Threat Modeling and Experiments for an IFE Final Optic

Jeff Latkowski, Maria Caturla, Alison Kubota, Sham Dixit, Joel Speth, Steve Payne

Laser IFE Meeting

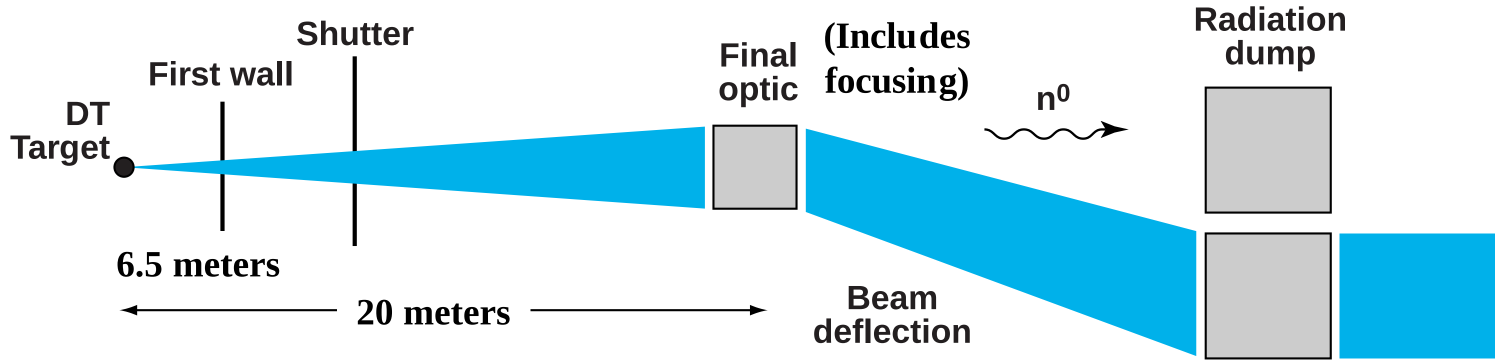
November 13-14, 2001

Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Introduction

- Radiation source term/threat to final optic
- Radiation damage and annealing in SiO_2
- Heating/cooling and design of a thin diffractive Fresnel lens
- Irradiation studies for CaF_2 and Al
- Experimental study of x-ray ablation
- Ion radiation damage to final optic
- Summary and future work

Updated source term for x-rays, neutrons, γ-rays, and ions: final optic at 20 m



Threat	Target Emission	First Wall	Final Optic
X-rays	5.6 MJ/shot	1.1 J/cm^2 per shot (for vacuum; can be reduced with fill gas)	0.11 J/cm^2 (for vacuum; can be reduced with fill gas)
Neutrons	280 MJ/shot	190 krad/s; 3.5 MW/m^2; 9×10^{13} n^o/cm^2-s (14 MeV)	19.6 krad/s; 0.36 MW/m^2; 9.7×10^{12} n^o/cm^2-s (14 MeV)
γ-rays	<< 1 MJ/shot	41 krad/s	3.2 krad/s
Ionic debris	110 MJ/shot	21 J/cm^2 per shot; 1.4 MW/m^2 (for vacuum; can be reduced with fill gas)	2.2 J/cm^2 per shot; 0.15 MW/m^2 (for vacuum; can be reduced with fill gas)

