Three-Dimensional Nuclear Analysis for the Final Optics System with GIMMs

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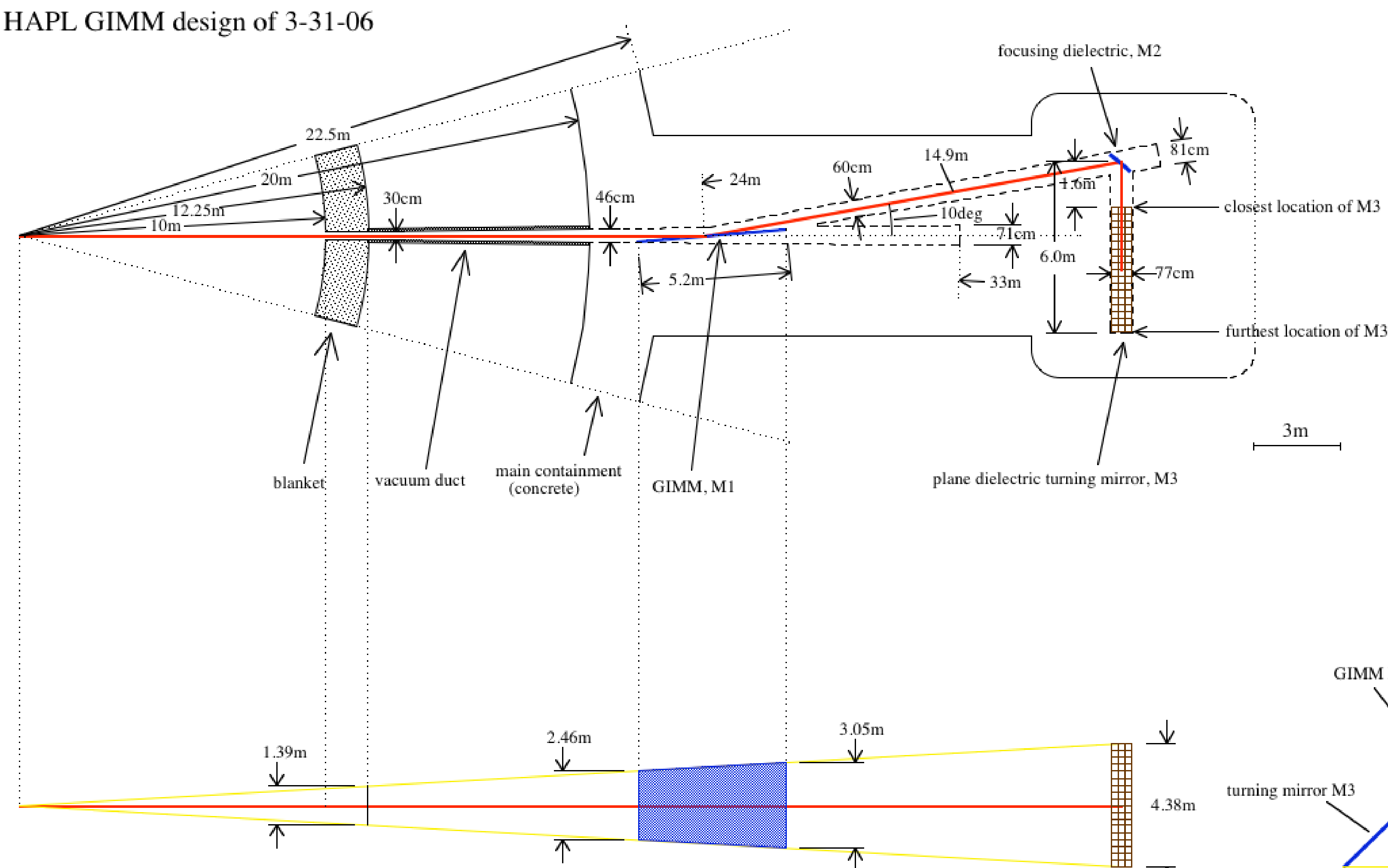
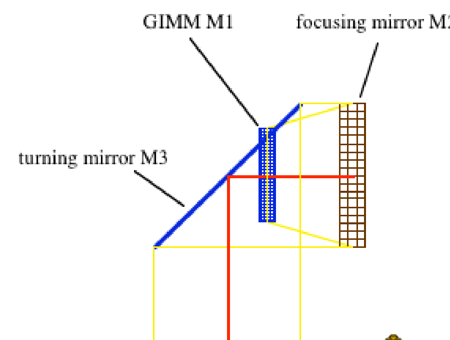
Design Parameters for Baseline HAPL Design

