Radiation Environment at Final Optics of HAPL

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HAPL Meeting
ORNL
March 21-22, 2006

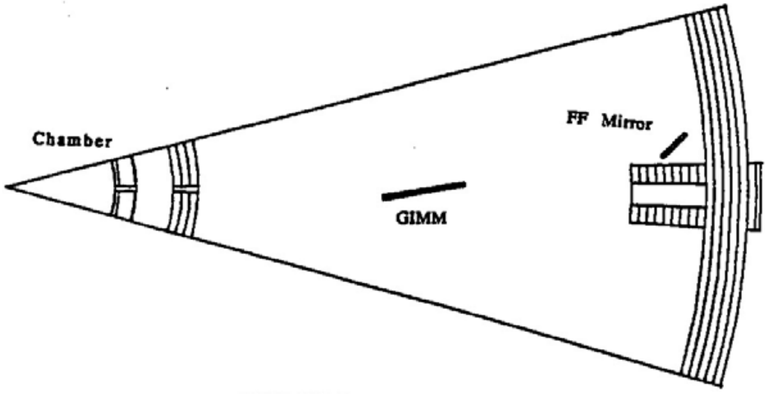
Design Parameters for Baseline HAPL Design

Target yield	350 MJ
Rep Rate	5 Hz
Fusion power	1750 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	0.9 MW/m^2
GIMM angle of incidence	85°
GIMM distance from target	24 m
GIMM dimensions	3.4 m high x 4.05 m wide

Previous 3D Analysis of SIRIUS-P

SIRIUS-P design parameters

2444 MW fusion power
Chamber radius 6.5 m
Blanket/reflector ($SiC/Li_2O/TiO_2$) 1.5 m
GIMM @ 25 m and FF mirror @ 40 m
GIMM diameter 5 m
GIMM angle of incidence 85°
Containment building @ R = 42 m
Trap diameter 1.3 m and depth 4 m



A thick dense GIMM used in SIRIUS-P

- Total thickness **24 cm thick** with front and rear 2 cm thick zones modeled separately
- Front and rear zones have 75% Al6061 and 25% water
- Middle honeycomb structure is 20 cm thick with 0.833 g/cc Al

Scaled results from SIRIUS-P to HAPL Conditions

- Fast neutron (E>0.1 MeV) flux @ **center of GIMM $8.9x10^{12}$ n/cm^{2}s**
- Fast neutron (E>0.1 MeV) flux @ **dielectric FF mirror $4.3x10^{10}$ n/cm^{2}s**

