Chamber responses and Safety and Fusion Technology in HiPER facility

J. M. Perlado 1), J. Collier 2), M. Tyldslay 2), L. Gizzi 3), B. Rus 4),

D. Neely 2), C. Strangio 5), M. Dunne 6)

1) Instituto de Fusión Nuclear (DENIM)/ETSII/Universidad Politécnica, Madrid, Spain
2) STFC Rutherford Appleton Laboratory, Didcot, UK
3) IPCF-CNR, Italy
4) Academy of Science-PALS, Czech Republic
5) ENEA Frascati, Italy
6) presently, Lawrence Livermore National Laboratory (USA) *(when summary sent STFC RAL,UK)*
E-mail: mperlado@telefonica.net

Abstract
HiPER - The proposed European Laser-Driven Fusion Facility is actually being developed as an ESFRI Project with collaboration of many different European (but also international) laboratories. The project was upgraded to the present state of two clear steps in proposing funding for next phase development to arrive finally to a Inertial Fusion Power Plant. In addition to aspect in laser, target (both defining and manufacturing), injection and tracking, CHAMBER design is a key aspect in this new phase in which the project has entered. An overview of the state of art of different options of Chamber, their necessary assessments with the safety and environment considerations will be presented together with proposals for fusion technology experiments.

1. - Introduction

The HiPER project final goal is to design, after these first years inside the frame of the European ESFRI program, an Inertial Fusion Facility based on Fast Ignition concept where demonstration of ignition and gain (in the range of 44 compression beams giving 200 kJ in 5 ns and a PW beam line of 70 kJ in 10 ps) will be combined with a complementary exploration of longer term research in Inertial Fusion Energy and different spin-off in basic physics, astrophysics, nuclear physics, high density matter, etc. To get those purposes several steps are being envisioned.

From already general criteria we will need to consider aspects such as: i) withstand earthquakes; ii) be resistant to debris, radiation, shrapnel and neutrons effects from experiments; iii) maintain deep vacuum and ultra-freezing environments required for experiments; iv) accommodate the many diagnostic instruments, beam lines, and associated optics and equipment; v) maintain as low as possible the activation of the materials component of the chamber in order to induce the minimum radioactivity and make easy the operation and maintenance; vi) take into account tritium permeation, diffusion, contamination in that phase of operation. We will present the main criteria when designing the main chamber: fabrication (thickness of shell, welding…); the installation of penetration in the chamber and vacuum leak checking; chamber shielding and uncertainties in it; and the chamber survey and alignment for location of optics and laser ports.

From calculations available in different type of targets we are extracting data of energy yields from debris, X-rays, and neutrons, also considering the different energy spectra. The capsule design will be critical together with the calculation of those numbers, but even with no actual final design for fast ignition, CHAMBER research is imperative. A potential low fraction of X-rays could come from the fact that targets are fully ionized at the end of the burn and bremmstrahlung is the dominant emission. An important difference is also the angular dependence of X-rays, and particles emission (this aspect could be very critical for fast ignition conical targets). A key aspect will appear when considering the repetitive operation in

HiPER, even at lower energies, because the effects on some of the components are not well known. It is already known that for some frequencies there could be differences in the material performance but no experimental proof has already been done. Multiscale Modeling already done will be presented adequate to HiPER proposal.

From the point of view of safety and environment of the facility we are calculating the evolution of the activity (associated magnitudes are contact dose rate and index of waste disposal) accumulated in the chamber along the period of operation before the cleaning of the chamber and evacuation of fuel residual. A second question is to determine the activity accumulated in the storage facility that collects the activated material which is discharged from the chamber annually during its lifetime. For the problem related to the accumulated activity, we need to define the scenario of irradiation (HiPER designs a and b) in the internal surface of the first wall (where the material of the burn fuel is deposited) and inject different types of materials in the times scheduled by the programming of shots during the operational year before the discharge. Related to the activity of the storage facility, that is a pure cooling problem, and the material to be injected is that accumulated during operation time from addition of that yearly discharged. We will need to determine the target material (and positioner) accumulated after a defined period of time in the interior of the chamber, including its temporal evolution, photon production, and contact dose rate in the internal surface of the chamber together with the disposal ratio. We plan to present the methodology to follow in these aspects in HiPER designs and the strategy for assess the viability of such number of chambers, including primary and secondary activation of the chambers.