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

Baseline HAPL Optics Configuration with GIMM



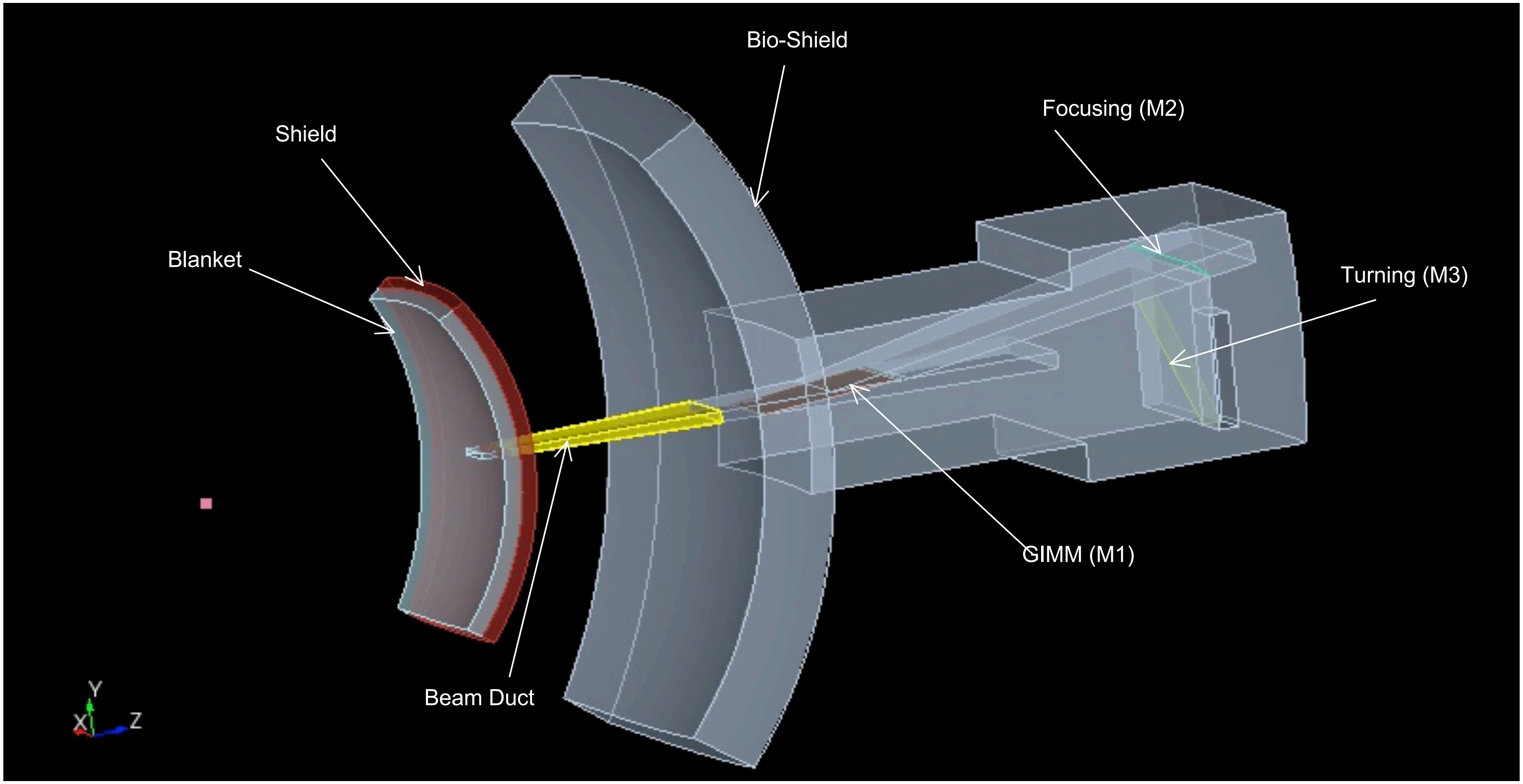


Provided by Malcolm McGeoch

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 with direct neutronics calculations in the CAD model
- Used MCNPX-CGM (MCNPX v2.6b with CGM (ACIS version 14.1))
- Continuous energy FENDL-2.1 nuclear data used
- Modeled one beamline with reflecting boundaries
- All 3 mirrors and accurate duct shape (6:1 aspect ratio) included in model
- Neutron traps used behind GIMM and M2
- Two lightweight GIMM design options considered
- 1 cm thick Sapphire M2 and M3 mirrors modeled
- 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