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

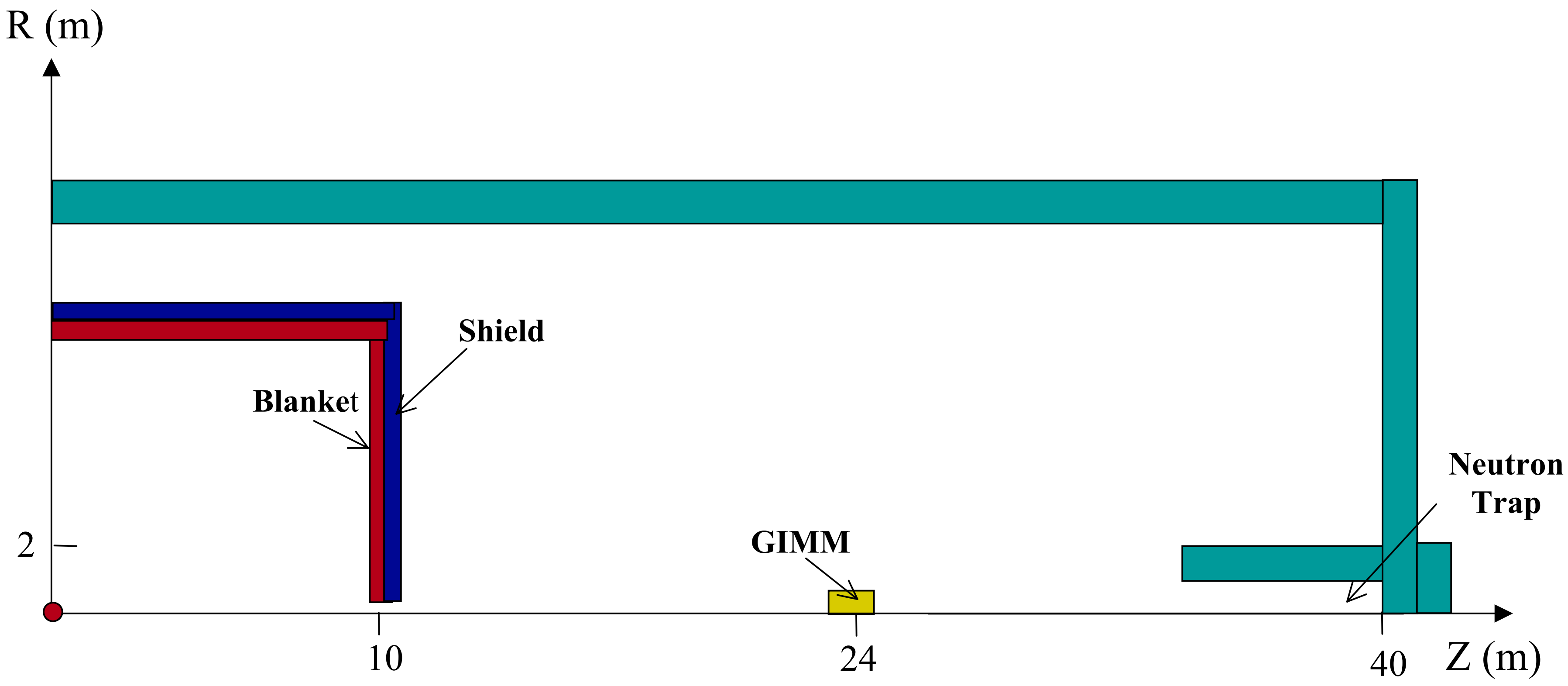
Option 2: Lightweight AlBeMet substrate

- 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

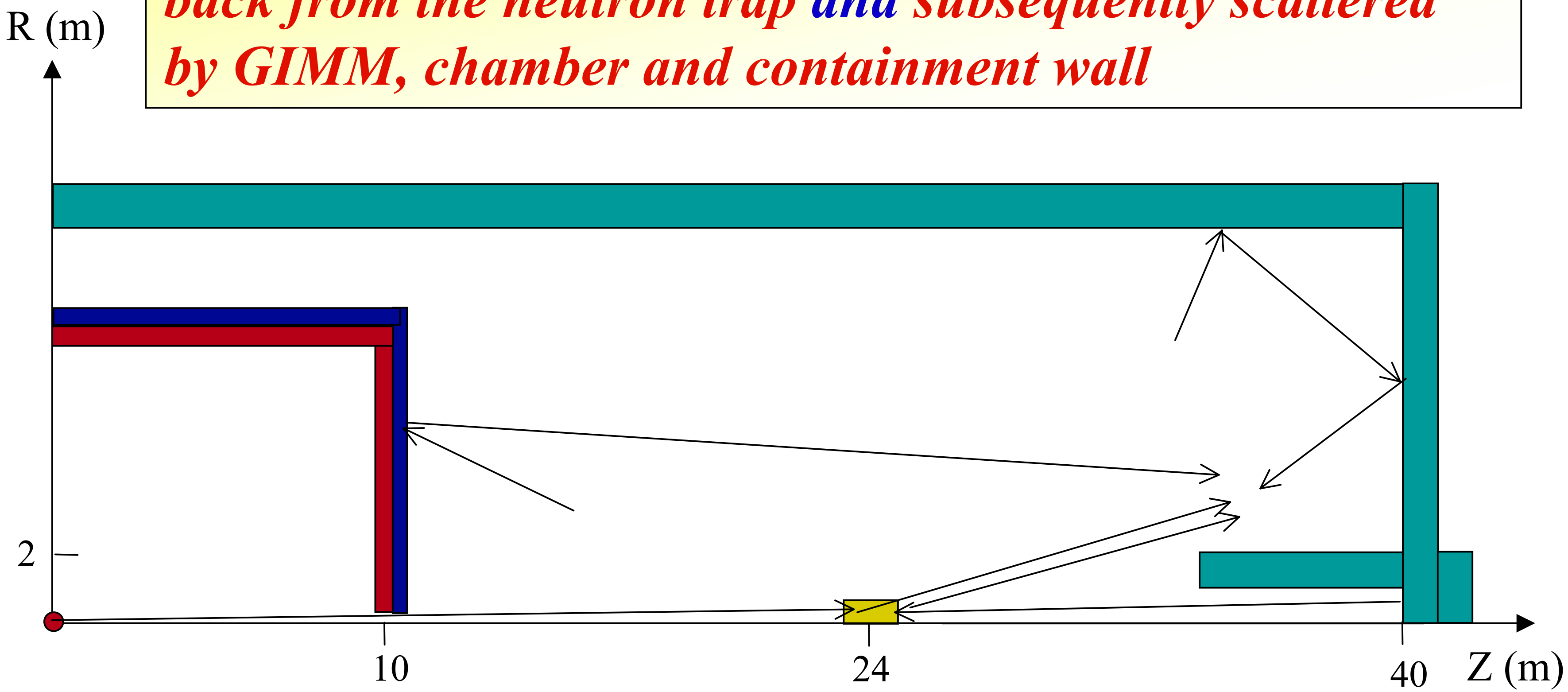
2-D Neutronics Analysis

- 2-D neutronics calculation performed in R-Z geometry to compare the impact of the GIMM design option on the radiation environment at the dielectric mirror
- The two lightweight GIMM design options were considered along with other two extreme cases of thick Al GIMM (SIRIUS-P) and transparent GIMM
- 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 0.15 m high x 2 m wide modeled as circular port with 0.3 m radius
