Nuclear Assessment for Final Optics of HAPL

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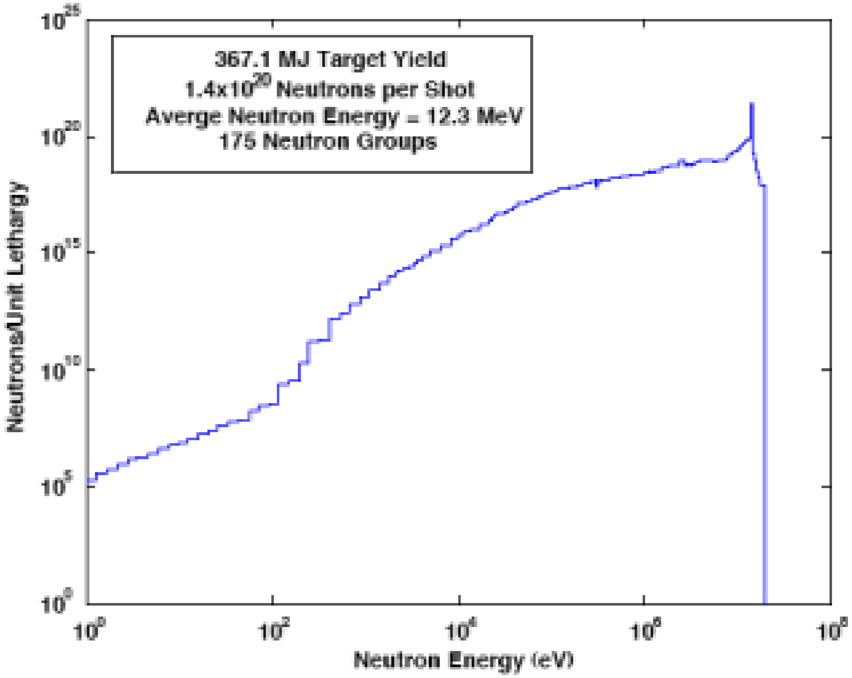
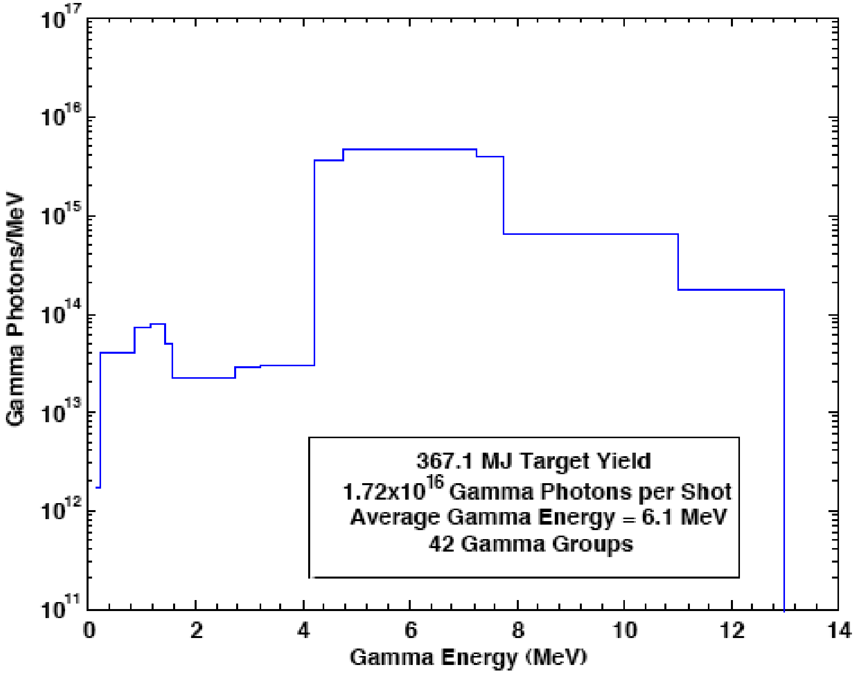
Design Parameters for Baseline HAPL Design

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

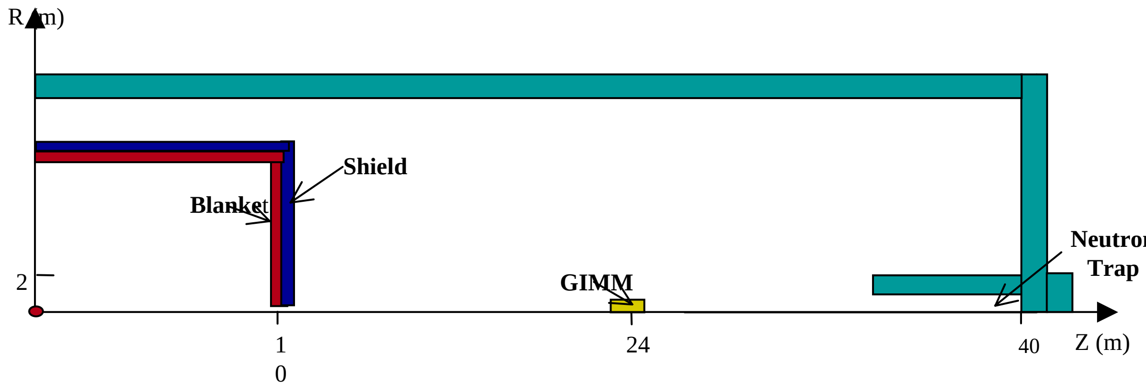
Energy Spectra of Source Neutrons and Gammas Used in Neutronics Calculations





Impact of Liner Material on Reflection from Neutron Trap

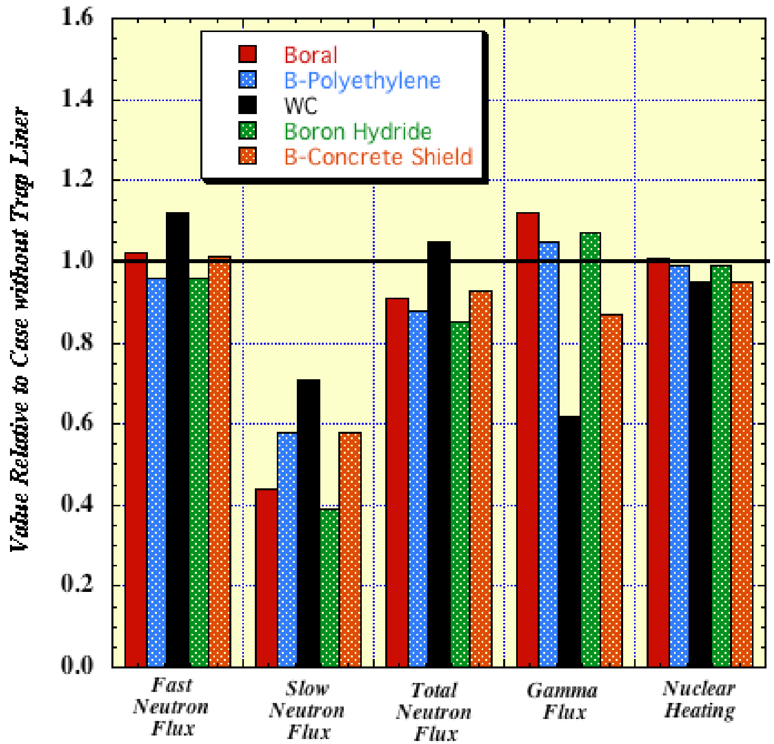
- Investigated effectiveness of lining inner surface of neutron trap on reflection
- Effect investigated with a transparent GIMM with all source neutrons impinging on the lined trap
- Flux calculated at 40 cm from bottom of trap
- Liners considered are:
  - Boral (Al+B_4C)
  - Borated Polyethylene
  - WC
  - Boron Hydride ($B_{10}H_{14}$)
- Option of adding boron to the concrete shield was also investigated



