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

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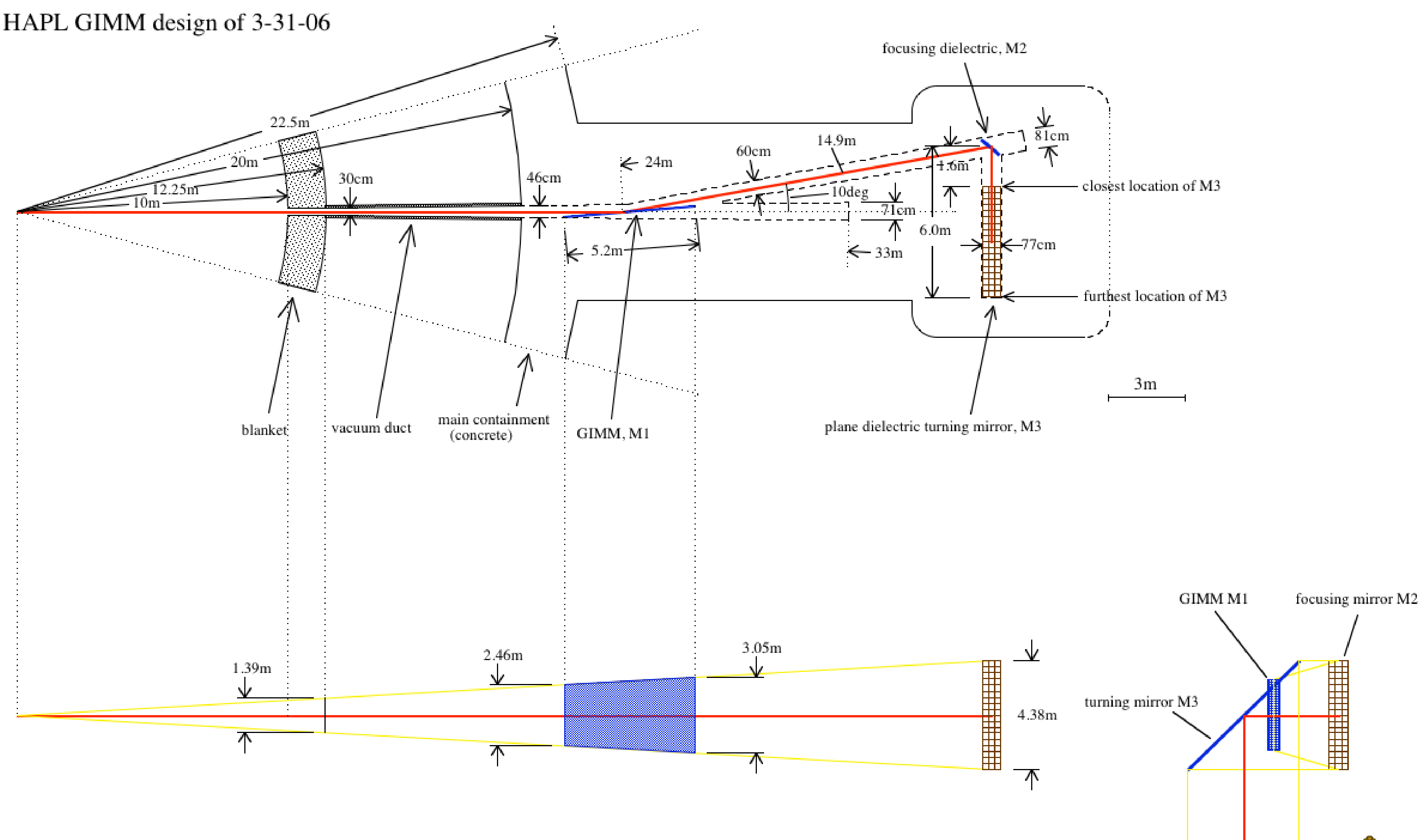
Design Parameters for Baseline HAPL Design