- GIMM modeled circular with 0.6 m radius
- Neutron trap at 40 m has 1 m radius and 6 m depth (aspect ratio of 3)
- 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
- 1 m thick containment building and trap walls used with 70% concrete, 20% carbon steel C1020, and 10% H_2O

2-D R-Z Model Used in the Analysis

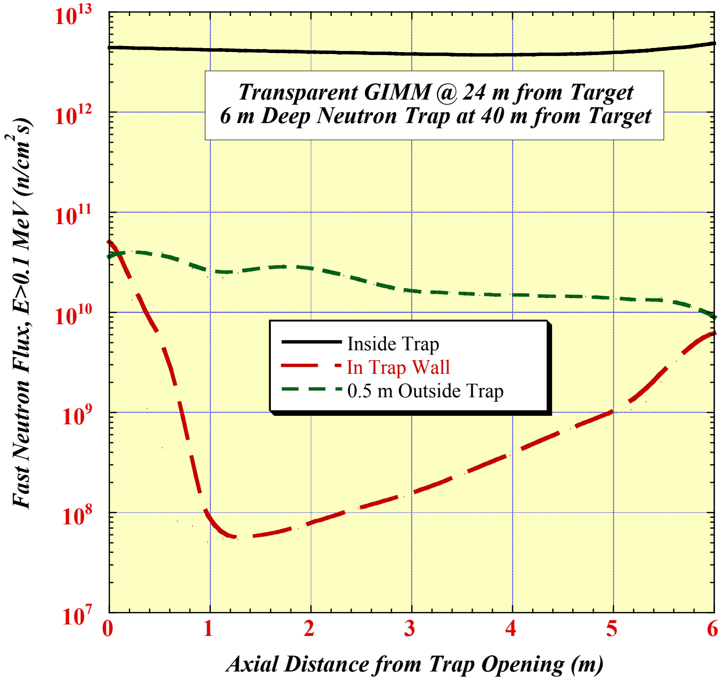


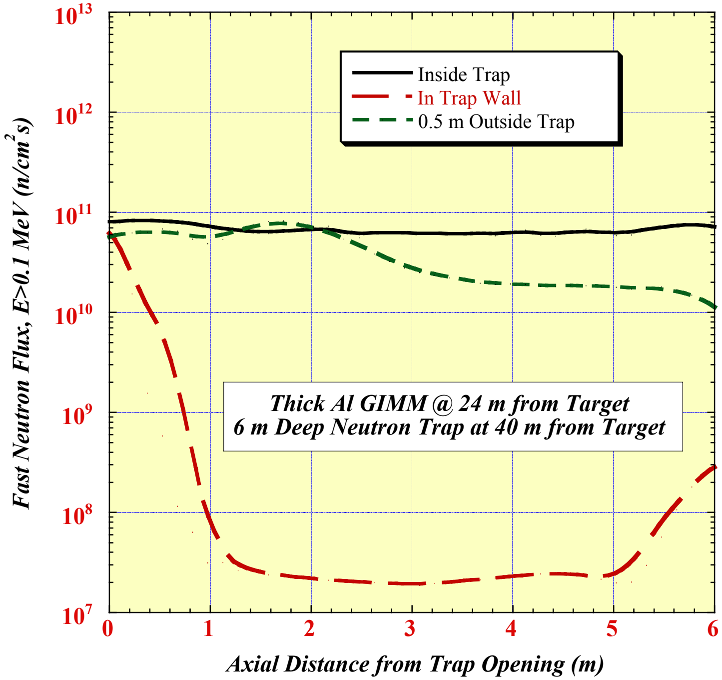
Neutron flux at dielectric mirror contributed by neutrons directly scattered from the GIMM and those reflected back from the neutron trap and subsequently scattered by GIMM, chamber and containment wall



