Effect of Mirror Defect and Damage On Beam Quality

T.K. Mau and Mark Tillack
University of California, San Diego
UCSD

ARIES Project Meeting

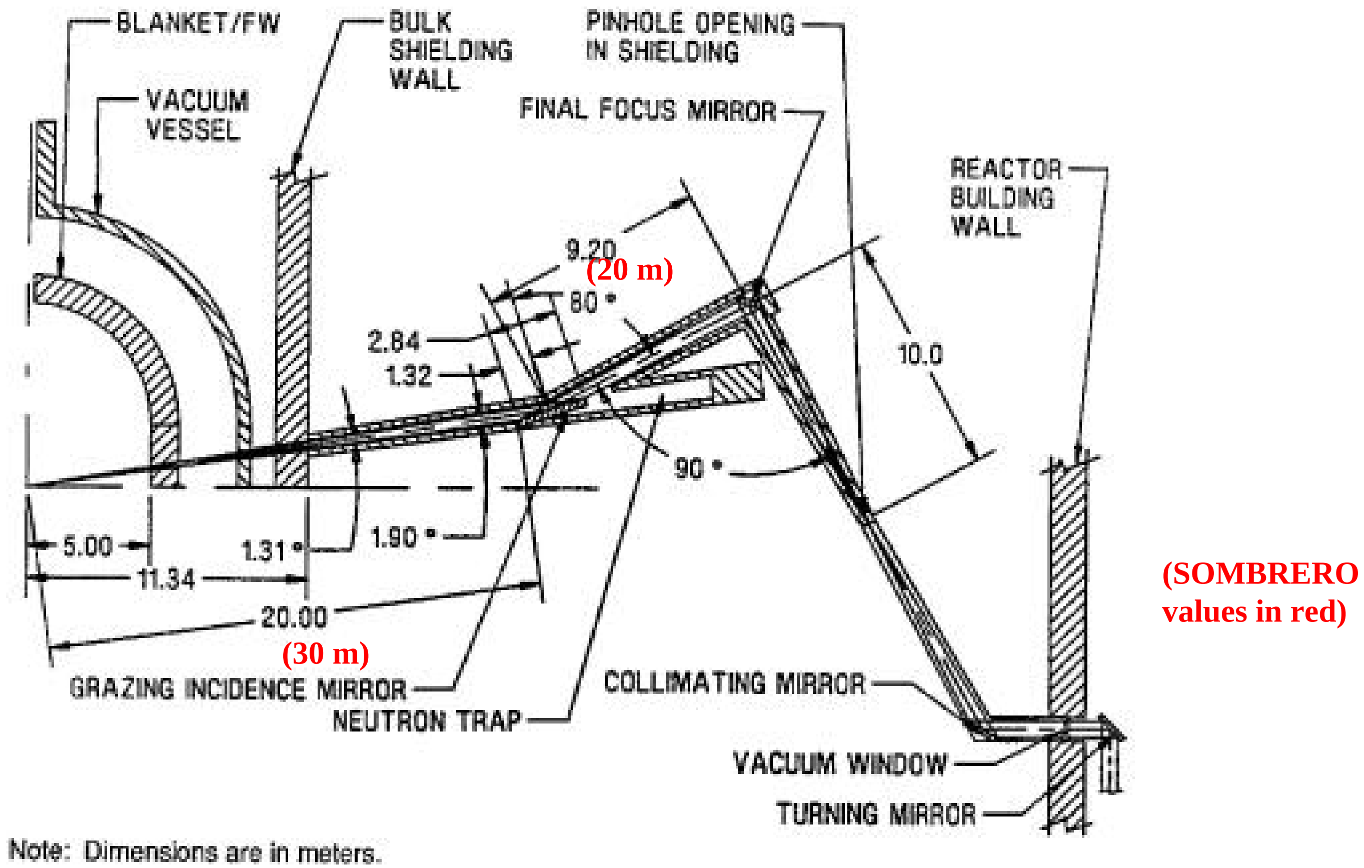
March 8-9, 2001
Livermore, California

OUTLINE

- Objectives of final optics study
- GIMM surface defect types and analysis approaches
- Summary of Fresnel modeling of gross surface contaminant on mirror performance
- Analytic estimate for microscopic surface damage
- Future plans

Geometry of the final laser optics

- Goal of study is to determine design windows for GIMM and other optical subsystems for ARIES/IFE studies by relating these damages to heat deposition and neutron fluence.



