Shielding Protection Schemes for Final Optics

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UCSD

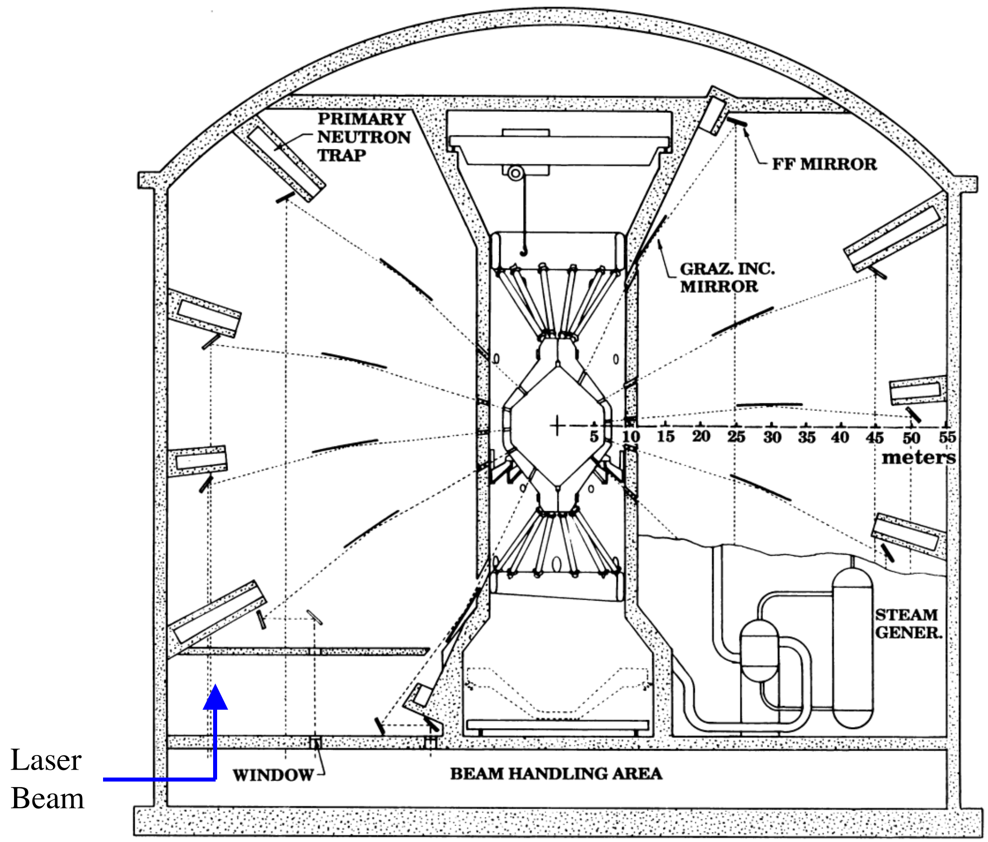
Objectives

- Review shielding schemes and streaming analysis performed over past 25 years
- Highlight shielding-related :
  - Features
  - Issues/concerns
  - Findings
  - Recommendations
- Develop shielding criteria for ARIES-IFE
- Propose protection scheme for ARIES-IFE optics

Both Laser and Pre-formed-plasma-channel-based HIB Drivers Employ Final Optics for Laser Transmission

SOMBRERO

(KrF Laser Driver)



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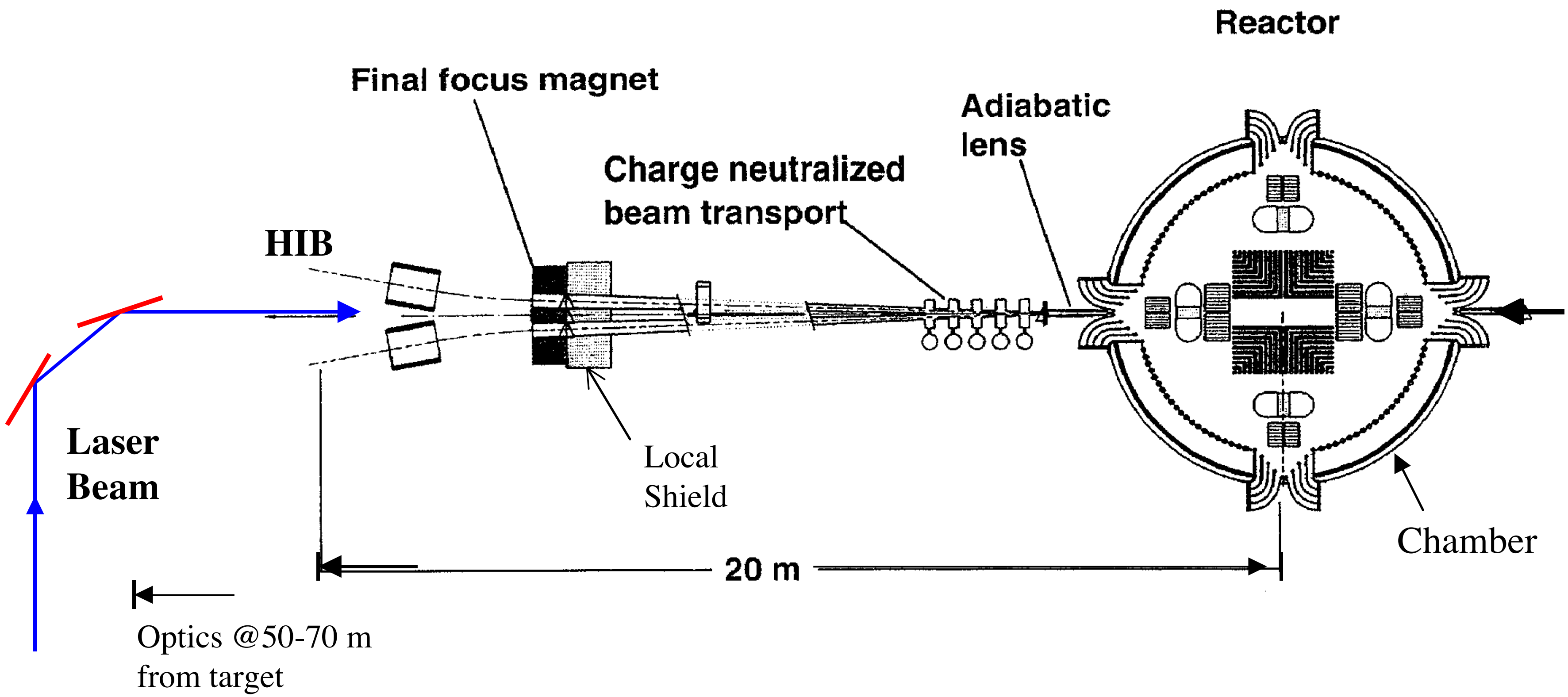
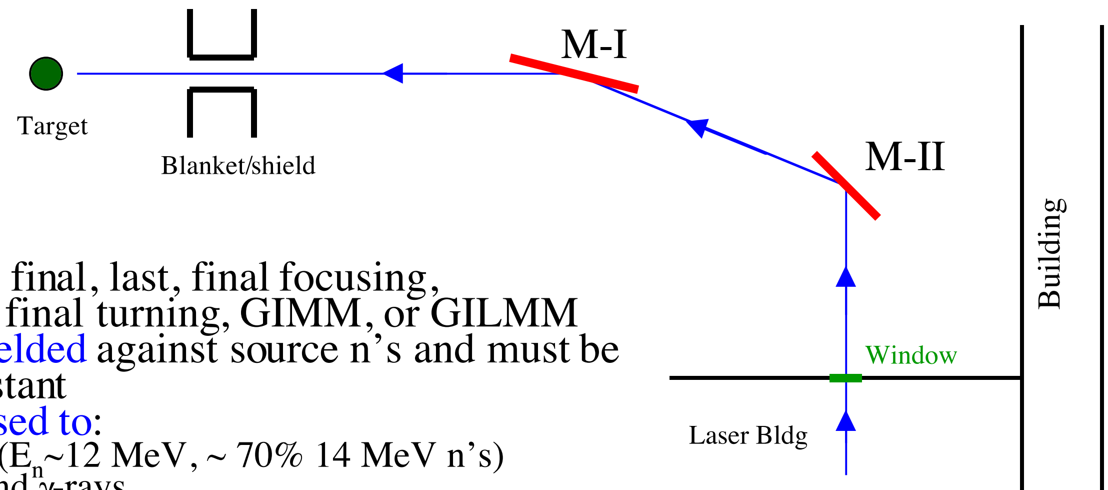
Schematic of Final Transport System for Pre-formed-Channel-based HIB Driver



