Damage Mechanisms and Limits for Laser IFE Final Optics

M. S. Tillack
UC San Diego

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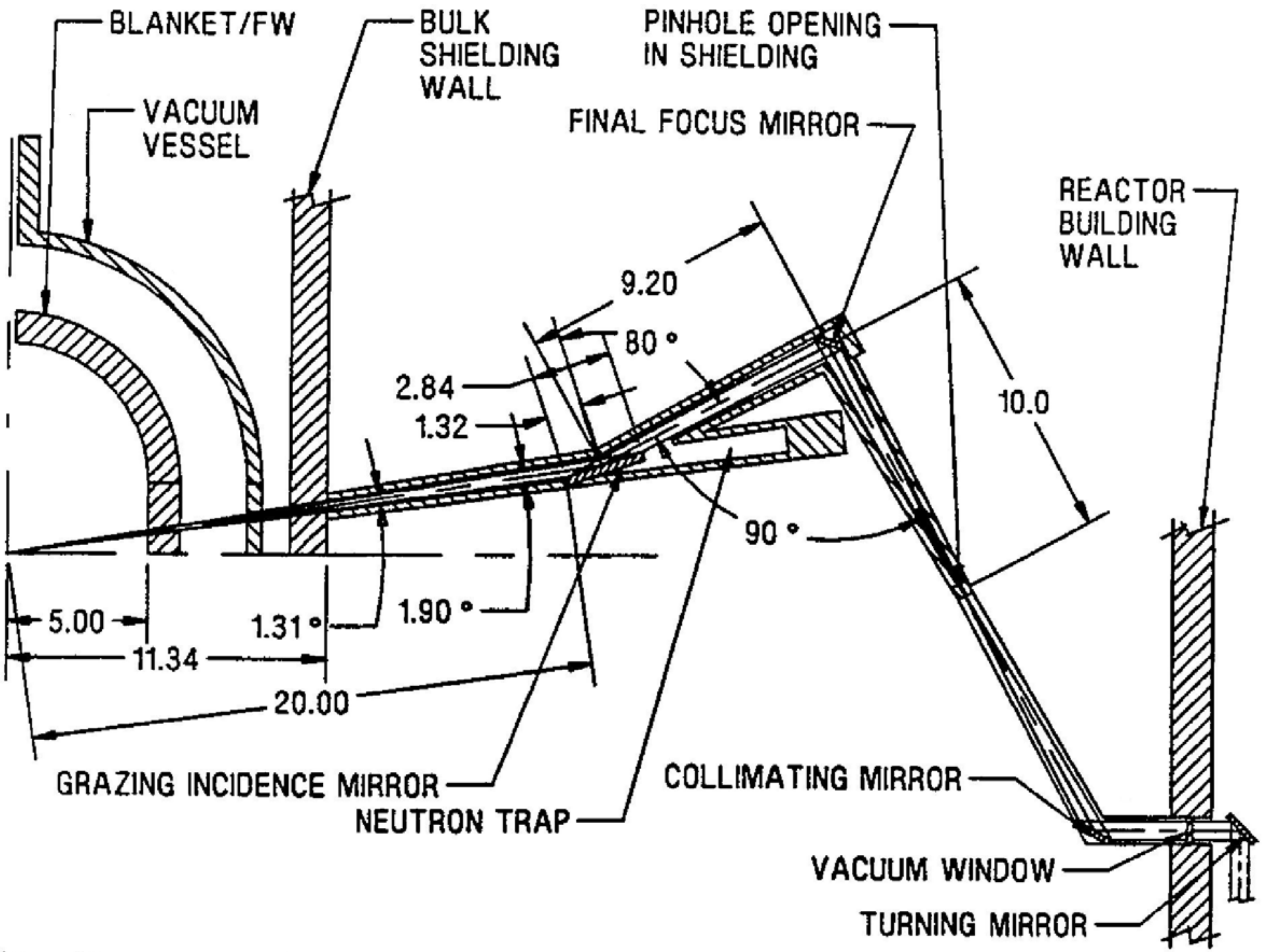
1. Design options and requirements

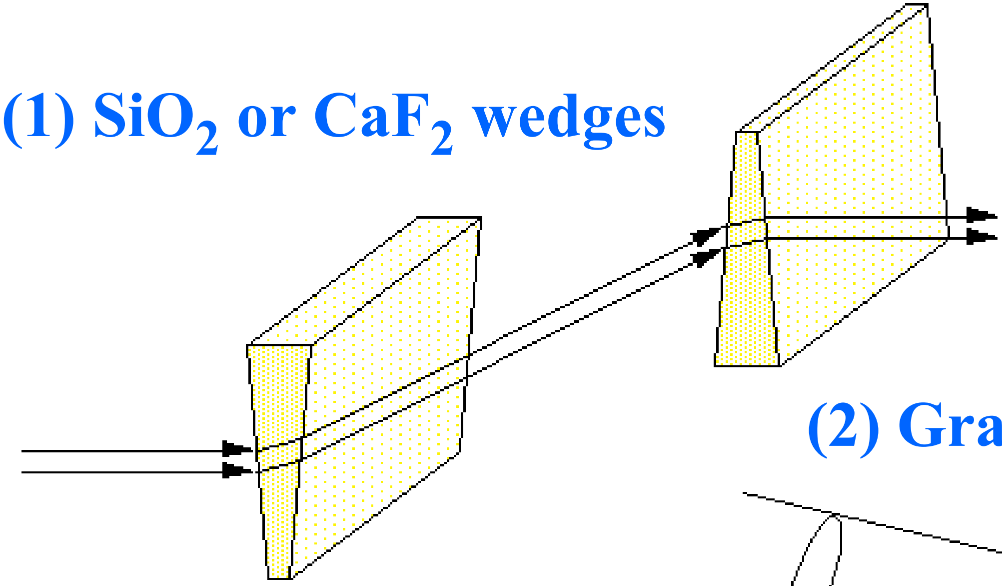
Prometheus-L Reactor Building Layout



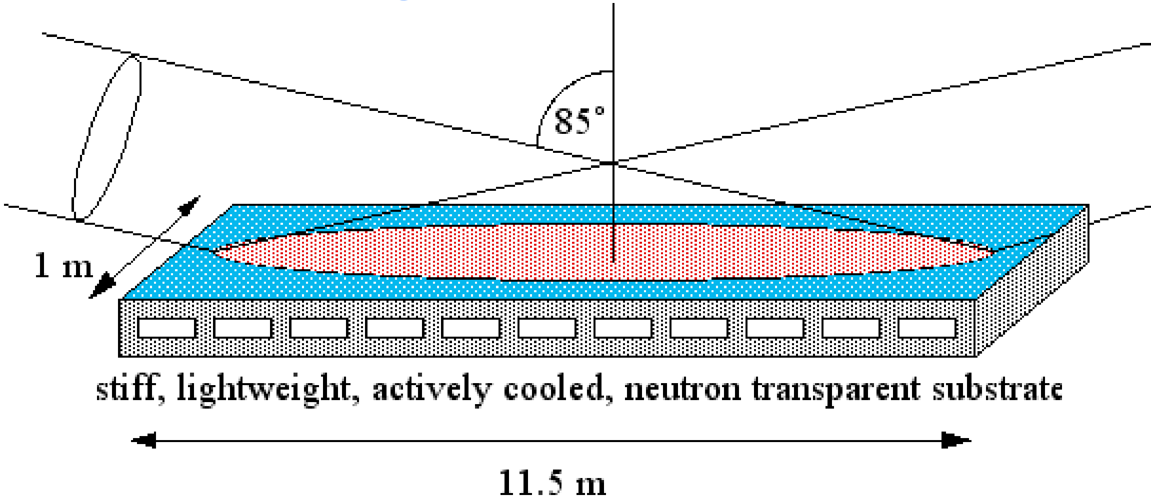
Note: Dimensions are in meters.

