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HEAVY-ION BEAM AND REACTOR CHAMBER INTERFACE DESIGN*

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The design of the heavy-ion beam and the HYLIFE-II reactor chamber interface must provide final focusing quadruple triplets, neutron shielding, fast shutters, vapor condensation and pumping, thermal insulation, and blast-resistant structures. The smallest half-angle encompassing all beams striking the target might be $\pm 14°$ for an array of 4×4 beams or $\pm 9°$ if the four corner beams are eliminated, given a 12-beam array. The target gain drops considerably from the 0° published values because of this finite angle. The assumed one-sided irradiation reduces the number of bending magnets. A 350-MJ yield might be achieved with a 5-MJ driver (gain of 58, nominal 1000-megawatts of electricity (MWe) net power, and a repetition rate of 8 Hz). For either lower repetition rate or lower gain, the yield must be increased by increasing the driver energy. The beam ports are protected from radiation by an array of vertical and horizontal, neutronically thick, liquid jets.

1 INTRODUCTION

In this paper we describe the heavy-ion beam and reactor chamber interface design. The reactor chamber example used is HYLIFE-II, but other designs could equally well have been used. In two other papers (Refs. 1 and 2) the HYLIFE-II reactor is described.

2 BEAM AND CHAMBER INTERFACE

The heavy-ion beams from either a circular or linear accelerator are directed onto the target in the reactor chamber shown in Figures 1, 2, and 3. A length of about 400 m is required for drift compression of the beams. As a base case we consider one-sided illumination of the target so as to minimize bends (which are predicted to cause emittance growth, causing a larger spot size on the target and therefore a reduced gain), as shown in Figure 4. We have reduced the distance from the end of the last focusing magnet to the target from the 8 m of HYLIFE-I to 5 m for HYLIFE-II to make it easier to put the beams into a spot size of about 2.5 mm radius.

We have tried to put a compact array of 12 beams as close together as possible to reduce the half-angle ($\pm 9°$) encompassing these beams to as small a value as

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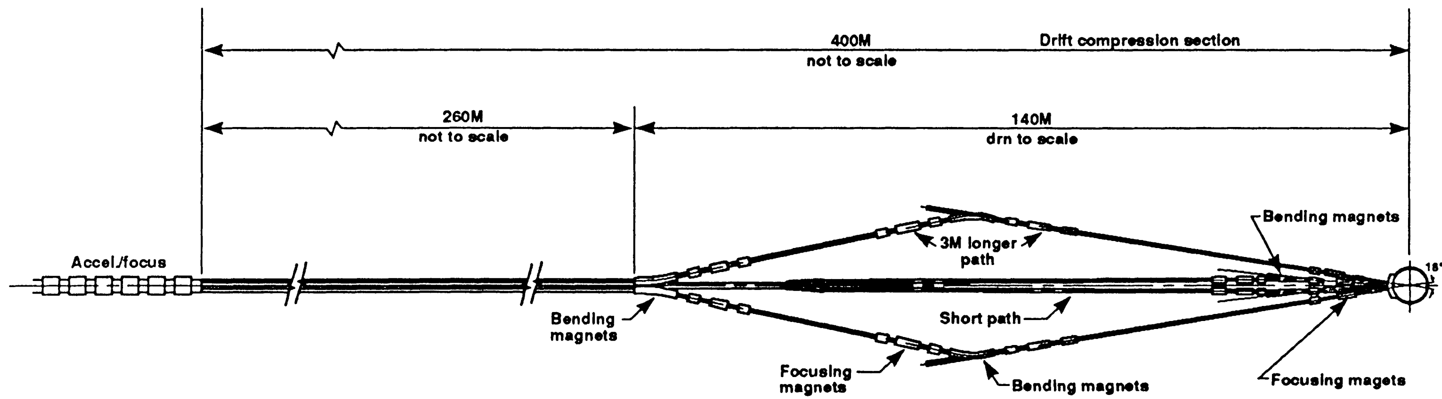

FIGURE 1 The last 400 m of the heavy-ion beam system is used to accomplish drift compression of the beams and the last 50 m is used for final focus from one side onto the target in the example shown. The desired pulse shape can be obtained by compressing, delaying, and stacking the 12 beams.

