IFE Plant Technology Overview and contribution to HiPER proposal

J. M. Perlado, J. Sanz*, J. Alvarez, D. Cereceda, S. Cuesta, S. Courtin, E. del Rio, J. Fernández, A. Fraile, D. Garoz, N. Gordillo, C. Guerrero, R. Gonzalez-Arrabal, N. Moral, R. Juarez, F. Ognissanto, A. Rivera, C. Sánchez*, R. Suarez, M. Victoria

Instituto de Fusión Nuclear (DENIM) / Universidad Politécnica de Madrid (UPM)

* also Departamento Ingeniería Energética, ETSII, Univ. Nacional Educación a Distancia (UNED)

from STFC_RAL U.K.: C. Edwards, J. Collier, M. Tyldesley, M. Tolley, D. Neely;

from Academy of Science-PALS Czech Republic: B. Rus; from CEA (France): B. Le Garrec;

from CELIA (France): G. Schurtz; from Oxford Tech. U.K.: S. Sanders

Abstract

HiPER is the European Project for Laser Fusion that has been able to join 26 institutions and signed under formal government agreement by 6 countries inside the ESFRI Program of the European Union (EU). The project is already extended by EU for two years more (until 2013) after its first preparatory phase from 2008. A large work has been developed in different areas to arrive to a design of repetitive operation of Laser Fusion Reactor, and decisions are envisioned in the next phase of Technology Development or Risk Reduction for Engineering or Power Plant facilities (or both). Chamber design has been very much completed for Engineering phase and starting of preliminary options for Reactor Power Plant have been established and review here.

1. Introduction

The next phase of HiPER Laser Fusion European Project is centered in the study of Technology Assessment (Risk Reduction or Business Case) in which, under the basis of already study physics in the preparatory phase extended two more years, it could be defined the better and economic solutions to propose to our societies and governments a realistic approach, as soon as possible, of generation of Energy by using technologies on Laser Fusion. The areas of Lasers (efficient and repetitive at the energy and power needed); the target design and demonstration under a first option of Shock Ignition; the target manufacturing at mass production, injection and tracking; the blanket design to accommodate an efficient heat deposition and tritium breeding compatible with low activation and material resistant to the irradiation conditions; and finally the Power Plant Systems to extract energy with safe operation, maintenance and accidental consideration under condition of a well defined manufacturing and manipulating plant for tritium, need to be revisited carefully. That work is expected to be performed in a common definition but with independent installations in different places and countries to be finally integrated in the facility. The Figure 1 represent such strategy in this moment where it is clearly indicated the importance of the key expectation with high probability of NIF ignition as the first step for acceptance of this proposition.

One key aspect that condition the decision of type of Blanket and technology is that HiPER is assuming a **Shock Ignition Direct Drive** conditioning the choice of Chamber to be at present state that of **Dry Wall**, instead of other options. The final tasks to be performed are:

- Target fusion performance demonstration under Shock Ignition (even that under no official HiPER policy, indirect drive effects can be pursued independently by some groups or countries to follow immediate demonstration of NIF targets)

- Diode based lasers
- Mass produced targets
- Target injection and tracking
- Fusion environment
 - Laser beam propagation
 - Protecting first wall
 - Materials to withstand ion flux and He implantation
 - Magnetic diversion of ions
 - Modular chamber
 - Final focusing optics
- Balance of plant

Figure 1. - Present Strategy of HiPER European Laser Fusion Energy Facility

2. Chamber Protection of Power Plant Reactors at Inertial Fusion

One of the key issues in the design of the Chamber is that of the potential Protection of Materials from the explosion of the target after its burnup. The emissions of charged particles, X-Rays and neutrons and gammas can produce negative effects in the surrounding materials. The effect of neutrons, with a long range of penetrations and a progressive deposition of energy in the materials are the key processes in the heat deposition and tritium breeding in the blanket, but it has also the deleterious effect of potential activation of the materials and radiation damage. The effect of charged particles (from nuclear fusion products, no burned fuel materials and additional materials original in the target composition) and X-Rays because of the short range of penetration can have always a negative effect in the first wall materials of the chamber. Then protection of such surface is considered: gas, wetted wall and thick wall protections. Under these hypotheses a large number of Power Plant Systems for Inertial Fusion have been considered and prepared (from HIBALL, LIBRA, PROMETHEUS, SOMBRERO and HYLIFE reactors to more recent concept of LIFE, KOYO-F or HiPER). Those concepts assume the potentials of the chamber protections already mentioned: LIFE (gas protection); KOYO-F (wet wall) and HiPER (no protection, then DRY WALL). Each one of them has advantage and disadvantages and depend its possibility very much of the type of target and

injection selected. It is easy to demonstrate that Indirect drive target (such as LIFE engine) can be compatible with a gas protection system from the target and wall survival in the process to be injected and tracked, what is not clearly demonstrated (in fact it is difficult to justify with present knowledge for direct drive target and fast ignition laser injection. In these case wet wall or dry wall are critical.

