Three-Dimensional Nuclear Analysis for the Final Optics of a Laser Driven Fusion Power Plant

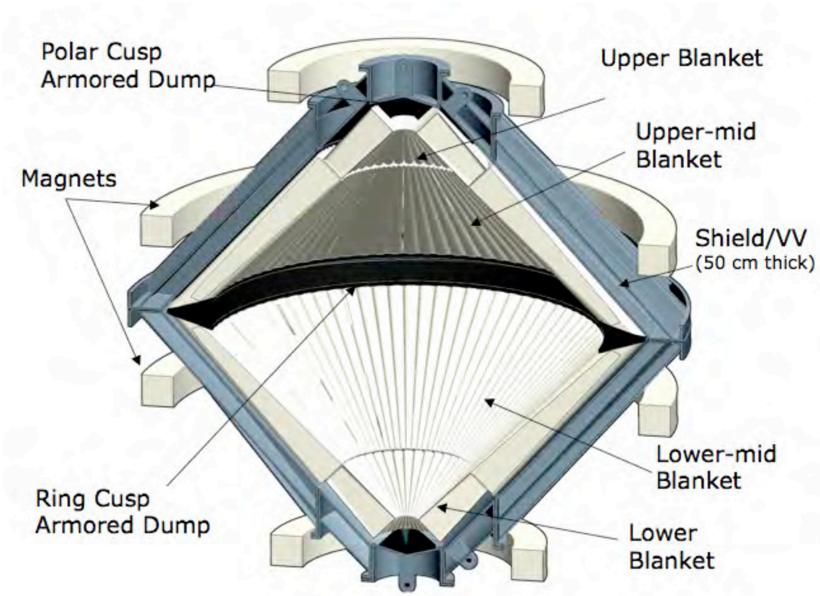
Mohamed Sawan
Ahmad Ibrahim, Tim Bohm, Paul Wilson

Fusion Technology Institute
University of Wisconsin, Madison, WI

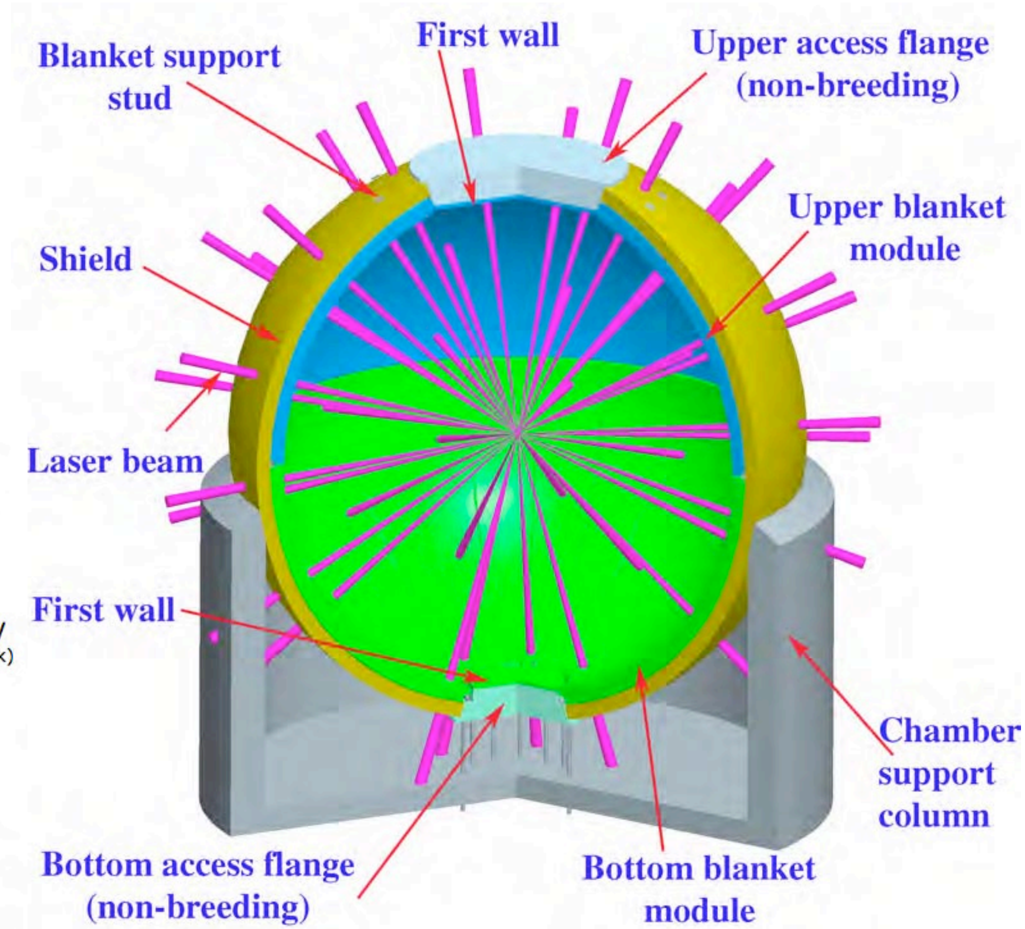
ISFNT-8
Heidelberg, Germany
Sept. 30 - Oct. 5, 2007

High Average Power Laser (HAPL) Conceptual Design

- Direct drive targets
- Dry wall chamber
- 40 KrF laser beams
- 367.1 MJ target yield
- 5 Hz Rep Rate



