Key paramaters in the design of HiPER reaction chamber

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Abstract

The future chamber reactor of HiPER will have to withstand short energy pulses (3 μs long) of up to 5 MJ of charged particles and X-rays with different repetition rates. Nowadays, tungsten has been selected as first wall material for a 5m radius reaction chamber. From the thermo-mechanical point of view, experiments have demonstrated that tungsten can withstand heat flux parameters up to 28 $MJm^{-2}s^{-1/2}$ without roughening and 40 $MJm^{-2}s^{-1/2}$ without undergoing melting. From the atomic point of view, He retention and bubble formation represents the biggest threat to its survivability, being doses of ~10^{17} He/cm^2 the upper limit for safe operation.

Comparison of these limiting values with those proposed for a 48 MJ shock ignition target in HiPER reveals that, under a reasonable plan of 1000 fusion shots during the chamber lifetime, tungsten should guarantee a proper performance of the first wall.

Introduction

HiPER, the European program for Inertial Confinement Fusion Energy (IFE), is about to enter in the technological phase prior to construction which is expected by the end of this decade. Its goal is to prove fusion in repetitive mode, acting as the intermediate step between the initial IFE single shot experiments (NIF and LMJ) and a future IFE demo reactor. Thus, HiPER is meant to work at a repetition rate of 5 to 10 Hz in burst campaigns of 100 MJ in100 shots. Although the types of ignition are still under discussion, the two most promising approaches are Fast ignition and Shock ignition schemes. The involved challenges are very demanding so, in order to make HiPER a reality, many difficulties have to be overcome. One of them is the design of a reaction chamber able to manage the fusion explosions.

Up to now, the requirements of the chamber in NIF and LMJ have mostly dealt with activation issues and not durability since both facilities are meant to work under very limited amount of fusion shots during their lifetime, having always the possibility to replace or repair damaged components between shots. In the case of HiPER, this approach is not possible and, therefore, the material requirements to design the chamber are much more demanding. Tungsten is currently the preferred material for that purpose due to its high melting point, thermal conductivity, and yield strength and its low sputtering and tritium retention [i]. However, one should bare in mind that W is quite brittle and prone to He bubble formation and blistering.

In this paper, we describe the different threats that the first wall material will have to face. Based on experimental studies available in the literature, we discuss how tungsten behaves under such threats, providing irradiation limits which guarantee the performance of tungsten under the extreme conditions taken place in an IFE reactor. Finally, we compare those limits with the irradiations produced by a 48 MJ shock ignition target after one thousand shots for a proposed 5 m radius reaction chamber.

Threats

In an inertial confinement fusion reaction, threats come in form of neutrons, electrons, gamma rays, X-rays and ions but, from the first wall point of view, the main effects will come from X-rays and ions. For simplicity, the effect of the radiation can be separated in two processes: the effects due to pure energy deposition and thermo-mechanical behaviour of the material and the effects at an atomic level which refer to the interaction of particles with atoms in the material lattice.

Energy deposition and Thermo-mechanical behaviour

In inertial confinement reactors, around 30% of the fusion energy is deposited on the first wall in form of high kinetic energy ions and X-rays. In the case of HiPER, i.e. in the case of direct drive targets, around 28% of the total fusion energy goes to ions and only 2% of it to X-rays. This energy can produce phase changes and mechanical stresses leading to the breakdown of the material. Tungsten, with a high melting point and a high yield strength has shown acceptable thermo-mechanical properties. The relevant parameter which determines the maximum energy that a material can handle without damage should be the temporal and spatial energy density ($J/cm^3/s$). However this parameter is never used since it not only depends on the incident radiation but also on the material properties (the radiation-material interaction cross section). Thus, most damage studies give the radiation energy fluence (J/cm^2) at which the material suffers modifications as key parameter, being this value only valid for a specific time deposition profile and kind and energy of incident particle. The heat flux parameter used by the magnetic fusion community includes the temporal dependence, introducing the thermal diffusion factor. This fact has allowed the comparison of thermo-mechanical investigations in tungsten under different time deposition regimes [ii,iii]. Obviating the dispersion of results due to the use different radiation particles, these studies suggest a lower limit of 28 $MJm^{-2}s^{-1/2}$ for roughening/cracking and 40 $MJm^{-2}s^{-1/2}$ for melting in tungsten. These values provide a guideline for the energy deposition limits that HiPER design can accept.

More specific studies, in which IFE reactor conditions are mimicked as much as possible, found roughening limits around 28 $MJm^{-2}s^{-1/2}$ for ion irradiation (RHEPP [iv] and around 60 $MJm^{-2}s^{-1/2}$ for X-rays exposition (XAPPER [v]and Z accelerator [vi]).