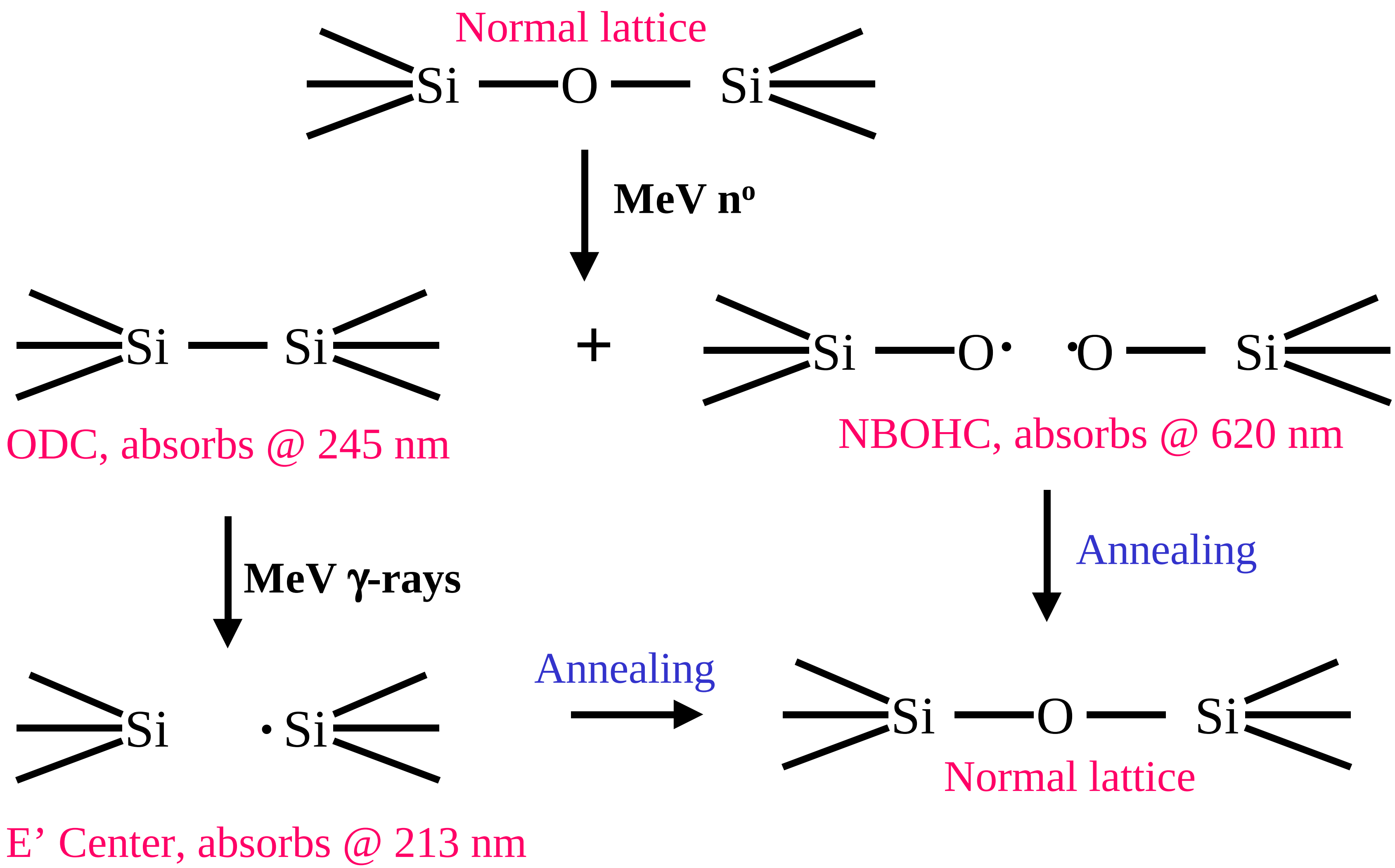
Note: Target emissions calculated for NRL target scaled up to 400 MJ assuming the energy partitioning remains the same.

