Heavy-Ion Fusion Final Focus Magnet Shielding Designs

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ABSTRACT

At the Thirteenth International Symposium on Heavy Ion Inertial Fusion (HIF Symposium), we presented magnet shielding calculations for 72-, 128, 200, and 288-beam versions of the HYLIFE-II power plant design.[1-2] In all cases, we found the radiation-limited lifetimes of the last set of final focusing magnets to be unacceptably short.[1] Since that time, we have completed follow-on calculations to improve the lifetime of the 72-beam case. Using a self-consistent final focusing model, we vary parameters such as the shielding thicknesses and compositions, focusing length, angle-of-attack to the target, and the geometric representation of the flibe pocket, chamber, and blanket. By combining many of these shielding features, we demonstrate a shielding design that would enable the last set of final focusing magnets to survive for the lifetime of the power plant.

I. INTRODUCTION

In previous work, we found that our point-of-departure final focus magnet lifetimes were unacceptably short.[1,3] In this work, we concentrate on improvement of the magnet lifetime for a self-consistent, 72-beam case. In Section II, we discuss the various shielding components and their effect upon the magnet lifetime. In Section III, we show results for cases in which multiple shielding features have been implemented in combined calculations. Section IV discusses three-dimensional effects in the flibe pocket, chamber, and blanket. Finally, in Section V, we draw conclusions from this work and suggest directions for future research.

In our estimation of the magnet lifetimes, we adopt two key limits: (1) the maximum dose (sum of neutron and gamma doses) to the insulators, and (2) the maximum fast neutron fluence to the superconducting materials. In this work, we conservatively use an insulator dose limit of 100 MGy for polyimide as suggested by Sawan and Walstrom.[4] This value is conservative in that a value as high as 4000 MGy may actually apply for an insulator that is not subjected to tensile stresses.

For NbTi, we adopt the fast ($E_n \geq 0.1$ MeV) neutron fluence limit of 10^{19} n/cm^2 that is suggested in the review paper by Sawan and Walstrom.[4] This assumes a 70% recovery from annealing after a fluence of 3×10^{18} n/cm^2.[4] Obviously, one would also need to ensure that the time between required anneals was not too short.

Figure 1 is a schematic of the beam-chamber interface. This schematic defines some useful terms that are used later in this work. As a beam approaches the target chamber, it passes through the last focusing magnet. It then goes through an opening in the blanket and first wall. Next, it passes through an opening in the flibe cross jets. Finally, it reaches the minimum spot size at the target. To ensure that a beam does not strike either solid structural material or a liquid jet, we assume a minimum beam clearance of 5 mm. The heavy-ion beams have a radius of ~ 5 cm within the last magnet and are focused down to ~ 2 mm at the target.

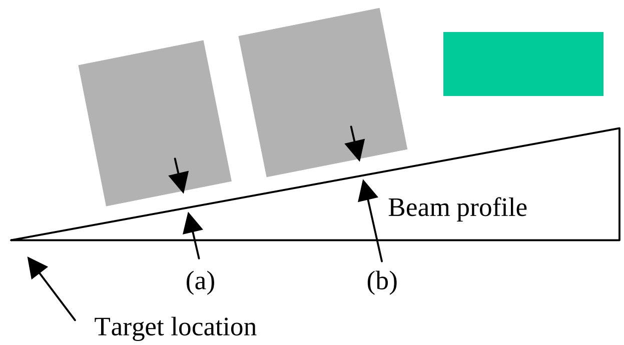

Fig. 1. Heavy-ion beams must avoid liquid jets and solid structures as they converge upon the target. Clearances are defined: (a) beam-to-flibe, and (b) beam-to-structure.

The first wall radius is 3 m. The flibe pocket begins 1 m from the target and provides a line density of 56 cm of flibe before the first wall. Finally, the center of the magnets sit from 5-7 m from the target. Even in the closest case, there is nearly 1 m of space between the back of the blanket and the front of the magnets. Some of this space will be needed for vacuum systems and beam neutralization. These components (and limitations they impose on shielding) will be included in future work.

Figure 2 shows the various parts of the final focusing magnets. Our calculations model the magnets using concentric cylinders that are 1 meter in length. The magnet build includes structure/cooling regions, inner bore shielding, the coil (modeled as 40% by volume NbTi superconductor, 40% Cu stabilizer, and 20% liquid He), structural banding (steel), and exterior shielding.

