\%$ [127, 128].

Figure 2.8: Scheme of the geometry of the track and the substrate. The colour map represents the thermal load.

For the material properties we define the elasto-plastic model, see Figure 2.9. The elastic region is defined with the the elastic modulus ($E = 72.5$ GPa) and the Poisson coefficient ($\mu = 0.17$) [126]. The plastic region characterizes the permanent deformation that takes place during track inclusion. For this purpose what we use of a low plastic modulus (E_p) and a low yield strength (Y_s), which for the sample track we define as $E_p = 1$ GPa and $Y_s = 1$ MPa.

With the model we study the effects of an elasto-plastic track inclusion. We intent to show a net plastic expansion when the track cools down. For this purpose, we study the residual strains and stresses and analyze how final plastic deformation can lead to a surface expansion.

In order to validate the FEM model we have compared it to thermal elastic inclusion theory. In the next section we show the procedure for the model validation.

Figure 2.9: Scheme of the bilinear elasto-plastic model applied in CodeAster. The material behaves elastically up to the plastic yield, Y_s , then plastic deformation take places with a plastic Young modulus (E_p).

Analytical Model

The elasto-plastic model developed in CodeAster has an analytical solution by generalizing the thermal elastic inclusion theory including plastic effects. The development of this analytical solution turns out useful for quick parametric analysis and for validation of FEM models under different configurations.

The thermal elastic inclusion theory, developed by Eshelby's, describes long cylinder elastic inclusion, characterized by eigen strains $(\epsilon_r^*, \epsilon_\varphi^*, \epsilon_z^*)$ [128–130]. According to this theory the stresses are described as:

$$\begin{aligned}\sigma_r &= \frac{G}{1-\nu} \left(-\frac{3}{4} \cdot \epsilon_r^* - \frac{1}{4} \cdot \epsilon_\varphi^* - \nu \cdot \epsilon_z^* \right) \\ \sigma_\varphi &= \frac{G}{1-\nu} \left(-\frac{1}{4} \cdot \epsilon_r^* - \frac{3}{4} \cdot \epsilon_\varphi^* - \nu \cdot \epsilon_z^* \right) \\ \sigma_z &= \frac{G}{1-\nu} \left(-\nu \cdot \epsilon_r^* - \nu \cdot \epsilon_\varphi^* - 2 \cdot \epsilon_z^* \right)\end{aligned}\tag{2.11}$$

We generalize the model in order to include plastic effects. With the model we can directly calculate the stresses as function of the eigenstrains $(\epsilon_r^* = \epsilon_\varphi^* = \epsilon_z^* = \epsilon_{th}^* = \alpha \cdot \Delta T)$:

$$C_p^{*-1} \sigma + C_{el}^{*-1} \sigma = -\epsilon_{th}\tag{2.12}$$

$$\sigma = - \left(C_p^{*-1} + C_{el}^{*-1} \right)^{-1} \cdot \epsilon_{th}\tag{2.13}$$

$$C_{el}^* = \frac{G}{1-\nu} \begin{pmatrix} 3/4 & 1/4 & \nu \\ 1/4 & 3/4 & \nu \\ \nu & \nu & 2 \end{pmatrix}\tag{2.14}$$

$$C_p^* = \frac{G_p^*}{1-\nu} \begin{pmatrix} 3/4 & 1/4 & 1/2 \\ 1/4 & 3/4 & 1/2 \\ 1/2 & 1/2 & 2 \end{pmatrix}$$

Where C_{el}^* , C_p^* are the Eshelby's stiffness matrixes, and $G_p^* = \frac{E_p^*}{2(1+\nu)} = \frac{\frac{E \cdot E_p}{E - E_p}}{2(1+\nu)}$ the equivalent shear plastic modulus. With the previous equations, the stresses are obtained. In order to calculate the strains we use Equation (2.15).

Once the stresses are obtained we calculate the total strains as:

$$\epsilon = \epsilon_p + \epsilon_{el} + \epsilon_{th} = C_p^{-1} \sigma + C_{el}^{-1} \sigma + \epsilon_{th} \quad (2.15)$$

$$C_{el}^{-1} = \frac{1}{E} \begin{pmatrix} 1 & -\nu & -\nu \\ -\nu & 1 & -\nu \\ -\nu & -\nu & 1 \end{pmatrix} \quad (2.16)$$

$$C_p^{-1} = \frac{1}{E_p} \begin{pmatrix} 1 & -1/2 & -1/2 \\ -1/2 & 1 & -1/2 \\ -1/2 & -1/2 & 1 \end{pmatrix}$$

Where ϵ are the total strains, ϵ_p the plastic strains, ϵ_{el} the elastic strains, $\epsilon_{th} = \alpha \cdot \Delta T$ the thermal eigenstrains, and C_{el} , C_p the stiffness matrix.

In Figure 2.10 the stresses and strains for a fictitious track are shown, and the CodeAster and Analytical model compared. As expected the results show a good agreement between the models. The minor differences are caused by the 2D axisymmetry in CodeAster, which gives slight differences between ϵ_r and ϵ_φ , and σ_r and σ_φ . Also shear stresses appear in the CodeAster model in the track interface. These shear stresses, increasing the plastic deformation in the interface, which is not predicted by the analytical theory. We observe this effect in Figure 2.11, where the residual stress and strain profiles as a function of depth are shown.

Figure 2.10: Strains and stresses in the track for the Codeaster Model (red) and Analytical Model (blue). The model reproduces a fictitious track or $r = 3$ nm and eigenstrains $\epsilon^* = \alpha \cdot \Delta T = 1\%$. The material properties are a young modulus $E = 7.25$ GPa, plastic modulus $E_p = 1$ GPa, yield strength $Y_s = 4$ MPa and Poisson modulus $\mu = 0.17$.

Figure 2.11: a) Strains and b) stresses profile with distance (r) the track axis for the Codeaster Model (red) and Analytical Model (blue). The model reproduces a fictitious track or $r = 3$ nm and eigenstrains $\epsilon^* = \alpha \cdot \Delta T = 1\%$. The material properties are a young modulus $E = 7.25$ GPa, plastic modulus $E_p = 1$ GPa, yield strength $Y_s = 4$ MPa and Poisson modulus $\mu = 0.17$.

2.5 Optical performance of ICF Final Lenses

2.5.1 Overview

In order to address the optical performance of the final lens, a multicode approach is developed. We study how the temperature of the final lens affects to its focal distance and therefore to laser focusing. Small temperature variations introduce optical aberrations, which lead to non-uniformities in the laser energy deposition. Therefore a detailed study of the lens temperature and its optical effects is required.

The temperature of the final lens depends on the heat load from neutron irradiation (see Section 2.2) and on the temperature control system. We obtain the temperature

profile simulating the final lens system using Fluent [102].

For the evaluation of the optical performance, a raytracing code was developed. The raytracing code calculates the focal spot for one laser for the HiPER laser conditions. Finally, the focal spot is projected into the spherical target with the 48 direct drive laser beams of the HiPER project.

2.5.2 Evaluation of Lens Temperature

A detailed explanation of the temperature requisites is given in Chapter 5. In order to minimize temperature induced aberrations in laser focusing, the temperature of the final lens has to be controlled in detail.

In order to calculate the temperature of the final lens we first study the heat load. As explained in Section 2.2, the neutron and x-ray sources are obtained from the Aries project [104], and scaled to the different HiPER scenarios. The deposited neutron dose in the lens is calculated with MCNPX [95] and nuclear libraries ENDF/B-VII.1 [105]. Apart from the neutron spectra, x-rays reach the lens acting as a surface load. The neutron and x-ray dose profiles are used as an input for Fluent in order to solve the thermal problem.

The temperature profile in the final lens is calculated using Fluent [102] making use of the fluid properties obtained from CoolProp database [131]. In the model the boundary layer has been simulated to retain near wall effects, see Figure 2.12 (a). In order to simulate turbulence we use $\kappa - \epsilon$ turbulence model, and radiative effects are included with surface to surface (S2S) model.

The simulations are done in 2D models, reproducing different sliced sections of the fluid channel. In order to obtain the map of temperatures, we interpolate linearly the results of different slices, obtaining a temperature map in 3D, see Figure 2.12 (b). This simplification ignores cross-flow effects but allows for estimation of the lens temperature required in this work, retaining boundary layer effects.

Finally, an optimization analysis is done with Fluent in order to determine which conditions (fluids, pressure, pattern flow) are better to uniformize the temperature in the lens.

Figure 2.12: Fluent simulations of the temperature profile in the final lens. a) Model of the simulations, b) Temperature profile of the cooling channel for different slices, c) Interpolation of the results in order to obtain the temperature map in the lens.

2.5.3 Evaluation of the Lens Focusing

The temperature profile is used to calculate the focal distance on the final lens. With the focal distance in the lens we do ray-tracing of the laser. The ray-tracing is done with a paraxial optics system based on transfer matrices [132]. For this purpose different raytracing modules have been developed.

Effect of temperature on focal distance

Transmission lenses are used in the final optics of ICF in order to focus the laser into the target. For HiPER, the design assumes the use of biconvex lenses [5]. For biconvex lenses the focal distance is calculated as:

$$\frac{1}{f} = \frac{n_2 - n_1}{n_1} \cdot \left(\frac{1}{R_1} - \frac{1}{R_2} \right) + \frac{e \cdot \left(\frac{n_2 - n_1}{n_1} \right)^2}{n_2/n_1 \cdot R_1 \cdot R_2} \sim \frac{n_2 - n_1}{n_1} \cdot \left(\frac{1}{R_1} - \frac{1}{R_2} \right) \quad (2.17)$$

Where, f is the focal distance, n the refractive index, R the curvature radius and e the lens thickness. For our simulations will assume ideal thin lenses ($e = 0$).

The influence of a thermal gradient in the lens on the optical aberrations is studied. Aberrations due to a thermal gradient appear due to two effects: a) variation of refractive index, and b) variation of geometry. These effects alter locally the focal distance, inducing aberrations in the focal spot. The two effects can be analysed as independent phenomena by means of:

$$\frac{df}{dT} = \underbrace{\frac{\partial f}{\partial n} \cdot \frac{\partial n}{\partial T} \cdot dT}_{\text{Refractive Index}} + \underbrace{\frac{\partial f}{\partial R} \cdot \frac{\partial R}{\partial T} \cdot dT}_{\text{Geometry}} \quad (2.18)$$

In this work, only the refractive index variation is studied as the geometrical effect is negligible. For silica the thermal expansion is $\alpha \sim 5 \cdot 10^{-7}$ and refractive index variation is $\frac{\partial n}{\partial T} \sim 4 \cdot 10^{-5}$. This means that the influence of the geometrical effect is around two orders of magnitudes lower than the influence of the refractive index variation.

Transfer Matrixes

With the use of paraxial (linear) optics it is possible to simulate the focal spot from the incident laser beam. Mathematically, the beam is defined by its phase-space. The focal spot or image space ($\bar{s}_1$) is calculated from the incident laser beam or object space ($\bar{s}_0$) through a linear transformation characterized by the transfer matrix (M):

$$\bar{s}_1 = M \cdot \bar{s}_0 \quad (2.19)$$

Where $\bar{s}$ is the phase-space of the beam, composed by its deviation from the central path (s) and its divergence (s'):

$$\bar{s}_0 = \begin{pmatrix} s_0 \\ s'_0 \end{pmatrix} \quad \bar{s}_1 = \begin{pmatrix} s_1 \\ s'_1 \end{pmatrix} \quad (2.20)$$

The transfer matrix M is the composition of the different optical elements of the system. Which can be summarized in focusing components, characterized the focal distance, f , and drift components characterized by the drift length, l :

$$M = M_{drift} \cdot M_{focus} \cdots = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \cdots \quad (2.21)$$

The final lens has an axial symmetry, focusing only in the radial direction. Therefore the use of polar coordinates greatly simplifies the problem.

We define the object space ($\overline{s_0}$) in polar coordinates (ρ, φ), and its base (u_ρ, u_φ). We also define the image space ($\overline{s_1}$) in the object base through the factors r_ρ and r_φ . Therefore we have:

$$\begin{aligned}\overline{s_0} &= \begin{pmatrix} s_0 \\ s'_0 \end{pmatrix} = \begin{pmatrix} \rho \cdot u_\rho \\ \rho' \cdot u_\rho + \rho \cdot \varphi' \cdot u_\varphi \end{pmatrix} \\ \overline{s_1} &= \begin{pmatrix} s_1 \\ s'_1 \end{pmatrix} = \begin{pmatrix} r_\rho \cdot u_\rho + r_\varphi \cdot u_\varphi \\ r'_\rho \cdot u_\rho + r'_\varphi \cdot u_\varphi \end{pmatrix}\end{aligned}\tag{2.22}$$

The object space is converted into the image space through transfer matrices. A focusing lens only focuses the radial component ($\rho \cdot u_\rho$), acting as a drift length (l) for the polar component ($\rho \cdot \varphi' \cdot u_\varphi$). Therefore, radial and polar components are independent and two systems are created:

$$\begin{pmatrix} r_\rho \cdot u_\rho \\ r'_\rho \cdot u_\rho \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \rho_0 \cdot u_\rho \\ \rho' \cdot u_\rho \end{pmatrix}\tag{2.23}$$

$$\begin{pmatrix} r_\varphi \cdot u_\varphi \\ r'_\varphi \cdot u_\varphi \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ \rho \cdot \varphi' \cdot u_\varphi \end{pmatrix}\tag{2.24}$$

With [Equations \(2.23\) and \(2.24\)](#), the image space is calculated in polar coordinates (r_ρ, r_φ). Finally we transform the image space to Cartesian coordinates (x_1, y_1):

$$\begin{pmatrix} x_1 \\ y_1 \end{pmatrix} = \begin{pmatrix} r_\rho \cdot \sin(\varphi) - r_\varphi \cdot \cos(\varphi) \\ r_\rho \cdot \cos(\varphi) + r_\varphi \cdot \sin(\varphi) \end{pmatrix}\tag{2.25}$$

Laser beam raytracing

With the previous system the focal spot from an incident laser beam is calculated. The aberrations in the focal spot are introduced in [Equation \(2.23\)](#) by the geometrical dependence of the focal distance, $f(\rho, \varphi)$.

In an ideal system, without aberrations, the focal spot is defined by a supergaussian distribution:

$$I_{SG} = I_0 \cdot e^{\left(\frac{\sqrt{x_1^2 + y_1^2}}{r_0} \right)^{-m}} \quad (2.26)$$

Where I_{SG} is the laser energy profile in the focal spot, I_0 is the nominal laser intensity, r_0 the size of the focal spot, m the supergaussian coefficient (2 for a Gaussian distribution), and x_1, y_1 the local coordinates in the focal spot.

In order to minimize the effects of discretization, it is possible to characterize the focal spot as the convolution product of the ideal super-gaussian focal spot (I_{SG}) by the aberration focal spot ($I_{Ab.}$). The ideal focal spot, Equation (2.26), is a continuous analytical expression, while the aberration focal spot is the result of focusing a point beam², which gives a discrete distribution, $I_{Ab.}(x_i, y_j)$, as observed in Figure 2.13 (b).

Using the convolution product we minimize the effect of discretization in our simulations. Therefore, we obtain a continuous focal spot that is the summation (convolution) of deviated (aberrated) supergaussian spots:

$$I(x, y) = I_{SG} * I_{Ab.}(x, y) = \sum_{i,j} I_{Ab.}(x'_i, y'_j) \cdot I_{SG}(x - x'_i, y - y'_j) \quad (2.27)$$

In order to calculate the aberrated focal spot, we do the raytracing using a MonteCarlo approach that simulates n particles following the supergaussian distribution. From the position of the n particles we extract a histogram, see Figure 2.13 (a), that discretely characterizes intensity in the focal spot $I(x_i, y_j)$.

Superposition of 48 laser beams

With the previous model we estimate the focal spot of one laser beam. However in ICF, the target is illuminated by a multitude of laser beams. In this work we use the schema of HiPER (see Section 1.2), based on 48 lasers into for spherical illumination of the target [27]. For the addition of the $N_L = 48$ beams, we calculate the laser intensity in a target of radius R .

²A point beam has a focal spot that follows Dirac delta distribution.

Each beam is characterized by its local base (u_x^l, u_y^l, u_z^l) . Where u_z^l is the laser direction, and u_x^l, u_y^l the other two components of the base. Therefore for each point in the target (x, y, z) , we can calculate its position in local laser coordinates (x^l, y^l, z^l) as:

$$\begin{pmatrix} x^l \\ y^l \\ z^l \end{pmatrix} = \begin{pmatrix} u_x^l \\ u_y^l \\ u_z^l \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad (2.28)$$

The total laser intensity is the summation over the different beams ³:

$$I(x, y, z) = \sum_{l=1}^{N_L} I(x^l, y^l, z^l) \approx \sum_{l=1}^{N_L} I(x^l, y^l) \quad (2.29)$$

Once the laser intensity in one point of the target is obtained, the process is repeated for n random points. Thus, we obtain the laser energy deposition in n points, which allows us to estimate the lens optical performance, see Figure 2.13 (c).

If a continuous estimation of the laser energy deposition is required it is possible to convert the n the random points into a mesh through Delaunay triangulation [133], as observed in Figure 2.13 (d).

Figures of Merit

From the previous expressions, the laser energy deposition profile in the target is obtained. An evaluation of the final lens optical performance is necessary to assess the validity of the final lens system. In particular, the effect of aberrations on the illumination uniformity must be addressed. A poor uniformity level will lead to instabilities during the target compression process.

The illumination uniformity level is quantified through its standard deviation (σ):

$$\sigma = \frac{\left(\int (I(\Omega) - \bar{I})^2 d\Omega \right)^{1/2}}{\sqrt{4\pi} \cdot \bar{I}} \quad (2.30)$$

³In our case the intensity in the focal spot is almost constant axially, therefore the simplification $I(x^l, y^l, z^l) \approx I(x^l, y^l)$.

Figure 2.13: Results for the calculation of the optical aberrations. a) focal spot for one laser beam, d) focal spot aberrations from an ideal object space with no divergence, c) laser energy deposition intensity in the target for n random rays, d) laser intensity map over the target surface calculated with Delaunay triangulation.

Where $\bar{I}$ is the average intensity, I the intensity at the target surface and Ω the integration variable.

To guarantee that the illumination uniformity is suitable for ignition, σ should be kept below 1% [33]. Although the illumination uniformity (σ) is the most important parameter, we also studied the efficiency of laser deposition (η). The efficiency is calculated as the ratio of power deposited in the target to the laser power.

$$\eta = \frac{\int I(\Omega) d\Omega}{P_0} \quad (2.31)$$

Where I is the laser intensity, Ω the integration variable over the target surface and P_0 is the laser power.

Code Validation

In order to validate the raytracing code we compared the geometrical non-uniformities (σ) of the model with the analysis done by Temporal and Canaud in Ref. [33].

For this purpose we study the illumination uniformity level (σ) for different supergaussian profiles, see Equation (2.26). We study the variation of σ , as function of the coefficient m and its focal spot size r_0 . Then we compare our results to those obtained by Temporal and Canaud for the same HiPER configuration in Ref. [33]. We show the comparison in Figure 2.14, where we observe the same results, where the minimums of the non-uniformities are obtained for $m = 2$, $r_0/R = 0.62$ and $m = 4$, $r_0/R = 4$, having values of $\sigma \sim 0.16\%$.

Figure 2.14: Standard deviation (σ) for a laser deposition as a function of the beam supergaussian parameters m and r_0 . a) Results with the raytracing code used in this work, b) results from Ref. [33].

Chapter 3

Irradiation of Fusion Materials

One of the challenging tasks in fusion reactors is the development of materials able to withstand the hostile environment (high thermal loads and atomistic damage) during power plant operation. In this Chapter we characterize the irradiation conditions that will take place in the HiPER project (see [Section 1.2](#)). The irradiation can be divided in neutron irradiation, deposited uniformly in the material and ion and X-ray irradiation deposited in the first micrometers of the irradiated surface.

In order to study neutron irradiation we use the methodology described in [Section 2.2](#). We analyze neutron irradiation, estimating the main irradiation parameters, such as the irradiation spectra, damage rates (dpas), gas formation or the spectra of recoils (PKA spectra). We discuss neutron irradiation for structural steel, tungsten first wall and silica final lenses. In the case of silica we estimate the formation of colour centres and the absorption coefficients for ICF laser wavelengths.

Regarding ion and X-ray irradiation we discuss the irradiation spectra and summarize its effects on tungsten. For this purpose we use the methodology described in [Section 2.3](#), and analyse temporal and spatial distribution. In order to estimate the irradiation effects we discuss the use of the heat flux factor to define a damage threshold. Regarding ion irradiation in silica we devote [Chapter 4](#) to its study. In [Chapter 4](#) we discuss in detail how ion irradiation affects silica surface densification, and develop a model to describe its evolution under different irradiation fluences.

Summarizing, in this Chapter we intend to give an overview of the irradiation conditions and its main effects on tungsten and silica. In further Chapters we discuss in more detail some aspects of irradiation (track compaction, crack formation) and study

its technological implications. In this context in [Chapter 5](#) we give a conceptual design for HiPER silica final lenses and in [Chapter 6](#) we discuss different aspects for the design of the HiPER tungsten First Wall.

3.1 HiPER Irradiation Conditions

Fusion energy power plants are based on the DT reaction. This reaction produces a fast neutron (14.1 MeV) and an alpha particle (3.5 MeV). Partial thermalization of the fusion products, the contribution of secondary fusion reactions (D-T, D-He) and the target debris complete the irradiation spectra.

We study the irradiation conditions for the different HiPER scenarios (see [Section 1.2](#)). The irradiation spectra is obtained from the Aries project for a 154 MJ direct target [104]. For HiPER Demo, the spectrum of a 154 MJ target yield is shown in [Figure 3.1](#). For HiPER Experimental and Prototype facilities, the target yields is rescaled to 20 and 50 MJ respectively.

In [Table 3.1](#) we summarize the energy yields for the different irradiation species. The most significant contributions are due to fusion neutrons ($\sim 71\%$ of target yield), energetic burn products (H, D, T, He) and debris (D and T ions from non-burnt plasma and low energy He). Heavier ions, such as C or Au, carry only around 0.5% of the total energy, but are relevant since its mitigation is more complicated than for lighter ions. In total, ions carry nearly 27% of the total energy released by the explosion. The remaining energy is carried by X-rays ($\sim 2\%$).

In order to have a full picture of irradiation conditions in ICF materials, we describe *i*) neutron irradiation in [Section 3.2](#), *ii*) ion and X-ray irradiation on tungsten in [Section 3.3](#) and *iii*) ion irradiation on silica in [Chapter 4](#).

Figure 3.1: Irradiation spectra in HiPER Demo with the explosion of a direct drive target with a yield of 154 MJ.

Table 3.1: Particle yield, energy yield and mean energy for different species in direct drive target with a yield of 154 MJ used for HiPER Demo.

Radiation form		Particle Yield #/shot	Energy Yield		Mean Energy (MeV)
			MJ/shot	(%)	
Burn	H	$1.3 \cdot 10^{18}$	0.5	0.4%	2.5
	D	$8.6 \cdot 10^{18}$	4.8	3.1%	3.5
	T	$1.0 \cdot 10^{19}$	4.3	2.8%	2.7
	3He	$1.5 \cdot 10^{16}$	0.002	0.002%	1.0
	He	$1.6 \cdot 10^{19}$	9.9	6.4%	3.8
Burn Total		$3.6 \cdot 10^{19}$	19.5	12.6%	13.5
Debris	H	$7.5 \cdot 10^{18}$	0.1	0.07%	0.09
	D	$3.9 \cdot 10^{20}$	8.9	5.7%	0.14
	T	$3.7 \cdot 10^{20}$	11.1	7.2%	0.19
	3He	$6.8 \cdot 10^{16}$	0.0	0.001%	0.18
	He	$3.6 \cdot 10^{19}$	1.3	0.9%	0.23
	C	$5.3 \cdot 10^{18}$	0.6	0.4%	0.66
	Au	$6.1 \cdot 10^{16}$	0.2	0.10%	15.4
Debris Total		$8.1 \cdot 10^{20}$	22.1	14.3%	16.9
Ions Total		$8.5 \cdot 10^{20}$	41.6	27%	30.4
X-rays		-	2.1	1.4%	-
Neutrons		$4.9 \cdot 10^{19}$	109	71%	13.8
Total		$2.8 \cdot 10^{21}$	154	100%	0.9

3.2 Neutron irradiation

3.2.1 Fluxes, Gas Formation, PKAs spectra and damage production

Neutron irradiation is deposited uniformly, heating the irradiated material and creating defects and impurities. The defects are created mainly through collisions, while impurities, remarkably H and He, appear through transmutation. Low energy ($< \text{MeV}$) neutrons mainly interact with matter by means of elastic collisions, whereas high energy ($> \text{MeV}$) neutrons also produce inelastic processes, leading to the generation of light species and gamma emission.

In order to evaluate neutron damage we use the methodology described in [Section 2.2](#). We consider several aspects, such as the flux intensity, flux spectra, PKA spectra, damage production (dpa) and gas formation. In [Table 3.2](#) the main parameters for irradiation in HiPER Demo for steel (iron) Structural Material, tungsten First Wall, and silica Final Lenses are summarized.

We study the irradiation conditions of steel (iron) in HiPER to characterize the facility. In fact, in [Chapter 7](#) we use irradiation conditions in iron in order to compare HiPER to other irradiation facilities.

Regarding neutron irradiation in a steel (iron) structural material, in [Table 3.2](#) we observe that HiPER Demo has damage rates of ~ 7 dpa/fpy and gas formation of ~ 300 appm/fpy and ~ 100 appm/fpy for H and He, respectively. It is expected that RAFMS steels can keep its structural conditions up to ~ 10 -20 dpa [22]. Thus, operation for around 2-3 years could be possible. Chamber replacement every several years is a

Table 3.2: Main irradiation conditions in HiPER Demo. Irradiation conditions in the iron Structural Material, tungsten First Wall and silica Final Lenses.

	Iron	Tungsten	Silica
Distance to neutron source (cm)	650	650	1600
Neutron flux ($\text{m}^{-2}\text{s}^{-1}$)	$1 \cdot 10^{18}$	$1 \cdot 10^{18}$	$2 \cdot 10^{17}$
Average Power density (kW m^{-3})	6830	8115	510
Damage (dpa/fpy)	7.3	1.6	0.25
H (appm/fpy)	306	3	49
He (appm/fpy)	97	0.7	83
H/dpa	42	1.9	72
He/dpa	13	0.5	122

feasible approximation for first ICF reactor, due to its modular integration [4].

Regarding neutron irradiation in tungsten, we observe that damage rates reach $\sim 1\text{--}2$ dpa/fpy. Gas formation is lower because high production rates only appear for more energetic neutrons ($E > 14$ MeV). Neutron irradiation will lead to gas formation of ~ 3 appm/fpy and ~ 0.7 appm/fpy for H and He respectively. Transmutation of tungsten to rhenium $\sim 0.25\%$ /fpy should also be considered [87, 134]. The main effects of neutron irradiation in tungsten are swelling, hardening, and thermal conductivity decrease [134–136] in the long term operation (years).

Neutron irradiation in silica leads to damage rates ~ 0.25 dpa/fpy with gas formation of ~ 50 appm/fpy and ~ 80 appm/fpy for H and He, respectively. The effects of neutron irradiation turn out critical for the silica final lenses. This is due to the formation of colour centres that absorb in certain bands with potential detrimental effects over the transmitted laser flux, in addition to adverse effects inside the lenses as a consequence of the irradiation damage. In the next section we discuss in detail these effects.

In Figure 3.2 we provide the Primary Knock-on Atom (PKA) spectra generated in iron, tungsten and silica. We observe that the lighter oxygen atoms of silica can reach recoil energies up to ~ 5 MeV, while silicon atoms reach up to ~ 3 MeV and heavier Fe or

Figure 3.2: PKA spectra for iron (red), tungsten (green) and silica (blue) under the irradiation conditions in HiPER Demo. For silica we show the oxygen (blue dashed), silicon (blue dotted) and total (blue straight) PKAs spectra.

W recoils get maximum energies around 0.1-1 MeV. Regarding the effects of the PKAs in silica, they induce changes of electronic excitation origin in density, stoichiometry and optical properties, for stopping power of the order of 2-6 keV/nm [137–143]. However, only a negligible fraction of the total recoils in silica reach this threshold stopping power. In iron, the threshold for electronic damage exceeds 25 keV/nm [144], which cannot be reached with the Fe recoils expected in the HiPER First Wall.

3.2.2 Formation of colour centres in silica

Silica final lenses will be exposed to severe irradiation conditions in laser fusion facilities where thousands of pulses will be reached in a range of minutes. An important effect is the generation of colour centres following neutron irradiation. These colour centres produce laser absorption with fatal consequences for the plant operation.

The typical structure of SiO_2 , is a 4-fold bond, with each silicon atom bonded to 4 oxygen atoms. When a neutron collides with a nucleus, different types of defects are generated, with different absorption wavelengths.

The most interesting defects are the Oxygen Deficient Centres (ODC) and E' -centres [63, 64, 66, 145, 146]. ODC form when an oxygen is displaced and a 3-fold on the Si is formed, with the resting covalent bond between two Si [64]. This covalent bond can be ionized upon the arrival of gamma irradiation generating E' centres. Finally, when the displaced oxygen encounters a defect an annealing process may take place.

The ODC and E' defects are relevant for ICF applications, since their main absorption bands may partially contain the laser wavelength. This is so because absorption of ODC peaks at wavelengths of 248 nm, and the absorption of E' centres at 214 nm [147]. The absorption takes place in a broad wavelength range, containing the third and fourth harmonics (351 nm and 262 nm, respectively) of solid state lasers based on Nd-glass as those used in laser fusion.

We have calculated the colour centre production in silica making use of the model proposed by Marshall et al. [63] and reviewed by Latkowsky et al. [66]. This model was also used by Rivera et al. and Garoz et al. [14, 15] for the analysis of colour centre formation in HiPER final lenses.

The model calculates the defect concentration from the irradiation dose rates (D), the ODC to E' conversion (β) and the annealing factor (τ). Taking into account all

these factors the evolution of the defect concentration is described as:

$$\frac{dN_{ODC}}{dt} = M_n \cdot D'_n - \beta'_{E'} \cdot D'_\gamma \cdot N_{ODC} - N_{ODC}/\tau \quad (3.1)$$

$$\frac{dN_{E'}}{dt} = \beta'_{E'} \cdot D'_\gamma \cdot N_{ODC} - N_{E'}/\tau \quad (3.2)$$

Where N_{ODC} is the concentration of ODC, $N_{E'}$ the concentration of E'-centres, τ is the annealing time for defects; M_n is the number of defects per PKA; $\beta_{E'}$ accounts for the ODC to E' conversion; D'_γ is the gamma dose rate, D'_n is the neutron dose rate and τ is the characteristic annealing time (τ).