Reference: S. Yu et al., Nuclear Instruments and Methods A415 (1998) 174

Schematic of Final Optics



- **M-I mirror**:
  - Referred to as final, last, final focusing, final turning, GIMM, or GILMM
  - Cannot be shielded against source n's and must be radiation-resistant
  - Directly exposed to:
    - Source n's (E_n~12 MeV, ~ 70% 14 MeV n's)
    - Target x- and γ-rays
    - Target ion debris
    - Vapor from liquid walls
- **M-II mirror**:
  - Referred to as final focusing, turning, second, next to last, or dielectric coated
  - Subject to:
    - Secondary n's (< 10% 14 MeV n's) scattered from M-I and building

      $\Longrightarrow$ lower damage, longer lifetime compared to M-I
    - γ -rays and target x-rays scattered from M-I
- DPSSL driver employs wedges instead of M-I mirrors
- Windows serve as vacuum and T barriers

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Background

- Optics lifetime is strong function of:
  - Radiation damage limit (unknown)
  - Distance from target
  - Size of beam port
  - Damage fraction recovered by annealing
  - Shielding protection schemes (applicable to M-II only)
  - Design approaches to accommodate radiation-induced swelling
- Annealing of optics at high temperature reduces laser absorption, removes radiation defects, and prolongs lifetime
- DPSSL driver calls for up to 20 times larger beam ports compared to KrF driver

Background (Cont.)

- Candidate final optics materials:
  - Mirrors:
    - Substrates: Al alloys, SiC/SiC, or C/C
    - Coolants: H_2O, He, or LN2
    - Coatings:
      - Metallic: Al, Mg, Cu, Ag, or Au
      - Oxide: Al_2O_3 (~10 nm)
      - Dielectric: ZnS or MgF_2
      - Liquid (~100 μm): Li, Na, Ga, Al, or Pb
  - Wedges: SiO_2 or CaF_2
  - Windows: SiO_2
- Neutron flux at M-I is dominated by 14 MeV source n's and can be estimated analytically. 1-D analysis provides fairly accurate radiation damage and lifetime for M-I
- 3-D analysis is essential for M-II radiation damage/lifetime

Radiation Issues/Concerns

- **Metallic mirrors and wedges**:
  - n & γ radiation degrade optical performance, deteriorate focusing quality, and increase laser absorption by introducing:
    - Defects: vacancies and interstitials from atomic displacements, color centers (darkness)
    - Transmutations (10^4-10^5 less damaging than defects)
    - Densification with radiation dose
    - Surface roughening due to sputtering
    - **Swelling** causing surface undulations and defocusing
  - Deformation by swelling and creep could limit lifetime if radiation-induced degradations by other mechanisms are tolerable (< 1%)

Radiation Issues/Concerns (Cont.)

- **Dielectric mirrors**:
  - n's destroy dielectric coatings by:
    - Chemical decomposition (radiolysis)
    - Destroying interface between layers
  - Experimental measurements* indicated factor of 10 degradation in mirrors' optical properties at fast n fluence of 10^{16}-10^{17} n/cm^2 (E_n > 0.1 MeV)

    ⇒ Unshielded dielectric mirrors will not last more than one hour

    Move dielectric mirrors away from direct-line-of-sight of source n's

    Develop radiation-resistant dielectric coatings

- **Liquid mirrors**:
  - Disturbance of liquid surface by n & γ heating

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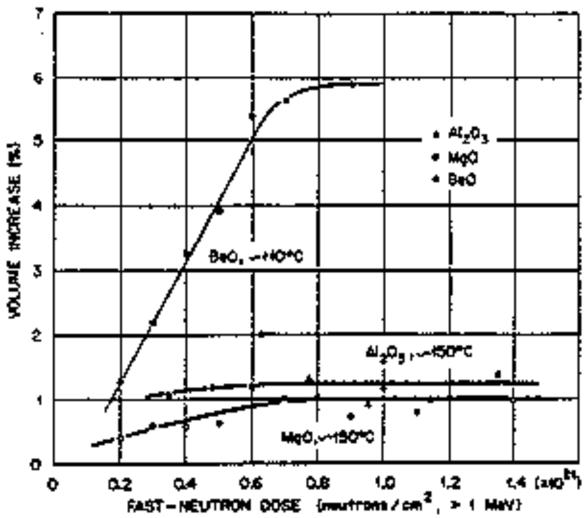
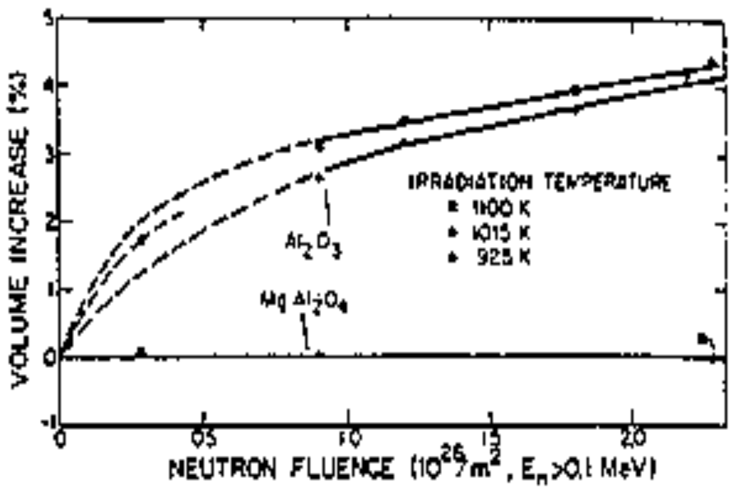
* Reference: R. Bieri and M. Guinan, "Grazing incidence metal mirrors as the final elements in a laser driver for inertial confinement fusion", UCRL JC-103817 (Oct 1990)

Al_2O_3 Coating Exhibits High Swelling Compared to MgO and Spinel[1,2]





- Spinel ($MgAl_2O_4$) offers lowest n-induced swelling and could be considered as oxide coating. Optical properties need to be checked[3]
- Harder fusion spectrum reduces fission fluence limit for swelling by factor of ~2
- Fast n fluence, dpa, dose, and swelling are interrelated

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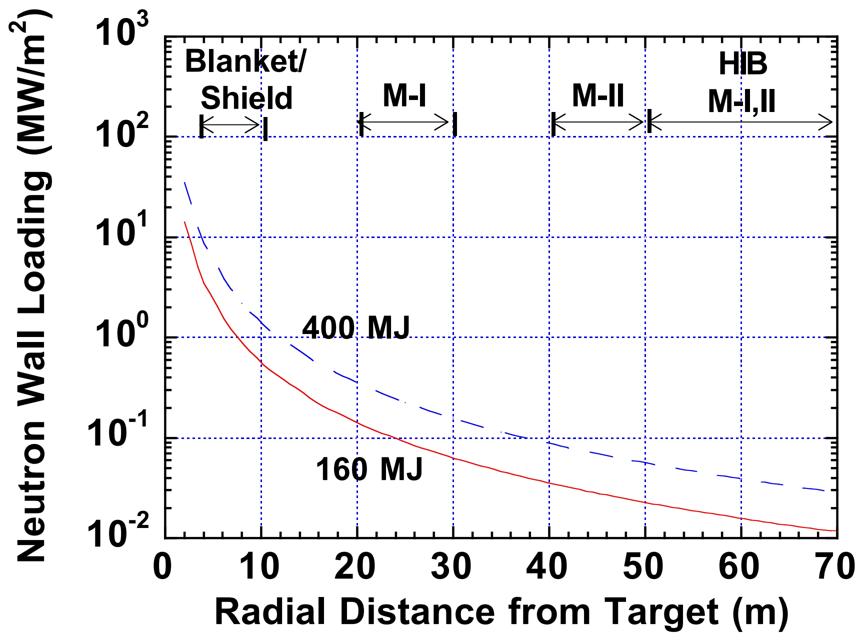
* Refs: 1- L. El-Guebaly, "Materials Problems for Highly Irradiated ICRH Launchers in Fusion Reactors," Fusion Technology 8 (1985) 553
F. Clinard and G. Hurley, Journal of Nuclear Materials 108 & 109 (1982) 655
2- C. Kinoshita et.al.,"Why is magnesia spinel a radiation-resistant material?, Journal of Nuclear Materials 219 (1995) 143-151
3- A.Ibarra et.al., "Neutron-induced changes in optical properties of $MgAl_2O_3$ spinel", Journal of Nuclear Materials 219 (1995) 135-138