Geometrical Model Used in 3-D Neutronics Analysis



GIMM Design Options for HAPL

- Two options considered for GIMM materials and thicknesses
- Both 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

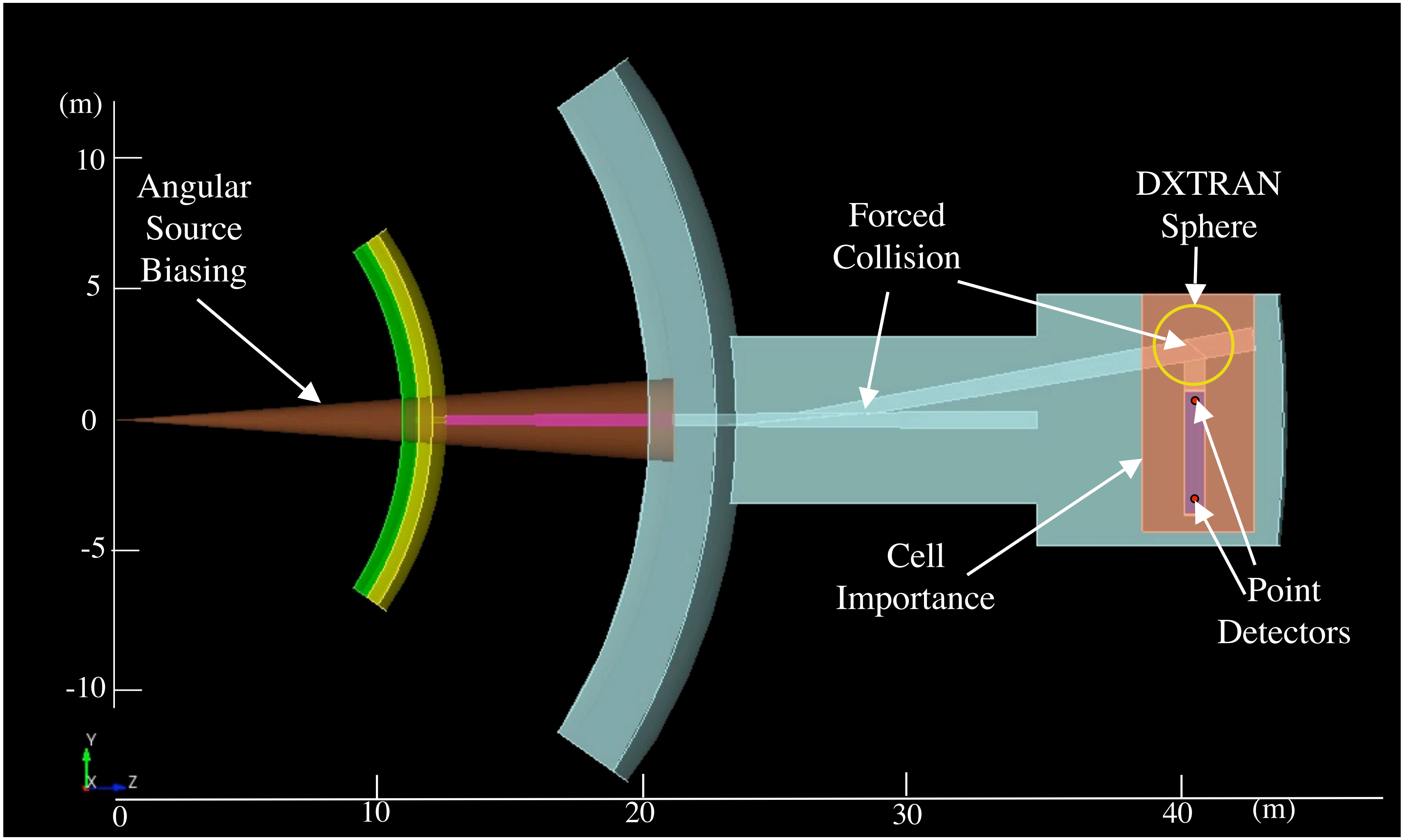
Option 2: Lightweight AlBeMet substrate

- The substrate consists of two AlBeMet162 (62 wt.%Be) face plates surrounding a AlBeMet foam(or honeycomb) with 12.5% density factor
- The foam is actively cooled with slow-flowing He gas
- Total thickness is 1"
- Total areal density is 16 kg/m^2