Threats to the final optic – neutrons and gamma-rays

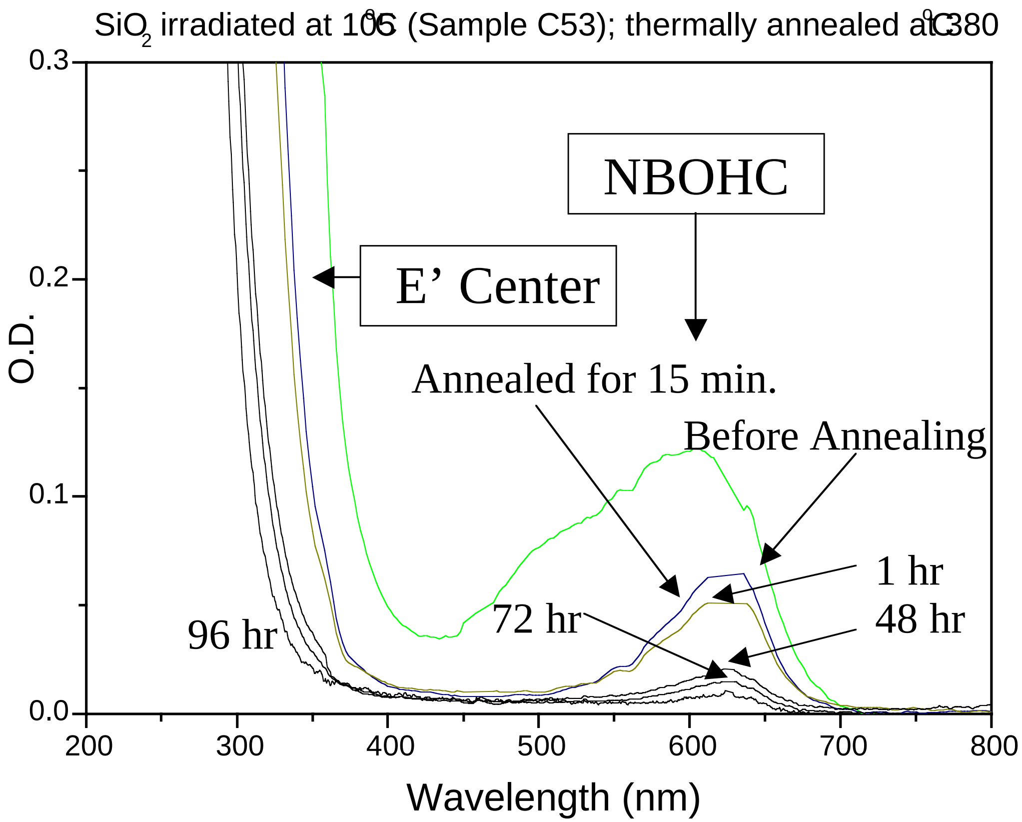
- SiO_2 samples irradiated at LANCE facility:
  - Total neutron dose of **0.7–1.0 × 10^{11} rad (~0.16 FPY)**
  - Neutron dose rate of LANSCE (~10 krad/s) and IFE (19.6 krad/s) are comparable

- Predicted transmutation of an IFE SiO_2 final optic:
  - H = 63 appm/FPY
  - He = 155 appm/FPY
  - Mg = 34 appm/FPY
  - Al = 9 appm/FPY

Neutron irradiation leads to simultaneous formation of E', ODCs (oxygen deficient centers), and NBOHCs (non-bridging oxygen hole centers)



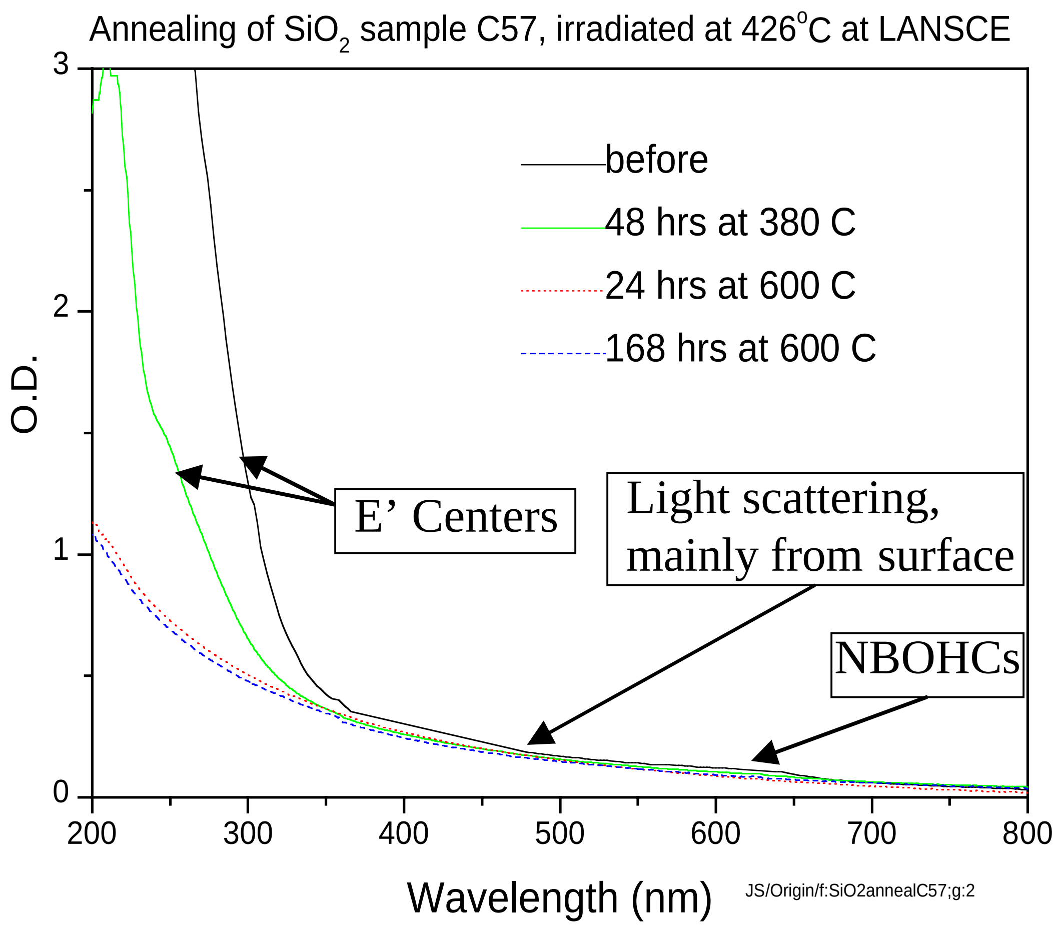
Following a dose of ~10^{11} rad n° at 105 °C, it is possible to anneal away the NBOHCs, ODCs, and E' Centers