Neutron Wall Loading @ Mirrors

(assuming normal n incidence and all optics in direct-line-of-sight of target)



- 0.06-0.4 MW/m^2 will degrade M-I optical properties and activate materials
- Grazing incidence reduces M-I Γ by cos θ^* (flux and damage will not change)
- Offsetting M-II softens n spectrum and reduces fast n flux by 2-3 orders of magnitude $\Longrightarrow$ longer life

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* Angle between beam and normal to mirror

Radiation Effects @ M-I

(Assuming bare Al mirror @ 30 m from target)

Target yield	**160 MJ**	**400 MJ**
Fast n fluence ($n/cm^2 s$ @ 1 FPY, $E_n > 0.1$ MeV)	2e20	5e20
Fast n flux ($n/cm^2 s$, $E_n > 0.1$ MeV)	6.7e12	1.7e13
Total n flux ($n/cm^2 s$)	1.1e13	2.7e13
Total γ flux ($\gamma/cm^2 s$)	8.6e12	2e13
Atomic displacement (dpa/FPY)	0.4	1
Nuclear heating (W/cm^3):		
n	0.07	0.18
γ	0.12	0.3
Total	0.2	0.48
Dose (rads/s):		
n	2.7e3	6.7e3
γ	4.5e3	1.1e4
Total	7.2e3	1.8e4

- Reported peak values vary as $1/r^2$ and scale roughly with target yield
- **For Al**: 1 dpa $\equiv$ 5.4e20 n/cm^2 ($E_n > 0.1$ MeV)
  $\equiv$ 1-3% swelling ?
  $\equiv$ 6e11 rads

  1 n/cm^2 ($E_n > 0.1$ MeV) $\equiv$ 4e-10 rads

  1 γ/cm^2 $\equiv$ 5e-10 rads

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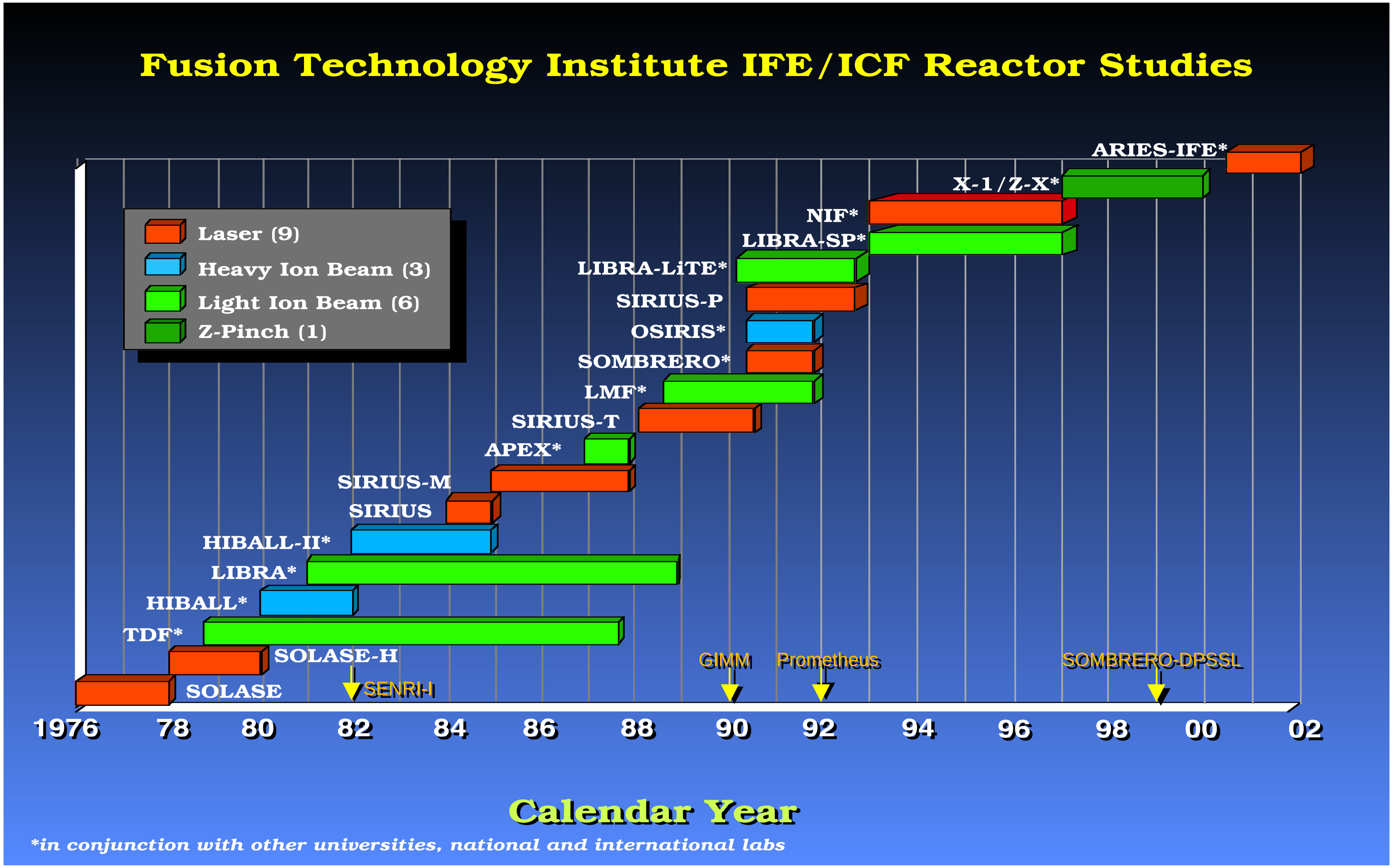
Several Designs Developed Mirror's Protection Schemes Over Past 25 years



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Most Design Studies Performed 3-D Streaming Analysis

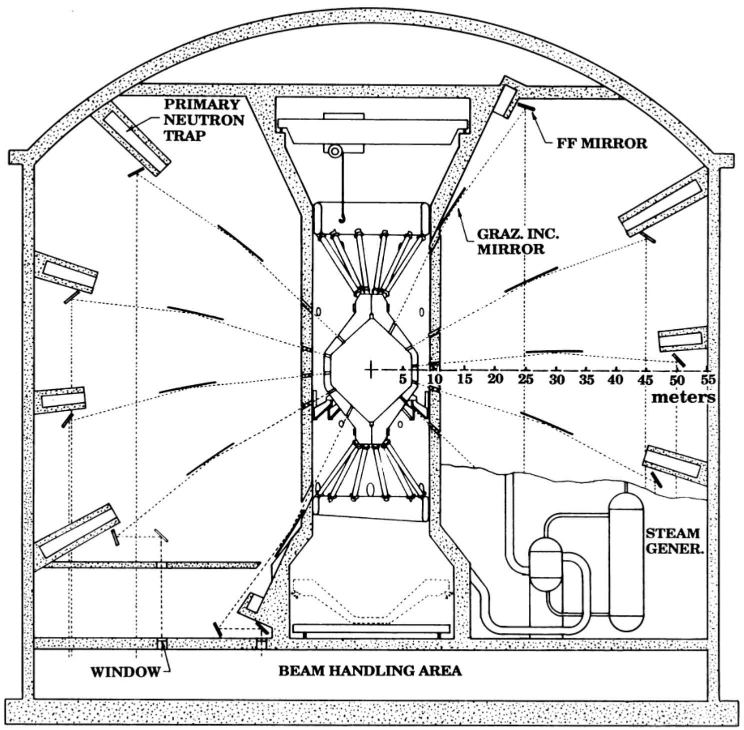
Study	Institute**	Year of Study	3-D Analysis?	Scaled from Previous UW 3-D Analysis?
SOLASE*	UW	1977	yes	
SENRI-I	Japan	1982	yes	
SIRIUS-M*	UW	1988	yes	
GIMM	LLNL	1990	yes	
SOMBRERO	UW	1992		yes
Prometheus	MDA/UCLA	1992		yes
SIRIUS-P*	UW	1993	yes	
SOMBRERO- with DPSSL	LLNL	1999	yes	
ARIES-IFE#	UW	2001-2002	yes	

