Nuclear Environment at Final Optics of HAPL

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High Average Power Laser (HAPL) Conceptual Design



Large Chamber Design



Design with Magnetic Intervention

Baseline HAPL final optical parameters:

2.5 MJ at 5 Hz, 40 illumination beams each 62.5kJ

2 J/cm² in optical distribution ducts

Duct aspect ratio 6:1, each beam 3x18 beamlets (area of one beam = $3x18x(0.24)^2 = 3.1 \text{ m}^2$)

Focal length 39 m

Vertical "slits" in blanket, total 0.7% of 4π

24 cm x 24 cm beamlet from de-multiplex array



HAPL Final Optics with Grazing Incidence Metallic Mirrors

- Use GIMM as solution to problem of protecting final focusing mirrors from neutron damage
- Dielectric FF mirrors placed out of direct line-of-sight of target
- Secondary neutrons from interactions with GIMM and containment building can result in significant flux at final focusing mirrors
- To reduce secondary flux neutron traps are utilized in containment building
- 3-D neutronics analysis performed for the HAPL final optics system with GIMMs to determine nuclear environment with several GIMM design options
- Large chamber configuration used in analysis but results are applicable to MI chamber



Design Parameters Used in Analysis

Target yield	367.1 MJ
Rep Rate	5 Hz
Fusion power	1836 MW
Chamber inner radius	10.75 m
Thickness of Li/FS blanket	0.6 m
Thickness of SS/B ₄ C/He shield	0.5 m
Chamber outer radius	11.85 m
GIMM angle of incidence	85°
GIMM distance from target	24 m





Baseline HAPL Optics Configuration with GIMM

HAPL GIMM design of 3-31-06





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Detailed 3-D Neutronics Analysis

>3-D neutronics calculation performed to determine nuclear environment at GIMM (M1), focusing mirror (M2), and turning mirror (M3) and compare impact of GIMM design options Used the Monte Carlo code DAG-MCNP with direct neutronics calculations in the CAD model >Modeled one beam line with reflecting boundaries >All 3 mirrors and accurate duct shape (6:1 AR) modeled Neutron traps used behind GIMM and M2 **Four** GIMM design options considered 1 cm thick Sapphire M2 and M3 mirrors modeled Detailed radial build of blanket/shield included in model Containment building (@20 m from target) housing optics with 70% concrete, 20% carbon steel C1020, and 10% H₂O ➤3 cm thick steel beam duct used between chamber and containment building



Geometrical Model Used in 3-D Neutronics Analysis



8

GIMM Design Options Analyzed for HAPL

≻All options have 50 microns thick Al coating

Option 1: Lightweight SiC substrate

- The substrate consists of two SiC face plates surrounding a SiC foam with 12.5% density factor
- The foam is actively cooled with slow-flowing He gas
- Total thickness is 1/2"
- Total areal density is 12 kg/m²

→ *Option 2:* Higher density SiC substrate

- The substrate consists of two SiC face plates surrounding a SiC foam with 50% density factor
- Total thickness is 1/2"
- Total areal density is 24 kg/m²

Option 3: Lightweight AlBeMet substrate

- The substrate consists of two AlBeMet162 (62 wt.%Be) face plates surrounding a AlBeMet foam(or honeycomb) with 12.5% density factor
- Total thickness is 1" (for stiffness)
- Total areal density is 16 kg/m²

• Option 4: Lightweight Al-6061 substrate

- The substrate consists of two <u>Al-6061</u> face plates surrounding Al-6061 foam(or honeycomb) with 12.5% density factor
- Total thickness is 1" (for stiffness)
- Total areal density is 20 kg/m²



Flux at Front Faceplate of GIMM

		Flux
		(CITS-)
SIC GIMM	Neutrons E>0.1 MeV	1.39x10 ¹³ (±2.1%)
(0.125 foam d.f.)	Total Neutrons	1.43x10 ¹³ (±2.1%)
	Total Gamma	1.57x10 ¹² (±5.5%
SiC GIMM	Neutrons E>0.1 MeV	1.47x10 ¹³ (±0.7%)
(0.5 foam d.f.)	Total Neutrons	1.53x10 ¹³ (±0.7%)
	Total Gamma	2.63x10 ¹² (±1.7%)
AlBeMet GIMM	Neutrons E>0.1 MeV	1.21x10 ¹³ (±2.1%)
(0.125 foam d.f.)	Total Neutrons	1.30x10 ¹³ (±2.1%)
	Total Gamma	1.88x10 ¹² (±4.4%)
AI-6061 GIMM	Neutrons E>0.1 MeV	1.16x10 ¹³ (±0.7%)
(0.125 foam d.f.)	Total Neutrons	1.21x10 ¹³ (±0.7%)
	Total Gamma	2.40x10 ¹² (±1.6%)