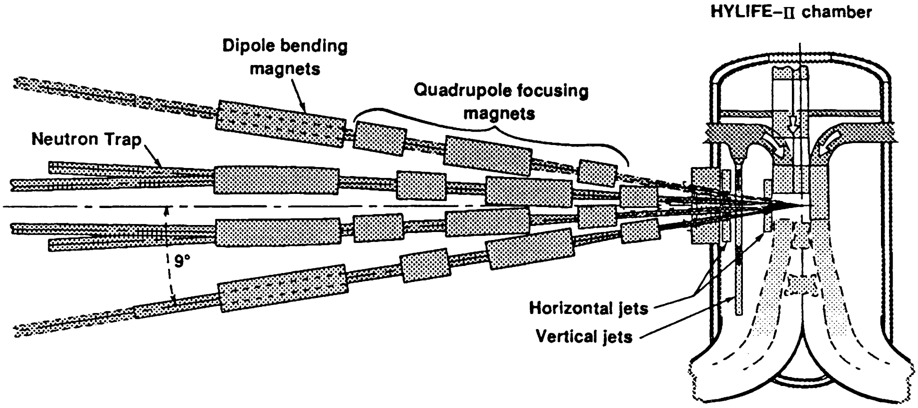

FIGURE 2 Twelve beams are focused onto the target in the HYLIFE-II reaction chamber. The $\pm 9°$ half-angle encompassing the beams is set by neutron shielding of the magnets.

possible. The 4 × 4 array of 16 beams had a half-angle of $\pm 14°$. Eliminating the four corner beams gives an array of 12 beams that fit into $\pm 9°$, as shown in Figure 2. The approximate effect of the beam array angle on gain is shown in Figure 5.

We know the magnets need shielding to reduce the energy deposited in the conductor during a pulse so that the temperature rise stays within the limits required to avoid a magnet quench. Steady power removal is probably not a technical limit,

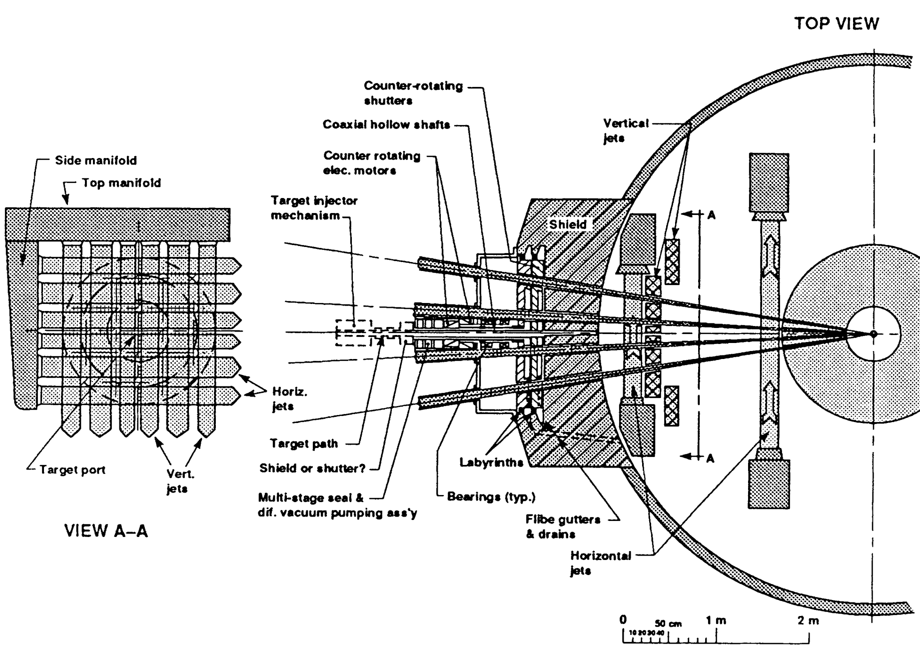

FIGURE 3 The walls around the beam ports are protected from neutrons and x rays by neutronically thick Flibe jets. Counter-rotating shutters protect the beam tube from Flibe splash and vapor.