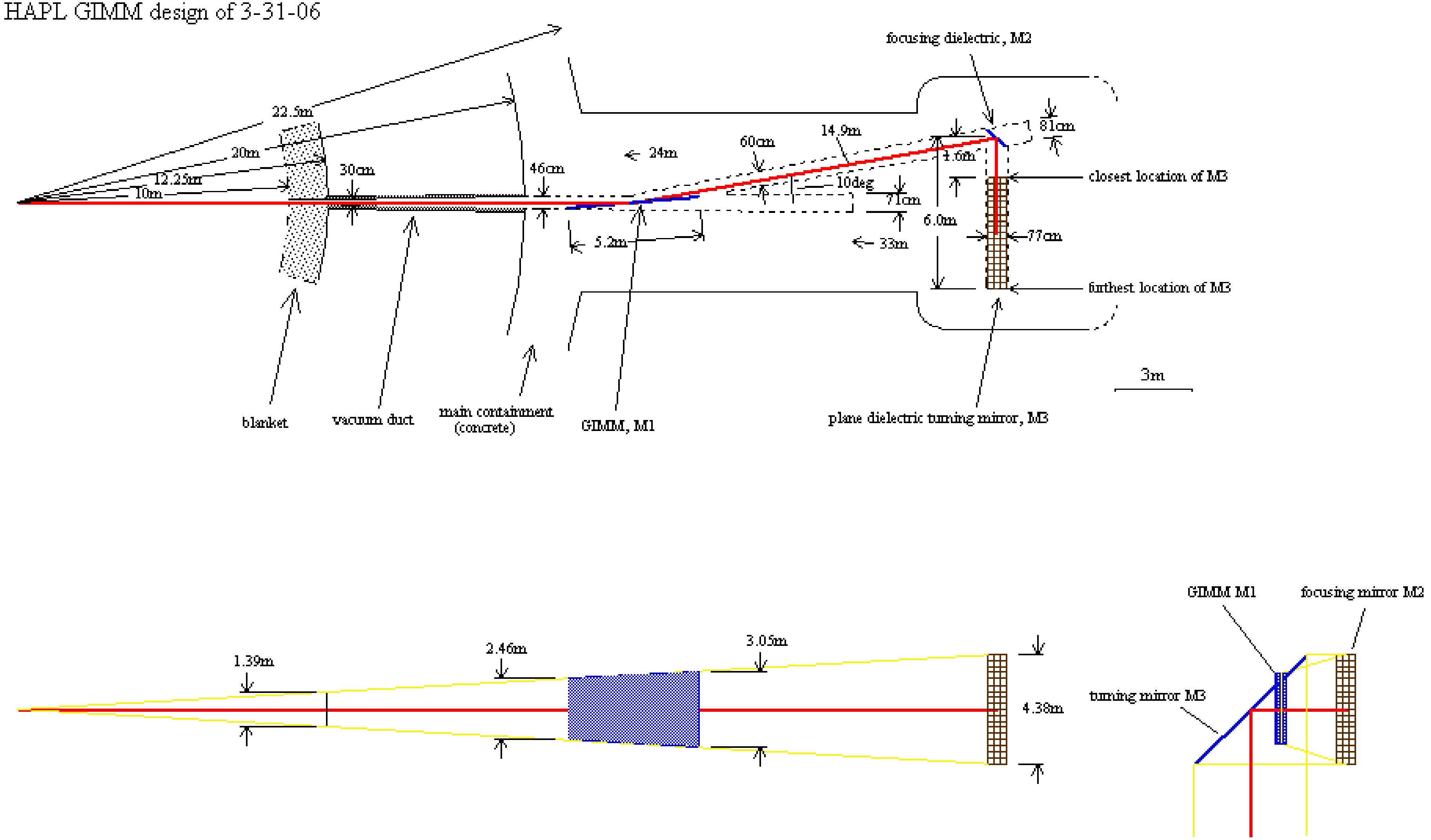
Impact of Liner Material on Reflection from Neutron Trap

	1 cm Boral liner	1 cm borated polyethylene liner	1 cm WC liner	1 cm Boron hydride liner	5% B in concrete shield
Fast neutron flux	(+2%)	(-4%)	(+12%)	(-4%)	(+1%)
Slow neutron flux	(-56%)	(-42%)	(-29%)	(-61%)	(-42%)
Total neutron flux	(-9%)	(-12%)	(+5%)	(-15%)	(-7%)
Gamma flux	(+12%)	(+5%)	(-38%)	(+7%)	(-13%)
Nuclear heating	(+1%)	(-1%)	(-5%)	(-1%)	(-5%)

- Boron is more effective in reducing the low energy component of the neutron flux with modest effect on fast neutron flux and gamma flux increases
- Heavy material like WC is effective only in reducing gamma flux
- Materials rich in hydrogen and boron (boron hydride, borated polyethelyne) have the best impact on fast neutron flux that is believed to impact optics lifetime



Baseline HAPL Optics Configuration with GIMM



Provided by Malcolm McGeoch

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Detailed 2-D Neutronics Analysis

- 2-D neutronics calculation performed in R-Z geometry to compare the impact of the GIMM design option and duct lining on the radiation environment at the dielectric mirror
- Two lightweight GIMM design options were considered
- Z axis is along the beam line
- Due to 2-D modeling limitation, circular GIMM, beam port, and neutron trap were used with the area of beam port preserved
- Beam port at chamber wall is 0.23 m high x 1.38 m wide modeled as circular port with 0.225 m radius
- GIMM modeled circular with 0.45 m radius
- Neutron traps used behind GIMM and M2
- Effective thickness of GIMM layers as seen by source neutrons was modeled (effective thickness = actual thickness/cos85)
- Detailed layered radial build of blanket/shield included in model
- Containment building housing the optics and neutron traps used with 70% concrete, 20% carbon steel C1020, and 10% H_2O