The annealing term variation with temperature can be approximated to an exponential law:

$$\frac{\tau}{\tau_0} \approx e^{\frac{T_0}{T}} \quad (3.3)$$

Where τ_0 is the annealing time at a temperature T_0 . Finally, from the defect concentration the absorption coefficient (α) can be calculated as:

$$\alpha(\lambda) = \sum_i \sigma_i \cdot N_i \cdot L_i(\lambda) = \sum_i \alpha_i \cdot L_i(\lambda) \quad (3.4)$$

$$L_i(\lambda) = \frac{1}{1 + \frac{(\lambda_i - \lambda)^2}{\Delta\lambda_i^2}} \quad (3.5)$$

Where α_i is the absorption coefficient of a defect i ; σ_i the defect production cross section; N_i the defect concentration; λ the absorption wavelength, λ_i the peak wavelength for a defect i and $\Delta\lambda_i$ the half width, and the inclusion of $L_i(\lambda)$ comes from the lorentzian approximation of the microscopic absorption coefficient. The values used for the parametric model are listed in [Table 3.3](#).

Using the previous model we estimate the colour centre concentrations and absorption coefficient in HiPER scenarios at different temperatures. In the different HiPER scenarios, a total absorption of at most 1%, is considered acceptable. This means for lenses of thickness in the few cm range that the absorption coefficient should be kept below $\sim 10^{-2} \text{ cm}^{-1}$.

Table 3.3: Parameters for silica used in the colour centre model.

Parameter			Parameter		
σ_{ODC} (m ²)	$1.70 \cdot 10^{-13}$	[66]	$\sigma_{E'}$ (m ²)	$3.20 \cdot 10^{-13}$	[66]
λ_{ODC} (nm)	248	[147]	$\lambda_{E'}$ (nm)	214	[147]
$\Delta\lambda_{ODC}$ (nm)	13	[147]	$\Delta\lambda_{E'}$ (nm)	15	[147]
$\beta_{E'}$ (Gy ⁻¹)	$7 \cdot 10^{-5}$	[66]	τ_0 (s)	$4 \cdot 10^{-10}$	[66]
M_n ($\frac{\text{defects}}{\text{keV-PKA}}$)	0.37	[66]	T_0 (K)	21000	[66]

In Figure 3.3 (a) the defect evolution for HiPER Demo is shown. The temperature determines the defect evolution in silica, because defect annealing is a thermally activated process. When defect formation and annealing are at equilibrium a steady state is reached. The steady state is reached in ~ 100 s at 850 K while is not yet observed in ~ 1000 s at $T < 700$ K. If we compare the formation of E' and ODC, we observe that at low temperatures the presence of E' centres is much higher. This is because at high temperature ODC anneal out before ODC-E' conversion takes place, therefore the presence of E' centres is relatively much lower.

Regarding the evolution of the absorption coefficient, see Figure 3.3 (b), we observe that for temperatures of ~ 850 K, annealing already has a strong effect, with absorption coefficients $\sim 10^{-2}$ cm⁻¹ in the 350 nm wavelength.

Regarding the absorption spectra, see Figure 3.3 (c), at low temperature the absorption due to E' centres is the dominant effect, while at high temperature the ODC defects are the main contributor to absorption. We observe this effect looking at the large peak centred at 248 nm due to OCD defects, and to the peak at 213 nm associated to E'-centres. Due to the broad absorption band, the absorption spectrum extends beyond the 350 nm band.

In Figure 3.3 (d) the absorption coefficient as a function of the temperature is shown. It is observed that the annealing process becomes effective for temperatures higher than 700 K, and with low absorption coefficients (< 1 cm⁻¹) for temperatures higher than 800 K.

In this section we outline the effect of neutron irradiation on silica, describing the formation of colour centres. The formation of colour centres has technological implications on the development of ICF final lenses. In Chapter 5 we discuss in detail its implications, and develop the design of a temperature control system for the HiPER final lenses.

Figure 3.3: a) Time evolution of the ODC and E' defects until the stationary regime is attained. b) time evolution of absorption coefficient for wavelengths of 350 nm c) absorption coefficient in stationary regime for different wavelengths, and d) absorption coefficient in stationary regime for different temperatures. The analysis is done for the irradiation conditions in HiPER Demo.

3.3 Ion and X-ray irradiation of tungsten

In this section we describe the ion and X ray irradiation spectra and summarize their effects on tungsten. We specifically analyse the heat flux factor and compare it to an experimental damage threshold. In [Chapter 6](#) we describe the design for HiPER tungsten First Wall, discussing the implications of irradiation and analysing its thermomechanical effects, fatigue and crack formation

3.3.1 Irradiation Spectra

Ion and X-ray irradiation takes place in the first microns of the irradiated material, which leads to high thermal loads with deleterious thermomechanical effects. These high thermal loads combined with atomistic damage can lead to crack networks, roughening, blistering and erosion of the irradiated surface.

Accurate calculation of the thermomechanical response of the First Wall to irradiation requires a proper knowledge of the temporal and depth distribution of the deposited energy [13]. For this purpose we use the methodology described in Section 2.3. Next, we describe the irradiation temporal and depth distribution for the different HiPER scenarios described in Section 1.2: HiPER Experimental, Prototype and Demo.

In Figure 3.4 (a) we observe how for HiPER Demo, X-rays arrive almost immediately (~ 22 ns) after the ignition, followed by fast burn products (D, T and He at ~ 0.65 μ s) and debris ions (slow D,T and He at ~ 1.5 μ s). For HiPER Prototype the ion arrival follows the same pattern as for Demo but with targets of lower yield (50 MJ instead of 154 MJ). For HiPER Experimental (smaller chamber) the irradiation arrival is faster (~ 17 ns for X-rays, ~ 0.36 μ s for fast D, T and He and ~ 1.1 μ s for slow D,T) but with targets of lower yields (20 MJ instead of 154 MJ). Therefore, the energy deposition in the First Wall takes place within times lower than 10 μ s.

The distribution depth of the deposited energy in a tungsten First Wall for HiPER Demo is shown in Figure 3.4 (b). We observe that X-ray deposit most of its energy in the first micrometer, deuterium and tritium in the firsts 2 μ m, and most of helium

Figure 3.4: a) Power per unit area as a function of time and b) energy fluence as a function of depth. The figure shows the results for the tungsten first wall in the HiPER Demo facility.

irradiation goes up to $\sim 4 \mu\text{m}$. In total it is important to note that more than 50% of the energy carried by X-rays and ions is deposited in the first few μm of the First Wall and around 90% is deposited in the first 5 μm . The rest (10%) is deposited within depths up to 100 μm by the most energetic ions ($>1 \text{ MeV}$). According to simple consideration, the thickness of the First Wall must be at least 100 μm in order to stop all the ions before they reach the substrate.

3.3.2 The Heat Flux Factor, F_{HF}

In the previous section the irradiation conditions in the tungsten first wall are described. Next, we discuss the use of the heat flux factor, F_{HF} , in order to describe thermomechanical effects of irradiation.

The thermomechanical effects of irradiation are derived from the heating of the irradiated surface. Analytically, the irradiation can be simplified as a surface flux. For a surface heat flux the temperature can be expressed as [148, 149]:

$$\Delta T_{FHF} = 2 \cdot P \cdot \tau^{1/2} \cdot (\pi k \rho c)^{-1/2} = 2 \cdot F_{HF} \cdot (\pi k \rho c)^{-1/2} \quad (3.6)$$

$$F_{HF} = P \cdot \tau^{1/2} \quad (3.7)$$

Where ρ , c , k are the material density, specific heat and conductivity, P is the energy flux, τ the pulse duration and F_{HF} is the heat flux factor.

As we observe in Equation (3.6), it is possible to make an estimation of the temperature analysing the heat flux factor (F_{HF}) [148–150]. Therefore, this parameter constitutes a simple method to normalize the thermomechanical effects of irradiation with pulses of different durations.

It is important to point out that the use of F_{HF} in order to describe thermomechanical effects is only valid when heat diffusion effects are dominant and irradiation can be simplified as a surface flux. On the contrary, irradiation with short pulses (τ) or high penetrating depths (L) can be characterized as an adiabatic heating:

$$\Delta T_{Vol.} = \frac{P \cdot \tau}{L} \cdot \frac{1}{\rho \cdot c} \quad (3.8)$$

Taking the ratio between the surface flux, Equation (3.7), and adiabatic heating, Equation (3.8), temperature estimations, we can define a heat diffusion length, L_{dif} , as:

$$\frac{\Delta T_{HHF}}{\Delta T_{Volu.}} = \frac{2 \cdot P \cdot \tau^{1/2} \cdot (\pi k \rho c)^{-1/2}}{\frac{P \cdot \tau}{L} \cdot \frac{1}{\rho c}} = \frac{L}{\frac{1}{2} \sqrt{\frac{\pi k \tau}{\rho c}}} = \frac{L}{L_{dif}} \quad (3.9)$$

$$L_{dif} = \frac{1}{2} \sqrt{\frac{\pi k \tau}{\rho c}} \quad (3.10)$$

If $L/L_{dif} \ll 1$ heat diffusion effects are dominant, while for $L/L_{dif} \gg 1$ adiabatic heating is dominant. For X-ray irradiation due to the short irradiation pulses, L/L_{dif} is >10 and its effect correspond to an adiabatic heating that cannot be characterized through the use of F_{HHF} . In the case of tungsten under ICF irradiation conditions, L/L_{dif} is ~ 0.05 for debris ions and ~ 1 for burn ions. Therefore, the effects of debris irradiation are well explained with the F_{HHF} factor. Since debris irradiation leads to most detrimental effects (see Chapter 6), overall thermomechanical effects can be addressed through the use of F_{HHF} in the case of ICF.

3.3.3 Damage Threshold

As we explain in the previous section, the heat flux factor F_{HHF} can be used to describe effects of pulsed ion irradiation on ICF materials. Therefore we use it in order to compare the irradiation conditions expected in HiPER with the effects observed in experimental campaigns.

A relevant experimental campaign of pure tungsten irradiation was done by Renk et al. [151, 152]. In these experiments effects of irradiation with nitrogen with pulses of $\sim 0.3 \mu s$ and energies in the 0.4-0.8 MeV range were studied. For irradiation at room temperature, damage appeared after a low number of cycles (50-100) at energy fluences per pulse of $\sim 1.25 \text{ J/cm}^2$, which results in a heat flux factor threshold, $F_{HHF} \sim 23 \text{ MW m}^{-2} \text{ s}^{0.5}$. For higher energy fluences, surface roughening and micro-cracks leading to erosion and mass loss in the surface region are observed. The different damage effects are related to the thermomechanical response of the material, which depends on the heat flux factor. Linke et al. [150] compared damage appearance in different type of facilities (electron, plasma and ion beam) and different pulse durations (from μs to s).

For the different cases, roughening was observed to appear at $F_{HF} \sim 20 \text{ MW m}^{-2} \text{ s}^{0.5}$, cracking effects from $\sim 20\text{-}50 \text{ MW m}^{-2} \text{ s}^{0.5}$, melting at $\sim 100 \text{ MW m}^{-2} \text{ s}^{0.5}$, and boiling at $\sim 200 \text{ MW m}^{-2} \text{ s}^{0.5}$.

The previous values are orientative for irradiation with a low number of cycles at room temperature. However the irradiation temperature has a strong effect on crack formation and propagation. At higher temperatures, tungsten has a more ductile behaviour showing better mechanical properties and improving fracture toughness [153], which helps irradiation resistance leading to higher damage thresholds [154]. On the other hand, repetitive irradiation leads to the appearance of fatigue effects which may appear at lower thresholds at $\sim 3\text{-}5 \text{ MW m}^{-2} \text{ s}^{0.5}$ for $10^5 - 10^6$ number of cycles [155].

Also, beam irradiation (as with nitrogen in Refs. [151, 152]) turns out appropriate to study the thermomechanical loading, however light ions, and in particular helium, induce additional effects, such as the formation of bubbles, which lead to stress concentration, swelling and enhanced surface erosion [156, 157]. Pulsed He irradiation experiments carried out with ion energy of $\sim 0.5 \text{ MeV}$, pulse duration of $0.5 \text{ }\mu\text{s}$ at energy fluences $\sim 1 \text{ J/cm}^2$ and beyond remarkably low accumulated ion fluence threshold, $4 \cdot 10^{15} \text{ cm}^{-2}$, [156] show different irradiation effects (pores, surface protrusions, bubbles related to stress cracks, enhanced roughening). Note that the ion fluence threshold for these effects under pulsed irradiation is at least two orders of magnitude lower than the threshold for low flux He irradiation-induced pore formation. Associated to these effects, mass loss takes place, which leads to unacceptable erosion for continuous operation. Furthermore, H irradiation enhances damage effects, inducing hydrogen embrittlement of tungsten [158, 159]. Regarding X-ray irradiation, due to the short pulses ($\sim 0.1 \text{ ns}$) its effects correspond to an adiabatic heat and cannot be characterized through the use of the heat flux factor. For X-ray irradiation no damage is expected for single shot fluences up to $\sim 1 \text{ J/cm}^2$ [151], however this threshold should be assessed under repeated irradiation. The damage thresholds also differ for different forms of tungsten, depending on the tungsten composition and microstructure. For example grain oriented tungsten or W-Re alloys have a higher initial roughening threshold than randomly oriented tungsten, however lower stability is observed, with the threshold decreasing with irradiation [156].

In Table 3.4 we show the energy fluences and heat flux factor, F_{HF} , for the different HiPER scenarios. For the X-rays, the energy fluences are 0.09 , 0.13 and 0.4 J/cm^2 for Experimental, Prototype and Demo, respectively, which is below 1 J cm^{-2} [151] reported for damage. For the case of ion irradiation burn products and debris lead

Table 3.4: Energy, pulse duration, depth range and energy fluence for the different irradiation types in the scenarios of HiPER. Radiation spectra from ARIES project [104].

Radiation Form	Pulse width (ns)	Mean Depth Range (μm)	Energy Fluence (J/cm^2)			F_{HF} ($\text{MW m}^{-2}\text{s}^{0.5}$)		
			Exp.	Proto.	Demo	Exp.	Proto.	Demo
X-rays	0.1	2.0	0.1	0.1	0.4	-	-	-
Burn Ions	600	8	0.8	1.2	3.7	10.4	15.4	47.3
Debris Total	2000	0.5	0.9	1.3	4.0	6.2	9.2	28.5
Ions Total	3000	4.2	1.7	2.5	7.7	9.7	14.4	44.4

to similar deposited energy fluences but arrive at different times, with shorter pulses in the case of burn ions, which leads to more detrimental effects. Analysing the heat flux factor, F_{HF} , for burn ions, we obtain $F_{\text{HF}} = 10.4, 15.4$ and $47.3 \text{ MW m}^{-2} \text{ s}^{0.5}$ for Experimental, Prototype and Demo. Comparing these values to the F_{HF} damage threshold $\sim 23 \text{ MW m}^{-2} \text{ s}^{0.5}$ [151], we observe that HiPER Experimental is below the damage threshold. However, the values obtained for HiPER Prototype and Demo are close to or above the damage limit.

In this section we have described the irradiation spectra and we have studied the use of the heat flux factor in order to define a damage threshold. In Chapter 6 we discuss the irradiation implications on the design of the HiPER tungsten First Wall, describing in detail temperature, stress profiles, fatigue and crack propagation in the different HiPER scenarios.

Chapter 4

Ion irradiation of Silica

In this Chapter we discuss effects of ion irradiation in silica under ICF expected conditions.

In previous works [14, 15] it was concluded that ion irradiation should be mitigated from HiPER final lenses in order to avoid critical silica surface damage. However the question arises on whether even the small fraction of swift heavy ions from target debris should be mitigated or not. This question is relevant since swift heavy ions mitigation requirements are more exigent than for light species. In order to answer to this question an experimental campaign was carried by O. Peña-Rodríguez et al. [120] at CMAM facilities.

The experimental results were surprising, at low irradiation fluence they showed surface compaction, as expected, but at high fluences a density drop was observed, which was not explained by previous models. After a first unsuccessful attempt to explain track compaction [20], in this Chapter we develop a model that seems to successfully explain silica surface density at different irradiation fluencies. Most of the results discuss in this Chapter will be published also in Ref. [21].

We use the methodology presented in Section 2.4, using Molecular Dynamics (MD) and Finite Elements Methods (FEM) in order to explain track compaction at low and high irradiation fluences. Then we develop a parametrical model that describes surface compaction at different fluences and compare it with the experimental results, observing good agreement.

Regarding the implications of this study for ICF, we conclude that even small fraction of heavy ions should be mitigated from the final lenses. Full mitigation is required in

order to avoid surface compaction that can have critical effects on laser focusing.

In this Chapter we try to give a fundamental description of effects of ion irradiation in silica. In [Chapter 5](#) a more technological approach is followed, giving a conceptual design for the design of HiPER final lenses and proposing an ion mitigation system.

4.1 Introduction

Ion irradiation on dielectric materials unleashes several processes, like ionization and the formation and subsequent decay of defects, governed by heat diffusion and atomic rearrangement. Finally, the mechanical properties are altered in the irradiated region. Strain and stress fields appear, densification takes places and other properties such as the refractive index are affected.

From a thermomechanical point of view, what can be observed after irradiation is a surface heating that leads to expansion of the irradiated surface and compression stresses. In previous works [[14](#), [15](#)], the effects of ion irradiation in silica were already studied. These works showed that ion irradiation leads to high surface temperatures that will produce damage on silica surface just after a few shots. Therefore a mitigation strategy will be necessary for ion irradiation in silica.

We have estimated the temperature in silica under the irradiation conditions expected in the HiPER Demo scenario. For this estimation we adapt the CodeAster model described in [Section 2.3](#) for irradiation in silica. In [Figure 4.1](#) we observe how the temperature increases during the pulse duration and cools down in-between pulses. We observe that the temperature operational limit is attained just after one pulse (~ 1223 K [[126](#)]), and the temperature peak is near melting point (~ 1900 K) at every shot. Under these conditions it will not be possible to operate the lens and some system for ion mitigation is required. If we limit irradiation to the arrival of only swift heavy ions (Au, C), we observe that its arrival would only increase ~ 10 K the surface temperature. Allowing swift heavy ions arrival would relax design requirements for ion mitigation system (see [Section 5.4](#)).

Next we discuss the effects of swift heavy irradiation. For this purpose we analyze the experimental results, discuss MD and FEM simulations and develop a parametrical model for irradiation compaction at different irradiation fluences.

Figure 4.1: Temperature variation after irradiation in silica final lenses assuming total ion irradiation and only heavy ions in the HiPER Demo scenario.

4.2 Swift Heavy Ion irradiation

Irradiation of silica with swift heavy ions (i.e., with energy above 0.1 MeV/amu) induces several effects of technological relevance. On one hand, it leads to material modification, usually with detrimental results (as in Nuclear fusion facilities [14]), and, on the other hand, it can be used to optimize or tailor the physical properties, e.g., for the fabrication of waveguides [160, 161].

In this regime, energy is mostly transferred from the projectile to the electronic system, generating ballistic electrons that subsequently produce a significant number of secondary electrons through impact ionization. As a result, a high electronic excitation density is achieved in a nanometre-sized region around the ion trajectory. The stored energy is then transferred to the lattice in ps timescales, due to several processes, remarkably, electron-phonon scattering. This sudden energy enhancement produces strong atom disorder, bond breaking and a temperature raise, followed by a fast atom rearrangement and cool-down. Permanent effects such as density, stoichiometry and composition changes, as well as defect generation result in nanometre-sized tracks with physico-chemical properties dramatically altered with respect to those of the virgin material. Tracks show complex forms, usually composed of an underdense density core and an overdense halo [162, 163], with different properties, depending on the ion energy.

In most cases, the density averaged over the whole track increases with respect to the virgin material.

For low fluences little overlap of tracks occurs. In this *single track regime*, the material properties behave linearly with fluence. Thus, the sample density in the surface region increases due to the accumulation of high density tracks. Then, for higher ion fluence, the probability of track overlapping increases. In the *overlapping track regime*, further densification only takes place in unirradiated regions, slowing down surface densification, which follows a Poisson-like distribution. Finally, when the unirradiated surface fraction is very small, mechanical effects due to track inclusion become important, and each track inclusion results in a permanent deformation defining a *plastic regime*.

During an experimental campaign using bromine ion with energies in the range 5-40 MeV we were able to observe the surface compaction in the *single track* and *track overlapping regimes*, as we discussed in previous works [20, 120, 125]. We also observed a density drop above a certain irradiation fluence, which roughly corresponds to the appearance of the *plastic regime*.

The appearance of a *plastic regime* has been reported in previous works [127–129, 164–167]. These works describe how silica undergoes continuous deformation. This causes the appearance of an irradiation-enhanced plastic flow that can be explained with the thermo-elastic track inclusion theory. The continuous deformation is observed as a dimensional growth in the perpendicular direction to irradiation, accompanied by an shrinking in the parallel direction. Apparently from the deformations rates in the parallel and perpendicular directions density should be conserved. However, small deviations in the surface density could be hardly appreciated observing just deformation rates. From our experimental campaign we can estimate the density variation from direct measurement of the refractive index. Which allowed us to observe a density drop corresponding to appearance of the plastic regime. In order to explain this density drop we introduce an expansion term during track inclusion in the plastic regime and propose a model that explains the density evolution over the irradiation fluence.

Summarizing, in this Chapter we give a full description of the evolution of the silica surface under irradiation in the different regimes. In [Section 4.4](#) we study the effect of single tracks on the un-irradiated silica surface, discussing how ion arrival induces track compaction and describing the track morphology. In [Section 4.5](#) we describe the evolution of compaction governed by track overlapping and in [Section 4.6](#) we explain how ion arrival to irradiated surfaces introduces anisotropic strains that leads to the plastic

regime where surface expansion may appear. Finally, in [Section 4.7](#) we develop a model that describes the evolution of the silica surface density over the different irradiation regimes.

4.3 Experimental observation of ion-induced density variation

Irradiation of silica with bromine ions (5-40 MeV) was performed at CMAM facilities [\[119\]](#) by O. Peña-Rodríguez et al. [\[120\]](#). Irradiation of silica with Br ions in the MeV range leads to densification of the surface, which induces a change of the refractive index. During the experimental campaign (see [Section 2.4.2](#)), we measured the variation of the refractive index with the ion fluence. Then, we can obtain the surface density, from the refractive index by means of empirical expressions like the Lorentz Lorenz formula [\[168\]](#),

$$n = \sqrt{\frac{2\rho + 8.0324}{8.0324 - \rho}} \quad (4.1)$$

$$\Delta\rho = \frac{\rho - \rho_0}{\rho_0} \quad (4.2)$$

where n is the refractive index, ρ the surface density, ρ_0 the surface density before irradiation and $\Delta\rho$ the density variation.

In [Figure 4.2](#) we show the refractive index obtained from the in situ reflectance experiments as a function of irradiation fluence (continuous lines) in addition to the fits obtained with the parametric model (dashed lines). The main parameters of the parametric model (track radius, compaction and expansion term) for the different irradiation energies are shown [Table 4.1](#), further discussion of these parameters is given throughout this work.

From the experimental data we observe how initially the refractive index increases linearly (*single track regime*). For higher fluences, a sublinear behaviour is observed as a consequence of the more relevant track overlap effect reaching a maximum at fluences $\sim 10^{13} \text{ cm}^{-2}$ (*overlapping track regime*). Then, a maximum is reached and the refractive index starts to decrease (*plastic regime*) down to a constant value for fluences $> 10^{14} \text{ cm}^{-2}$.

We observe that the evolution of the refractive index (density) is highly dependent on the ion energy. The higher the energy, the lower the fluence to efficiently initiate the compaction. This is related to the track radius, which increases for increasing ion energy. After the initial compaction stage a maximum density variation between 2.5 and 3.5% is reached in the overlapping track regime. Beyond the maximum, we observe a density decrease down to 2-3%. We associate this decrease to the appearance of a plastic regime during track inclusion.

Table 4.1: List of parameters used in the parametric model for the different Br ion energies.

E (MeV)	S_e (keV/nm)	r (nm)	$\Delta\rho_{\text{comp.}}$ (%)	$\Delta\rho_{\text{exp.}}$ (%)
5	2.0	1.8	2.9	-0.01
10	3.4	2.1	3.0	-0.01
15	4.7	2.7	2.9	-0.02
25	5.8	3.0	3.5	-0.05
40	7.2	3.8	3.4	-0.05

Figure 4.2: Refractive index variation (left axis) as function of fluence for Br ion irradiation. The straight lines show the experimental results, and the dashed lines the model used to approximate surface compaction for different ion fluences. The corresponding density variation according to Equation (4.1) is given in the right axis.

4.4 Single track regime

When an ion impinges on the silica, it deposits its energy in the first microns, in a nm-sized cylindrical region around the ion trajectory. Ions with specific energy above ~ 0.1 MeV/u impinging on silica produce a rearrangement of the silica network leading to smaller ring structures [65]. The result is the generation of latent tracks with a pronounced density enhancement due to silica compaction, Kluth et al. [140] observed a complex track structure composed of an underdense core and an overdense halo. We also studied this effect in a previous work [125] and were able to obtain the fine details of the complex track formation by means of a combination of MD simulations and experiments under different irradiation conditions.

Next, we show how the combination of MD simulations (see model description in Section 2.4.3) and experiments provide a clear picture of single track formation for different irradiation conditions. The density variation at the silica surface obtained by MD as a function of the radial distance to the ion trajectory is shown in Figure 4.3 (a) for different stopping powers, which correspond to the experimental irradiation conditions (Br ions of energy in the range 15-40 MeV). The MD results clearly evidence the formation of single tracks with an overall density enhancement with respect to that of unirradiated silica, and agree with the values reported in Table 4.1 for the parametrical fit of the experimental results. The complex nature (core and halo regions) becomes obvious for $S_e > 6$ keV/nm. The resulting core regions cover a low density central region of radius 1-2 nm, while the halo is compacted up to $\sim 3.5\%$ and extends to a radius of ~ 4 nm. For lower stopping powers the core cannot be observed or it is too small to be reproduced by our MD simulations, i.e., a stopping power threshold must be reached to induce core formation.

With MD we obtain the track size and compaction as a function of the stopping power. In order to fully characterize the ion track we calculate the ion stopping power as a function of its depth with SRIM [97], see Figure 4.3 (b). We observe the stopping power of irradiation in our experiments ranges from $S_e \sim 7$ keV/nm for Br ions of 40 MeV, to ~ 1 keV/nm for ions of 5 MeV. In the different cases the irradiation depth is up to several microns.

Coupling the results from MD and SRIM we are able to reconstruct the tracks, as shown in Figure 4.3 (c). We clearly observe the tracks for ions of 25 MeV and 40 MeV. For the case of 40 MeV we observe that the track core expands and the compaction is

Figure 4.3: a) MD simulation results obtained with a hot cylinder radius $a = 3.0$ nm showing the density variation as a function of the distance to the ion trajectory for different stopping powers. b) SRIM: Stopping power for different ions as a function of the ion depth in silica. c) MD + SRIM: Track density variation for different ions, reconstruction of the track from density variations from MD and stopping powers as a function of depth from SRIM.

observed in the outer halo. For 25 MeV, we observe that the core is less densified than the halo, but without attaining expansion. For the cases of 5, 10 and 15 MeV the track reconstruction is done using MD simulations of 4 keV/nm, and the simulations are not accurate enough to predict track compaction.

The accumulation of tracks in the single track regime with an overall density higher than the virgin material leads to silica compaction as observed experimentally by means of the refractive index raise (Figure 4.2). Then as the surface is irradiated track overlapping becomes dominant where as shown next a maximum compaction is attained which is similar to the track average density.

4.5 Track overlapping regime

The complex track structure, with an underdense core (of area c) and an overdense halo (of area h) observed by Kluth et al. [140] and reproduced in our MD simulations, has an effect on the experimentally determined overall density variation at the surface. At low fluences the surface density varies linearly because tracks are isolated. At certain fluence, track overlap starts to occur.

Then, one may mistakenly think (as demonstrated next) that the total normalized halo area (H) saturates faster than the total normalized core area (C), resulting in a maximum density variation (when H saturates) followed by a drop in the density variation (until C saturates). A proper description of the complex track structure can be done following Ref. [163]. We assume, as a first approach, that every new impact generates the complex track (core + halo) independently of whether the area of impact was already irradiated or not. Then, the rate equations that describe the evolution of H (high density zones) and C (low density zones) as a function of fluence (φ) can be written as:

$$\frac{dH}{d\varphi} = h - h \cdot H - c \cdot H \quad (4.3)$$

$$\frac{dC}{d\varphi} = c - c \cdot C - h \cdot C \quad (4.4)$$

The solution to this system of differential equations is:

$$H = \frac{h}{h+c} (1 - e^{-(h+c)\cdot\varphi}) \quad (4.5)$$

$$C = \frac{c}{h+c} (1 - e^{-(h+c)\cdot\varphi}) \quad (4.6)$$

It is obvious that the growth kinetics of the high density (H) and of the low density (C) areas are equal, describing a Poisson distribution. Figure 4.4 shows an example of ion irradiation reaching track overlapping at high fluence. For comparison (open symbols), Monte Carlo simulations [169] are included to account for the track accumulation process, resulting in a very good agreement with Equations (4.5) and (4.6). Therefore, we conclude that both H and C grow following the same kinetics, which indicates that the origin of the observed surface density evolution is related to the mechanical response of the material to track accumulation.