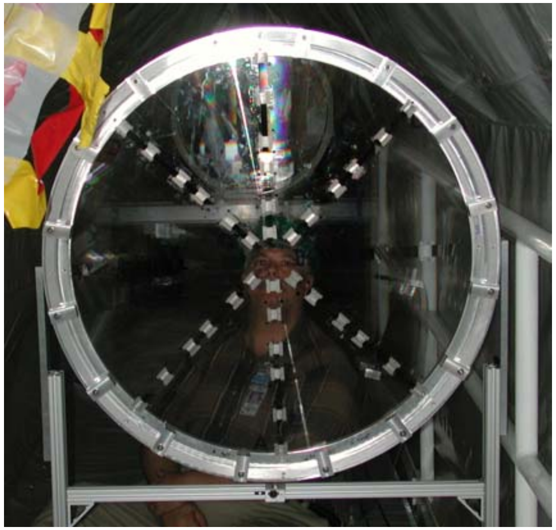
Options for the Final Optic

(1) SiO_2 or CaF_2 wedges



(2) Grazing incidence metal mirror





(3) Thin diffractive optic (*e.g.*, 1 mm thick Fresnel lens)

Final Optic Damage Threats

Two main concerns:

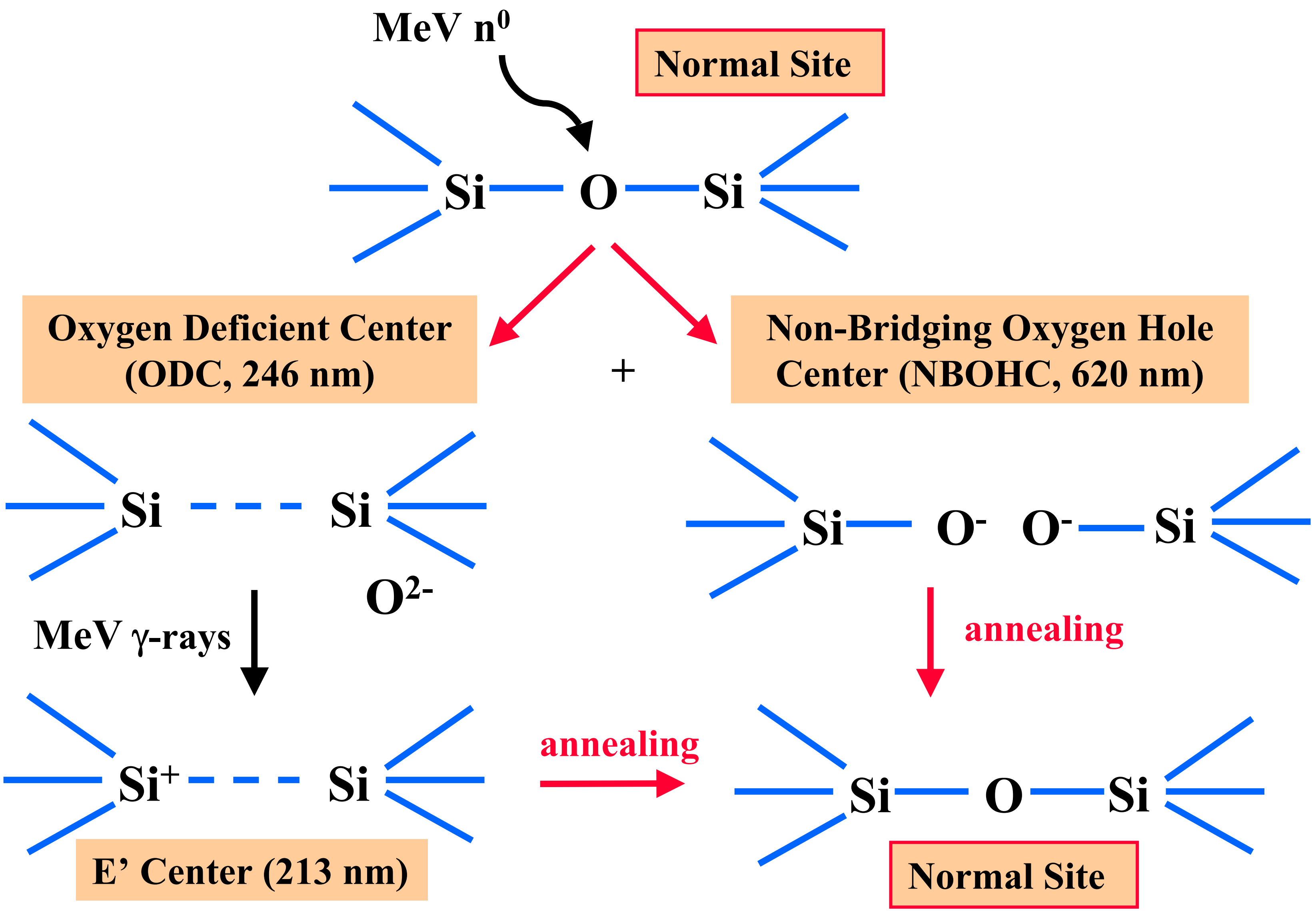
- Damage that increases absorption (<5%)
- Damage that modifies the wavefront –
  - spot size/position (200µm/20µm) and spatial uniformity (1%)

Final Optic Threat	*Nominal Goal*
Optical damage by laser	>5 J/cm^2 threshold (normal to beam)
Sputtering by ions Ablation by x-rays (~25 mJ/cm^2, partly stopped by gas)	Wavefront distortion of <λ/3 * (~100 nm) ($6x10^8$ pulses in 2 FPY: $2.5x10^6$ pulses per allowed atom layer removed)
Defects and swelling induced by γ-rays (~3) and neutrons (~18 krad/s)	Absorption loss of <5% Wavefront distortion of < λ/3 *
Contamination from condensable materials (aerosol and dust)	Absorption loss of <5% >5 J/cm^2 threshold

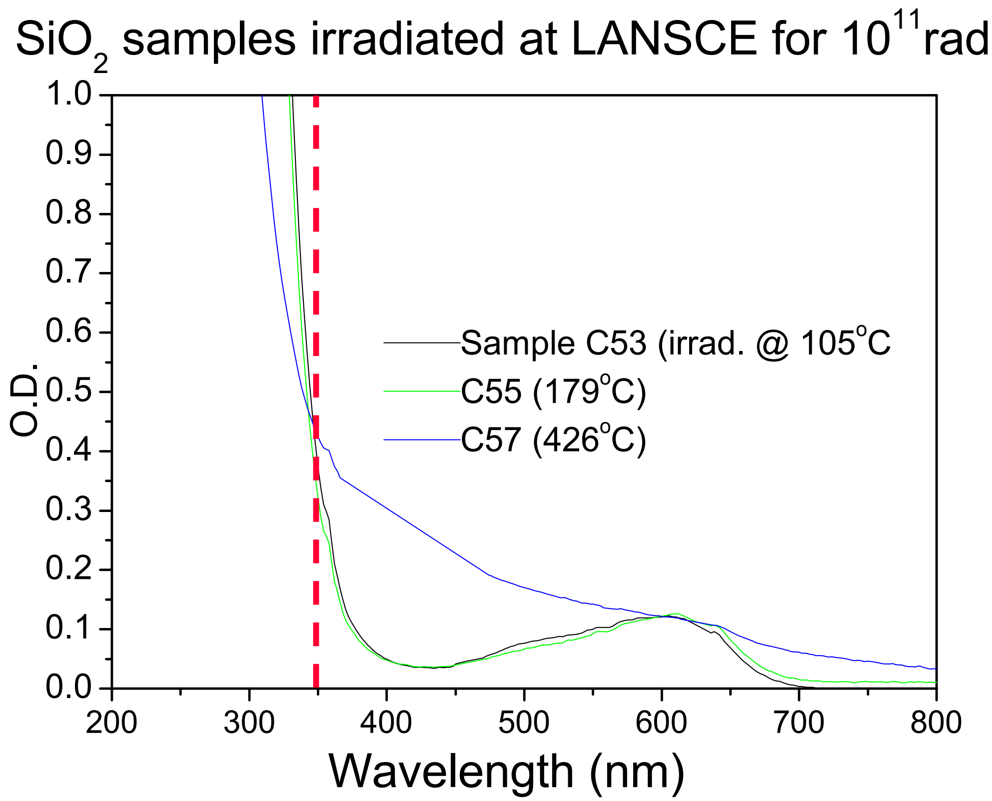
* "There is no standard theoretical approach for combining random wavefront distortions of individual optics. Each λ/3 of wavefront distortion translates into roughly a doubling of the minimum spot size." (Ref. Orth)