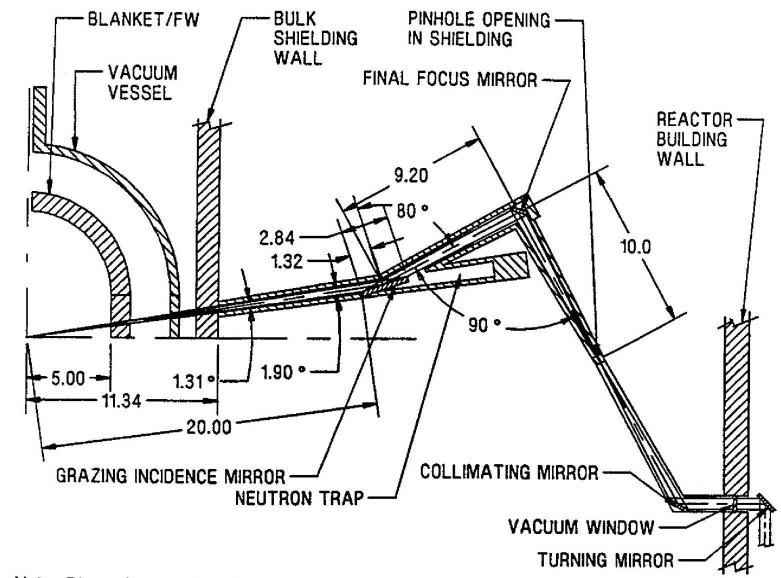
** Performed nuclear analysis
* Extensive shielding analysis
# Ongoing study

ARIES-IFE Shielding Criteria

- Criteria developed to judge merits of potential shielding scheme
- Criteria are related to neutronics, final optics system, pumping requirements, maintenance, and safety tasks. They include:
  - Effectiveness of shielding approach
  - Maintainability of building internals after shutdown
  - Accessibility of final optics with remote handling equipment
  - Tritium-contaminated area
  - Volume of penetration shield
  - Evacuated volume
  - Others:
    - Waste issues (level, volume, etc. May limit GIMM lifetime or material choices)
    - Survivability of final optics (may call for multiple defense system)

SOMBRERO and Prometheus





Note: Dimensions are in meters.

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ARIES-IFE Shielding Criteria (Cont.)

Criteria	Open Beamlines#	Shielded Beamlines##
Maintainability of building internals after shutdown	Remote	Hands-on for limited time before opening shield doors
Accessibility of final optics using remote handling equipment	Easy	Moderately easy after removing shield doors
Tritium contaminated area	5×10^4 m^2	8×10^3 m^2
Volume of penetration shield*	---	1,600 m^3
Evacuated volume	10^6 m^3	3×10^3 m^3

____
* Compared to ~7,000 m^3 bulk shield and ~70,000 m^3 building
# SOMBRERO-type
Prometheus-type

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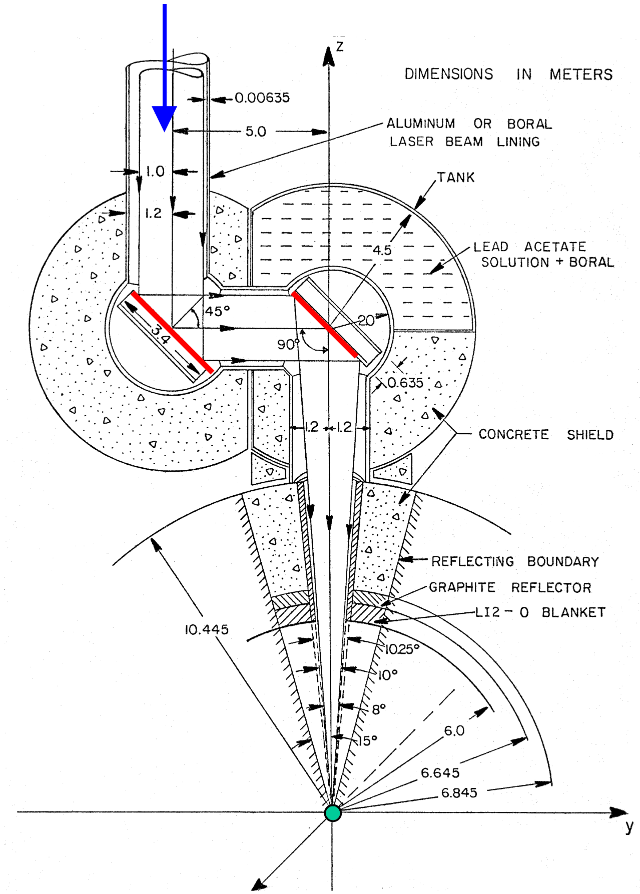
SOLASE
(UW, 1977)

- Main features:
  - 12 **large** beams
    (~1 m diameter @ FW)
  - Shielded beamlines
  - Mirrors at ~ 15 m
  - Boral* or SS liner for beamlines
  - Concrete shield/building to minimize cost

- Design Issues:
  - Nuclear heating, dpa, He and H levels at Al/H_2O metallic mirrors
  - Neutron leakage through SiO_2 windows to laser building
  - Biological dose around beamlines during and after operation



* 36% B_4C and 64% Al, by volume

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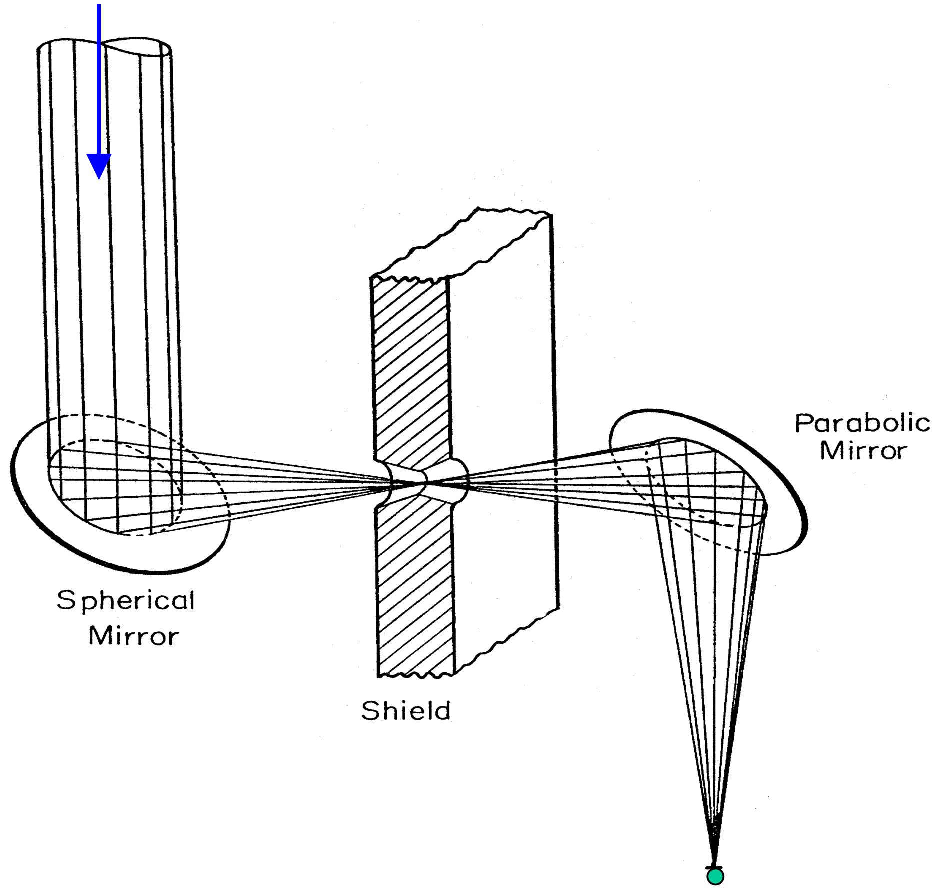
SOLASE (Cont.)