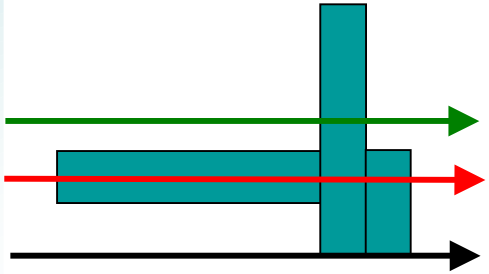
Reducing thickness and/or density of GIMM reduces scattering from GIMM but increases amount of neutrons incident on trap and scattered back from it

Impact of GIMM on Flux Inside and Around Trap

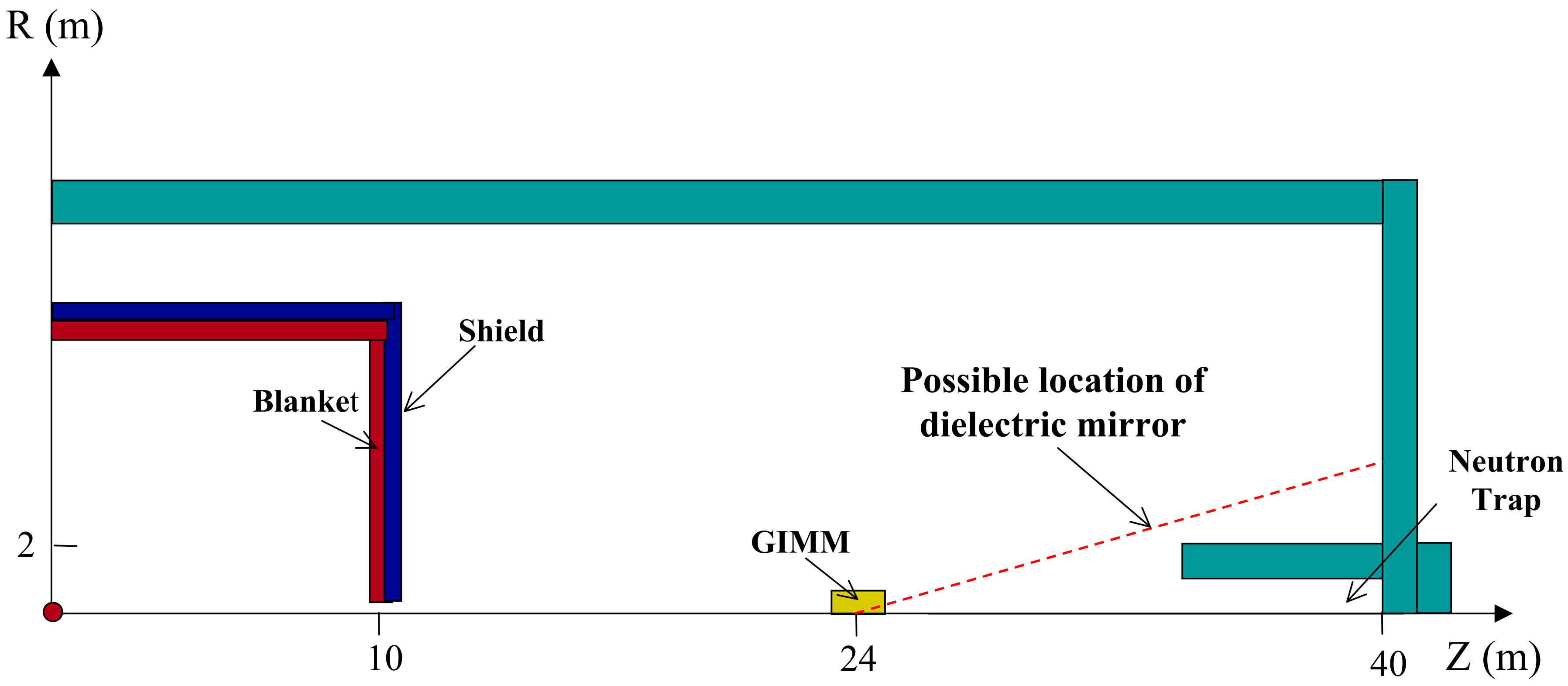




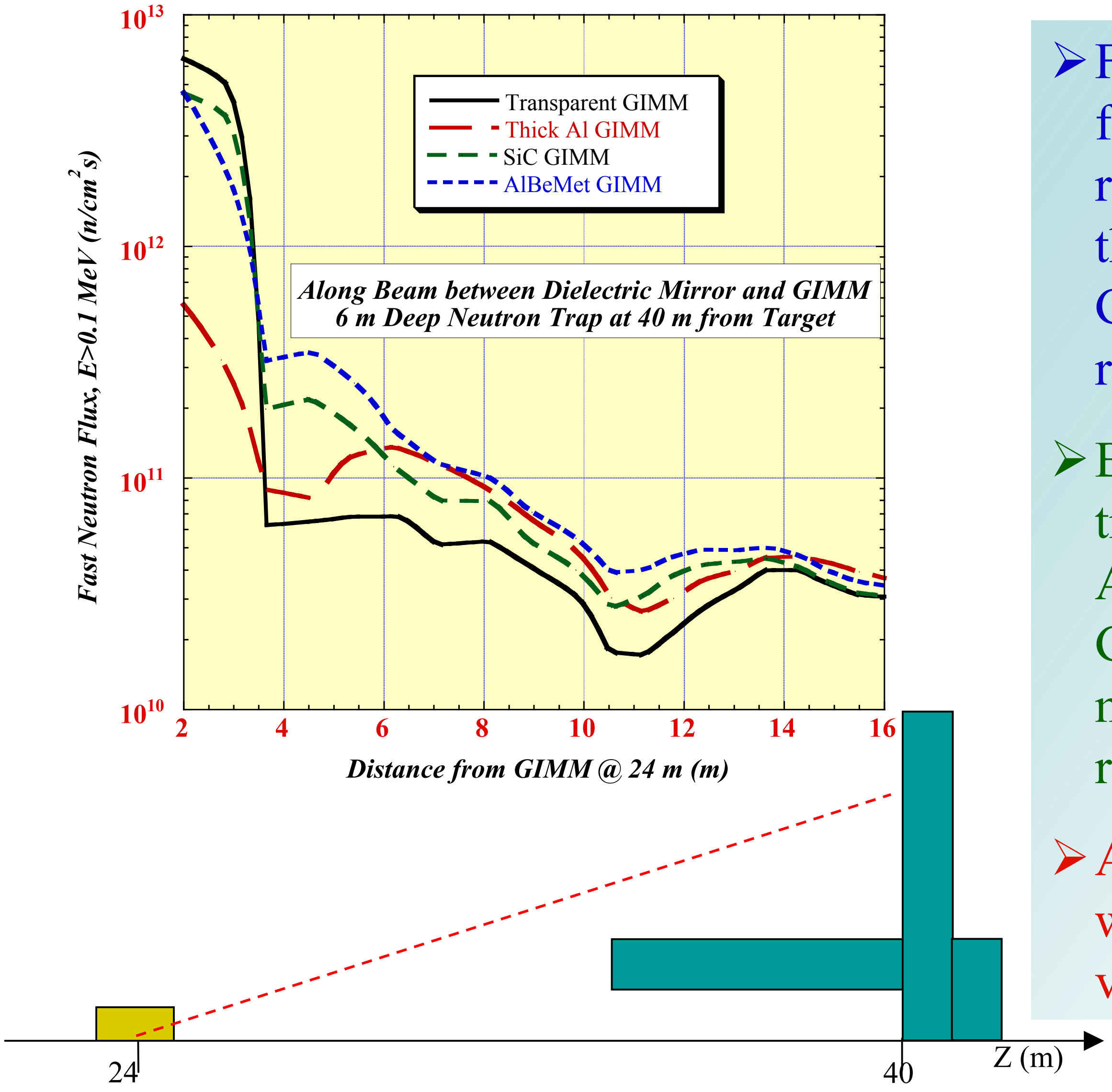
- Flux inside trap decreases by two orders of magnitude with thick Al GIMM
- Flux in trap wall decreases particularly close to the bottom of the trap due to reduced scattering from trap
- Reduced scattering from trap results in increasing flux outside trap wall by less than a factor of two despite added contribution from GIMM scattering