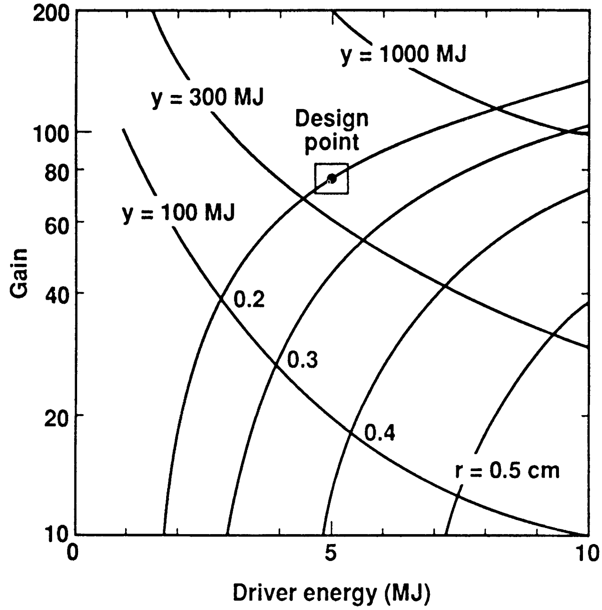

FIGURE 4 Target gain vs driver energy for various beam spot sizes. The gain curves are more fully discussed in Ref. 2 and a reference therein. The half angle was zero, the beam ion was $^{200}HG_g^+$ at 10 GeV with a range of 0.1 g/cm^2.

but dose to the conductor and insulator will dictate its lifetime. We have provided over 1 m of line-of-sight shielding against 14-MeV neutrons from the target. In the model being used for the Monte Carlo neutron shielding calculation shown in Figure 6, we have only 30 mm of shielding from multiple-bounce neutrons and their x rays. HIBALL-II[3] used 300 mm shielding. Any increase in shielding from the 30 mm will increase the outer radius of each of the final focusing magnets and therefore the half

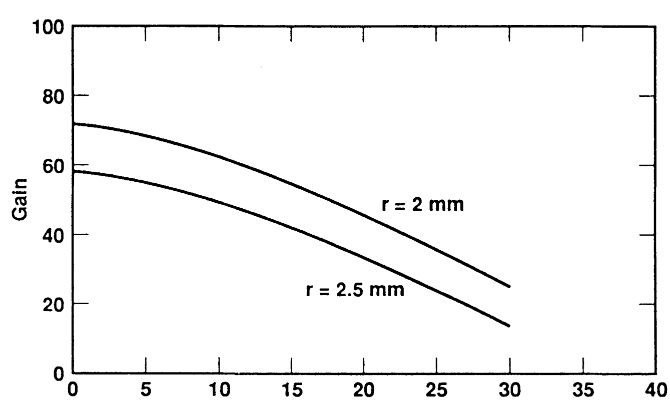

FIGURE 5 As the angle encompassing the beams increases, the target gain drops. The driver energy was 5 MJ and the range was 0.1 g/cm^2.