As parameters such as the magnet stand-off distance and spot size at the target are varied, the magnet build is calculated using a self-consistent model for the final focus system. Details of this model are given in ref. 5.

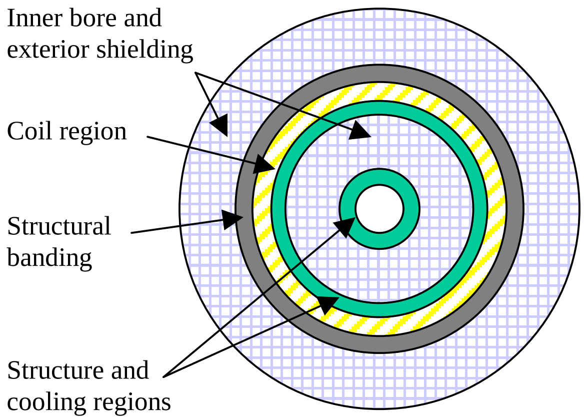

Fig. 2. The final focusing magnets have been modeled as several concentric cylinders that are 1 m in length.

II. SHIELDING FEATURES AND RESULTS

The importance of many different shielding features was analyzed for the present work. We investigated, for example, the importance and cause of cross-talk between neighboring beamlines, the effect of shielding position, thickness, and composition, and the importance of magnet focusing length, beam clearances from shielding components and/or liquid jets, shielding provided by structural supports, and the areal density of the target.

Table I lists various parameters used for the basecase calculation. These parameters led to a design with a magnet lifetime of 0.6 full-power-years (FPY) based upon the fast neutron flux to the NbTi superconductor or 2.6 FPY based upon the total dose to the insulators.

Table I. Parameters used for basecase calculation

Parameter	Value
Inner bore shielding	5 cm tungsten
Exterior shielding	None
Frontal shielding	None
Flibe pocket	Spherical shell
Chamber & blanket	Spherical shell
Target	Monoenergetic (14.1 MeV) point neutron source
Focusing length	5.5 m (magnet goes from 5-6 m)
Beam-to-structure and beam-to-flibe clearances	5 mm
Magnet packing	Closest possible

A. Cross-Talk

An interesting result from the HIF Symposium was the strong peaking of the fast neutron fluence observed in the center of the magnet array. Since this appears to result from a coupling between neighboring magnets, we dubbed the effect "cross-talk." Figure 3 shows the annual fast neutron fluence as a function of magnet rows and columns. The four corner magnets have an average result of 9.61×10^{18} n/cm^2-y, but the centermost magnets have a fluence of 2.22×10^{19} n/cm^2-y (a lifetime of only 0.45 FPY). This, however, does not resolve whether the effect is due primarily to scattering between magnets or scattering between penetrations (particles scattered from the edge of one penetration into a neighboring one).

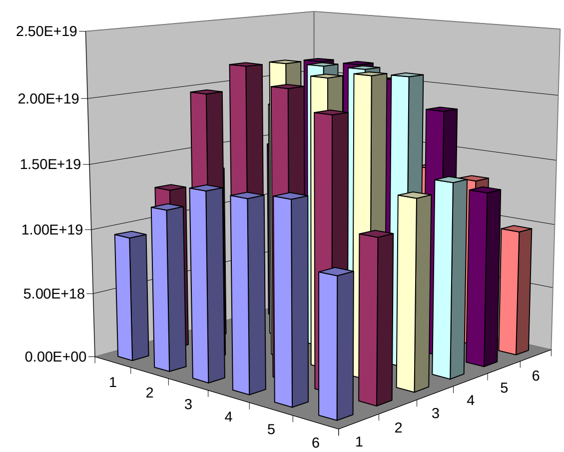

Fig. 3. Strong peaking of the annual fast neutron fluence (units are n/cm^2-y) is observed at the center of the array.

To determine which effect dominates, we ran a case with only a single magnet and a single penetration. This produced a fluence that was 8.7× lower than that of the centermost magnets in the basecase. As a second test, we considered a case with a single penetration but we restored all 72 magnets. This increased the fluence by 24%—still 7.0× lower than the corner magnets in the basecase. We infer from this that scattering in the flibe pocket dominates. The presence of neighboring magnets is a relatively small factor.