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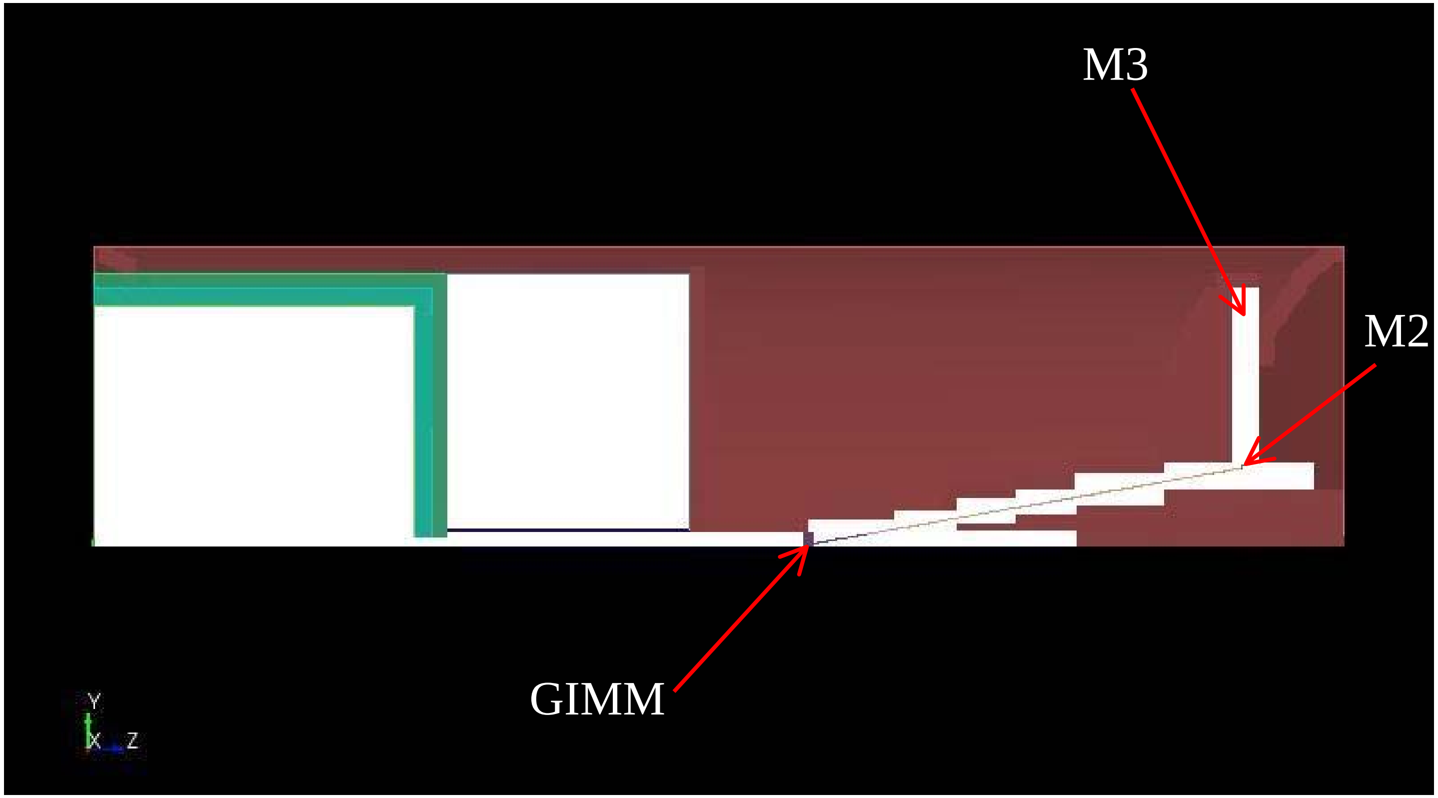
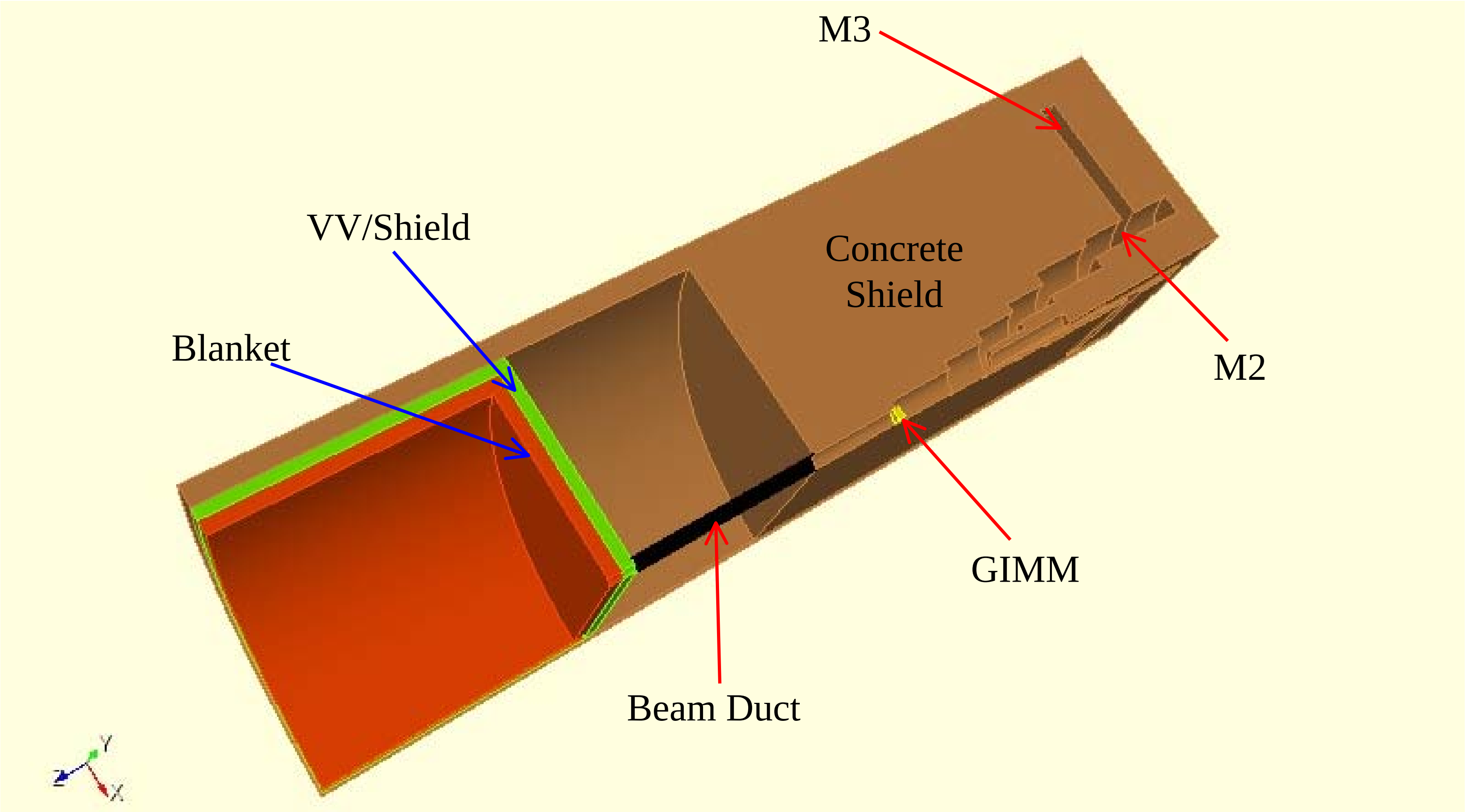
Vertical Cross Section in the 2-D Neutronics Model