2. Transmissive optics, issues and R&D

Neutrons and γ-rays create defects in SiO_2 which result in photon absorption

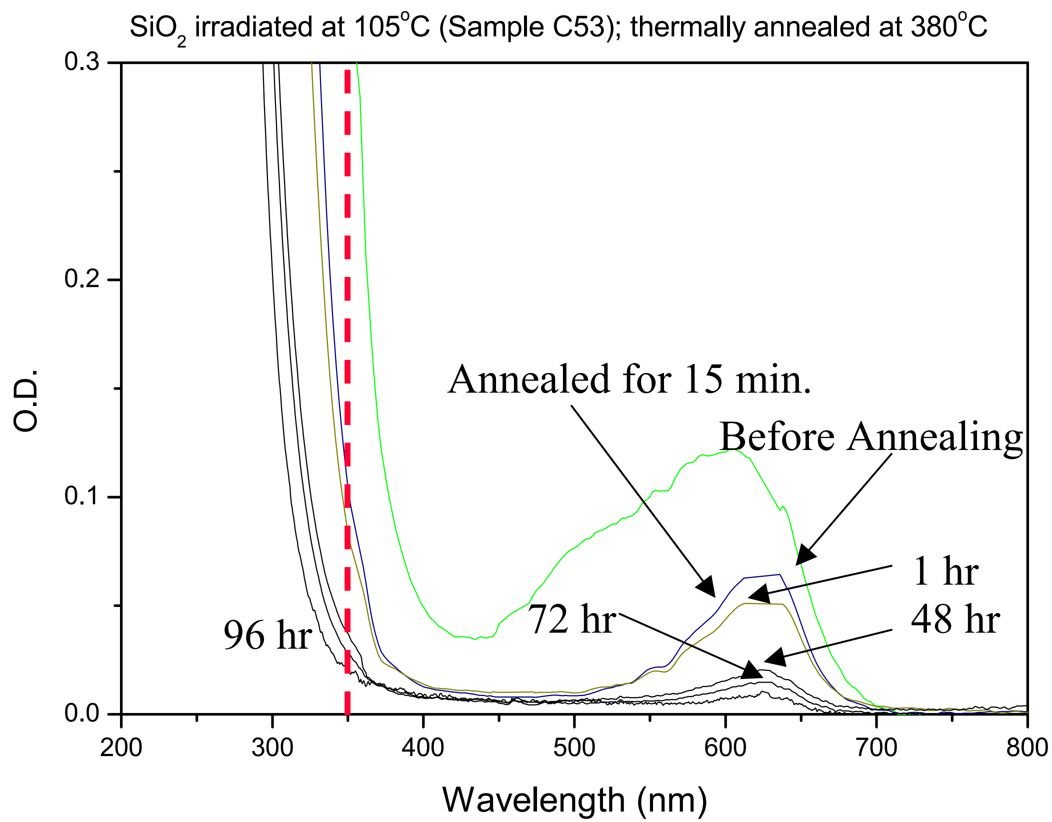


SiO_2 irradiated at LANSCE for 10^{11} rad



- The non-bridging oxygen hole center (NBOHC) evidences absorption at 620 nm, while the E' and oxygen deficient center (ODC) occurs in the UV
- NBOHC is apparent for samples irradiated at 105 °C and 179 °C, while the sample irradiated at 426 °C reveals a slow rise to shorter wavelength

Following a dose of ~10^{11} rad n° at 105 °C, it is possible to anneal away the NBOHCs, ODCs, and E' Centers



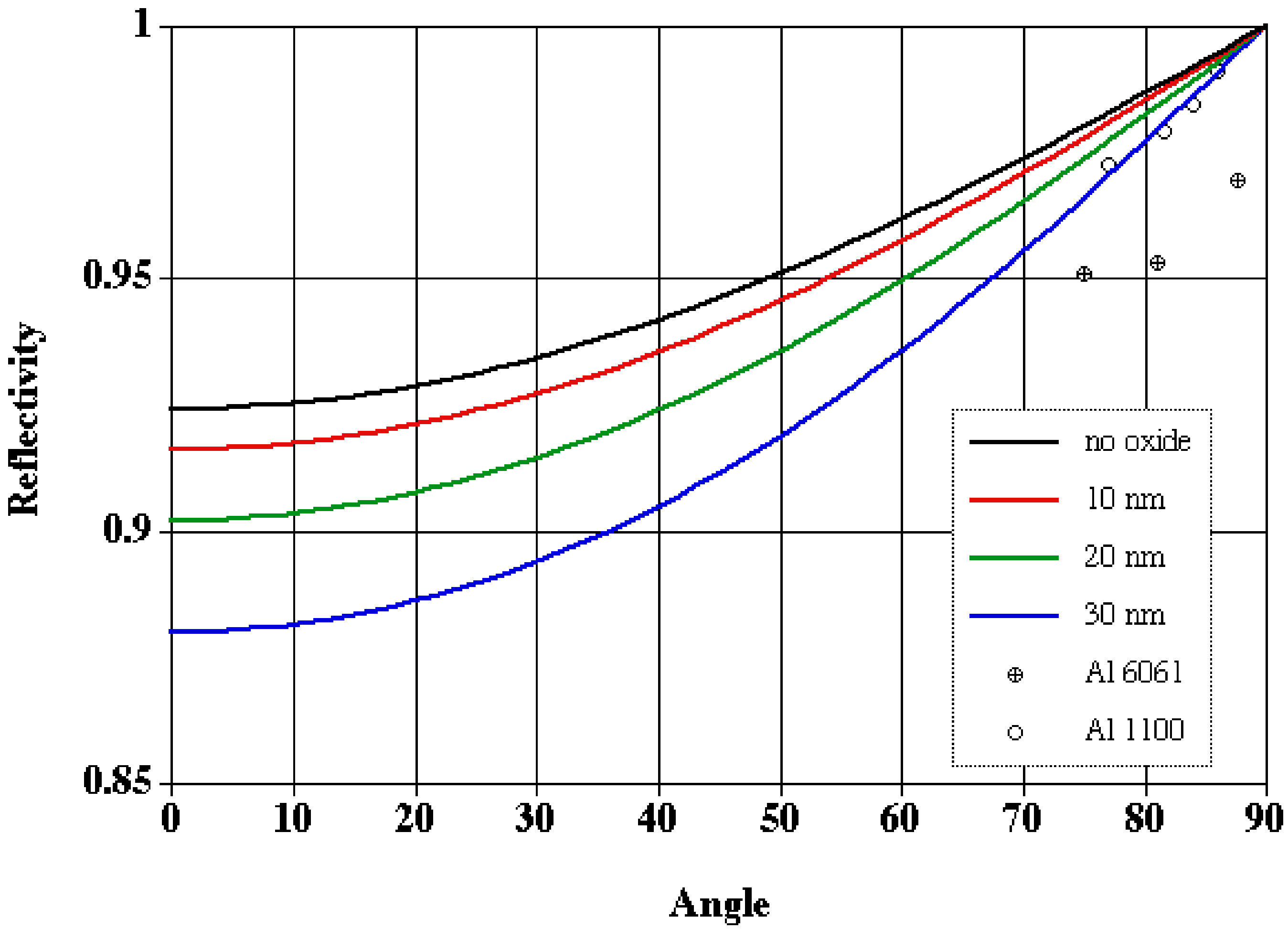
- NBOHC absorbs at 620 nm, $\sigma_{abs} = 1.6 \times 10^{-19}$ cm^2 (from lit.)
- E' Center absorbs at 213 nm, $\sigma_{abs} = 3.2 \times 10^{-17}$ cm^2 (from lit.)
- Cross sections compare by factor of 200 (predicted)
- Observed ratio of 110 from data in figure in reasonable agreement with predicted ratio
- No scattering is observed in sample due to low irradiation T