Design with Magnetic Intervention



Large Chamber Design

Baseline HAPL final optical parameters:

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

2 J/cm^2 in optical distribution ducts

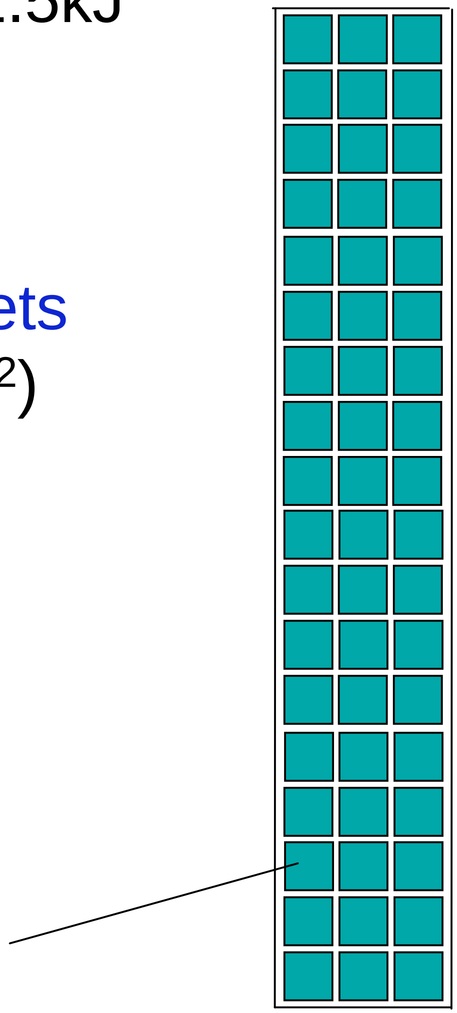
Duct aspect ratio 6:1, each beam 3x18 beamlets

(area of one beam = 3x18x(0.24)^2 = 3.1 m^2)

Focal length 39 m

Vertical “slits” in blanket, total 0.7% of 4π

(slit size 1.32 m high x 0.22m wide)



24 cm x 24 cm beamlet
from de-multiplex array

HAPL Final Optics with Grazing Incidence Metallic Mirrors

- Use of GIMM was first proposed by Bieri and Guinan as solution to problem of protecting final focusing mirrors from neutron damage

  Bieri and Guinan, Fusion Technology 19, 673-678 (1991)

- 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

  M. Sawan, "Three-Dimensional Neutronics Analysis for the Final Optics of the Laser Fusion Power Reactor SIRIUS-P," Proc. IEEE 16th Symposium on Fusion Engineering, Champaign, IL, Sept. 30- Oct. 5 1995, IEEE Cat. No. 95CH35852, Vol. 1, pp. 29

  S. Reyes, J. Latkowski, and W. Meier, "Radiation Damage and Waste Management Options for the SOMBRERO Final Focus System and Neutron Dumps", UCRL-JC-134829, August 1999

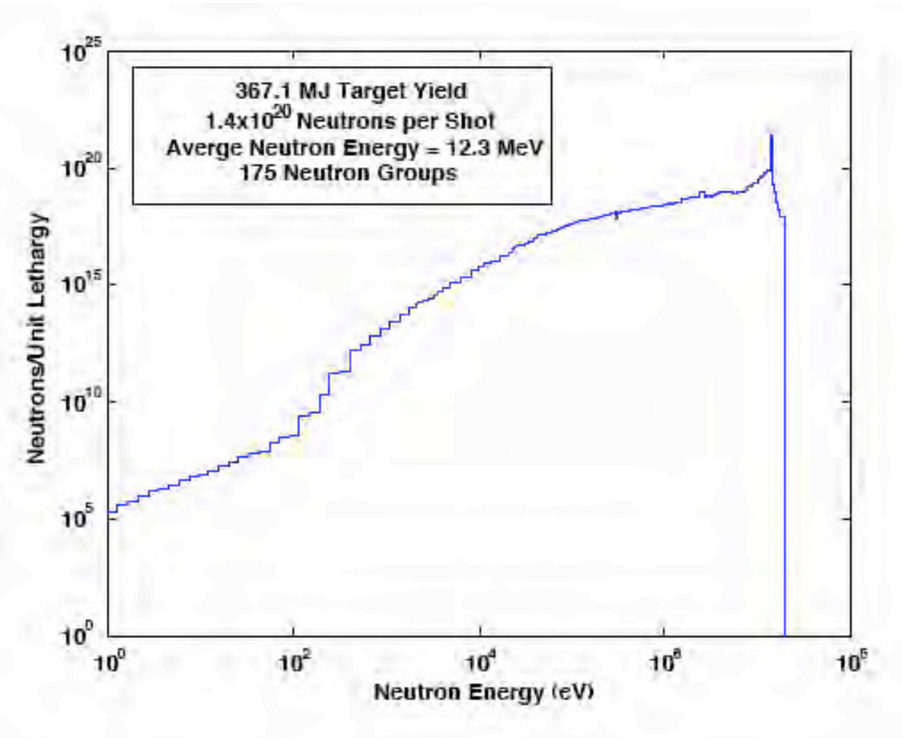
- A HAPL final optics system utilizing GIMMs was developed and assessed