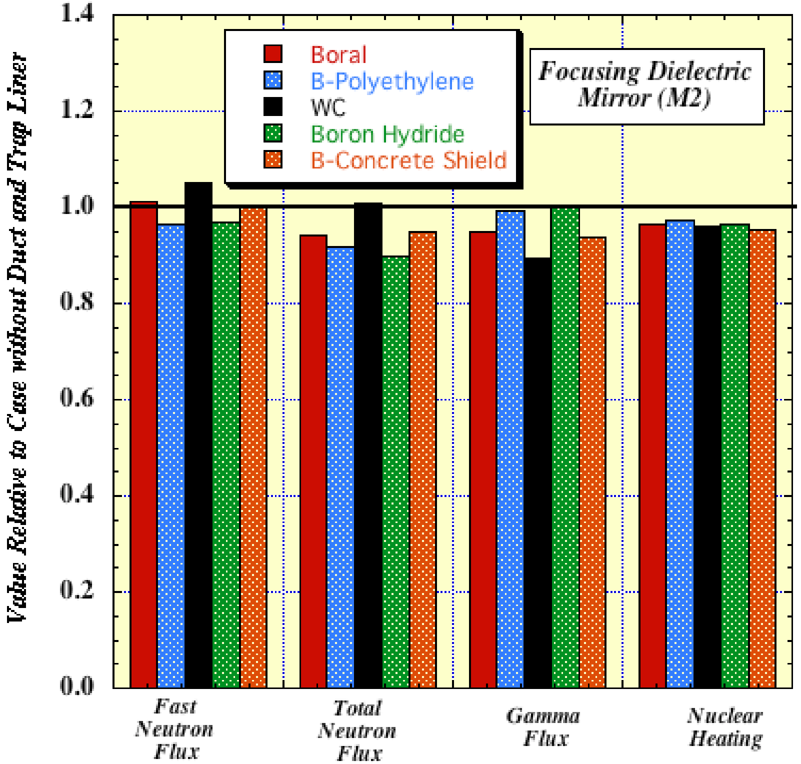
Isometric View of the 2-D Neutronics Model



Impact of Liner Material on Radiation Level at M2

Radiation levels at focusing dielectric mirror M2 relative to the case without liners
(M2 @ 14.9 m from SiC GIMM)

	1 cm Boral liner	1 cm borated polyethylene liner	1 cm WC liner	1 cm Boron hydride liner	5% B in concrete shield
Fast neutron flux	1.011	0.965	1.053	0.968	1.000
Total neutron flux	0.942	0.917	1.006	0.898	0.948
Gamma flux	0.950	0.993	0.893	1.000	0.936
Nuclear heating	0.964	0.971	0.961	0.964	0.951



- Boron hydride and borated polyethelyne have the best impact on fast neutron flux that is believed to impact optics lifetime
- However, effect at M2 is very small since flux is dominated by direct neutrons scattered from GIMM with smaller contribution from neutrons scattered from duct wall
- Design complexity from adding liner is not justified

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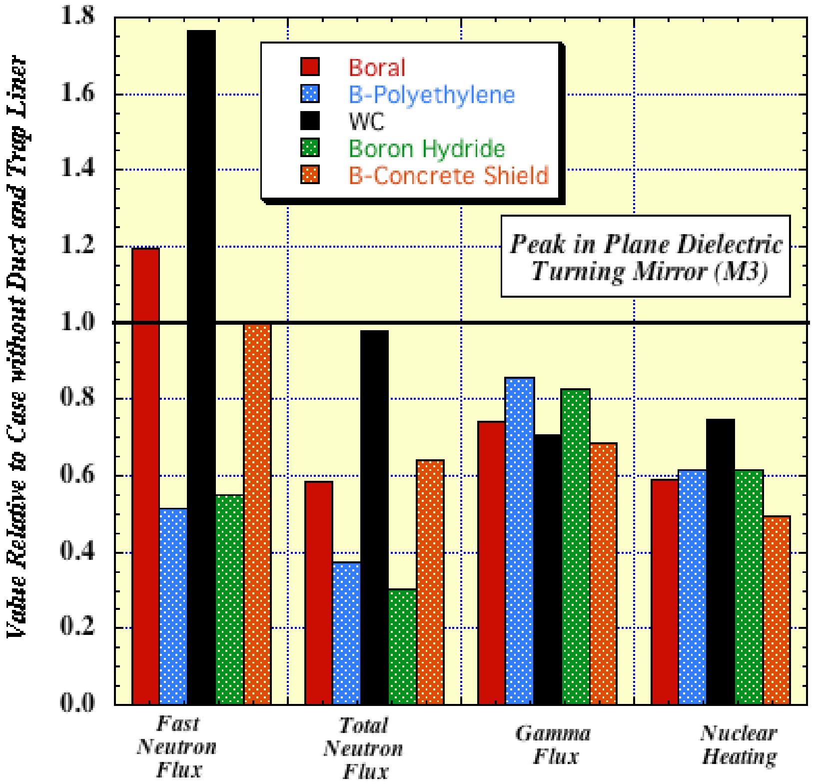
Impact of Liner Material on Radiation Level at M3

Peak radiation levels at plane dielectric turning mirror M3 relative to the case without liners
(M3 @ 1.6 m from M2)

	1 cm Boral liner	1 cm borated polyethylene liner	1 cm WC liner	1 cm Boron hydride liner	5% B in concrete shield
Fast neutron flux	1.194	0.512	1.767	0.552	1.005
Total neutron flux	0.583	0.372	0.978	0.303	0.639
Gamma flux	0.744	0.856	0.706	0.828	0.684
Nuclear heating	0.591	0.615	0.746	0.615	0.492



- Effect of liner enhanced at M3
- Boron hydride and borated polyethelyne have the best impact on fast neutron flux that is believed to impact optics lifetime
- However, effect at M3 is at most a factor of 2 reduction
- Since flux at M3 is much smaller than that at M2, design complexity from adding liner is not justified