The data is consistent with the simultaneous creation and annihilation of E' and NBOHCs

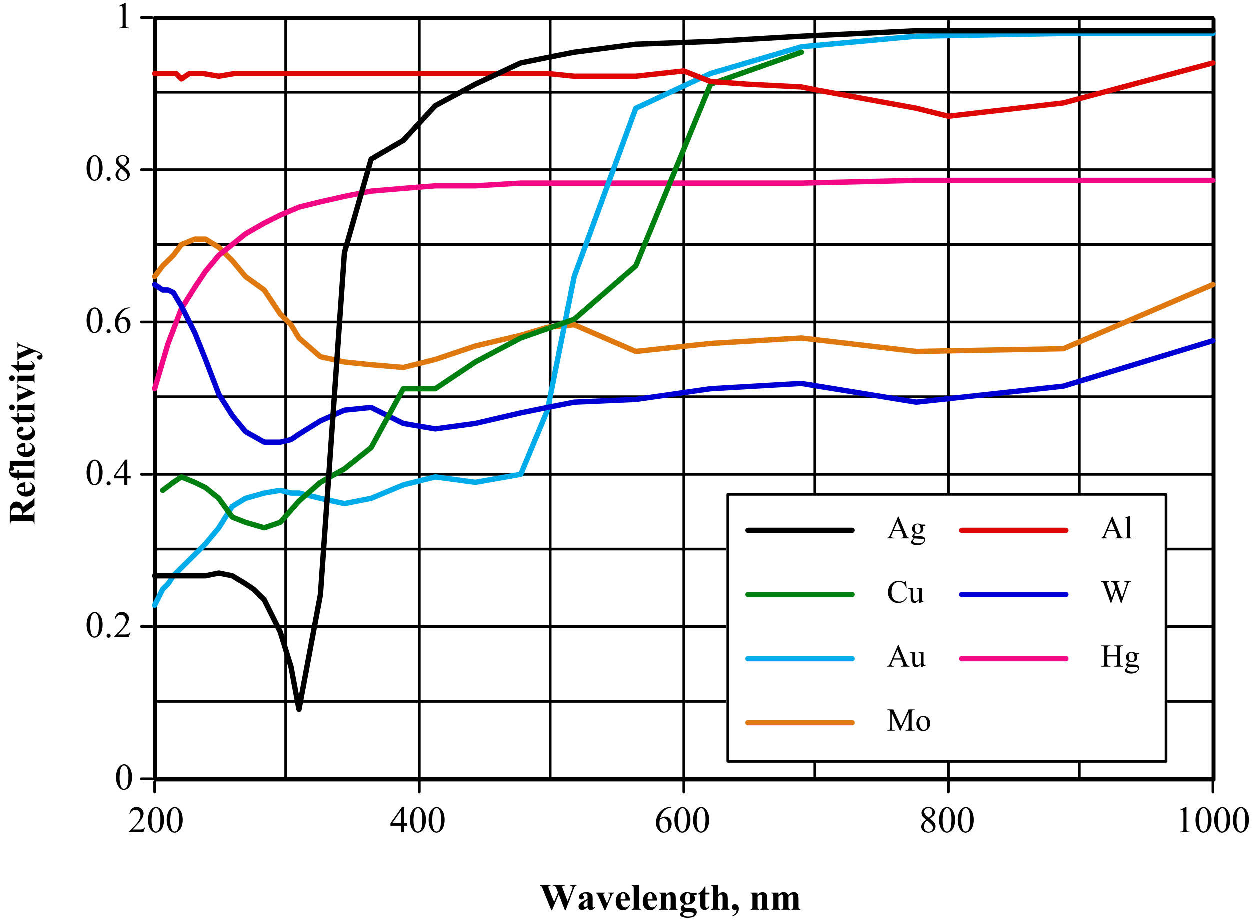
3. Reflective optics, issues and R&D

High reflectivity of metals at shallow angles enables their use as a final optic

Reflectivity of oxidized Al to s-polarized light at 532 nm



Normal incidence reflectivity of various metals

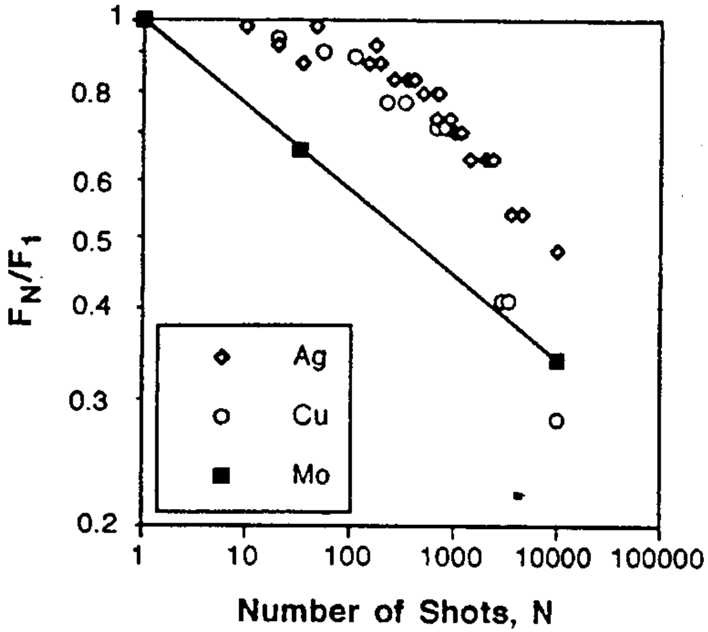


GIMM development issues*

- Experimental verification of laser damage thresholds
- Protection against debris and x-rays (shutters, gas jets, *etc*.)
- Wavefront issues: beam smoothness, uniformity, shaping, f/number constraints
- Experiments with irradiated mirrors
- In-situ cleaning techniques
- Large-scale manufacturing
- Cooling

* from Bieri and Guinan, Fusion Tech. 19 (May 1991) 673.