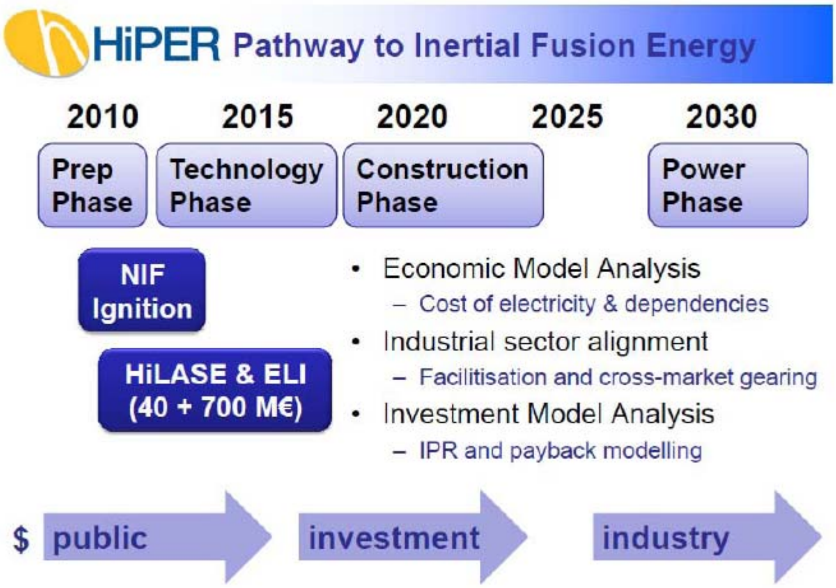
HiPER can provide essential data for IFE in areas in Fusion Technology: Target chamber phenomena and materials responses to target emissions; Prototypical IFE fusion power technologies in the chamber area; Performance testing of IFE target fabrication and injection methods. HiPER would thus play a critical role in providing the basis for design of the follow-on Engineering Test Facility in these areas. Using well established HiPER target output, we will get beneficial knowledge of future technologies with some modification of HiPER main chamber design to allocate these experiments. That is the goal in this phase. These experiments include important tests in the areas of IFE-specific target physics and IFE fusion power technologies (nuclear heating, transport, activation and shielding, tritium management, IFE materials science, and safety/environment). This group constitutes the majority of IFE experiments, and the majority of IFE-specific shots. Thus, the main impact to consider is their contribution to the total HiPER shot envelope and allowed chamber activation, along with all other user-group shots.

2. - Proposals of Chambers

After the first phase of HiPER as ESFRI pre-design project up to April 2011 (where basic knowledge of potential chambers and discussion on what will be available from the point of view of Technology, Safety and RadioProtection) some expected definition of steps (new phases) are open in the European initiative, that include the design of an Engineering Facility operated in the burst mode (100 shot per operation / no continuous repetition) named HiPER 4a. Finally, the goal of European initiative HiPER is the Phase 4b devoted to build a power plant (reactor) to demonstrate commercial viability of laser-fusion. The present duration of such Technological Phase (or Risk Reduction) is estimated in approximately seven years as it is envisioned in next Figure where other development of phase Power Plant is also included.

In addition to this initiative there are, in full coincidence on time, the **LIFE (Laser Inertial Fusion Engine) project at the Lawrence Livermore National Laboratory (USA)** and **LIFT (Laser Inertial Fusion Technology) from Institute of Laser Engineering (ILE)** of the University of Osaka (Japan) together with other Japanese institutions.

Therefore, the HiPER 4b facility requires a robust reactor assembly that is suitable for a commercially acceptable period of operation in order to demonstrate Reliability, Availability and Maintainability requirements for energy generation, without undergoing major overhaul.



