Shielding Protection Schemes for Final Optics

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With input from M. Sawan (UW) and L. Waganer (Boeing)

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

• **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 ($E_n \sim 12$ 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
      - $\Rightarrow$ 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
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
• Candidate final optics **materials:**
  – **Mirrors:**
    • **Substrates:** Al alloys, SiC/SiC, or C/C
    • **Coolants:** H$_2$O, He, or LN2
    • **Coatings:**
      – Metallic: Al, Mg, Cu, Ag, or Au
      – Oxide: Al$_2$O$_3$ (~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 & $\gamma$ 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%)
• **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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Al₂O₃ Coating Exhibits High Swelling Compared to MgO and Spinel¹,²

- Spinel (MgAl₂O₄) 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**

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 $\Gamma$ by $\cos \theta^*$ (flux and damage will not change)
- Offsetting M-II softens n spectrum and reduces fast n flux by 2-3 orders of magnitude  ⇒ longer life

* Angle between beam and normal to mirror
Radiation Effects @ M-I
(Assuming bare Al mirror @ 30 m from target)

<table>
<thead>
<tr>
<th>Target yield</th>
<th>160 MJ</th>
<th>400 MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fast n fluence</strong> (n/cm²s @ 1 FPY, Eₙ &gt; 0.1 MeV)</td>
<td>2e20</td>
<td>5e20</td>
</tr>
<tr>
<td><strong>Fast n flux</strong> (n/cm²s, Eₙ &gt; 0.1 MeV)</td>
<td>6.7e12</td>
<td>1.7e13</td>
</tr>
<tr>
<td><strong>Total n flux</strong> (n/cm²s)</td>
<td>1.1e13</td>
<td>2.7e13</td>
</tr>
<tr>
<td><strong>Total γ flux</strong> (γ/cm²s)</td>
<td>8.6e12</td>
<td>2e13</td>
</tr>
<tr>
<td><strong>Atomic displacement</strong> (dpa/FPY)</td>
<td>0.4</td>
<td>1</td>
</tr>
</tbody>
</table>

Nuclear heating (W/cm³):
- 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/r² and scale roughly with target yield
- **For Al:** 1 dpa ≡ 5.4e20 n/cm² (Eₙ > 0.1 MeV)
  ≡ 1-3% swelling ?
  ≡ 6e11 rads
1 n/cm² (Eₙ > 0.1 MeV) ≡ 4e-10 rads
1 γ/cm² ≡ 5e-10 rads
Several Designs Developed Mirror’s Protection Schemes Over Past 25 years

Fusion Technology Institute IFE/ICF Reactor Studies

Calendar Year

*in conjunction with other universities, national and international labs
**Most Design Studies Performed 3-D Streaming Analysis**

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

** 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
### ARIES-IFE Shielding Criteria (Cont.)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Open Beamlines#</th>
<th>Shielded Beamlines##</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintainability of building internals after shutdown</td>
<td>Remote</td>
<td>Hands-on for limited time before opening shield doors</td>
</tr>
<tr>
<td>Accessibility of final optics using remote handling equipment</td>
<td>Easy</td>
<td>Moderately easy after removing shield doors</td>
</tr>
<tr>
<td>Tritium contaminated area</td>
<td>$5 \times 10^4 \text{ m}^2$</td>
<td>$8 \times 10^3 \text{ m}^2$</td>
</tr>
<tr>
<td>Volume of penetration shield*</td>
<td>---</td>
<td>$1,600 \text{ m}^3$</td>
</tr>
<tr>
<td>Evacuated volume</td>
<td>$10^6 \text{ m}^3$</td>
<td>$3 \times 10^3 \text{ m}^3$</td>
</tr>
</tbody>
</table>

* Compared to ~7,000 m$^3$ bulk shield and ~70,000 m$^3$ building
# SOMBRERO-type
## Prometheus-type
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/H₂O metallic mirrors
  – Neutron leakage through SiO₂ windows to laser building
  – Biological dose around beamlines during and after operation

* 36% B₄C and 64% Al, by volume
**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 ⇒ 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 ⇒ 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)

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* Between beam and normal to mirror
SOLASE (Cont.)
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:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Reduction in leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point crossover optics with 10 cm orifice</td>
<td>$10^3$-$10^4$</td>
</tr>
<tr>
<td>Double distance between mirrors</td>
<td>3</td>
</tr>
<tr>
<td>Borated water absorber behind M-II</td>
<td>6</td>
</tr>
<tr>
<td>Very thin M-II (100 µm Cu)</td>
<td>$10^4$ (!)</td>
</tr>
</tbody>
</table>

- **Recommendations:**
  - Combine point crossover, black body absorber, and thin mirror techniques to achieve $10^7$ reduction in leakage (!)
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/H₂O metallic mirrors
- Heating in SiO₂ windows
- Leakage to laser building
- Accessibility of building during operation and after shutdown
- Volume of penetration shield

* 36% B₄C and 64% Al, by volume
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
SIRIUS-M and SIRIUS-T
(UW-1988)               (UW-1991)

• 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/cm²) by $\cos \theta^*$
  - 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
• 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
      ⇒ 300-1000 X shorter lifetime
    • No waste disposal problem for 1-2 FPY Al mirrors
    • Remote maintenance for Al mirrors
**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/cm² 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
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 $\gamma$ 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
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 \(10^{20}-10^{22}\ \text{n/cm}^2\) and annealing recovery fraction (0-90%). For example, \(10^{21}\ \text{n/cm}^2\) and 80% recovery \(\Rightarrow\) 17 FPY lifetime
- Neutron trap with aspect ratio (L/D) of ~2 limits back-scattering to M-II
- For \(10^{18}\ \text{n/cm}^2\) 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
• **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
  – SiO₂ wedges @ 30 m instead of GIMM
  – n trap with $A = 1$ ($L = D = 5$ m @ 50 m)
  – M-II @ 50 m with ZnS or MgF₂ dielectric coating on SiO₂ 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
• **Major findings:**
  
  − **Fluence limit to wedges**
    - Fluence limit: $10^{20}$ n/cm$^2$ to $10^{22}$ n/cm$^2$
    - Lifetime: 0.33 FPY to 33 FPY
    - Cumulative volume over 30 FPY: 1600 m$^3$ to 16 m$^3$

  − **Fluence limit to M-II**
    - Fluence limit: $10^{18}$ n/cm$^2$ to $10^{19}$ n/cm$^2$
    - Lifetime: 0.25 FPY to 2.5 FPY
    - Cumulative volume over 30 FPY: 2700 m$^3$ to 270 m$^3$

  − 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
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 m³)
  – 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

* 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

* 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

* Recently proposed by Per Peterson, UC-Berkeley