Given that scattering in the flibe pocket seems to dominate the "cross-talk" effect and that high-energy neutron scattering is strongly forward-peaked, we investigated the angle between neighboring magnets. In previous cases, magnets were packed as close as possible in order to minimize the array size (the angle from the center to corner beams). In doubling the angle between neighboring magnets (the space between was filled with shielding), we found that the ratio between the fluence at the center of the array and at the corners fell to only 1.1, and the overall average fell by 1.9×. With a more modest angle increase of 50%, the overall average still fell by 1.7×—this seems to be a reasonable compromise between the array angle and magnet lifetime (current target designs favor smaller array angles)

B. Capture Zones

By using *capture zones* one can determine which parts of a problem have the greatest impact on the overall result. Whenever a particle enters a capture zone it is destroyed, and thus, may not reach a particular region to cause an effect. By studying capture zones we learned, for example, that the majority of the dose and neutron fluence reach the superconducting coils by way of the exterior banding. Use of a capture zone at the exterior of each magnet reduced the coil fluence by 5× and the total coil dose by 4×, while use of an interior capture zone reduced the fluence and total dose by 2.4× and 1.5×, respectively. As a result of these findings, subsequent calculations included both interior and *exterior* shielding. Finally, we found that frontal shielding can only reduce the dose to the superconductors by a factor of two.

C. Focusing Length

The distance from the center of the target chamber to the center of a final focusing magnet would appear to be an important consideration for shielding of the magnet. From a geometric point-of-view, however, we found the results to be relatively insensitive to the focusing length. The basecase assumed a focusing length of 5.5 meters. Making the focusing length 1 m shorter reduced the lifetime by 10-20%, while increasing the focusing length by 1 m increased the lifetime by only 2-8%. It should be noted, however, that these calculations account only for geometric factors—one could fill newly available space with additional shielding.

D. Shield Thickness and Composition

We investigated an increase in the thickness of the inner bore shielding. Our results indicate that each 5 cm of tungsten shielding lead to roughly a factor of two reduction in both the fluence and total dose. Unfortunately, as shown in Fig. 4, the solid-angle subtended by the overall array increases at close to the same rate. Additionally, the addition of inner shielding results in a need for higher magnetic fields, which, in turn, require more core material and increased banding. These factors work to increase the overall array angle. An increase in the array angle reduces the effectiveness of the thick-liquid shielding and stresses compatibility with currently available target designs. It is clear that simply adding more shielding is not an effective solution for current accelerator designs with tens to hundreds of beams.

Because two criteria are being used to estimate the final focus magnet lifetime, a balance between the total dose to the insulator (dominated by gamma-rays) and the fast neutron fluence in the superconductor needs to be achieved. The basecase design, for example, results in a magnet lifetime prediction of 2.6 FPY based upon the total dose but only 0.6 FPY based upon the fast neutron fluence. By modifying the shielding composition, we seek a balance between these two effects and increase the overall magnet lifetime.

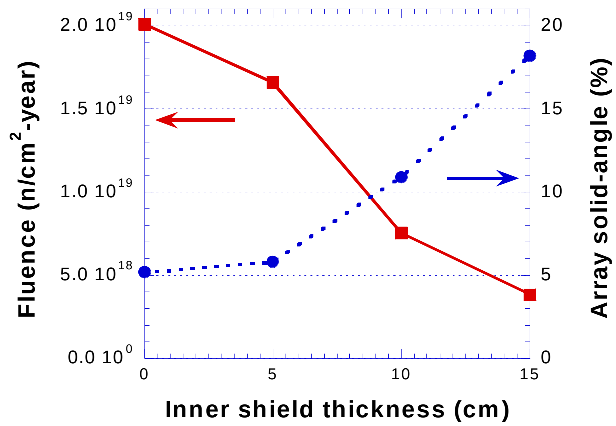

Fig. 4. Adding inner bore shielding reduces the fast neutron fluence but increases the array size.

A number of shielding compositions were analyzed. Each used 5 cm each of inner bore and exterior shielding. Materials considered include tungsten, boron carbide, and three proprietary materials produced by Reactors Experiments, Incorporated: a tungsten impregnated-polyethylene, a titanium-hydride-polyethylene, and a tungsten-titanium-hydride polyethylene. Table II summarizes the results from eight different calculations that were completed to explore this parameter space.