Since the growth kinetics of low and high density regions (core and halo) are the

Figure 4.4: Evolution of the normalized total halo (H) and core (C) areas as a function of fluence as calculated with Equations (4.5) and (4.6) and by means of Monte Carlo simulations, continuous lines and square open symbols, respectively. In this example every ion produces at the surface a track as that depicted in the inset. As a first approach, we assumed that every ion generates a track independently of whether the impact region was previously irradiated or not.

same, we can describe the surface evolution by means of a Poisson distribution:

$$\Delta\rho(\varphi) = \Delta\rho_{comp.} (1 - e^{-\varphi \cdot (h+c)}) = \Delta\rho_{comp.} (1 - e^{-\varphi \cdot \pi r^2}) \quad (4.7)$$

Where $\Delta\rho_{comp.}$ is the average track density:

$$\Delta\rho_{comp.} = \frac{c \cdot \Delta\rho_c + h \cdot \Delta\rho_h}{c + h} \quad (4.8)$$

By fitting the experimental results of Figure 4.2 with Equation (4.7) it is possible to find the track size ($h + c$), radius (r) and track average density ($\Delta\rho_{comp.}$). In Table 4.1 we show the fitted radius (r) and track density ($\Delta\rho_{comp.}$) for the different irradiation energies and in Figure 4.5 we compare in detail the evolution of the Poisson compaction and the experimental data for 25 MeV Br irradiation. We show the relative contribution of the core and halo regions to the surface compaction. In the case of 25 MeV Br tracks, most of the contribution is due to the highly compacted halo, with larger area ($h = 26 \text{ nm}^2$) and compaction ($\Delta\rho_h = 3.65\%$) than the core region ($c = 2 \text{ nm}^2$, $\Delta\rho_c = 1.5\%$). From the complex track we obtain an average density of $\Delta\rho_{comp.} = 3.5\%$ in track sizes of $h + c = 28 \text{ nm}^2$ or an equivalent track radius $r = 3 \text{ nm}$. We observe that the model explains correctly track compaction at the beginning of the irradiation, up to $\varphi \sim 10^{13} \text{ ions/cm}^2$. However, for higher fluences (plastic regime), the experimental curve drops whereas the Poisson model predicts saturation.

Figure 4.5: Surface density variation in silica for irradiation with Br of 25 MeV, straight line shows the data the Experimental results and the dashed lines the Poisson model described by Equation (4.7). The Poisson model parameters are $c = 2 \text{ nm}^2$, $\rho_c = 1.5\%$, $h = 26 \text{ nm}^2$ and $\rho_h = 3.65\%$ for average track properties $h + c = 28 \text{ nm}^2$ and $\rho_{comp.} = 3.5\%$

4.6 Plastic Regime

In the plastic regime, initially the density drops as a consequence of track inclusion-induced expansion, and finally a saturation is expected due to the appearance of an irradiation enhanced plastic flow.

The final appearance of an irradiation enhanced plastic flow can be explained using the thermo-elastic track inclusion model discussed in Refs. [127–129, 164, 166, 167]. This model assumes that during irradiation the tracks are heated and expanded up to a flow temperature (T^*). At the flow temperature the track becomes fluid and a mechanical equilibrium is reached, restructuring the track strains. This induces frozen strains when the track cools down. Then, an anisotropic deformation is introduced, having an expansion in the perpendicular plane to irradiation (ϵ_r^* , ϵ_φ^*) and is accompanied by a decrease in the parallel direction (ϵ_z^*). In total, the model predicts volume and density conservation. With the accumulation of flow strains during irradiation an irradiation enhanced plastic flow develops. With this thermo-elastic track inclusion model, the flow strains can be estimated as:

$$\epsilon_r^* = \epsilon_\varphi^* = -\frac{1}{2} \cdot \epsilon_z^* = \frac{1 + \nu}{5 - 4 \cdot \nu} \cdot \alpha \cdot \Delta T^* \quad (4.9)$$

$$\Delta \rho_{flow} = 1 - (1 + \epsilon_r^*) \cdot (1 + \epsilon_\varphi^*) \cdot (1 + \epsilon_z^*) = 0$$

where ϵ_r^* , ϵ_φ^* , ϵ_z^* are the flow strains, α the coefficient of thermal expansion, ΔT^* the track flow temperature and ν the coefficient of poisson. Taking $\nu = 0.17$, $\alpha = 1.7 \cdot 10^{-6}$ and $\Delta T^* = 3500$ K [128], the flow strains are $\epsilon_r^* = \epsilon_\varphi^* = -\frac{1}{2}\epsilon_z^* \sim 0.17\%$.

The thermo-elastic track inclusion explains the appearance of flow strains and an irradiation enhanced plastic flow. The theory agrees with the observation and allows for the estimation of flow strains and deformations [127–129, 164, 166, 167]. However, as shown in Equation (4.9), the theory does not predict any density change over irradiation. The theory is developed from observation of strain rates, and therefore small deviation from Equation (4.9) that may result in density variations are not captured. This way, using the thermo-elastic track model we cannot predict the density drop observed in Figure 4.2. In order to study the density drop, we need to modify the model including an elasto-plastic behaviour. This modification allows the appearance of a small density variation after track inclusion that can account for the density drop.

We have simulated the track inclusion with the bilinear elasto-plastic FEM model described in Section 2.4.4. With the elasto-plastic model, the expansion effects related to track inclusion can be studied. In the model the track region is heated and expands resulting in a compressed state. When the track begins to cool down, it changes from a compressed to a tensile state. During this process, the track suffers an internal reconfiguration leading to frozen strains that appear as a residual deformation when the track has cooled down.

In Figure 4.6 (a) we depict the evolution of the stresses with time. Initially track inclusion leads to compressed stresses, where the yield strength of the model ($Y_s = 1$ MPa) is attained soon after track inclusion, meaning that most of track inclusion takes

Figure 4.6: Results of track simulation using CodeAster bi-linear elasto-plastic model: a) stresses evolution with time, b) residual stresses and c) strains after irradiation as function of distance to the track axis. The figure shows the radial, r , polar, φ , and axial, z , components of the strain, ϵ , and stresses, σ , tensors. The model was applied to a track of radius 3 nm and maximum track load $\alpha \cdot \Delta T = 1\%$. The material properties are a Young modulus $E = 72.5$ GPa, plastic modulus $E_p = 1$ GPa, yield strength $Y_s = 1$ MPa and Poisson modulus $\mu = 0.17$.

place under plastic behaviour. Then over track inclusion the stresses increase until the track the track begins to cool down, when the track changes from a compressed to a tensile state. Is in this stage where, assuming some degree of track hardening, the stresses freeze and lead to a residual state when the track has cooled down. In Figure 4.6 (b) and (c) we show the residual stresses and strains profile as function of its distance to the track axis. The residual stresses are 20-40 MPa leading to residual strains of $\epsilon_r \sim \epsilon_\varphi \sim 0.04\%$. The surface expansion can be estimated from the strains as $\Delta\rho_{exp.} \sim -(\epsilon_r + \epsilon_\varphi + \epsilon_z) \sim -0.08\%$. Regarding the distribution of the stresses and strains in the track, due to the symmetry conditions, radial and polar strains are similar and due to the very high aspect ratio of the track (depth in the range of micrometers, radius of a few nanometres). This leads to a strain-free surface along the axial direction, which is compensated by the higher residual axial stresses. These values just offer a generic estimation of the residual state, showing a proof of principle of the expansion effects. For a more detailed analysis an accurate description of the elasto-plastic material properties under irradiation would be necessary.

Comparing the track compaction in the single track regime $\Delta\rho_{comp.} \sim 3\%$ (see Figure 4.3), with the residual expansion due to track inclusion, $\Delta\rho_{exp.} < 0.1\%$ (see Table 4.1 and Figure 4.6), we observe that the expansion effects are much lower than the initial track compaction ($\Delta\rho_{exp.} \ll \Delta\rho_{comp.}$). Therefore, expansion effects will become dominant only once track compaction has saturated.

4.7 Evolution of surface density over irradiation

With the theory described in previous sections, we develop a model that describes the silica surface density evolution for the different ion fluences. For the compaction in the *single track regime* the sample density increases linearly with the number of high density tracks impinging on the surface. In *overlapping track regime*, the density evolution follows a Poisson distribution, defined by Equation (4.7). For irradiation at high fluence (*plastic regime*) the surface expansion evolution can be described with three terms: the track size (πr^2), a net expansion due to track inclusion ($\Delta\rho_{exp.}$) and its dependence with fluence $f(\varphi)$:

$$\left. \frac{d\rho}{d\varphi} \right|_{Plastic\ Regime} = \pi r^2 \cdot \Delta\rho_{exp.} \cdot f(\varphi) \quad (4.10)$$

In order to describe the evolution with fluence, we use a parametric model that activates expansion effects at the beginning of the plastic regime through the use of a transition function $f(\varphi)$. The transition function represents an approximation to the variation of material properties with irradiation, leading to the different irradiation regimes. For the transition function we use an exponential fit:

$$f(\varphi) = K \cdot \left(1 - e^{-(\sigma \cdot \varphi \cdot \pi r^2)^m}\right) \cdot e^{-(\sigma \cdot \varphi \cdot \pi r^2)^m} \quad (4.11)$$

where r is the track radius, φ the fluence, m and σ are the parameters of the transition function and K a normalization factor.

We use as parameters of the transition function $K = 4$, $m = 1.5$ and $\sigma = 0.05$. We have selected these parameters in order to match the experimental data. However, the parameters of the transition function also have a physical interpretation. The exponential fit used in Equation (4.11) can be interpreted as a N-Impact model [163] that describes how successive ions ($m = 1.5$) affect small regions of the track ($\sigma = 0.05$). In this context, the transition function, $f(\varphi)$, describes the variation of the silica material properties with successive ions. Initially, $f(\varphi)$ is null in the compaction regime, then it maximizes in order to characterize the elasto-plastic regime and finally it becomes null in the irradiation enhanced plastic flow regime.

In order to get the density evolution as a function of the irradiation fluence in the different regimes, we combine Equations (4.8), (4.10) and (4.11):

$$\begin{aligned} \frac{d\rho}{d\varphi} &= \left. \frac{d\rho}{d\varphi} \right|_{\text{Overlapping Regime}} + \left. \frac{d\rho}{d\varphi} \right|_{\text{Plastic Regime}} = \\ &= \pi r^2 \left(\Delta\rho_{\text{comp.}} \cdot e^{-\varphi \cdot \pi r^2} + \Delta\rho_{\text{exp.}} \cdot 4 \cdot \left(1 - e^{-(0.05 \cdot \varphi \cdot \pi r^2)^{1.5}}\right) \cdot e^{-(0.05 \cdot \varphi \cdot \pi r^2)^{1.5}} \right) \end{aligned} \quad (4.12)$$

In Figure 4.2 the dashed lines show the surface density evolution in the experiments and the parametrical model given by Equation (4.12). The parametric model agrees quantitatively with the experimental results. We observe firstly, how in the track overlapping regime, the track compaction leads to a density variation $\sim 2-3\%$ in fluences lower than 10^{13} cm^{-2} . Then, in the plastic regime the track expansion is dominant and the density decreases slightly at fluences $10^{13} - 10^{14} \text{ cm}^{-2}$. Finally, for the higher fluences ($> 10^{14} \text{ cm}^{-2}$), the plastic regime leads to a saturation due to the development of an irradiation enhanced plastic flow associated to density conservation, as described by Equation (4.9).

In Table 4.1 we show the parameters used in the model. For the overlapping regime we use Equation (4.8) in order to calculate the track radius r , and track compaction $\Delta\rho_{comp.}$. Then, the expansion effects are estimated by fitting $\Delta\rho_{exp.}$ with Equation (4.12). We observe that the expansion term $\Delta\rho_{exp.}$ is at most 0.05%, caused by plastic strains $\epsilon_r = \epsilon_\varphi = \Delta\rho/2 \sim 0.025\%$. It is important to compare this value to the flow strains predicted by the thermo-elastic inclusion theory with Equation (4.9), $\epsilon_r^* = \epsilon_\varphi^* = -1/2 \cdot \epsilon_z^* \sim 0.17\%$. Comparing both values, we observe that the plastic strains are an order of magnitude lower than the flow strains. This could explain why the density variation at high fluence has not been reported in previous works [127–129, 164–167]. Since these works study the dimensional change of the irradiated sample, probably the expansion term was undistinguishable from the strain deformation due to irradiation enhanced plastic flow. In our case we measured the surface density through the refractive index [120], the flow does not affect our measurements and we can observe the expansion effect at middle irradiation fluences.

4.8 Conclusions

In this work we explain the evolution of the silica surface compaction upon irradiation with swift heavy ions. We study the experimental results of a Br ion irradiation campaign, describing the different stages of irradiation: from single track and overlapping track regimes leading to an initial compaction, to a plastic regime that shows a density drop and a final saturation.

For low irradiation fluence, compaction is the dominant effect. The *single track regime* is characterized by means of MD simulations, which reproduce the reported complex track structure composed of an underdense core and an overdense halo with an overall track density higher than that of un-irradiated silica. The accumulation of tracks leads to the *overlapping track regime* that follows a Poisson law. At higher fluences, the density reaches a maximum followed by a density drop. We attribute the drop to expansion effects that appear in a *plastic regime*. We show with a FEM elasto-plastic model that this expansion may take place after track relaxation. At high fluences the density variation ceases due to the development of an irradiation enhanced plastic flow, associated to density conservation. From the different irradiation regimes, we propose a parametrical model that describes the surface densification for different irradiation fluences, showing a good agreement with experimental results. Further improvements

to the model can address the degradation of material properties along irradiation, its effects on surface expansion, and the transition to the irradiation enhanced plastic flow.

Regarding the repercussion of this analysis for ICF, we observe the appearance of the irradiation enhanced viscous flow and surface expansion for fluencies of $\sim 10^{14}$ ions/cm². In ICF, under HiPER Demo conditions, we have fluences for the heavy ions of $\sim 2 \cdot 10^{12}$ ions cm⁻² pulse⁻¹ in the case of carbon debris, and $\sim 2 \cdot 10^{10}$ ions cm⁻² pulse⁻¹ for gold. This means that an irradiation enhanced viscous flow would appear after seconds of irradiation with carbon ions and minutes for gold ions. Therefore, the irradiation effects would be observed since the beginning of operation.

As we discuss in [Chapter 5](#), low variations on the silica refractive index will affect lens focusing, leading to high illumination non-uniformities and the impossibility to attain ignition. Furthermore ion irradiation could enhance laser damage due defects and impurities, lowering the damage threshold of ~ 10 J/cm² [\[170\]](#) for smooth un-irradiated silica.

Therefore we conclude that full mitigation of ion irradiation, including swift heavy ions is a must for the correct operation of silica final lenses. In [Section 5.4](#) we outline the main design parameters for the ion mitigation system.

Chapter 5

Conceptual design of HiPER Final Lenses

In previous Chapters we describe the effects on irradiation on silica. In [Chapter 3](#) we describe the effects of neutron irradiation and the formation of colour centres, and in [Chapter 4](#) we describe effects of ion irradiation and the necessity of ion mitigation. In this Chapter we address technological issues on how to minimize the effects of irradiation on silica final lenses. For this purpose we discuss the introduction of a temperature control system and an ion mitigation system.

For the final optics we study silica transmission final lenses and address the major issues regarding the unavoidable neutron irradiation they must withstand. In [Chapter 3](#) we show how neutron irradiation will create defects (colour centres) that absorb ICF laser. In previous works for HiPER final optics [[14](#), [15](#)] it was estimated how the colour centres can be annealed out at high temperatures. In order to keep the lenses at high temperature, a temperature control system must be employed. The temperature profile of the final lenses can induce a non-uniform steady state temperature profile. This is a major concern because it is the origin of unacceptable aberrations that severely affect the target illumination. In this Chapter, we discuss the design of the temperature control system and devise an active intervention system based on a heat-transfer fluid. We discuss the optical aberrations introduced by the lens temperature profile, defining the control system requirements to keep the temperature profile as smooth as possible. Finally, we determine the minimum distance between the final lenses and the target. We conclude that a distance of 8 m can be used for HiPER Experimental, whereas the lenses should be placed at ~ 16 m in the case of a full scale reactor (HiPER Demo). The

results presented in this Chapter were also published in Ref. [18].

Regarding ion irradiation, in Chapter 4 we show that full mitigation is required in order to avoid silica surface compaction that changes the refractive index and degrades the irradiated surface. In this Chapter we analyze how mitigation could be introduced using electrostatic and magnetic fields.

5.1 Introduction

The European laser fusion project HiPER is developing technologically feasible components for a laser fusion power plant with an evacuated dry wall chamber likely operating with a shock ignition scheme and direct targets (see Section 1.2). One of the key components is the final optics.

A non-uniform steady state temperature profile is a major concern because it is the origin of unacceptable aberrations that severely affect the target spots. We have devised an active intervention system based on a heat-transfer fluid to keep the temperature profile as smooth as possible. The main characteristics of the temperature control system are defined throughout this Chapter and enable the operation of the plant, both for the start-up procedure and for the normal operation.

At least one optical component will face irradiation, therefore it must be protected from irradiation stemming from the target explosions at the chamber centre. In order to minimize irradiation, it is necessary to focus the beam with optical components far from the target.

The solution adopted in HiPER is the use of a cassette of lenses. The HiPER Final Optical Assembly has been detailed in Ref. [3] and is shown in Figure 5.1. The size of the lens is $\sim 0.6 \times 0.6 \text{ m}^2$. Behind the final optical component, a small pinhole is installed to separate the rest of the facility. With this design, a 8 m focal length, f , gives a total distance between target chamber centre and pinhole of 32 m because the lens is placed at $2f - 2f$ position (magnification = -1).

An alternative to the cassette of lenses is the use of Grazing Incidence Metallic Mirrors (GIMM). This concept was studied in the 1990s in the framework of Prometheus [67, 68] and Sombrero [69–71] projects and later in the 2000s in the Aries and HAPL projects [72, 73]. However, GIMM mirrors have several drawbacks: they are sensitive to

neutron irradiation and have a low threshold for laser damage and they are difficult to mount and focus. But the main drawback of the metallic mirrors is the distance from target: 24 m to focal point, which is 3 times longer than the NIF/LMJ focal length (8 m); so far it is almost impossible to reach the same beam pointing accuracy on target [54].

The use of a cassette of lenses chosen for HiPER is analysed in this Chapter. Following previous studies [14, 15] we analyse problems related to neutron irradiation on silica transmission final lenses, particularly the lens focusing dependence on temperature, both, during the start-up and during normal operation. We show that a temperature control system is a must for proper lens performance and discuss several possibilities concluding that the only realistic solution requires the use of a hot gas flow. We discuss the different design conditions and parameters used in this work. Although some parameters used in this study may differ from those finally used for the HiPER system, the purpose of this study is to provide a starting point for a realistic conceptual design that can be considered as a reference. Finally, as described in Chapter 4, an ion mitigation system is required. We address the requirements of the ion mitigation system, studying electrostatic and magnetic mitigation.

Figure 5.1: Schema showing the configuration of the final lens in the HiPER Demo power plant. The laser is transported in the laser chain and passes through the Final Optics Assembly (FOA) where it is smoothed and shaped. Then the laser passes through the pinhole that protects from irradiation and is finally focused onto the target by means of the final lens.

5.2 Design Conditions for HiPER Final Lenses

As explained in [Section 1.2](#), in order to minimise risks, HiPER will be divided in different phases aimed to prove continuous mode operation in a laser fusion power plant. In this Chapter we analyse in detail the case of a pre-commercial power plant (HiPER Demo), that will produce an output power close to $\sim 1 \text{ GW}_e$. For this purpose high gain targets (yield around 150 MJ) should be designed operating at high repetition rates ($\sim 10 \text{ Hz}$).

5.2.1 Ignition Scheme

As described in [Section 1.2](#), for the HiPER project, an advanced direct drive ignition scheme, shock ignition [\[30\]](#), is the preferred option. This scheme will use 48 laser beams to obtain a symmetric target illumination [\[35\]](#). Each laser beam has a supergaussian profile, and is divided in a bundle of beamlets to produce a zooming effect [\[38\]](#) that allows for a shock ignition scheme.

The zooming effect is obtained with the Arbitrary Beam Selection (ABS) system. It allows switching on and off the adequate beamlets at each stage of the ignition scheme. Three types of beamlets are proposed in this work (see [Figure 5.2](#)), for the different stages (foot, compression and shock). The beamlets are shaped and smoothed in the FOA, and then relayed through a pinhole of $\sim 4 \text{ mm}$ diameter (see [Figure 5.1](#)). Finally, the beamlets are focused onto the DT target with the use of silica transmission lenses. We assume square biconvex lenses divided in a configuration of 4×4 quadrangles. Each lens quadrangle is used for a laser beamlet with the configuration shown in [Figure 5.2](#). When each laser beamlet is focused onto the target they have a supergaussian profile:

$$I = I_0 \cdot e^{-\left(\frac{r}{\Delta}\right)^m} \quad (5.1)$$

Where $m = 2$, $\Delta = 0.62 \cdot R_0$ and R_0 is 2, 1.25 or 0.5 mm for foot, compression and shock beamlets respectively. This choice for R_0 is based on an initial target radius of 2 mm. Targets of around 2 mm are necessary for target gains of 150 MJ. The critical radius during the shock has been taken as $\sim 0.5 \text{ mm}$ [\[35\]](#) and finally we have considered an intermediate size for the compression stage.

In order to guarantee that the illumination uniformity is suitable for ignition, σ

Figure 5.2: The final lens is divided in 4×4 quadrangles for the different laser beamlets. The foot beamlets pass through the four quadrangles of the corners (blue), the compression beamlets through the eight quadrangles of the sides (green) and the final shock beamlets through the four central quadrangles (red). The different laser beamlets are focused onto the DT target forming supergaussian profiles of different size (right).

should be kept below 1% [33] (see Equation (2.30) in Section 2.5). This requirement applies specially during the foot and compression stages because instabilities are formed in these stages. The illumination uniformity depends on several factors. The most important are geometrical restrictions (beam line configuration), system errors (pointing errors, target positioning) or the beam supergaussian profile. The illumination uniformity dependency on these factors was studied for HiPER in Refs. [33, 34]. In this work a new factor is introduced: the dependence of the illumination uniformity on the temperature of the final lens.

5.2.2 Lens Dimensions and Target Distance

The dimensions of the final lenses are limited by laser damage. Damage in silica with nanosecond lasers appears for fluences higher than 10 J/cm^2 [170]. For a target yield of $\sim 150 \text{ MJ}$, a laser shot of $\sim 1 \text{ MJ}$ (in 48 beams) is needed. This energy is deposited along the different stages (foot, compression and shock). The compression is the most demanding one accounting to 75% [36] of the deposited laser energy. The remaining 25%

will be mostly deposited during the shock stage. In order to keep the laser energy density below 10 J/cm^2 , the dimensions of the lens are $60 \times 60 \text{ cm}^2$. With these dimensions, a laser fluence of $\sim 8.7 \text{ J/cm}^2$ will be reached during the compression stage and $\sim 5.8 \text{ J/cm}^2$ during the shock stage.

Once the lens dimensions are defined, it is important to address the lens distance to the target. The distance is firstly determined by the irradiation conditions and the maximum working temperature, assumed to be 1223 K [126]. Assuming full ion mitigation (see Section 5.4), the lenses are irradiated only by the fusion neutrons and X-rays.

In Ref. [14] we studied the lens behaviour for a Prototype plant with an output power of $50\text{-}500 \text{ MW}$ ($1\text{-}10 \text{ Hz}$, 50 MJ). Under these conditions it is possible to place the lenses at 8 m keeping its temperature below 1223 K . However, in the case of HiPER Demo, pre commercial conditions (10 Hz , 150 MJ) the lens should be placed further than 8 m in order to keep the lens temperature below 1223 K . Moreover, as discussed along this work, keeping the temperature below 1223 K is not the only condition necessary for the operation of the lens. In addition, it is necessary to keep a flat temperature profile along the lens and a constant temperature over time. Even making use of a sophisticated temperature control system based on a flow of gas, the most optimistic temperature profiles at 8 m turn out inappropriate (details are given in the Section 5.3.6).

Assuming a realistic situation, i.e., biconvex transmission silica lenses, pre-commercial power plant conditions (HiPER Demo) and direct drive targets, we must accept that the final lenses must be located far away from the targets. Therefore, in this work, we have set the lens position at 16 m from the targets. It will be shown that at this distance, it is possible to design a temperature control system that assures a correct performance during all possible power plant operation regimes (start-up, normal operation and special operation modes). Also, it is interesting to note that the larger the distance between final lens and target, the easier it turns out to implement an ion mitigation strategy, which will have to be mandatorily implemented for power plant operation. In Section 5.4 we give a brief description of the ion mitigation system characteristics.

Once the lens position is set, a number of important parameters can be calculated, such as the focal length, the lens thickness, the neutron flux or the neutron-generated light species in the lenses. We discussed in Section 2.2 the methodology to obtain these parameters and in Table 5.1 there is a list of the design parameters employed along this work.

Table 5.1: Design conditions for the HiPER final lenses. Irradiation conditions from Ref. [17].

Parameter	Value
Number of lasers	48
Ignition Scheme	Direct Drive – Shock Ignition
Target gain	150 MJ
Repetition rate	10 Hz
Beam profile $I = I_0 \cdot \exp(-(\frac{r}{\Delta})^m)$	$m = 2$, $\Delta = 0.62 \times R_0$
Target radius- R_0 (foot, compression, shock)	2 mm, 1.25 mm, 0.5 mm, respectively
Lens distance to chamber centre	16 m
Lens Focal Length	8 m
Lens size	60×60 cm ² (4×4 quadrangles of 15×15 cm ²)
Maximum lens thickness	28 mm
Neutron Flux in the lens	$2 \times 10^{17} \text{ m}^{-2}\text{s}^{-1}$
Averaged power density due to neutrons	510 kW/m ³
Hydrogen production in the lens	49 appm/fpy
Helium production in the lens	83 appm/fpy

5.3 Temperature control system for HiPER final lenses

5.3.1 Temperature Requirements

Temperature limits

Due to neutron irradiation, colour centres are created in the final lenses [17, 63, 66], see Section 3.2.2. As a result, optical absorption at ~ 350 nm becomes appreciable. This is the typical laser wavelength for laser fusion facilities (third harmonic of solid state lasers that use Nd as dopant). Therefore, a loss of transparency in this band is undesired. Temperature plays a beneficial role, because colour centres efficiently anneal out at temperatures above 800 K. Continuous operation for long periods of time relies on an efficient mechanism for colour centre annealing thus, the final lens systems must be designed to operate at a temperature higher than 800 K. As mentioned above, maximum working temperature is 1223 K [126]. Therefore, the final lens operation temperature must be within the range from 800 to 1223 K.

Temperature variation

In addition, the final lens temperature must be kept constant during all the plant operation scenarios. This is due to the fact that the focal length varies with temperature,

Figure 5.3: Silica variation of refractive index and focal distance with temperature.

we show this variation in Figure 5.3.

For a thin lens the focal length variation with temperature is shown in Equation (5.2).

$$\frac{\partial f}{\partial T} = \frac{\partial f}{\partial n} \cdot \frac{\partial n}{\partial T} + \frac{\partial f}{\partial R} \cdot \frac{\partial R}{\partial T} = -f \cdot \left(\frac{\partial n / \partial T}{n-1} + \alpha \right) \approx -f \cdot \frac{\partial n / \partial T}{n-1} \quad (5.2)$$

Where f is the focal length, T is the temperature, n is the refractive index and R is the lens curvature radius. The term $\frac{\partial n / \partial T}{n-1}$ is the variation of the focal length related to the variation of the refractive index and α is the material thermal expansion, which gives the variation of the focal length due to geometry variation. For the case of silica $\frac{\partial n / \partial T}{n-1} \sim 3 \cdot 10^{-5} \text{ K}^{-1}$ [171], and $\alpha \sim 5 \cdot 10^{-7} \text{ K}^{-1}$ [126], i.e. two orders of magnitude lower ¹.

For lenses located 16 m away from the target, deviations in temperature of $\sim 20 \text{ K}$ induce variations of $\sim 5 \text{ mm}$ in the lens focal length. The variation in the lens focal length will divert the laser focal spot. This deviation will be $\sim 0.4 \text{ mm}$ for the foot beamlets, $\sim 0.3 \text{ mm}$ for the compression beamlets and $\sim 0.1 \text{ mm}$ for the shock beamlets. When we compare these deviations with the focal spot size, 2 mm, 1.25 mm and 0.5 mm

¹The focal distance is also be affected by the lens weight. The deformation due to lens weight is $\epsilon \sim 10^{-7}$. This effect is similar to the thermal deformation ($\alpha \cdot \Delta T$) and its influence on the focal distance is much lower that the variation of the refractive index due to temperature.

for foot, compression and shock stages, respectively, we observe that the deviation is significant and affects the energy deposition on the target.

Therefore, the lenses must be designed to operate at their design temperature (T_0). This temperature must be maintained during the different operational regimes (start-up, partial regime or normal operation) and only small deviations are allowed.

Temperature profile

Biconvex lenses have a larger thickness in their centre (~ 28 mm at 16 m from target) than in the sides (~ 5 mm). This causes a higher energy deposition (from neutrons) in the lens centre than in the sides. Since the thermal conductivity of silica is very low, a steady state non-uniform temperature profile is established along the radial dimensions of the lens. The result is a significantly higher temperature in the centre than in the sides. Different temperatures in the different parts of the lens (centre, sides, and corners) cause optical aberrations. We calculate these optical aberrations using the methodology described in [Section 2.5](#).

A demonstration example is shown in [Figure 5.4](#) for the compression stage. Beamlets pass through the 8 quadrangles of the sides. [Figure 5.4 \(a\)](#) shows an ideal case with all the quadrangles at the same temperature. Each beamlet is focused on a supergaussian spot and the superposition of all the laser beamlets illuminates the target with a high uniformity level ($\sigma = 0.16\%$). In [Figure 5.4 \(b\)](#) the beamlets pass through quadrangles at a temperature 20 K higher than the design one ($T_0 = 950$ K). The superposition of the 48 laser beams results in a larger spot and thus, the efficiency (η) is slightly reduced, but the illumination uniformity level is still good ($\sigma = 0.27\%$). Finally, in [Figure 5.4 \(c\)](#) the beamlets pass through quadrangles at different temperatures, half of them 20 K above the design temperature ($T_0 = 950$ K) and the other half 20 K below T_0 . The resulting spot is strongly deformed and not centred. Some regions of the target are overfocused and other underfocussed. Due to the lack of symmetry in the temperature profile the uniformity level in the target is not suitable for ignition ($\sigma \gg 1\%$).

Summarizing, the temperature profile along silica transmission final lenses must be as flat as possible, constant during all the operation procedures and within certain limits, 800-1223 K.

Figure 5.4: Example of the focal spot behaviour under different temperature variations. (Top) a schema of temperatures is shown (green for normal, red for hot and blue for cold temperature). (Middle) the focal spot for one beamlet is shown. (Bottom) target illumination resulting from the superposition of 48 laser beams is shown. Several scenarios are shown. Note that for the laser deposition on the target (bottom) the scales are different.

5.3.2 Temperature Control Systems Description

In order to fulfil the temperature requirements for the HiPER silica transmission final lenses, a temperature control system must be designed. We have studied the following systems: (a) no control system (i.e., lenses exposed to irradiation) just for comparison, (b) a control system based on heating resistances and (c) a control system based on a heat transfer fluid. The different systems are shown in Figure 5.5.