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	Neutrons E>0.1 MeV Total Neutrons Total Gamma	**1.39×10^{13}** (±2.1%) 1.43×10^{13} (±2.1%) 1.57×10^{12} (± 5.5%)
AlBeMet GIMM	Neutrons E>0.1 MeV Total Neutrons Total Gamma	1.21×10^{13} (±2.1%) 1.30×10^{13} (±2.1%) 1.88×10^{12} (±4.4%)

- Material choice and thickness slightly impacts peak flux in GIMM
- Neutron spectrum softer for AlBeMet with 93% >0.1 MeV compared to 97% for SiC

Nuclear Heating in GIMM

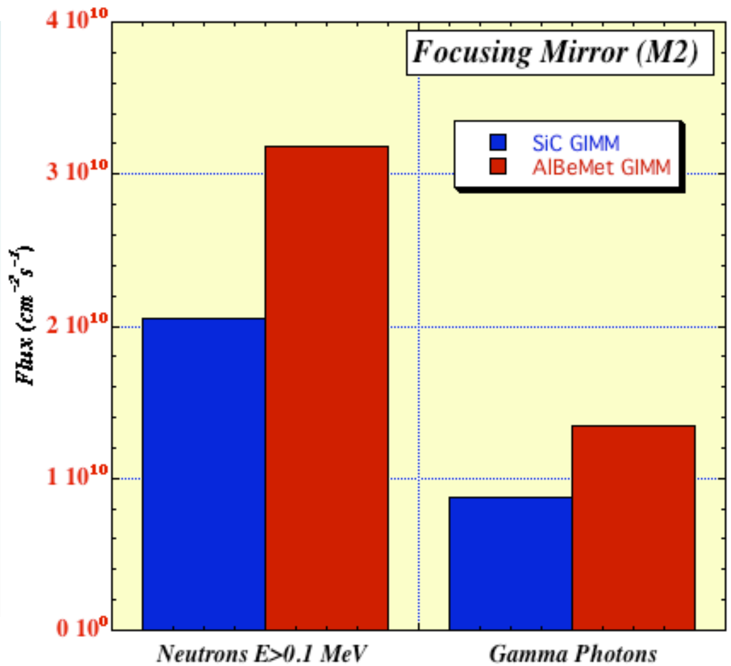
		Neutron Heating (W/cm^3)	Gamma Heating (W/cm^3)	Total Heating (W/cm^3)
SiC GIMM	Al Coating	0.42 (±2.2%)	0.03 (±7.0%)	0.45 (±2.1%)
	Front Faceplate	0.55 (±2.2%)	0.04 (±8.3%)	**0.59** (±2.1%)
	Foam	0.056 (±2.2%)	0.005 (±8.5%)	0.061 (±2.1%)
	Back Faceplate	0.36 (±2.2%)	0.03 (±7.6%)	0.39 (±2.1%)
AlBeMet GIMM	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 Focusing Dielectric Mirror M2 Located @14.9 m from GIMM

		Flux ($cm^{-2}.s^{-1}$)	Fluence per full power year (cm^{-2})
SiC GIMM	Neutrons E>0.1 MeV	2.05×10^{10} (±4.0%)	6.46×10^{17}
	Total Neutrons	2.27×10^{10} (±4.0%)	7.15×10^{17}
	Total Gamma	0.88×10^{10} (±6.9%)	2.77×10^{17}
AlBeMet GIMM	Neutrons E>0.1 MeV	**3.18×10^{10}** (±3.9%)	**1.00×10^{18}**
	Total Neutrons	3.57×10^{10} (±3.8%)	1.12×10^{18}
	Total Gamma	1.35×10^{10} (±5.9%)	4.25×10^{17}