Table II. Magnet lifetimes for various shield designs

Shielding material (inner/outer)	Magnet lifetime (FPY) based upon...	
	Total dose	Neutron fluence
5 cm W each	5.8	0.9
5 cm B_4C each	2.2	1.8
5 cm B_4C / 5 cm W	3.0	1.5
5 cm W / 5 cm B_4C	4.0	1.3
4 cm B_4C + 1 cm W each	3.2	1.7
5 cm W-poly each	4.0	2.6
5 cm Ti-hydride-poly each	1.2	3.3
5 cm W-Ti-hydride-poly each	3.0	2.8

E. Beam Clearances

It is impossible to place heavy-ion beams arbitrarily close to rapidly flowing liquids or even solid structural materials. The self-consistent final focusing design model assumes a beam pipe clearance equal to 25% of the maximum beam radius plus 5 mm. We initially assumed a clearance of 5 mm would also be needed between the beams and flibe jets or the shielding block. A smaller clearance translates directly into more efficient shielding of the final focusing magnets. Figure 5 shows that elimination of the clearances reduces both the total dose and fluence by more than 2×. Increasing the clearances from 5 mm to 1 cm would increase these metrics by ~ 1.8×. Additional work has shown that the key clearance distance is the beam-to-structure clearance distance;

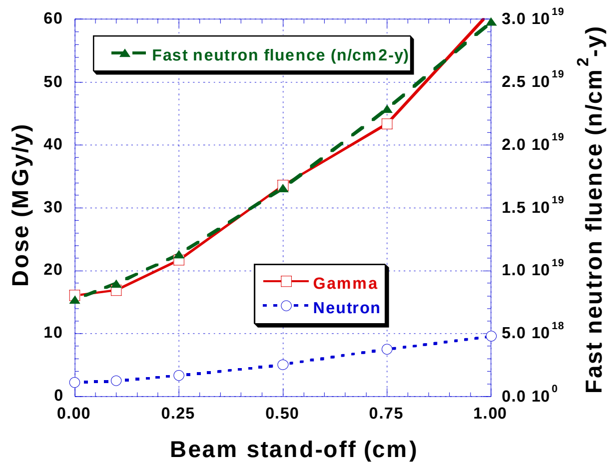

Fig. 5. Eliminating the clearance between the beams and shielding would increase magnet lifetime by ~ 2.2× in the basecase shielding.

the beam-to-flibe clearance does not appear to be important in determining the magnet lifetime.

It is not clear at this time whether the clearance distance can be reduced or even if it is adequate. Future work will seek to address this issue. For now, we will continue to use a 5 mm assumption.

F. Other Effects

In the above calculations, the entire magnet array was modeled as if it was floating in space—no credit has been taken for incidental shielding provided by the structural supports. Introduction of an "egg-crate" structure for support of the magnet array does, in fact, provide significant shielding benefits. Use of a boron carbide structure reduced the fast neutron flux by 40% and the total dose rate by more than 20%. Optimization of the egg-crate needs to be performed in concert with the rest of the shielding design.

The effects of the areal density (ρr) of the target were not initially taken into account. For a ρr of 3 g/cm^2, we find that the fast neutron flux falls by 10%, while the total dose rate falls by 14%.

III. COMBINED FEATURES

The next step in our analyses was to run several cases in which we combined various shielding features in an effort to increase the magnet lifetime.

In the first combined case, we used a 6.5 m focusing length with the space between the back of the blanket and the magnets filled with borated water. Tungsten was used for both inner and outer bore shielding (5 cm each). A beam stand-off distance of 5 mm was assumed, and a boron carbide egg-crate was included. Based on the total dose, we predict an average magnet lifetime of 20.6 FPY. The fast neutron fluence, however, leads to a lifetime of only 2.9 FPY.

In case #2, we included the target ρr, used a more detailed model for the flibe pocket, removed the borated water, added 30 cm of tungsten-polyethylene shielding in front of the magnet array, and increased the spacing between magnets by 50%. The inner and outer bore shielding was maintained at 5 cm each, but the composition was altered to be 1 cm of tungsten and 4 cm of tungsten-polyethylene. The fluence-base lifetime increased slightly to 3.4 FPY, but the dose-based lifetime fell significantly to only 5.6 FPY.

In case #3, we only changed the frontal shielding. The thickness was increased from 30 to 120 cm and the composition went from tungsten-polyethylene to alternating layers of 10 cm tungsten and 20 cm of Ti-hydride-polyethylene. The dose-based lifetime rebounded somewhat to 13.6 FPY, and the fluence-based lifetime increased by 2.4× to 8.2 FPY.