A description of a system (b) based on heating resistances is given in Figure 5.5 (b). The heating resistances are placed between the lens quadrangles and control the temperature at the quadrangle borders. The centre of the lens quadrangles should remain at an acceptable temperature thanks to heat conduction from the quadrangles borders. However, due to the low conductivity of silica the temperature gradient is high and temperature in the quadrangle centres is not effectively controlled. With a finer grid for the heating resistances the temperature could be controlled. But a finer grid is not a feasible solution as the laser would impact on the resistances with negative effects, and

Figure 5.5: Temperature control systems studied in this work. (a) no temperature control system. (b) heating resistances are used between the lens beamlet quadrangles. (c) A heat transfer fluid is used (CO_2 with a channel of 6 mm in the figure).

the complexity of the system would be greatly increased. Therefore, such a solution has been discarded.

In order to have a better control of the temperature, a system (c) using a heat transfer fluid is proposed with much better results. This system is shown in Figure 5.5 (c). The fluid will heat the whole lens surface resulting in a flat temperature profile. In the next paragraphs, the conditions to obtain a flat temperature profile as well as other design parameters are discussed.

5.3.3 Performance of Temperature Control Systems

Above, several aspects about system (c), using a heat transfer fluid, were studied, and no major problem is expected. In Figure 5.6, a comparison among the different systems (a), (b) and (c) is shown and it is observed that a flat temperature profile can only be obtained with system (c).

For system (a), with no temperature control, we observe in Figure 5.6 (a) how the neutron irradiation induces a steady temperature profile along the biconvex lenses. The temperature profile has a temperature gradient of ~ 100 K, which will induce unacceptable aberrations for plant operation. In addition, it will not be possible to maintain a constant temperature during the different regimes of operation making impossible to pass from start-up to full regime operation. For system (b), with heating resistances, we observe in Figure 5.6 (b) that due to the low conductivity of silica only a small part of the lens is kept at the desired temperature (T_0). The temperature difference between the coldest part (corners) and the hottest one (lens centre) is ~ 100 K. Therefore, in order to guarantee a uniform temperature profile, the temperature has to be controlled over the whole lens surface as proposed in system (c). In Figure 5.6 (c) we observe how it is possible to have a temperature deviation of only ~ 20 K when a heat transfer fluid is used ². In the next section, we study how this temperature profile guarantees a focal spot with high illumination uniformity.

²Only the temperature variation in the lens is considered. Regarding the temperature in the window, its effect on laser focusing is neglected due to the window flatness. Also the temperature variation in the window is low, only ~ 5 K.

Figure 5.6: Temperature deviation in relation to the design temperature (T_0) for different control systems. (a) no temperature control system. (b) heating resistances are used between the lens beamlet quadrangles. (c) A heat transfer fluid is used (CO_2 with a channel of 6 mm in the figure).

5.3.4 Design Conditions for the Temperature Control System

The temperature control system for the HiPER silica final lens is composed by the structural components, windows, the lenses and the heat transfer fluid. In Figure 5.7, we show the general scheme and in the next section we discuss several design requirements for this system.

Figure 5.7: Scheme of the design of the temperature control system for the HiPER final lenses.

Fluid Selection

As operation at temperatures between 800 and 1223 K is required, a gaseous fluid will be used. In order to have good heat transfer conditions, the fluid pressure must be ~ 100 kPa. A pressure drop ³ of ~ 1 kPa along the channel is enough to set fluid flows able to heat the lens.

And a fluid temperature of ~ 950 K guarantees that both the lens and windows are above 800 K and colour centre annealing is efficient.

The heat-transfer fluid should be transparent to the HiPER laser wavelength (350 nm), chemically stable in order to prevent reaction with silica at the operational temperatures

³We refer to the pressure drop along the lens channel. The total pressure drop in the control system would require the estimation of the total pipe line and singular pressure losses, which is out of the scope of this work.

(>800 K) and with good heat-transfer properties. Four fluids that fulfil these requirements have been studied: helium, carbon dioxide, argon and xenon. The use of He allows for thin boundary layers and high heat transfer coefficients. However, since He density is low, high volumetric flows are needed. In the case of CO₂, the channel width should be slightly larger than for helium. However, as CO₂ is heavier, the volumetric flow and pumping power are lower, which can be translated into an easier engineering implementation of the system. Regarding Ar, it presents similarities with CO₂, as both have similar densities. However, Ar thermal conductivity and specific heat capacity are lower, which leads to worse cooling properties. Ar could be an alternative to He or CO₂ in case He permeation or corrosion issues with CO₂ could pose any problem in the final implementation of the system. Finally Xe, as the heaviest fluid presents the worst cooling properties. Xe is of interest if the target chamber is to be filled with xenon gas as in the case of some indirect drive target facilities (e.g., LIFE project). However, for direct target illumination (e.g., HiPER project), an evacuated chamber is needed and Xe fluid does not present any advantage for a temperature control system. Neutron interaction with the fluid will be much lower than with silica. Due to the lower fluid density and lower thickness of the fluid channel most of the activation will take place in the silica lens and windows. However, the fluid system will have to be controlled to avoid high activation levels or leakages. The transmutation rate for the fluid will be ~ 100 appm/fpy.

Silica is quite resistant to corrosion by elements or compounds. Exceptions are some acids, alkalis, alkaline-earths and some oxides at high temperature [126]. Therefore, corrosion by the selected fluids will not be a problem, provided the impurity level is kept under control.

Flow Pattern

As show in Figure 5.6 (c), in the temperature control system the fluid is confined in two channels between the lens and silica-made windows. Due to the lens curvature, the channel width changes throughout the channel. Therefore, as we observe in Figure 5.8 (a), the fluid velocity is higher in the middle of the channel than at the inlet/outlet. It is also important to point out that the fluid temperature changes over the channel. In Figure 5.8 (b) we show how the fluid outlet temperature is lower than the inlet temperature. If a parallel flow pattern along both channels is chosen, the temperature profile would not be symmetric, decreasing the uniformity level in the focal spot, similar to the situation depicted in Figure 5.4 (c). Therefore, it is necessary to have a counter

flow configuration, which leads to a symmetric temperature profile in the lens, optimizing the illumination uniformity. It is also necessary to optimize the channel width. The channel width should be as narrow as possible in order to minimize the fluid flow rate, but wide enough to guarantee an effective heat transfer to the lens.

Figure 5.8: a) Velocity and b) Temperature profiles for a Helium channel of 6 mm width.

Windows Design

The size of the lens and windows is defined by the optical and mechanical requirements. A lens and window size of $60 \times 60 \text{ cm}^2$ is defined in order to keep the laser energy density below 10 J/cm^2 . The lens thickness at its borders is 5 mm in order to hold the lens. Due to the lens curvature radius ($\sim 7.8 \text{ m}$), the lens thickness is $\sim 28 \text{ mm}$ at its centre.

In Figure 5.9 we show how the window thickness must be at least 15 mm to withstand the stresses due to the differential pressure between fluid (100 kPa) and

Figure 5.9: a) Variation of the maximum equivalent stress (Von Mises) as a function of the windows width. b) Equivalent stress (Von Mises) for a windows of 15 mm thickness, for a pressure of 0.1 MPa (1 Bar) the maximum stress are 43.7 MPa.

chamber (vacuum). With this thickness the maximum stress in the window is ~ 40 MPa, below the tensile strength (48 MPa) and the bending stress (67 MPa) [126].

The windows do not focus the laser, due to their flatness. There is only a small laser deviation of ~ 0.1 mm along the window. This effect is negligible compared to the size of the lens 60×60 cm². Also, due to the symmetric configuration, this negligible deviation in the first window is corrected in the second window.

In this work the windows are designed with the minimum thickness that supports the stresses. However if more resistance is required it is possible to have thicker windows. With thicker windows of ~ 30 mm, the maximum stresses would be reduced to ~ 10 MPa. Instead of having thicker windows it is also possible to add a support grid that strengthens the windows. The support grid can be introduced between the different lens quadrangles in a 4×4 configuration. With this solution, the stresses could be reduced to ~ 3 MPa.

He Permeability

Beam laser lines require high vacuum conditions for operation, therefore the lens temperate control system should be leak-tight. There are two main paths for helium leakage into the beam line, through the lens holders and through helium diffusion in silica. Regarding the lens holders leak-tight conditions should be guaranteed, with design specifications that fall out the scope of this work.

Regarding helium diffusion, the He concentration, C , in the system is governed by the diffusivity, D , solubility, S , and the He source from neutron irradiation, $\dot{C}$. We obtain the coefficients for the silica Helium diffusion (D) and solubility (S) from Ref. [172]:

$$D = 7.4 \cdot 10^{-4} \cdot \exp\left(\frac{-6910 \pm 41 \frac{\text{kJ}}{\text{kg}}}{RT}\right) \frac{\text{cm}^2}{\text{s}} \quad (5.3)$$

$$S = 1.28 \cdot 10^{17} \cdot \exp\left(\frac{-1226 \pm 125 \frac{\text{kJ}}{\text{kg}}}{RT}\right) \frac{\text{atoms}}{\text{cm}^3 \text{Bar}} \quad (5.4)$$

The evolution of the concentration is described by the Fick's law:

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2} + \dot{C} \quad (5.5)$$

In the case of the windows, the boundary conditions are a free surface where the He concentration is null, and other surface in contact with a He flow where the concentration equals the solubility, S . For windows of thickness d , the concentration profile f can be calculated as:

$$C = -\frac{\dot{C}}{2D}x^2 + \left(\frac{S}{d} + \frac{\dot{C}}{2D} \cdot d\right) \cdot x \quad (5.6)$$

In Figure 5.10, we show the He concentration profile in the windows at 800 K and at 300 K. In the figure we show the He concentration due to permeability from the flow channel (red line), the He formation due to neutron irradiation (green line) and the total concentration (blue line). At high temperature, due to the high diffusivity, most of the concentration is due to permeability. At low temperatures with lower diffusivities, the neutron irradiation accounts for most of the He concentration. The figure shows how solubility at ~ 800 K is ~ 5 appm. Evaluating the permeation flow through the windows we have $\sim 10^{13}$ atoms $\text{cm}^{-2} \text{s}^{-1}$, which gives a total of $\sim 2 \cdot 10^{18}$ atoms s^{-1} into the vacuum chamber. This rate is low and can be pumped out by the chamber vacuum system.

Figure 5.10: He concentration in the windows, due to permeability from the fluid channel, due to neutron irradiation and total. Results at the operational temperature of 800 K and at 300 K.

5.3.5 Optical Performance of the Final Lens

The focal spot is highly dependent on the temperature profile and a detailed evaluation with realistic temperature profiles is necessary. The proposed fluids (He, CO₂, Ar and Xe) were analyzed to optimize the channel width in order to improve the illumination non uniformities, σ , and laser efficiency, η . The methodology used to calculate these magnitudes is described in [Section 2.5](#).

[Figure 5.11](#) shows the uniformity level (σ) as a function of channel width for different fluids, while [Figure 5.12](#) shows the efficiency of laser deposition (η) during normal operation. In all the cases, the lens design temperature (T_0) is set at the corner temperature (~ 900 - 950 K). This way, a good illumination uniformity is expected for the foot beamlets, regardless the fluid or channel width. However, for compression and shock beamlets, the temperature profile may induce aberrations that may lead to poor illumination uniformity.

The shock beamlets pass through the lens centre and compression beamlets pass through the lens side quadrangles. These quadrangles are at higher temperature than the corners (foot) due to neutron irradiation and therefore aberrations are introduced. In [Figure 5.11](#) and [Figure 5.12](#) it is observed how He and CO₂ systems with channel widths

Figure 5.11: Uniformity level (σ) for different heat transfer fluids as a function of channel widths during normal operation for the different ignition stages (foot, compression and shock).

Figure 5.12: Laser energy deposition efficiency for different heat transfer fluids and channel widths during normal operation for the different laser beams.

higher than $\sim 4\text{-}6$ mm have high illumination uniformity ($\sigma < 1\%$) and high efficiency ($\eta \sim 90\%$). For Ar or Xe, due to their worst cooling properties, the aberrations are higher than for He or CO_2 . This causes a higher level of non-uniformities (σ) with lower efficiency (η).

From the analysis of the illumination uniformity and efficiency, we conclude that either He or CO_2 could be chosen. However, it is also important to consider that pumping CO_2 is easier than pumping He, due to its higher density. For a channel of 6 mm, $\sim 2 \text{ m}^3/\text{s}$ of He should be pumped out, very high compared to only $\sim 1 \text{ m}^3/\text{s}$ of CO_2 . As shown in Figure 5.13, in terms of pumping power it translates to $\sim 2.3 \text{ kW}$ for He and $\sim 1 \text{ kW}$ for CO_2 . In addition, pumping and handling are easier in the case of CO_2 .

In the previous paragraphs, the illumination uniformity and efficiency at normal operation were analysed. But, what happens during start-up, when there is no neutron irradiation? In normal operation conditions, the lens temperature is defined by the neutron irradiation ($510 \text{ kW}/\text{m}^3$) and the heat transfer fluid (inlet temperature 950 K, pressure drop 1 kPa). The temperature of the lens is near the design temperature (T_0) and operation of the lens is possible. However, during the start-up there is no neutron irradiation. If the heat transfer fluid remains at the same conditions that for normal operation, the lens would cool down and would not focus correctly the laser.

Figure 5.13: Pumping power for the different fluids and channel widths.

Table 5.2: Main parameters of the final lenses for start-up and normal operation with a channel width of 6 mm.

Fluid	Design T_0 (K)	Operation Regime	Fluid T_f (K)	η			σ		
				Foot	Comp.	Shock	Foot	Comp.	Shock
He	947	Start-up	985	92%	92%	92%	0.17%	0.18%	0.46%
		Normal	950	92%	92%	89%	0.16%	0.23%	0.46%
CO ₂	943	Start-up	995	92%	92%	92%	0.19%	0.18%	0.18%
		Normal	950	92%	92%	87%	0.17%	0.28%	0.29%
Ar	926	Start-up	1030	91%	92%	92%	0.21%	0.26%	0.41%
		Normal	950	92%	91%	82%	0.19%	0.25%	0.76%
Xe	909	Start-up	1060	91%	91%	92%	0.35%	0.59%	0.53%
		Normal	950	92%	90%	74%	0.17%	0.37%	1.08%

Therefore, it is necessary that the fluid transmits more heat to the lens during the start-up until the lens is at its design temperature (T_0). For this purpose the temperature of the fluid is increased. In Table 5.2 we show how increasing the fluid temperature during the start-up it is possible to keep a good illumination uniformity ($\sigma < 1\%$) with high efficiencies ($\eta \sim 90\%$).

In Table 5.2, the design temperature (T_0) of the lens is also presented. The design temperature is set to the value of the lens corner temperature at normal operation when fluid temperature is fixed. The different heat transfer properties of the analysed fluid, He and CO₂ allow for a design temperature in the range 940-950 K, while the design temperature for Ar and Xe is ~ 930 K and ~ 910 K, respectively. Therefore, a higher difference between T_0 and fluid temperature is required in Ar and Xe designs.

The same effect is observed for the fluid temperature during the start-up. In order to keep the lens temperature around (T_0), the fluid temperature is raised from 950 to ~ 990 K for He and CO₂, and from 950 to ~ 1060 K for Ar and Xe.

Finally, between start-up and normal operation there will be a transient operation that makes necessary to adapt the fluid temperature to the neutron irradiation level. Thus, the fluid temperature would be between those ones corresponding to start-up and normal operation temperatures.

5.3.6 Final Lens distance to target

In the previous sections we studied the possibility to control the temperature of a lens placed at 16 m from the target. At this distance the pinhole would be placed at 32 m from the target (see Figure 5.1). A more compact solution would be advantageous.

In order to have a conservative solution, we have studied the system using helium

with a channel width of 20 mm. As observed in Figure 5.11, He has the best heat transfer properties (along with CO₂). In addition, increasing the channel width (beyond ~ 10 mm) shows no further improvement.

In Figure 5.14, the variation of temperature in relation to T_0 is shown. It is clearly observed that at 8 m, the temperature variation along the lens is higher than 100 K. Placing the lens at 12 m, the temperature variation is corrected to ~ 40 K and placing the lens at 16 m, the temperature variation is less than 15 K. This reduction in the temperature gradient is caused by the lower irradiation and flatter geometry of the lens located far away from the target.

In Table 5.3, the performance of the lens is shown, it is observed that with the lenses at 16 m the efficiency is high ($\eta \sim 90\%$) and the illumination uniformity is good ($\sigma < 1\%$). However if the lens is placed at 8 the illumination uniformity is not acceptable ($\sigma > 1\%$). Placing the lens at 12 m an intermediate scenario is found, where the illumination uniformity is good ($\sigma < 1\%$) for foot and compression beams and worse for shock beams ($\sigma > 1\%$).

With these considerations, we conclude that it is possible to place the lenses at 16 m from the target with the temperature control systems proposed. At the expense of increasing the non-uniformities at the end of the ignition (shock beams), it would be possible to place the lenses at ~ 12 m from the target. Finally the lenses cannot be placed much nearer (~ 8 m) as the non-uniformities would increase for all the ignition stages.

Table 5.3: Optical performance of the lens at different distances for a case using helium and a channel of 20 mm.

Fluid	Design T_0 (K)	Operation Regime	Fluid T_f (K)	η			σ		
				Foot	Comp.	Shock	Foot	Comp.	Shock
He	918	8	800	78%	37%	5%	2.39%	2.32%	1.45%
	926	12	900	92%	89%	63%	0.17%	0.58%	1.83%
	950	16	950	93%	92%	89%	0.16%	0.46%	0.21%

Figure 5.14: Temperature deviation in relation to the design temperature (T_0) for different lens distance to chamber center. Lens is located at 8 m (a), 12 m (b) and 16 m (c) for chamber centre. A heat transfer fluid is used (He with a channel of 20 mm).

5.4 Ion Mitigation to prevent final lenses fatal irradiation

In the previous sections, the design of the temperature control system in order to minimize effects of neutron irradiation is described.

In Chapter 4 the necessity of an ion mitigation system for the final optics was exposed. In the next paragraphs we discuss the possibility of including an ion mitigation system. As shown in Figure 5.15, the ion mitigation system would be placed at the chamber laser opening, then irradiation is deflected and finally arrives to an irradiation dump, avoiding irradiation of the final lenses. In order to deflect the ion irradiation either electrostatic or magnetostatic fields can be used. In Ref. [74] proposed a mitigation strategy based on the use of Helmholtz coils, in this section we study the use of electrostatic deflectors or generic magnetic dipoles.

In the mitigation system, the ions are deflected and angle α . In order to effectively mitigate the ions, the deflected angle α should be:

$$\alpha = \frac{w_{lens}}{d} = \frac{0.6 \text{ m}}{7 \text{ m}} = 0.085 \text{ rad} \quad (5.7)$$

where $w_{lens} = 0.6 \text{ m}$ is the lens size. The drift length, d , is the distance from the mitigation system to the lens, which we assume to be $d \sim 7 \text{ m}$. Therefore we need to deflect the ions for angles $\alpha > 85 \text{ mrad}$.

Typically in a mitigation system the ion trajectory is defined by its curvature radius

Figure 5.15: Scheme of the mitigation system for ion irradiation from HiPER Final lenses.

(ρ). The deflected angle (α) is related to the ions curvature radius (ρ) along the mitigation system with length L :

$$\alpha = \frac{L}{\rho} > 0.085 \text{ rad} \quad (5.8)$$

Regarding the size of the mitigation system we assume a length $L=1$ m, with an iron gap defined by the beam opening of $\sim w_{gap} = 35$ cm. The curvature radius (ρ) required for the system is defined by the deflected angle $\alpha = L/\rho > 85$ mrad. For a system of $L = 1$ m length, the required radius is $\rho \sim 11$ m.

In [Table 5.4](#) the main parameters of the mitigation system are summarized.

5.4.1 Electrostatic Deflector

Regarding mitigation with an electric field, the deflection of ions is defined by the electric rigidity:

$$\chi_E = \frac{2 \cdot T}{q} = E \cdot \rho \quad (5.9)$$

where T is the ion energy, q its charge, E the electric field and ρ the ions curvature radius.

We observe that the first part of the equation (T/q) is related to the irradiation spectra, and the second part ($E \cdot \rho$) to the characteristics of the system.

Analysing the irradiation spectra (see [Section 3.1](#)) the most unfavourable case would be species with low charges and high energies. It corresponds to Au ions of 45 MeV, which would have a charge state of at least ~ 6 [74], and to light species (Helium) up to 20 MeV with a charge state of one. For these species, in [Table 5.4](#) we observe how the electric rigidity could be up to 20 MV and electric fields of ~ 0.6 MeV/m would be required. These requirements are difficult to fulfill by conventional systems. There could be complex technical solutions offering such high electrostatic fields [173]. However even in this high voltage solutions, specific issues regarding high voltage connections and insulation should be studied.

From this analysis we show that the use of an electrostatic deflector could be an

option for ion mitigation. However it probably offers a high complex technical and costly solution, and magnetic dipoles may offer a simpler alternative.

5.4.2 Magnetic Dipole

Regarding mitigation with a magnetic dipole, the deflection of ions in a magnetic field is defined by the magnetic rigidity:

$$\chi_b = \frac{p}{q} = B_n \cdot \rho \quad (5.10)$$

In order to create these magnetic fields a magnetomotive force is required:

$$F_M = \oint \frac{B}{\mu} dl \quad (5.11)$$

where $p = \sqrt{2mT}$ is the momentum, q is the charge, B_n the magnetic field, and ρ ions curvature radius in the magnetic field.

The most difficult ions to mitigate will correspond to those with higher magnetic rigidity, which corresponds to high energies, high masses and low charges. This would correspond to Au ion of ~ 45 MeV and the charge state ~ 6 [74]. In Table 5.4 we observe that for its mitigation magnetic rigidities ~ 2 T m with magnetic fields ~ 0.2 T m are required. Regarding the design parameters for such a magnet, the permeability in the iron is much higher than in the air gap and the magnetomotive force is $F_M \approx \frac{B}{\mu_0} \cdot w_{gap} \sim 50\,000$ AT. The current density limit for copper is ~ 5 A/mm² [74]. Therefore, cross sections of $\sim 10\,000$ mm² (100×100 mm²) would be required and the power consumption of the system would be ~ 12 kW assuming copper resistivity of $1.7 \cdot 10^{-8}$ Ω m.

A system using this type of magnetic dipoles seems a manageable technical solution for ion mitigation [174]. However further analysis are still necessities, studying in detail the irradiation charge state, avoiding the presence of neutrals or a thermomechanical assessment of the irradiation dump.

Summarizing, the use of magnetic dipoles seems feasible solution for ion deflection, while the use of electrostatic deflectors may be a complex technical solution due to the high voltage required for ion deflection. In Table 5.4 the main conditions for electrostatic and magnetic mitigation are summarized.

Table 5.4: Main parameters of the mitigation system for mitigation of most restrictive irradiation species: He-20 MeV and Au-45 MeV

Parameter	Value	
System Length (m)	1	
Iron Gap (m)	0.35	
Deflected Angle (mrad)	85	
Curvature Radius (m)	11.6	
Deflected Ion	He	Au
Charge State	1	6
Energy (MeV)	20	45
Electric Rigidity (MV)	20	7.5
Electrostatic Field (MV/m)	1.7	0.6
Magnetic Rigidity (T m)	1.3	2.3
Magnetic Field (T)	0.1	0.2

5.5 Conclusions

Throughout this work we have evaluated the neutron irradiation on the HiPER silica transmission final lenses and how the temperature profile affects the laser focusing. We have shown that laser focusing is quite sensitive to temperature variations and thus, the temperature has to be carefully controlled during plant operation.

It is important to keep a high temperature during operation (>800 K) to promote an efficient annealing of colour centres but below the maximum working temperature of silica (<1223 K). In order to avoid variations in the focal length the temperature must remain constant during operation and uniform along the lens in order to minimize optical aberrations.

The pre-commercial scenario of HiPER Demo has been studied. In this scenario final lenses must be placed at a distance of ~ 16 m. In order to control the temperature a heat-transfer fluid system is proposed. Several fluids have been studied. He and CO_2 are adequate to control the lens temperature. CO_2 appears as the best solution due to its cooling properties and easier engineering implementation. The behaviour of the system at normal operation and during start-up has been studied and it is concluded that it is possible to keep a good illumination uniformity ($\sigma < 1\%$) and a high efficiency ($\eta \sim 90\%$) by adjusting the fluid temperature.

The main limitations of the proposed solution are the requirement to operate at high temperature (>800 K) and the necessity to place the lenses at 16 m from the target, which results in large facility dimensions. Other solutions may solve the previous

limitations at the expense of adding other potential problems. A careful analysis similar to this work must be done in order to study alternatives to transmission lenses, e.g., Fresnel lenses or GIMM mirrors [25].

With the use of Fresnel lenses the size of the facility could be reduced. Fresnel lenses are thinner than transmission lenses and they could be placed nearer the target (8 m, 12 m). However operation at high temperature is still necessary in order to anneal out colour centres. The focal length variation with temperature is similar for Fresnel and transmission lenses. Therefore, the temperature control system proposed in this work could be also used with Fresnel lenses as the final optical component. Fresnel lenses offer a good alternative to transmission lenses and are in effect the main option for the LiFE project [3]. The main problem of Fresnel lenses stems from the mechanization requirements, which may lead to laser damage and worse laser focusing capabilities.

To avoid operation at high temperature materials different from silica must be used. GIMM mirrors could be a solution but its reflectance is highly dependent on the surface quality, which is altered after neutron irradiation. In addition, laser damage is a concern in metal mirrors, as well as, neutron irradiation-induced creep. Further progress in alloys, probably based on the inclusion of nm-sized particles, could improve the radiation resistance of the mirrors. Also, with GIMM mirror large focal lengths (~ 24 m) are necessary. Therefore, using GIMM mirrors the facility size would be similar or even larger than using biconvex lenses.

Finally, it is important to point out that the presented solution is based on the experimental evidence [63, 66] that defects in silica anneal out at high temperature (> 800 K). However, unexpected response to irradiation could occur since these results are obtained with neutron fluxes far lower than those expected in HiPER and with different neutron spectra. In addition, the effect of gases (hydrogen, helium) or impurities also requires further research under realistic irradiation conditions, because, they may induce laser absorption, or even trigger laser damage. Also the impact of stresses induced by neutron interaction, beam polarization and on wave-front distortion should be studied with experimental basis. Finally it has to be assessed that the combination of effects does not induce mechanical failure in the system due to creeping, ratcheting or fatigue.

Regarding ion mitigation we briefly characterize the mitigation requirements, which comprise full mitigation of He up to 20 MeV and Au up to 45 MeV. For the mitigation system, magnetic dipoles with fields of 0.1-0.5 T seems the most feasible solution.

Chapter 6

Conceptual design of HiPER First Wall

In this Chapter we address a quantitative study to evaluate First Wall performance under realistic irradiation conditions in the different scenarios. In [Chapter 3](#) we described the radiation fluxes, characterizing neutron and ion irradiation spectrum and main damage parameters (displacements per atom, gas formation). We study the different HiPER scenarios described in [Section 1.2](#), corresponding to different phases in the development of nuclear fusion technologies, experimental facilities (Experimental), reactors operating in a relaxed mode far from full power (Prototype) and full scale reactors (Demo). From the irradiation spectrum we study the evolution of First Wall temperature and the thermomechanical response of the material using the methodology described in [Section 2.3](#).

We evaluate the First Wall performance under realistic irradiation conditions in the different scenarios. We centre the analysis in the study of the thermomechanical effects and crack propagation, giving a qualitative discussion of atomistic effects. The results indicate that the First Wall will plastically deform up to a few microns underneath the surface. Continuous operation in a power plant leads to fatigue failure with crack generation and growth. Finally, crack propagation and the minimum tungsten thickness required to fulfil the First Wall protection role is studied. The response of tungsten as a First Wall material as well as its main limitations are discussed.

We conclude that a tungsten First Wall can be used in experimental facilities, but alternatives should be considered for a full scale reactor. The results presented in this Chapter were also published in Ref. [\[19\]](#).

6.1 Introduction

One of the challenging tasks in ICF reactors is the development of First Wall (FW) materials able to withstand the hostile environment (high thermal loads and atomistic damage) during power plant operation. The behaviour of a tungsten First Wall is studied under the irradiation conditions predicted for the different operation scenarios of the European Laser fusion project HiPER, which is based on direct drive targets and an evacuated dry wall chamber.

In this context, we study the different scenarios described in [Section 1.2](#), corresponding to different phases in the development of nuclear fusion technologies, experimental facilities (Experimental), reactors operating in a relaxed mode far from full power (Prototype) and full scale reactors (Demo). The geometry of the HiPER chamber is shown in [Figure 6.1](#), showing the main elements of the model: the tungsten First Wall, steel substrate and LiPb coolant.

In [Table 6.1](#) the main conditions of the different HiPER scenarios are shown. The chamber radius is 5 m for the Experimental facility and 6.5 m for the Prototype and Demo reactors. The chamber consists of different layers. (i) tungsten First Wall (FW); (ii) substrate, which gives mechanical support to the First Wall [\[47\]](#); (iii) thick liquid LiPb blanket [\[45\]](#) coolant, (iv) biological shielding for irradiation. The First Wall is made of pure tungsten with a thickness of 1 mm. For the pure tungsten, isotropic behaviour is implemented using the material properties reported in the ITER material handbook [\[112, 113\]](#). The substrate is assumed to be an oxide dispersion strengthened reduced activation ferritic/martensitic (ODS-RAFM) steel [\[47\]](#) which is able to operate

Figure 6.1: a) Schemes of the HiPER laser fusion reactor chambers. b) Sketch of FEM model of the reactor First Wall.

Table 6.1: Main operational parameters in the different HiPER scenarios studied in this work: Experimental, Prototype and Demo.

Parameter	Experimental	Prototype	Demo
Frequency	Few shots per bunch	1 Hz	10 Hz
Shot Energy (MJ)	20	50	154
Chamber radius (m)	5	6.5	6.5

at temperatures as high as 925 K. The selected thickness is ~ 1 cm [45]. The coolant is eutectic LiPb (Pb at 17%), which operates between 600 and 800 K having a convection coefficient of $\sim 10 \text{ kW m}^{-2} \text{ K}^{-1}$ [45].