- NBOHC absorbs at 620 nm, $\sigma_{abs} = 1.6$ _ 10^{-19} cm^2 (from lit.)
- E' Center absorbs at 213 nm, $\sigma_{abs} = 3.2$ _ 10^{-17} cm^2 (from lit.)
- Cross sections ratio of 200, compared to 110 from data

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

Following a dose of ~10^{11} rad n° at 426 °C, annealing of the E' Centers is observed

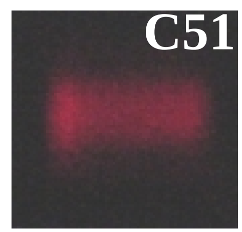


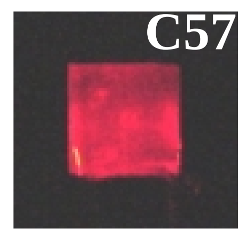
- Annealing at 380 °C reduces the E' defect population (for λ < 350 nm)
- Annealing at 600 °C completely eliminates the E' centers
- Slow rise in the baseline is due to scattering, and cannot be annealed

10^{11} rad neutron irradiation of SiO_2 induces scatter and absorption losses using a HeNe laser

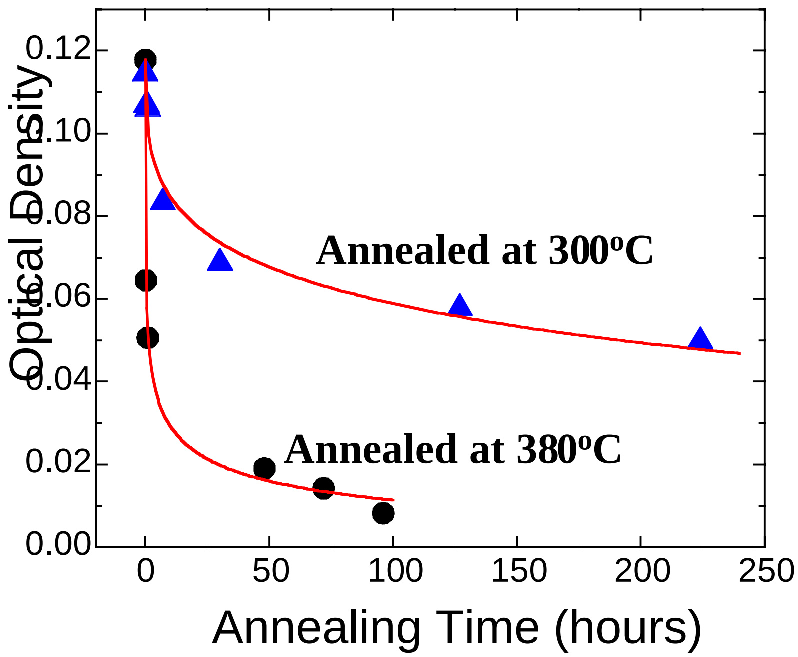
Sample	Irradiation T(ºC)	Absorption α_{abs}(633 nm)	Scatter α_{scatt}(633 nm)	Comments
Pristine	None	0.0%/mm	0.00%/mm	
C53	105ºC	2.8%/mm	0.52%/mm	
C54	105ºC	2.3%/mm	0.60%/mm	Average = 0.49%/mm (Pristine–C52)
C51	127ºC	1.9%/mm	0.35%/mm	
C52	127ºC	1.9%/mm	0.49%/mm	
C55	179ºC	2.5%/mm	0.73%/mm	Average = 0.74%/mm (C55–C56)
C56	179ºC	2.2%/mm	0.74%/mm	
C57	426ºC	0.4%/mm	29.6% total	Due to surface scatter (C57–C58)
C58	426ºC	0.6%/mm	36.0% total	