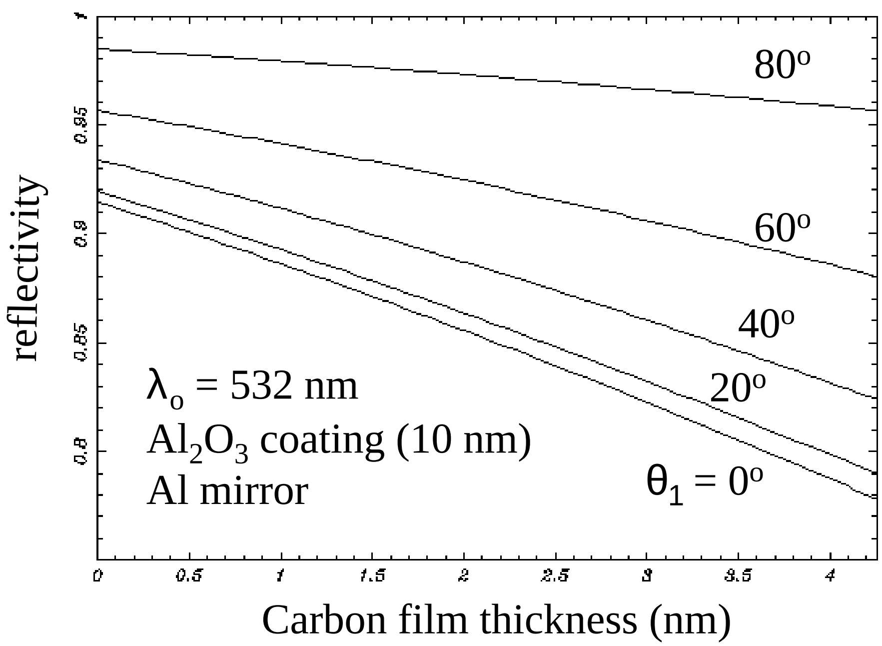
Prometheus-L reactor building layout

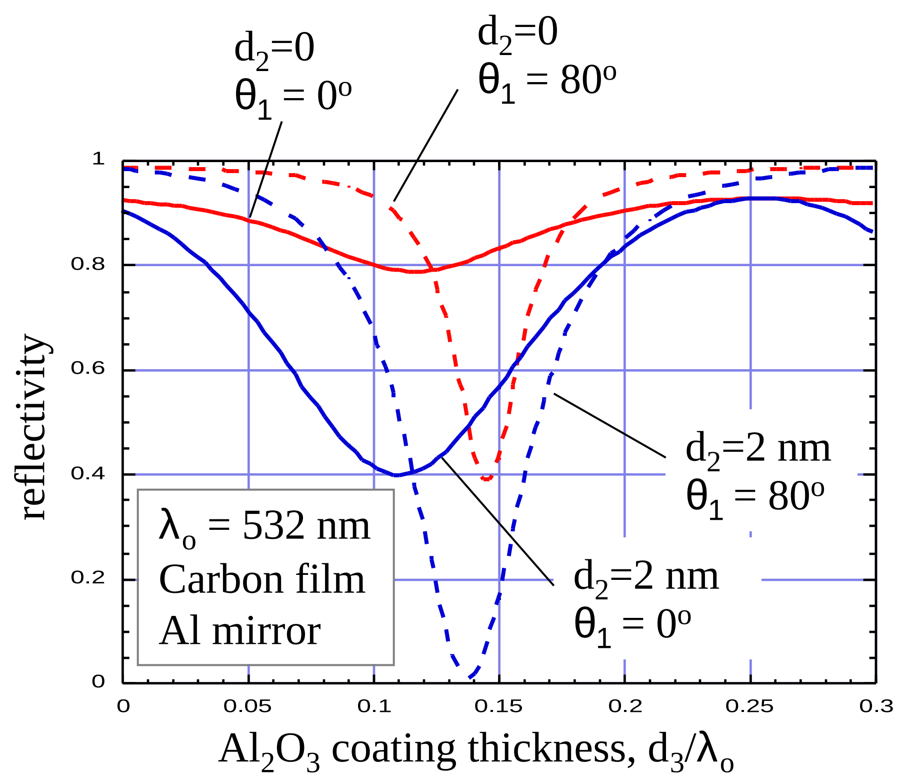
Mirror Defects and Damage Types, and Approaches to Assess their Effects on Beam Quality

