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Abstract

The transport of ions in pre-formed plasma channels is considered for heavy ion fusion power plants. Analysis has been performed of the behavior of channels in a target chamber gas, of the effect of channels on the shielding of the final focus of the driver from target generated neutrons and of the target generated blast that propagates in the plasma channel to the final focus. On the basis of this analysis, transport channels seem to be consistent with a particular heavy ion fusion power plant concept.

1. Introduction

Ion transport in pre-formed plasma channels has for some time been thought of as a possibly attractive option for light and heavy ion beam fusion power plants. Channels can guide ions over distances of several meters through target chamber environments and can allow higher beam emittances and microdivergences. The advantage of long transport length is flexibility of target chamber design. Higher allowed emittance can lead to accelerator designs with other attractive features, such as lower cost.

The presence of plasma channels in the target chamber require certain accommodations. The target chamber gas much be consistent with the proper behavior of pre-formed plasma channels. Also, the target chamber first wall protection system must include penetrations for the channels. These will compromise the wall protection in the region of the ion beams by allowing neutrons and the target generated blast to reach the first wall and ion beam final focus structures.

In this paper we will assess, in a preliminary way, the effects of the channels on the protection of the target chamber and accelerator. We have studied these issues for a particular target chamber concept, HYLIFE-II [1]. We have performed channel formation and blast simulations with a 1-D radiation-hydrodynamics computer code and 1-D neutronics calculations.

2. Facility Description

We have assessed these issues within the context of a particular heavy ion fusion reactor concept. This concept adapts the HYLIFE-II reactor concept by adding transport channels. This concept also includes final transport for heavy ion beams. In this concept, jets of molten salt Flibe (a mixture of fluorine, lithium, and beryllium) absorb the target debris, x rays, and neutrons and protect the target chamber. The jets are thick enough to stop target generated neutrons, so the first wall of the target chamber experiences neutron damage rates that are sufficiently low to allow it to be a lifetime component. To provide adequate thickness, three sets of 50 cm thick jets are employed. Gaps in the jets allow the formation of laser guided pre-formed plasma channels and the injection of targets. These jets are formed by a set of nozzles in the top of the target chamber. Gaps in the jets are created by oscillating the nozzles. For convenience, we have called this concept HIFC (Heavy Ion Fusion with Channels).

This concept includes the design of a final ion beam transport system [2]. This system includes insulators to prevent electrical breakdown between the channels and the target chamber walls, an adiabatic lens to focus the ions beams into the channels, a differential gas pumping system, a set of superconducting focusing magnets, and an optics system for lasers that guide the paths of the channels. All of these systems are sensitive to neutron and blast damage, and proper shielding systems must be included and the damage assessed.

3. Channel Behavior

The target chamber conditions must be consistent with formation of plasma chambers. The HIFC concept fills the target chamber with 5 torr of xenon. The formation of plasma channels in 5 torr of xenon has been studied with the BUCKY 1-D radiation-magnetohydrodynamics computer code [3]. A 50 kA discharge current was applied to the channel, where the current rise time is varied. The channel is assumed to be initially at a radius of between 2.5 cm and 3 cm, rarefied to 0.1 torr, and at 0.7 eV. Simulations of the pinch of the channel have been performed for radiation transport turn on and off in the code. Radiation transport was found to spread the channel, preventing a small channel radius. The choice of target chamber gas could be adjusted to reduce channel spreading by radiation transport. The channel behavior needs to be optimized to provide the smallest possible channel, so the ion beam radius is small enough to irradiate the required spots on the target. Optimization of the channels with BUCKY simulations is planned, as is verification of the code with z-pinch experiments.

4. Neutronics Analysis

Thick curtains of falling Flibe are employed to protect the chamber wall from neutrons generated in the target. Neutron streaming through penetrations in the curtains could produce significant damage to the sensitive components of the beam transport system. Neutronics analysis has been performed to assess the shielding requirements for the superconducting final focusing magnets and the electrical insulators employed in the adiabatic plasma lens and between the channel and the chamber. In addition, the final laser optics will be exposed to direct streaming source neutrons. The placement of the laser metallic mirrors relative to the target was determined to allow them to be lifetime components. The results presented here are normalized to the fusion power of 2580 MW (430 MJ target yield at 6 Hz) and 30 full power years (FPY) of operation.

Spinel is chosen as insulator material since it offers the lowest mechanical and structural degradation in a nuclear environment among its class of solid ceramic insulators [4, 5]. The insulator at the chamber wall is protected from the neutrons emitted from the target by a total Flibe thickness of 150 cm. The resulting peak end-of-life fast neutron fluence is 2.4×10^{19} n/cm^2, more than three orders of magnitude below the fluence design limit. The value at the back of insulator is only 9.5×10^{17} n/cm^2. The insulator in the adiabatic lens is shielded from the source neutrons by the insulator at the chamber wall and the 10 cm steel electrode at the chamber side of the adiabatic lens in addition to the shielding provided by the 150 cm Flibe jet assemblies. The peak end-of-life fast neutron fluence in the insulator of the adiabatic lens is only 3.6×10^{17} n/cm^2.

The final superconducting quadrupole magnet in the ion beam final focusing system is located at 10 meters from the plasma adiabatic lens. Radiation limits are taken from ITER [6]. Additional shielding is needed in front of the quadrupole assembly in this region to supplement the shielding effect of the 15 cm total thickness of the steel electrodes of the adiabatic lens. A shield consisting of 70% SS and 30% water was considered. The insulator dose limit was found to be the most limiting parameter that determines the shielding requirement. Based on this analysis a shield thickness of 90 cm is required. This design is conservative because no credit is taken for the additional shielding provided by the baffle chamber and pumping units located between the adiabatic lens and the final focusing magnets.