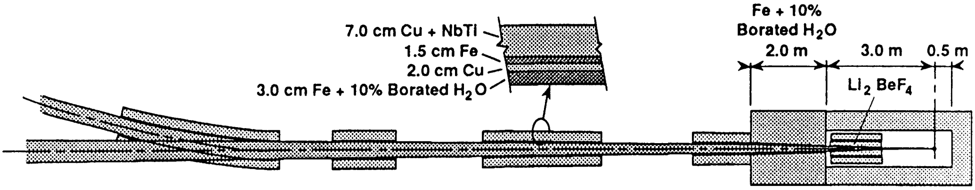

FIGURE 6 Model of beam line for shielding analysis. Neutron shielding of final quadrupole focus for superconducting magnets sets packing and angle between the 12 beams.

angle, thus resulting in reduced gain (Figure 5). Any increase in shielding on the inside of the focusing magnets will move the conductors to a larger radius and a higher field at the conductor will be needed for the same focusing strength. This will drive the cost of the final focusing system up. The shielding calculation and design is an ongoing area of study. If the heating is too much, we will consider normal conducting magnets for the last quadrupole or two in each beam line.

Counter-rotating shutters shown in Figure 3 are provided to prevent or discourage fluorine-lithium-beryllium (Flibe) liquid and vapor from entering the beam tubes. We expect to operate the beam tube walls for a good distance away from the chamber at a temperature above the melting point of fluorine-lithium-beryllium or "Flibe" (460°C) so that the vapor entering the beam tube will condense on the walls and drain to a a collection point. The vapor pressure at 475°C is 0.0013 Pa or $1.25 \times 10^{11}/cm^3$, as shown in Figure 7. This is well below the vacuum propagation density, where so little beam stripping and Flibe ionization occurs that space charge is not neutralized and focusing would not be effected[5].

A set of nozzles in the chamber provides a continuous spray of droplets of cool Flibe at 600°C. Bai and Schrock[4] have shown that the Flibe vapor will condense on the droplets, bringing the pressure (density) close to the vapor-pressure limit in a time fast enough to permit an 8 Hz repetitive rate. At $1 \times 10^{13}/cm^3$ there is predicted to be partial neutralization in the chamber and therefore some defocusing and an increase in spot size[5]. Another analysis[6] predicts propagation at a density of $1 \times 10^{14}/cm^3$. In HIBALL-II[3] the required density for propagation was 4 to $8 \times 10^{10}/cm^3$. In HILIFE-II we can have higher density because the distance to the target is shorter, we allow some partial neutralization defocusing and Flibe has less stripping due to the lower atomic number. Lower temperature Flibe spray than 600°C near the beam path can depress the density if needed. This is an area needing further study.

Other jets of Flibe that are neutronically thick (50 cm) are directed horizontally and vertically around the 12 beams and the target injection port (Figure 3), so as to protect the walls immediately around the ports from neutron and x-ray damage. The set of jets makes the chamber wall a lifetime component (30 y). The jets also protect nozzles and manifolds that are closer to the neutron source and therefore see a higher flux of neutrons. More design and analysis will be needed to determine the thickness of the jets that is required to ensure adequate component lifetime.