In this work we use the FEM model described in Section 2.3. The FEM model is used in order to quantitatively evaluate the performance of a tungsten First Wall under realistic irradiation conditions in the proposed HiPER scenarios (Experimental, Prototype and Demo). Atomistic effects due to ion irradiation and light species retention are not considered in the simulations but are discussed in comparison to the thermo-mechanical effects. The goal is to determine the operation windows of the First Wall, needed for the construction phase of HiPER. Throughout this chapter we firstly calculate the radiation-induced temperature enhancement and stress generation are determined for every scenario. Finally, the crack propagation and the minimum W thickness required to fulfil the First Wall protection role is studied. The response of tungsten as First Wall material as well as its main limitations are discussed for the HiPER scenarios.

6.2 First Wall Requirements

The main requisite for the First Wall material is to have excellent structural stability since severe cracking or mass loss would hamper their protection role. Additional practical requirements for plasma facing materials are: (i) high thermal shock resistance, (ii) high thermal conductivity, (iii) high melting point, (iv) low physical and chemical sputtering and (v) compatibility with the heat sink structure. Moreover, safety and regulation reasons impose low tritium retention as a must. Due to its properties, tungsten is one of the most attractive materials proposed for First Wall applications [9].

The thermomechanical response of tungsten to intense thermal loads has been extensively studied either experimentally [150–152, 175] or by computer simulations [84–86]. The results indicate that the degradation of tungsten properties under thermal loads is a

serious concern for the use of tungsten as a First Wall material. Surface deterioration such as thermal shock-induced crack networks [158, 176], roughening [159], blistering, erosion of the loaded tungsten surface [155, 177], appear well below the melting temperature of tungsten. These effects turn out to be unacceptable for a First Wall material.

In Section 3.3 we studied the irradiation spectra and discussed the irradiation damage threshold as function of the heat flux factor, F_{HF} and energy fluence. For ion irradiation, damage appears at heat flux factors, $F_{HF} \sim 23 \text{ MW m}^{-2} \text{ s}^{0.5}$. [151, 152]. In the case of X-ray irradiation, it has been demonstrated that fluences up to $\sim 1 \text{ J/cm}^2$ [151] do not induce appreciable damage on tungsten. In this study we do not include neutron effects since they do not limit plant operation in the short term. For long term operation (years) in HiPER Demo, neutron fluxes of $\sim 2 \text{ MW/m}^2$, lead to damage rates of $\sim 1 \text{ dpa/fpy}$, He concentration of $\sim \text{appm/fpy}$ and tungsten transmutation to rhenium $\sim 0.25\%/\text{fpy}$ [87, 134], which will induce swelling, hardening, and thermal conductivity decrease [134–136].

Regarding thermomechanical conditions, we assess that the First Wall is kept below the tungsten melting temperature (3700 K [113]). At these high temperatures the yield stress lowers down from 1.2 GPa at room temperature to below 100 MPa at more than 2000 K [112]. The operation at high temperatures during the pulse will therefore mean the appearance of plastic effects, characterized by plastic strains and deformations. The results indicate that the First Wall will plastically deform up to a few microns underneath the surface. Continuous operation in power plant leads to fatigue failure with crack generation and growth.

Also operation at high temperature activates recrystallization processes which enhance irradiation effects. Local recrystallization has been observed at temperatures, in the range 1300–1800 K [178, 179]. This recrystallization was ascribed to hot spots in zones with low thermal conductivity. In the hot spots, the recrystallization temperature is only exceeded for a short time, therefore, recrystallization effects are only observed after repeated irradiation. Furthermore, the induced plastic deformation also lowers the recrystallization temperature. Recrystallization has important consequences on tungsten. It induces microstructural transformation and grain growth, which, in turn, affects the mechanical properties of tungsten reducing its strength and hardness.

In this Chapter, we study the thermomechanical effects that appear as a consequence of the deposition of energy in the First Wall. However, irradiation effects are also dependent on microstructural properties, (chemical composition, grain size and orientation, etc) and atomistic effects (defect formation, sputtering, and ion retention, etc), which are

not explicitly included in our model (see Section 2.3). These effects can be characterized through macroscopic properties such as damage thresholds, fatigue S-N curves or fracture toughness. We consider isotropic pure tungsten [112, 113]. Therefore, specific assessments should be done to account for the specific features of the employed type of tungsten. Other effects such as surface erosion, roughening and cracking are not included in the model. Finally, concerning strains, grain structure, viscous effects or roughening play an important role in the final deformation. All these points must be considered when analysing our results since real cases can significantly differ from our bilinear elasto-plastic model. However, despite these cautions, our model based on isotropic pure tungsten provides useful results for many practical situations. We can quantify temperatures, stresses and strains and provide an overall picture of the thermomechanical tungsten response to irradiation. In addition, fair comparison among different facilities regarding the First Wall behaviour can be established.

6.3 Substrate and Coolant Requirements

6.3.1 Substrate Thickness

One key parameter for the analysis of the First Wall is the thickness of the substrate material. The thickness of the structural material determines the temperature at the FW/substrate interface, and therefore the temperature of the First Wall in the steady state when the pulse cools down.

The substrate thickness is dictated by a limitation of 10% [43] of thinning due to corrosion during the planned 5 years of plant operation. Following the works of Sannier et al. [180, 181] on corrosion of an ODS-RAFM steel in contact with LiPb, Juarez et al. [45] estimated corrosion rates under HiPER conditions to be $\sim 200 \mu\text{m}/\text{yr}$. Therefore, the minimum thickness for the substrate is $\sim 1 \text{ cm}$. Also, the maximum thickness of the structural material is limited by the temperature in the FW/structural interface temperature.

To properly calculate the temperature at the interface between the First Wall and the substrate layer, we have to distinguish two different scenarios depending on the reactor operation mode. (i) For HiPER experimental, the total amount of energy deposited in the First Wall during one bunch can be easily dissipated through the First Wall. Therefore, at the end of the bunch the temperature at the interface will increase only few

degrees. (ii) HiPER Prototype and Demo reactors will work in a continuous operation mode and they reach the steady state regime when the energy deposited in the FW becomes equal to that dissipated to the coolant at the outer surface.

In the steady state regime, the temperature decreases from the inner to the outer surfaces. Therefore, it decreases from the First Wall surface to the substrate and finally the heat is removed by the coolant. Due to the high thermal conductivity of tungsten ($173 \text{ W m}^{-1} \text{ K}^{-1}$), the thickness of the First Wall does not affect significantly to the interface temperature. In fact the difference between the First Wall surface and the FW/substrate interface is only $\sim 5^\circ \text{C}$ for the design thickness of 1 mm (see Figure 6.4).

The temperature at the FW/substrate as a function of the substrate thickness is shown for HiPER Demo in Figure 6.2. A comparison of different structural materials is shown (F82H, SS316 and Al). F82H or SS316 steels are studied as they are HiPER materials, with operating temperatures of 925 K for ODS-RAFM and 1025 K for SS316 steel [47]. Al is just shown due to its high thermal conductivity, however its use is quite limited as tensile strength lowers down to $\sim 25 \text{ MPa}$ at temperatures or 600 K.

The temperature at the FW/structural interface increases with the substrate thickness. It depends on the substrate material, being proportional to the thermal conductivity. It is observed that the maximum ODS-RAFM steel thickness is $\sim 1 \text{ cm}$. For SS316, its

Figure 6.2: Temperature at the FW/structural layer interface as a function of the thickness of the structural material.

lower conductivities but higher operating temperature allows also for thickness ~ 1 cm. Al with higher thermal conductivity keeps lower interface temperatures, however its mechanical behaviour is compromised by low strengths at 600 K. These data illustrate that if needed (e.g. because of mechanical reasons) the thickness of the structural layer can be increased by selecting materials with high thermal conductivity. Nevertheless such a study falls out of the scope of this work and ODS-RAFM is proposed.

6.3.2 Coolant Temperature

Other important factor to be considered is the variation of the temperature at FW/substrate interface with the coolant temperature.

In [Figure 6.3](#) the effect of the coolant temperature has been analysed for an ODS RAFM substrate thickness of 1 cm. The range of temperature of the LiPb proposed coolant is between 600 K and 800 K. The temperature at the interface FW/substrate increases with coolant temperature. For HiPER prototype the temperature never reaches the upper limit noted by the service temperature of the substrate material. But in the scenario of HiPER Demo the range is limited until a coolant temperature of 600 K.

Therefore, we are in the lower part of the temperature operational range of LiPb. This implies lower efficiencies for the thermodynamic cycle of the power plant. In order to operate at higher temperature a reduction in the structural material thickness is necessary. However this solution would imply that corrosion exceeds in more than 10%. A possibility to minimize the corrosion rates is the use of surface coatings [\[182\]](#).

It is also important to point out that our study is done using LiPb as the reference scenario. However other cooling concepts such as He could be considered. This latter case is known as dual coolant blanket where He is the coolant that flows next to the reactor wall, and the LiPb is used in a posterior layer to absorb the energy of neutrons [\[44, 183\]](#).

Figure 6.3: Temperature at the FW/substrate as a function of the coolant temperature for different scenarios, HiPER Demo and Prototype reactors. The dotted line indicates the maximum operation temperature for the ODS-RAFM steel.

6.4 Thermomechanical effects of irradiation on HiPER First Wall

6.4.1 Radiation-induced thermal response

Irradiation energy leads to an increase in the temperature of the First Wall. First the First Wall surface is heated during the irradiation arrival. Then, the heat is transmitted through the First Wall to the substrate, and from the substrate to the coolant. In the Experimental case, with a limited number of shots, the First Wall will recover its initial temperature (300 K) shortly after irradiation. However, in the Prototype and Demo cases, operating in continuous pulsed modes (1 and 10 Hz), the First Wall is heated after each pulse, until a steady state is reached. To characterize the heating between pulses we define the base temperature as the temperature between the irradiation pulses.

Figure 6.4 shows the base temperature as a function of time for the Prototype and Demo facilities. For the operation of the plant we have to consider two different regimes: the “reactor start-up” corresponding to operation times lower than ~ 6 s for Prototype (1 Hz, 50 MJ) and ~ 60 s for Demo (10 Hz, 154 MJ) and the “steady state regime”

Figure 6.4: Calculated base temperature at the First Wall surface (red line), FW/substrate interface (blue line), and substrate/coolant interface (green line) as a function of time during the start-up for the HiPER Prototype (dashed line) and Demo (solid line) facilities.

for longer times. In the case of Prototype and Demo, the initial base temperature will be of 600 K, corresponding to the temperature of the coolant. For Prototype the temperature difference between the start-up and the steady state is of only 10 K, up to 610 K in the First Wall surface, and will have a minor impact on the behaviour of the First Wall. However for the Demo case, with higher energies, the First Wall surface, will heat up to 934 K. Due to the high thermal conductivity of tungsten, the temperature gradient in the First Wall is low and the temperature at the FW/substrate interface is 928 K. This means the substrate at the interface slightly above the operational temperature of the ODS-RAFM (925 K), which can lead to performance problems and in the joining. Finally, the temperature along the substrate decreases down to 680 K in the substrate/coolant interface for Demo.

The temperature evolution of the First Wall during each pulse is marked by the irradiation of x-ray, burn and debris ions, which induce three temperature peaks. In Figure 6.5 (a), we show the temperature evolution for the Experimental facility during an experimental pulse. In the FW surface (0 μm), the temperature evolution coincides in time with the radiation arrival. Before irradiation, the First Wall surface is at a room temperature (300 K). With the arrival of X-rays, an initial temperature peak of

Figure 6.5: First Wall (FW) temperature as a function of time at different depths underneath the FW surface for a) HiPER Experimental (first pulse), b) HiPER Prototype (steady state) and c) HiPER Demo (steady state).

550 K is reached. Then, the temperature abruptly decreases until the arrival of ions, which takes place in two steps. First, we observe the arrival of burn ions, which heat the surface up to ~ 700 K. Then, the surface cools down to ~ 650 K and with the arrival of debris ions the temperature increases up to ~ 900 K. Later on, tungsten cools down to room temperature, thus, the maximum calculated temperature for the Experimental facility is ~ 900 K, well below the melting point for tungsten (3700 K [113]). Since the

energy from X-rays and ions is deposited in the first microns, the temperature drops fast with increasing depth underneath the First Wall surface. For depths $\geq 10 \mu\text{m}$ only the arrival of ions contribute to the temperature enhancement. We also observe that for higher depths, the temperature peak appears later (due to heat conduction), having a temperature peak at $\sim 10^{-6}$ s for the First Wall surface ($0 \mu\text{m}$) and at $\sim 10^{-4}$ s for depths of $100 \mu\text{m}$.

The temperature evolution in HiPER Prototype and Demo is similar to that in the Experimental facility. The main differences are the higher irradiation fluences (see Table 3.4) and the fact that continuous irradiation leads to a steady state regime. Figure 6.5 (b) and (c) show the temperature evolution during a pulse once the steady state regime is reached for HiPER Prototype and Demo. The temperature at the First Wall surface notably increases after the arrival of radiation, especially at depths $\leq 10 \mu\text{m}$ where the major part of the energy is deposited. We observe the three temperature peaks that appear during the pulse, the first one related to the X-rays, the second one due to the burn ions and the third one due to debris ion deposition. The maximum temperature is ~ 1400 K and ~ 3400 K for HiPER Prototype and Demo, respectively, which are lower than the melting point of tungsten (3700 K [113]). However recrystallization effects (1300 - 1800 K [178, 179]) will affect operation in Demo facility and has to be studied in case of continuous operation in a Prototype reactor.

6.4.2 Mechanical response of the tungsten First Wall

Despite the temperature never exceeds the melting point, it affects the yield stress, that decreases from around 1.2 GPa at room temperature too below 100 MPa at more than 2000 K [112]. Thus, the stresses induced by the thermal loads easily exceed the yield stress resulting in plasticization. As discussed in Section 3.3, continuous cyclic load may lead to damage, in particular, the formation of deleterious cracks with unacceptable consequences for the First Wall material. We can get a first approximation to damage analysing the irradiation fluence. For the case of X-rays, the energy fluences are 0.09 , 0.13 and 0.4 J/cm² for Experimental, Prototype and Demo, respectively. These values are below 1 J/cm² [151] reported for damage. For the case of ion irradiation burn and debris have similar energy fluences but arrive at different times, with shorter pulses in the case of burn ions, which leads to more detrimental effects. We introduce the effect of

pulse duration with the heat flux factor, F_{HF} , and for burn ions¹, we obtain $F_{HF}=10.4$, 15.4 and 47.3 MW m⁻² s^{0.5} for Experimental, Prototype and Demo. Comparing these values to the F_{HF} damage threshold ~ 23 MW m⁻² s^{0.5} [151], we observe that HiPER Experimental is below the damage threshold. However, the values obtained for HiPER Prototype and Demo are close to or above the damage limit.

In order to understand possible damage in the First Wall, in this section we focus on the calculation of the thermomechanical response of the First Wall. The temperature enhancement during each pulse generates cyclic stresses at the First Wall. The origin of the stresses is due to the geometrical restrictions of the spherical chamber and the expansion of the materials associated to the temperature enhancement. Therefore, we observe an axial displacement characterized by the strains (ϵ_{xx}), accompanied by a transverse constraint observed in the stresses (σ_{yy}).

In Figure 6.6 (a), the transverse stress (σ_{yy}) and axial strain (ϵ_{xx}) for the HiPER Experimental facility are depicted. During the pulse arrival (up to $\sim 10^{-5}$ s) the material heats up, leading to an axial expansion (positive ϵ_{xx}) and transverse compression (negative σ_{yy}). In the First Wall surface, three peaks can be noted during the pulse. The first one is associated to the X-ray irradiation, the second one to the burn ions and the third one to debris ions. The effects of irradiation are less pronounced for increasing depth, being negligible for depths ≥ 100 μm . After the pulse, for times longer than 10^{-5} s, the material cools down, the surface retracts (decrease in ϵ_{xx}) and a permanent plastic deformation is observed. In order to compensate for the axial plastic deformation, tensile transverse stresses appear (positive σ_{yy}) reaching up to ~ 650 MPa. Regarding the effects of irradiation below the surface, we observe only one peak for depths ≥ 10 μm , in contrast with the three peaks at the surface. The peak turns out less pronounced with increasing depth, being negligible for more than ~ 100 μm . We also observe that at higher depths the peak appears later, at around 10^{-6} s at the First Wall surface (0 μm) and 10^{-4} s at depths of 100 μm . At the end of the pulse, the deformation (ϵ_{xx} at the end of the pulse) is irreversible at the surface (0 μm) while at higher depths (≥ 10 μm) it decreases to negligible values.

The stresses and strains for Prototype, Figure 6.6 (b), and Demo, Figure 6.6 (c), scenarios differ from those of the Experimental scenario, due to three reasons: (i) operation in the steady state regime (ii) the base temperature is higher in the Prototype and Demo facilities and (iii) the energy per pulse is higher. Due to steady state operation,

¹If we calculate F_{HF} considering all ion irradiation arriving in 3 μs , we have similar values of 9.7, 14.4 and 44.4 47.3 MW m⁻² s^{0.5} for Experimental, Prototype and Demo respectively.

Figure 6.6: Transverse stress (left) and axial strains (right) as a function of time for different depths. a) HiPER Experimental (first pulse), b) HiPER Prototype (steady state) and c) HiPER Demo (steady state).

Figure 6.7: Axial strain (a) and transverse stress (b) profiles as a function of depth for HiPER Experimental, Prototype and Demo facilities. The stresses and strains at the end of pulse (σ_{base} , ϵ_{base}) and during the pulse (σ_{pulse} , ϵ_{pulse}) are denoted by continuous and dashed lines, respectively.

the stresses and strains before the pulse are the same as after the pulse. Temperature variation makes the First Wall to undergo compressive and tensile stresses. Before the pulse, the First Wall the material is in a tensile state, during the pulse, the surface expands axially and compresses transversely, and after the pulse recovers its initial tensile state.

In order to better understand the effect of the base temperature on the First Wall, it is interesting to observe the stress and strain profiles (Figure 6.7). We show the profiles of strains and stresses taking place during the pulse ² (ϵ_{pulse} , σ_{pulse}) and the base values at the end of the pulse (ϵ_{base} , σ_{base}) when the material recovers the base temperature. We observe that ϵ_{base} , σ_{base} are large in the First Wall surface, with stresses $\sim$ GPa, quickly decreasing in the first microns defining the plastic region. The plastic region is $\sim 5 \mu\text{m}$ for the Experimental facility, $\sim 10 \mu\text{m}$ for the Prototype facility and $\sim 100 \mu\text{m}$ for the Demo facility. Beyond the plastic region we observe a plateau that reaches the FW/substrate interface. This plateau appears as a consequence of the temperature mismatch between the base temperature and the room temperate. Therefore the plateau is null ($\sigma_{yy} = 0$) for the Experimental (operating at room temperature), is low in the Prototype scenario ($\sigma_{yy} \sim 15 \text{ MPa}$, $\epsilon_{xx} \sim 5 \cdot 10^{-5}$) and much higher for Demo ($\sigma_{yy} \sim 300 \text{ MPa}$, $\epsilon_{xx} \sim 2 \cdot 10^{-2}$). At the FW/substrate interface a change from tensile stresses in the First Wall to compressive stresses in the substrate takes place for Prototype and Demo. Such a change stems from the differences in the thermal expansion coefficients of tungsten and the substrate (larger for the ODS RAFM steel than for tungsten). In Table 6.2 we summarize the maximum expected temperature, stress and strain for the First Wall in the different scenarios.

Table 6.2: Main thermomechanical results for the tungsten First Wall in the different HiPER scenarios.

HiPER Scenario	Max. Temperature (K)		Max. Stress (MPa)		Max. Strain		Plastic Region (μm)
	T_{pulse}	T_{base}	σ_{pulse}	σ_{base}	ϵ_{pulse}	ϵ_{base}	
Experimental	875	300	-440	650	$6 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	5
Prototype	1410	610	-550	1050	$1.2 \cdot 10^{-2}$	$2.5 \cdot 10^{-3}$	10
Demo	3400	934	-770	1250	$6 \cdot 10^{-2}$	$4 \cdot 10^{-3}$	100

²First pulse in the Experimental scenario and a pulse during steady state regime in the Prototype and Demo scenarios.

6.4.3 First Wall Damage Appearance

According to these data, fatigue will limit the lifetime of the First Wal. The maximum number of cycles (N_f) that a tungsten First Wall can withstand without failure can be calculated by means of equation $\epsilon_p = 34 \cdot N_f^{-0.46}$ [84], where ϵ_p is the maximum plastic deformation reached during the cycle load and N_f the number of cycles for fatigue. On these basis the lifetime of the Experimental facility for $\epsilon_p = 6 \cdot 10^{-3}$ is ~ 150 millions of cycles. The expected number of experiments to be carried out in this facility, assuming five shots per day during 5 years is 1800. Therefore, tungsten First Wall will withstand the operation conditions for which the HiPER Experimental facility is designed. For the Prototype facility, the maximum strain is $1.2 \cdot 10^{-2}$, allowing for $\sim 20\,000\,000$ cycles. Cracks would appear after 550 hours (23 days) of operation. For Demo, the maximum plastic strain is $6 \cdot 10^{-2}$, allowing for $\sim 1\,000\,000$ cycles. That means that cracks will appear at the First Wall surface after just 28 hours of operation.

It is very relevant to note that, in the case of Demo, a He fluence higher than $4 \times 10^{15} \text{ cm}^{-2}$ is reached in times of the order of minutes. This fluence corresponds to the threshold for surface fatal damage (protrusions, bubbles, roughening) in pulsed He irradiation conditions [156] (see Section 2.3). Therefore, in addition to the severe effects stemming from the thermomechanical response, easily quantified with our model, effects of atomistic origin, much more difficult to take into account, play a competing detrimental role. It is important to stress the extreme situation the First Wall faces, in particular in the case of the Demo facility. In the case of evacuated dry wall chambers, (HiPER) the only feasible solution to the expected He-related problems is to develop new materials with superior radiation resistance properties, in particular, materials less prone to helium effects.

Schemes based on engineered surfaces such as tilted surfaces [156], W-foams [85] or nanostructured materials [82, 83, 184] are promising since they lower the energy flux reducing thermomechanical effects. They also tend to reduce the number of generated defects and facilitate the release of He, suppressing the number of He atoms trapped at defects, which is probably the origin of the detrimental atomistic effects [76, 77]. Ongoing efforts are devoted to these topics, however, dedicated experiments are missing and really needed to optimize the design of the new materials, understand the interaction of He and defects and the role of temperature. In this sense, we consider that since the dismantle of RHEPP in Sandia Nat. Lab. (NM), the lack of appropriate experimental pulsed irradiation facilities is a serious limitation to this important task.

6.4.4 Tungsten First Wall thickness and crack propagation

Several aspects need to be considered when estimating the required tungsten thickness: (i) the stopping of ions in order to keep them away from the substrate ($\geq 100 \mu\text{m}$), (ii) the accommodation of the stresses generated in the First Wall, which requires a thickness $\sim 100 \mu\text{m}$ in order to accommodate the plastic stresses (see Figure 6.7), and (iii) crack propagation along the First Wall, to prevent undesired growth up to the substrate.

Cracks are induced by cyclic loading caused by ion irradiation. The thermal load from ion irradiation is responsible for expansion and plasticization of tungsten under large compressive stresses. Then, after the heat deposition, tungsten cools down and reverts the previous expansion, leading to tensile stresses in the First Wall surface. If there are cracks in the First Wall surface, they will propagate in the axial direction under the transverse tensile stress. This leads to a crack opening mode (mode I) that can be characterised with the stress intensity factor K_I [185]. On these bases, the crack will experience immediate growth if K_I in the crack tip is higher than the fracture toughness (K_{IC}) of tungsten, which is $\sim 5 \text{ MPa m}^{1/2}$ for temperatures $\sim 300 \text{ K}$ and $\sim 10 \text{ MPa m}^{1/2}$ for higher temperatures [153]. Below the fracture toughness ($K_I < K_{IC}$), cracks will slowly grow under cyclic loading, when the stress intensity factor range $\Delta K_I = K_I^{max} - K_I^{min}$ is over the fatigue threshold, ΔK_{th} . However, experimental data under irradiation conditions and high temperatures are required in order to give a detailed assessment of the fatigue threshold and crack growth. In the next paragraphs we estimate the maximum crack growth attained when the crack tip reaches a stressless state.

This situation is illustrated in Figure 6.8, which shows the evolution of a crack with a length of $100 \mu\text{m}$ during the pulse duration for the Demo facility. It is observed that during the first $2 \mu\text{s}$, tungsten is heated, plasticizes and develops transverse compressive stresses. For times $\geq 10 \mu\text{s}$ the tungsten surface cools down, the material in the crack edges retracts leaving an open crack with the crack tip under tensile stress.

We study how the crack characteristics (crack length and crack separation) affect its propagation. The origin of the stresses in the crack pit is the plastic strain, which needs to be accommodated when the material cools down after the pulse. If the crack length is small, most of the plastic strains induce a tensile state, which leads to high stress concentration in the crack pit (high K_I). When the crack grows, the plastic strains lead to the opening of the crack, the material relaxes and the stress concentration in the crack pit is lower (low K_I). Similarly when the crack separation is large, all the

Figure 6.8: Evolution of a crack of length $100 \mu\text{m}$ and spacing of $400 \mu\text{m}$ in Demo reactor. The figure is deformed with a scale factor of 10x.

plastic deformation between the cracks, need to be compensated by the tensile stresses, which pile up in the crack pit (high K_I). When the cracks are closer, the total plastic deformation is reduced, leading to lower stresses and K_I .

Figure 6.9 (a) shows K_I as a function of depth for the different HiPER scenarios for a constant separation between cracks of $1000 \mu\text{m}$. As expected, the K_I factor decreases with depth. The maximum K_I is 2, 5 and $\sim 8 \text{ MPa m}^{1/2}$ for HiPER Experimental, Prototype and Demo facilities. Assuming K_{IC} to be $\sim 5 \text{ MPa m}^{1/2}$, cracks will not critically propagate in the Experimental facility because the total number of cycles expected in an experimental reactor is low. In the case of Prototype or Demo reactors, the high crack intensities, near or above fracture toughness will lead to rapid crack growth.

In Figure 6.9 (b), we show the stress intensity (K_I) for Demo for different crack lengths and crack separations. We observe that K_I is higher than the fracture toughness (K_{IC}) for cracks separated more than $200 \mu\text{m}$. Therefore, cracks will grow rapidly after its formation. When the crack grows and K_I is below the fracture toughness, cracks will slowly grow until a near stressless state is attained in the crack tip. As irradiation goes on, new cracks will be formed, reducing the separation between cracks and limiting crack growth. When crack densities of $\sim 2500 \text{ cracks/cm}^2$ are attained (separation of $\sim 200 \mu\text{m}$) the crack length will be limited to $100\text{-}200 \mu\text{m}$.

Based on these results a First Wall thickness $\geq 200 \mu\text{m}$ would correctly stop ion irradiation, accommodate temperature transients, stresses and limit crack propagation to the First Wall. The thickness of the tungsten First Wall is very relevant in order to address technological problems, such as the joining between the tungsten and the steel

Figure 6.9: (a) Stress intensity factor in mode I (K_I) as a function of the crack length for HiPER Experimental (blue line), Prototype (green line) and Demo (red line) facilities with isolated cracks separated by 1000 μm , (b) Stress intensity factor in mode I (K_I) as a function of the crack length for the Demo reactor with isolated cracks separated by 1000 μm (blue line), by 800 μm (green line), by 600 μm (red line), by 400 μm (light blue line), and by 200 μm (purple line).

[152, 186, 187], assessing it to withstand the stresses that appear in the FW/substrate interface. We propose a First Wall thickness of 1 mm as a conservative approach for the design of the First Wall. Anyway, more experimental validation of materials is necessary since tungsten damage threshold and fracture toughness can be severely affected by irradiation. Atomistic effects such as He accumulation, create additional stress concentration favouring crack appearance [156]. In this case, the high temperatures during the shot could help to release helium and reduce this effect [157] but still intensive experimentation is necessary. The presented model only studies perpendicular crack propagation on a flat surface in the opening mode, however cracks can adopt complex shapes. The crack shape is affected by surface erosion, crack branching and crack irradiation, therefore, its behaviour can only be assessed through experiments.

6.5 Conclusions

A systematic study on the thermomechanical response of a tungsten First Wall in the different HiPER scenarios to realistic irradiation conditions is presented. The energy carried by ions and X-rays ($\sim 25\%$ of the total shot energy) is deposited in the first 100 μm of tungsten during times of $\sim 4 \mu\text{s}$. During irradiation three temperature peaks appear,

corresponding to pulses of X-rays, burn ions and debris ions generated with every target implosion and ignition. As a result, the First Wall expands until the irradiation ceases and the material cools down, leading to a tensile state and the appearance of a plastic region. The plastic region affects the first microns of the First Wall.

Fatigue appears due to the cyclic nature of the irradiation. The lifetime of the First Wall in the different HiPER scenarios is limited by the fatigue loading. On these bases, an Experimental facility could operate with a tungsten First Wall, thanks to the employed low energy targets and the limited demand of shots in such a facility. In the case of a full scale power plant (Demo), damage will appear in the First Wall. We encounter several problems: the peak temperature during each pulse is near the melting temperature, the energy fluence is above reported threshold damage values and cracks would appear and propagate shortly after the beginning of operation. In the case of a reactor operating with relaxed conditions (Prototype), the First Wall will withstand the irradiation conditions only for a short term (days). Special attention should be paid to long term operation due to fatigue problems, the expected appearance of cracks and the erosion of the First Wall. Regarding the thickness of the tungsten First Wall, the main limiting factor is crack propagation. We estimate that a tungsten First Wall with a thickness of $\sim 100 \mu\text{m}$ is enough to fulfil its protection role. Such a thin First Wall can be fabricated by affordable methods such as Physical Vapour Deposition (PVD), offering different joining possibilities.

Since operation for full scale reactors (Demo) with a tungsten First Wall appears unfeasible, some scientific and technological research must still be done. This requires experiments at high temperatures under realistic irradiation conditions to better characterize the effects of irradiation and develop strengthened materials.

Chapter 7

Materials irradiation in the medium sized neutron source of ESS-Bilbao

In previous Chapters we have addressed fundamental effects of irradiation on ICF materials (see [Chapter 3](#) and [Chapter 4](#)) and discussed technological solutions to minimize these effects (see [Chapter 5](#) and [Chapter 6](#)). However, in order to advance in the characterization of irradiation effects and the development of technological solutions intensive experimental research is still required. In this Chapter we stress the necessity of experimentation in order to validate materials and components.