The lifetime of the final laser mirrors depends on the neutron fluence limit for the dielectric coated or metallic mirrors, damage recovery with annealing and the location of the mirror relative to the target. The final laser mirror located along the channel axis is in the direct line-of-sight of source neutrons emitted from the target and will experience the largest radiation damage. Dielectric coated mirrors are more sensitive to neutron radiation which degrades the optical transmission of the dielectric material, decomposes the dielectric materials, and destroys the interfaces between dielectric layers. The sensitive dielectric mirrors can be protected by removing them from the line-of-sight for target neutrons and the more radiation resistant grazing incidence metallic mirrors are placed in the direct-line-of-sight [7, 8]. Assuming no damage recovery with annealing, the lifetime is determined by dividing the fast neutron fluence limit by the fast neutron flux at the mirror. In order for the mirrors to last for the full 30 FPY of reactor operation, they have to be located at minimum distances from the target of 262, 83, or 26.2 m for fluence limits of 1020, 1021, and 1022 n/cm^2, respectively. Experimental data on radiation damage to metallic mirrors are essential to allow for a more accurate prediction of the lifetime.

5. Blast Analysis

The target explosion generates a blast in the xenon target chamber gas that represents a threat to the survival of the insulators at the target chamber wall. The target x-rays and debris heat the xenon near the target to a degree that radiative transfer and hydrodynamic motion propagates into the transport channel and eventually to the first wall. This process has been modeled with a series of calculations with the BUCKY [3] 1-D radiation hydrodynamics code. The blast initially expands spherically until it reaches the first of the Flibe jets at 50 cm from the target. Then the blast is modeled as a slab moving in the transport channel. Finally, the blast spherically expands again between the last of the jets and the wall, where ceramic insulators are located.

The results of the BUCKY simulations are shown in Table 1. The peak pressure and impulse on the insulators are not large and an insulator can probably be designed to withstand this loading. The pressure on the insulators is shown as a function of time in Figure 1. The peak pressure is low enough that the shocks will not be launched into the insulators. The insulators will vibrate, which could lead to fatigue damage. To address this issue, a detailed design and structural analysis of the insulators should be performed.

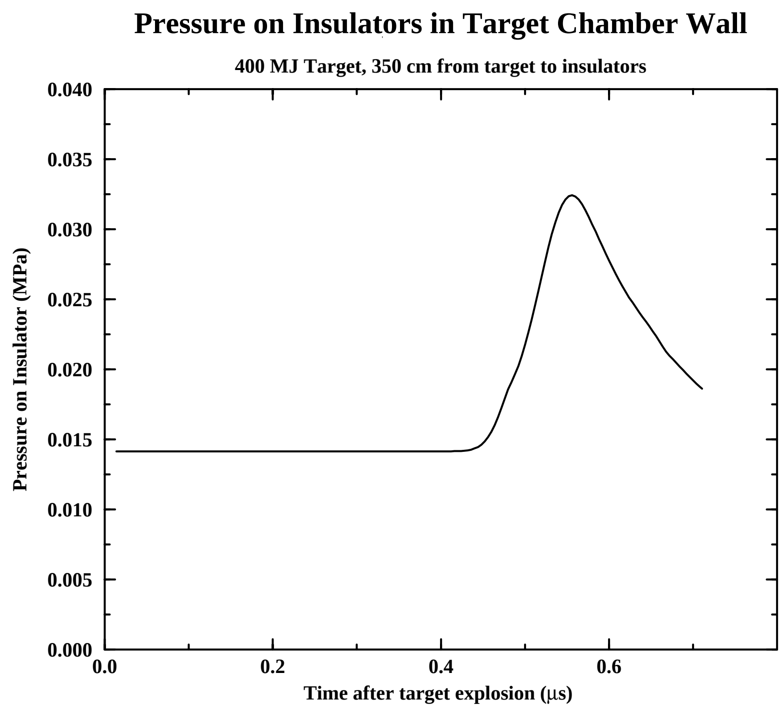

Figure 1. Pressure on insulator stack versus time. The result of a series of one-dimensional BUCKY simulations.

6. Conclusions

We have considered channel transport in a heavy ion fusion reactor concept and have found no insurmountable effects on the target chamber and final focus design. Specifically,

- 5 torr of xenon gas is consistent with both channel transport and first wall protection.
- Structures in the final focus section of the accelerator can be adequately protected from target neutrons streaming in channels with added shielding for the superconducting final focusing magnets.
- The insulators receive an estimated impulse of 12.5 Pa-s several times per second. This impulse is small compared to mechanical loadings in other inertial fusion target chamber concepts.

Table 1. Blast on Insulators

Parameters		Results	
Target Yield	400 MJ	Absorbed X-ray	473 J/cm^2
X-Ray Yield	80 MJ	Absorbed Debris	1271 J/cm^2
Debris Yield	40 MJ	Peak Pressure	0.024 MPa
X-Ray Fluence	1969 J/cm^2	Time of Peak	551 μs
Debris Fluence	1271 J/cm^2	Impulse	12.5 Pa-s
Channel Length	275 cm		
Channel Density	0.2 μg/cm^3		

Acknowledgement

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