HiPER Pathway to Inertial Fusion Energy

2010 2015 2020 2025 2030

Prep Phase

Technology Phase

Construction Phase

Power Phase

NIF Ignition

HiLASE & ELI (40 + 700 M€)

- Economic Model Analysis
  - Cost of electricity & dependencies
- Industrial sector alignment
  - Facilitisation and cross-market gearing
- Investment Model Analysis
  - IPR and payback modelling

$ public → investment → industry

Estimated progress of HiPER project

The basic elements of reactor consist of the final optic assembly (including the moving “engagement” mirror), the target engagement control system, the injector, the reactor outer containment, and blanket, energy extraction system to the primary heat exchanger, tritium handling systems and the first wall. The considered optimal strategy is also to define an Engineering Systems (HiPER 4a) in which it would be possible to test in burst mode all the technologies necessaries for a reactor, mainly repetition of laser and injection, under a CHAMBER with less requirements and no blanket (heat extraction and tritium breeding) in it. The CHAMBER research is thought to be conducted through independent facilities where the areas mentioned below could be demonstrated, and finally integrated in an experimental frame in such phase. The key aspect here is to reduce very strongly the risk associated to the final build up of the Power Plant going to such phase of HiPER 4b with a high degree of success. At the same time the goal is to get the large interest of industries and governments in an ENERGY initiative based in a realistic demonstration, as expected, of ignition and gain as soon as 2011 in National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (USA), and in Laser MegaJoule (LMJ) in Commissariat l’Energie Atomique (CEA) in Bordeaux (France) probably first experiments in 2014.

Certainly, in addition to the CHAMBER design, the laser needed for real efficient/repetitive reactor will be design and the target (whatever option is selected) clearly defined for gain operation together (if possible) with adequate manufacturing, injection and tracking. Current ignition scheme options include Fast Ignition (FI), Shock Ignition (SI) and Central Ignition (CI) with Direct Drive (DD) and Indirect Drive (ID). HiPER design (as mentioned) is based on Fast/Shock Ignition schemes, and demonstration of those potentialities is critical for the Project as a Pan European and also international project; in that sense follow up of present experiments at OMEGA-EP (Laboratory for Laser Energetic/ Rochester University, USA) and FIREX (Institute Laser Engineering / Osaka University, Japan) in this present time are absolutely critical. Certainly in Europe experiments in French facility PETAL when available will also be decisive for this HiPER idea; but other present, or close to be in operation, facilities such as GEMINIS, HILASE, ELI will be critical. In previous works we identify the dry wall and wet wall reactor options that are currently (and in the next years) to be evaluated for HiPER (perhaps gas protection?). It draws on the work performed in reactor design discussing the merits and demerits of each design type. It reviews the suitability of these different reactor types for the different ignition schemes and target designs currently being considered, and comments on possible solutions for use in HiPER. We need a down select decision to be made for the HiPER Phase 4b reactor. That will be (and it has already started) in close collaboration with LIFE and LIFT.

IFE power plant conceptual design studies have been performed for over thirty years, essentially in USA (SOLASE (1977), SOMBRERO (1991), PROMETHEUS, HAPL (2001-8), HYLIFE-2, LIFE (2010) and a long list), but also in Japan (SENRI, KOYO, KOYO-F, FALCON). In Europe, there have been also design studies such as HIBALL I-II, LIBRA and LIBRA _LITE, HIDIF. From these studies a lot of ideas have appeared from different laboratories, some of the key aspects have been lighted now, and in some cases experiments for proof of principles have been performed. For HiPER next steps there are essentially two main chamber types, wet and dry wall. The HiPER reactor would be significantly complex probably being circa 50 laser beam entries, potentially more than one injector, a number of diagnostic ports and entry points for remote maintenance access. The number of penetrations would be subject to detailed design, this being concluded during HiPER 4a operations circa 2020 to 2030. In addition to these problems is key to design very carefully the RadioProtection Systems (Shielding concerning the different areas of the Reactors. During the operation of HiPER first engineering facility, up to $2{\cdot}10^5$ MJ per year of fusion neutrons yields are foreseen. This irradiation level could be distributed in 100MJ detonations, accounting up to 100 detonations in a single burst, with 10Hz repetition rate. A burst would take place every month. The dose rates are computed and different concrete shields are evaluated within the target bay. During the operation of the facility the stays inside the bio-shield are exclusion areas. Between bursts, manual maintenance might be performed inside the bio-shield but outside the final optics (FO) shield. Inside the FO shield the residual dose rates are so high that only remote maintenance is allowed. The FO shield reduces the delivered dose rate in a factor of 435.5