In this context, we study the possibility of using medium sized neutron sources, such as ESS-Bilbao, for experimentation on nuclear fusion materials. Using the methodology described in [Section 2.2](#) we study irradiation parameters (PKA spectrum, gas formation and displacements per atom), and compare them for medium sized neutron sources and nuclear fusion facilities. From the analysis we conclude that both irradiation spectra match quite well and comparable irradiation patterns are expected. This is of special interest for the characterization of neutron damage on laser fusion final lenses. The results presented in this Chapter were also published in Ref. [\[16, 17\]](#)

7.1 Introduction

Most of the efforts regarding the development of facilities for neutron damage irradiation have been focused towards the development of structural materials for the chamber of magnetic fusion plants. For these chambers, it is necessary to develop structural

materials capable of resisting several tens of dpa (displacements per atom). In the line of developing such materials, different possibilities for neutron irradiation have been explored [188–193]. They include in addition to IFMIF, spallation sources, accelerator driven systems and fission reactors. The major conclusion is that only IFMIF seems appropriate for neutron irradiation studies of structural materials.

On the other hand, the modular nature of the laser fusion power plants allows for the replacement of the chamber periodically, lowering the requirements for the structural materials. However, the operation of these plants depends on the final optical elements, exposed to neutron irradiation. In the case of the European project HiPER (High Power Laser Energy Research facility) [5], the final optical elements will be silica lenses located a few meters away from the chamber centre (8-16 m) [14]. Therefore, a detailed qualification of the optical materials with realistic neutron fluxes will be needed to avoid the risk of fatal operation failure.

In this Chapter we discuss the viability of a medium sized neutron source, such as ESS-Bilbao [92, 93] or Julich HBS [94], for experimental studies of fusion materials. Making use of the design of target station we have calculated the neutron spectrum expected in the fast neutron line. Then, using the methodology described in Section 2.2, we have studied the neutron irradiation effects in two model materials: iron and silica. We have calculated the expected PKA (primary knock-on atom) spectra and light species production as well as the damage production in these materials. Regarding structural materials, we conclude that ESS-Bilbao or a similar neutron irradiation facility would play a minor role due to the resulting low neutron fluxes (about two orders of magnitude lower than in fusion reactors). On the other hand, a medium sized neutron source such as ESS-Bilbao turns out to be relevant for studies of final lenses in laser fusion power plants. A comparison with the conditions expected for HiPER final lenses shows that the fluxes will be only a factor 5 smaller in ESS-Bilbao and the PKA spectra will be very similar. Taking into account, in addition, that relevant effects on lenses occur from the onset of irradiation, we conclude that an appropriate irradiation cell with in situ characterization techniques would be very attractive for applied neutron damage studies of laser fusion final lenses.

7.2 The ESS-Bilbao medium sized neutron source

The ESS-Bilbao neutron source[92, 93], is conceived as a multipurpose facility, that would offer a fast neutron beam line for materials irradiation, neutron lines for condense matter research and an accelerator facility compliant with the ESS-AB requirements

Nowadays (beginning of 2017), ESS-Bilbao has an intense proton source up to 50 mA, and a RFQ is under construction for its acceleration up to 3 MeV. However, the project has entered in a stand-by and the installation of DTL components for energies up to 50 MeV and a proton target have been postponed with no date.

Since already existing small or medium sized neutron sources (ISIS, ILL) are ageing and will need substitution [194] we expect ESS-Bilbao or similar medium sized neutron sources, such as Julich HBS, to be available in the near future. Medium sized neutron sources will therefore be necessary for developing instrumentation, formation of scientists, and experimentation that cannot be done otherwise in intense neutron sources such as SNS, JSNS or ESS-AB. In this scenario, the results presented in this Chapter become relevant for the experimentation of nuclear fusion materials in medium sized neutron sources.

The ESS-Bilbao medium sized neutron source [92, 93] is based on intense proton beams with up to 75 mA current, 50 MeV proton energy, 0.1-1.5 ms pulse duration and 20-50 Hz repetition rate¹. One of the proposed experimental stations is a medium sized neutron source for materials irradiation.

In the ESS-Bilbao, the neutrons would be produced through stripping reactions caused by the incident proton beam in a beryllium target (see Figure 7.1). The stripping reactions produce neutrons that are biased in the forward direction. To gain advantage from the biased neutron production, the fast neutron line is placed in the forward direction, and moderators for the production of thermal and cold neutrons are placed forming 45°. In the fast neutron line an irradiation cell for materials damage analysis will be installed. This irradiation cell can be placed at a distance of 10-20 cm from the beryllium target. The position 20 cm away from the target is the most suitable to avoid operational interference between the irradiation cell and other systems of the neutron source (moderators of the cold and thermal neutron lines). However, in order to have higher neutron fluxes, we study the location at 10 cm from the target. This design provides flexibility to meet a broad range of experimental conditions.

¹For this work a pulse of 1.5 ms operating at 20 Hz has been assumed.

Figure 7.1: Model of the ESS-Bilbao neutron target (from the target group of ESS-Bilbao [92]). The irradiation cell is placed near the target (10-20 cm) maximizing the damage production. Top: CAD model of the target and its main components; bottom: MCNPX model.

7.3 Neutrons in nuclear fusion and ESS-Bilbao

The future fusion energy power plants will be based on the DT reaction. This reaction produces a fast neutron (14.1 MeV) and an alpha particle (3.5 MeV). Depending on the confinement method (magnetic or inertial) and in the latter case depending on the illumination method (direct or indirect), different radiation spectra are produced. At the moment the HiPER project opts for an advanced ignition scheme with direct targets and an evacuated dry wall chamber with silica transmission final lenses (see [Section 1.2](#)). In

this Chapter we study the pre-commercial conditions expected in HiPER Demo. With these conditions, $\sim 70\%$ of the fusion energy will be carried by neutrons and the rest ($\sim 30\%$) by ion pulses. The fusion neutrons cannot be mitigated and thus, they will reach the surrounding materials. In order to study and qualify the material under neutron irradiation, appropriate facilities will be necessary.

In the ESS-Bilbao irradiation cell, the samples could be irradiated to reproduce conditions representative for nuclear fusion reactors. For this purpose the irradiation conditions in ESS-Bilbao and fusion (HiPER Demo) must be compared (see Figure 7.2). The comparison shows that although similar, the spectra do not match exactly. The major difference is due to the 14 MeV fusion neutrons that give rise to a marked peak in the HiPER spectrum absent in the ESS-Bilbao spectrum. On the other hand, the ESS-Bilbao spectrum shows a high energy tail absent in HiPER.

What does this imply when irradiating fusion materials? The answer is not straightforward and in the next section the most important aspects are discussed.

Figure 7.2: Neutron spectrum originated in HiPER with the explosion of a direct drive target with a yield of 154 MJ according to LASNEX simulations carried out in the framework of the ARIES project [104] and in the ESS-Bilbao fast neutron line by every proton pulse.

7.4 Viability of ESS-Bilbao as a neutron irradiation facility

In order to evaluate the neutron damage in a neutron facility several aspects have to be considered, such as the flux intensity, flux spectra, PKA spectra, dpa and gas production. In Table 7.1 the main parameters for HiPER Demo and ESS-Bilbao are summarized.

For structural materials, the average neutron flux expected in the HiPER Demo chamber (6.5 m radius) is $1 \cdot 10^{18} \text{ m}^{-2} \text{ s}^{-1}$, almost two orders of magnitude higher than the average neutron flux that can be achieved in ESS-Bilbao. In addition, we must take into account that the major motivation for the study of structural materials is to improve the radiation resistance properties. Therefore, experimentalists will be mainly interested in qualifying the materials at fluences far too high to be reached in ESS-Bilbao. The use of ESS-Bilbao as a neutron irradiation facility for structural materials will be limited to certain studies, mainly for academic purposes.

On the other hand, in HiPER Demo the optical final lenses will receive an average neutron flux of $\sim 2 \cdot 10^{17} \text{ m}^{-2} \text{ s}^{-1}$. The average neutron flux that can be achieved in

Table 7.1: Main characteristics of HiPER and ESS-Bilbao.

	HiPER	ESS-Bilbao	
Neutron Yield (n/shot)	$5 \cdot 10^{19}$	$5 \cdot 10^{13}$	
Average neutron energy (MeV)	11.8	7.7	
Repetition rate (Hz)	10	20	
Damage on Iron			
Distance to neutron source (cm)	650	10	20
Average neutron flux ($\text{m}^{-2}\text{s}^{-1}$)	$1 \cdot 10^{18}$	$4 \cdot 10^{16}$	$2 \cdot 10^{16}$
Damage (dpa/fpy)	7.3	0.14	0.05
H (appm/fpy)	306	7.2	2.2
He (appm/fpy)	97	2.2	0.6
H/dpa	42	51	42
He/dpa	13	15	12
Damage on Silica			
Distance to neutron source (cm)	1600	10	20
Average neutron flux ($\text{m}^{-2}\text{s}^{-1}$)	$2 \cdot 10^{17}$	$4 \cdot 10^{16}$	$2 \cdot 10^{16}$
Damage (dpa/fpy)	0.23	0.03	0.01
H (appm/fpy)	49	5.6	1.6
He (appm/fpy)	83	8.2	2.4
H/dpa	72	66	46
He/dpa	122	97	67

ESS-Bilbao is $\sim 2 - 4 \cdot 10^{16} \text{ m}^{-2} \text{ s}^{-1}$. The latter is only a factor 5 lower than the neutron flux expected in a pre-commercial HiPER Demo power plant. Thus, the time required to reach certain neutron fluence in ESS-Bilbao will be close to the time required in HiPER. Since significant phenomena (colouration, compaction, refractive index variation) can be studied in silica at low fluences (minutes to hours of irradiation), the ESS-Bilbao irradiation line appears as an adequate facility to carry out neutron irradiation studies of silica.

The differences in neutron spectra between the ESS-Bilbao irradiation facility and the HiPER power plant must be also considered. Low energy neutrons mainly interact with matter by means of elastic collisions, whereas high energy neutrons produce non-elastic reactions, leading to the generation of light species and gamma emission. The displacement cascades also depend on the neutron energy. Regarding the influence of the neutron spectra in the energy deposition, the first half of the deposited energy occurs for similar neutron energies (10-15 MeV) in both facilities. However, in ESS-Bilbao the energy deposition takes place in a wide energy range (1-50 MeV), whereas in HiPER most of the energy is deposited by neutrons with energies exceeding 10 MeV, and peaking at 14 MeV. In both cases the influence of low energy neutrons (<1 MeV) is low.

An important parameter for the comparison of neutron damage in ESS-Bilbao and HiPER is the PKA spectrum. Following the methods described in [Section 2.2](#), we have calculated the PKA spectra generated in iron and silica (see [Figure 7.3](#)). We observe that the spectra generated in both facilities are similar. This means that the neutron damage will be similar, although it is produced at a lower rate in ESS-Bilbao. The major differences in the PKA spectra appear at high energies, because of the high energy tail in the neutron spectrum of ESS-Bilbao. This will lead to some high energy recoils absent in HiPER. We discard that they could produce damage by electronic excitation mechanisms [\[195\]](#). In silica, these mechanisms produce changes in density, stoichiometry, optical properties as well as generation of defects and typically take place above certain stopping power threshold of the order of 2-6 keV/nm depending on the ion velocity [\[137–143\]](#). Recoiled O atoms can never reach even the lowest threshold value (2 keV/nm), whereas recoiled Si atoms with energy above ~ 3 MeV have an electronic stopping power of ~ 2 keV/nm. Such high Si recoil energies are hardly reached in HiPER and in ESS Bilbao they represent a negligible fraction of the total recoil number. In iron, the threshold for electronic damage exceeds 25 keV/nm [\[144\]](#), which cannot be reached with the Fe recoils expected in both HiPER and ESS Bilbao.

Figure 7.3: PKA spectra in iron and silica samples calculated for ESS-Bilbao and HiPER facilities. The PKA spectrum for silica is calculated as the sum of oxygen and silicon contributions.

As explained in [Section 2.2](#), in order to estimate the damage level, we have used the NRT model [106]. Although very simple, it is useful for the purpose of comparing different facilities because it provides a meaningful quantity, the number of displacements per atom (dpa) and we can account for the non-linear defect production due to PKAs of different energies. The dpa level expected per year is included in [Table 7.1](#) for silica and iron in both HiPER Demo and ESS-Bilbao facilities. An analysis of the damage shows, as expected, that the dpa level reached in HiPER will be higher than in ESS-Bilbao due to the higher neutron fluxes. However, the ratios of light species levels to dpa agree quite well in both cases, as expected from the neutron and PKA spectra.

As already mentioned, the main drawback of ESS-Bilbao is its low neutron flux, not enough to reproduce damage at high fluences in structural materials. However, in the next section it is shown that since interesting effects appear in silica at low fluences, ESS Bilbao can be a useful facility to study them.

7.5 Damage production in silica

As explained in detail in [Chapter 5](#), silica components are expected to be present in future fusion power plants: mirrors, lenses, windows. They will be exposed to severe irradiation conditions in laser fusion facilities, in particular neutron irradiation will lead to the generation of colour centres. These colour centres produce laser absorption with fatal consequences for the plant operation.

We have estimated the colour centre production using the model proposed by Marshall et al. [63] and reviewed by Latkowsky et al. [66], see [Section 3.2.2](#). Using this model we have estimated the colour centre concentrations and absorption coefficient in HiPER Demo and ESS-Bilbao at different temperatures (see [Figure 7.4](#)).

Regarding the defect evolution, the steady state is reached in ~ 60 s at 850 K and in ~ 1000 s at 750 K. Associated to ODC concentration, a large peak centred at 248 nm appears in the absorption coefficient. It turns out to be a broad peak that extends beyond the 350 nm band. In addition, a second peak associated to E'-centres appears at 213 nm. In ESS-Bilbao the E' centre generation rate is lower than in HiPER. This is because the formation of E' centres does not depend linearly on the dose rates but it scales quadratically. Therefore, as in ESS-Bilbao the level of irradiation is lower than in HiPER, for the same temperature, the E' centre peak (213 nm) is less marked, as appreciated in [Figure 7.4](#).

The temperature determines the defect evolution in silica because defect annealing is a thermally activated process. As an example, [Figure 7.4](#) shows the role of temperature. Irradiations in ESS-Bilbao at 750 K will lead to defect concentrations and hence absorption coefficient similar to those of HiPER at 850 K. Therefore an adequate temperature control in an ICF plant will be necessary to maintain the silica final lens absorption below tolerable limits [14]. On the other hand, the temperature in an experimental facility as ESS-Bilbao will be a crucial parameter to understand the defect kinetics and in turn elaborate models to apply in realistic situations.

Experimental data from ESS-Bilbao will allow us to validate materials and improve available models. For example the Marshall-Latkowsky model used in this section does not include the influence of the neutron spectrum or the effect of light species and impurities.

Figure 7.4: a) Time evolution of the ODC and E' defects until the stationary regime is attained. b) Comparison of the absorption coefficient in stationary regime (~ 60 s for 850 K and ~ 1000 s for 750 K). Analysis for ESS-Bilbao (10-20 cm) and HiPER in a silica lens of 5 cm thickness.

7.6 Other neutron irradiation facilities

In the previous sections, the damage analysis for ESS-Bilbao and its comparison with HiPER Demo is shown. However it is also interesting to compare ESS-Bilbao with other experimental facilities. In the last decades, the adequacy of different neutron sources for fusion materials irradiation has been addressed, in Ref. [189] Vladimirov and Bouffard give an interesting comparison between different neutron facilities. Of special interest are Demo, HFR, ESS and IFMIF. These facilities represent different types of neutron sources: *a)* Demo as a magnetic confinement nuclear fusion prototype power plant, *b)* HFR (Petten) as a typical mixed spectrum fission reactor, *c)* ESS as a spallation neutron source and *d)* IFMIF as a facility developed specifically for the irradiation of nuclear fusion materials.

A comparison of these facilities with ESS-Bilbao and HiPER is shown in Figure 7.5, Figure 7.6, and Table 7.2. The neutron flux in ESS-Bilbao is much lower than in other experimental facilities. Regarding the neutron spectrum (Figure 7.5) we realize that none of the neutron sources is able to reproduce the neutron spectrum generated in fusion plants, characterised by a marked peak at 14 MeV. The best approach to the

Figure 7.5: Neutron flux per unit lethargy in different nuclear facilities using: ESS-Bilbao, HiPER, Demo, HFR, IFMIF, and ESS. The neutron flux for Demo, HFR, IFMIF and ESS are obtained from Ref. [189].

fusion spectrum is obtained in IFMIF and ESS-Bilbao. Although in the latter case the neutron flux is low, in both cases the spectrum presents a sharp drop at neutron energies slightly higher than 14 MeV. Regarding the PKA spectra, see Figure 7.6, it is obvious that IFMIF provides the PKA spectrum that best resembles the fusion plants. Next, as discussed in Section 7.4, ESS-Bilbao produces an acceptable PKA spectrum. However, the other two neutron facilities, ESS and HFR, strongly differ from the fusion PKA spectra. In ESS a marked tail of high energy PKAs is present that would probably dominate the neutron effects on an irradiated material. On the other hand, in HFR the average PKA energy is too low to reproduce the effects induced by fusion neutrons.

Summarizing, the comparison with other neutron facilities shows that it is not easy to obtain spectra as those expected in future fusion power plants. Fast reactors do not turn out a good option to mimic fusion damage. On the other hand, spallation sources have shown their potential, but some factors have to be considered such as differences in the PKA spectra, light species production and spallation product yield [190, 193]. IFMIF, constructed ad-hoc for fusion materials irradiation, shows a spectrum adequate for fusion damage reproduction.

Figure 7.6: PKA spectra of different nuclear facilities using ^{56}Fe as the reference material. The analysed facilities are ESS-Bilbao, HiPER, Demo, HFR, IFMIF, and ESS. The lower curve of ESS-Bilbao corresponds to the regions nearer the target (10 cm) and the upper to the regions further from the target (20 cm). The neutron flux for Demo, HFR, IFMIF and ESS are obtained from Ref. [189].

Table 7.2: Damage comparison for the reference facilities, using iron (^{56}Fe) as the reference material. The damage characteristics for DEMO, IFMIF, ESS and HFR have been obtained from Ref. [189].

	Damage (dpa/fpy)	H (appm/fpy)	He (appm/fpy)	H/dpa	He/dpa
ESS-Bilbao	0.05-0.14	2.2-7.2	0.6-2.2	42-51	12-15
HiPER	7.3	306	97	42	13
Demo	30	1240	320	41	11
IFMIF	20-55	1000-2400	250-600	35-54	10-12
ESS	5-10	160-360	25-60	33-36	5-6
HFR	2.5	1.9	0.8	0.76	0.32

7.7 Conclusions

We have analyzed a neutron medium sized neutron source such as ESS-Bilbao as a tool for the study of materials irradiation under nuclear fusion conditions. Throughout the article we studied the neutron spectra, PKA spectra, dpa and light species production in different materials. This showed that the spectra in ESS-Bilbao matches quite well the fusion spectra and comparable irradiation patterns are expected. When comparing the PKA spectra of ESS-Bilbao and IFMIF, a similar shape is observed, much better fitted for fusion damage reproduction than fast reactors or spallation sources.

Damage rates in ESS-Bilbao will be low and qualification of structural materials (up to tens of dpa) will not be possible. For that purpose, facilities like IFIMF will be necessary. In the field of structural materials, a medium sized neutron source as ESS Bilbao could contribute to address the initial stages of damage. On the other hand, it can play an important role in the analysis of silica-based optical materials for fusion, related to the improvement of damage models and validation of materials. Apart from studies on silica, other materials relevant for the fusion community could be studied, this is the case of lithium ceramics, ceramic insulators or electronic components.

Chapter 8

Conclusions and Further Work

8.1 Conclusions

The thesis presents a detailed analysis of irradiation effects the HiPER Laser Fusion Power Plant. We specifically address irradiation effects on the silica Final Lenses and on the tungsten First Wall. During this work we cover different aspects related to irradiation, from the analysis of fundamental effects to its implications on the design of components and the requirements for irradiation in an experimental facility.

In the different Chapters full discussion of the irradiation effects and its implication is given. As a summary the main achievements of the thesis are:

- i [Characterization of irradiation conditions in the different HiPER scenarios](#). Study of the irradiation spectra, gas formation, resulting damaged (dpas), formation of colour centres, PKA spectra, heat deposition, etc.
- ii [Development of a model for the characterization of silica surface density evolution with ion irradiation](#). The model specially addresses the density drop observed in an experimental campaign, that we attribute to the effect of residual stresses after track inclusion.
- iii [Characterization of ICF final optics operation under irradiation conditions expected in the HiPER reactor](#). We develop a methodology in order to estimate the effect of thermal aberrations and conclude that some temperature control is required. Finally we propose a system in order to control the lens temperature. This system, operating with Helium cooled channels keep low temperature gradients, resulting in a low level

of aberrations.

- iv **Study of irradiation effects in the tungsten First Wall for different HiPER reactor scenarios.** We conclude that operation in experimental reactors is feasible with a tungsten First Wall. However when higher energies or repetitive operation is required degradation of the tungsten First Wall appears. In the case of the HiPER Prototype facility, operation for a period of time would be possible, while problems are expected in the long term scenario. In the case of a full scale reactor, degradation of the first wall is expected shortly after the beginning of operation.
- v **Study of the use of a medium sized neutron source for neutron irradiation of materials.** We base the analysis in the design of the ESS-Bilbao facility. We conclude that the neutron damage is similar to nuclear fusion. We base our analysis in the comparison of the PKA spectra and gas production ratios comparison. The main constraint is the low damage rates expected in ESS-Bilbao. Therefore neutron damage effects appearing at low damage rates can be accurately characterized in ESS-Bilbao, as is the case of the formation of colour centres in silica.

8.2 Further Work

From the analysis of the current work, we identify the main lines of work that would help to improved understanding of irradiation effects and proposal of solutions for components operating in Inertial Fusion reactors.

In the Chapters of the thesis more discussion about the shortcomings of the work and possible improvements is given. As a summary the main works that should follow to the current thesis are:

- 1 **Development of a model for the characterization of silica surface density evolution with ion irradiation.** Improvements to the model can address the degradation of material properties along irradiation, its effects on surface expansion, and the transition to the irradiation enhanced plastic flow.
- 2 **Characterization of ICF final optics operation under irradiation conditions expected in the HiPER reactor.** The main limitation is the effect of high irradiation rates on the silica behavior. In this case the formation of impurities or gas retention can lead to compounds and stable defects with laser absorption. In this work resistance to

laser damage has been assessed for polished silica. However it can be triggered by impurities, leading to silica degradation can lead to laser damage that destroys the final optics.

Regarding ion mitigation, we show how magnetic dipoles can mitigate irradiation. However detailed design of the dipoles, as well as other components such as irradiation dumps are still pending.

- 3 [Study of irradiation effects in the tungsten First Wall for different HiPER reactor scenarios](#). We conclude that operation for full scale reactors with a tungsten First Wall appears unfeasible. Therefore scientific and technological research must still be done. This requires experiments at high temperatures under realistic irradiation conditions to better characterize the effects of irradiation and develop strengthened materials.
- 4 [Study of the use of a medium sized neutron source for neutron irradiation of materials](#). All along the thesis we show that experimentation in irradiation conditions similar to nuclear fusion is a must. We show how experimentation in a facility such as ESS-Bilbao could be useful, however most of the shortcomings in experimental data could only be solved with the full development of a facility such as IFMIF

Publications, Conferences & Stays Abroad

Publications

- A. R. Páramo, F. Sordo, O. Peña-Rodríguez, A. Prada, J. Olivares, M. L. Crespillo, J. M. Perlado, and A. Rivera, “Evolution of silica surface density under ion irradiation”, *Under Revision* 2017
- D. Garoz, A. R. Páramo, A. Rivera, J. M. Perlado, and R. González-Arrabal, “Modelling the thermomechanical behaviour of the tungsten first wall in HiPER laser fusion scenarios”, *Nuclear Fusion*, vol. 56, no. 12, p. 126014, 2016, DOI: [10.1088/0029-5515/56/12/126014](https://doi.org/10.1088/0029-5515/56/12/126014)
- A. R. Páramo, F. Sordo, D. Garoz, O. Peña-Rodríguez, A. Prada, J. Olivares, M. L. Crespillo, J. M. Perlado, and A. Rivera, “Mechanical response to swift ion irradiation-induced nano-tracks in silica”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Proceedings of the 12th International Conference on Computer Simulation of Radiation Effects in Solids, Alacant, Spain, 8-13 June, 2014, vol. 352, pp. 145–147, June 2015, DOI: [10.1016/j.nimb.2014.12.073](https://doi.org/10.1016/j.nimb.2014.12.073)
- A. R. Páramo, F. Sordo, D. Garoz, B. Le Garrec, J. M. Perlado, and A. Rivera, “Transmission final lenses in the HiPER laser fusion power plant: system design for temperature control”, *Nuclear Fusion*, vol. 54, no. 12, p. 123019, Dec. 2014, DOI: [10.1088/0029-5515/54/12/123019](https://doi.org/10.1088/0029-5515/54/12/123019)
- A.R. Páramo, F. Sordo, J.M. Perlado, and A. Rivera, “Viability of the ESS-Bilbao neutron source for irradiation of nuclear fusion materials”, *Journal of Nuclear*

Materials, vol. 444, no. 1–3, pp. 469–474, Jan. 2014, DOI: [10.1016/j.jnucmat.2013.10.014](https://doi.org/10.1016/j.jnucmat.2013.10.014)

- A. R. Páramo, F. Sordo, A. Rivera, and J. M. Perlado, “Use of the ESS Bilbao Installations for Laser Fusion Studies”, *Physics Procedia*, 3rd International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS III, 31 July–3 August 2012, Bilbao, Spain & the 4th International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS IV, 23-27 September 2013, Sapporo, Hokkaido, Japan, vol. 60, pp. 2–14, 2014, DOI: [10.1016/j.phpro.2014.11.003](https://doi.org/10.1016/j.phpro.2014.11.003)

Stays Abroad

- **“Mechanics of Materials and Structures” group of the University of Gent.**

Duration: 15 January 2015 - 15 May 2015.

Supervisors: Wim Van Paepegem, Professor Mechanics of Composite Materials and David Garoz, Researcher on the Department of Materials Science and Engineering.

Achievements: Modelization with CodeAster of the crack propagation of tungsten and silica under irradiation conditions expected in a nuclear fusion reactor. The work developed during this Stay Abroad is described in Ref. [19] and [Chapter 6](#).

Conferences

- A. R. Páramo, F. Sordo, D. Garoz, B. Le Garrec, J. M. Perlado and A. Rivera. Transmission final lenses in the HiPER laser fusion power plant: system design for temperature control. Oral Presentation. *SPIE Optics and Photonics 2015*.
- A. R. Páramo, F. Sordo, D. Garoz, B. Le Garrec, J. M. Perlado and A. Rivera. Transmission final lenses in the HiPER laser fusion power plant: system design for temperature control. Oral Presentation. *IYNC2014*.
- A. R. Páramo, F. Sordo, D. Garoz, O. Peña-Rodríguez, A. Prada, J. Olivares, M. L. Crespillo, J. M. Perlado and A. Rivera. Mechanical response to swift ion

irradiation-induced nano-tracks in silica. Poster Presentation. *COSIRES2015*

- A. R. Páramo, F. Sordo, D. Garoz, B. Le Garrec, J. M. Perlado and A. Rivera. Transmission final lenses in HiPER laser fusion power plant: system design for temperature control. *Cost Workshop Celia-Bordeaux 5-7 Mars 2014*.
- A. R. Páramo, F. Sordo, J.M. Perlado and A. Rivera. Study of the use of ESS-Bilbao for Irradiation of Nuclear Fusion Materials. Oral Presentation. *39 Reunión Anual SNE*.
- A. R. Páramo, F. Sordo, J.M. Perlado and A. Rivera. Study of Fluid the use of ESS-Bilbao for irradiation of nuclear fusion materials. Poster Presentation. *ISFNT-11*.
- A. Rivera, A. R. Páramo, F. Sordo, D. Garoz and J.M. Perlado. The performance of the silica final lenses in HiPER experimental facility and power plant. Oral Presentation. *SPIE Optics + Optoelectronics*.
- J.M. Perlado, A. R. Páramo, F. Sordo, D. Garoz and A. Rivera. Focal distance variation due to neutron dose on silica final lenses for ICF. Oral Presentation. *IFSA 2013*.
- A. R. Páramo, F. Sordo, J.M. Perlado and A. Rivera. Use of the ESS Bilbao installations for laser fusion studies. Poster Presentation. *UCANS III*.
- A. R. Páramo, F. Sordo, D. Garoz, J.M. Perlado and A. Rivera. Illumination Inhomogeneities due to Temperature Gradients in HiPER Final Optics. Poster Presentation. *HiPOLIN 2013*.

Bibliography

- [1] Thomas M. Anklam et al., “Life: The Case for Early Commercialization of Fusion Energy”, *Fusion Science and Technology*, vol. 60, no. 1, pp. 66–71, July 2011, DOI: [10.13182/FST10-329](#) (cit. on pp. 1–3).
- [2] M. Dunne and others, “Timely delivery of laser inertial fusion energy (LIFE)”, *Fusion Science and Technology*, vol. 60, no. 1, pp. 19–27, 2011, DOI: [10.13182/FST10-316](#) (cit. on pp. 1–3).
- [3] A. Bayramian et al., “Compact, Efficient Laser Systems Required for Laser Inertial Fusion Energy”, *Fusion Science and Technology*, vol. 60, no. 1, pp. 28–48, July 2011, DOI: [10.13182/FST10-313](#) (cit. on pp. 1, 2, 6, 74, 101).
- [4] J. F. Latkowski et al., “Chamber design for the laser inertial fusion energy (LIFE) engine”, *Fusion Science and Technology*, vol. 60, no. 1, pp. 54–60, July 2011, DOI: [10.13182/FST10-318](#) (cit. on pp. 1, 2, 4, 7, 8, 46).
- [5] B. Le Garrec et al., “HiPER laser reference design”, *SPIE Optics+ Optoelectronics*, vol. 8080, pp. 80801V–80801V, 2011, DOI: [10.1117/12.891244](#) (cit. on pp. 1, 2, 4, 35, 122).
- [6] HiPER Project Team, “HiPER Preparatory Phase Study” (cit. on pp. 1, 2).
- [7] J. M. Perlado et al., “IFE plant technology overview and contribution to HiPER proposal”, *SPIE Optics+ Optoelectronics*, vol. 8080, 80801Z–80801Z–10, May 2011, DOI: [10.1117/12.891266](#) (cit. on pp. 1, 2).
- [8] David Maisonnier et al., “DEMO and fusion power plant conceptual studies in Europe”, *Fusion Engineering and Design*, Proceedings of the Seventh International Symposium on Fusion Nuclear Technology ISFNT-7, vol. 81, no. 8–14, pp. 1123–1130, Feb. 2006, DOI: [10.1016/j.fusengdes.2005.08.055](#) (cit. on pp. 1, 2).
- [9] D. Maisonnier et al., “Power plant conceptual studies in Europe”, *Nuclear Fusion*, vol. 47, no. 11, pp. 1524–1532, Nov. 2007, DOI: [10.1088/0029-5515/47/11/014](#) (cit. on pp. 1, 2, 104).