Surface deformation leads to roughening and possible loss of laser beam quality



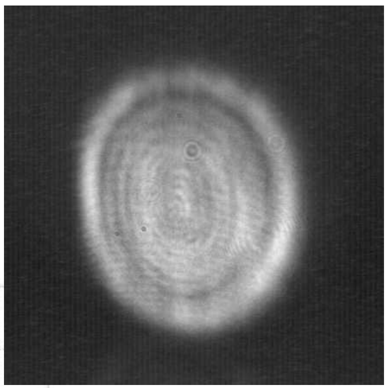
- F_1 varies from a few to ~ 10 J/cm^2.
- LIDT is a strong function of material & number of shots – it degrades up to a factor of 10 after only 10000 shots (survival to ~10^8 shots is needed).
- Uncertainty in saturation behavior

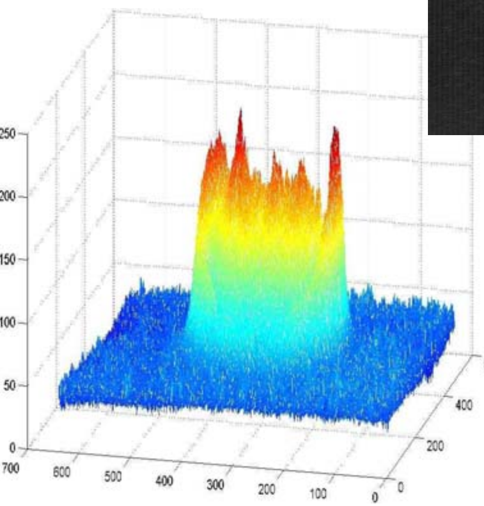
- **Single Shot Effects on LIDT:**
  - Laser heating generates point defects
  - Coupling between diffusion and elastic fields lead to permanent deformation

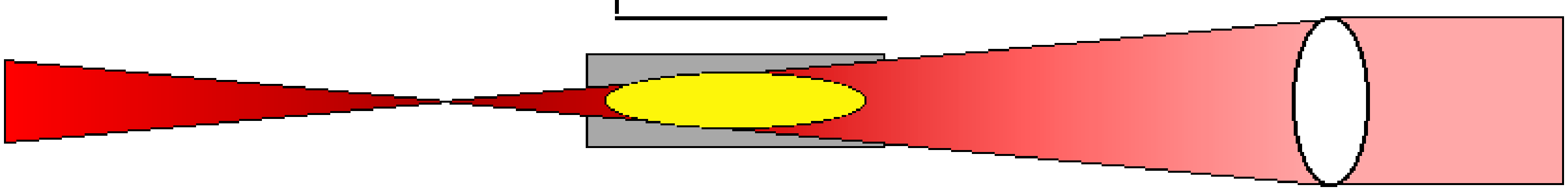
- **Progressive Damage in Multiple Shots:**
  - Thermoelastic stress cycles shear atomic planes relative to one another (slip by dislocations)
  - Extrusions & intrusions are formed when dislocations emerge to the surface, or by grain boundary sliding.

Laser Damage Experiments on Metal Mirrors

Spectra Physics YAG laser:
2J, 10 ns @1064 nm;
800, 500, 300 mJ @532, 355, 266 nm
Peak power density ~10^{14} W/cm^2



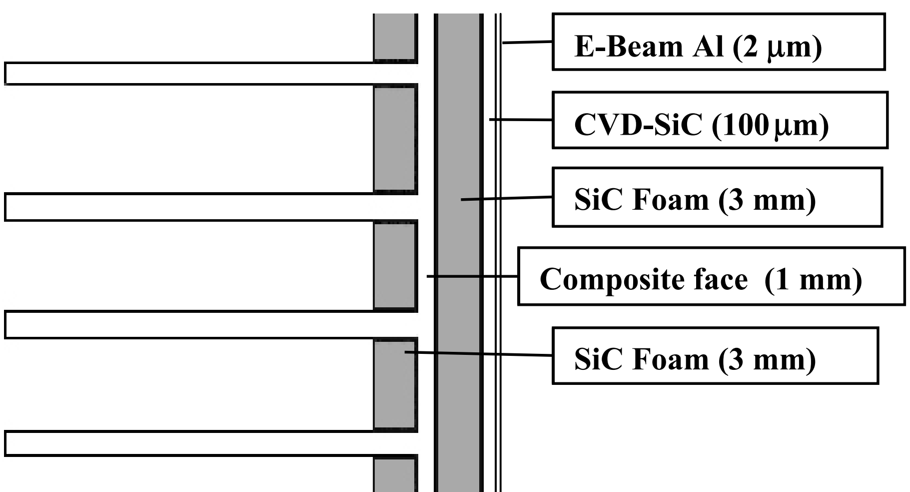




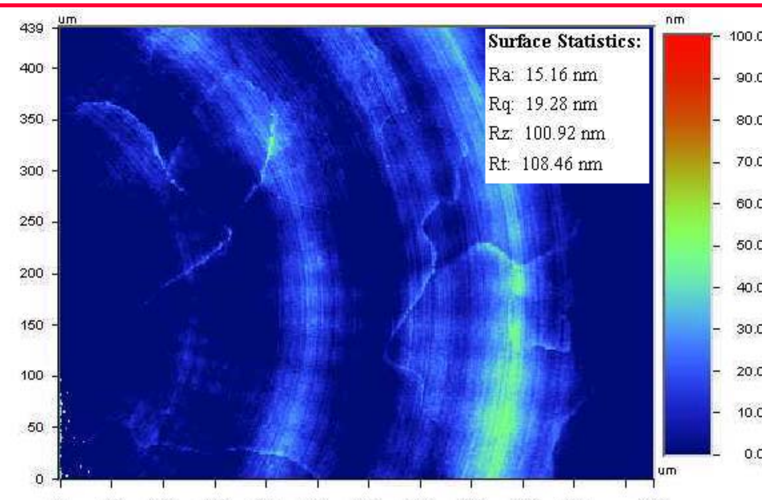
The two principle methods of fabrication are diamond turning and substrate coating