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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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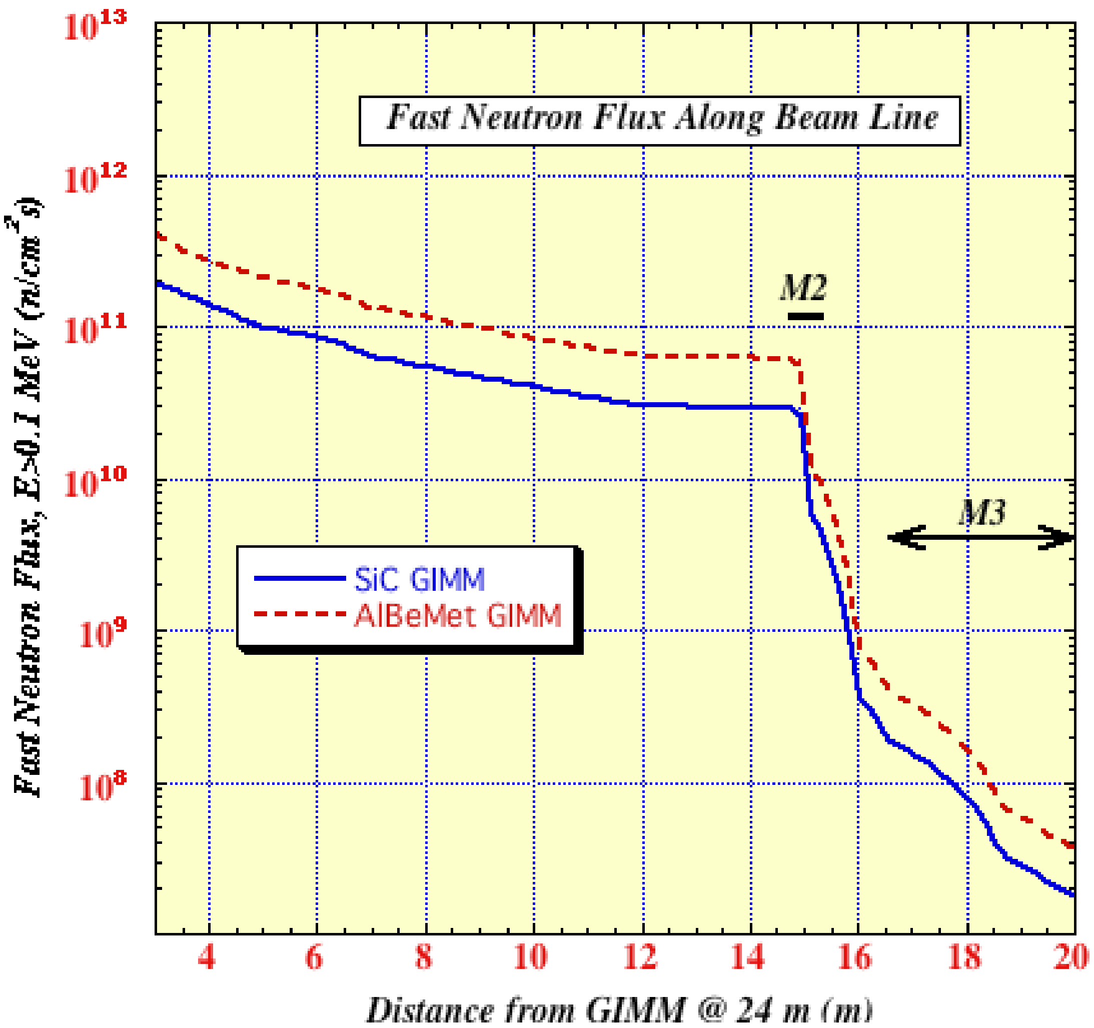
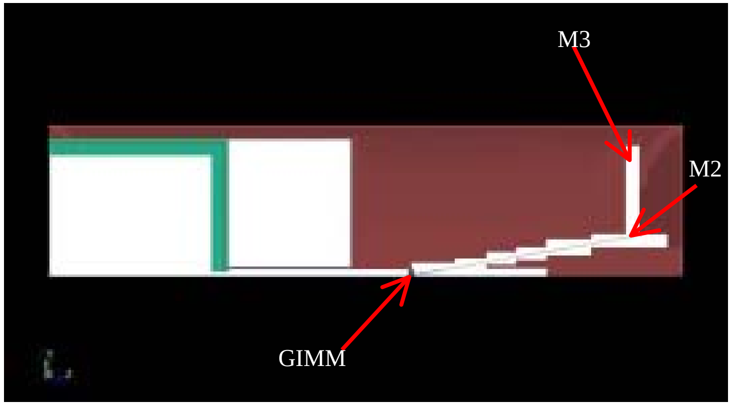
Fast neutron Flux Along Beam Line



- Neutron flux is higher by a factor of ~2 with AlBeMet GIMM due to larger thickness and neutron multiplication in Be
- Significant drop in flux occurs at beam duct bend around location of M2
- Peak fast neutron flux at M3 is ~2 orders of magnitude lower than that at M2



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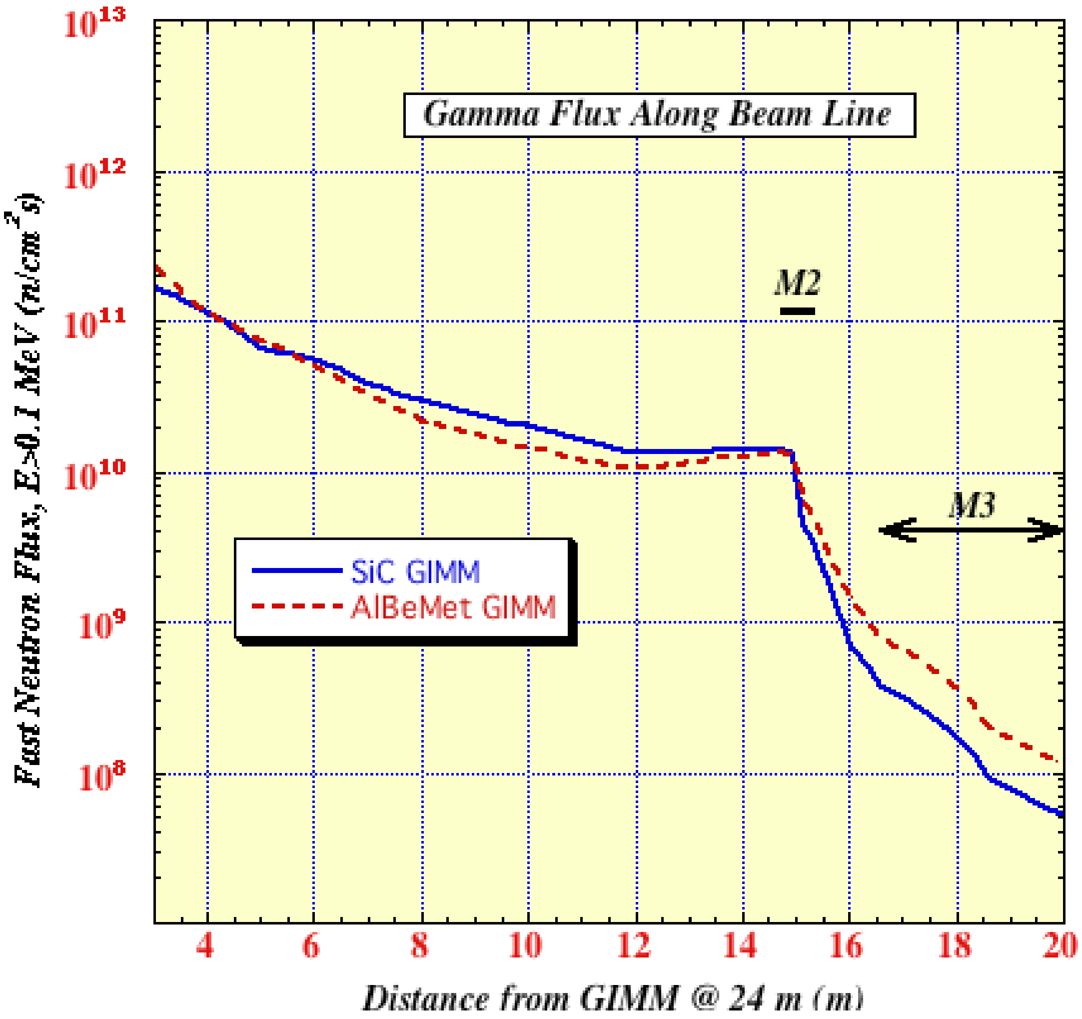
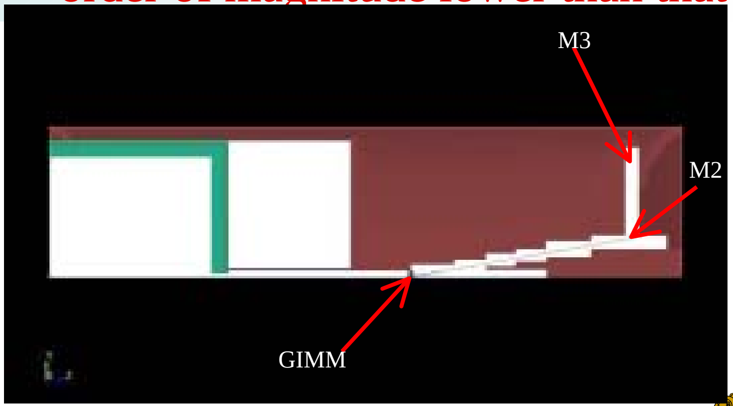
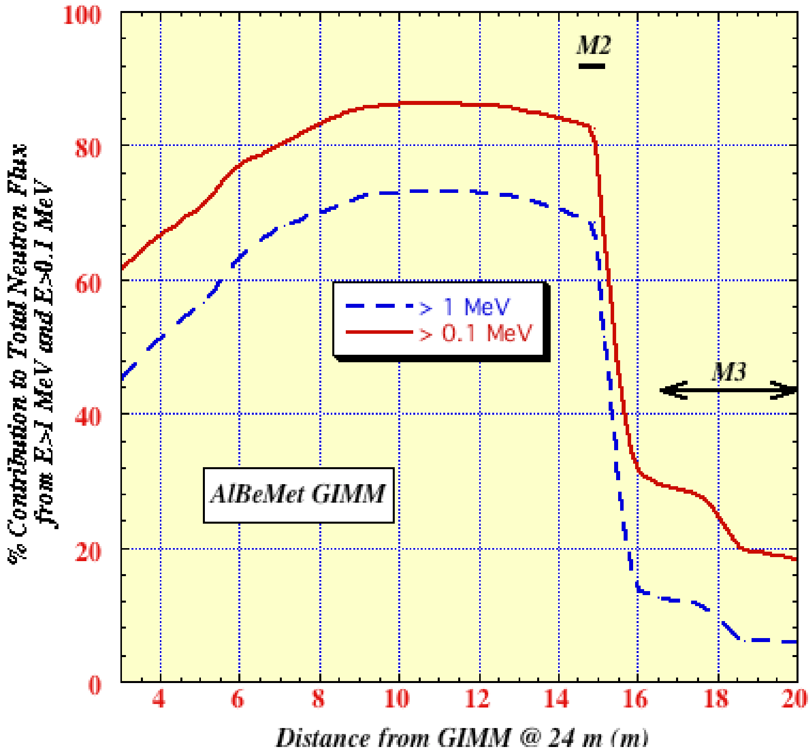
Gamma Flux Along Beam Line

