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NUCLEAR ASSESSMENT OF FINAL OPTICS OF A KrF LASER DRIVEN FUSION POWER PLANT

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In the HAPL program, power plant designs are assessed with targets driven by 40 KrF laser beams. The final optics system that focuses the laser onto the target may include a grazing incidence metallic mirror (GIMM) located at 24 m from the target with 85° angle of incidence. The GIMM is in direct line of sight of the target and has a 50 micron thick aluminum coating. Two options were considered for the substrate material; SiC and AlBeMet. The impact of the GIMM design options on the nuclear environment at the dielectric focusing and turning mirrors was assessed. Using AlBeMet results in about a factor of two higher neutron flux. We considered beam duct configuration modifications such as utilizing neutron traps to reduce radiation streaming. In addition, we investigated the impact of lining the beam ducts and neutron traps with different materials that help slowing down and absorbing neutrons.

I. INTRODUCTION

The High Average Power Laser (HAPL) program aims at developing laser inertial fusion energy based on direct drive targets and a dry wall chamber.[1] The final optics system that focuses the laser onto the target includes grazing incidence metallic mirrors (GIMM) located at 24 m from the target with 85° angle of incidence. The use of the GIMM was first proposed by Bieri and Guinan[2] as a solution to the problem of protecting the final focusing mirrors from neutron damage. These mirrors are placed out of the direct line-of-sight of the target. However, secondary neutrons resulting from interactions of the streaming source neutrons with the GIMM and the containment building can result in significant flux at the final focusing mirrors. To reduce the secondary neutron flux and increase the lifetime of the mirrors, neutron traps can be utilized in the containment building. This approach was found to significantly help reduce neutron streaming and damage in the final focusing mirrors[3,4] and is adopted for the HAPL final optics. It was suggested also in previous analysis that lining the beam ducts with a strong neutron absorber could reduce neutron streaming.[5] In this paper, we present the results of a two-dimensional (2-D) neutronics analysis of the final optics system of HAPL with different GIMM design options. We assessed the impact of the GIMM design options and duct lining on neutron streaming and nuclear environment at the dielectric final optics.

II. DESCRIPTION OF FINAL OPTICS SYSTEM

The plasma-facing final mirror, denoted M1, has to be sufficiently far from the plasma to withstand the neutron flux for several years without significant degradation of its reflectivity or optical quality. It also has to be protected from the impact of fast ions by a magnetic field region somewhere between the plasma and M1. Its size is determined by the need for the laser fluence on the mirror to be below the long-term optical damage threshhold, and the "f-number" requirement on the focused beams. A trial optical system under consideration comprises a planar GIMM in the M1 location, with the more difficult focusing function reserved for the M2 or even M3 location not directly in line-of-sight of target. Additional requirements on all elements in the final optical train relate to the need for a high degree of mechanical stability, and ease of access from outside the containment building via robotics. Mirror M1 must not be too costly to replace or refurbish when required.

In Fig. 1 the final three optical elements of a possible design are sketched. The optical beam cross section is rectangular, with a high aspect ratio of 6. With such a ratio the length of the GIMM is reduced to the point where the aspect ratio of the GIMM itself is of the order of unity, and by choosing the vertical orientation the design of flow within the blanket is simplified considerably. The arrangement shown in Fig. 1 has the GIMM embedded within the wall of the main containment vessel, to trap neutrons scattered from the GIMM and at the same time provide stable support. There is a "neutron trap" directly behind the GIMM with at least 3 m depth. A secondary trap is included behind the focusing dielectric M2 to further attenuate the neutron beam scattered from the GIMM. Although in Fig. 1 the optical beam is only 30 cm wide at the blanket, its vertical extent is six times this. In this design, mirror M3 is a plane turning mirror that connects the optical path to the "equatorial plane" of the reactor, where major groups of laser beams are incident from laser amplifiers located on that floor. This final section of the optical beamline is repeated 40 times at locations around the sphere of the containment structure, to achieve acceptable irradiation uniformity on target.