Dimensional Defects		Compositional Defects	
Gross deformations, $\delta > \lambda$	Surface morphology, $\delta < \lambda$	Gross surface contamination	Local contamination
CONCERNS			
• Fabrication quality • Neutron swelling • Thermal swelling • Gravity loads	• Laser-induced damage • Thermomechanical damage	• Transmutations • Bulk redeposition	• Aerosol, dust & debris
MODELLING TOOLS			
Optical design software	Scattering by rough surfaces (Kirchhoff)	Fresnel multi-layer solver	Scattering by particles

Surface Contaminants Can Degrade Reflectivity

- Surface contaminants (such as carbon) on mirror protective coatings can alter reflectivity, depending on layer thickness and incident angle.
- Reflectivity is reduced with increasing contaminant thickness.
- Effect of surface contaminant is diminished at gracing incidence.





Assessment Approach on Transmutation Effect

- Neutron irradiation of the mirror can cause transmutations of the protective coating and metal substrate, thus altering their optical properties.

- Assume the ambient material and transmutant have dielectric constant ε_a and ε_b, respectively, and volume fraction of transmutant is f_b.

Using the effective medium approximation (EMA), an effective ε_{eff} can be defined using the Bruggeman expression:

$$0 = (1 - f_b)\frac{\varepsilon_a - \varepsilon_{eff}}{\varepsilon_a - 2\varepsilon_{eff}} + f_b\frac{\varepsilon_b - \varepsilon_{eff}}{\varepsilon_b - 2\varepsilon_{eff}}$$

- The fraction f_b is an increasing function of the neutron fluence.

- This model can be incorporated into the Fresnel solver to account for effect of transmutations on mirror reflectivity. However, need input from neutronics and information on transmutant dielectric properties.

Mirror Defects and Damage Types, and Approaches to Assess their Effects on Beam Quality

Dimensional Defects		**Compositional Defects**	
Gross deformations, $\delta>\lambda$	Surface morphology, $\delta<\lambda$	Gross surface contamination	Local contamination
		CONCERNS	
• Fabrication quality • Neutron swelling • Thermal swelling • Gravity loads	• Laser-induced damage • Thermomechanical damage	• Transmutations • Bulk redeposition	• Aerosol, dust & debris
		MODELLING TOOLS	
Optical design software	Scattering by rough surfaces (Kirchhoff)	Fresnel multi-layer model	Scattering by particles

Wave Scattering from Random Rough Surfaces

- Assuming no coupling between polarizations, scalar theory applies.

- In the presence of a scatterer, total field is given by

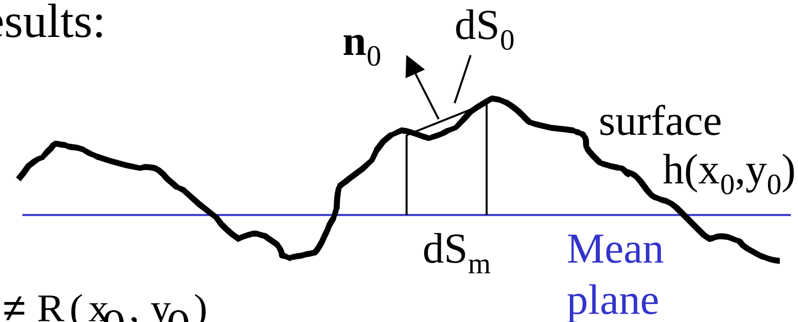
$$\psi(\vec{r}) = \psi^{inc}(\vec{r}) + \psi^{sc}(\vec{r})$$