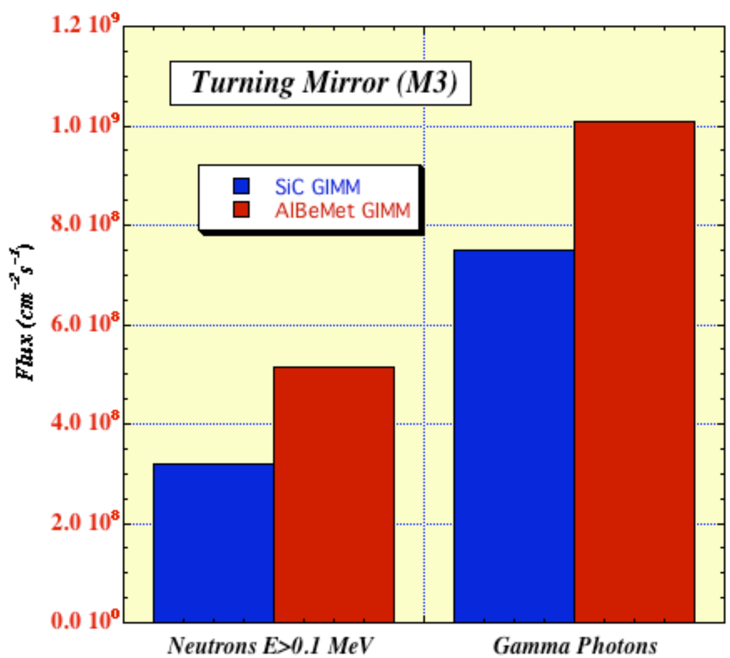
- Results are slightly lower than 2-D predictions (by <50%)
- Neutron flux is a factor of ~1.6 higher with AlBeMet GIMM
- Total neutron and gamma fluxes are more than two orders of magnitude lower than at GIMM
- Neutron spectrum is hard with ~90% of neutrons @ E>0.1 MeV



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

		Peak Flux ($cm^{-2}.s^{-1}$)	Peak Fluence per full power year (cm^{-2})
SiC GIMM	Neutrons E>0.1 MeV	3.18×10^{8} (±7.3%)	1.00×10^{16}
	Total Neutrons	8.44×10^{8} (±8.2%)	2.66×10^{16}
	Total Gamma	7.51×10^{8} (±8.0%)	2.37×10^{16}
AlBeMet GIMM	Neutrons E>0.1 MeV	**5.14×10^{8}** (±7.6%)	**1.62×10^{16}**
	Total Neutrons	1.31×10^{9} (±8.8%)	4.13×10^{16}
	Total Gamma	1.01×10^{9} (±5.5%)	3.18×10^{16}

- Peak flux values at M3 are higher than those predicted from 2-D calculations by factors <2
- Neutron flux is a factor of ~1.6 higher with AlBeMet GIMM
- Total neutron flux is about two orders of magnitude lower than at M2 with smaller gamma flux reduction
- Neutron spectrum is softer with ~40% of neutrons @ E>0.1 MeV



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Nuclear Heating in Sapphire M2 and M3 Mirrors

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

- Nuclear heating values in dielectric mirrors are lower than 2-D predictions by factors <2
- 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