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

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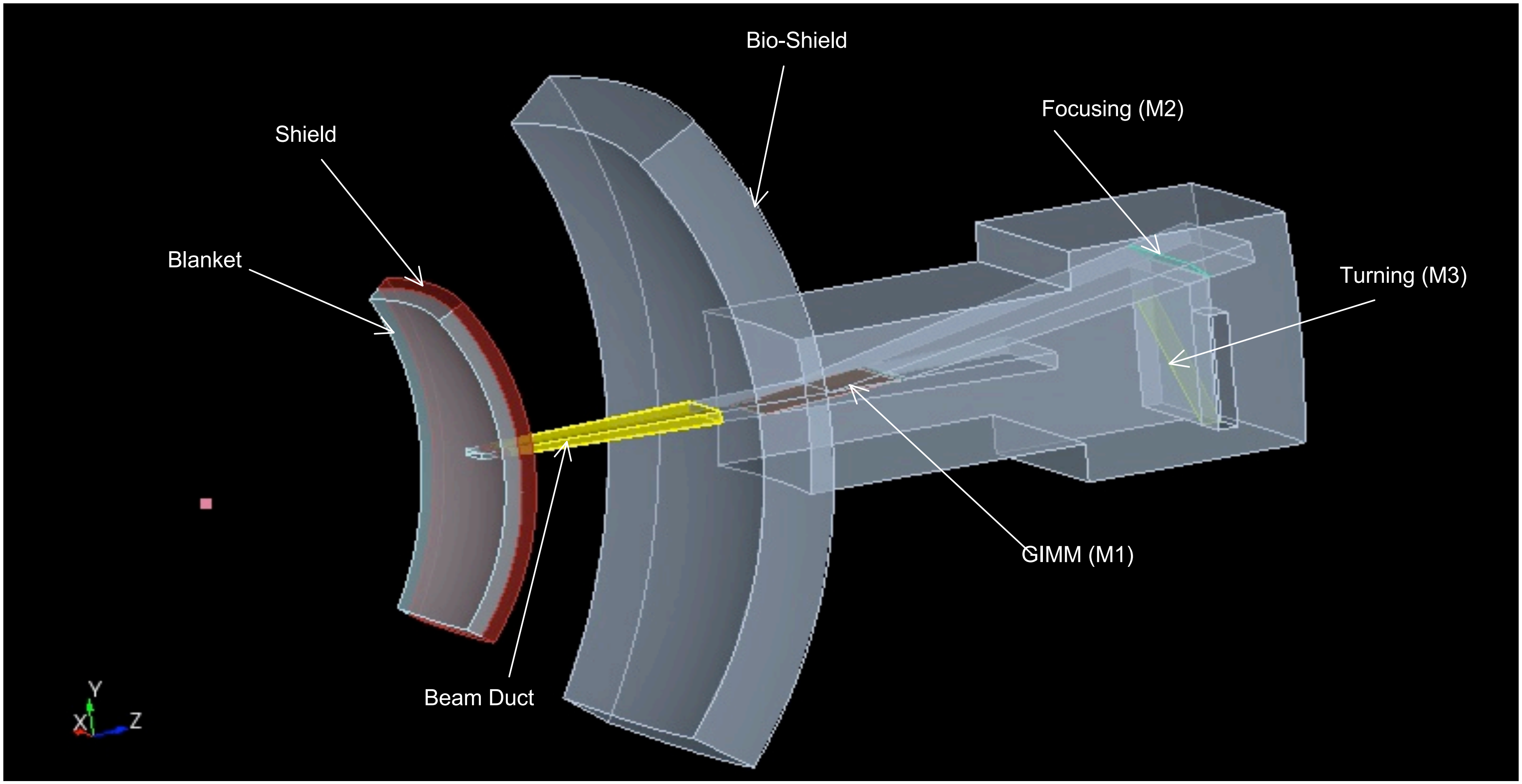
Geometrical Model Used in 3-D Neutronics Analysis



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

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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