As mentioned several reactor configurations are actually considered based on dry or wet walls. *Dry Wall* reactors operate with a base pressure of approximately 10^{-4} mbar (~0.1 mTorr) and rely on wall distance (but other options such as special geometries, materials are explored) from the fusion event and wall material properties to resist the huge fluxes stemming from every explosion. In order to minimize the chamber dimensions, different *Gas Protection* scenarios have been proposed. They rely on a certain density of gas (typically Xe) inside the chamber, in the order of 10^{-2} mbar (tens of mTorr) @ST. With the current knowledge, gas protection scenarios appear incompatible with FI schemes due to non-linear interactions between the PW ignition laser pulse and the gas. In other ignition schemes, in particular with ID target, gas protection is an option, and we will need to explore. We will not consider a high gas density because it can affect laser transport (not only in FI scheme) and target injection, especially in the case of DD targets. *Wet Wall* reactors of all variants rely on the low vapour pressure liquid coating of internal reactor walls mitigating the effects of operation. They are very attractive due to the self-healing nature of liquid. However, some drawbacks have been reported. In particular, aerosol formation can affect laser transport, target tracking and engagement. Further research must be devoted to these topics. Finally, some works propose to use magnetic intervention for ion deflection. Detailed calculations indicate that a properly designed magnetic field may lead all generated charged particles to a divertor out of the chamber. Despite some disadvantages such as its complexity, cost and divertor-related problems this idea must not be ruled out.

No solution is optimal yet for HiPER 4b, and that is one of major objective for European laboratories, in particular as present responsible in HiPER. During phase 3 and 4a of HiPER, physics schemes, target packages, materials and modeling research and prototyping will be undertaken to find technologically safe solutions. Maybe the most favored reactor option now would be a dry wall chamber which could be suitable for all ignition schemes currently under consideration and their associated target types. Limitations of currently available first wall materials to meet the operation demands seem solvable by means of further R&D programs in this topic. Within the R&D still necessary, this area appears as one of the most easily successful in the coming years. In addition, (undesired) enhance of chamber dimensions or magnetic intervention could work if an appropriate solution for first wall materials is not found.

3. - Strategic Lines and Results

HiPER, both options of 4a (Engineering) and 4b (Power Plant), has many areas in CHAMBER design where put emphasis, which could be different depnding on what facility it can be talking about. We list now a systematic approach of list task to be developed by groups in this field:

a) Knowledge of physics for damage in materials and protection of the chamber walls and optics from debris ions, x-rays, alpha particles and shrapnel

b) Provision of a working life suitable for commercial applications. That implies work to be performed in both areas of Materials resistant to irradiation and being of low/reduced activation mimimizing the radioactive waste in the facility

c) Operation at repetition rate and the potential for re-setting the first wall protection measures after a shot to a level suitable to permit another shot to be undertaken

d) Minimising the effect of first wall ablation or aerosol sputtering effects from posting increased challenges to the injection and engagement of a target

e) Breeds tritium at a minimum breeder ratio of 1.1 to permit continued operation with minimum tritium inventory.

f) Ensuring that the chamber size and port arrangements make achievable:
   a. final optic protection from ions
   b. laser spot size and accuracy of pointing on target
   c. diagnostic protection
   d. target survival
   e. target engagement