- Annealing does not reduce scatter, which probably arises from O_2 bubbles
- Surface of C57 and C58 samples have been etched (possibly due to acidic atmosphere)





The decay of the NBOHC absorption (620 nm) is fitted to a "stretched exponential" function



- Fit to $\alpha = \alpha_0 \exp[-(t/\tau)^\beta]$
- Annealing NBOHC at 380 ºC yields
  - τ = 2.3 hrs, β = 0.22
  - τ_{anneal} = 228 hrs
- Annealing NBOHC at 300 ºC yields
  - τ = 314 hrs, β = 0.33
  - τ_{anneal} = 1884 hrs

➢ Using $\tau_{anneal} = \tau_0 \exp(T_0/T)$ yields:

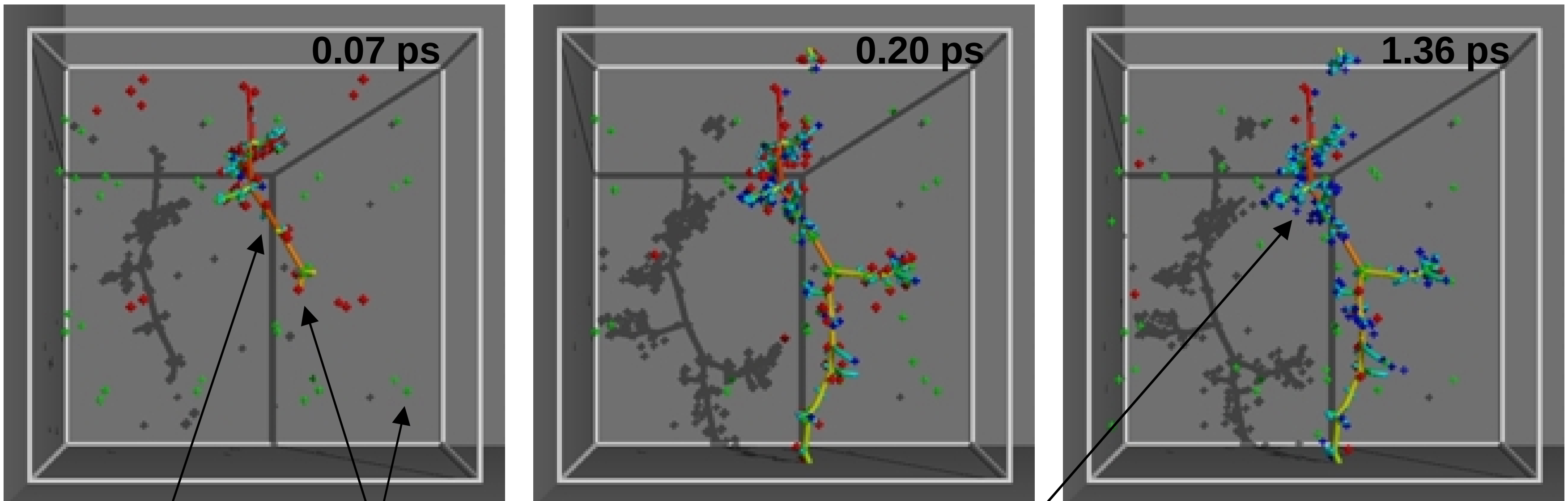
  ➢ T_0 ~ 10,000 K (0.86 eV), $\tau_0 = 5.9 \times 10^{-5}$ hr