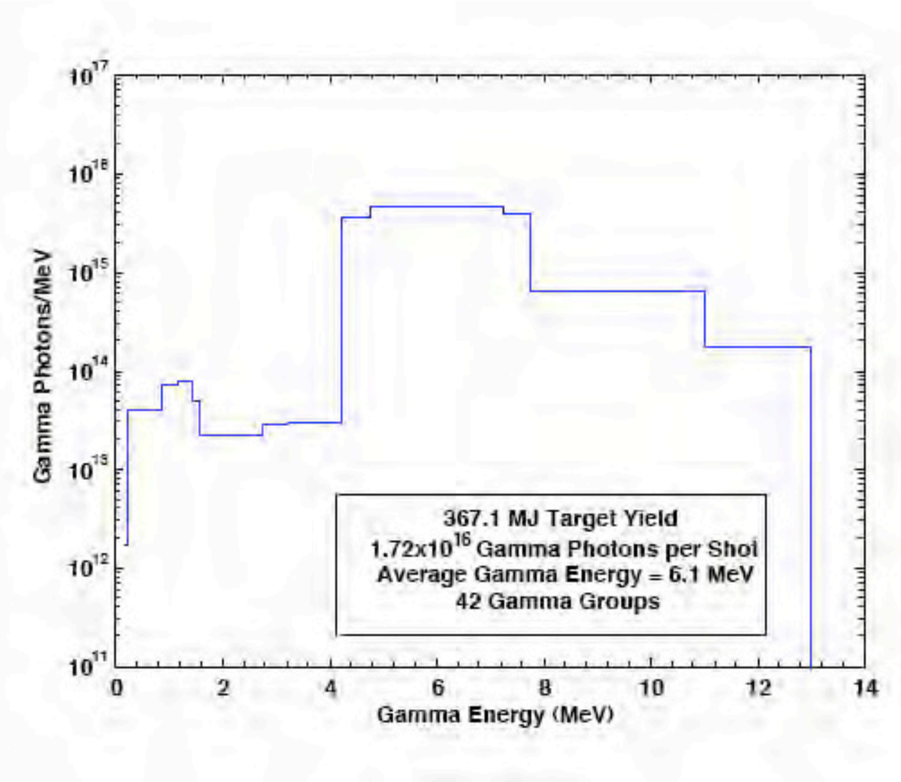
THE UNIVERSITY of WISCONSIN MADISON

Design Parameters for High Average Power Laser (HAPL) Conceptual Design

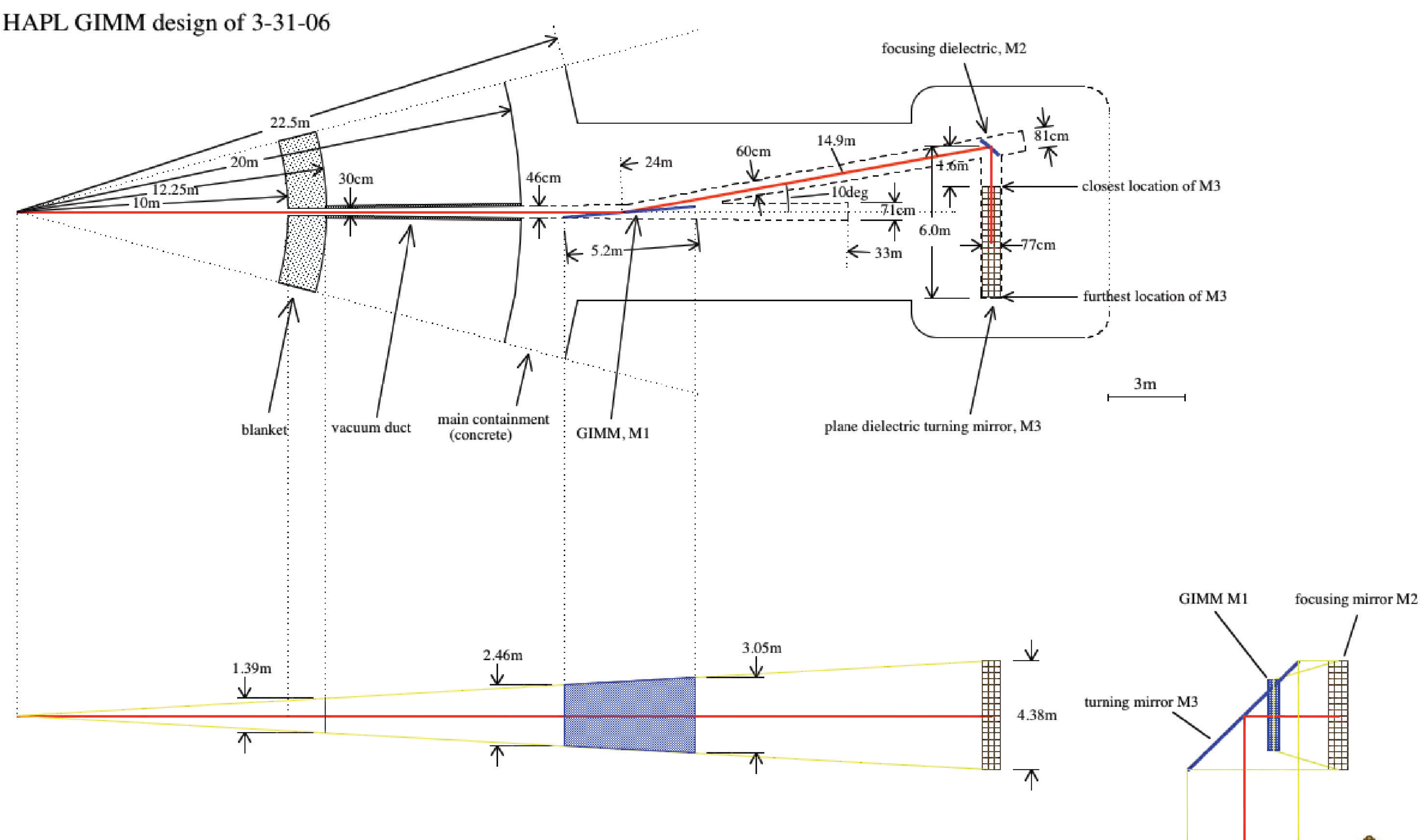
Target yield	367.1 MJ
Rep Rate	5 Hz
Fusion power	1836 MW
Chamber inner radius	10.75 m
Thickness of Li/FS blanket	0.6 m
Thickness of SS/B_4C/He shield	0.5 m
Chamber outer radius	11.85 m
NWL @ FW	0.94 MW/m^2
GIMM angle of incidence	85°
GIMM distance from target	24 m