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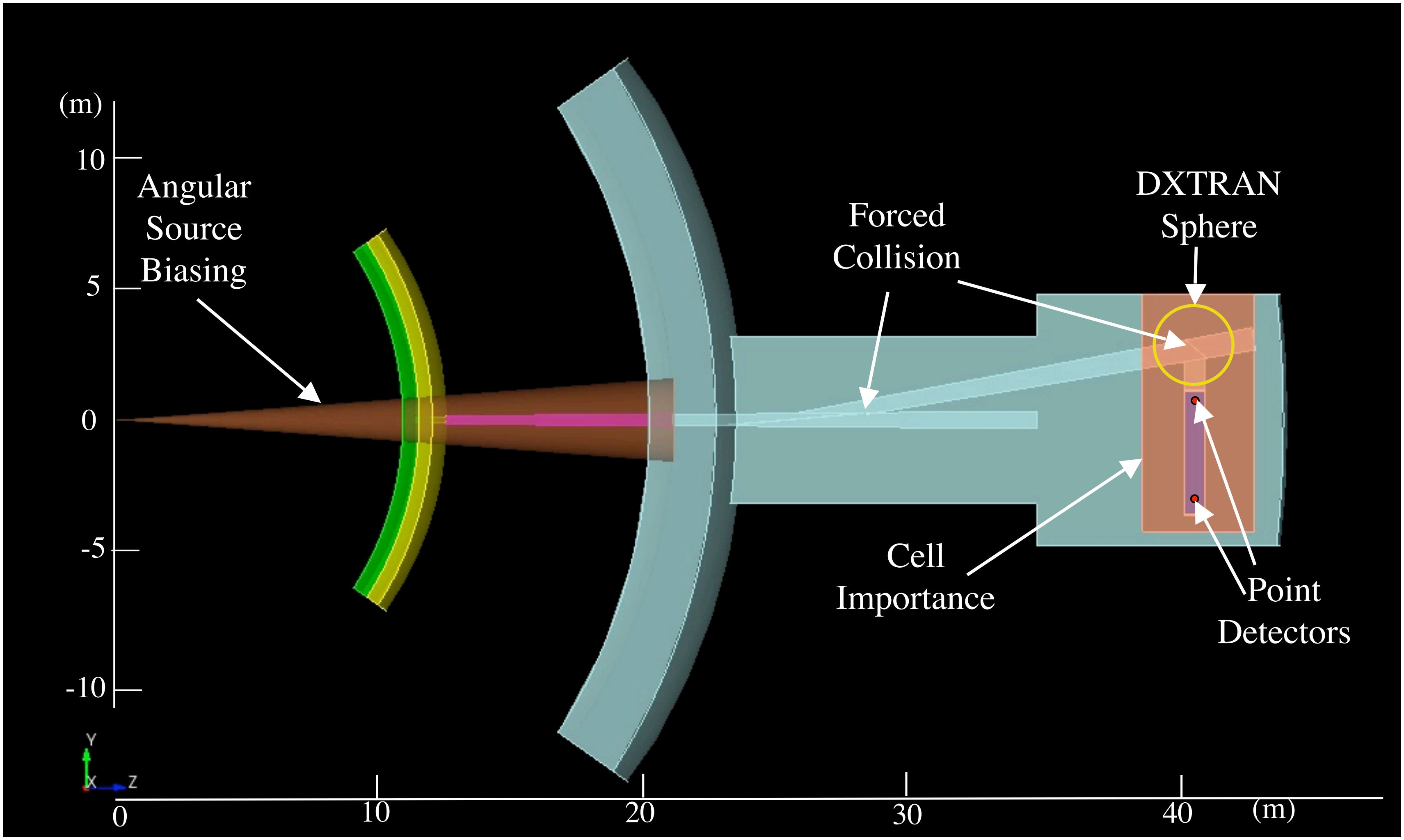
Variance Reduction Techniques Applied



Flux at Front Faceplate of GIMM

		Flux ($cm^{-2}.s^{-1}$)
SiC GIMM	Neutrons E>0.1 MeV	**$1.39x10^{13}$** (±2.1%)
	Total Neutrons	$1.43x10^{13}$ (±2.1%)
	Total Gamma	$1.57x10^{12}$ (± 5.5%)
AlBeMet GIMM	Neutrons E>0.1 MeV	$1.21x10^{13}$ (±2.1%)
	Total Neutrons	$1.30x10^{13}$ (±2.1%)
	Total Gamma	$1.88x10^{12}$ (±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)

