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Potential common radiation problems for components and diagnostics in future magnetic and inertial confinement fusion devices

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ABSTRACT

This work aims at identifying common potential problems that future fusion devices will encounter for both magnetic and inertial confinement approaches in order to promote joint efforts and to avoid duplication of research. Firstly, a comparison of radiation environments found in both fusion reaction chambers will be presented. Then, wall materials, optical components, cables and electronics will be discussed, pointing to possible future areas of common research. Finally, a brief discussion of experimental techniques available to simulate the radiation effect on materials is included.

1. Introduction

Engineers and scientists must meet the challenge of producing a long-lasting and clean source of energy such as fusion. In order to achieve fusion energy, there are currently two basic approaches: magnetic (MC) and inertial confinement (IC). Although these methodologies are radically different in the way they achieve the plasma densities and required temperatures to produce fusion, they face common radiation damage issues. The harsh environment that both fusion reaction chambers have to withstand consists of high fluxes of neutrons, gamma, X-rays and energetic light ions (see references in Section 2). Even when differences in the radiation pulse length (~200 ns for IC and hundreds of seconds for MC) affect the material response, similar thermo-mechanical and atomistic effects are found. Accumulation of tritium and activation are also a common matter of concern. These undesirable effects have to be understood and controlled so that the proper functioning of the facility is assured.

Large experimental facilities are required to test chamber components under such extreme radiation conditions. Joint development and use of certain facilities can be beneficial for both, MC and IC communities. In the same way, R&D in new materials, diagnostic components and remote handling designed for one approach can be beneficial for its counterpart.

The aim of this paper is to identify common potential problems in MC and IC fusion to promote collaboration, reduce costs, and avoid research duplication.

2. Radiation fluxes

Basically, the production of fusion and radiation in IC is cyclic in nature (pulsed) whereas MC fusion takes place in near steady state conditions (long pulses). However, the most remarkable radiation events in MC appear as prompt emissions: (i) type I edge localized modes (ELM) and (ii) disruptions [1,2]. Table 1 compares the rough values of these MC events at the ITER divertor to those of a typical 154 MJ direct drive target in IC [3]. In a direct drive IC fusion explosion, apart from the penetrating neutrons, the major part of the energy goes to three species: fusion product α-particles and (non-burnt) debris D and T ions (see Fig. 1).

From table I one can see that deposited energies in the MC events are much larger than those in IC. However, peak powers are higher in IC. In order to see the effect of such a deposition of energy on the chamber components one should consider the kinetic velocity of the impinging particles. Since in IC the incoming ions are much more penetrating than in MC, energy is deposited along a larger depth, reducing appreciably the energy and power density on the material (see Fig. 2). The pulse duration and heat diffusion must also be taken into account. This is frequently expressed

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Table 1
Optimistic conditions assumed for ITER divertor and for a typical direct drive target (yield 154 MJ) [2,3].

		Time (s)	Deposited energy ($MJ\,m^{-2}$)	Power ($MW\,m^{-2}$)	Heat flux parameter ($MW\,m^{-2}\,s^{-1/2}$)	Particle energy (eV)	Particle flux ($m^{-2}\,s^{-1}$)
Divertor	Steady state	1000	–	15	–	1–30	$<10^{24}$
	ELM	0.2×10^{-3}	1	5×10^{3}	70	1–30	$<10^{24}$
	Disruptions	1×10^{-3}	20	2×10^{4}	600	1–30	$<10^{24}$
Direct target	α-Particles	200×10^{-9}	0.03	1.5×10^{5}	70	2.1×10^{6} avg.	1×10^{25}
	DT debris	1.5×10^{-6}	0.06	4×10^{4}	50	150×10^{3} avg.	2×10^{22}

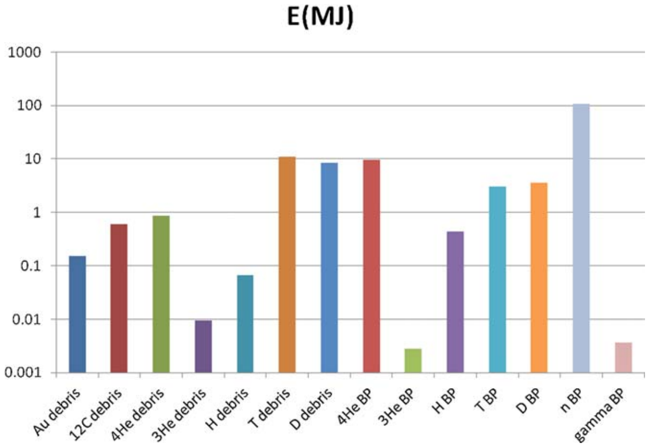

Fig. 1. Energy distribution for different particles produced by a direct drive target of 154 MJ. BP stands for burn products.