75 nm Al on superpolished flat:
±2Å roughness, 10Å flatness

GENERAL ATOMICS

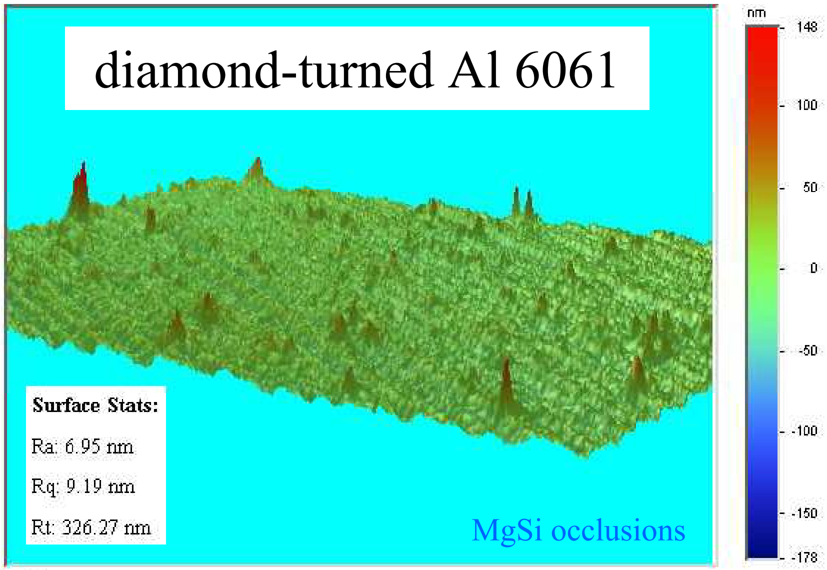


MER composite mirror

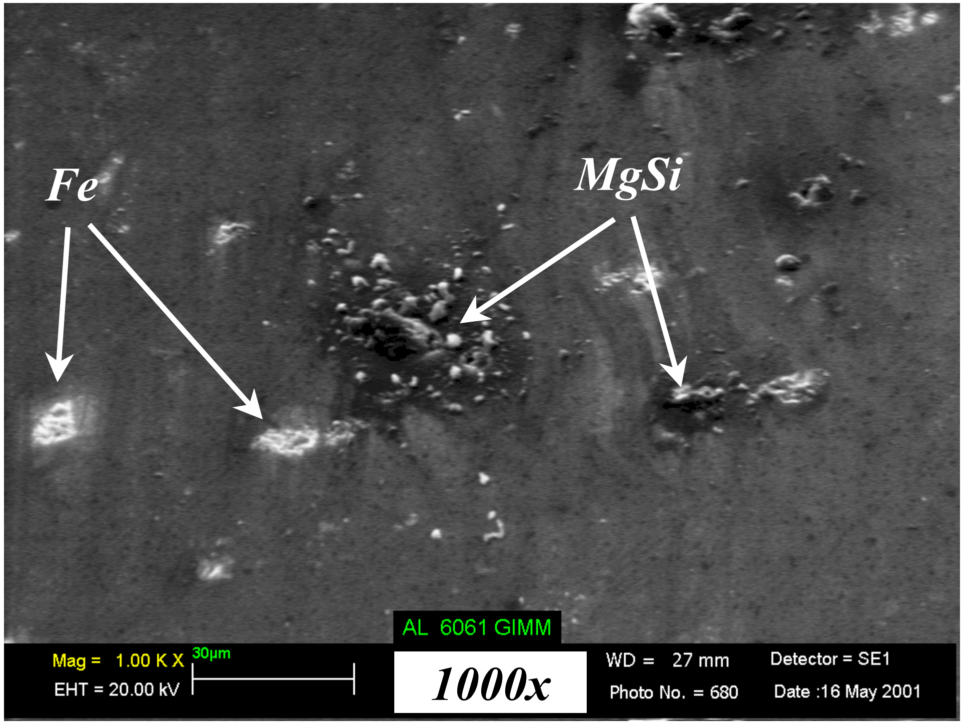


Al 1100 showing grain boundaries and tool marks

Damage to aluminum at grazing angles



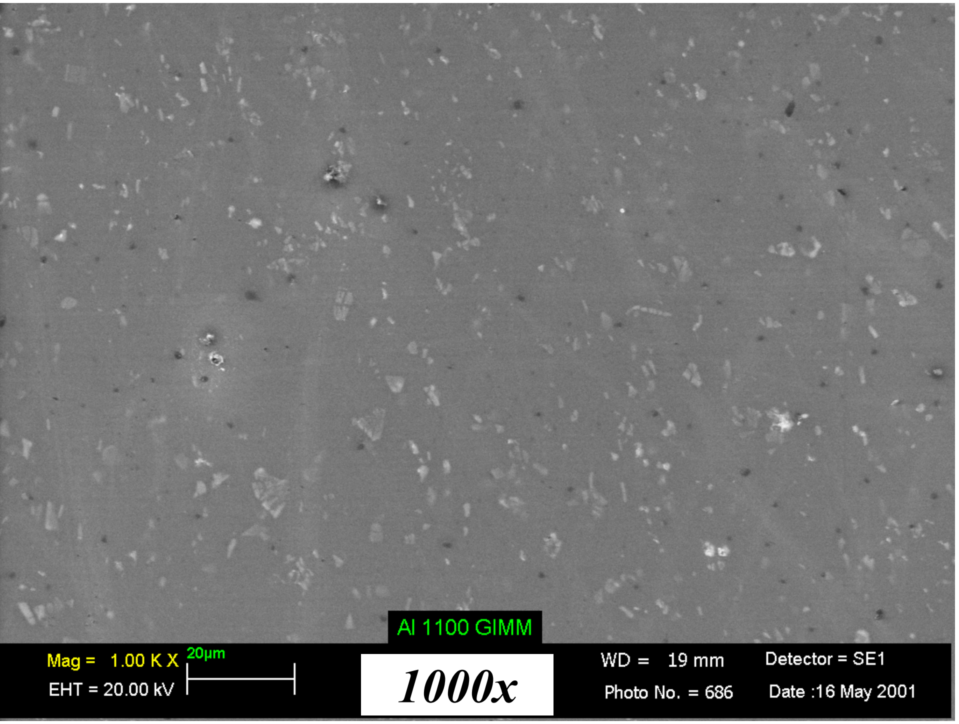
Several shots in Al 6061 at 80°, 1 J/cm²



Silicide occlusions in Al 6061 preferentially absorb light, causing explosive ejection and melting at only 1 J/cm^2; Fe impurities appear unaffected