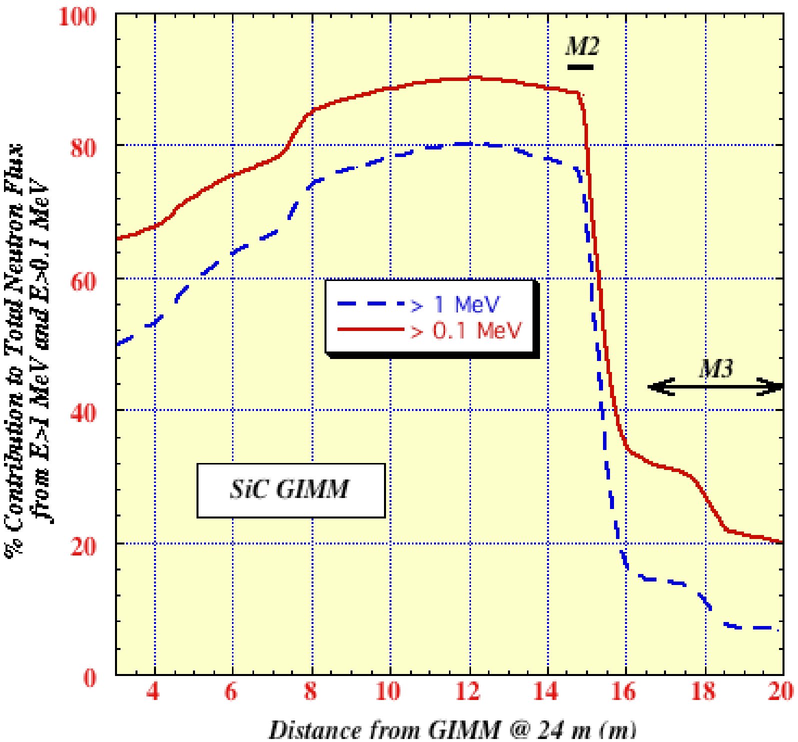


- Gamma flux is comparable up to M2 due to dominant contribution from GIMM but is higher at M3 with AlBeMet GIMM due to dominant contribution from gamma generated in shield by the larger neutron flux
- Significant drop in flux occurs at beam duct bend around location of M2
- Peak gamma flux at M3 is ~ an order of magnitude lower than that

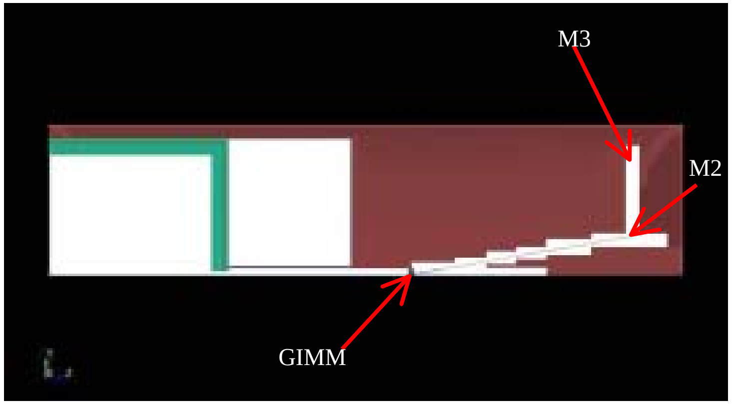


Neutron Spectrum Along Beam Line





- Neutron spectrum gets harder in part of beam duct approaching M2 (not in direct view of GIMM neutron trap) with more direct contribution from GIMM and less from trap
- Neutron spectrum softens significantly at M3
- Neutron spectrum is slightly harder with SiC GIMM



Flux at Front of GIMM

- Contribution to neutron flux at GIMM from scattering inside chamber is small (<3%)
- Up to 37% of fast neutron flux contributed from scattering in GIMM itself
- Material choice and thickness impact peak flux in GIMM
- Neutron flux is higher for AlBeMet (due to Be(n,2n)) and gamma flux is higher for SiC (due to Si inelastic scattering)
- Neutron spectrum softer for AlBeMet with 86% >0.1 MeV compared to 95% for SiC

		Flux $(cm^{-2}.s^{-1})$	% Secondary neutrons
SiC GIMM (R= 23.93 m)	Neutrons E>1 MeV	1.15×10^{13}	17.8%
	Neutrons E>0.1 MeV	**1.27×10^{13}**	**23.9%**
	Total Neutrons	1.34×10^{13}	27.4%
	Total Gamma	**4.53×10^{12}**	
AlBeMet GIMM (R= 23.85 m)	Neutrons E>1 MeV	1.27×10^{13}	25.1%
	Neutrons E>0.1 MeV	**1.55×10^{13}**	**37.3%**
	Total Neutrons	1.81×10^{13}	72.9%
	Total Gamma	**2.58×10^{12}**	

Nuclear Heating in GIMM

		Neutron Heating (W/cm^3)	Gamma Heating (W/cm^3)	Total Heating (W/cm^3)
SiC GIMM	Al Coating	0.22	0.24	0.46
	Front Face Plate	0.57	0.11	**0.68**
	Foam	0.062	0.016	0.078
	Back Face Plate	0.41	0.10	0.51
AlBeMet GIMM	Al Coating	0.24	0.14	0.38
	Front Face Plate	0.48	0.07	**0.55**
	Foam	0.051	0.008	0.059
	Back Face Plate	0.32	0.05	0.37