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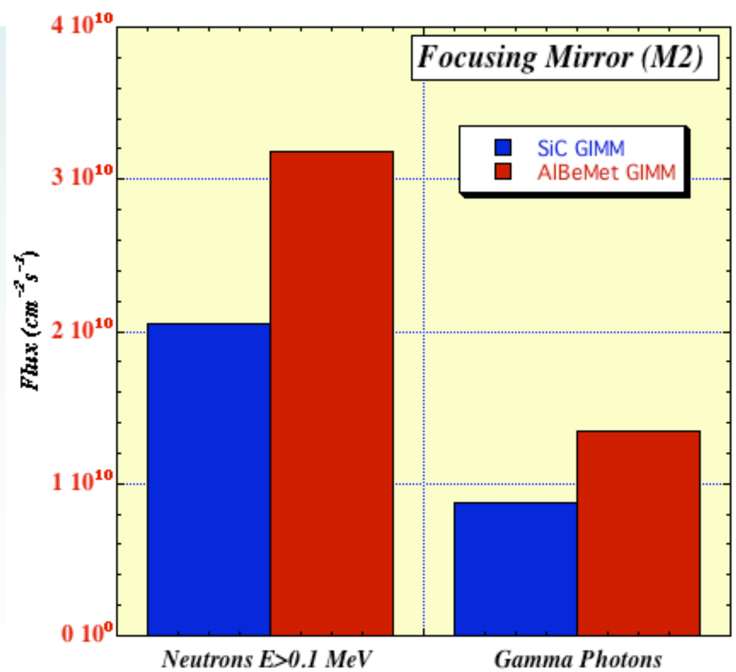
Flux at Focusing Dielectric Mirror M2 Located @14.9 m from GIMM

		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}

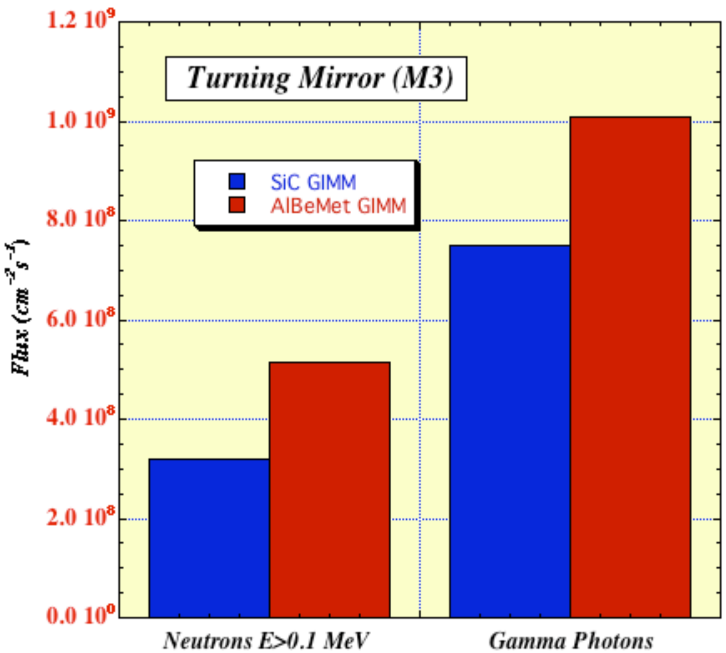
- Results are slightly lower than 2-D predictions (by <50%)
- Neutron flux is a factor of ~1.6 higher with AlBeMet GIMM
- Total neutron and gamma fluxes are more than two orders of magnitude lower than at GIMM
- Neutron spectrum is hard with ~90% of neutrons @ E>0.1 MeV



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	$3.18x10^8$ (±7.3%)	$1.00x10^{16}$
	Total Neutrons	$8.44x10^8$ (±8.2%)	$2.66x10^{16}$
	Total Gamma	$7.51x10^8$ (±8.0%)	$2.37x10^{16}$
AlBeMet GIMM	Neutrons E>0.1 MeV	**$5.14x10^8$** (±7.6%)	**$1.62x10^{16}$**
	Total Neutrons	$1.31x10^9$ (±8.8%)	$4.13x10^{16}$
	Total Gamma	$1.01x10^9$ (±5.5%)	$3.18x10^{16}$