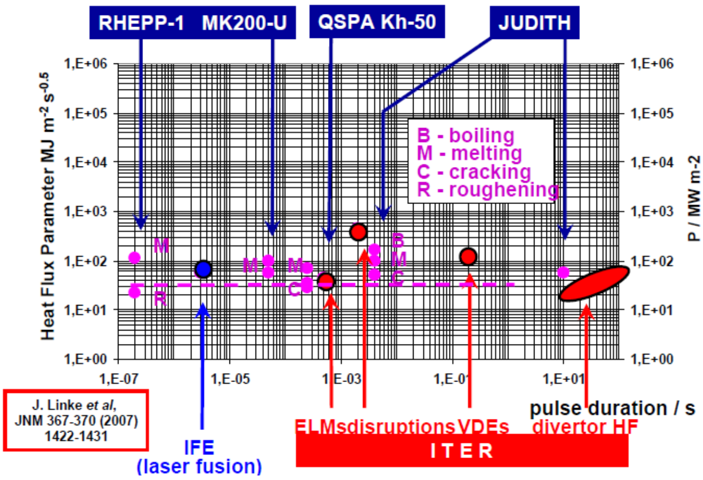
g) Radioprotection design of the different areas of the reactor HiPER in its different options (Shielding, penetrations and operation conditions depending of areas, inclyding necessity of remote handling or potential personnel intervention in time intervals)

Then, key issues for creating an operating reactor with a matched ignition scheme are:

First wall life
Target survival in the environment
Ability to engage lasers appropriately with target
Final optic life assuming that neutrons, X-rays, γ-rays and shrapnel will hardly be avoided, in particular in evacuated chambers
Structural material performance under intense pulsed neutron irradiation

From that list Chamber design inside HiPER has started to identify key aspect correlated with experiments proposed in the near future. Those experiments and proposal are both for HiPER 4a and 4b, in spite that we will have different conditions and work very special need to be define the type of blanket in HiPER. In addition with information given here, there is also in this conference several papers giving precise details of results in First Wall, Optics, and Safety and Radio Protection for HiPER.

The major difficulty to make accurate predictions on materials performance stems from the simultaneous interactions (synergetic effects) of different types of radiation (neutrons, energetic photons, charged particles) with the surrounding materials. In particular, for Inertial Confinement Fusion (ICF) reactors with targets such as those expected for HiPER, the major threats to target facing materials come from the arrival of high fluxes of a large variety of energetic particles (mainly D, T, He and C) shortly after the deposition of a high power pulse of X-rays and the subsequent passage of a high flux of neutrons (energy up to 14 MeV/neutron). If we want to assess where we are in potential experiments in Inertial Fusion:



In order to study the combined effect of light species (D/He) and heavier ions (C) on first wall materials and final optics components subjected to ICF radiation conditions, one needs to use a multi-beam system. It is_proposed to use the double beam facility available at the group of *Ion Physics in Forshcugzentrum Rossendorf.*

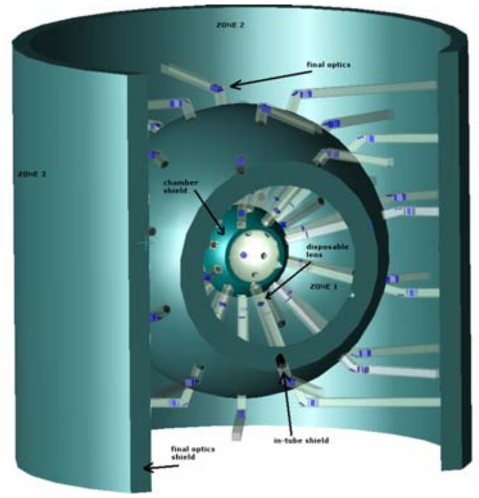
For the final optics, we will need to compare high quality optical graded silica samples with KU1 silica, well known for its radiation degradation resistance. In addition, we need to consider the performance of (unavoidable) anti-reflective coatings (e.g. hafnia) subjected to ICF ion irradiation. For this purpose a plan proposed by Instituto Fusion Nuclear of UPM is to reproduce the effects due to simultaneous implantation of C-He/D typical of an ICF reactor. The study will be carried out at different sample temperatures and up to doses of 10^{17} cm^{-2}, which are equivalent to 100000 shots of 20 MJ direct drive targets (as those planned for the first phases of HiPER). The diffusion and retention (depth profiling) of light atoms will be studied by resonance nuclear reaction analysis (RNRA) as a function of temperature and thermal desorption spectroscopy (TDS). The structural and morphological properties of implanted samples will be investigated by X-ray diffraction (XRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM). The combined use of these techniques will make possible the understanding of the combined effects of damage and gas retention (bubble formation) and the development of macroscopic detrimental effects such as swelling and blistering under realistic ICF conditions. The mechanical (W) and optical (silica) properties will also be investigated after irradiation to relate the observed effects.