Possible Locations of Dielectric Mirror Relative to GIMM and Neutron Trap

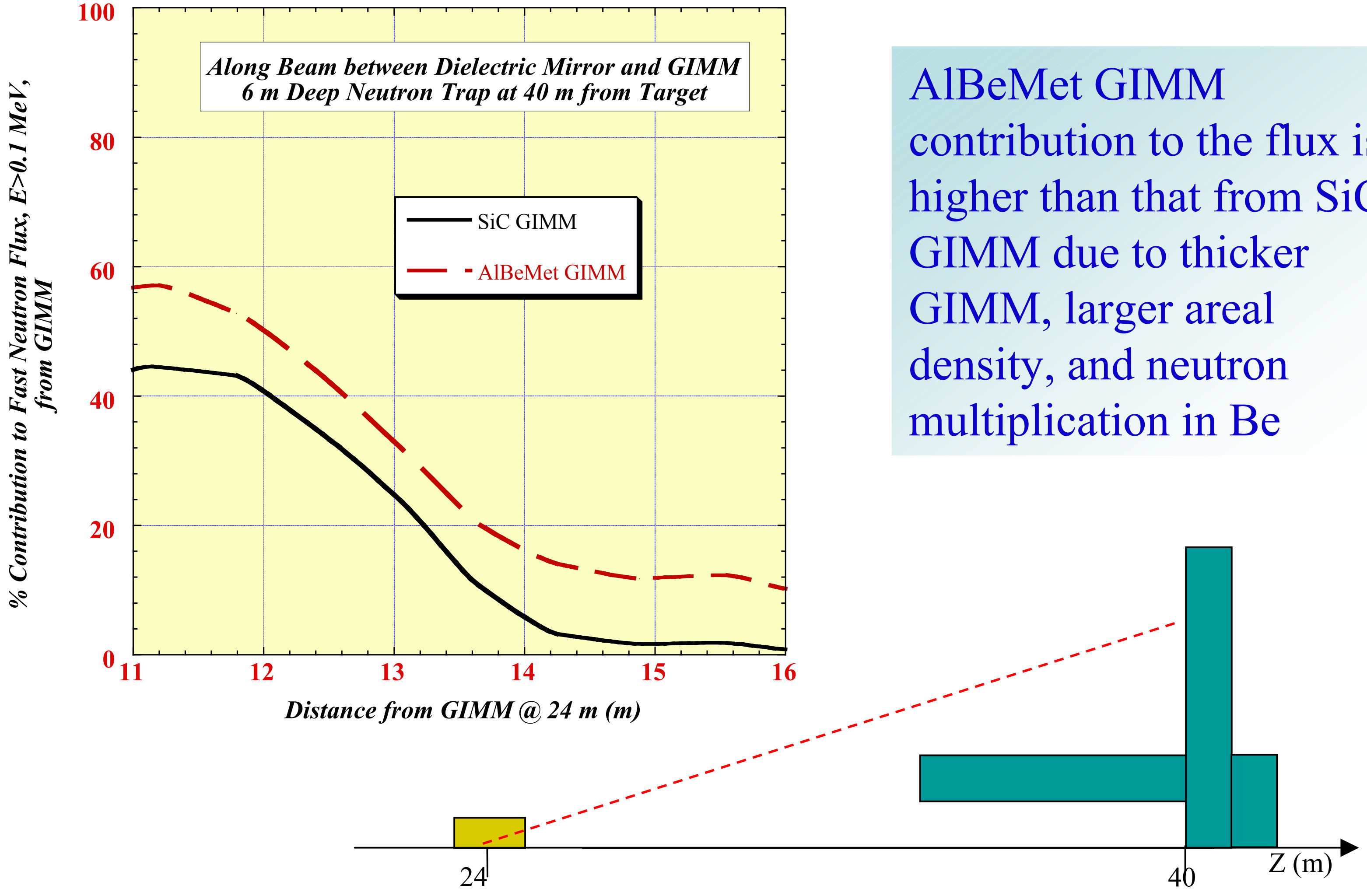


Neutron Flux Along Possible Locations of Dielectric Mirror



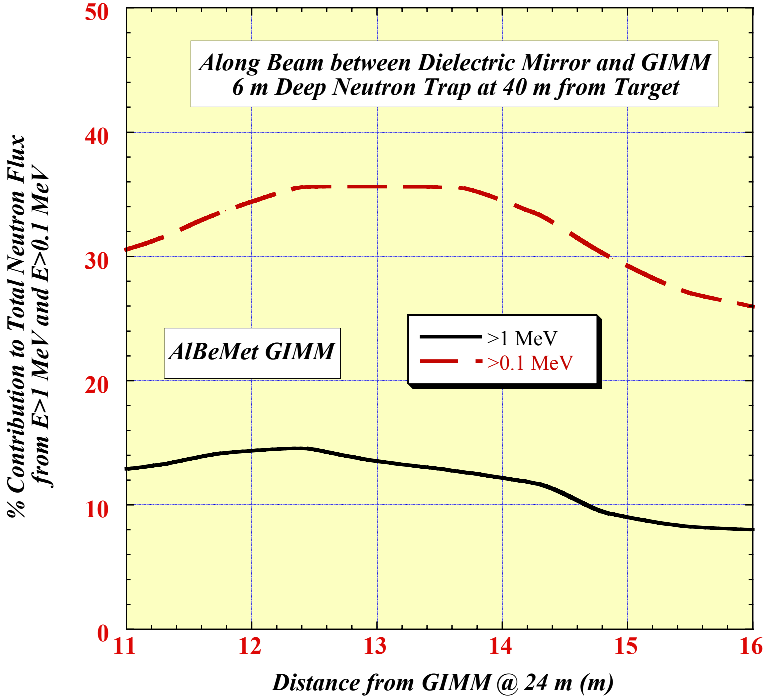
- Flux behind GIMM and in front of trap opening is reduced with increased GIMM thickness due to increased GIMM attenuation and reduced reflection from trap
- Between GIMM and front of trap flux is higher with AlBeMet GIMM due to GIMM scattering and multiplication and larger reflection from trap
- Adjacent to trap flux is highest with AlBeMet GIMM but values are within ~25% range