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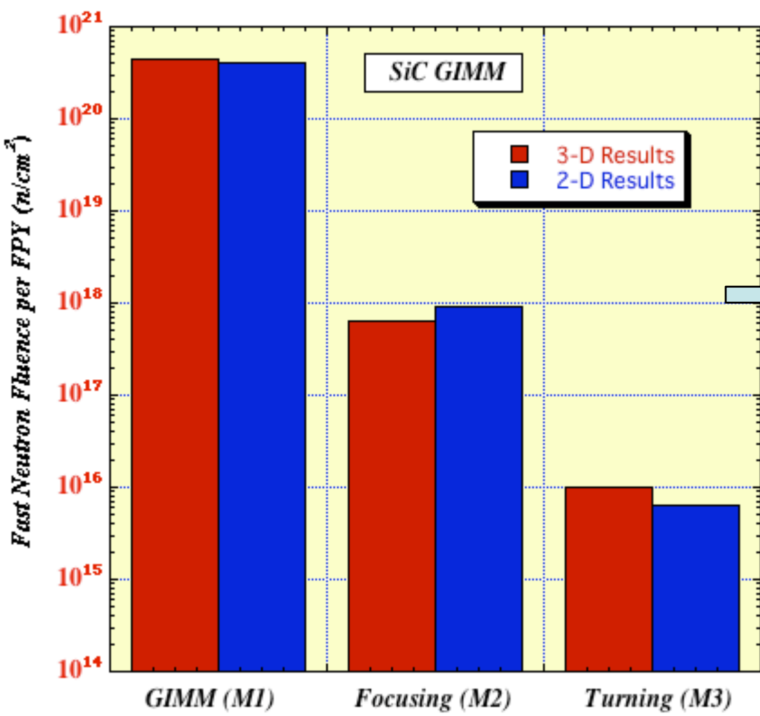
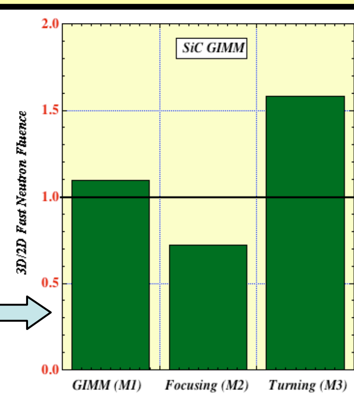
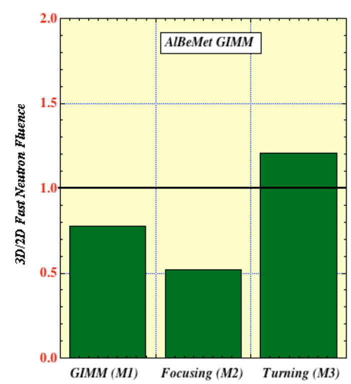
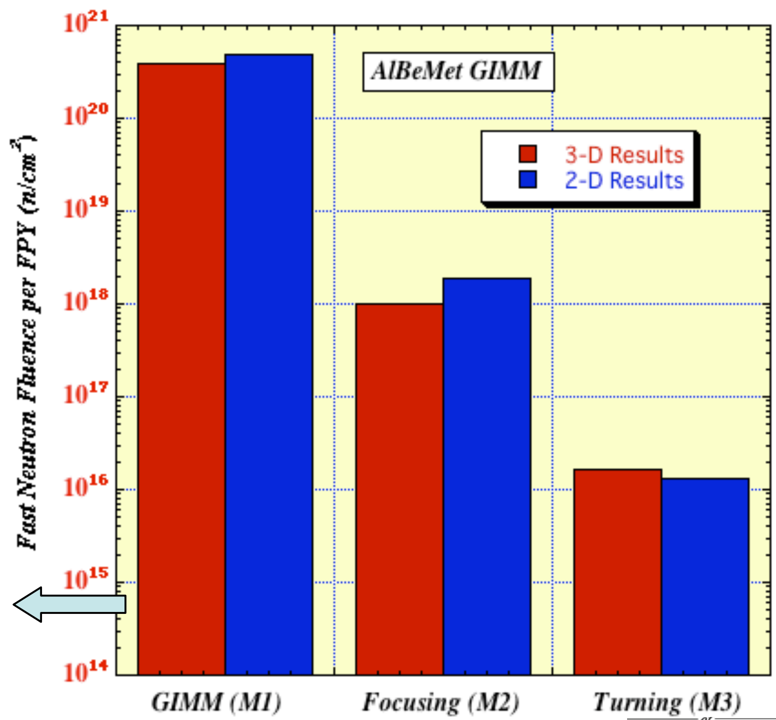
Peak Fast (E>0.1 MeV) Neutron Fluence per Full Power Year at Mirrors in Final Optics of HAPL

	Peak Fast Neutron Fluence per FPY (n/cm^2)	
	SiC GIMM	***AlBeMet GIMM***
GIMM (M1)	*4.38×10^{20} (±2.1%)*	*3.81×10^{20} (±2.1%)*
Focusing Mirror (M2)	*6.46×10^{17} (±4.0%)*	*1.00×10^{18} (±3.9%)*
Turning Mirror (M3)	*1.00×10^{16} (±7.3%)*	*1.62×10^{16} (±7.6%)*