As first option W is a promising candidate for the reactor first wall due to its high melting temperatures, good thermal conductivity, low sputtering and low tritium retention. The implanted-induced effects of H, D and He as single light species in W have been widely studied. However, as far as we know, synergetic effects which may reduce significantly the operational window of W as a first wall material have been only reported for Magnetic Fusion (MF) conditions at room temperature. Moreover, the interaction with C poses additional risks on material performance. The work the Instituto (DENIM) intend to carry out (in facilities such as *Jannus or TIARA facilities)*_ is related to the study of the combined effect of light species (D,^{3}He) and heavier ions (^{12}C) on first wall materials for ICF reactors. In particular, we will co-implant D, ^{3}He and ^{12}C in single- and poly-crystalline W samples. In order to simulate a prototypical IF energy ion, the implantation energies would be selected to be 0.75 MeV for ^{12}C, 1.51 MeV for ^{3}He and 0.5 MeV for D. The fluences used for implantation will range from $1x10^{15}$ to $1x10^{17}$ $cm^{-2.}$ The implantation would be done at different temperatures (from room temperature up to above 1000 ºC). These conditions are very similar to those expected for the first phases of HiPER. The second part of the work is related to the characterization of the diffusion and retention (depth profiling) of light atoms immediately after co-implantation. For this purpose, we intend to carry out resonance nuclear reaction analysis (RNRA) by using the ^{3}He(d, p)^{4}He and the ^{12}C(d,p)^{13}C nuclear reactions.

The effect of tritium is critical and will be in Power Plants; then proposals such as following (by Insituto Fusion Nuclear, DENIM) is the study of diffusion and retention (depth profiling) of light atoms, H, which can be produced by transmutation or introduced by interaction with the plasma, in the materials to be used in future fusion reactors. The understanding of this phenomena is crucial in order to be ready for the design of the future reactor HiPER 4b, and it is one of the significant differences between fusion technologies and other related areas (fission or spallation sources, for example). To this end Li_2SiO_3, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3 and ODS steel samples were grown under different conditions in order to achieve a different microestructural configuration and implanted with deuterium at different energies (the projected ranges of the implanted hydrogen ions were calculated with the TRIM code to be around 0.8 μm and 1.6 μm for 50 keV and 100 keV energies, respectively), at different doses (up to $5\ x10^{16}cm^{-2}$) and at room temperature. In order to study the hydrogen diffusion not only as a function of micoestructural properties but also as a function of annealing temperature some of the samples were annealed after implantation at different temperatures in the interval between 100 and 400ºC.. The microstructure of the samples has been investigated by XRD prior to and after ion-implantation. The work that we intended to carry out in *Rossendorf* is related to the hydrogen depth profiling characterization in as-implanted and post-annealed implanted samples. To this end we will perform depth profiling experiments by using H (^{15}N,He)^{12}C nuclear reaction. Depth profiling of deuterium in deuterium-implanted fusion materials (Lithium-compounds ceramics and ODS steels with different microstructure and annealed at several temperatures in the range from 300 to 700ºC). The work that we intended to carry out in *Katholike Universiteit Leuven (KUL)* is related to the deuterium depth profiling characterization in as-implanted and post-annealed implanted samples. To this end we are intended to perform depth profiling experiments by using the D(^{3}He, p) ^{4}He nuclear reaction. In order to look for the optimal analysis conditions we ask for three days to analyze the most representative samples and to study the feasibility of the experiment.