- [10] L.V Boccaccini et al., “Materials and design of the European DEMO blankets”, *Journal of Nuclear Materials*, vol. 329-333, pp. 148–155, Aug. 2004, DOI: [10.1016/j.jnucmat.2004.04.125](https://doi.org/10.1016/j.jnucmat.2004.04.125) (cit. on pp. 1, 2, 4).
- [11] J. Álvarez et al., “Materials Research for Hiper Laser Fusion Facilities: Chamber Wall, Structural Material and Final Optics”, *Fusion Science and Technology*, vol. 60, no. 2, pp. 565–569, Aug. 2011, URL: http://www.ans.org/pubs/journals/fst/a_12443 (cit. on pp. 2, 7).
- [12] J. Alvarez et al., “Potential common radiation problems for components and diagnostics in future magnetic and inertial confinement fusion devices”, *Fusion Engineering and Design*, vol. 86, no. 9-11, pp. 1762–1765, Oct. 2011, DOI: [10.1016/j.fusengdes.2011.01.080](https://doi.org/10.1016/j.fusengdes.2011.01.080) (cit. on pp. 2, 7).
- [13] J. Alvarez et al., “The role of spatial and temporal radiation deposition in inertial fusion chambers: the case of HiPER”, *Nuclear Fusion*, vol. 51, no. 5, p. 053019, May 2011, DOI: [10.1088/0029-5515/51/5/053019](https://doi.org/10.1088/0029-5515/51/5/053019) (cit. on pp. 2, 7, 51).
- [14] D. Garoz et al., “Silica final lens performance in laser fusion facilities: HiPER and LIFE”, *Nuclear Fusion*, vol. 53, no. 1, p. 013010, Jan. 2013, DOI: [10.1088/0029-5515/53/1/013010](https://doi.org/10.1088/0029-5515/53/1/013010) (cit. on pp. 2, 4, 6, 7, 47, 56–58, 73, 75, 78, 122, 129).
- [15] A. Rivera et al., “Lifetime of silica final lenses subject to HiPER irradiation conditions”, vol. 7916, 2011, 79160S–79160S–12, DOI: [10.1117/12.876163](https://doi.org/10.1117/12.876163) (cit. on pp. 2, 6, 7, 47, 56, 57, 73, 75).
- [16] A. R. Páramo et al., “Use of the ESS Bilbao Installations for Laser Fusion Studies”, *Physics Procedia*, 3rd International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS III, 31 July–3 August 2012, Bilbao, Spain & the 4th International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS IV, 23-27 September 2013, Sapporo, Hokkaido, Japan, vol. 60, pp. 2–14, 2014, DOI: [10.1016/j.phpro.2014.11.003](https://doi.org/10.1016/j.phpro.2014.11.003) (cit. on pp. 2, 121, 138).
- [17] A.R. Páramo et al., “Viability of the ESS-Bilbao neutron source for irradiation of nuclear fusion materials”, *Journal of Nuclear Materials*, vol. 444, no. 1–3, pp. 469–474, Jan. 2014, DOI: [10.1016/j.jnucmat.2013.10.014](https://doi.org/10.1016/j.jnucmat.2013.10.014) (cit. on pp. 2, 79, 121, 137).
- [18] A. R. Páramo et al., “Transmission final lenses in the HiPER laser fusion power plant: system design for temperature control”, *Nuclear Fusion*, vol. 54, no. 12, p. 123019, Dec. 2014, DOI: [10.1088/0029-5515/54/12/123019](https://doi.org/10.1088/0029-5515/54/12/123019) (cit. on pp. 2, 74, 137).

- [19] D. Garoz et al., “Modelling the thermomechanical behaviour of the tungsten first wall in HiPER laser fusion scenarios”, *Nuclear Fusion*, vol. 56, no. 12, p. 126014, 2016, DOI: [10.1088/0029-5515/56/12/126014](https://doi.org/10.1088/0029-5515/56/12/126014) (cit. on pp. 2, 102, 137, 138).
- [20] A. R. Páramo et al., “Mechanical response to swift ion irradiation-induced nano-tracks in silica”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Proceedings of the 12th International Conference on Computer Simulation of Radiation Effects in Solids, Alacant, Spain, 8-13 June, 2014, vol. 352, pp. 145–147, June 2015, DOI: [10.1016/j.nimb.2014.12.073](https://doi.org/10.1016/j.nimb.2014.12.073) (cit. on pp. 2, 56, 59, 137).
- [21] A. R. Páramo et al., “Evolution of silica surface density under ion irradiation”, *Under Revision* 2017 (cit. on pp. 2, 56, 137).
- [22] W.R. Meier et al., “Fusion technology aspects of laser inertial fusion energy (LIFE)”, *Fusion Engineering and Design* Jan. 2014, DOI: [10.1016/j.fusengdes.2013.12.021](https://doi.org/10.1016/j.fusengdes.2013.12.021) (cit. on pp. 2–4, 45).
- [23] Sandra Brereton, “Overview of the national ignition facility.”, *Health physics*, vol. 104, no. 6, MEDLINE:23629059 June 2013, DOI: [10.1097/HP.0b013e31828cf5cd](https://doi.org/10.1097/HP.0b013e31828cf5cd) (cit. on p. 3).
- [24] O. A. Hurricane et al., “Fuel gain exceeding unity in an inertially confined fusion implosion”, *Nature*, vol. 506, no. 7488, pp. 343–348, Feb. 2014, DOI: [10.1038/nature13008](https://doi.org/10.1038/nature13008) (cit. on p. 3).
- [25] V.T. Tikhonchuk and K. Mima, “Alternative schemes for the inertial fusion energy”, *Fusion Engineering and Design*, vol. 86, no. 6-8, pp. 504–508, Oct. 2011, DOI: [10.1016/j.fusengdes.2011.01.007](https://doi.org/10.1016/j.fusengdes.2011.01.007) (cit. on pp. 3, 101).
- [26] Dimitri Batani et al., “Experimental results on advanced inertial fusion schemes obtained within the HiPER project”, *Nukleonika*, vol. 57, no. 1, pp. 3–10, 2012 (cit. on p. 3).
- [27] S. Atzeni et al., “Fast ignitor target studies for the HiPER project”, *Physics of Plasmas*, vol. 15, no. 5, pp. 056311–056311–10, Apr. 2008, DOI: [10.1063/1.2895447](https://doi.org/10.1063/1.2895447) (cit. on pp. 3, 38).
- [28] J. J. Honrubia and J. Meyer-ter Vehn, “Fast ignition of fusion targets by laser-driven electrons”, *Plasma Physics and Controlled Fusion*, vol. 51, no. 1, p. 014008, 2008, DOI: [10.1088/0741-3335/51/1/014008](https://doi.org/10.1088/0741-3335/51/1/014008) (cit. on p. 3).
- [29] B Canaud and M Temporal, “High-gain shock ignition of direct-drive ICF targets for the Laser Mégajoule”, *New Journal of Physics*, vol. 12, no. 4, p. 043037, Apr. 2010, DOI: [10.1088/1367-2630/12/4/043037](https://doi.org/10.1088/1367-2630/12/4/043037) (cit. on p. 3).

- [30] X. Ribeyre et al., “Shock ignition: an alternative scheme for HiPER”, *Plasma Physics and Controlled Fusion*, vol. 51, no. 1, p. 015013, Jan. 2009, DOI: [10.1088/0741-3335/51/1/015013](https://doi.org/10.1088/0741-3335/51/1/015013) (cit. on pp. 3, 76).
- [31] X. Ribeyre et al., “Shock ignition: modelling and target design robustness”, *Plasma Physics and Controlled Fusion*, vol. 51, no. 12, p. 124030, Dec. 2009, DOI: [10.1088/0741-3335/51/12/124030](https://doi.org/10.1088/0741-3335/51/12/124030) (cit. on p. 3).
- [32] M. Temporal, B. Canaud, and B. J. Le Garrec, “Irradiation uniformity and zooming performances for a capsule directly driven by a 32×9 laser beams configuration”, *Physics of Plasmas*, vol. 17, no. 2, pp. 022701–022701–7, Feb. 2010, DOI: [10.1063/1.3309489](https://doi.org/10.1063/1.3309489) (cit. on p. 4).
- [33] M. Temporal and B. Canaud, “Stochastic homogenization of the laser intensity to improve the irradiation uniformity of capsules directly driven by thousands laser beams”, *The European Physical Journal D*, vol. 65, no. 3, pp. 447–451, Dec. 2011, DOI: [10.1140/epjd/e2011-20366-x](https://doi.org/10.1140/epjd/e2011-20366-x) (cit. on pp. 4, 40, 41, 77).
- [34] A. Schiavi, S. Atzeni, and A. Marocchino, “Illumination stability for high repetition rate laser facilities in direct-drive inertial confinement fusion”, *EPL (Europhysics Letters)*, vol. 94, no. 3, p. 35002, May 2011, DOI: [10.1209/0295-5075/94/35002](https://doi.org/10.1209/0295-5075/94/35002) (cit. on pp. 4, 77).
- [35] S. Atzeni et al., “Studies on targets for inertial fusion ignition demonstration at the HiPER facility”, *Nuclear Fusion*, vol. 49, no. 5, p. 055008, 2009, DOI: [10.1088/0029-5515/49/5/055008](https://doi.org/10.1088/0029-5515/49/5/055008) (cit. on pp. 4, 76).
- [36] B. Le Garrec, J. M. Di-Nicola, and V. Beau, “Métrologie des faisceaux et de la tache focale de la LIL”, *Journal de Physique IV (Proceedings)*, vol. 138, no. 1, pp. 297–307, Jan. 2007, DOI: [10.1051/jp4:2006138034](https://doi.org/10.1051/jp4:2006138034) (cit. on pp. 4, 77).
- [37] B. J. Le Garrec and J. M. Sajer, “The design of LMJ focal spots for indirect drive experiments”, *Journal of Physics: Conference Series*, vol. 112, p. 032018, 2008, DOI: [10.1088/1742-6596/112/3/032018](https://doi.org/10.1088/1742-6596/112/3/032018) (cit. on p. 4).
- [38] B. Canaud and F. Garaude, “Optimization of laser–target coupling efficiency for direct drive laser fusion”, *Nuclear fusion*, vol. 45, no. 12, p. L43, 2005, DOI: [10.1088/0029-5515/45/12/L01](https://doi.org/10.1088/0029-5515/45/12/L01) (cit. on pp. 4, 76).
- [39] Ryan Nora, “Hydrodynamics of inertial confinement fusion: conventional hot spot and shock ignition”, PhD thesis, University of Rochester, 2015, URL: <http://hdl.handle.net/1802/29713> (cit. on p. 4).
- [40] E. Mas de les Valls et al., “Lead–lithium eutectic material database for nuclear fusion technology”, *Journal of Nuclear Materials*, Heavy Liquid Metal Cooled Reactors and Related Technologies Proceedings of the Fourth International Work-

- shop on Materials for Heavy Liquid Metal Cooled Reactors and Related Technologies, vol. 376, no. 3, pp. 353–357, June 2008, DOI: [10.1016/j.jnucmat.2008.02.016](https://doi.org/10.1016/j.jnucmat.2008.02.016) (cit. on p. 4).
- [41] W. R. Meier and W. R. Meier, *Assessment of Tritium Breeding Blankets from a Systems Perspective-Status Report*, Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States), 2014, DOI: [10.2172/1165762](https://doi.org/10.2172/1165762) (cit. on p. 4).
 - [42] I. Palermo et al., “Neutronic design studies of a conceptual DCLL fusion reactor for a DEMO and a commercial power plant”, *Nuclear Fusion*, vol. 56, no. 1, p. 016001, 2016, DOI: [10.1088/0029-5515/56/1/016001](https://doi.org/10.1088/0029-5515/56/1/016001) (cit. on p. 4).
 - [43] S. Malang, A. R. Raffray, and N. B. Morley, “An example pathway to a fusion power plant system based on lead–lithium breeder: Comparison of the dual-coolant lead–lithium (DCLL) blanket with the helium-cooled lead–lithium (HCLL) concept as initial step”, *Fusion Engineering and Design*, vol. 84, no. 12, pp. 2145–2157, Dec. 2009, DOI: [10.1016/j.fusengdes.2009.02.049](https://doi.org/10.1016/j.fusengdes.2009.02.049) (cit. on pp. 4, 106).
 - [44] C.P.C. Wong et al., “An overview of dual coolant Pb–17Li breeder first wall and blanket concept development for the US ITER-TBM design”, *Fusion Engineering and Design*, vol. 81, no. 1-7, pp. 461–467, Feb. 2006, DOI: [10.1016/j.fusengdes.2005.05.012](https://doi.org/10.1016/j.fusengdes.2005.05.012) (cit. on pp. 4, 108).
 - [45] R. Juárez et al., “Thermo-fluid dynamics and corrosion analysis of a self cooled lead lithium blanket for the HiPER reactor”, *Nuclear Fusion*, vol. 55, no. 9, p. 093003, 2015, DOI: [10.1088/0029-5515/55/9/093003](https://doi.org/10.1088/0029-5515/55/9/093003) (cit. on pp. 4, 5, 103, 104, 106).
 - [46] Rafael Juarez Mañas et al., “Studies of a Self Cooled Lead Lithium blanket for HiPER Reactor” 2011, DOI: [10.1051/epjconf/20135911005](https://doi.org/10.1051/epjconf/20135911005) (cit. on p. 4).
 - [47] N. Baluc et al., “Status of R&D activities on materials for fusion power reactors”, *Nuclear Fusion*, vol. 47, no. 10, S696–S717, Oct. 2007, DOI: [10.1088/0029-5515/47/10/S18](https://doi.org/10.1088/0029-5515/47/10/S18) (cit. on pp. 4, 5, 103, 107).
 - [48] J. C. Chanteloup et al., “Multi kJ level laser concepts for HiPER facility”, *Journal of Physics: Conference Series*, vol. 244, p. 012010, 2010, DOI: [10.1088/1742-6596/244/1/012010](https://doi.org/10.1088/1742-6596/244/1/012010) (cit. on p. 4).
 - [49] J. C. Chanteloup and D. Albach, “Current Status on High Average Power and Energy Diode Pumped Solid State Lasers”, *IEEE Photonics Journal*, vol. 3, no. 2, pp. 245–248, Apr. 2011, DOI: [10.1109/JPHOT.2011.2140097](https://doi.org/10.1109/JPHOT.2011.2140097) (cit. on p. 4).

- [50] S. Jacquemot et al., “Studying ignition schemes on European laser facilities”, *Nuclear Fusion*, vol. 51, no. 9, p. 094025, Sept. 2011, DOI: [10.1088/0029-5515/51/9/094025](https://doi.org/10.1088/0029-5515/51/9/094025) (cit. on p. 4).
- [51] Milan Kalal and Ondrej Slezak, “Overview and recent progress in SBS PCM approach to self-navigation of lasers on direct drive IFE targets”, May 2011, p. 808021, DOI: [10.1117/12.892313](https://doi.org/10.1117/12.892313) (cit. on p. 4).
- [52] J. Badziak and S. Jabłoński, “Acceleration of a solid-density plasma projectile to ultrahigh velocities by a short-pulse ultraviolet laser”, *Applied Physics Letters*, vol. 99, no. 7, p. 071502, Aug. 2011, DOI: [10.1063/1.3628243](https://doi.org/10.1063/1.3628243) (cit. on p. 4).
- [53] Bedrich Rus et al., “Repetition rate target and fusion chamber systems for HiPER”, *SPIE Optics+ Optoelectronics*, vol. 8080, pp. 808020–808020–9, 2011, DOI: [10.1117/12.891254](https://doi.org/10.1117/12.891254) (cit. on p. 4).
- [54] P. Di Nicola et al., “Beam and target alignment at the National Ignition Facility using the Target Alignment Sensor (TAS)”, vol. 8505, 2012, 85050B–85050B–9, DOI: [10.1117/12.930173](https://doi.org/10.1117/12.930173) (cit. on pp. 4, 6, 75).
- [55] M. Tolley et al., “HiPER targetry: production and strategy”, May 2011, p. 808023, DOI: [10.1117/12.891879](https://doi.org/10.1117/12.891879) (cit. on p. 4).
- [56] Rafael Juárez Mañas, “Neutronics design and radiological aspects of HiPER facilities”, phd, E.T.S.I. Industriales (UPM), 2013, URL: <http://oa.upm.es/15087/> (cit. on p. 4).
- [57] Rafael Juárez, Javier Sanz, and José M. Perlado, “Advances in neutronics and radiological protection of HiPER 4a”, *Fusion Engineering and Design*, vol. 87, no. 4, pp. 336–343, 2012, DOI: [10.1016/j.fusengdes.2012.02.064](https://doi.org/10.1016/j.fusengdes.2012.02.064) (cit. on p. 4).
- [58] Consuelo Sánchez et al., “Design and analysis of helium Brayton power cycles for HiPER reactor”, *Fusion Engineering and Design*, Proceedings of the 27th Symposium On Fusion Technology (SOFT-27); Liège, Belgium, September 24–28, 2012, vol. 88, no. 9–10, pp. 2679–2683, Oct. 2013, DOI: [10.1016/j.fusengdes.2012.12.007](https://doi.org/10.1016/j.fusengdes.2012.12.007) (cit. on p. 4).
- [59] B. Le Garrec et al., “HiPER laser: from capsule design to the laser reference design”, *SPIE Proceedings*, Feb. 2011, 79160F–79160F, DOI: [10.1117/12.879716](https://doi.org/10.1117/12.879716) (cit. on p. 4).
- [60] B J Le Garrec et al., “HiPER laser architecture principles”, *Journal of Physics: Conference Series*, vol. 244, no. 3, p. 032020, Aug. 2010, DOI: [10.1088/1742-6596/244/3/032020](https://doi.org/10.1088/1742-6596/244/3/032020) (cit. on p. 4).

- [61] T. Dash, “Preparation and Neutronic Studies of Tungsten Carbide Composite”, *Fusion Science & Technology*, vol. 65, no. 2 Apr. 2014, DOI: [10.13182/FST13-663](https://doi.org/10.13182/FST13-663) (cit. on p. 4).
- [62] A. R. Raffray, “Threats, design limits and design windows for laser IFE dry wall chambers”, *Journal of nuclear materials*, vol. 347, no. 3, pp. 178–191, 2005, DOI: [10.1016/j.jnucmat.2005.08.015](https://doi.org/10.1016/j.jnucmat.2005.08.015) (cit. on pp. 5, 7).
- [63] C. D. Marshall, J. A. Speth, and S. A. Payne, “Induced optical absorption in gamma, neutron and ultraviolet irradiated fused quartz and silica”, *Journal of non-crystalline solids*, vol. 212, no. 1, pp. 59–73, 1997, DOI: [10.1016/S0022-3093\(96\)00606-0](https://doi.org/10.1016/S0022-3093(96)00606-0) (cit. on pp. 6, 47, 79, 101, 129).
- [64] A. Kubota et al., “Modeling defect production in silica glass due to energetic recoils using molecular dynamics simulations”, *Journal of nuclear materials*, vol. 307, pp. 891–894, 2002, DOI: [10.1016/S0022-3115\(02\)01008-5](https://doi.org/10.1016/S0022-3115(02)01008-5) (cit. on pp. 6, 17, 18, 47).
- [65] A. Kubota et al., “Threats to ICF reactor materials: computational simulations of radiation damage induced topological changes in fused silica”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 202, pp. 88–92, 2003, DOI: [10.1016/S0168-583X\(02\)01837-2](https://doi.org/10.1016/S0168-583X(02)01837-2) (cit. on pp. 6, 17, 62).
- [66] J. F. Latkowski et al., “Fused silica final optics for inertial fusion energy: Radiation studies and system-level analysis”, *Fusion Science and Technology*, vol. 43, no. 4, WOS:000182844200005, pp. 540–558, June 2003, DOI: [10.13182/FST43-540](https://doi.org/10.13182/FST43-540) (cit. on pp. 6, 47, 49, 79, 101, 129).
- [67] L. M. Waganer, D. E. Driemeyer, and V. D. Lee, *Inertial Fusion Energy Reactor Design Studies: Prometheus-L, Prometheus-H. Volume 1, Final Report*, DOE/ER/54101 T1-Vol.1; MDC-92E0008, Mar. 1992, DOI: [10.2172/10172807](https://doi.org/10.2172/10172807) (cit. on pp. 6, 74).
- [68] L. M. Waganer, D. E. Driemeyer, and V. D. Lee, *Inertial Fusion Energy Reactor Design Studies: Prometheus-L, Prometheus-H. Volume 2, Final Report*, DOE/ER/54101 T1-Vol.2; MDC-92E0008, Mar. 1992, DOI: [10.2172/10174875](https://doi.org/10.2172/10174875) (cit. on pp. 6, 74).
- [69] R. L. Bieri and M. W. Guinan, *Grazing Incidence Metal Mirrors as the Final Elements in a Laser Driver for Inertial Confinement Fusion*, UCRL-JC-103817-Rev.1; CONF-901007-9-Rev.1, Lawrence Livermore National Lab., CA (USA), Nov. 1990, URL: <https://www.osti.gov/scitech/biblio/6298879> (cit. on pp. 6, 74).

- [70] W. R. Meier et al., *Osiris and Sombrero Inertial Fusion Power Plant Designs, Volume 1: Executive Summary & Overview*, DOE/ER/54100-1-Vol.1, W.J. Schafer Associates, Inc. (US), Mar. 1992, DOI: [10.2172/833813](#) (cit. on pp. 6, 74).
- [71] W. R. Meier et al., *Osiris and Sombrero Inertial Fusion Power Plant Designs, Volume 2: Designs, Assessments, and Comparisons*, DOE/ER/54100-1-Vol.2, W. J. Schafer Associates, Inc. (US), Mar. 1992, DOI: [10.2172/836548](#) (cit. on pp. 6, 74).
- [72] M. S. Tillack et al., “Damage threats and response of final optics for laser-fusion power plants”, *Proc. Inertial Fusion Sci. Appl*, pp. 717–721, 2001 (cit. on pp. 6, 74).
- [73] M. S. Tillack and J. E. Pulsifer, “Long-term survival of grazing-incidence metal mirrors for laser fusion”, *Fusion Science and technology*, vol. 56, no. 1, p. 446, 2009, DOI: [10.13182/FST09-32](#) (cit. on pp. 6, 74).
- [74] Ryan P. Abbott and Jeffery F. Latkowski, “Ion deflection for final optics in laser inertial fusion power plants”, *Fusion science and technology*, vol. 52, no. 4, p. 916, 2007, URL: http://www.ans.org/pubs/journals/fst/a_1610 (cit. on pp. 7, 97–99).
- [75] G. Valles et al., “A multiscale approach to defect evolution in tungsten under helium irradiation”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Proceedings of the 12th International Conference on Computer Simulation of Radiation Effects in Solids, Alacant, Spain, 8-13 June, 2014, vol. 352, 00001, pp. 100–103, June 2015, DOI: [10.1016/j.nimb.2014.12.034](#) (cit. on p. 7).
- [76] A. Rivera et al., “Effect of ion flux on helium retention in helium-irradiated tungsten”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Proceedings of the 11th Computer Simulation of Radiation Effects in Solids (COSIRES) Conference Santa Fe, New Mexico, USA, July 24-29, 2012, vol. 303, 00003, pp. 81–83, May 2013, DOI: [10.1016/j.nimb.2012.10.038](#) (cit. on pp. 7, 116).
- [77] G. Valles et al., “The influence of high grain boundary density on helium retention in tungsten”, *Journal of Nuclear Materials*, vol. 457, 00000, pp. 80–87, Feb. 2015, DOI: [10.1016/j.jnucmat.2014.10.038](#) (cit. on pp. 7, 116).
- [78] Gonzalo Valles Alberdi, “Object kinetic Monte Carlo simulations of irradiated tungsten for nuclear fusion reactors”, phd, E.T.S.I. Industriales (UPM), 2016, URL: <http://oa.upm.es/43457/> (cit. on p. 7).

- [79] C. Guerrero et al., “First principles study of the behavior of hydrogen atoms in a W monovacancy”, *Journal of Materials Science*, 00000, pp. 1–11, Oct. 2015, DOI: [10.1007/s10853-015-9464-4](https://doi.org/10.1007/s10853-015-9464-4) (cit. on p. 7).
- [80] C. L. Guerrero et al., “Ab initio study of tungsten defects near the surface”, *Modelling and Simulation in Materials Science and Engineering*, vol. 24, no. 4, p. 045006, 2016, DOI: [10.1088/0965-0393/24/4/045006](https://doi.org/10.1088/0965-0393/24/4/045006) (cit. on p. 7).
- [81] N. Gordillo et al., “Morphological and microstructural characterization of nanostructured pure α -phase W coatings on a wide thickness range”, *Applied Surface Science*, vol. 316, pp. 1–8, Oct. 2014, DOI: [10.1016/j.apsusc.2014.07.061](https://doi.org/10.1016/j.apsusc.2014.07.061) (cit. on p. 7).
- [82] R. González-Arrabal et al., “Hydrogen accumulation in nanostructured as compared to the coarse-grained tungsten”, *Journal of Nuclear Materials*, vol. 453, no. 1–3, pp. 287–295, Oct. 2014, DOI: [10.1016/j.jnucmat.2014.06.057](https://doi.org/10.1016/j.jnucmat.2014.06.057) (cit. on pp. 7, 116).
- [83] C. González et al., “H trapping and mobility in nanostructured tungsten grain boundaries: a combined experimental and theoretical approach”, *Nuclear Fusion*, vol. 55, no. 11, 00000, p. 113009, Sept. 2015, DOI: [10.1088/0029-5515/55/11/113009](https://doi.org/10.1088/0029-5515/55/11/113009) (cit. on pp. 7, 116).
- [84] James P. Blanchard and Carl J. Martin, “Thermomechanical effects in a laser IFE first wall”, *Journal of Nuclear Materials, Laser Fusion Materials*, vol. 347, no. 3, pp. 192–206, Dec. 2005, DOI: [10.1016/j.jnucmat.2005.08.007](https://doi.org/10.1016/j.jnucmat.2005.08.007) (cit. on pp. 7, 23, 104, 116).
- [85] John D. Sethian et al., “An overview of the development of the first wall and other principal components of a laser fusion power plant”, *Journal of Nuclear Materials*, vol. 347, no. 3, pp. 161–177, Dec. 2005, DOI: [10.1016/j.jnucmat.2005.08.019](https://doi.org/10.1016/j.jnucmat.2005.08.019) (cit. on pp. 7, 104, 116).
- [86] A. R. Raffray et al., “Progress towards realization of a laser IFE solid wall chamber”, *Fusion engineering and design*, vol. 81, no. 8, pp. 1627–1638, 2006, DOI: [10.1016/j.fusengdes.2005.07.041](https://doi.org/10.1016/j.fusengdes.2005.07.041) (cit. on pp. 7, 104).
- [87] H. Bolt et al., “Materials for the plasma-facing components of fusion reactors”, *Journal of Nuclear Materials, Proceedings of the 11th International Conference on Fusion Reactor Materials (ICFRM-11)*, vol. 329–333, Part A, 00205, pp. 66–73, 2004, DOI: [10.1016/j.jnucmat.2004.04.005](https://doi.org/10.1016/j.jnucmat.2004.04.005) (cit. on pp. 7, 46, 105).
- [88] H. Bolt et al., “Plasma facing and high heat flux materials – needs for ITER and beyond”, *Journal of Nuclear Materials*, vol. 307–311, Part 1, pp. 43–52, Dec. 2002, DOI: [10.1016/S0022-3115\(02\)01175-3](https://doi.org/10.1016/S0022-3115(02)01175-3) (cit. on p. 7).