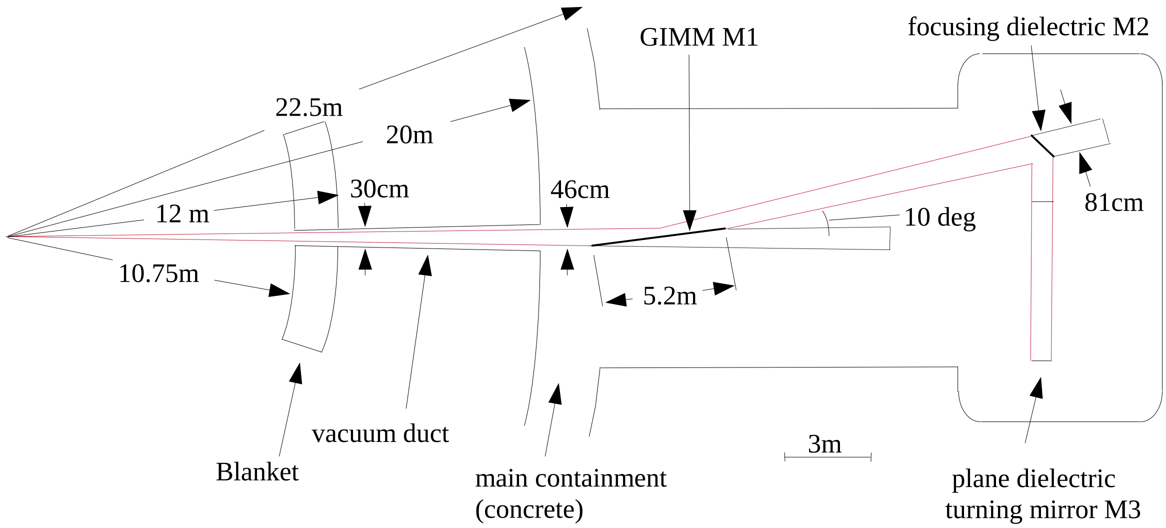

Fig. 1. Plan view of a "low latitude" optical beamline. Vertical scale increased for clarity.

III. CALCULATION PROCEDURE

Two-dimensional (2-D) neutronics calculations were performed in R-Z geometry to compare the impact of the GIMM design option and duct lining on the radiation environment at the mirrors in the HAPL final optics system. The TWODANT module of the DANTSYS 3.0 discrete ordinates particle transport code system[6] was used to perform the neutronics calculations utilizing the FENDL-2 nuclear data library.[7] The Z axis is along the beamline. A 0.6 m thick self-cooled lithium/ferritic steel blanket[8] is used with inner surface at 10.75 m from the target. The blanket is followed by a 0.5 m thick SS/B_4C/He shield. The detailed layered radial build of blanket/shield was included in the model. The target is represented by a point source at the center of the chamber emitting neutrons with a softened energy spectrum resulting from interactions between fusion neutrons and the dense target materials. The reference HAPL target yield is 367.1 MJ.[9] For a repetition rate of 5 Hz, this corresponds to a total fusion power of 1836 MW. The target emits 1.4×10^{20} neutrons per shot with an average energy of 12.3 MeV. In addition, 1.7×10^{16} gamma photons with an average energy of 6.1 MeV are emitted from the target. The neutron wall loading at the first wall (FW) is 0.94 MW/m^2.

Due to the 2-D modeling limitation, circular GIMM, beam port, and neutron trap were used with the area of beam port preserved. The GIMM has an angle of incidence of 85° with its center located at 24 m from the target. The beam port at the chamber wall is modeled as a circular port with 0.225 m radius. The GIMM was modeled as circular with 0.45 m radius and effective thickness as seen by source neutrons (effective thickness = actual thickness/cos85). Neutron traps were utilized behind the GIMM and the focusing dielectric mirror M2 as shown in Fig. 2. The containment building housing the optics and neutron traps consists of 70% concrete, 20% carbon steel C1020, and 10% H_2O.

Two lightweight GIMM design options were considered. Both options have 50 micron thick Al coating. One option uses SiC substrate and the other uses the Al alloy AlBeMet162 (62 wt.% Be). The substrate consists of two faceplates surrounding a foam of the same material with a 12.5% density factor. The foam is actively cooled with slow-flowing helium gas. The total thickness of the SiC GIMM is 1/2" while the AlBeMet GIMM has to be thicker (1") to achieve similar stiffness.[10] The total areal densities of the SiC and AlBeMet GIMMs are 12 and 16 kg/m^2, respectively.

IV. IMPACT OF LINER MATERIAL CHOICE

We investigated the impact on neutron streaming of lining the inner surface of the duct and neutron traps with strong neutron absorbers. Lining materials considered included boral (a mixture of Al/B_4C), borated polyethylene with 10% B, boron hydride ($B_{10}H_{14}$), and WC. A 1 cm thick liner was used. The option of adding 5% boron to the concrete shield was also investigated. The calculations were performed using the SiC GIMM design option and the values of total neutron flux, fast neutron flux (E>0.1 MeV), gamma flux, and nuclear heating at M2 and M3 were determined and compared to the case without liner or added boron. The results are summarized in Fig. 3 for M2.