- According to Kirchhoff theory, $\psi^{sc}(\vec{r})$ is given by

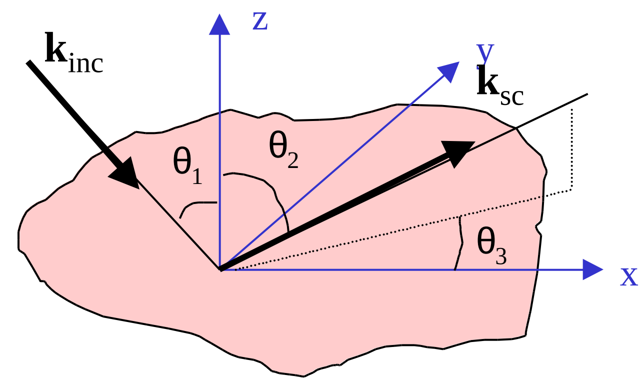
$$\psi^{sc}(r) = \int_{S_0} \left[\psi(\vec{r}_0)\frac{\partial G(\vec{r},\vec{r}_0)}{\partial n_0} - G(\vec{r},\vec{r}_0)\frac{\partial \psi(\vec{r}_0)}{\partial n_0} \right] d\vec{S}_0$$

where S_0 is surface of scatterer and $G(\mathbf{r},\mathbf{r}_0)$ is the full-space Green's function.

- Approximations required for analytic results:
  - Plane wave incidence
  - Far-field approximation : $r \gg r_0$
  - Integration over mean plane
  - Constant reflection coefficient : $R \neq R(x_0, y_0)$



Scattered Coherent Field



- The average scattered (coherent) field is [Ogilvy]

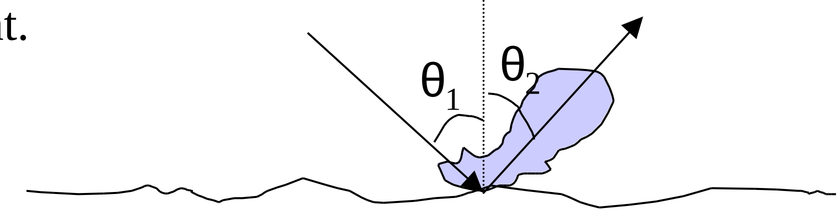
$$\langle \psi^{sc} \rangle = \frac{-ike^{ikr}}{4\pi r} 4XYc\,\chi(k_z)\left(\frac{\sin k_x X}{k_x X}\right)\left(\frac{\sin k_y Y}{k_y Y}\right) = \chi(k_z)\psi_0^{sc}$$

where 4XY is area of mean plane, ψ_0^{sc} is field scattered from smooth surface, $\kappa(k_z)$ is the characteristic function of the rough surface

$$\chi(s) = \int_{-\infty}^{\infty} p(h)\, e^{ish}\, dh$$

p(h) is the statistical height distribution, and $c = \cos\theta_2(1+R) - \cos\theta_1(1-R)$,
$k_x = (2\pi/\lambda)[\sin\theta_1 - \sin\theta_2\cos\theta_3]$, $k_y = -(2\pi/\lambda)\sin\theta_2\sin\theta_3$, $k_z = -(2\pi/\lambda)(\cos\theta_1+\cos\theta_2)$

- ψ_0^{sc} is peaked at $\theta_2=\theta_1$ and $\theta_3=0$ [specular reflection], and has a lobe-like spectrum around this point.



At X/λ >>1, and Y/λ >> 1, this lobe-like structure disappears and there is only reflection in the specular direction.

Overall Scattered Intensity from a "Gaussian" Rough Surface

- The diffuse (non-coherent) portion of the scattered field is averaged to zero. However, the diffuse scattered intensity is nonzero, and given by

$$\langle I_d \rangle = \langle \psi^{sc} \psi^{sc*} \rangle - \langle \psi^{sc} \rangle \langle \psi^{sc*} \rangle$$

- Our interest is focused on the specularly reflected coherent intensity I_{coh}, which is the component that is aimed at the target.