Energy Spectra of Source Neutrons and Gammas Used in Neutronics Calculations





Baseline HAPL Optics Configuration with GIMM



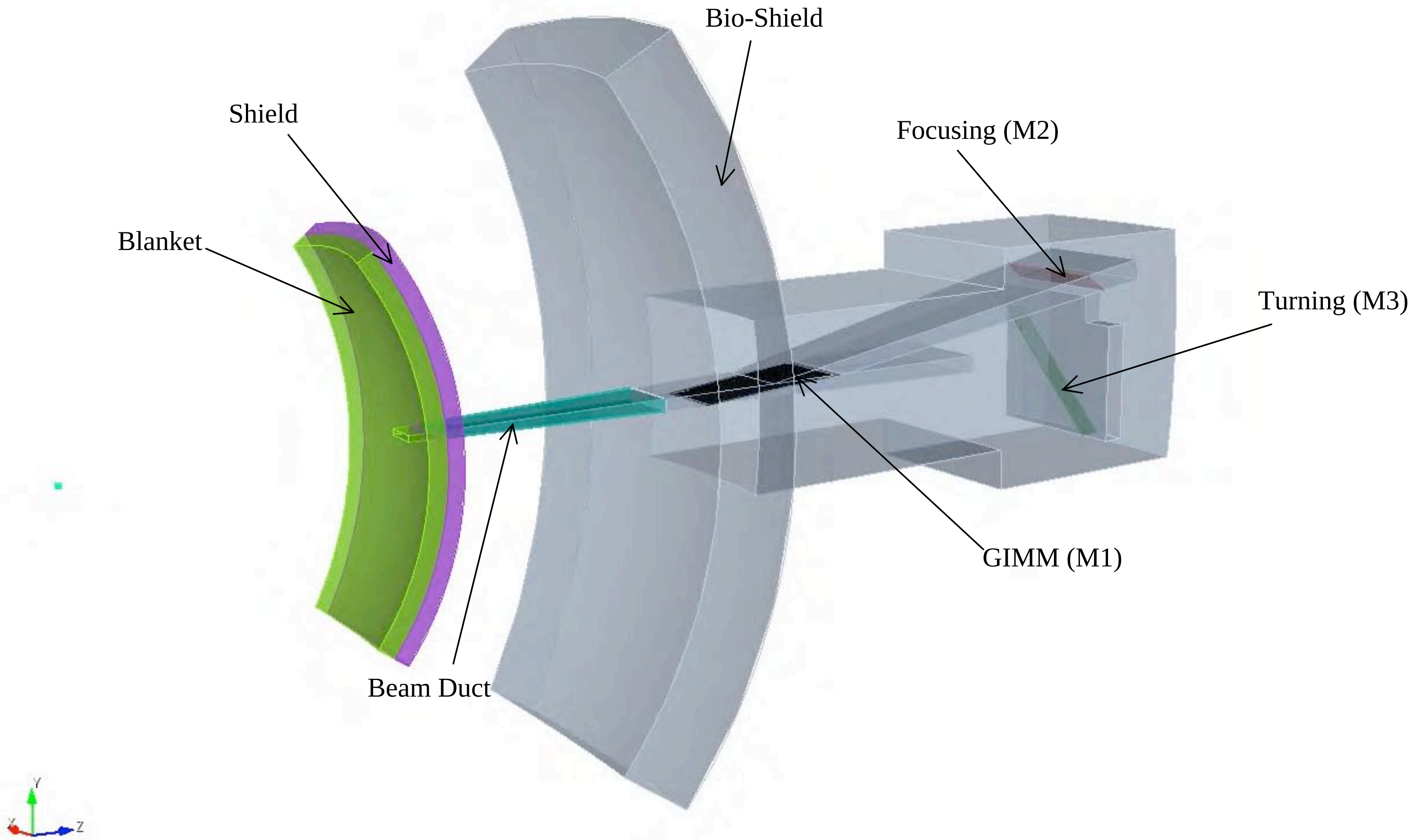
Provided by Malcolm McGeoch

Detailed 3-D Neutronics Analysis

- 3-D neutronics calculation performed to determine the nuclear environment at the GIMM (M1), focusing mirror (M2), and turning mirror (M3) and to compare the impact of the GIMM design options
- Used the Monte Carlo code MCNPX-CGM (MCNPX v2.6b with CGM (ACIS version 14.1)) with direct neutronics calculations in the CAD model
- Continuous energy FENDL-2.1 nuclear data used
- Modeled one beam line with reflecting boundaries
- All 3 mirrors and accurate duct shape (6:1 aspect ratio) included in model
- 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 (inner surface @20 m from target) housing optics and neutron traps used with 70% concrete, 20% carbon steel C1020, and 10% H_2O
- 3 cm thick steel beam duct used between shield and containment building
- Results compared to previous 2-D calculations