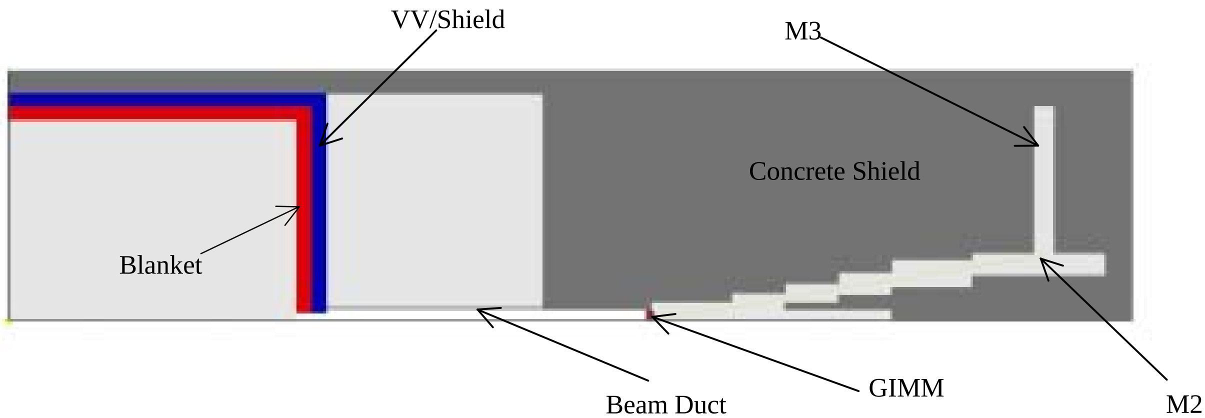

Fig. 2. Vertical cross section in the 2-D neutronics model.

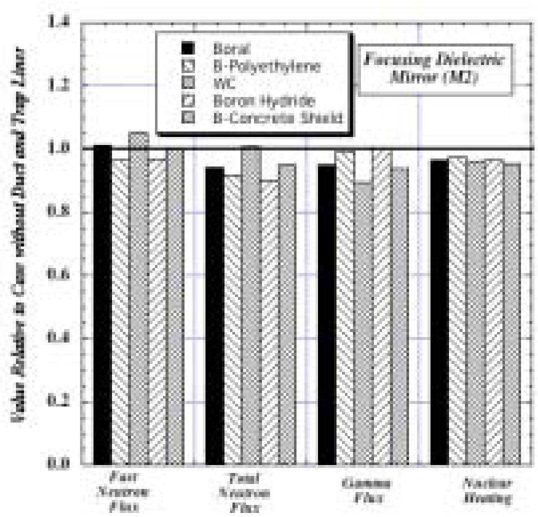

Fig. 3. Impact of liner choice on radiation level at M2.

Boron is more effective in reducing the low energy component of the neutron flux with modest effect on the fast neutron flux and gamma flux. Heavy material such as WC is effective only in reducing the gamma flux. Materials rich in hydrogen and boron (boron hydride, borated polyethelyne) have the best impact on fast neutron flux (due to neutron slowing down by hydrogen) that is believed to impact optics lifetime. However, the concern is the survivability of these hydrogenous materials in the severe irradiation environment. In addition, the effect at M2 is very small since the flux is dominated by the neutrons scattered from the GIMM with smaller contribution from the neutrons scattered from the duct wall. The effect at M3 is enhanced due to the significant contribution from neutron scattering from the duct between M2 and M3. The fast neutron flux at M3 is reduced by a factor of ~2 when boron hydride or borated polyethylene lining is used. Since the flux at M3 is several orders of magnitude smaller than that at M2, the factor of 2 flux reduction at M3 does not justify the added design complexity. Hence, no duct lining will be utilized in the HAPL optics system.