Some conclusions that can be obtained from First Wall Survival depending on Protection are:

- **Wet wall** due to its self-healing nature could be a good option as first wall. However, aerosol concerns are common to all liquid-protected chambers because:
 - Homogeneous nucleation and growth from the vapor phase
 - Supersaturated vapor
 - Ion-seeded vapor
 - Impurity-seeded vapor
- Phase decomposition from the liquid phase
- Thermally driven phase explosion
- Pressure driven fracture
- Hydrodynamic droplet formation (flow conditioning)
- **Dry wall** chambers can meet the requirements increasing the chamber dimensions what is an undesired option, then solution is going through NEW MATERIALS
 - Magnetic intervention has shown to work but it is not the best option due to complexity and cost.
 - The limiting factor for the use of W is He retention in radiation-induced cavities leading to blistering and material exfoliation.

With respect to the gas protection, such as proposed in LIFE concept:

- **Gas protection** permits to mitigate the thermal loads keeping the first wall material below the threshold at which thermo-mechanical effects are fatal. For example, if W is used for first wall should not exceed 2400°C.
 - However, due to incompatibilities with target injection, the gas pressure must be kept in the 10^{-2} mbar (tens of mTorr) range, much lower than needed for full ion mitigation.
 - In any case the most deleterious ions (He particles from fusion reactions) will not be fully attenuated. As a result, He retention could be not expected even with gas protection, except that in case of He, it is interacting with other materials in the Indirect Drive Target case and none of such particle really arrive to first wall.

When assuming that in HiPER a Dry Wall solution is taken in order to be fully compatible with target survival and laser injection, it is important to remark that in such case we need to go to a very consistent R&D in **new materials** that will give an optimal solution. The following points may be met by first wall materials:

- a. The **thermal load** must not harm the material. This implies to avoid excessive thermal load in the first μm of material. Instead the load must be deposited significantly deeper. This implies to design high area surfaces (needle-like).
- b. Development of **stable nano-structures** is desirable because (i) they are less prone to vacancy clustering, (ii) they facilitate He release.
- c. The materials must be **porous** enough to facilitate the release of light species, in particular He.

- d. Any candidate material must be studied under realistic IFE conditions for a *sufficient number of cycles*.

3. HiPER design: Engineering Facility (4a)

The work performed in HiPER Chamber has been consistent with the two options considered in the Technology Assessment, and it has produced a very much detailed chamber design for the Engineering Repetitive Facility and a Program of work (already started) for the Reactor Power Plant system. Here, below (Figure 2) is the final view of the designed chamber after interacting with both laser systems and remote handling areas.

Figure 2. - Layout of HiPER Engineering Facility (HiPER 4a) with indications of areas for protection

	<u>HiPER DEVELOPMENT(4a)</u>	<u>HiPER POWER PLANT (4b)</u>
Description	Experimental facility	Demonstration reactor
Operation	Bunches of 100 shots, max. 5 DT explosions	Continuous (24/7)
Yield (MJ)	<20	>20 (100)
Rep. rate (Hz)	1-10	10-20
Power (GWt)	-	0.3 (1-3)
T cycle	No	Yes
Blanket	No	Yes

Table 1. - Working conditions for HiPER Engineering (4a) for Burst Mode and those assumed for HiPER Power Plant Reactor assumed in our calculations.

As it is indicated in the Table 1, the work performed for the chamber design in this phase is based in those conditions of Burst mode for the Engineering/Demonstration (4a) and the Power Plant Design (4b). The conclusions from both mode of operation are very much different (as expected) from the Chamber design perspective, including the conditions of the first wall materials, those of optics (and their positioning) in the systems and of course the operation/maintenance and potential accidental conditions. In the following we review the most critical aspect in a design that can be at most well defined including solutions from Remote Handling. In any case, it is important to remark that Engineering Facility will be the integration of elements to be defined in the next period of 7-8 years that demonstrate the repetitive operation of systems, but in the mean time a solution can be obtained for mass target manufacturing, demonstration of final target design and Chamber options for continuous operation. This facility could also be considered for advance/dedicated experiments in that concern of the chamber and it would be thought to be adapted as easy as possible for a future reactor with similar structure, in case the decision would be to have both facilities.

The design of chamber is given in Figure 3 in a bi-dimensional view, consisting in a 1 mm W armor with 10 cm thick austenitic steels, surrounded by 40 cm of Borated concrete:

Figure 3. - Layout of HiPER 4a where calculations have been performed showing also the radioprotection considered.

The temporal and spatial deposition of charge particles and X-Rays have been calculated for a 48 MJ Shock ignition target at 5 m radius target, and the consideration of first wall using W from the point of view of melting, thermal stress and tritium retention have been calculated with the positive result of use of such thin layer of W as armor at the Burst facility (see Figure 4). The question of neutron and gamma damage in this facility will be concentrated not in the structural materials (no blanket / no tritium breeding) but essentially in the effect on the final optics, conditioning its design.