- Major findings:
  - M-I has 100 times damage of M-II
  - Boral liner reduces n leakage through windows by factor of 10
  - Mirrors must be actively cooled during and after operation
  - No personnel access to building during operation
  - Mirrors should be remotely maintained after shutdown (no hands-on)

- Recommendations:
  - Larger number of beams with smaller radii to reduce leakage $\Rightarrow$ higher L/D
  - Flux trap along beam duct
    - Used later in GIMM (LLNL-90), SOMBRERO (UW-92), SIRIUS-P (UW-93), Prometheus (MDA-92), and HIB designs
  - Sharper beam bend to reduce streaming $\Rightarrow$ Smaller incidence angle*
    - Used later in SENRI-I
    - Not feasible for GIMM
  - Rotating shutter to close penetrations between shots
    - Used later in GIMM (LLNL-90), Prometheus (MDA-92), and HIB designs
  - Place M-I away from target to reduce damage
    - concerns: higher f #, larger building, misalignment, out-focusing
  - Beam crossover optics to protect M-II for life and reduce leakage
    - Concern: gas breakdown due to high laser intensity at orifice
    - Used later in SENRI-I (J-82), SIRIUS-M (UW-88), SIRIUS-T (UW-91), and Prometheus (MDA-92)

* Between beam and normal to mirror

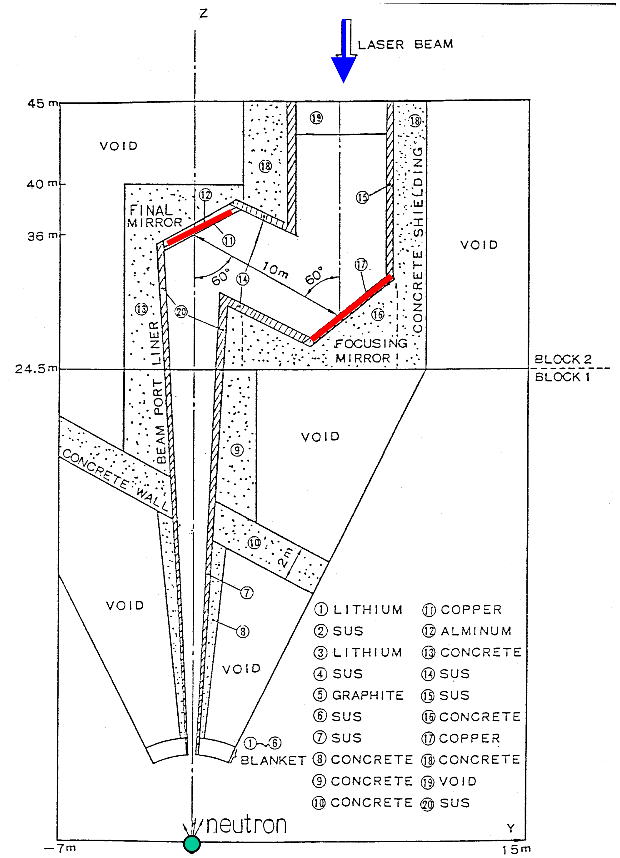
SOLASE (Cont.)



Point Cross-Over

SENRI-I
(Japan, 1982)

- Main features:
  - 8 beamlines
  - 60° beam bend
  - Beam crossover (not shown)
  - Various n trap materials behind M-II
- Design issues:
  - Effectiveness of leakage reduction techniques:
    - Point crossover
    - orifice diameter
    - Absorber behind M-II
  - Sensitivity of leakage to M-II location and thickness



SENRI-I (Cont.)

- Major findings:
  - Leakage through windows varies as square of orifice diameter
  - Effectiveness of leakage reduction techniques:

	Reduction in leakage
Point crossover optics with 10 cm orifice	10^3-10^4
Double distance between mirrors	3
Borated water absorber behind M-II	6
Very thin M-II (100 μm Cu)	10^4 (!)

- Recommendations:
  - Combine point crossover, black body absorber, and thin mirror techniques to achieve 10^7 reduction in leakage (!)

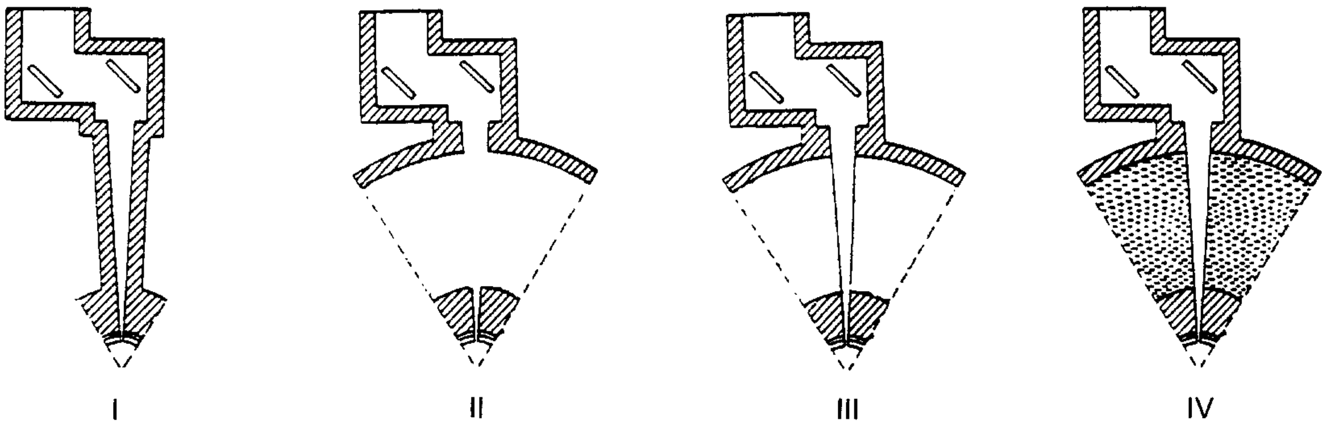
SIRIUS-M
(UW, 1988)

- Main features:
  - 32 beamlines
  - 8 shielding configurations examined to protect mirrors and windows
  - 1 cm thick boral* liner for shielded beamlines

- Design issues:
  - Optimum thickness of 3 shielding components: bulk shield, penetration shield, and building
  - Heating and dpa to Al/H_2O metallic mirrors
  - Heating in SiO_2 windows
  - Leakage to laser building
  - Accessibility of building during operation and after shutdown
  - Volume of penetration shield

* 36% B_4C and 64% Al, by volume

SIRIUS-M (Cont.)
Shielding Options I-IV



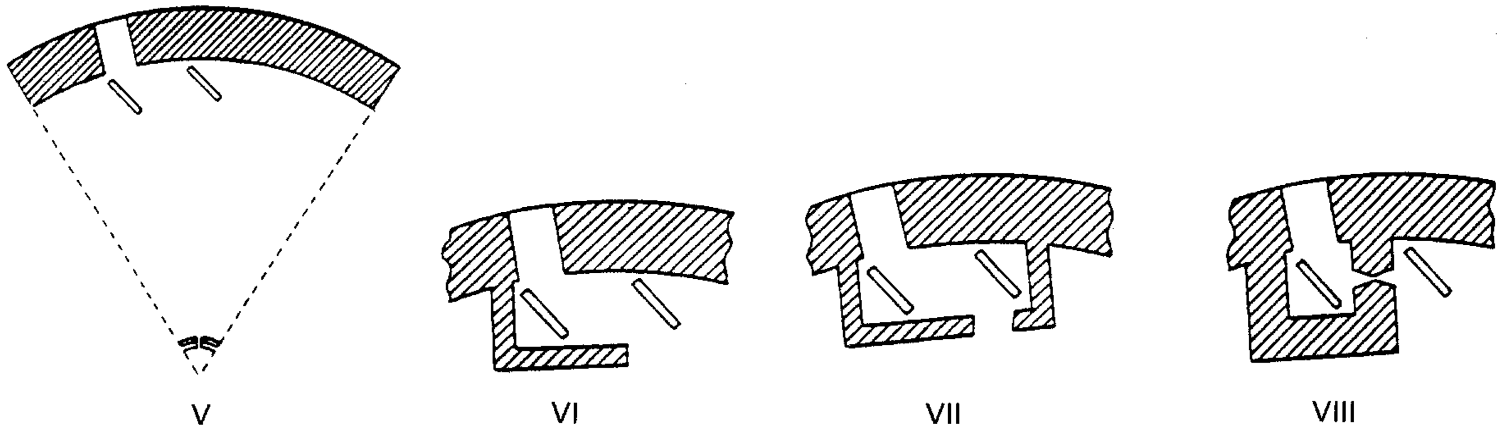
- Main features:
  - 3 m thick concrete bulk shield surrounds chamber (70 cm thick) to reduce biological dose to workers below limit during operation (in absence of penetrations)
  - 1 m thick concrete penetration shield surrounds mirrors
  - Options for penetration shield:
    - **Option I**: 1 m thick concrete shield around beamline
    - **Options II, III, and IV**: 1 m thick concrete building
    - **Option III, IV**: 1 cm thick Al duct around beamline
    - **Option IV**: borated water fills space between building and shield

SIRIUS-M (Cont.)
Shielding Options I-IV

- Major findings:
  - All options result in ~ same damage to M-I and M-II
  - Source neutrons dominate damage to M-I
  - Factor of 70 lower damage at M-II compared to M-I
  - Building internals have minimal impact on n streaming through windows
  - In all options, highest biological dose during operation occurs outside M-I shield
  - **Option I** results in factor of 2-3 higher biological dose outside shield surrounding mirrors
  - No personnel access during operation around beamlines or inside building
  - Remote maintenance for mirrors after shutdown