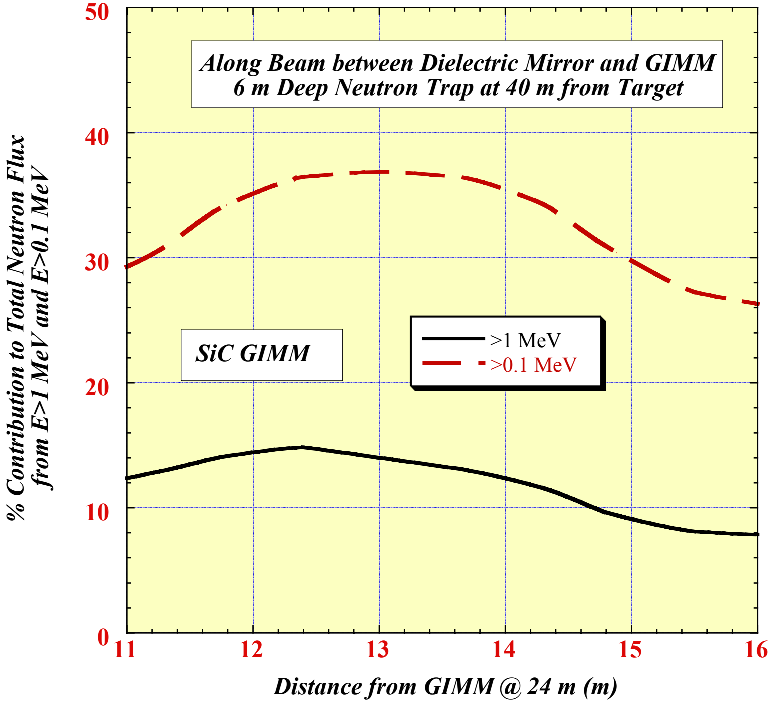
GIMM Contribution to Neutron Flux at Dielectric Mirror

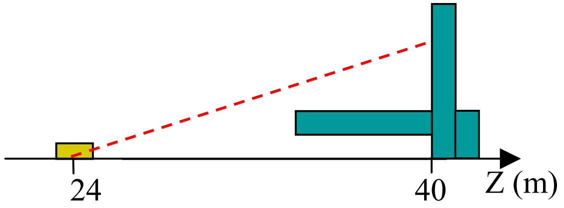


AlBeMet GIMM contribution to the flux is higher than that from SiC GIMM due to thicker GIMM, larger areal density, and neutron multiplication in Be

Neutron Energy Spectrum at Dielectric Mirror







- ~26-36% of neutrons @ E>0.1 MeV
- ~8-15% of neutrons @ E>1 MeV
- Softest spectrum at locations close to concrete walls

Flux at Front of GIMM

- Contribution to neutron flux at GIMM from scattering inside chamber is small (<3%)
- Up to 36% 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 slightly softer for AlBeMet with 91% >0.1 MeV compared to 97% for SiC

		Flux (cm^{-2}.s^{-1})	% Secondary neutrons
Transparent GIMM (R= 24 m)	Neutrons E>1 MeV	$8.38\text{x}10^{12}$	0.4%
	Neutrons E>0.1 MeV	**$8.63\text{x}10^{12}$**	**0.8%**
	Total Neutrons	$8.78\text{x}10^{12}$	2.4%
	Total Gamma	$9.7\text{x}10^{10}$	
SiC GIMM (R= 23.93 m)	Neutrons E>1 MeV	$1.02\text{x}10^{13}$	17.5%
	Neutrons E>0.1 MeV	$1.10\text{x}10^{13}$	21.5%
	Total Neutrons	$1.13\text{x}10^{13}$	23.7%
	Total Gamma	**$3.6\text{x}10^{12}$**	
AlBeMet GIMM (R= 23.85 m)	Neutrons E>1 MeV	$1.13\text{x}10^{13}$	25.1%
	Neutrons E>0.1 MeV	**$1.35\text{x}10^{13}$**	**35.9%**
	Total Neutrons	$1.48\text{x}10^{13}$	41.6%
	Total Gamma	$2.5\text{x}10^{12}$	