Contribution from scattering inside chamber is small (<3%)</p>

- Fast neutron flux dominated by direct contribution from target with less than ~30% contributed from scattering in the GIMM itself
- Material choice and thickness slightly impact peak flux in GIMM
- Neutron spectrum softer for AlBeMet with 93% >0.1 MeV compared to 97% for SiC



Nuclear Heating in GIMM Front				
	Neutron Heating (W/cm ³)	Gamma Heating (W/cm ³)	Total Heating (W/cm ³)	Total Areal Nuclear Heating (mW/cm ²)
SiC GIMM (0.125 foam d.f.)	0.55 (±2.2%)	0.04 (±8.3%)	0.59 (±2.1%)	71
SiC GIMM (0.5 foam d.f.)	0.57 (±0.7%)	0.06 (±3.3%)	0.63 (±0.8%)	76
AIBeMet GIMM (0.125 foam d.f.)	0.47 (±2.2%)	0.02 (±10.1%)	0.49 (±2.2%)	118
AI-6061 GIMM (0.125 foam d.f.)	0.19 (±0.7%)	0.04 (±2.5%)	0.23 (±0.8%)	56

- Power densities are ~0.3-0.6 W/cm³
- For 1.2 mm thick SiC faceplate nuclear heating is 71 mW/cm²
- For the twice thicker AlBeMet faceplate nuclear heating is 118 mW/cm²
- Areal nuclear heating is larger than heat flux from laser (22 mW/cm²) and xrays (23 mW/cm²) and should be considered for cooling requirement



Flux at Dielectric Focusing Mirror M2 Located @14.9 m from GIMM

		Flux (cm ⁻² .s ⁻¹)
SiC GIMM	Neutrons E>0.1 MeV	2.05x10 ¹⁰ (±4.0%)
(0.125 foam d.f.)	Total Neutrons	2.27x10 ¹⁰ (±4.0%)
<i>12 kg/m</i> ²	Total Gamma	0.88x10 ¹⁰ (±6.9%)
SiC GIMM	Neutrons E>0.1 MeV	2.93x10 ¹⁰ (±3.4%)
(0.5 foam d.f.)	Total Neutrons	3.29x10 ¹⁰ (±3.4%)
24 kg/m ²	Total Gamma	1.67x10 ¹⁰ (±3.1%)
AIBeMet GIMM	Neutrons E>0.1 MeV	3.18x10¹⁰ (±3.9%)
(0.125 foam d.f.)	Total Neutrons	3.57x10 ¹⁰ (±3.8%)
16 kg/m ²	Total Gamma	1.35x10 ¹⁰ (±5.9%)
AI-6061 GIMM	Neutrons E>0.1 MeV	2.64x10 ¹⁰ (±3.1%)
(0.125 foam d.f.)	Total Neutrons	2.98x10 ¹⁰ (±3.3%)
20 kg/m ²	Total Gamma	1.58x10 ¹⁰ (±3.0%)

- Total neutron and gamma fluxes are more than two orders of magnitude lower than at GIMM
- Neutron spectrum is hard with ~90% of neutrons @ E>0.1 MeV

2-D analysis overestimates the flux at dielectric focusing mirror by up to a factor of 2 due to significant geometrical approximations that tend to enhance streaming. This demonstrates the importance of utilizing accurate 3-D models for the streaming analysis in laser final optics systems



Impact of GIMM Material and Density on Flux at Dielectric Focusing Mirror M2



 For GIMM design options that do not include Be, we find that neutron flux at M2 scales roughly with the square root of the total areal density of GIMM

- Neutron flux is a factor of ~1.6 higher with AlBeMet GIMM compared to the lightweight SiC GIMM due to neutron multiplication in Be
 Gamma generation from inelastic scattering in Si and Al give higher gamma flux at M2 compared to case with AlBeMet GIMM
 - Larger thickness required for stiffness in cases of AlBeMet and Al-6061 is an important contributor to enhanced neutron flux at M2





Peak Flux at Turning Mirror M3 Located @ 1.6-6 m from M2



- Fast neutron flux is about two orders of magnitude lower than at M2 with smaller reduction in total neutron and gamma fluxes
- Neutron spectrum is softer with ~40% of neutrons @ E>0.1 MeV
- Fast neutron flux at M3 has a steeper increase with the GIMM areal density (excluding AlBeMet) [a power of ~0.7 vs. ~0.5 for M2]