- Recommendations:
  - Thicken penetration shield around mirrors from 1 to 3 m to protect workers during operation.
  - 40 cm thick concrete shield around beamlines allows hands-on maintenance inside building after shutdown, providing that shield remains intact

SIRIUS-M (Cont.)
Shielding Options V-VIII



- Main features:
  - No shield surrounding chamber
  - 3 m thick concrete building to meet biological dose limit during operation (away from penetrations)
  - Local concrete shield surrounds M-II in Options VI, VII, and VIII
  - Shield around M-I in Option VII only
  - Beam crossover with 10 cm orifice diameter for Option VIII (differential pumping in beamlines to avoid gas breakdown)

SIRIUS-M (Cont.)
Shielding Options V-VIII

- Major findings:
  - All options result in ~ same damage to M-I (dominated by source n's)
  - M-II of Option V, VI, VII, and VIII has factor of **20, 60, 70, and 6000** lower damage compared to M-I, respectively
  - Option V results in highest n leakage to laser building (factor of 15 > Options VI, VII)
  - Option VIII results in lowest n leakage to laser building (10^2-10^3 < Options V-VII)
  - Biological dose **during operation:**
    - Personnel access allowed **outside** building providing that beamlines to laser building are surrounded with 1-3 m thick shield
  - Biological dose **after shutdown:**
    - No personnel access allowed **inside** building
    - Remote maintenance for M-I and M-II
    - Hands-on maintenance allowed for M-II of Option VIII

- Recommendations:
  - Option VIII is the best from shielding viewpoint

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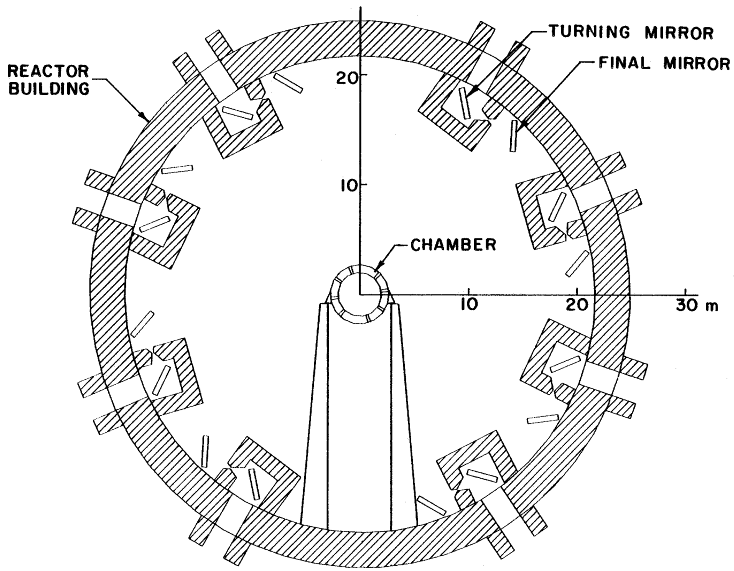
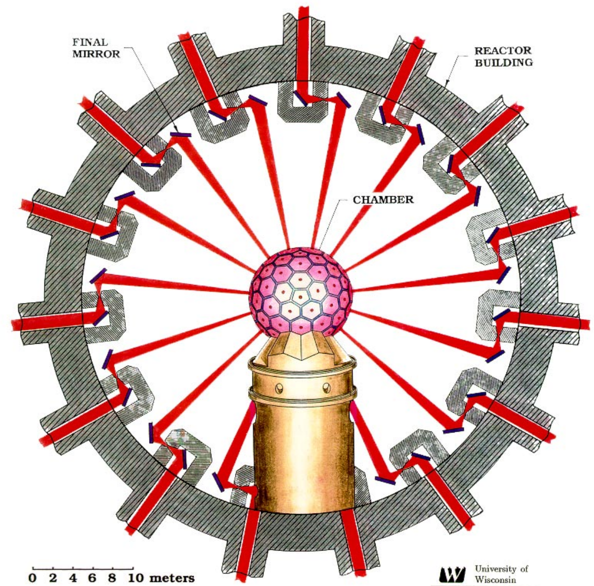
SIRIUS-M and SIRIUS-T
(UW-1988) (UW-1991)



SIRIUS-M
(32 beams)

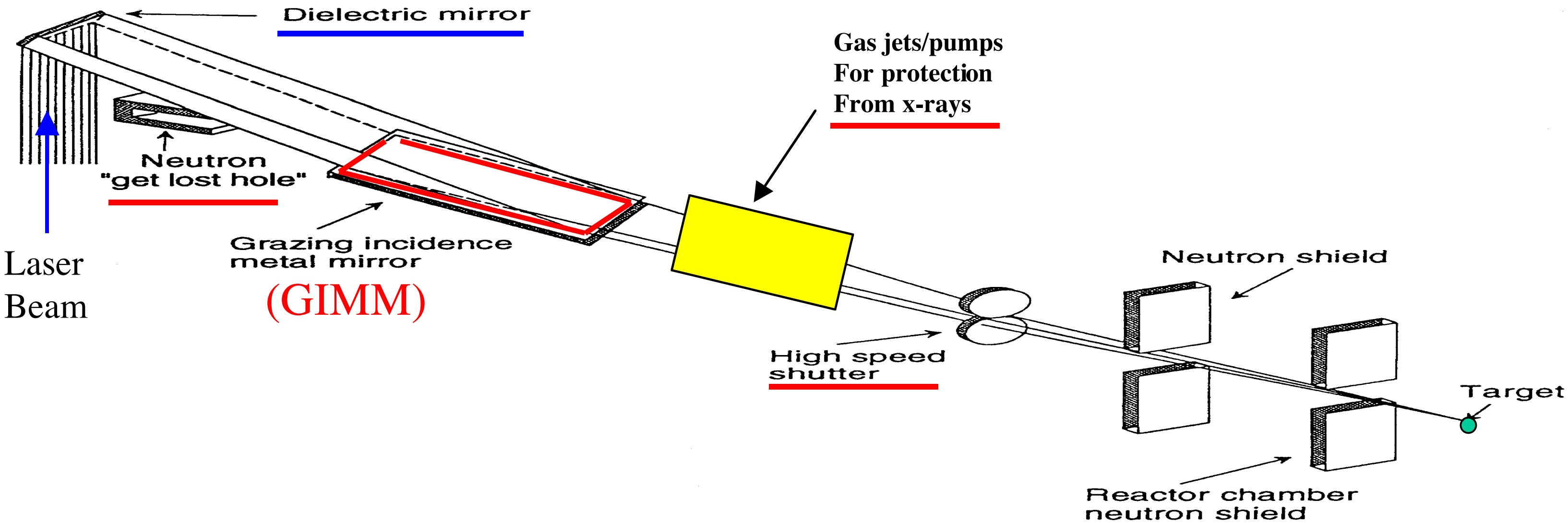


SIRIUS-T
(92 beams)

- Main features:
  - Beam crossover to protect M-II for life and minimize leakage to laser building

Grazing Incidence Metal Mirror (GIMM)

(Bieri and Guinan, LLNL 1990)



- Main features:
  - GIMM @ 30 m and dielectric mirror @ 50 m
  - Grazing incidence improves laser reflectivity and reduces absorptance
  - Large GIMM reduces laser fluence (J/cm^2) by cos θ*
  - Thin protective metals or oxides are more radiation-resistant than dielectric coatings
  - Sensitive dielectric mirrors moved away from direct-line-of-sight of target n's

* Incidence angle between beam and normal to mirror

GIMM (Cont.)