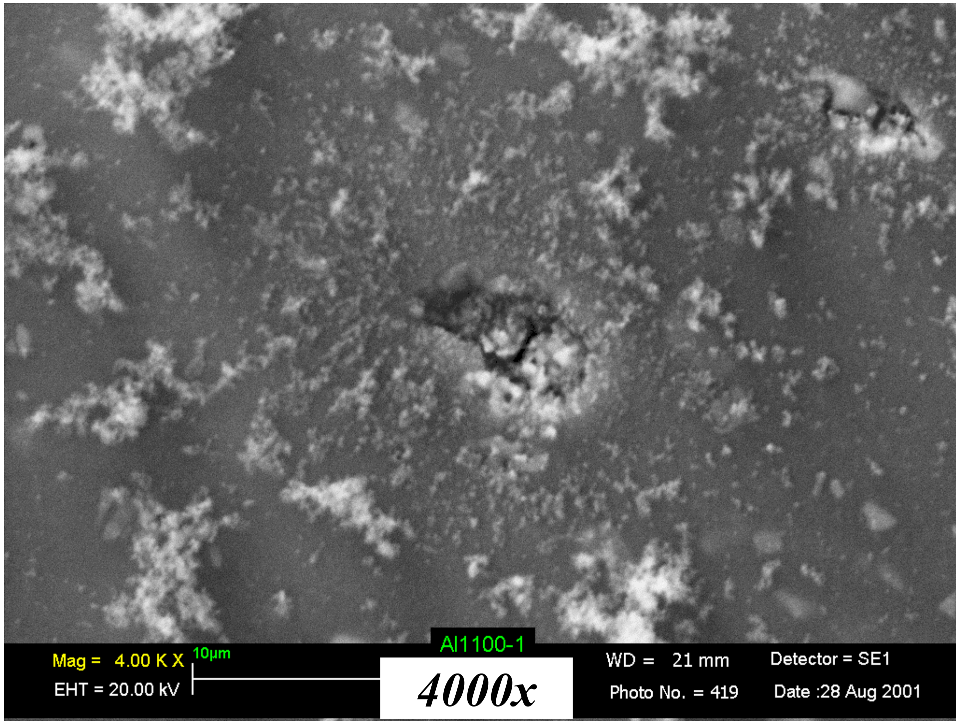
Damage to Al-1100 at grazing angles

1000 shots in Al 1100 at 85°, 1 J/cm²



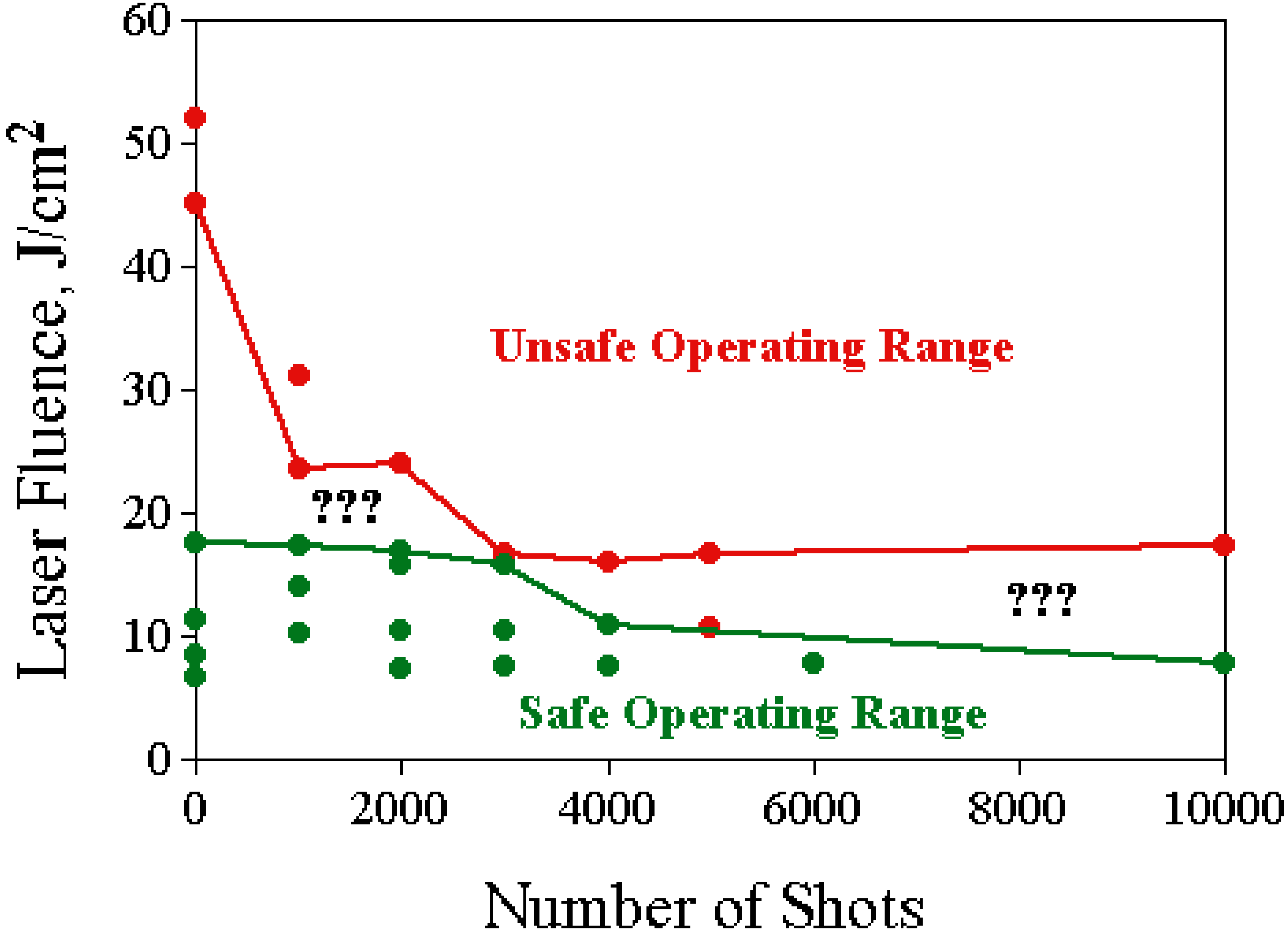
Exposure of Al 1100 to 1000 shots at 85° exhibited no damage up to 18 J/cm²

10000 shots in Al 1100 at 85°, 20 J/cm²



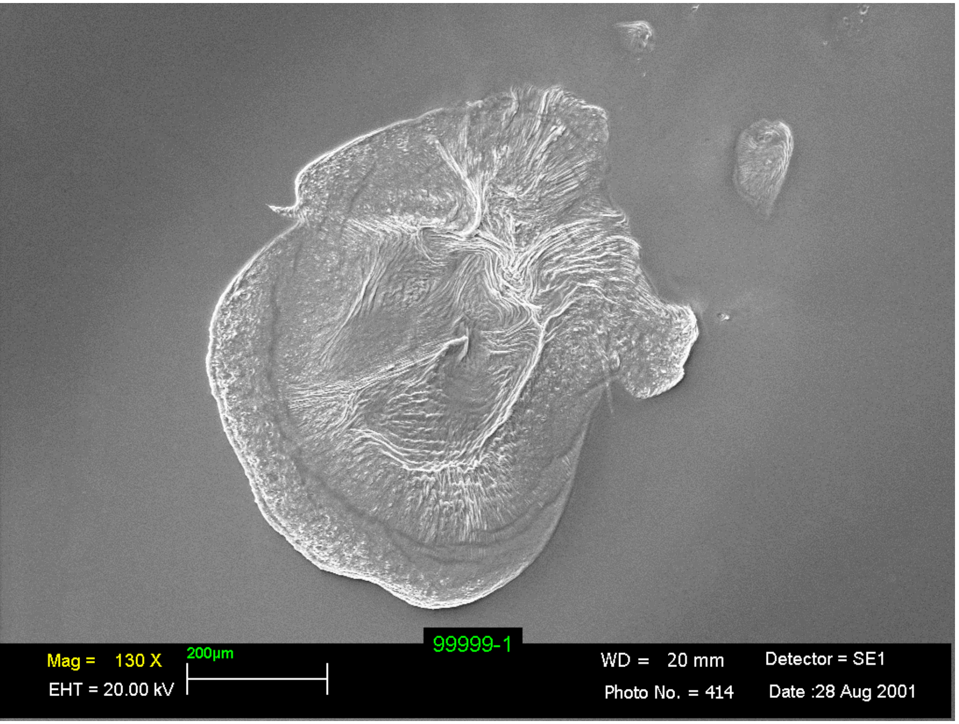
Exposure of Al 1100 to 10000 shots at 85° exhibits catastrophic damage at fluence >20 J/cm²