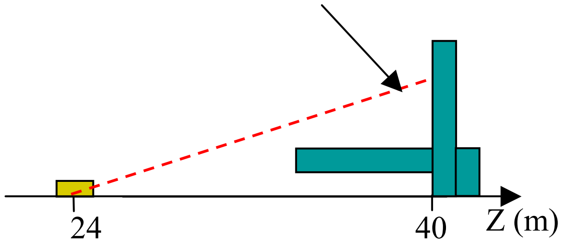
Nuclear Heating in GIMM

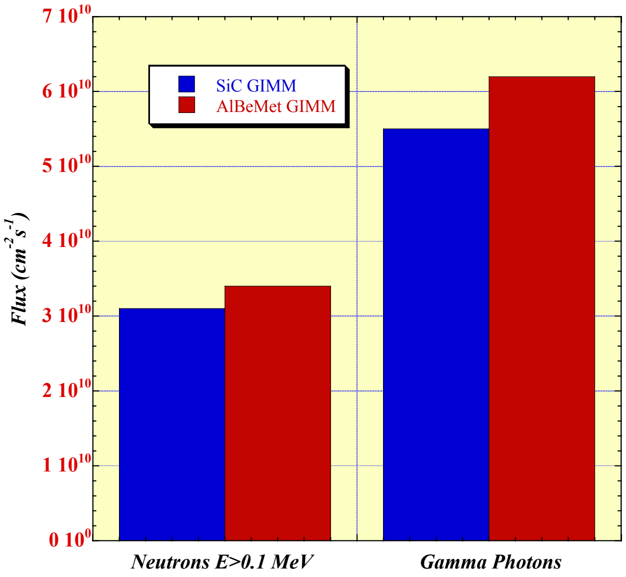
		Neutron Heating (W/cm^3)	**Gamma Heating (W/cm^3)**	**Total Heating (W/cm^3)**
SiC GIMM	Al Coating	0.16	0.08	0.24
	Front Face Plate	0.37	0.10	**0.47**
	Foam	0.041	0.014	0.055
	Back Face Plate	0.28	0.10	0.38
AlBeMet GIMM	Al Coating	0.17	0.05	0.22
	Front Face Plate	0.43	0.04	**0.47**
	Foam	0.045	0.005	0.05
	Back Face Plate	0.29	0.03	0.32

- Values are at center of GIMM @ 24 m from target and variation along the 3 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 much smaller in the AlBeMet design
- For 1.2 mm thick SiC face plate nuclear heating is 57 mW/cm^2
- For the twice thicker AlBeMet face plate nuclear heating is 114 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 Mirror Located @16 m from GIMM

		Flux ($cm^{-2}.s^{-1}$)	Fluence per year @80% availability (cm^{-2})
SiC GIMM	Neutrons E>1 MeV	$9.3x10^9$	$2.3x10^{17}$
	Neutrons E>0.1 MeV	$3.1x10^{10}$	$7.8x10^{17}$
	Total Neutrons	$1.2x10^{11}$	$3.0x10^{18}$
	Total Gamma	$5.5x10^{10}$	$1.4x10^{18}$
AlBeMet GIMM	Neutrons E>1 MeV	$1.1x10^{10}$	$2.8x10^{17}$
	Neutrons E>0.1 MeV	**$3.4x10^{10}$**	**$8.6x10^{17}$**
	Total Neutrons	$1.3x10^{11}$	$3.3x10^{18}$
	Total Gamma	**$6.2x10^{10}$**	**$1.6x10^{18}$**





- Flux is ~10% higher with AlBeMet GIMM
- Total neutron and gamma fluxes are about two orders of magnitude lower than at GIMM
- ~26% of neutrons @ E>0.1 MeV
- ~8% of neutrons @ E>1 MeV
- Gamma flux is about half the total neutron flux

What can we do to reduce flux at dielectric mirror and lens?

- Use as thin and small size GIMM as possible with minimal support structure
- Use of low density and less scattering, more absorption GIMM material is preferable (e.g., He cooling instead of water)
- Place FF dielectric mirror as close as possible to containment wall away from trap opening
- Increase depth of neutron trap as much as feasible
- If beam ducts are used for vacuum and tritium containment, both components of flux @ FF mirror (scattering from trap and GIMM) increase. The wall of the beam duct can be made of a thin absorber
- Line the inner surface of trap and beam duct with strong absorber

  In past studies we showed that lining the ducts by 1/4" (0.635 cm) boral (Al+36% B_4C) reduced streaming by an order of magnitude
- Increasing the distance between lens and dielectric mirror helps reducing the flux at the lens
- 3D calculations with detailed modeling of final optics configuration and GIMM layered structure will be performed once we converge on a design