- Values are at center of GIMM @ 24 m from target and variation along the 5.2 m length of GIMM scales as $1/R^2$
- Power densities in face plates are comparable for the two designs but contribution from gamma heating is smaller in the AlBeMet design
- Nuclear heating in GIMM increased by 30-40% when imbedded in concrete shield
- For 1.2 mm thick SiC face plate nuclear heating is 82 mW/cm^2
- For the twice thicker AlBeMet face plate nuclear heating is 132 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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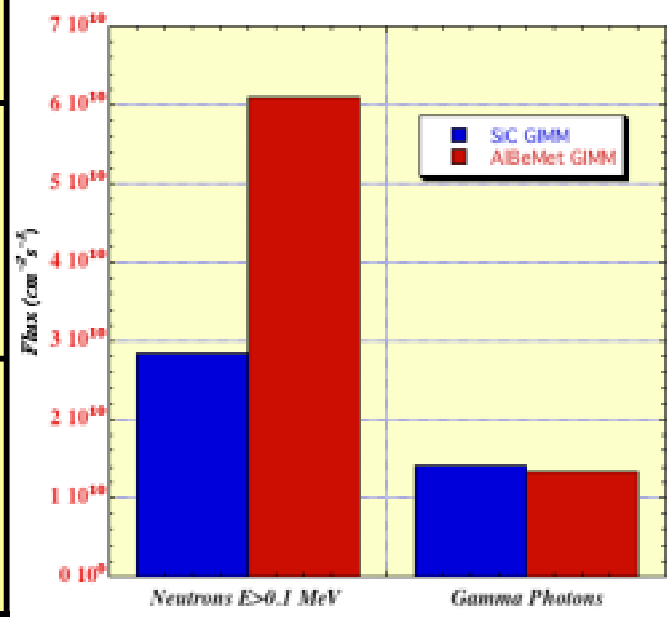
Flux at Focusing Dielectric Mirror M2 Located @14.9 m from GIMM

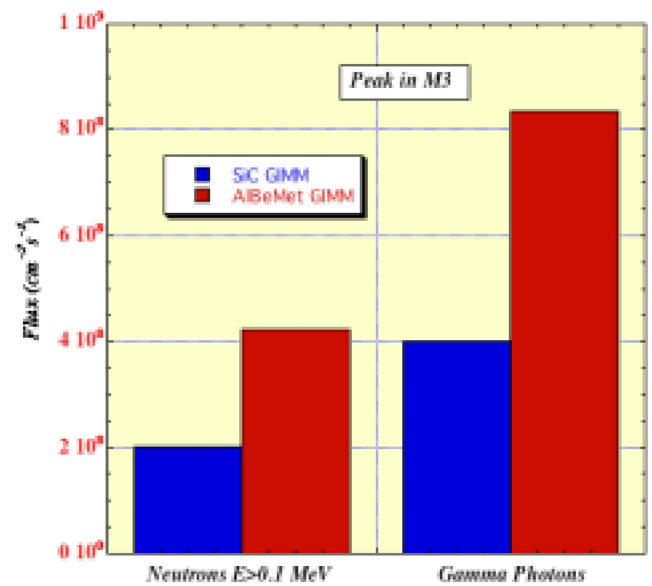
		Flux ($cm^{-2}.s^{-1}$)	Fluence per full power year (cm^{-2})
SiC GIMM	Neutrons E>1 MeV	$2.48x10^{10}$	$7.81x10^{17}$
	Neutrons E>0.1 MeV	$2.85x10^{10}$	$8.98x10^{17}$
	Total Neutrons	$3.25x10^{10}$	$1.02x10^{18}$
	Total Gamma	$1.41x10^{10}$	$4.44x10^{17}$
AlBeMet GIMM	Neutrons E>1 MeV	$5.06x10^{10}$	$1.59x10^{18}$
	Neutrons E>0.1 MeV	**$6.10x10^{10}$**	**$1.92x10^{18}$**
	Total Neutrons	$7.38x10^{10}$	$2.32x10^{18}$
	Total Gamma	$1.34x10^{10}$	$4.22x10^{17}$



- Neutron flux is about a factor of 2 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 ~85% of neutrons @ E>0.1 MeV and ~70% of neutrons @ E>1 MeV
- Gamma flux is comparable for two GIMM cases

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

		Peak Flux ($cm^{-2}.s^{-1}$)	PeakFluence per full power year (cm^{-2})
SiC GIMM	Neutrons E>1 MeV	$9.00x10^{7}$	$2.84x10^{15}$
	Neutrons E>0.1 MeV	$2.01x10^{8}$	$6.33x10^{15}$
	Total Neutrons	$6.23x10^{8}$	$1.97x10^{16}$
	Total Gamma	$4.02x10^{8}$	$1.27x10^{16}$
AlBeMet GIMM	Neutrons E>1 MeV	$1.79x10^{8}$	$5.67x10^{15}$
	Neutrons E>0.1 MeV	**$4.23x10^{8}$**	**$1.34x10^{16}$**
	Total Neutrons	$1.43x10^{9}$	$4.53x10^{16}$
	Total Gamma	$8.35x10^{8}$	$2.64x10^{16}$



- Neutron and gamma fluxes are about a factor of 2 higher with AlBeMet GIMM
- Total neutron flux is more than two orders of magnitude lower than at M2 with smaller gamma flux reduction
- Neutron spectrum is softer with ~30% of neutrons @ E>0.1 MeV and ~15% of neutrons @ E>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	1.03	0.70	**1.73**
	M3 Maximum	0.002	0.019	0.021
	M3 Minimum	0.0001	0.0020	0.0021
AlBeMet GIMM	M2	1.99	0.70	**2.69**
	M3 Maximum	0.004	0.041	0.045
	M3 Minimum	0.0002	0.0050	0.0052

- 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 a factor of 2 higher with AlBeMet GIMM compared to that with SiC GIMM