Nuclear Heating in Sapphire M2 and M3 Mirrors

		Neutron Heating (mW/cm ³)	Gamma Heating (mW/cm ³)	Total Heating (mW/cm³)
SiC GIMM	M2	0.71 (±4.5%)	0.22 (±5.4%)	<mark>0.93</mark> (±3.7%)
(0.125 foam d.f.)	M3 Maximum	0.0034 (±7.2%)	0.0138 (±6.1%)	0.0172 (±5.1%)
SiC GIMM	M2	0.97 (±1.6%)	<mark>0.44</mark> (±1.9%)	1.41 (±1.5%)
(0.5 foam d.f.)	M3 Maximum	0.0051 (±5.0%)	0.0214 (±5.0%)	0.0265 (±5.0%)
AlBeMet GIMM	M2	<mark>1.06</mark> (±4.4%)	0.24 (±8.6%)	1.30 (±3.9%)
(0.125 foam d.f.)	M3 Maximum	0.0050 (±5.5%)	0.0212 (±5.5%)	0.0262 (±4.6%)
•AI-6061 GIMM	M2	0.87 (±1.7%)	0.41 (±2.1%)	1.28 (±1.6%)
(0.125 foam d.f.)	M3 Maximum	0.0044 (±3.9%)	0.0183 (±3.5%)	0.0227 (±3.4%)

- Nuclear heating in M2 is ~1 mW/cm³
- Peak nuclear heating in M3 is about 2 orders of magnitude lower than in M2
- Nuclear heating in the dielectric mirrors are factors of ~1.4 higher with AIBeMet GIMM compared to that with lightweight SiC GIMM



Fast Neutron Flux Distribution in Final Optics of HAPL





Expected Lifetime of Mirrors in Final Optics of HAPL

	•Peak Fast Neutron Fluence per FPY (n/cm ²)		
	•GIMM •(M1)	•Focusing Mirror (M2)	Turning Mirror (M3)
SiC GIMM (0.125 foam d.f.)	•4.38x10 ²⁰ (±2.1%)	•6.46x10 ¹⁷ (±4.0%)	1.00x10 ¹⁶ (±7.3%)
SiC GIMM (0.5 foam d.f.)	•4.63x10 ²⁰ (±0.7%)	•9.23x10 ¹⁷ (±3.4%)	•1.64x10 ¹⁶ (±5.0%)
AIBeMet GIMM (0.125 foam d.f.)	•3.81x10 ²⁰ (±2.1%)	•1.00x10 ¹⁸ (±3.9%)	1.62x10 ¹⁶ (±7.6%)
AI-6061 GIMM (0.125 foam d.f.)	•3.65x10 ²⁰ (±0.7%)	•8.32x10 ¹⁷ (±3.1%)	•1.46x10 ¹⁶ (±5.9%)

- Flux drops by about three orders of magnitude as one moves from the GIMM to M2 and by an additional two orders of magnitude as one moves to M3
- Fluence limits for metallic and dielectric mirrors are not well defined. At issue is degradation of optical properties and structural integrity under irradiation
- For fluence limits of 10²¹ n/cm² (GIMM) and 10¹⁹ n/cm² (dielectric), expected GIMM lifetime is ~2 FPY, expected M2 lifetime is ~10 FPY, and M3 is lifetime component



Summary and Conclusions

- Fast neutron flux at the optics depends on material choice for the GIMM and total GIMM areal density
- Fast neutron flux at dielectric focusing mirror M2 was found to increase with the square root of total areal density of GIMM (excluding AlBeMet)
- AlBeMet GIMM results in highest flux level (factor of ~1.6 higher than with lightweight SiC GIMM) due to neutron multiplication in Be and larger thickness required for stiffness
- Other considerations, such as cost, ease of fabrication, radiation resistance, and stiffness, should be accounted for when choosing the reference GIMM design
- Significant drop in nuclear environment occurs as one moves from the GIMM to dielectric focusing and turning mirrors
- Neutron spectrum softens significantly at M3 (~40% >0.1 MeV vs. ~90% at M2 and ~95% at GIMM)
- For fluence limits of 10²¹ n/cm² (GIMM) and 10¹⁹ n/cm² (dielectric), expected GIMM lifetime is ~2 FPY, expected M2 lifetime is 10 FPY, and M3 is lifetime component
- Experimental data on radiation damage to metallic and dielectric mirrors are essential for accurate lifetime prediction



Future Work

- Consider other GIMM designs and assess impact on the neutron flux at potential dielectric mirror and window locations
- Work with material group on defining radiatioton limits for GIMM and dielectric mirrors for better determination of optics lifetime
- Analyze other possible optics configurations with MI. Nuclear environment at optics affected more by configuration than by GIMM material choice
- Assess the option with all dielectric mirrors
- Ultimate goal is to determine the reference configuration and optics design that maximizes the lifetime of the mirrors and window