- [89] R. W. Petzoldt et al., “Direct drive target survival during injection in an inertial fusion energy power plant”, *Nuclear Fusion*, vol. 42, no. 12, p. 1351, 2002, DOI: [10.1088/0029-5515/42/12/301](https://doi.org/10.1088/0029-5515/42/12/301) (cit. on p. 8).
- [90] F. Najmabadi, A. R. Raffray, and L. Bromberg, “Operational Windows for Dry-Wall and Wetted-Wall IFE Chambers”, *Fusion Science and Technology*, vol. 46, no. 3, pp. 401–416, 2004, URL: http://www.ans.org/pubs/journals/fst/a_580 (cit. on p. 8).
- [91] Pascal Garin and Masayoshi Sugimoto, “Main baseline of IFMIF/EVEDA project”, *Fusion Engineering and Design*, vol. 84, no. 2-6, WOS:000267795600026, pp. 259–264, June 2009, DOI: [10.1016/j.fusengdes.2008.12.040](https://doi.org/10.1016/j.fusengdes.2008.12.040) (cit. on p. 8).
- [92] F. Sordo et al., “Neutronic design for ESS-Bilbao neutron source”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 707, pp. 1–8, Apr. 2013, DOI: [10.1016/j.nima.2012.12.092](https://doi.org/10.1016/j.nima.2012.12.092) (cit. on pp. 8, 15, 122–124).
- [93] F. J Bermejo and F Sordo, “Technical design report: ESS-Bilbao Target Station”, Bilbao: ESS Bilbao, 2013 (cit. on pp. 8, 122, 123).
- [94] U. Rücker et al., “The Jülich high-brilliance neutron source project”, *The European Physical Journal Plus*, vol. 131, no. 1, pp. 1–14, 2016, DOI: [10.1140/epjp/i2016-16019-5](https://doi.org/10.1140/epjp/i2016-16019-5) (cit. on pp. 8, 122).
- [95] D. B. Pelowitz, *MCNPX user’s Manual*, Version 2.7.0, April 2011 LA-CP-11-00438, Apr. 2011 (cit. on pp. 11, 15, 34).
- [96] R. E. Macfarlane and D. W. Muir, *The NJOY nuclear data processing system: Version 91*, vol. -1, Oct. 1994 (cit. on pp. 12, 15, 17).
- [97] James F. Ziegler, M.D. Ziegler, and J.P. Biersack, “SRIM – The stopping and range of ions in matter (2010)”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 268, no. 11-12, pp. 1818–1823, June 2010, DOI: [10.1016/j.nimb.2010.02.091](https://doi.org/10.1016/j.nimb.2010.02.091) (cit. on pp. 12, 20, 27, 62).
- [98] G H Kinchin and R S Pease, “The Displacement of Atoms in Solids by Radiation”, *Reports on Progress in Physics*, vol. 18, no. 1, pp. 1–51, Jan. 1955, DOI: [10.1088/0034-4885/18/1/301](https://doi.org/10.1088/0034-4885/18/1/301) (cit. on pp. 13, 16).
- [99] EDF R&D, “Manuel d’utilisation: introduction au Code_Aster. Electricité de France” (cit. on pp. 13, 20, 21, 28).
- [100] Josselin Delmas and Aimery Assire, “Salome-Meca : une plate-forme au service de la simulation mécanique”, *10e colloque national en calcul des structures*, Giens,

- France, May 2011, URL: <https://hal.archives-ouvertes.fr/hal-00592745> (cit. on p. 13).
- [101] *SALOME Platform*, URL: <http://www.salome-platform.org/> (cit. on pp. 13, 22).
- [102] Fluent Inc., *Fluent 6.3 User's Guide*, Sept. 2006 (cit. on pp. 13, 34).
- [103] Mark Lutz, *Programming Python*, "O'Reilly Media, Inc.", 2001 (cit. on p. 14).
- [104] Aries Program, URL: <http://aries.ucsd.edu/ARIES/WDOCS/ARIES-IFE/> (cit. on pp. 14, 15, 20, 34, 43, 55, 125).
- [105] *Evaluated Nuclear Data File (ENDF)*, URL: <http://www.nndc.bnl.gov/exfor/endl00.jsp> (cit. on pp. 15, 17, 18, 34).
- [106] M.J. Norgett, M.T. Robinson, and I.M. Torrens, "A proposed method of calculating displacement dose rates", *Nuclear Engineering and Design*, vol. 33, no. 1, pp. 50–54, Aug. 1975, DOI: [10.1016/0029-5493\(75\)90035-7](https://doi.org/10.1016/0029-5493(75)90035-7) (cit. on pp. 16, 17, 128).
- [107] A. Y. Konobeyev, C. H. M. Broeders, and U. Fischer, "Improved displacement cross sections for structural materials irradiated with intermediate and high energy protons", *Proc. of AccApp*, vol. 7, pp. 241–248 (cit. on p. 18).
- [108] H. W. Bertini, "Low-energy intranuclear cascade calculation", *Physical Review*, vol. 131, no. 4, p. 1801, 1963, DOI: [10.1103/PhysRev.131.1801](https://doi.org/10.1103/PhysRev.131.1801) (cit. on p. 19).
- [109] H. W. Bertini, "Intranuclear-cascade calculation of the secondary nucleon spectra from nucleon-nucleus interactions in the energy range 340 to 2900 MeV and comparisons with experiment", *Physical Review*, vol. 188, no. 4, p. 1711, 1969, DOI: [10.1103/PhysRev.188.1711](https://doi.org/10.1103/PhysRev.188.1711) (cit. on p. 19).
- [110] Lawrence Dresner, "EVAP: A FORTRAN program for calculating the evaporation of various particles from excited compound nuclei" 1963, URL: <https://www.osti.gov/scitech/biblio/4638868> (cit. on p. 19).
- [111] J. H. Hubbel and S. M. Seltzer, *NIST: X-Ray Mass Attenuation Coefficients*, URL: <https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients> (cit. on p. 20).
- [112] J. W. Davis and P. D. Smith, "ITER material properties handbook", *Journal of Nuclear Materials*, vol. 233–237, Part 2, pp. 1593–1596, Oct. 1996, DOI: [10.1016/S0022-3115\(96\)00202-4](https://doi.org/10.1016/S0022-3115(96)00202-4) (cit. on pp. 22, 23, 103, 105, 106, 112).
- [113] *ITER Material Properties Handbook*, *ITER Document No. S 74 RE 1* (cit. on pp. 22, 103, 105, 106, 111, 112).
- [114] S. Agostinelli et al., "Geant4—a simulation toolkit", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, July 2003, DOI: [10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8) (cit. on p. 23).

- [115] Samuel GENIAUT, “Manuel d’utilisation Code_Aster U4.82.03 Opérateur CALC_G”, July 2015 (cit. on p. 24).
- [116] Samuel GENIAUT, “Manuel de référence Code_Aster R7.02.05 Calcul des facteurs d’intensité de contraintes en thermoélasticité linéaire”, Nov. 2014 (cit. on p. 24).
- [117] J. R. Rice, “A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks”, *Journal of Applied Mechanics*, vol. 35, no. 2, pp. 379–386, June 1968, DOI: [10.1115/1.3601206](https://doi.org/10.1115/1.3601206) (cit. on p. 24).
- [118] Samuel GENIAUT, “Manuel de référence Code_Aster R7.02.03 Taux de restitution de l’énergie en thermo-élasticité non-linéaire”, Sept. 2013 (cit. on p. 24).
- [119] Centro de Microanálisis de Materiales, URL: www.cmam.uam.es (cit. on pp. 25, 60).
- [120] O. Peña-Rodríguez et al., “In situ monitoring the optical properties of dielectric materials during ion irradiation”, *Optical Materials Express*, vol. 6, no. 3, p. 734, Mar. 2016, DOI: [10.1364/OME.6.000734](https://doi.org/10.1364/OME.6.000734) (cit. on pp. 25, 56, 59, 60, 71).
- [121] *The ASCI MDCASK Benchmark Code*, URL: https://asc.llnl.gov/computing_resources/purple/archive/benchmarks/mdcask/ (cit. on p. 26).
- [122] B. P. Feuston and S. H. Garofalini, “Empirical three-body potential for vitreous silica”, *Journal of Chemical Physics*, vol. 89, no. 9, p. 5818, 1988, DOI: [10.1063/1.455531](https://doi.org/10.1063/1.455531) (cit. on p. 26).
- [123] F. Mota et al., “Identification and characterization of defects produced in irradiated fused silica through molecular dynamics”, *Journal of Nuclear Materials*, vol. 367, pp. 344–349, 2007, DOI: [10.1016/j.jnucmat.2007.03.130](https://doi.org/10.1016/j.jnucmat.2007.03.130) (cit. on p. 26).
- [124] CESVIMA-MAGERIT, URL: <http://www.cesvima.upm.es> (cit. on p. 26).
- [125] Antonio Rivera et al., “Permanent modification of silica mediated by ion-induced electronic excitation: experiments and atomistic modeling”, *Submitted to Scientific Reports* 2017 (cit. on pp. 26, 59, 62).
- [126] Heraeus Quarzglas - Home of Quartz Solutions (cit. on pp. 29, 57, 78–80, 87, 89).
- [127] A. Benyagoub, S. Klaumünzer, and M. Toulemonde, “Radiation-induced compaction and plastic flow of vitreous silica”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 146, no. 1–4, pp. 449–454, Dec. 1998, DOI: [10.1016/S0168-583X\(98\)00478-9](https://doi.org/10.1016/S0168-583X(98)00478-9) (cit. on pp. 28, 59, 67, 71).
- [128] S. Klaumünzer, “Ion tracks in quartz and vitreous silica”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, The Evolution of Ion Tracks and Solids (TRACKS03), vol. 225, no. 1–2,

- pp. 136–153, Aug. 2004, DOI: [10.1016/j.nimb.2004.05.014](https://doi.org/10.1016/j.nimb.2004.05.014) (cit. on pp. 28, 30, 59, 67, 71).
- [129] H Trinkaus, “Dynamics of viscoelastic flow in ion tracks: origin of plastic deformation of amorphous materials”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 146, no. 1–4, pp. 204–216, Dec. 1998, DOI: [10.1016/S0168-583X\(98\)00423-6](https://doi.org/10.1016/S0168-583X(98)00423-6) (cit. on pp. 30, 59, 67, 71).
- [130] A. Bensaoula, “Direct-current-magnetron deposition of molybdenum and tungsten with rf-substrate bias”, *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, vol. 2, no. 2, p. 389, 1984, DOI: [10.1116/1.572749](https://doi.org/10.1116/1.572749) (cit. on p. 30).
- [131] Ian Bell, Silvain Quoilin, and Jornt Wronski, URL: <http://coolprop.sourceforge.net/> (cit. on p. 34).
- [132] Eugene Hecht and Alfred Zajac, *óptica*, Addison-Wesley, 1988 (cit. on p. 35).
- [133] B. Delaunay, “Sur la sphère vide”, *Izvestia Akademii Nauk SSSR, Otdelenie Matematicheskikh i Estestvennykh Nauk*, vol. 6, pp. 793–800, 1934 (cit. on p. 39).
- [134] Akira Hasegawa et al., “Neutron irradiation behavior of tungsten”, *Materials Transactions*, vol. 54, no. 4, pp. 466–471, 2013, DOI: [10.2320/matertrans.MG201208](https://doi.org/10.2320/matertrans.MG201208) (cit. on pp. 46, 105).
- [135] Jaime Marian and Tuan L. Hoang, “Modeling fast neutron irradiation damage accumulation in tungsten”, *Journal of Nuclear Materials*, vol. 429, no. 1–3, pp. 293–297, Oct. 2012, DOI: [10.1016/j.jnucmat.2012.06.019](https://doi.org/10.1016/j.jnucmat.2012.06.019) (cit. on pp. 46, 105).
- [136] J. Matolich, H. Nahm, and J. Moteff, “Swelling in neutron irradiated tungsten and tungsten-25 percent rhenium”, *Scripta Metallurgica*, vol. 8, no. 7, pp. 837–841, July 1974, DOI: [10.1016/0036-9748\(74\)90304-4](https://doi.org/10.1016/0036-9748(74)90304-4) (cit. on pp. 46, 105).
- [137] J. Manzano-Santamaría et al., “Kinetics of color center formation in silica irradiated with swift heavy ions: Thresholding and formation efficiency”, *Applied Physics Letters*, vol. 101, no. 15, pp. 154103–154103–4, Oct. 2012, DOI: [10.1063/1.4757886](https://doi.org/10.1063/1.4757886) (cit. on pp. 47, 127).
- [138] Olli H. Pakarinen et al., “Molecular dynamics simulations of the structure of latent tracks in quartz and amorphous SiO₂”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 267, no. 8–9, pp. 1456–1459, May 2009, DOI: [10.1016/j.nimb.2009.01.071](https://doi.org/10.1016/j.nimb.2009.01.071) (cit. on pp. 47, 127).
- [139] Olli H. Pakarinen, Flyura Djurabekova, and Kai Nordlund, “Density evolution in formation of swift heavy ion tracks in insulators”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and*

- Atoms*, vol. 268, no. 19, pp. 3163–3166, Oct. 2010, DOI: [10.1016/j.nimb.2010.05.079](https://doi.org/10.1016/j.nimb.2010.05.079) (cit. on pp. 47, 127).
- [140] P. Kluth et al., “Fine Structure in Swift Heavy Ion Tracks in Amorphous SiO₂”, *Physical Review Letters*, vol. 101, no. 17 Oct. 2008, DOI: [10.1103/PhysRevLett.101.175503](https://doi.org/10.1103/PhysRevLett.101.175503) (cit. on pp. 47, 62, 64, 127).
- [141] Marcel Toulemonde et al., “Synergy of nuclear and electronic energy losses in ion-irradiation processes: The case of vitreous silicon dioxide”, *Physical Review B*, vol. 83, no. 5, p. 054106, Feb. 2011, DOI: [10.1103/PhysRevB.83.054106](https://doi.org/10.1103/PhysRevB.83.054106) (cit. on pp. 47, 127).
- [142] T. Mohanty et al., “Latent track creation in fused silica by 200 MeV silver beam”, *Radiation Measurements*, vol. 36, no. 1–6, pp. 137–140, June 2003, DOI: [10.1016/S1350-4487\(03\)00110-0](https://doi.org/10.1016/S1350-4487(03)00110-0) (cit. on pp. 47, 127).
- [143] C. Rotaru et al., “Track formation in two amorphous insulators, vitreous silica and diamond like carbon: Experimental observations and description by the inelastic thermal spike model”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 272, pp. 9–14, Feb. 2012, DOI: [10.1016/j.nimb.2011.01.022](https://doi.org/10.1016/j.nimb.2011.01.022) (cit. on pp. 47, 127).
- [144] A. Dunlop et al., “Effects induced by high electronic excitations in pure metals: A detailed study in iron”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 90, no. 1–4, pp. 330–338, May 1994, DOI: [10.1016/0168-583X\(94\)95566-2](https://doi.org/10.1016/0168-583X(94)95566-2) (cit. on pp. 47, 127).
- [145] David L. Griscom, “Optical Properties and Structure of Defects in Silica Glass : Optical Materials”, *Journal of the Ceramic Society of Japan*, vol. 99, no. 1154, pp. 923–942, Oct. 1991, DOI: [10.2109/jcersj.99.923](https://doi.org/10.2109/jcersj.99.923) (cit. on p. 47).
- [146] L. Skuja et al., “Oxygen-excess-related point defects in glassy/amorphous SiO₂ and related materials”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 2012, DOI: [10.1016/j.nimb.2012.02.038](https://doi.org/10.1016/j.nimb.2012.02.038) (cit. on p. 47).
- [147] Nobu Kuzuu, “X-ray induced absorption bands in synthetic fused silicas: OH content dependence of intensities of X-ray-induced absorption bands in type-III fused silicas”, *Journal of Non-Crystalline Solids*, vol. 179, pp. 170–178, Nov. 1994, DOI: [10.1016/0022-3093\(94\)90694-7](https://doi.org/10.1016/0022-3093(94)90694-7) (cit. on pp. 47, 49).
- [148] G. G. van Eden et al., “The effect of high-flux H plasma exposure with simultaneous transient heat loads on tungsten surface damage and power handling”, *Nuclear Fusion*, vol. 54, no. 12, p. 123010, 2014, DOI: [10.1088/0029-5515/54/12/123010](https://doi.org/10.1088/0029-5515/54/12/123010) (cit. on p. 52).

- [149] J. H. Yu et al., “The effect of transient temporal pulse shape on surface temperature and tungsten damage”, *Nuclear Fusion*, vol. 55, no. 9, p. 093027, 2015, DOI: [10.1088/0029-5515/55/9/093027](https://doi.org/10.1088/0029-5515/55/9/093027) (cit. on p. 52).
- [150] J. Linke et al., “High heat flux testing of plasma facing materials and components – Status and perspectives for ITER related activities”, *Journal of Nuclear Materials*, Proceedings of the Twelfth International Conference on Fusion Reactor Materials (ICFRM-12) Proceedings of the Twelfth International Conference on Fusion Reactor Materials (ICFRM-12), vol. 367–370, Part B, pp. 1422–1431, Aug. 2007, DOI: [10.1016/j.jnucmat.2007.04.028](https://doi.org/10.1016/j.jnucmat.2007.04.028) (cit. on pp. 52, 53, 104).
- [151] T. J. Renk et al., “IFE chamber dry wall materials response to pulsed X-rays and ions at power-plant level fluences”, *Fusion Engineering and Design*, 1st International Workshop on Innovative Concepts for Plasma - Interactive Components in Fusion Devices, vol. 65, no. 3, pp. 399–406, Apr. 2003, DOI: [10.1016/S0920-3796\(03\)00009-7](https://doi.org/10.1016/S0920-3796(03)00009-7) (cit. on pp. 53–55, 104, 105, 112, 113).
- [152] T.J. Renk et al., “Chamber wall materials response to pulsed ions at power-plant level fluences”, *Journal of Nuclear Materials*, vol. 347, no. 3, pp. 266–288, Dec. 2005, DOI: [10.1016/j.jnucmat.2005.08.021](https://doi.org/10.1016/j.jnucmat.2005.08.021) (cit. on pp. 53, 54, 104, 105, 119).
- [153] B. Gludovatz et al., “Fracture toughness of polycrystalline tungsten alloys”, *International Journal of Refractory Metals and Hard Materials*, vol. 28, no. 6, pp. 674–678, Nov. 2010, DOI: [10.1016/j.ijrmhm.2010.04.007](https://doi.org/10.1016/j.ijrmhm.2010.04.007) (cit. on pp. 54, 117).
- [154] J. Linke et al., “Performance of different tungsten grades under transient thermal loads”, *Nuclear Fusion*, vol. 51, no. 7, 00029, p. 073017, 2011, DOI: [10.1088/0029-5515/51/7/073017](https://doi.org/10.1088/0029-5515/51/7/073017) (cit. on p. 54).
- [155] Th Loewenhoff et al., “Evolution of tungsten degradation under combined high cycle edge-localized mode and steady-state heat loads”, *Physica Scripta*, vol. T145, p. 014057, Dec. 2011, DOI: [10.1088/0031-8949/2011/T145/014057](https://doi.org/10.1088/0031-8949/2011/T145/014057) (cit. on pp. 54, 105).
- [156] T. J. Renk et al., “Survivability of First-Wall Materials in Fusion Devices: An Experimental Study of Material Exposure to Pulsed Energetic Ions”, *Fusion Science and Technology*, vol. 61, no. 1, pp. 57–80, 2012, URL: http://www.ans.org/pubs/journals/fst/a_13339 (cit. on pp. 54, 116, 119).
- [157] S. B. Gilliam et al., “Retention and surface blistering of helium irradiated tungsten as a first wall material”, *Journal of Nuclear Materials*, Laser Fusion Materials, vol. 347, no. 3, 00047, pp. 289–297, Dec. 2005, DOI: [10.1016/j.jnucmat.2005.08.017](https://doi.org/10.1016/j.jnucmat.2005.08.017) (cit. on pp. 54, 119).

- [158] M. Wirtz et al., “Influence of high flux hydrogen-plasma exposure on the thermal shock induced crack formation in tungsten”, *Journal of Nuclear Materials*, vol. 420, no. 1–3, pp. 218–221, Jan. 2012, DOI: [10.1016/j.jnucmat.2011.09.035](https://doi.org/10.1016/j.jnucmat.2011.09.035) (cit. on pp. 54, 105).
- [159] M. Wirtz et al., “Impact of combined hydrogen plasma and transient heat loads on the performance of tungsten as plasma facing material”, *Nuclear Fusion*, vol. 55, no. 12, p. 123017, 2015, DOI: [10.1088/0029-5515/55/12/123017](https://doi.org/10.1088/0029-5515/55/12/123017) (cit. on pp. 54, 105).
- [160] J. Manzano et al., “Optical waveguides obtained by swift-ion irradiation on silica (a-SiO₂)”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 268, no. 19, pp. 3147–3150, Oct. 2010, DOI: [10.1016/j.nimb.2010.05.075](https://doi.org/10.1016/j.nimb.2010.05.075) (cit. on p. 58).
- [161] J. Olivares et al., “Nonlinear optical waveguides generated in lithium niobate by swift-ion irradiation at ultralow fluences”, *Optics Letters*, vol. 32, no. 17, pp. 2587–2589, Sept. 2007, DOI: [10.1364/OL.32.002587](https://doi.org/10.1364/OL.32.002587) (cit. on p. 58).
- [162] O. Peña-Rodríguez et al., “Kinetics of amorphization induced by swift heavy ions in α -quartz”, *Journal of Nuclear Materials*, vol. 430, no. 1–3, pp. 125–131, Nov. 2012, DOI: [10.1016/j.jnucmat.2012.07.001](https://doi.org/10.1016/j.jnucmat.2012.07.001) (cit. on p. 58).
- [163] G. García et al., “Amorphization kinetics under swift heavy ion irradiation: A cumulative overlapping-track approach”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 269, no. 4, pp. 492–497, Feb. 2011, DOI: [10.1016/j.nimb.2010.12.073](https://doi.org/10.1016/j.nimb.2010.12.073) (cit. on pp. 58, 64, 70).
- [164] H. Trinkaus and A. I. Ryazanov, “Viscoelastic Model for the Plastic Flow of Amorphous Solids under Energetic Ion Bombardment”, *Physical Review Letters*, vol. 74, no. 25, pp. 5072–5075, June 1995, DOI: [10.1103/PhysRevLett.74.5072](https://doi.org/10.1103/PhysRevLett.74.5072) (cit. on pp. 59, 67, 71).
- [165] M. L. Brongersma et al., “Origin of MeV ion irradiation-induced stress changes in SiO₂”, *Journal of Applied Physics*, vol. 88, no. 1, pp. 59–64, 2000, DOI: [10.1063/1.373624](https://doi.org/10.1063/1.373624) (cit. on pp. 59, 71).
- [166] A. Benyagoub et al., “Plastic deformation in SiO₂ induced by heavy-ion irradiation”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 65, no. 1–4, pp. 228–231, Mar. 1992, DOI: [10.1016/0168-583X\(92\)95039-T](https://doi.org/10.1016/0168-583X(92)95039-T) (cit. on pp. 59, 67, 71).

- [167] A. Benyagoub and M. Toulemonde, “Ion tracks in amorphous silica”, *Journal of Materials Research*, vol. 30, no. 9, pp. 1529–1543, May 2015, DOI: [10.1557/jmr.2015.75](#) (cit. on pp. 59, 67, 71).
- [168] K. Vedom and Pichet Limsuwan, “Piezo- and elasto-optic properties of liquids under high pressure. II. Refractive index vs density”, *The Journal of Chemical Physics*, vol. 69, no. 11, p. 4772, 1978, DOI: [10.1063/1.436530](#) (cit. on p. 60).
- [169] A. Rivera et al., “Effect of defect accumulation on ion-beam damage morphology by electronic excitation in lithium niobate: A MonteCarlo approach”, *Nuclear Instruments and Methods in Physics Research B*, vol. 268, pp. 2249–2256, July 2010, DOI: [10.1016/j.nimb.2010.03.031](#) (cit. on p. 65).
- [170] H. Bercegol et al., “Laser damage phenomena relevant to the design and operation of an ICF laser driver”, *Journal of Physics: Conference Series*, vol. 112, no. 3, p. 032013, May 2008, DOI: [10.1088/1742-6596/112/3/032013](#) (cit. on pp. 72, 77).
- [171] J. H. Wray and J. T. Neu, “Refractive index of several glasses as a function of wavelength and temperature”, *JOSA*, vol. 59, no. 6, pp. 774–776, 1969, DOI: [10.1364/JOSA.59.000774](#) (cit. on p. 80).
- [172] D. E. Swets, R. W. Lee, and R. C. Frank, “Diffusion Coefficients of Helium in Fused Quartz”, *The Journal of Chemical Physics*, vol. 34, no. 1, pp. 17–22, Apr. 1960, DOI: [10.1063/1.1731562](#) (cit. on p. 90).
- [173] J. Partanen et al., “High voltage conditioning of the electrostatic deflector of MARA”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Proceedings of the XVIIth International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS2015), Grand Rapids, MI, U.S.A., 11-15 May 2015, vol. 376, pp. 353–356, June 2016, DOI: [10.1016/j.nimb.2015.11.025](#) (cit. on p. 98).
- [174] Stephan Russenschuck, “[Design of accelerator magnets](#)”, *Proceedings of the CAS-CERN Accelerator School: Basic Course on General Accelerator Physics, Loutraki, Greece*, p. 118, 2000 (cit. on p. 99).
- [175] G. De Temmerman et al., “ELM simulation experiments on Pilot-PSI using simultaneous high flux plasma and transient heat/particle source”, *Nuclear Fusion*, vol. 51, no. 7, p. 073008, July 2011, DOI: [10.1088/0029-5515/51/7/073008](#) (cit. on p. 104).
- [176] T. Hirai et al., “Cracking failure study of ITER-reference tungsten grade under single pulse thermal shock loads at elevated temperatures”, *Journal of Nuclear Materials*, vol. 390-391, pp. 751–754, June 2009, DOI: [10.1016/j.jnucmat.2009.01.313](#) (cit. on p. 105).

- [177] J. W. Coenen et al., “Melt-layer ejection and material changes of three different tungsten materials under high heat-flux conditions in the tokamak edge plasma of TEXTOR”, *Nuclear Fusion*, vol. 51, no. 11, p. 113020, 2011, DOI: [10.1088/0029-5515/51/11/113020](https://doi.org/10.1088/0029-5515/51/11/113020) (cit. on p. 105).
- [178] A. Suslova et al., “Recrystallization and grain growth induced by ELMs-like transient heat loads in deformed tungsten samples”, *Scientific Reports*, vol. 4, p. 6845, Nov. 2014, DOI: [10.1038/srep06845](https://doi.org/10.1038/srep06845) (cit. on pp. 105, 112).
- [179] Th. Loewenhoff et al., “Tungsten and CFC degradation under combined high cycle transient and steady state heat loads”, *Fusion Engineering and Design*, Tenth International Symposium on Fusion Nuclear Technology (ISFNT-10), vol. 87, no. 7–8, pp. 1201–1205, 2012, DOI: [10.1016/j.fusengdes.2012.02.106](https://doi.org/10.1016/j.fusengdes.2012.02.106) (cit. on pp. 105, 112).
- [180] J. Sannier et al., “Corrosion of austenitic and martensitic stainless steels in flowing Pb17Li alloy”, *Fusion Engineering and Design*, vol. 14, no. 3, pp. 299–307, Apr. 1991, DOI: [10.1016/0920-3796\(91\)90013-G](https://doi.org/10.1016/0920-3796(91)90013-G) (cit. on p. 106).
- [181] J. Sannier et al., “Comparison of austenitic and martensitic steel behaviour in semi-stagnant Pb17Li”, *Journal of Nuclear Materials*, vol. 191, pp. 975–978, Sept. 1992, DOI: [10.1016/0022-3115\(92\)90619-V](https://doi.org/10.1016/0022-3115(92)90619-V) (cit. on p. 106).
- [182] J. Konys, W. Krauss, and N. Holstein, “Development of advanced Al coating processes for future application as anti-corrosion and T-permeation barriers”, *Fusion Engineering and Design*, Proceedings of the Ninth International Symposium on Fusion Nuclear Technology, vol. 85, no. 10–12, pp. 2141–2145, Dec. 2010, DOI: [10.1016/j.fusengdes.2010.08.018](https://doi.org/10.1016/j.fusengdes.2010.08.018) (cit. on p. 108).
- [183] G. Rampal et al., “HCLL TBM for ITER-design studies”, *Fusion Engineering and Design*, vol. 75–79, pp. 917–922, Nov. 2005, DOI: [10.1016/j.fusengdes.2005.06.322](https://doi.org/10.1016/j.fusengdes.2005.06.322) (cit. on p. 108).
- [184] P.M. Piaggi et al., “Hydrogen diffusion and trapping in nanocrystalline tungsten”, *Journal of Nuclear Materials*, vol. 458, 00000, pp. 233–239, Mar. 2015, DOI: [10.1016/j.jnucmat.2014.12.069](https://doi.org/10.1016/j.jnucmat.2014.12.069) (cit. on p. 116).
- [185] Ted L. Anderson, *Fracture Mechanics: Fundamentals and Applications*, Third Edition, Boca Raton, FL: CRC Press, June 2005 (cit. on p. 117).
- [186] J Schlosser et al., “Design, fabrication and testing of an improved high heat flux element, experience feedback on steady state plasma facing components in Tore Supra”, *Fusion Engineering and Design*, vol. 39–40, pp. 235–240, Sept. 1998, DOI: [10.1016/S0920-3796\(98\)00272-5](https://doi.org/10.1016/S0920-3796(98)00272-5) (cit. on p. 119).

- [187] V Barabash et al., “Armor and heat sink materials joining technologies development for ITER plasma facing components”, *Journal of Nuclear Materials*, 9th Int. Conf. on Fusion Reactor Materials, vol. 283–287, Part 2, pp. 1248–1252, Dec. 2000, DOI: [10.1016/S0022-3115\(00\)00120-3](https://doi.org/10.1016/S0022-3115(00)00120-3) (cit. on p. 119).
- [188] P. Vladimirov and A. Möslang, “Comparison of material irradiation conditions for fusion, spallation, stripping and fission neutron sources”, *Journal of nuclear materials*, vol. 329, pp. 233–237, 2004, DOI: [10.1016/j.jnucmat.2004.04.030](https://doi.org/10.1016/j.jnucmat.2004.04.030) (cit. on p. 122).
- [189] P. Vladimirov and S. Bouffard, “Displacement damage and transmutations in metals under neutron and proton irradiation”, *Comptes Rendus Physique*, vol. 9, no. 3, pp. 303–322, 2008, DOI: [10.1016/j.crhy.2008.02.004](https://doi.org/10.1016/j.crhy.2008.02.004) (cit. on pp. 122, 131–133).
- [190] P. Vladimirov and A. Möslang, “Radiation damage conditions for ESS target hull and irradiation rigs”, *Journal of nuclear materials*, vol. 343, no. 1, pp. 205–211, 2005, DOI: [10.1016/j.jnucmat.2004.12.019](https://doi.org/10.1016/j.jnucmat.2004.12.019) (cit. on pp. 122, 132).
- [191] S. P. Simakov et al., “Comparative study of survived displacement damage defects in iron irradiated in IFMIF and fusion power reactors”, *Journal of Nuclear Materials*, vol. 386, pp. 52–55, 2009, DOI: [10.1016/j.jnucmat.2008.12.057](https://doi.org/10.1016/j.jnucmat.2008.12.057) (cit. on p. 122).
- [192] F. Mota et al., “Analysis of displacement damage in materials in nuclear fusion facilities (DEMO, IFMIF and TechnoFusion)”, *Fusion Engineering and Design*, vol. 86, no. 9, pp. 2425–2428, 2011, DOI: [10.1016/j.fusengdes.2010.12.041](https://doi.org/10.1016/j.fusengdes.2010.12.041) (cit. on p. 122).
- [193] J. M. Perlado, M. Piera, and J. Sanz, “Option for spallation neutron sources”, *Journal of Fusion Energy*, vol. 8, no. 3-4, pp. 181–192, 1989, DOI: [10.1007/BF01051648](https://doi.org/10.1007/BF01051648) (cit. on pp. 122, 132).
- [194] Colin Carlile and Caterina Petrillo, “Neutron scattering facilities in Europe - Present status and future perspectives”, ESFRI Report, European Landscape of Research Infrastructures-ESFRI, July 2016 (cit. on p. 123).
- [195] A. Rivera et al., “Giant enhancement of material damage associated to electronic excitation during ion irradiation: The case of LiNbO₃”, *physica status solidi (a)*, vol. 206, no. 6, pp. 1109–1116, June 2009, DOI: [10.1002/pssa.200824409](https://doi.org/10.1002/pssa.200824409) (cit. on p. 127).