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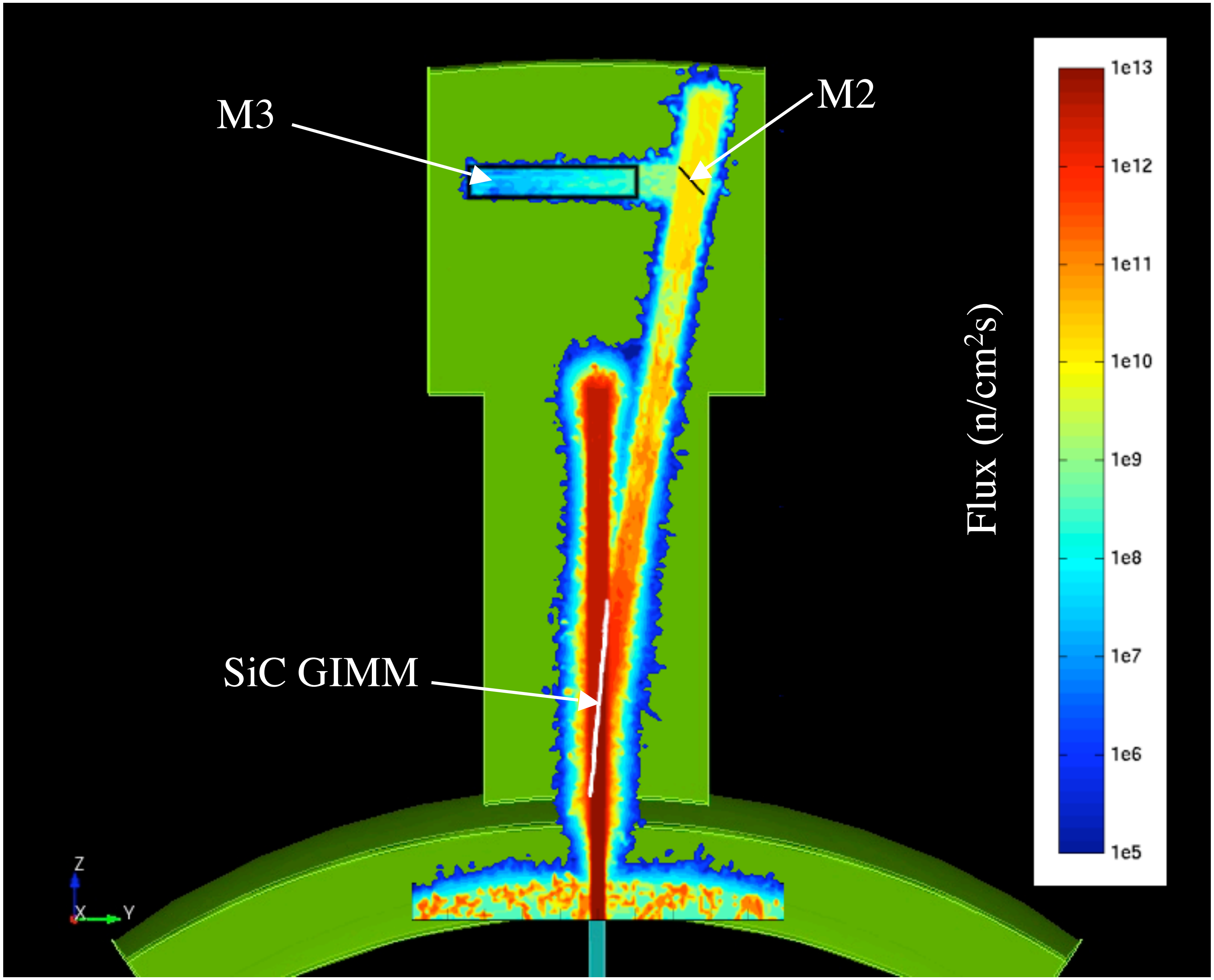
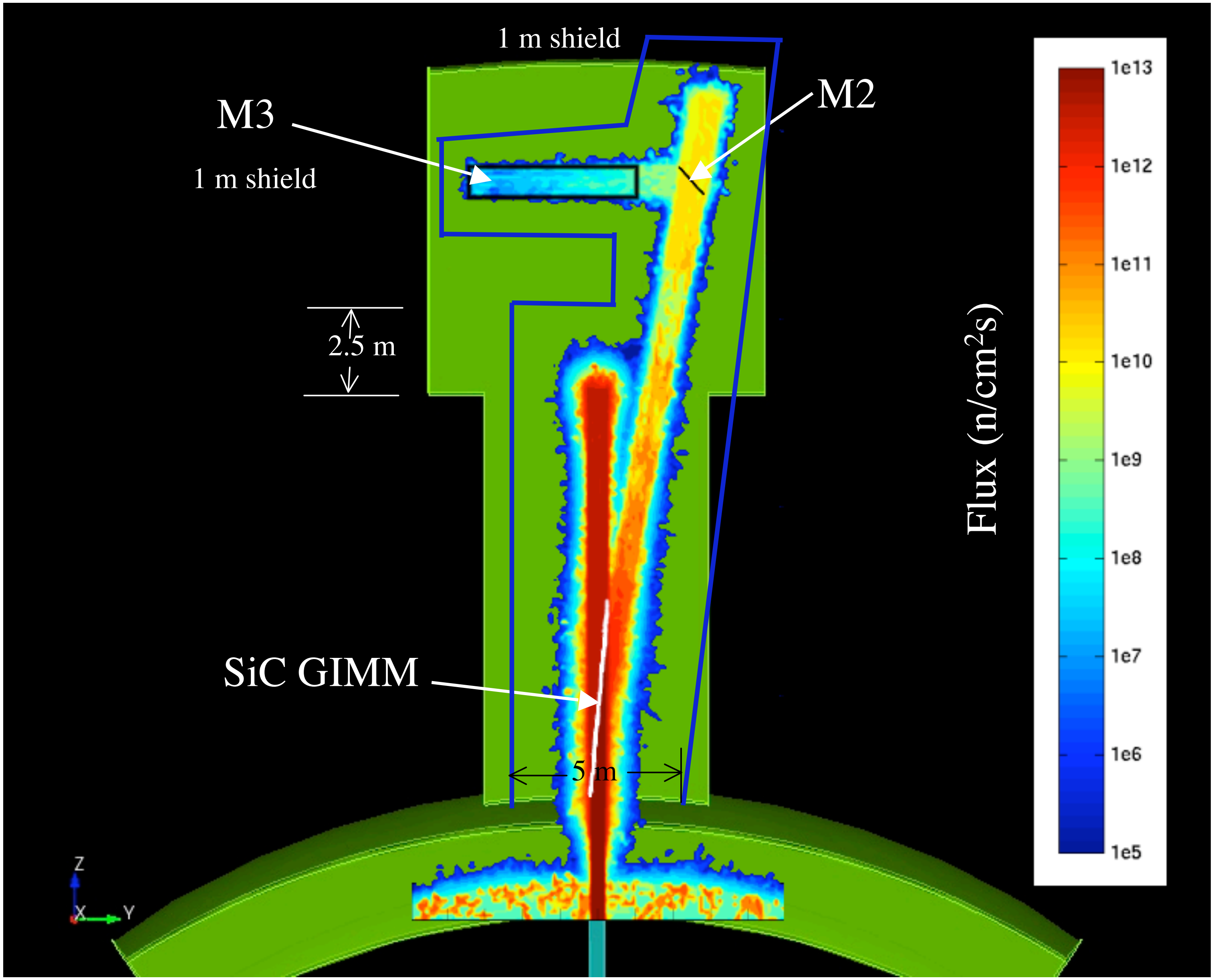
Fast Neutron Flux Distribution in Final Optics of HAPL

- 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

Fast Neutron Flux Distribution in Final Optics of HAPL



Proposed Shield Modification at Final Optics of HAPL



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Summary and Conclusions

- 3-D neutronics calculation performed to determine nuclear environment in the HAPL final optics and compare impact of possible GIMM design options
- 3-D results confirmed findings from 2-D analysis with difference in calculated nuclear flux and heating less than a factor of 2
- Neutron flux at dielectric mirrors is higher by a factor of ~1.6 with AlBeMet
- Neutron spectrum softens significantly at M3 (~40% >0.1 MeV vs. ~90% at M2)
- Detailed distribution of fast neutron flux generated
- Shield requirement around final optics determined to allow personnel access outside containment building during operation (dose <~1 mrem/h)
- Peak fast (E>0.1 MeV) neutron fluence per FPY:

GIMM	***4.4×10^{20} n/cm^2***
M2	***1.0×10^{18} n/cm^2***
M3	***1.6×10^{16} n/cm^2***

- Significant drop in nuclear environment occurs as one moves from the GIMM to dielectric focusing and turning mirrors
- Experimental data on radiation damage to metallic and dielectric mirrors are essential for accurate lifetime prediction
- 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

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