V. NUCLEAR ENVIRONMENT AT THE GIMM

Table I lists the calculated neutron and gamma fluxes at the front surface of the GIMM for the two design options. The contribution to neutron flux at the GIMM from scattering inside the target chamber is small, amounting to <3%. Up to 37% of the fast neutron flux in the AlBeMet GIMM is contributed from scattering in the GIMM itself with smaller contribution in the SiC GIMM. It is clear that the material choice and thickness impact the peak flux at the GIMM. The neutron flux is higher for AlBeMet (due to Be(n,2n) reactions) and the gamma flux is higher for SiC (due to Si inelastic scattering). The neutron spectrum is softer for AlBeMet with 86% of the neutrons above 0.1 MeV compared to 95% for SiC. The power density in the front faceplate of the GIMM is slightly higher for SiC (0.68 compared to 0.55 W/cm^3 for AlBeMet) with larger gamma contribution. For the 1.2 mm thick SiC faceplate, the nuclear heating is 82 mW/cm^2 compared to 132 mW/cm^2 for the twice thicker AlBeMet faceplate. This is compared to the heat flux from the laser (22 mW/cm^2) and the x-rays (23 mW/cm^2).

TABLE I. Neutron and Gamma Flux at Front of GIMM

		Flux (cm^{-2}s^{-1})
SiC GIMM	Neutrons E>1 MeV	1.15×10^{13}
	Neutrons E>0.1 MeV	1.27×10^{13}
	Total Neutrons	1.34×10^{13}
	Total Gamma	4.53×10^{12}
AlBeMet GIMM	Neutrons E>1 MeV	1.27×10^{13}
	Neutrons E>0.1 MeV	1.55×10^{13}
	Total Neutrons	1.81×10^{13}
	Total Gamma	2.58×10^{12}

VI. FLUX ALONG BEAMLINE

The neutron and gamma flux was calculated along the beamline in the duct beyond the GIMM. The calculations were performed for both GIMM designs to investigate the impact on the nuclear environment at the dielectric mirrors M2 and M3. Figure 4 shows the fast neutron flux as a function of distance from the GIMM. The neutron flux is higher by a factor of ~2 with the AlBeMet GIMM due to the larger thickness and neutron multiplication in Be. A significant drop in the flux occurs at the beam duct bend around the location of M2. As a result, the peak fast neutron flux at M3 is ~2 orders of magnitude lower than that at M2. The neutron spectrum gets harder in the part of the beam duct approaching M2 that is not in direct view of the GIMM neutron trap with more direct contribution from the GIMM and less from the trap as shown in Fig. 5. Beyond M2, the neutron spectrum softens significantly. The neutron spectrum is slightly softer with the AlBeMet GIMM. Figure 6 shows the gamma flux along the beamline. The gamma flux is comparable up to M2 due to the dominant contribution from the GIMM but is higher at M3 with the AlBeMet GIMM due to the dominant contribution from the gamma generated in the shield by the larger neutron flux. The peak gamma flux at M3 is about an order of magnitude lower than that at M2.

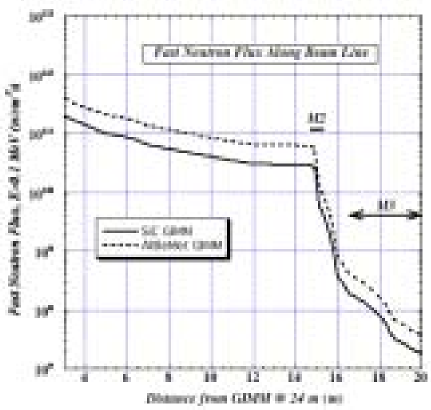

Fig. 4. Fast neutron flux along the beamline.

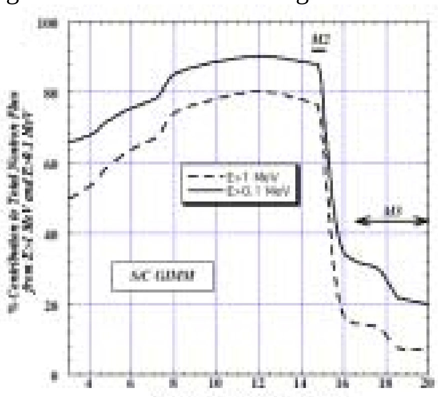

Fig. 5. High energy neutron fraction along beamline.

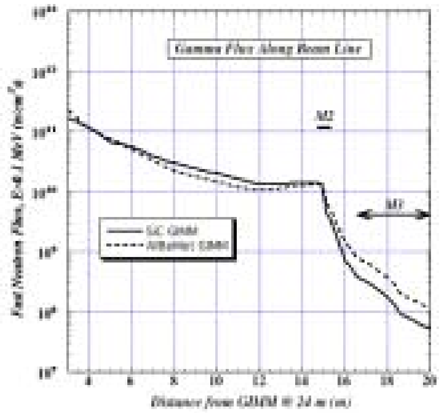

Fig. 6. Gamma flux along the beamline.