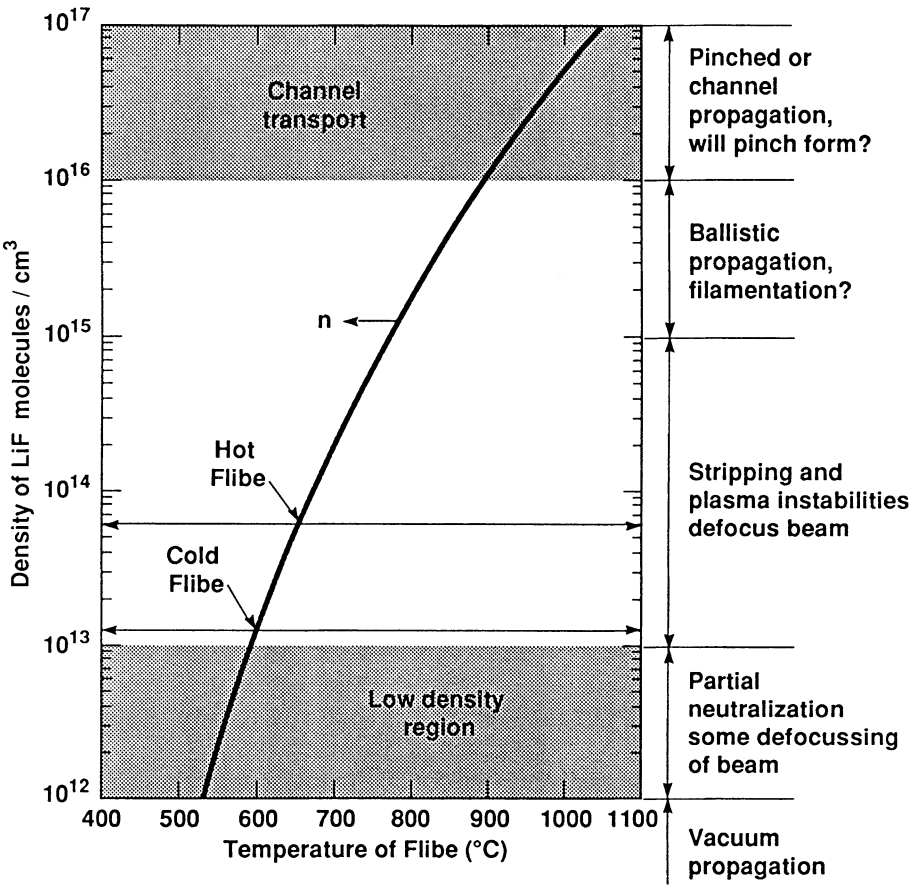

FIGURE 7 Density of LiF molecules determined by vapor pressure of Flibe (Li_2BeF_4). Condensation of Flibe vapor on Flibe droplets might permit beams to propagate, allowing an 8 Hz repetition rate unless chemical and kinetic effects are limiting.

3 CONCLUSIONS

Twelve heavy-ion beams are focused on a target in the HYLIFE-II reactor chamber. Provisions are made to:

- shield the final focus magnets (calculations in progress)
- provide fast rotating shutters to keep liquid and debris out of the beam tubes
- pump Flibe vapor by condensation on cool liquid droplets to permit propagation of the beam at an 8 Hz repetition rate
- shield the beam ports and all structures with neutronically thick Flibe jets

The ± 9-deg half angle between the 12 beams is predicted to degrade the target gain by 16%. A 3-m difference in path length permits delaying beam arrival times up to

30 ns relative to each other so that the desired pulse shape can be obtained by compressing, delaying, and stacking the 12 beams.

A self-consistent driver/reactor interface design is presented but is not yet complete enough to evaluate feasibility and cost. The shielding design could seriously impact the cost of electricity from the plant by adding cost for the final focusing system and by increasing the angle of the beams which degrades target performance. We have shown how the final focusing system affects target design and performance through the beam angle effect on target gain. Other effects such as one-sided versus two-sided illumination have a strong coupling with beam interface design. Clearly much more study is needed.

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REFERENCES

1. R. W. Moir, "HYLIFE-II inertial confinement fusion reactor design," *Fusion Techno.*, **19**, 617 (1991).
2. R. W. Moir, "HYLIFE-II inertial confinement fusion power plant design," these *Proceedings.*
3. B. Badger *et al.*, *HIBALL-II—An Improved Conceptual Heavy Ion Beam Driven Fusion Reaction Study*, University of Wisconsin report UWFDM-625 (1984), Kfk-3840 and FPA-84-4.
4. R. Y. Bai and V. E. Schrock, "An approximate method for analyzing transient condensation on spray in HYLIFE-II," *Fusion Technol.*, **19**, 732 (1991).
5. B. Langdon, "Chamber propagation," these *Proceedings.*
6. Hubbard, R. F., "Target chamber propagation of heavy ion beams in the pressure regime above 10^{-3} Torr," these *Proceedings.*