THE UNIVERSITY of WISCONSIN MADISON

Geometrical Model Used in 3-D Neutronics Analysis



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/m^2

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/m^2

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/m^2

Option 4: Lightweight Al-6061 substrate

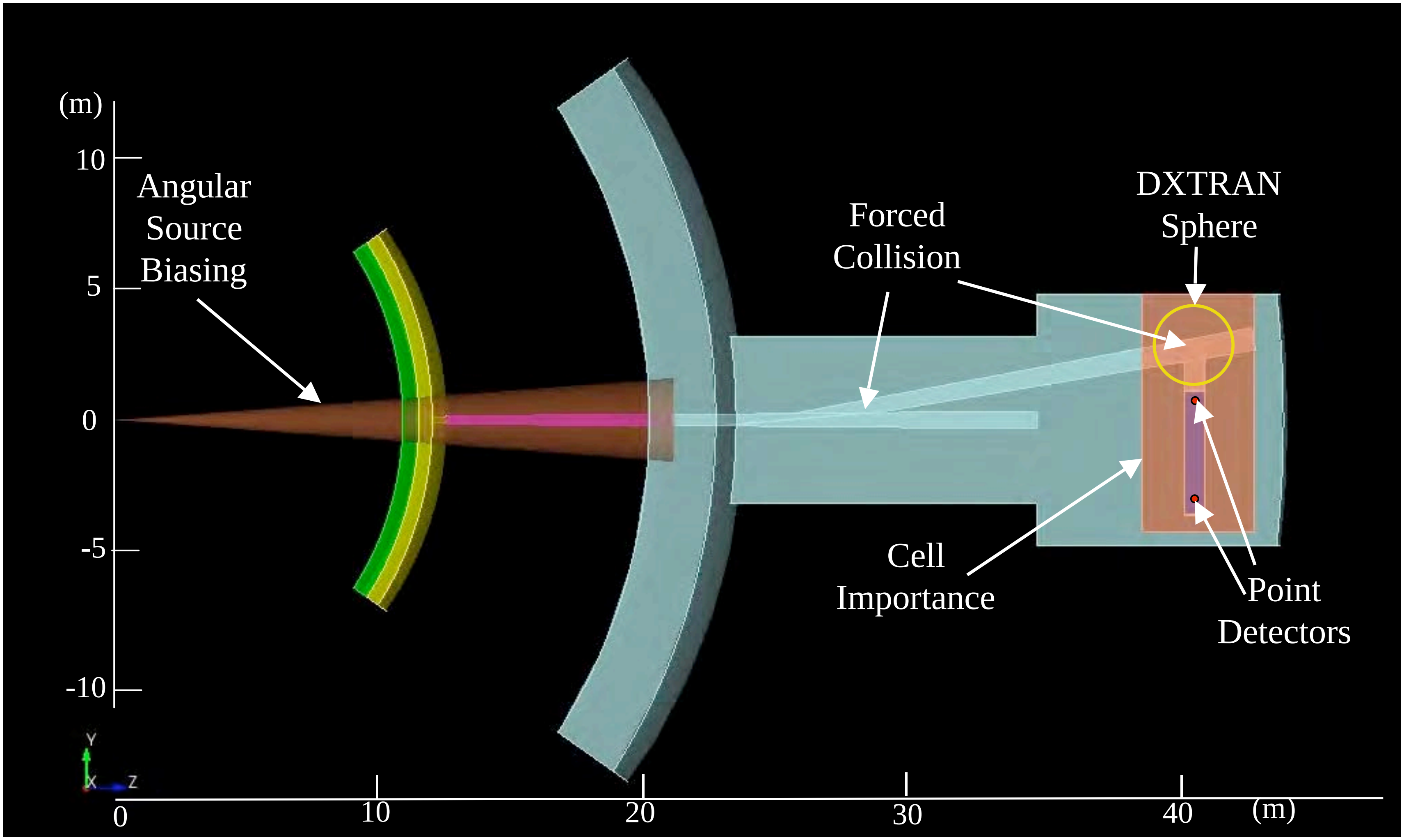
- The substrate consists of two Al-6061 face plates surrounding Al-6061 foam(or honeycomb) with 12.5% density factor
- Total thickness is 1" (for stiffness)
- Total areal density is 20 kg/m^2

THE UNIVERSITY of WISCONSIN MADISON

Calculation Procedure

- Total of 50 million source particles sampled using 10 parallel processors
- Total CPU time is 36 days (SiC) and 45 days (AlBeMet)
- Isotropic point source sampled using target spectrum
- Utilized variance reduction techniques to reduce the statistical uncertainties
  - Angular source biasing
  - Cell importance
  - Forced collision
  - DXTRAN spheres around M2
  - Point detectors in M3