We continued to try and reduce the fast neutron flux by switching the inner and outer bore shielding to Ti-hydride-polyethylene. The egg-crate was switched from B_4C to tungsten to try and make back more of the dose-based lifetime. The fluence-based lifetime indeed increased to 9.9 FPY, but the dose-based lifetime fell again to only 7.8 FPY. Case #4 was viewed as a failure, and we moved back to the design in case #3.

Case #5 varied from case #3 in the composition of inner and outer bore shielding. The shielding was layered to include 3 cm of tungsten-polyethylene sandwiched between two 1-cm-thick layers of tungsten. This case was quite an improvement with a fluence-based lifetime of 14.1 FPY and a dose-based lifetime of 28.2 FPY.

Finally, we reduced the beam clearances from 5 mm to only 1 mm. This produced long-lived magnets—31.7 FPY based upon fluence and 65.2 FPY based upon dose. Interactions with the accelerator community are needed to establish minimum clearances.

IV. THREE-DIMENSIONAL MODELS

In all calculations described up to this point, the flibe pocket has been modeled using simple approximations. Additionally, the first wall and blanket were modeled using spherical shells. As a next step, these components were modeled in greater detail.

A. Flibe Pocket

In the earliest calculations, the flibe pocket was modeled as a 60-cm-thick spherical shell with conical penetrations. In the second combined case, this was improved to rectangular slabs that more closely resembled the intended liquid geometry. Finally, we switched to a 3-D model for the liquid geometry. The first 3-D model for the flibe pocket produced an average magnet lifetime of 143 FPY based upon the total dose rate and 84.6 FPY based upon the fast neutron fluence. We discovered, however, that the flibe pocket was too "leaky." Neutrons scattered out of the cross-jet region, and the activation of the first wall increased by a factor equal to the increase in the magnet lifetime. To rectify this problem, we simply added additional flibe to the edges of the cross-jets. Figure 6 is a representation of the flibe pocket with the beam-paths shown as solid objects.

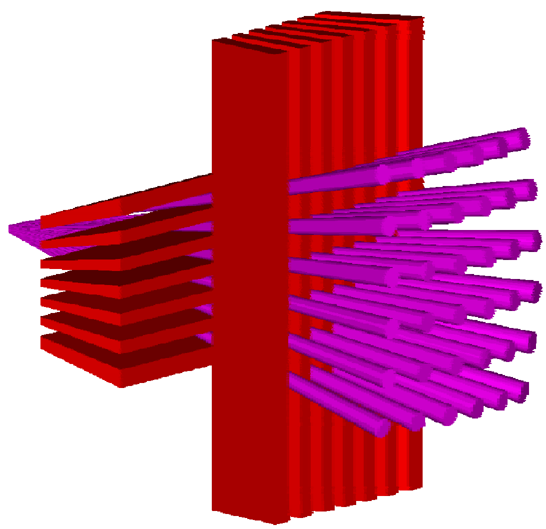

Fig. 6. The heavy-ion beams fit through the openings between horizontal and vertical flibe jets.

The 3-D representation of the flibe pocket improves the magnet shielding. With simple shell or slab approximations, the pocket forms a near-perfect collimator and particles are forced towards the magnet array. With discrete jets, however, the flibe pocket allows particles to scatter out of the general direction of the magnet array. Despite this, first wall activation is as low as in the earlier calculations—the remaining flibe regions absorb the scattered neutrons. The dose-based lifetime is 154 FPY, and the fluence-based lifetime is 96.9 FPY.

B. Chamber and Blanket

Our next step was to use a 3-D model for the HYLIFE-II chamber and blanket. Figure 7 shows the final model. Interestingly, the move to a detailed chamber/blanket model reduced the average magnet lifetime by ~ 30%. The lifetimes are 112 FPY based upon dose and 65.9 FPY based upon fluence. This is believed to be due, in part, to geometric considerations. Although the solid-angle fraction is held constant, the actual wall area of the penetrations is larger for the 3-D chamber due to the angles above and below the equator of the cylindrical section. For a spherical shell, this effect does not exist—all beams strike the wall at the same distance from chamber center.