Damage Regimes for Al-1100



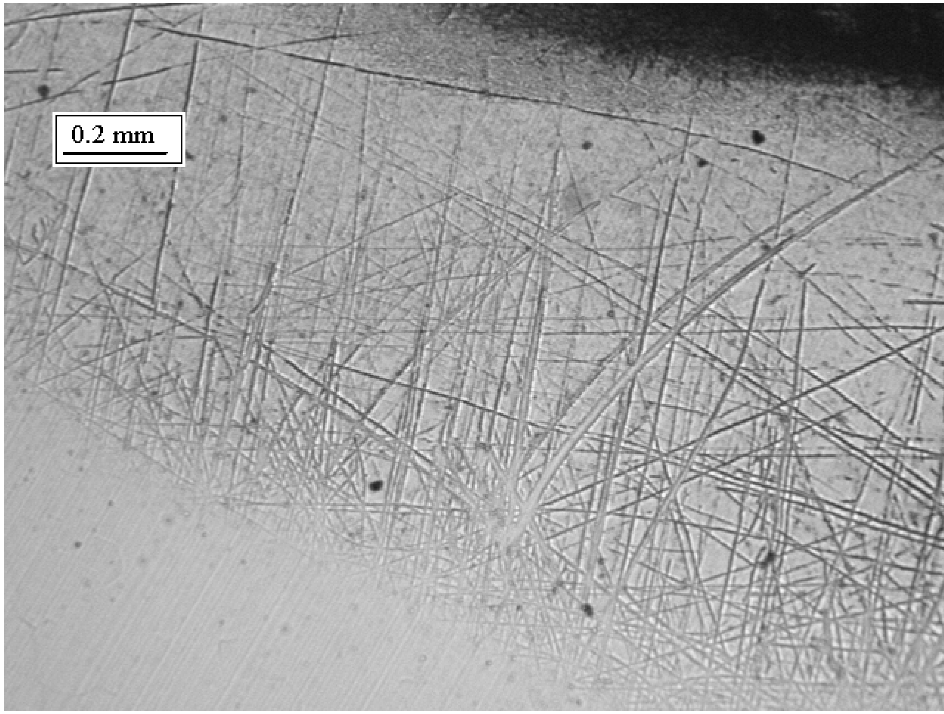
Damage to pure Al at grazing angles

Single pulse in pure Al at 85°, 180 J/cm²



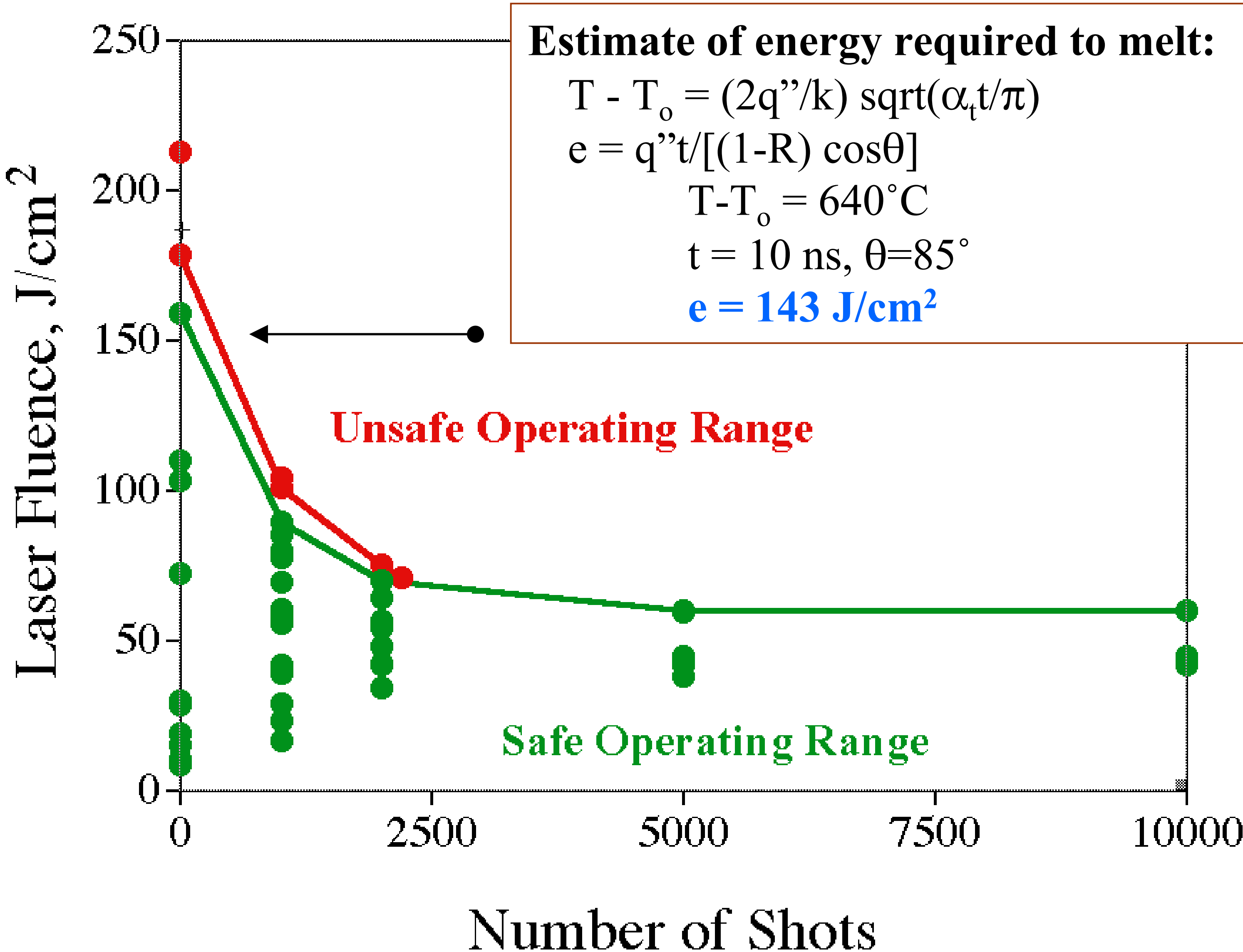
99.999% pure Al survives single shot damage up to the melting limit

10^4 shots, above the damage threshold



Under cycling loading, a variety of thermomechanical phenomena emerge

Damage Regimes for 99.999% pure Al



Estimate of energy required to melt:

$T - T_o = (2q''/k)\ \mathrm{sqrt}(\alpha_t t/\pi)$

$e = q''t/[(1-R)\cos\theta]$

$T-T_o = 640^\circ C$

$t = 10$ ns, $\theta = 85^\circ$

$e = 143\ J/cm^2$

Why do the mirrors survive beyond the yield point?

Estimate of energy required to cause plastic deformation:

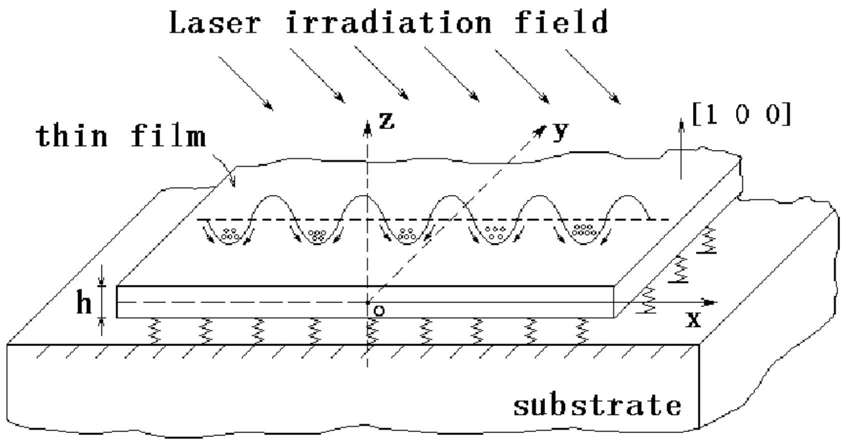
$2\sigma_y = E\,\alpha\,\Delta T_o/(1-\nu)$ *fully-constrained, ratchetting limit*

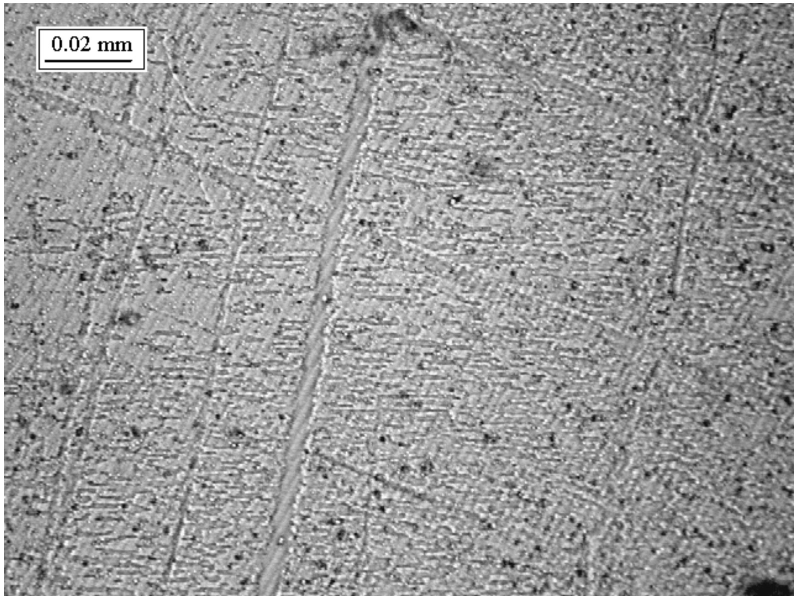
$E = 75$ GPa, $\nu = 0.33$, $\alpha = 25\times10^{-6}$

$\sigma_y = 13\text{-}24$ ksi (150-200 MPa)

$\Delta T \sim 71\text{-}107^\circ$C

$e \sim 16\text{-}24$ J/cm^2





- **Nonuniformities in the beam?**
- **Al_2O_3 capping layer stabilizes the interface?**
- **Something about grazing incidence irradiation stabilizes the instability?**