Variance Reduction Techniques Applied



Flux at Front Faceplate of GIMM

		Flux ($cm^{-2}.s^{-1}$)
SiC GIMM (0.125 foam d.f.)	Neutrons E>0.1 MeV	**1.39×10^{13}** (±2.1%)
	Total Neutrons	1.43×10^{13} (±2.1%)
	Total Gamma	1.57×10^{12} (± 5.5%)
AlBeMet GIMM (0.125 foam d.f.)	Neutrons E>0.1 MeV	1.21×10^{13} (±2.1%)
	Total Neutrons	1.30×10^{13} (±2.1%)
	Total Gamma	1.88×10^{12} (±4.4%)

- 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

		Neutron Heating (W/cm^3)	Gamma Heating (W/cm^3)	Total Heating (W/cm^3)
SiC GIMM (0.125 foam d.f.)	Al Coating	0.42 (±2.2%)	0.03 (±7.0%)	0.45 (±2.1%)
	Front Faceplate	0.55 (±2.2%)	0.04 (±8.3%)	**0.59** (±2.1%)
	Foam	0.056 (±2.2%)	0.005 (±8.5%)	0.061 (±2.1%)
	Back Faceplate	0.36 (±2.2%)	0.03 (±7.6%)	0.39 (±2.1%)
AlBeMet GIMM (0.125 foam d.f.)	Al Coating	0.36 (±2.2%)	0.03 (±5.0%)	0.39 (±2.1%)
	Front Faceplate	0.47 (±2.2%)	0.02 (±10.1%)	**0.49** (±2.2%)
	Foam	0.041 (±2.2%)	0.002 (±4.7%)	0.043 (±2.1%)
	Back Faceplate	0.23 (±2.2%)	0.02 (±5.1%)	0.25 (±2.1%)

- Total heating values are slightly lower than 2-D predictions (by <20%)
- Power densities are slightly lower in the AlBeMet GIMM
- For 1.2 mm thick SiC faceplate nuclear heating is 71 mW/cm^2
- For the twice thicker AlBeMet faceplate nuclear heating is 118 mW/cm^2
- This is compared to the heat flux from laser (22 mW/cm^2) and x-rays (23 mW/cm^2)

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

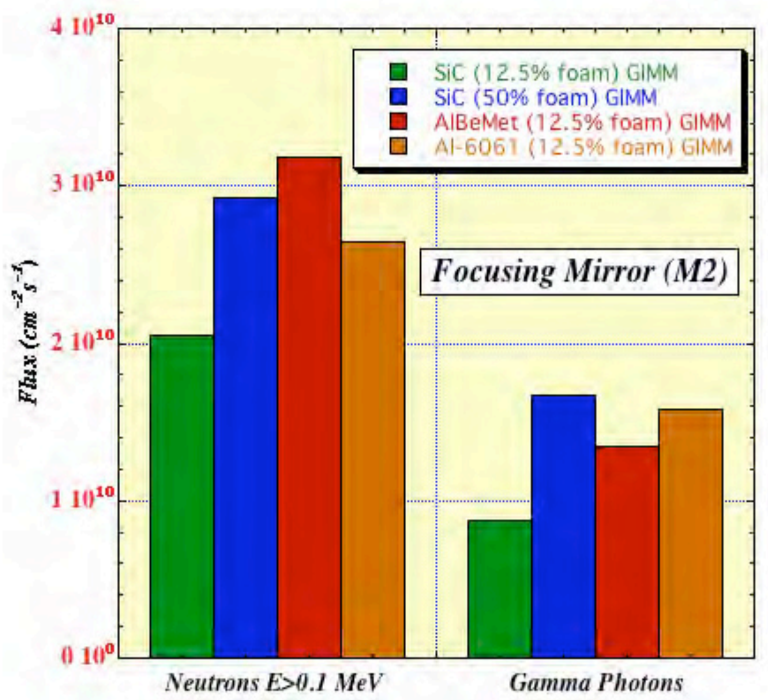
		Flux ($cm^{-2}.s^{-1}$)
SiC GIMM (0.125 foam d.f.) *12 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$2.05x10^{10}$ (±4.0%) $2.27x10^{10}$ (±4.0%) $0.88x10^{10}$ (±6.9%)
SiC GIMM (0.5 foam d.f.) *24 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$2.93x10^{10}$ (±3.4%) $3.29x10^{10}$ (±3.4%) $1.67x10^{10}$ (±3.1%)
AlBeMet GIMM (0.125 foam d.f.) *16 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	**$3.18x10^{10}$** (±3.9%) $3.57x10^{10}$ (±3.8%) $1.35x10^{10}$ (±5.9%)
Al-6061 GIMM (0.125 foam d.f.) *20 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$2.64x10^{10}$ (±3.1%) $2.98x10^{10}$ (±3.3%) $1.58x10^{10}$ (±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