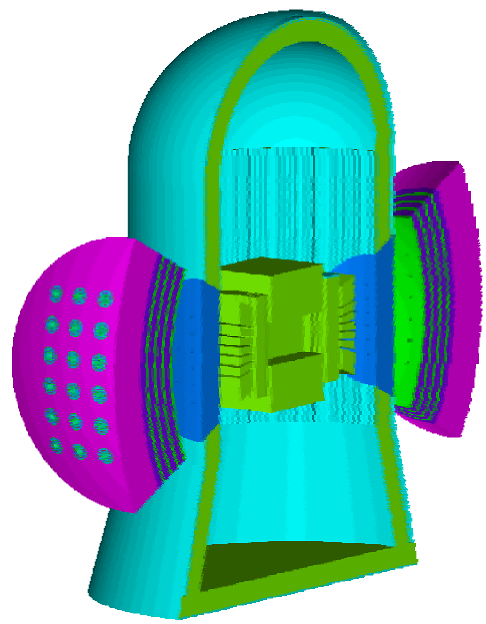

Fig. 7. The 3-D magnet shielding model includes many shielding features.

As the next round of calculations was completed, it became clear to us that the accelerator community was uncomfortable with our beam clearance assumption of only 1 mm. We restored the original 5 mm clearance and repeated the calculation. We calculate a magnet lifetime of 49.7 and 28.7 FPY with dose and fluence limits, respectively. If we modified the shielding to obtain a balance between the dose and fluence constraints, we would expect a lifetime of ~ 39 FPY—more than the expected power plant lifetime.

C. Cylindrical Cross Jets

One final set of calculations was performed for this work. Per Peterson of the University of California at Berkeley has proposed that the cross-jets should be made of cylindrical jets instead of rectangular slabs.[6] Potential advantages of cylindrical jets include less ripple (due to boundary layer trimming) and the ability to correct for pointing errors via flow control of individual nozzles.[6] Fig. 8 shows one cylindrical cross jet configuration.

Our calculations show that cylindrical jets protect the magnets as well as rectangular slab jets. The dose-based lifetime is estimated at 51.1 FPY, while the fluence-based lifetime is 28.5 FPY. Achieving a balance between the total dose rate and fast neutron flux should yield a magnet lifetime of ~ 40 FPY.

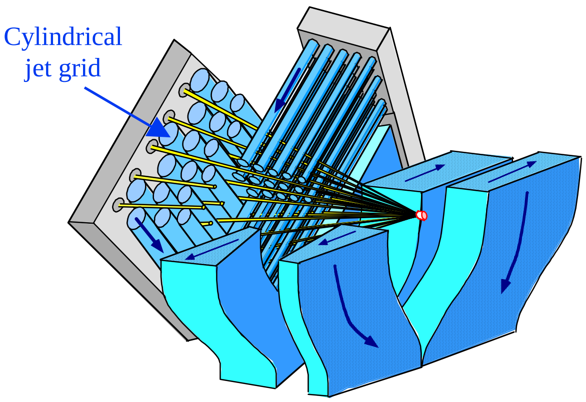

Fig. 7. The heavy-ion beams fit through the openings between horizontal and vertical flibe jets.

V. CONCLUSIONS AND FUTURE WORK

In the present work, several important conclusions have surfaced. One of the most important considerations in the calculation of the magnet lifetime is the clearance between the beams and shielding structures. We will work with members of the accelerator community to better define the limitations in this parameter and determine what level of improvement is feasible.

The models used here have only included the last set of magnets. In previous work, backscattering from the other magnets was determined to contribute only 10% to the dose rate and flux at the last set of magnets.[3] In future work, we will include the additional magnets to ensure that our shielding modifications do not increase the importance of backscattering. Additionally, future work will include variations in the total dose and fast neutron flux along the length of the magnet.

In ref. 3, it was noted that the use of tapered shielding along the inner bore was not effective in reducing radiation levels--this conflicts with findings in the HIBALL study.[7] We believe this discrepancy is due to the fact that HIBALL had only twenty beams and more inner bore shielding. As a result, it was relatively easy to produce highly collimated beams of radiation and tapering would be more effective. Future work will seek to resolve this discrepancy.

Cylindrical jet arrays appear to be quite attractive. We will complete additional assessments for cylindrical configurations that have higher liquid packing fractions.

Although our last few analyses suggest magnet lifetimes in excess of 30 FPY (the plant lifetime), they are inconsistent with current target requirements. Specifically, the angle of the magnet array is too large to meet the entrance angles for either the hybrid or close-coupled target designs. These designs are, of course, continuously being improved. The target designers are attempting to increase the angles, and we will try to reduce the radial build of the magnets to allow a smaller array angle.

We are working with the other stakeholders to develop a self-consistent design for the final focusing system. This design must meet the thermal hydraulics constraints while satisfying target, accelerator, economics, and, of course, shielding requirements.

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