- Major findings:
  - GIMM:
    - n-induced defects and surface roughening raise laser absorptance by < 1%
    - n-induced swelling and creep of GIMM and support structure will be life limiting for RT GIMM but not a concern for cryogenic mirror (because swelling and creep saturate at cryo-temperature)
    - Cryogenic cooling allows higher beam energy threshold and smaller GIMM. However, cryo-load could be prohibitive (10-100 MW_e)
    - Al swells less than Mg
    - Al alloys swell less than pure Al
  - Dielectric mirrors:
    - Limited data on n damage limit to dielectric coatings
    - **Assuming** n fluence limit of 10^{17}-10^{18} n/cm^2 (E_n > 1 MeV), mirror's lifetime ranges between 1 and 30 FPY, depending on estimated n flux
    - **If** mirror is placed in direct-line-of-sight @ 50 m, lifetime would be 1-10 days

      $\Rightarrow$ 300-1000 X shorter lifetime
    - No waste disposal problem for 1-2 FPY Al mirrors
    - Remote maintenance for Al mirrors

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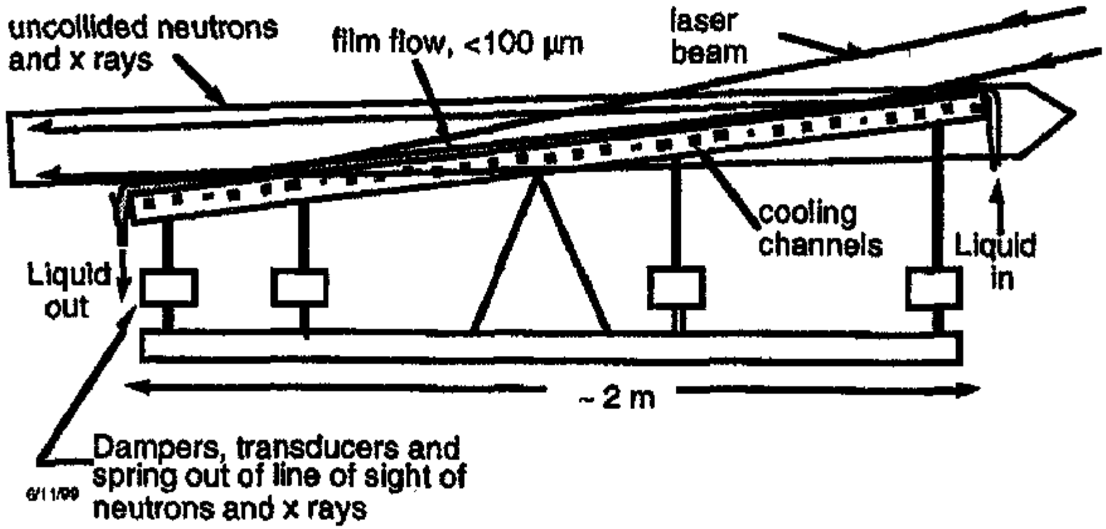
GIMM (Cont.)

- Concern:
  - Flaws/contaminants as small as 1 μm look locally like normal incidence. Local absorption increases from shot to shot, leading to failure
- Recommendations:
  - Dielectric mirrors:
    - Need experimental data for n damage limit
  - GIMM:
    - Need experimental verification of laser damage thresholds for metals and oxide coatings
    - Install "get lost holes" behind GIMM to trap n's
    - Protect GIMM between shots from ion debris and x-rays using:
      - High-speed mechanical shutters on beamlines
      - Few torr-m of Ar gas jets in beamlines
      - Low energy pre-pulse laser beams to vaporize surface contaminants condensing on GIMM
    - Develop manufacturing techniques for large high quality mirrors

Grazing Incidence Liquid Metal Mirror (GILMM) (Moir, LLNL 1999)



- Main features:
  - No nuclear analysis
  - Thin film (< 100 µm) of LM (Na, Li, Hg, Al, Ga, or Pb) flowing down 85° inclined surface
  - 1-100 J/cm^2 laser heating limit, depending on LM, pulse duration, λ, and surface area
  - Surface imperfections heals due to flowing liquid
  - Radiation-resistant to n's with service lifetime > 30 years (!)
  - Li can stand x-rays, but Na needs Xe gas jets to avoid high temperature rise
  - Delivers high quality laser to target

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GILMM (Cont.)

- Requirements:
  - Flat and uniform surface over long distance
  - Wetted surface at all times
  - Slow flow of liquid surface to avoid shear flow instabilities and surface ripples
  - Limit heat flux to avoid sudden (isochoric) heating and rapid expansion

- Concerns:
  - Film stability for large inclination of mirror surface (at top/bottom of machine)
  - Dry out of surface requiring plant shutdown
  - Disturbances can be initiated by:
    - Uneven laser heating
    - Acoustic motion due to gas shock and target debris
    - n and γ heating

GILMM (Cont.)

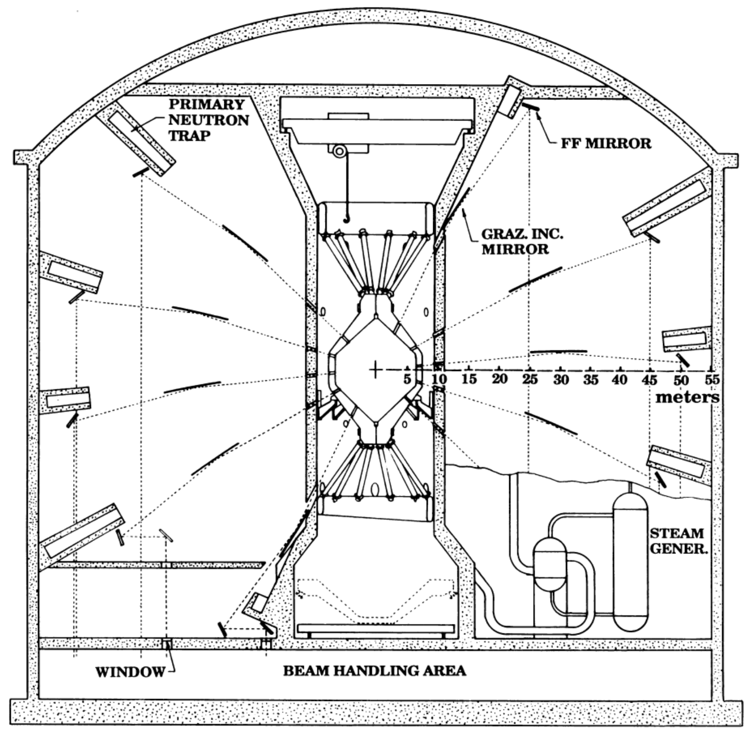
- Major findings:
  - For $\Delta T \sim 200$ °C, liquid Al (T_m= 660 °C) allows highest laser heating followed by Na, Ga and Li (106, 57, 28, and 8 J/cm^2 normal to beam, respectively)
  - High T_m of Al suggests use of Na and Li
  - Limitation on film thickness is unknown. However,
    - Maintaining wetting could determine thickness
    - Na film must be < 25 μm to avoid waves

- Recommendations:
  - Need experiments to:
    - Determine feasibility of concept
    - Prove stable thin flowing films can be made for steep slopes
    - Verify surface smoothness

SOMBRERO
(UW et al., 1992)

- Main features:
  - 60 beamlines - 17 cm diameter @ FW
  - 1.7 m concrete shield @ 10 m
  - 1.2 m concrete building @ 53 m
  - n flux trap mounted on building
  - Unshielded mirrors:
    - GIMM at 30 m
    - Dielectric coated mirror at 50 m

- Design issues:
  - Lifetime of M-I and M-II using range of radiation limits
  - Accessibility of building during operation and after shutdown



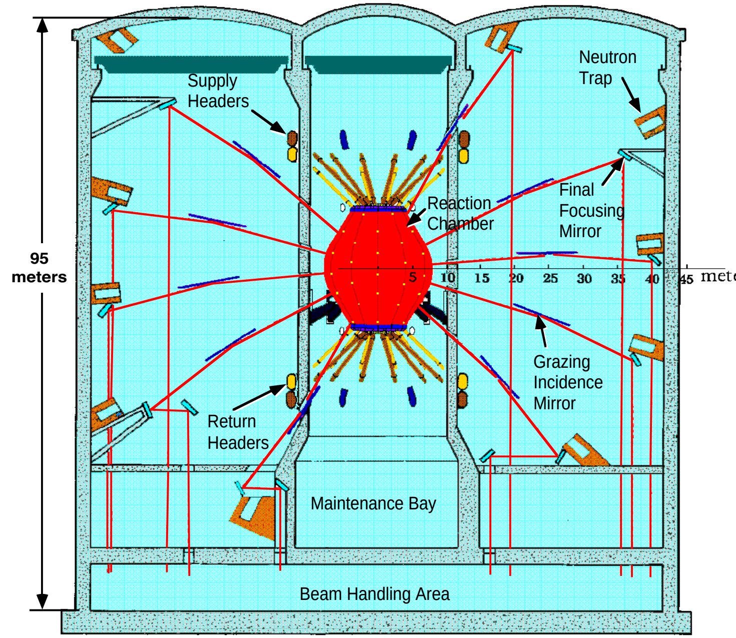
SOMBRERO (Cont.)