VII. NUCLEAR ENVIRONMENT AT THE DIELECTRIC MIRRORS M2 AND M3

Table II gives the neutron and gamma flux values at the focusing dielectric mirror M2 located at 14.9 m from the GIMM. The neutron flux is about a factor of 2 higher with the AlBeMet GIMM. The total neutron and gamma fluxes are more than two orders of magnitude lower than those at the GIMM. The neutron spectrum is relatively hard with ~85% of the neutrons above 0.1 MeV and ~70% above 1 MeV. The gamma flux values are comparable for the two GIMM design options.

TABLE II. Flux at M2

		Flux ($cm^{-2}s^{-1}$)
SiC GIMM	Neutrons E>1 MeV	2.48×10^{10}
	Neutrons E>0.1 MeV	2.85×10^{10}
	Total Neutrons	3.25×10^{10}
	Total Gamma	1.41×10^{10}
AlBeMet GIMM	Neutrons E>1 MeV	5.06×10^{10}
	Neutrons E>0.1 MeV	6.10×10^{10}
	Total Neutrons	7.38×10^{10}
	Total Gamma	1.34×10^{10}

Table III gives the neutron and gamma flux values at the plane dielectric turning mirror M3 located at 1.6-6 m from M2. The neutron and gamma fluxes are about a factor of 2 higher with AlBeMet GIMM. The fast neutron flux is about two orders of magnitude lower than that at M2 with a smaller gamma flux reduction. The neutron spectrum is softer with ~30% of the neutrons above 0.1 MeV and ~15% above 1 MeV.

Table IV gives the power densities resulting from nuclear heating in sapphire for the dielectric mirrors M2 and M3. Nuclear heating in M2 is more than 2 orders of magnitude lower than that in the GIMM. The peak nuclear heating in M3 is about 2 orders of magnitude lower than that in M2. Nuclear heating values in the dielectric mirrors are a factor of 2 higher with AlBeMet GIMM compared to that with SiC GIMM.

TABLE III. Flux at M3

		Peak Flux ($cm^{-2}s^{-1}$)
SiC GIMM	Neutrons E>1 MeV	9.00×10^{7}
	Neutrons E>0.1 MeV	2.01×10^{8}
	Total Neutrons	6.23×10^{8}
	Total Gamma	4.02×10^{8}
AlBeMet GIMM	Neutrons E>1 MeV	1.79×10^{8}
	Neutrons E>0.1 MeV	4.23×10^{8}
	Total Neutrons	1.43×10^{9}
	Total Gamma	8.35×10^{8}

TABLE IV. Nuclear Heating in Dielectric Mirrors

		Nuclear Heating (mW/cm^3)
SiC GIMM	M2	1.73
	M3 Maximum	0.021
	M3 Minimum	0.0021
AlBeMet GIMM	M2	2.69
	M3 Maximum	0.045
	M3 Minimum	0.0052

VIII. SUMMARY AND CONCLUSIONS

The final optics system that focuses the laser onto the target includes a GIMM located at 24 m from the target with 85° angle of incidence. Two options were considered for the GIMM substrate material; SiC and AlBeMet. 2-D neutronics calculations were performed to compare the impact of GIMM design option and duct lining on the radiation environment at the dielectric mirrors. Lining the beam ducts and neutron traps with materials rich in hydrogen and boron (e.g., boron hydride, borated polyethylene) has best impact on reducing fast neutron flux at the optics. However, the effect is very small (<4%) at the focusing mirror M2 but up to a factor of 2 reduction can be obtained at the turning mirror M3. Since the flux at M3 is much smaller than that at M2, the small benefit does not justify the added design complexity. Using AlBeMet GIMM results in about a factor of two higher neutron flux compared to the case with SiC GIMM due to the larger thickness and neutron multiplication in Be. The peak fast neutron flux at M3 is ~2 orders of magnitude lower than that at M2. The neutron spectrum is much softer at M3 with ~30% of the neutrons above 0.1 MeV compared to ~85% at M2. For the worst case with AlBeMet GIMM, the peak fast neutron fluence values per full power year at the GIMM, M2 and M3 are 4.9×10^{20}, 1.92×10^{18}, and 1.34×10^{16} n/cm^2, respectively. The results indicate that a significant drop in the nuclear environment occurs as one moves from the GIMM to the dielectric focusing and turning mirrors in the HAPL final optics system. Experimental data on radiation damage to metallic and dielectric mirrors are essential for accurate lifetime prediction. A three-dimensional model was developed for the system and calculations will be performed to confirm the findings of this analysis.

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