Impact of Magnetic Diversion on Laser IFE Reactor Design and Performance


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Abstract. This paper covers the results of a scoping study to assess the possible application of magnetic diversion to a laser IFE reactor. Its impact on the engineering design and performance of the reactor is discussed, key issues are identified, and the findings from this assessment are summarized.

1. INTRODUCTION
The High Average Power Laser (HAPL) program is carrying out a coordinated effort to develop laser inertial fusion energy (IFE) based on direct drive targets and a dry wall chamber [1]. The dry wall must accommodate the ion and photon threat spectra from the fusion micro-explosion over its required lifetime. Use of a buffer gas would help in reducing the threat to the armor by capturing some of the ion energy and re-radiating it to the first wall over a longer time. However, it would also give rise to issues associated with target injection, survival and placement, as well as with restoration of the chamber for the next shot. For that reason, the current HAPL strategy assumes as baseline a chamber with no protective gas; the armor/first wall configuration is based on tungsten and ferritic steel as preferred armor and structural materials, respectively. Armor lifetime is a key issue being addressed through a focused R&D program to help understand the thermo-mechanical behavior of the armor under the cyclic temperature peaks and gradients, and He implantation [1-2].

For a given target yield this strategy results in a fairly large chamber to ensure armor survival; e.g. with a radius of 10.5 m for a target yield of 350 MJ [1]. Thus, a parallel effort is underway to explore ways of rendering the overall concept more attractive based on size, design and performance. A possible option, as proposed by Robson [3], is to use magnetic diversion in order to steer the ions (representing ~25-30% of the yield energy) away from the chamber wall. This can dramatically reduce the peak surface temperature of the chamber wall because of all the threats to the wall, the ions are the greatest contributors to the wall temperature. This paper summarizes a scoping study to assess the possible application of magnetic diversion to a laser IFE reactor.

2. MAGNETIC DIVERSION CONCEPT
The target fusion micro-explosion creates an electrically-conducting plasma of ions and electrons. Imposition of a magnetic field on the chamber provides the possibility of slowing down and steering the charged ions in this plasma. Utilization of a cusp field for such magnetic diversion has been experimentally demonstrated previously (e.g. see ref. [4]) and is illustrated in Fig. 1 for a four-coil arrangement. Following the micro-explosion, the ions would compress the field against the chamber wall, the latter conserving the flux. Because of this flux conservation, the energetic ions would never get to the wall. The expansion of the plasma in such a cusp field is illustrated in Fig. 2 based on a 2-D shell model for the following example initial parameters: a shell energy of 105 MJ, velocity of
1.3x10^9 cm/s and coil current of 8 MA. The chamber wall is illustrated by the dashed line at 6.5 m from the center of the chamber. After 526 ns, the shell/wall/magnetic energy distribution of the compressed plasma is 4.7/7.7/92.8 MJ with a field at the shell of ~5500 gauss.

![Figure 1. Schematic of cusp field configuration.](image)

![Figure 2. Expansion of plasma in cusp field.](image)

![Figure 3. Schematic of external ion collector plates.](image)

Three different subsequent scenarios were assessed and are discussed in more detail in the next subsections: (1) let the shell collapse (the magnetic energy is transferred back to the plasma which escapes through the cusps, depositing the energy onto external collectors); (2) dissipate the magnetic energy resistively, which reduces the energy available to recompress the plasma and reduces the load on the external collectors; and (3) transfer the magnetic energy into an external circuit, which provides the economic benefits of direct energy conversion while allowing for wall protection. In all cases, the chamber wall itself would be designed to a lower heat flux (to accommodate the X-rays which represent only ~1-2% of the yield, and, in the second option, some of the magnetic energy which is dissipated over a much larger depth) while the neutrons are captured in the blanket structure.

### 2.1 Diverting Ions Out of Chamber

In this scenario, the ions are contained within the magnetic bottle and “slowly” leak out of the chamber through a toroidal slot and holes at the poles, where they are directed to specially-designed large-area collectors, as illustrated in Fig. 3 (although collector plates are also shown behind the poloidal holes, most of the ions would be dumped on the large toroidal collector ring). It is estimated that about 10% of the ions escape after each transit in the plasma bottle. The total time of flight of the ions from the micro-explosion is based on this transit time and on the time for the ions exiting the chamber to reach the collector plates. Figure 4 summarizes the results in terms of the maximum temperature of a tungsten armored collector plate as a function of the plate width and radius from the chamber center for a 350 MJ target yield. A fairly large plate area is required to maintain an acceptable maximum W temperature (assumed as 2400°C [2]). For example, this can be achieved with a 6.5 m wide collector plate at a radius of 15 m, while in the absence of magnetic diversion a 10.5 m chamber would be required [2]. Further design refinement such as utilizing dual duck-bill-shaped collectors at an angle could increase the incident area of the collector plates and help in reducing the overall dimensions. However, the resulting system is still fairly large and it is not clear whether the advantages gained outweigh the issues of using a magnetic field, including coil design and neutron shielding requirements, laser port accommodation, loss of breeding blanket coverage (~10%), and impact on possible use of a liquid wall coolant in the chamber.

### 2.2 Resistive Dissipation of Magnetic Energy

The magnetic energy in the compressed plasma can be dissipated by using a resistive wall in front of the chamber. The dissipated energy can then be recovered by cooling the resistive wall and conventionally transferring the energy to a power cycle fluid through a heat exchanger. This would remove most of the ion energy thereby reducing the ion load on the chamber wall and/or on the ion collector plates. However, a fairly thick resistive wall is needed (e.g. for the 6.5 m radius chamber, equivalent to a ~0.5 m thick region with a 300 ohm-cm resistivity) whose design configuration and cooling requirement would need to be integrated with the blanket. Key issues include the additional
design complexity and, more importantly, the additional attenuation of the neutrons through the resistive material and corresponding loss of tritium breeding in the blanket.

2.3 Electrical Conversion of Magnetic Energy
This seems the most attractive scenario as it helps to reduce the ion load on the chamber and provides the possibility of direct conversion of the ion energy to electricity, which can be used to power the laser and achieve substantial increase in overall efficiency. It is illustrated schematically in Fig. 5 (based on Mima's work [5]) where pick up coils are energized by the change in magnetic flux as it is compressed toward the chamber wall. The generated current can be used to power the laser, which requires about a third of the ion energy while the rest can be directly added to the grid. For example, out of a target gain of 140, the net electricity production would be about 40 for a typical plant with 36% power cycle efficiency. Direct conversion of 50% of the ion energy would increase the net electricity to 54, as illustrated in Fig. 6. One of the challenges with this approach is to keep the voltage induced in the pick up coils to manageable levels.

3. CONCLUSIONS
Magnetic diversion allows more robust choices for the chamber armor as the ions can be directed to external collector plates. However, issues associated with the design and size of the plates as well as the magnetic field impact on the design complexity and choice of coolant must be addressed. Magnetic diversion also opens up the attractive possibility of trying to convert the ion energy to electricity with much better efficiency than that obtained by conventionally transferring the ion energy to a power cycle fluid through a heat exchanger. Since the recycling power to the laser represents a high fraction of the electrical output from a conventional power plant (up to ~25%), this would help in improving the overall plant efficiency appreciably. This seems to be the most attractive option, which needs to be further studied to better understand its attractiveness and address the key issues impacting the design.

References