- 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



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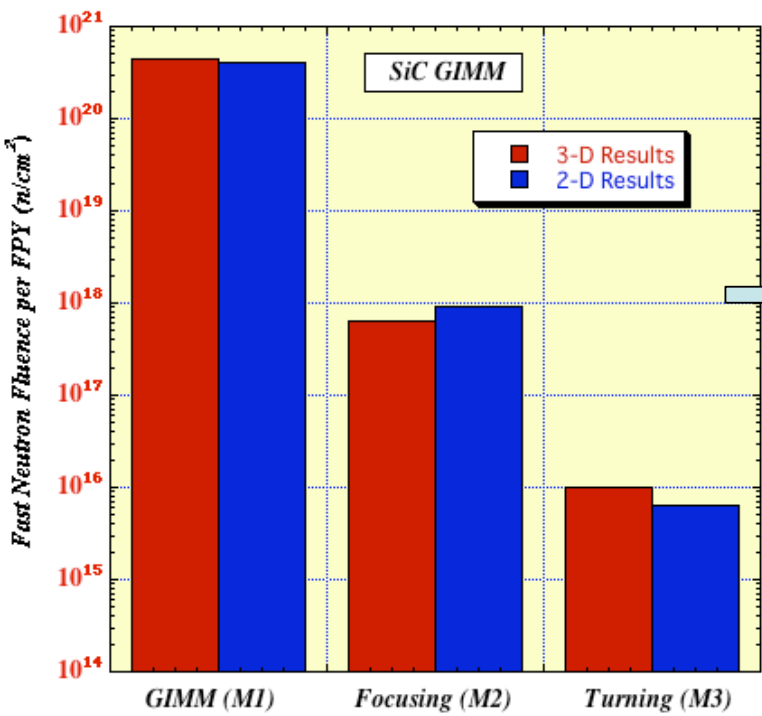
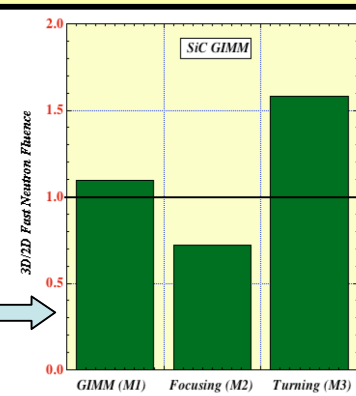
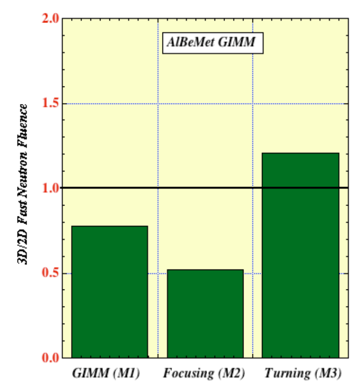
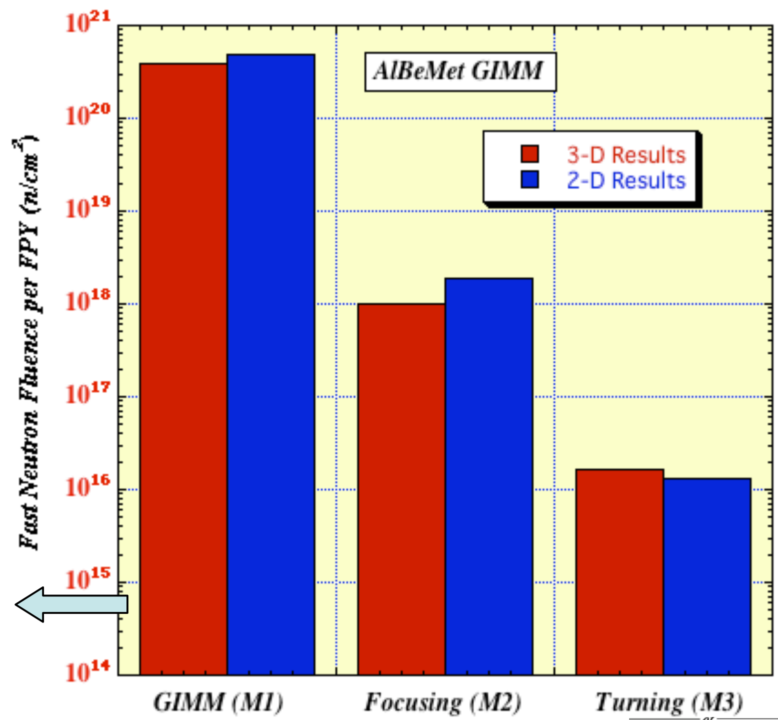
Peak Fast (E>0.1 MeV) Neutron Fluence per Full Power Year at Mirrors in Final Optics of HAPL