- Major findings:
  - 90% annealing prolongs M-I life by factor of 10
  - M-I lifetime ranges between 0.4 and 400 FPY, depending on fast n fluence limit (10^{20}-10^{22} n/cm^2) and annealing recovery fraction (0-90%). For example, 10^{21} n/cm^2 and 80% recovery $\Rightarrow$ 17 FPY lifetime
  - Neutron trap with aspect ratio (L/D) of ~2 limits back-scattering to M-II
  - For 10^{18} n/cm^2 fluence limit, M-II lifetime could reach 37 FPY (based on 1-D !)
  - Acceptable dose to workers providing that 2.2 m local shield installed behind n trap
  - No personnel access to building at any time

- Recommendations:
  - Check effectiveness of n trap with 3-D analysis
  - Develop R&D program to determine radiation limits to mirrors

SIRIUS-P
(UW, 1993)

- Main features:
  - Chamber design resembles SOMBRERO's
  - 1.5 m concrete shield @ 10 m
  - 1.2 m concrete building @ 42 m
  - n trap mounted on building
  - Unshielded mirrors:
    - GIMM at 25 m
    - Dielectric coated mirror at 40 m



- Design issues:
  - Lifetimes of M-I and M-II using range of radiation limits
  - Sensitivity of mirror damage to aspect ratio (A) of n trap

SIRIUS-P (Cont.)

- Major findings:
  - M-I lifetime ranges between 0.3 and 300 FPY, depending on fast n fluence limit (10^{20}-10^{22} n/cm^2) and annealing recovery fraction (0-90%).
    For example, 10^{21} n/cm^2 and 80% recovery $\Rightarrow$ 14 FPY lifetime
  - Neutron flux at M-II decreases with aspect ratio of n trap. Factor of 10 reduction for $A \geq 3$
  - M-II lifetime is 0.6 FPY for fluence limit of 10^{18} n/cm^2. Few days lifetime if placed in direct line-of-sight with source n's (100 X shorter lifetime)
  - Presence of M-I increases M-II flux by factor of 2

- Recommendations:
  - Aspect ratio of 3 is optimum for n trap
  - Careful choice of M-I materials could reduce n scattering to M-II
  - R&D program is needed to determine radiation limits to mirrors

Modified SOMBRERO with DPSSL Driver (LLNL, 1999)

- Modifications to SOMBRERO design:
  - 20 times larger 60-beams

    ⇒ 75 cm beam port diameter @ FW instead of 17 cm
  - SiO_2 wedges @ 30 m instead of GIMM
  - n trap with A = 1 (L = D = 5 m @ 50 m)
  - M-II @ 50 m with ZnS or MgF_2 dielectric coating on SiO_2 substrate

- Design issues:
  - Lifetimes of wedges and M-II using range of radiation limits
  - Fluence, heating, and recycling dose for wedges and M-II
  - WDR for wedges, M-II, n trap, and building
  - Cumulative volume of replaceable wedges and M-II

Modified SOMBRERO (Cont.)

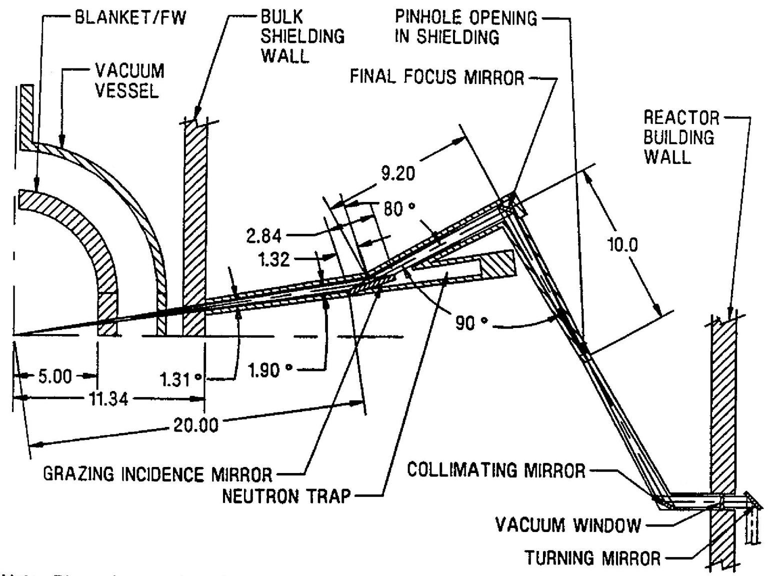
- Major findings:
  - **Fluence limit to wedges** — **10^{20} n/cm²** | **10^{22} n/cm²**

	10^{20} n/cm²	10^{22} n/cm²
Lifetime	0.33 FPY	33 FPY
Cumulative volume over 30 FPY	1600 m³	16 m³
Fluence limit to M-II	**10^{18} n/cm²**	**10^{19} n/cm²**
Lifetime	0.25 FPY	2.5 FPY
Cumulative volume over 30 FPY	2700 m³	270 m³

  - 15,000 and 400 rads/s dose to wedge and M-II, respectively
  - Wedges, M-II, n traps, and building are LLW, according to Fetter's limits
  - Hands-on recycling allowed for wedges, M-II/MgF_2, M-II/ZnS, n traps, and building after 10, 0.03, 10, 100, and 30 y following shutdown
- Recommendations:
  - Self-annealing @ 400 °C may extend wedges lifetime and reduce cumulative waste
  - Reuse of M-II substrate reduces cumulative waste volume
  - Reduce beam size and thin wedges to prolong M-II lifetime
  - MgF_2 is preferable over ZnS for offering lower recycling dose and WDR
  - Data on fluence and heating limits are required

Prometheus
(MDA et al., 1992)

- Main features:
  - 60 beams
  - Shielded beamlines:
    - GIMM at 21 m; He-cooled, Al coated SiC
    - Dielectric coated M-II at 30 m
  - 20-25 cm thick penetration shield surrounding beamlines to contain n's and tritium
  - n trap attached to penetration shield
  - Beam crossover to reduce leakage through windows with pumping on both sides of orifice to avoid gas breakdown
  - 1.65 m concrete shield @ 10 m
  - Concrete building @ 40 m
  - Building at atmospheric pressure
  - All enclosed beamlines will be pumped



Note: Dimensions are in meters.

Prometheus (Cont.)

- Design issues:
  - Lifetimes of M-I and M-II with multiple protection schemes
  - Personnel access to building during operation and after shutdown

- Major findings:
  - 2.3 km long, 20-25 cm thick penetration shield (1,600 m^3)
  - Acceptable dose to workers outside building
  - No personnel access to building during operation
  - After shutdown:
    - Adequate dose for hands-on maintenance, but remote maintenance is recommended, specially after opening shield doors to maintain mirrors
    - Remote maintenance for mirrors
  - GIMM with tapered Al coating are expected to be lifetime components* if:
    - Liquid Pb flows in beam port walls. Pb vapor attenuates debris and x-rays
    - Small magnets placed around beamlines to deflect ions and charged particles
    - Pre-pulse beams vaporize condensed Pb vapor and debris on mirrors
    - High-speed shutters intercept particles before reaching optics

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* No nuclear analysis performed for M-II to support the lifetime statement
Proposed schemes will not stop n's

Recommended Shielding Scheme for ARIES-IFE Optics

- Develop more efficient n trap design with A= 3 (confirm with 3-D analysis)
- Surround M-II with local shield (confirm with 3-D analysis)
- Enclose beamlines in **thin** tube* (~1 cm boral or SS) to:
  - Confine T in small volume
  - Maintain vacuum inside enclosures
  - Allow atmospheric pressure in building (could be oxygen-free and/or filled with He gas)
  - Plate out condensables on cold enclosures
- Thick penetration shield (~ 40 cm) surrounding beamlines is not needed unless hands-on maintenance is required inside building for **limited time** after shutdown prior to opening shield doors to maintain mirrors
- No need for beam crossover. It may not be effective in SOMBRERO-type design
- Minimize size of beam ports

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* Applied to beamlines between bulk shield and building only, excluding region inside bulk shield to facilitate chamber maintenance

Recommended Shielding Scheme for ARIES-IFE Optics (Cont.)

- Use spinel coating on SiC/SiC (or C/C) substrate for GIMM to lower n-induced swelling and prolong life
- Operate optics at high temperatures to continuously anneal radiation-induced damage
- Develop more radiation-resistant dielectric coatings for M-II
- Use multiple defense system to stop x-rays and ion debris :
  - Gas or liquid* jets
  - High-speed mechanical shutters
  - Pre-pulse laser beams to evaporate surface contaminants between shots
  - Small coils around beamlines to deflect charged particles
- Concrete shields required to meet dose limit to workers outside building during operation:
  - 2 m thick bulk shield
  - 1 m thick building
  - 2.5 m thick local shield behind each n trap

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* Recently proposed by Per Peterson, UC-Berkeley