From the Radio Protection in HiPER, we have studied the implications of a preliminary proposal of design from the standpoint of internal and shielding requirements of CHAMBER. The reference case is considered to be the most exigent irradiation scenario conceived for HiPER 4a. We will start with HiPER 4b defining in near future the Blanket structure and accommodation in the system. 100MJ neutron yields per shot, with 100 shots at 10 Hz in a single burst, one burst every week or month (other more realistic is 20MJ neutron yields, with 5 events in a 100 non-explosive shots per bursts at 10 Hz (explosions occur at 0.5 Hz)). A fully defined geometry has been used for very detailed 3D geometry considering penetrations and different areas (see other presentations).

Materials as SS304L, EUROFER and Al5083 has been considered with a borated concrete shield after that structure with a thin first wall of W. The expected lifetime of the facility for this scenario is 20 years. We have computed the prompt dose rates (PDR) and residual dose rates (RDR) delivered to the workers/public during the operation and in the period between bursts; we also computed the prompt dose delivered to the Final Optic Assembly (FOA), as a sensitive part of the facility.



The shields that have been proposed behave reasonably well, creating free-restriction areas outside the target bay, and allowing manual maintenance 36 hours after the shutdown in some stays. The FOA receives a dose rate 30 times lower in the presence of the FOA shield. We compute the quantities with the same design undergoing a softer irradiation scenario, resulting a waiting time to access to the restricted area shorter than one day. The FOA receives 20 times lower dose rates. We have also considered different materials for the tubes which transport the beams, as they are the main responsible for the RDRs. The choice of material for the reaction chamber is discussed for commercial and reduced-activation steels, with regards to waste management performance.

Acknowledgements

The authors acknowledge the support of the Funding Agencies undertaking this work (EC FP7 project number 211737): EC, European Commission, MSMT, Ministry of Education, Youth and Sports of the Czech Republic and STFC, Science and Technology Facilities Council of the United Kingdom. It has been also partially supported by Plan Nacional de I + D + I (2008 - 2011) Fusion Nuclear ENE2008-06403-C06-02 MICINN. This work is mainly consequence of group of people at Instituto Fusion Nuclear doing present proposals, and first author thanks J. Alvarez, A. Rivera, R. Gonzalez-Arrabal. S. Cuesta, D. Garoz. R. Juarez, J. Sanz for all the material in their specific articles and here.

References

[1] http://www.hiper-laser.org/index.asp

[2] R. Juarez et al., Overview on Neutronics, Safety and Radiological Protection of HiPER Facilty, IAEA FEC 2010, Daejon, October 10-17, (2010) IFE/P6-22

[3] J. Alvarez, et al., The Role of the Spatial and Temporal Radiation Deposition in Inertial Fusion Chambers, IAEA FEC 2010, Daejon, October 10-17, (2010) IFE/P6-23

[4] S. Cuesta et al, Modeling Advanced Materials for Nuclear Fusion Technology, IAEA FEC 2010, Daejon, October 10-17, (2010) IFE/P6-24

[5] R. González-Arrabal, et al., Study of diffusion and retention of light species (H and He) in pure W and W-based materials, IAEA FEC 2010, Daejon, October 10-17, (2010) IFE/P6-25

[6] Information on Laser Inertial Fusion Engine (LIFE) from Lawrence Livermore National Laboratory from Ed. Moses in IAEA FEC 2008, J. Latkowski, IAEA CRP Vienne 2010, W. Meier SOFT 2010, T. Díaz de la Rubia, Madrid Conference at UPM, 2009