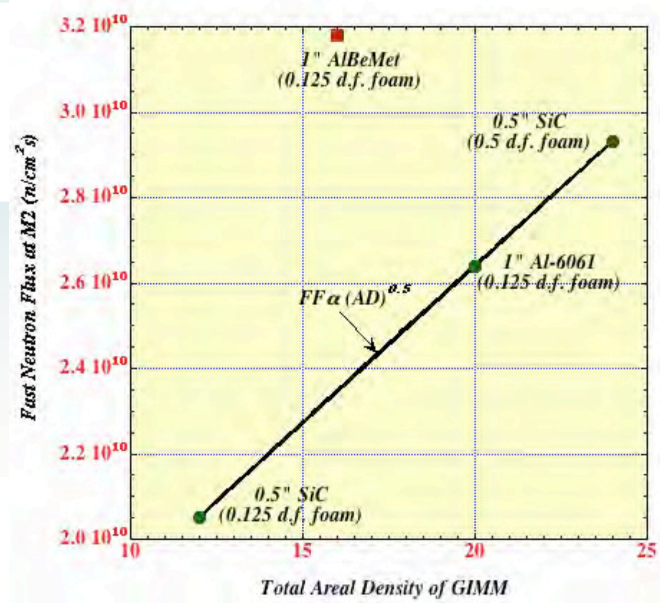
THE UNIVERSITY of WISCONSIN MADISON

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



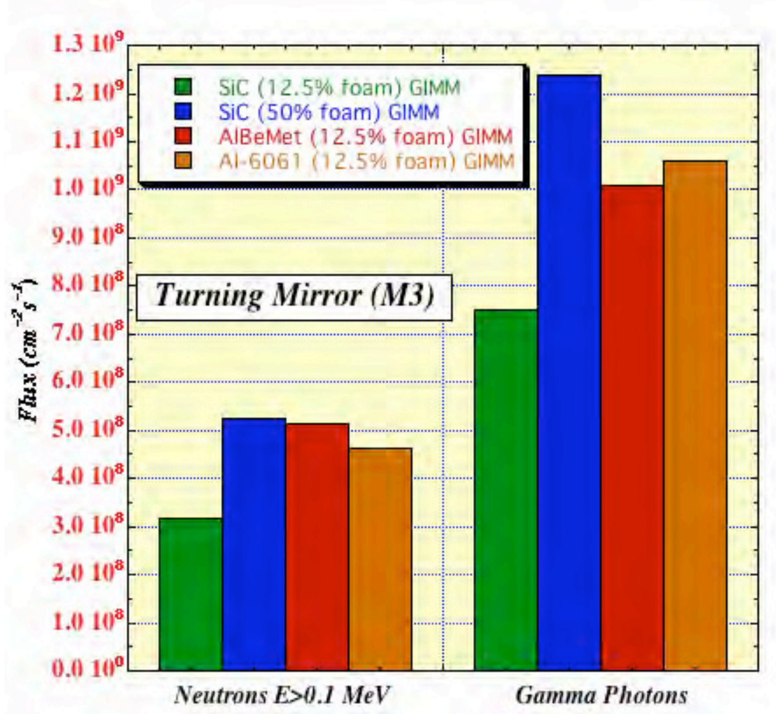
- Neutron flux is a factor of ~1.6 higher with AlBeMet GIMM compared to the lightweight SiC GIMM due to neutron multiplication in Be
- Gamma generation from inelastic scattering in Si and Al give higher gamma flux at M2 compared to case with AlBeMet GIMM
- Larger thickness required for stiffness in cases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

- 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



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

		Flux ($cm^{-2}.s^{-1}$)
SiC GIMM (0.125 foam d.f.) *12 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$3.18x10^8$ (±7.3%) $8.44x10^8$ (±8.2%) $7.51x10^8$ (±8.0%)
SiC GIMM (0.5 foam d.f.) *24 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$5.26x10^8$ (±5.0%) $1.26x10^9$ (±5.7%) $1.24x10^9$ (±7.7%)
AlBeMet GIMM (0.125 foam d.f.) *16 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$5.14x10^8$ (±7.6%) $1.31x10^9$ (±8.8%) $1.01x10^9$ (±5.5%)
Al-6061 GIMM (0.125 foam d.f.) *20 kg/m²*	Neutrons E>0.1 MeV Total Neutrons Total Gamma	$4.63x10^8$ (±5.9%) $1.20x10^9$ (±6.7%) $1.06x10^9$ (±7.4%)



- 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]

THE UNIVERSITY of WISCONSIN MADISON

Nuclear Heating in Sapphire M2 and M3 Mirrors

		Neutron Heating (mW/cm^3)	Gamma Heating (mW/cm^3)	Total Heating (mW/cm^3)
SiC	M2	0.71 (±4.5%)	0.22 (±5.4%)	**0.93** (±3.7%)
GIMM	M3 Maximum	0.0034 (±7.2%)	0.0138 (±6.1%)	0.0172 (±5.1%)
(0.125 foam d.f.)	M3 Minimum	0.0004 (±9.4%)	0.0014 (±8.1%)	0.0018 (±6.6%)
AlBeMet	M2	1.06 (±4.4%)	0.24 (±8.6%)	**1.30** (±3.9%)
GIMM	M3 Maximum	0.0050 (±5.5%)	0.0212 (±5.5%)	0.0262 (±4.6%)
(0.125 foam d.f.)	M3 Minimum	0.0006 (±7.3%)	0.0020 (±5.2%)	0.0026 (±4.3%)

- Nuclear heating in M2 is more than 2 orders of magnitude lower than in the GIMM
- 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 AlBeMet GIMM compared to that with SiC GIMM