Initially, HiPER laser lines are planned to work on transmission (lenses). Final optics “close” to the explosions (8 m) but even for Phase 4a, protection of final optics is an open question. Certainly Ions must be removed and work (B. Rus) has been developed for designing an electrostatic deflector in a range of 3 m (from chamber wall to FOA position) to removed almost 100 % of ions. Meanwhile, the effect of neutrons, gamma and X-rays needs to be addressed much more, using current materials for final optics such as Fused silica, KU1, or other and irradiation experiments are required and

(some) already planned for ions installations and proposal under neutrons for NIF facility. Complementary work is being performed by using Molecular Dynamics and Kinetic MonteCarlo in order to define the magnitude of defects and colour centre in the system.

Figure 4.- Temperature, Thermal Stress and Time dependent Tritium retention for Burst HiPER4a
The study of the assessment of the different areas in HiPER 4a from the dose levels and the conditions of operation in the system has been fully studied with and indication of the classification of such areas as indicated in Figure 5 (consistent with Figure 1).

Figure 5.- Determination of Classification areas and importance of components in the activation by neutrons.

During operation Areas 1 and 2 are exclusion areas. Between Burst (with the assumed conditions) Area 1 is still a remote handling area, but Area 2 can be considered for hand-on qualification after 36 hours. The Area 3 is always no exclusion area. The most important contributors to doses are the FOA protection tubes. The improvements of the design from this concern are: use of low activation materials for the tubes; reduction of bio-shield thickness for pinhole dose; exploration of a better constructive and operation design of FOA shield.

4. HiPER design: Power Plant Reactor (4b)

In order to complete the design of the Power Plant a lot of aspects need to be assessed that are review in the previous sections. In this case, the blanket is a system with heat deposition and coolant for extraction of it and a tritium breeder system. The study of first wall armor in a Dry Wall consideration at 24/7 operation is very much different, the damage and activation of structural materials is critical here and give very much the answer to the lifetime of systems. In addition, the consideration of accidental conditions, and potential releases of activated materials and tritium handling cover a key importance. The work performed until this moment gives a response to the no use of W in the way it was in the Burst mode, and identifies a plan for research of new materials and at the same time a full 3D neutronics assessment with interaction with thermo-fluid codes and accidental codes is now necessary for defining the reactor.

Figure 6.- The design of Reactor where is included the type of environment considering now the blanket and power systems.

Figure 7.- Profile of Deposition from Shock Ignition Target in the Wall and proposal of Experiment for Ion effect analysis in Dry Wall System adopted in HiPER

The emissions from target and arrival to first wall are the source term to evaluate now the availability of W as solution in the first wall. The answer has been that no material can withstand now with the thermal and stress conditions under a 24/7 reactor system and Dry Wall between 5 or 6.5 m radius. Then a program of experiments is needed. From the review of present facilities it is noted the non useful of what it would be used in magnetic even in more catastrophic situations and in consequence proposal for a new ion generation by laser facility is being emerging. See for these considerations Figure 7. Motivated by that previous works (*this phase*), we will explore:

1-Nanograin W and nano-diamond

2-Carbon and W based Foams

3-Velvet/cone like structures based on Carbon fibres, carbon nanotubes

In order to proof our options in these First Wall materials and optics a list of experiments has been proposed:

In order to study the combined effect of light species (D/He) and heavier ions © on first wall materials and final optics components subjected to IFE radiation conditions, one needs to use a multi-beam system. A proposal is running 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 IFE ion irradiation. For this purpose a plan is proposed to reproduce the effects due to simultaneous implantation of C-He/D typical of an ICF reactor.

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 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,3He) and heavier ions (^{12}C) on first wall materials for IFE reactors. In particular, we will co-implant D, 3He and ^{12}C in single- and polycrystalline 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 ^3He and 0.5 MeV for D. The fluences used for implantation will range from 1×10^{15} to $1 \times 10^{17} \text{ cm}^{-2}$. The implantation would be done at different temperatures (from room temperature up to above 1000 °C). These conditions are very similar to those expected for the first phases of HiPER. The effect of tritium is critical: work at *Rossendorf* and *Katholieke Universiteit Leuven (KUL)* for diffusion and depth profiling characterization.

For the Structural materials research, the research is focused in the same materials and participating in the same program than already existing in Magnetic Programs with consideration of Ferritic-Martensitic and ODS steels, and SiC composites materials. Experimental and Multiscale Modeling is running in such Programs to define the effect of radiation damage and finally the lifetime of those components.

With respect to Blanket systems for Reactor and Power Plant the work will be reported in near future but in spite of the final options of cooling and tritium breeding a simple consideration of subdivision of the two hemisphere of Reactor in subsystems well managed with box structure from where coolant can flow and extract energy and tritium breeding.

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