	Peak Fast Neutron Fluence per FPY (n/cm^2)	
	SiC GIMM	***AlBeMet GIMM***
GIMM (M1)	*$4.38x10^{20}$ (±2.1%)*	*$3.81x10^{20}$ (±2.1%)*
Focusing Mirror (M2)	*$6.46x10^{17}$ (±4.0%)*	*$1.00x10^{18}$ (±3.9%)*
Turning Mirror (M3)	*$1.00x10^{16}$ (±7.3%)*	*$1.62x10^{16}$ (±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

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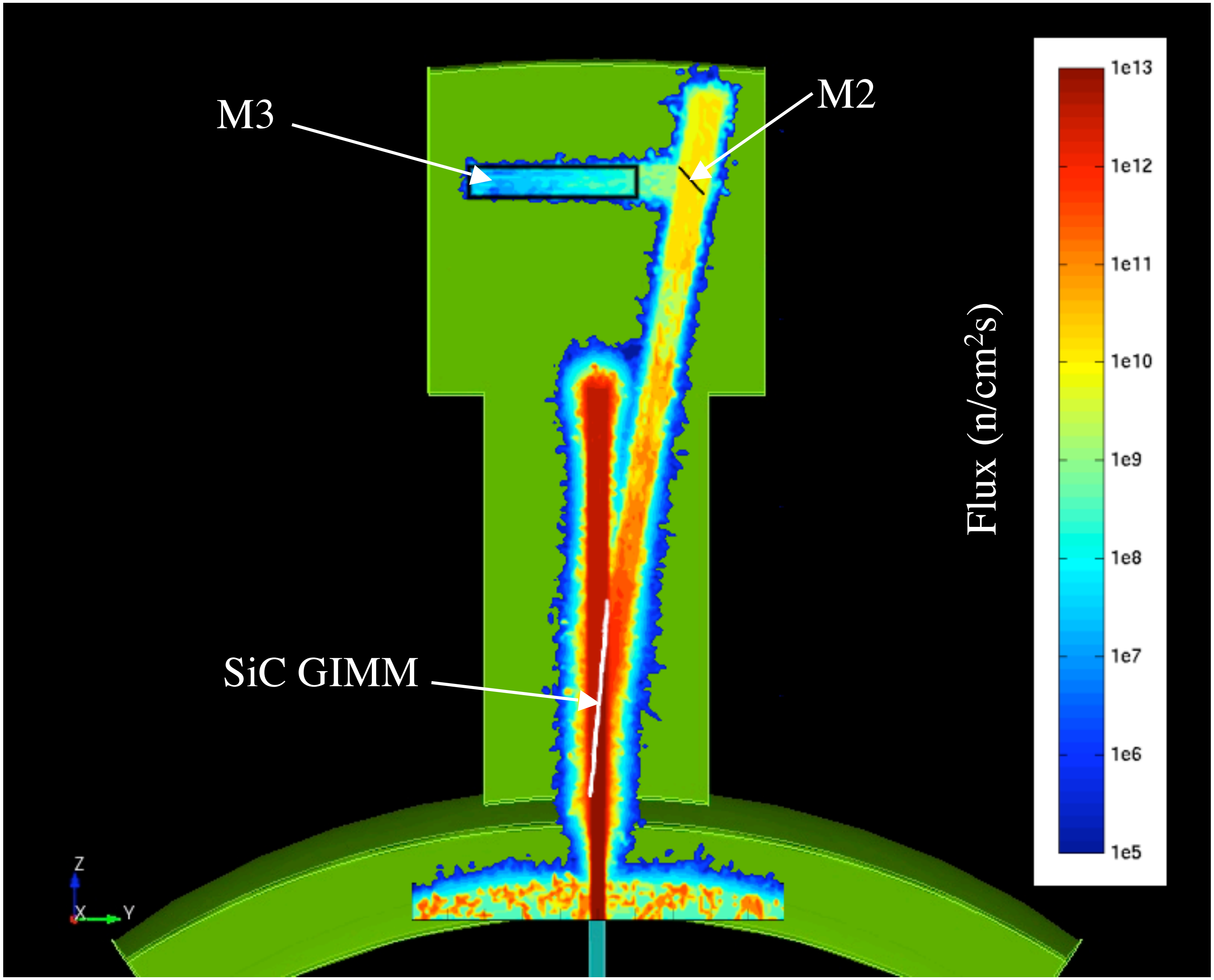
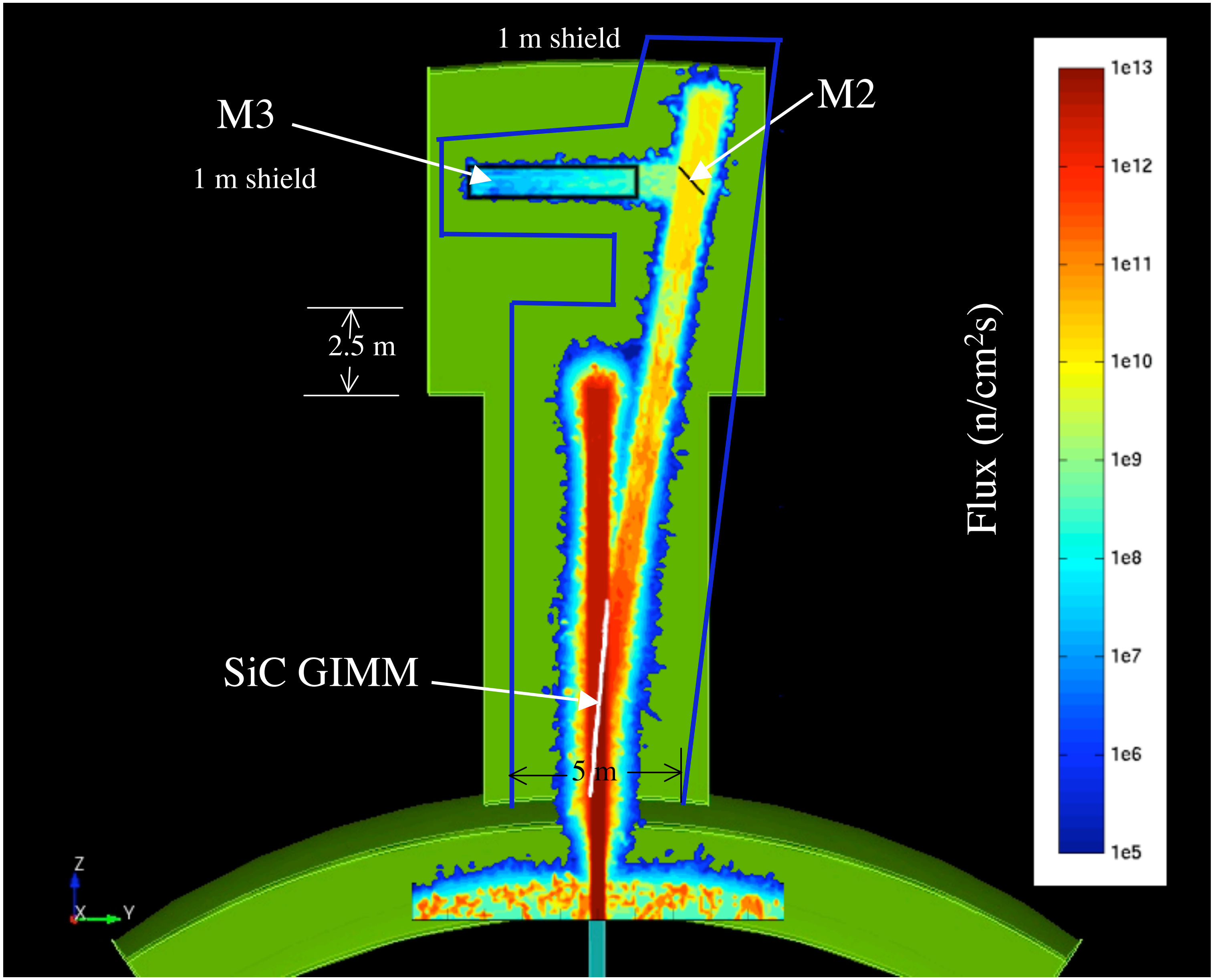
Fast Neutron Flux Distribution in Final Optics of HAPL



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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