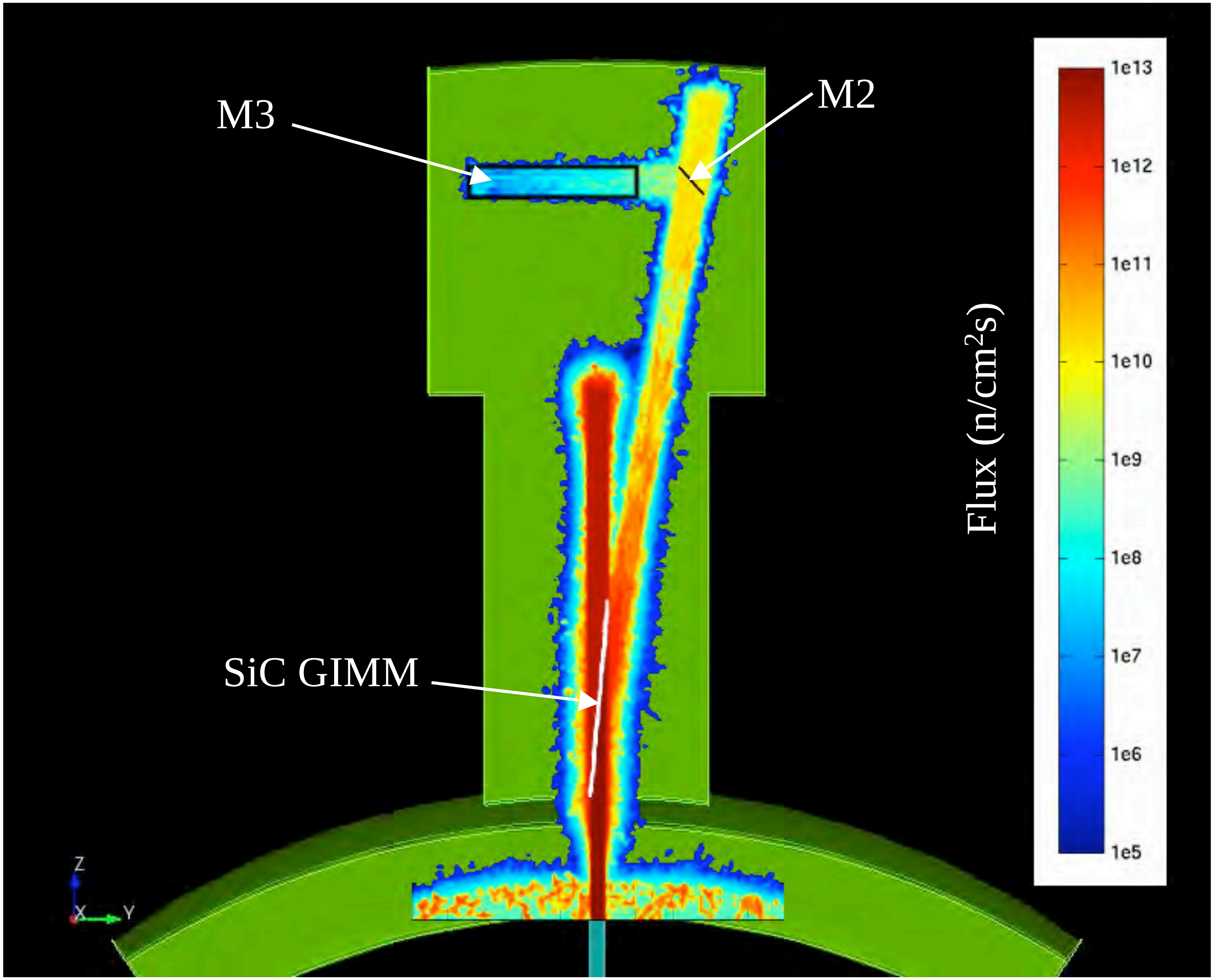
THE UNIVERSITY of WISCONSIN MADISON

Fast Neutron Flux Distribution in Final Optics of HAPL

- Utilized the mesh tally capability of MCNPX to determine detailed flux distribution
- Used neutron low energy cutoff of 0.1 MeV to calculate fast flux
- Rectangular mesh tallies 10cm x 10cm x 10cm in size extending from x = -5 to +5 cm, y =-500 to +500 cm, and z =1900 to 4300
- Sampled 100 million source neutrons on 10 parallel processors requiring total CPU time of 36.1 days

THE UNIVERSITY of WISCONSIN MADISON

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.)	*4.38×10^{20} (±2.1%)*	*6.46×10^{17} (±4.0%)*	*1.00×10^{16} (±7.3%)*
SiC GIMM (0.5 foam d.f.)	*4.63×10^{20} (±0.7%)*	*9.23×10^{17} (±3.4%)*	*1.64×10^{16} (±5.0%)*
AlBeMet GIMM (0.125 foam d.f.)	*3.81×10^{20} (±2.1%)*	*1.00×10^{18} (±3.9%)*	*1.62×10^{16} (±7.6%)*
Al-6061 GIMM (0.125 foam d.f.)	*3.65×10^{20} (±0.7%)*	*8.32×10^{17} (±3.1%)*	*1.46×10^{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 here degradation of optical properties and structural integrity under irradiation
- For fluence limits of 10^{21} n/cm^2 (GIMM) and 10^{19} n/cm^2 (dielectric), expected GIMM lifetime is ~2 FPY, expected M2 lifetime is ~10 FPY, and M3 is lifetime component

THE UNIVERSITY of WISCONSIN MADISON

Summary and Conclusions

- 3-D neutronics calculation performed directly in the exact CAD model of the HAPL final optics system to determine nuclear environment and compare impact of possible GIMM design options
- 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 10^{21} n/cm^2 (GIMM) and 10^{19} n/cm^2 (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

THE UNIVERSITY of WISCONSIN MADISON