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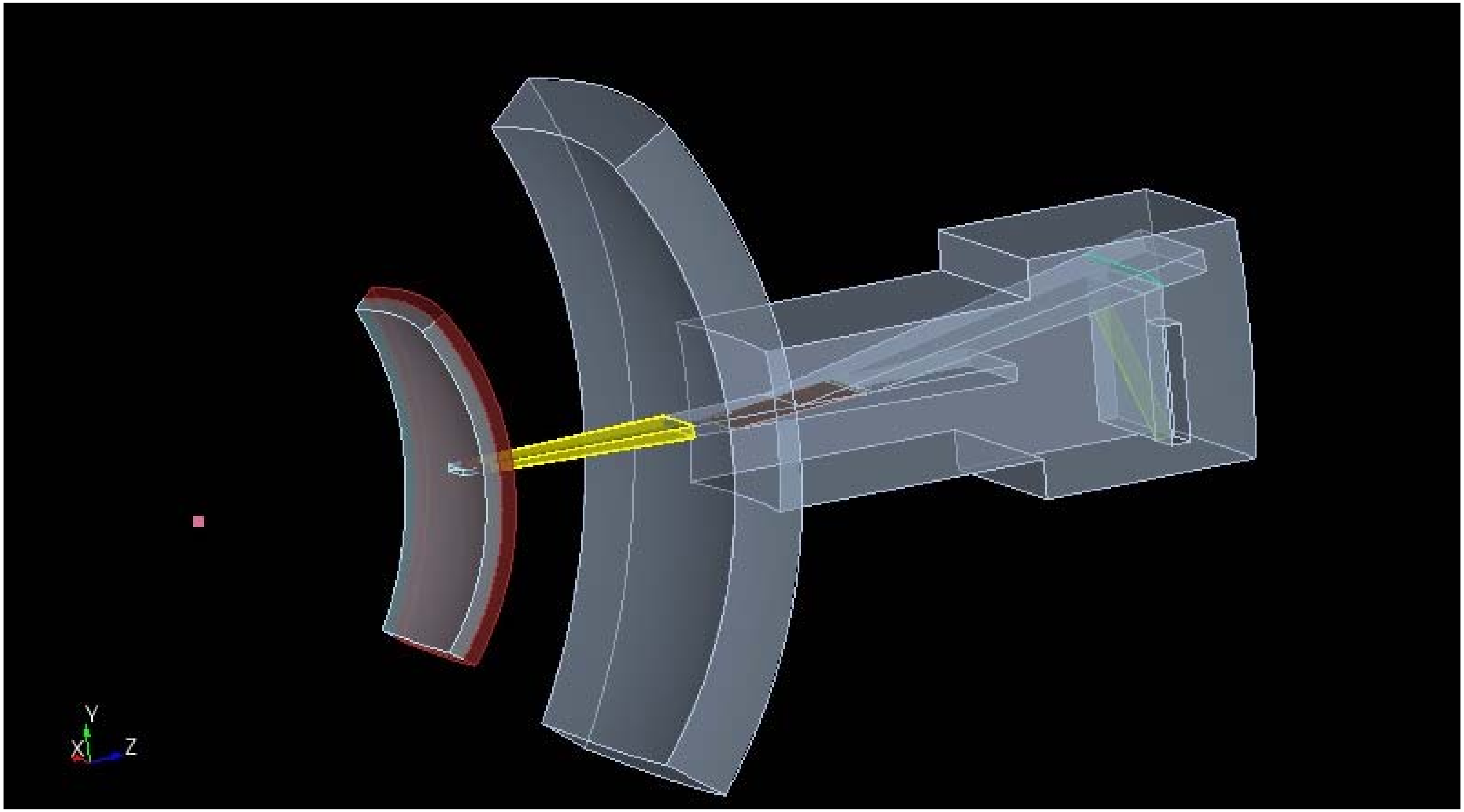
Started Modeling Final Optics for Detailed 3-D Analysis with MCNP-CGM

- Modeled one duct with reflecting boundaries
- All 3 mirrors and accurate duct shape included



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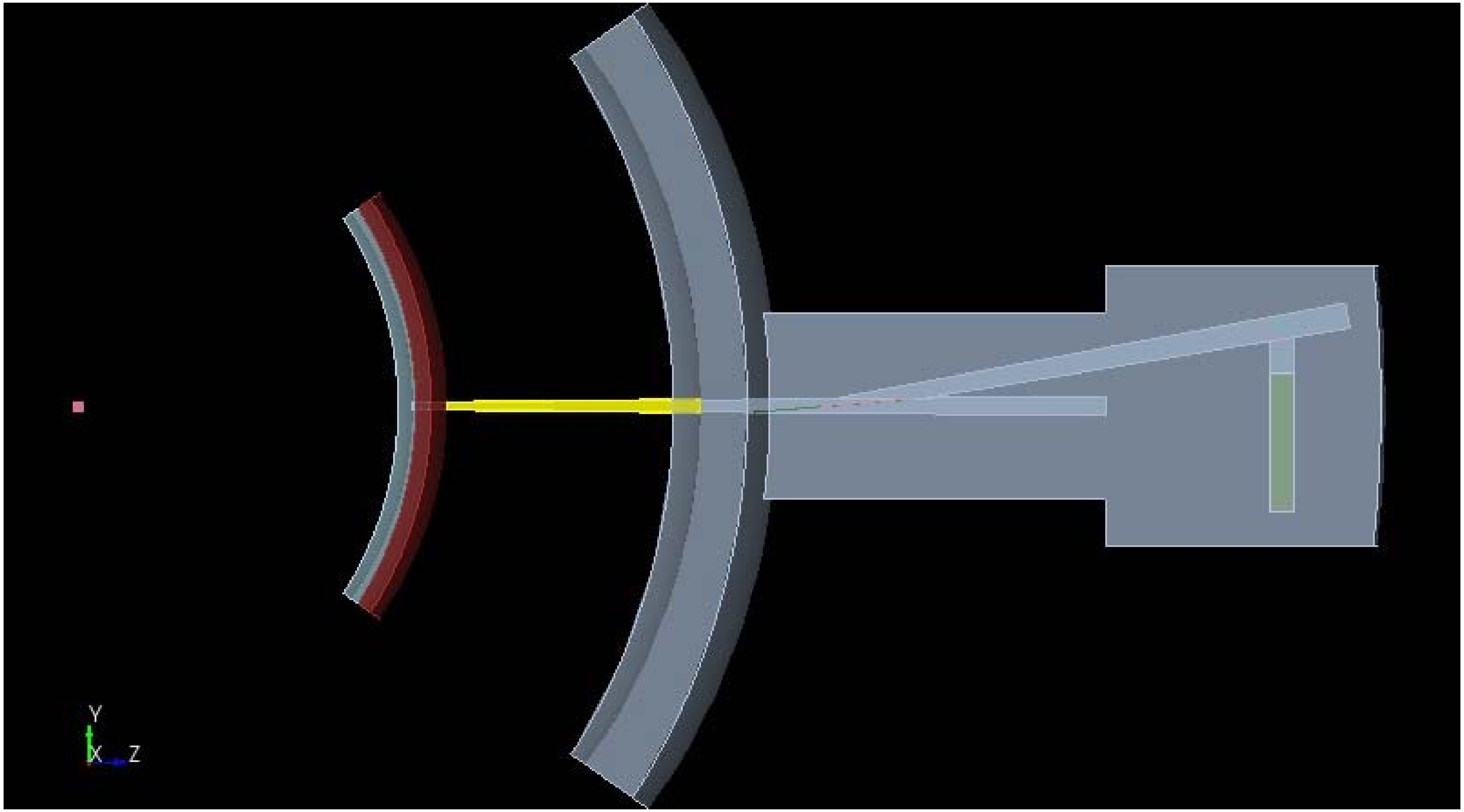

Summary and Conclusions

- 2-D neutronics calculation performed to compare impact of GIMM design option and duct lining on the radiation environment at the dielectric mirrors
- Lining beam ducts with materials rich in hydrogen and boron (boron hydride, borated polyethelyne) have best impact on fast neutron flux
- Effect is small (<4%) at M2 but up to a factor of 2 reduction at M3
- Since flux at M3 is much smaller than at M2, design complexity from adding liner is not justified
- Neutron flux at GIMM is higher for AlBeMet and gamma flux is higher for SiC
- Neutron flux at dielectric mirrors is higher by a factor of ~2 with AlBeMet GIMM due to larger thickness and neutron multiplication in Be
- Peak fast neutron flux at M3 is ~2 orders of magnitude lower than at M2
- Neutron spectrum softens significantly at M3 (~25% >0.1 MeV) compared to ~85% at M2
- Peak fast (E>0.1 MeV) neutron fluence per FPY:

GIMM	***4.9×10^{20} n/cm^{2}s***
M2	***1.92×10^{18} n/cm^{2}s***
M3	***1.34×10^{16} n/cm^{2}s***

- Model for 3-D neutronics of final optics