Atomistic interactions

The interaction of incident ions with the first wall atoms produces a variety of effects such as sputtering, defect formation, and changes in the material properties due to implantation, diffusion and trapping. Whereas sputtering may not be a major problem since most of the incident ions in inertial fusion are light species (H, D, T and He), trapping of light species, in particular of He, seem to be the decisive issue. Under certain concentrations, its aggregation into bubbles can cause blistering and cracking of the material. Having in mind that, the available studies are restricted to implantation of monoenergetic He ions on W at a specific kinetic energy, they agree that doses of 10^{17} He/cm^2 [vii,viii] yield to accumulation of He and surface modification of W. However, different factors such as the temperature cycle of the material, the incident energy of the implanted ions, microstructure of the sampled and synergetic effects can modify this limit. Thus, new experiments need to be performed to better characterize the maximum admissible value of He in W for a safe operation.

H isotopes are expected to diffuse at the working temperatures of tungsten [ix,x]. Carbon, on the other hand, will get implanted and remain in the tungsten as an impurity, being only relevant if its concentration becomes important [xi].

Synergetic effects of the different ions are a current field of research in fusion. The collective effect of the different ions is not the same than the sum of their individual effects [xii,xiii,xiv].

HiPER case for a 48MJ shock ignition target

In order to compare the presented parameters with an irradiation scheme on the walls of the future HiPER chamber, we present the characteristics of a 48MJ IFE shock ignition target (Table 1) and its effect after one thousand shots (realistic value of total number of shots in the lifetime of the HiPER chamber). From the thermo-mechanical point of view and considering a 5 m radius chamber, this target deposits around 4 J/cm^2 in about 3 μs which corresponds to a heat flux parameter of 23 $MJm^{-2}s^{-1/2}$. This value is below any observable change in tungsten and only the cyclic transition between the ductile-brittle transition temperature (DBTT) may cause serious damage [iii]. From the atomistic point of view we see that:

- among all ions, C is the one with the highest sputtering yield. SRIM calculations show values of 0,05 W atoms per incoming C ion, i.e. 10 monolayers after 1000 shots.
- Under the light of Table 1, the number of defects produced in tungsten are not expected to be responsible of main mechanical failures
- The problem of He retention and bubble formation is not significant in this case either. Even considering that all He ions get trapped in the first wall, the total dose after 1000 shots will be well below the accumulation threshold of 10^{17} He/cm^2.
- The concentration of carbon ions on W after 1000 fusion shots will be at most 800ppm limited to the first micron.

X-rays	Energy (keV)	Fluence* (J/cm^2)	%	Number Particles	Fluence* (p/cm^2)	%
X-ray	666	0,212		4,7 *10^{20}	1,5*10^{14}	
Ions	**Energy (keV)**	**Fluence* (J/cm^2)**	**%**	**Number Particles**	**Fluence* (p/cm^2)**	**%**
H	270	0,09	2,2%	1,2*10^{19}	3,8*10^{12}	4,9%
^{2}H	3200	1,02	25,9%	1,1*10^{20}	3,3*10^{13}	43,3%
^{3}H	3550	1,13	28,7%	9,5*10^{19}	3,0*10^{13}	39,0%
^{3}He	9	0,003	0,1%	1,9*10^{17}	6,1*10^{10}	0,1%
^{4}He	3630	1,16	29,4%	1,7*10^{19}	5,4*10^{12}	7,0%
^{12}C	1680	0,54	13,6%	1,4*10^{19}	4,4*10^{12}	5,6%
^{13}C	15	0,005	0,1%	1,2*10^{17}	3,7*10^{10}	0,1%

Table 1 – X-ray and Ion products of a 48 MJ shock ignition target [[xv]]. In grey, the most relevant ions. *Fluences for a 5 m radius chamber.

Although these results may imply that the problem of the first wall may be solved, the situation will be quite different for a demo reactors with probably 10^8 shot/year. These threats are far from being ignored and, therefore, the material tests obtained by facilities as NIF or HiPER will become crucial in collecting new damage data of materials.

Summary

The goal of HiPER is to prove inertial fusion viability in (realistic) repetitive mode (5-10 Hz) in burst campaigns of 100 MJ with direct targets of up to ~50 MJ. Considering tungsten as the first wall material, the chamber should survive the fusion explosions without suffering significant melting or roughening. Other important issue, such as He retention, will not affect the armour during the lifetime of the reactor due to the limited foreseen number of explosions. Nevertheless, further experiments will be required for the next HiPER phase (full power) when the number of shots and target energy will increase. In particular, synergetic effects must be deeper understood in order to select an appropriate armour material.

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