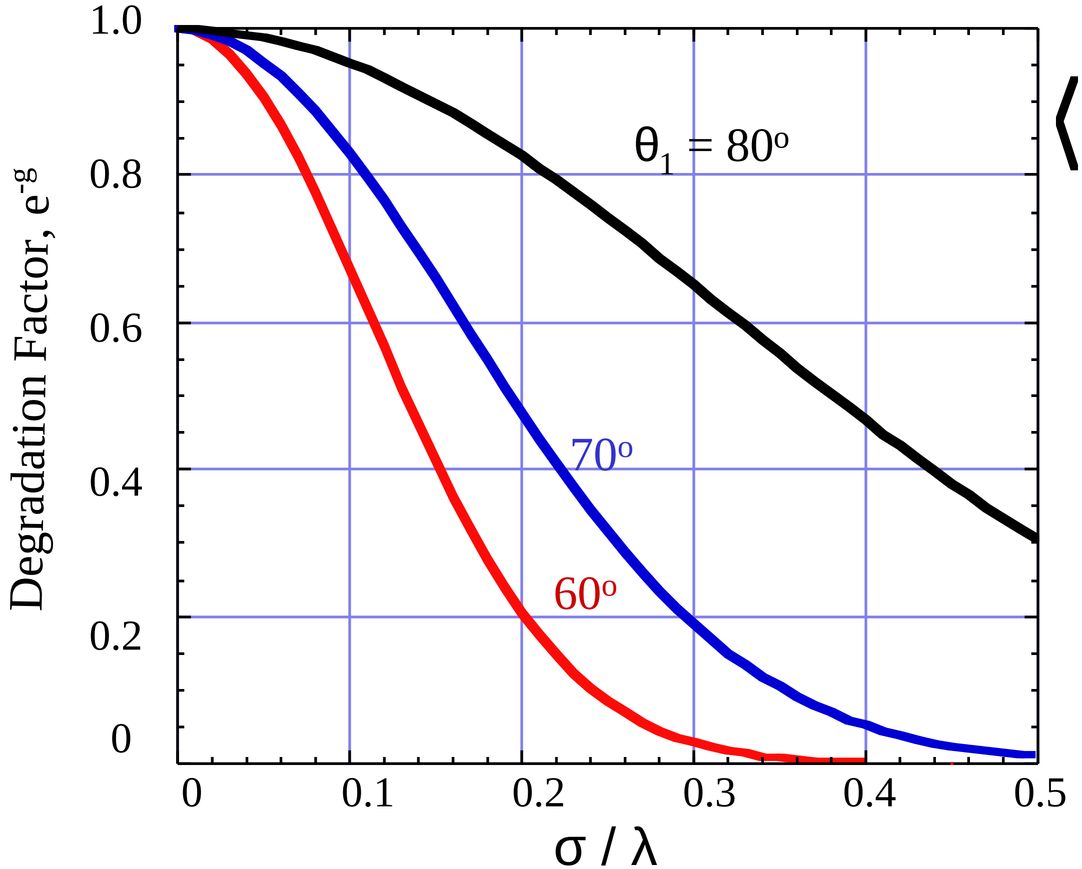
- We assume a Gaussian height distribution of the form $p(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right)$ where σ is the rms height of the damaged surface. Thus, $\kappa(k_z) = \exp\{-k_z^2\sigma^2/2\}$.

- Overall scattered intensity is $\langle I^{sc} \rangle = I_0 e^{-g} + \langle I_d \rangle$ where $g = (4\pi\sigma\cos\theta_1/\lambda)^2$

- The assumption of near-Gaussian surface statistics is valid for "those surfaces with a profile that is everywhere the result of a large number of local events, the results of which are cumulative. … Surfaces produced by engineering methods, such as turning, are less likely to possess Gaussian height statistics than those arising from natural processes, such as fatigue cracks or terrain."[J.A. Ogilvy]. **Laser-induced and thermomechanical damages may have Gaussian statistics if these are induced cumulatively**.

Specularly Reflected Intensity can be Degraded by Surface Roughness

- Grazing incidence is less affected by surface roughness.
- To avoid loss of laser beam intensity, $\sigma / \lambda < 0.01$.



$$\langle I^{sc} \rangle = I_0 e^{-g} + \langle I_d \rangle$$

At $\theta_1 = 80^o$, $\sigma/\lambda = 0.1$,

$e^{-g} = 0.97$.

SUMMARY & FUTURE PLANS

- Fresnel analysis of oxide-coated metal mirrors has been carried out using a 4-layer model and assuming smooth surfaces.
  - Surface contaminant can have impact on reflectivity, which is minimized by grazing incidence.

- Applying Kirchhoff theory and assuming Gaussian surface statistics, specularly reflected beam intensity can be degraded if $\sigma / \lambda > 0.01$, for grazing incidence . (σ : rms surface height, $\theta_1 = 80^o$)
  - How does effect vary with different surface characteristics?

- Two future tasks:

  (1) Use optical design software to assess gross deformation effects e.g., ZEMAX

  (2) Use technique of wave scattering by particles to assess effects of local contaminants on mirror (and in fused silica wedges).