by means of the so-called heat flux parameter which is defined as $H = E(\Delta t)^{-1/2}$, where E represents the deposited energy and Δt the deposition time [4]. H values for different MC and IC processes are given in Table 1. Similar H values are shown to induced similar thermal effects, so materials designed to withstand heat loads from ELMs are expected to thermally hold up IC explosions and vice versa. So far we have compared both MC and IC radiation fluxes in terms of thermal loads into the materials that in turn may produce deleterious thermo-mechanical effects such as roughening, cracking or melting. Nevertheless, ion-matter interactions resulting in defect production, i.e. ion implantation, play also an important role. Understanding the ion-induced phenomena is not straightforward due to synergistic effects stemming from the simultaneous implantation of several ion species. Note that although the ingredients for defect-driven phenomena exist in both MC and IC, the implantation species, energies and fluxes drastically differ.

To date, the effect of gamma rays and neutrons (see Table 2) also represent a common problem mostly on damage of optical components (see below) and activation issues. In the future, when fusion reactors work as electrical power stations, the effect of neutron displacements (100 dpa/year) will also be determinant for the survivability of the reactors.

3. Common material issues for divertor/first wall

In addition to carbon-based materials, currently, the most promising material for the MC divertor and IC armor is tungsten [6–8].

From a thermo-mechanical point of view neither of the so-far studied materials can withstand the most disadvantageous MC conditions, e.g. disruptions. For W, analytical solutions of one-dimensional heat equation under disruption conditions yield temperatures exceeding 30,000 K on the surface (ignoring melting and vaporization) which would lead to unavoidable mass loss and damage. In the case of ELMs in MC and He fusion products in IC, temperatures would raise above 3000 K, close to the melting point and above the thresholds for cracking formation. The IC community is working on developing alternative materials that enable the use of dry wall chambers with reduced radius ($R < 5$–6 m). The new materials must fulfill certain requirements: (i) large surface area to accommodate the thermal load over a larger volume; (ii) high thermal conductivity to impede excessive heating due to reduced thermal removal [9].

From an atomistic point of view, IC W-based armor materials present a serious problem regarding He nucleation in vacancy clusters that, in turn, leads to blistering and exfoliation of the material with fatal mass losses. This problem is also an issue in MC. In both cases modeling of blistering is not trivial due to the synergistic effects taking place. A way of minimizing this problem can be achieved by developing: (iii) porous materials to facilitate the release of He and other light species; (iv) self-healing materials i.e. nanocrystals in which vacancies easily migrate to grain boundaries reducing the formation of large vacancy clusters and thus He nucleation.

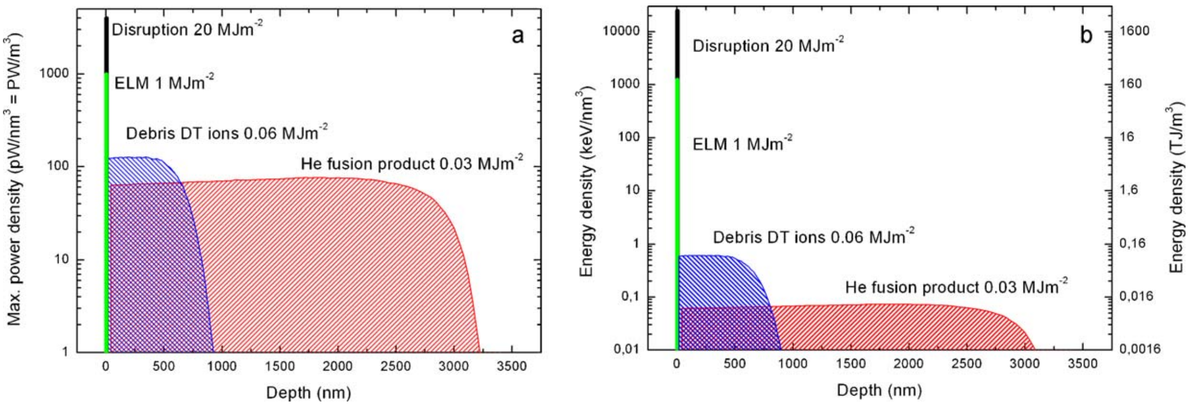

Fig. 2. (a) Power density as a function of depth in a W sample for different MC and IC conditions. (b) Energy density deposited in a W sample as a function of depth.