Defect generation by SPR-III and LANSCE indicate that radiation annealing is occurring

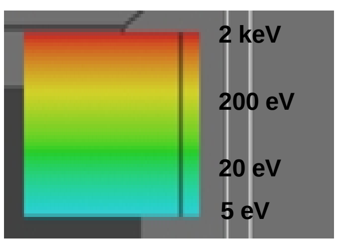
- SPR-III run – 3.2×10^5 rad
  - _ Produced *1880 defects* per 10 MeV-equivalent collision
- LANSCE run – 1.0×10^{11} rad
  - _ Produced *only 0.35 defects* per 10 MeV-equivalent collision
- Defects are experiencing "self-healing" due to radiation annealing
  - _ Assume atoms reaching 10,000 ^oC are locally annealed (0.86 eV activation energy)
  - _ 10 MeV n^o collision heats 10^6 atoms to 10,000 ^oC (11% momentum transfer)
- Calculated limiting defect concentration = [(6.6×10^{22} SiO_2-atoms/cm^3) / (10^6 melted-atoms/collision)] (1880 defects/collision) = 1.2×10^{18} defects/cm^3
- Measured limiting defect concentration = 2×10^{18} defects/cm^3
- Limiting defect absorption is:
  - _ ~ 0.1 mm^{-1} at 0.35 μm for T < 300^{o}C
  - _ < 0.1 mm^{-1} for T > 400^{o}C

Atomistic modeling provides insight into behavior of defects produced during n^0 irradiation

2 keV Recoil in Fused Silica (0.4% OH Content)



Cascade Track



Structural Defects

- ODC
- NBOHC

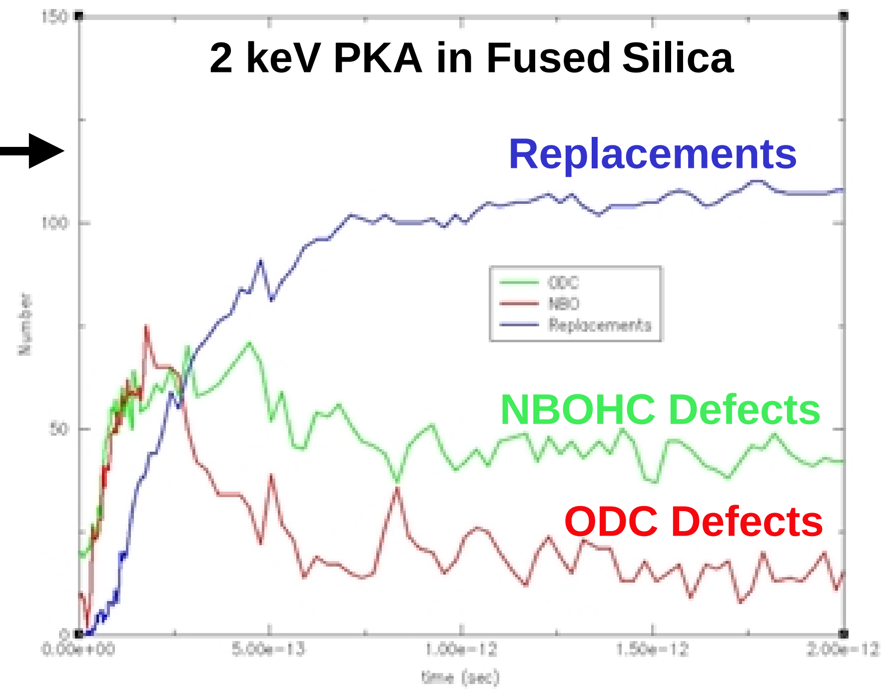
Replacement

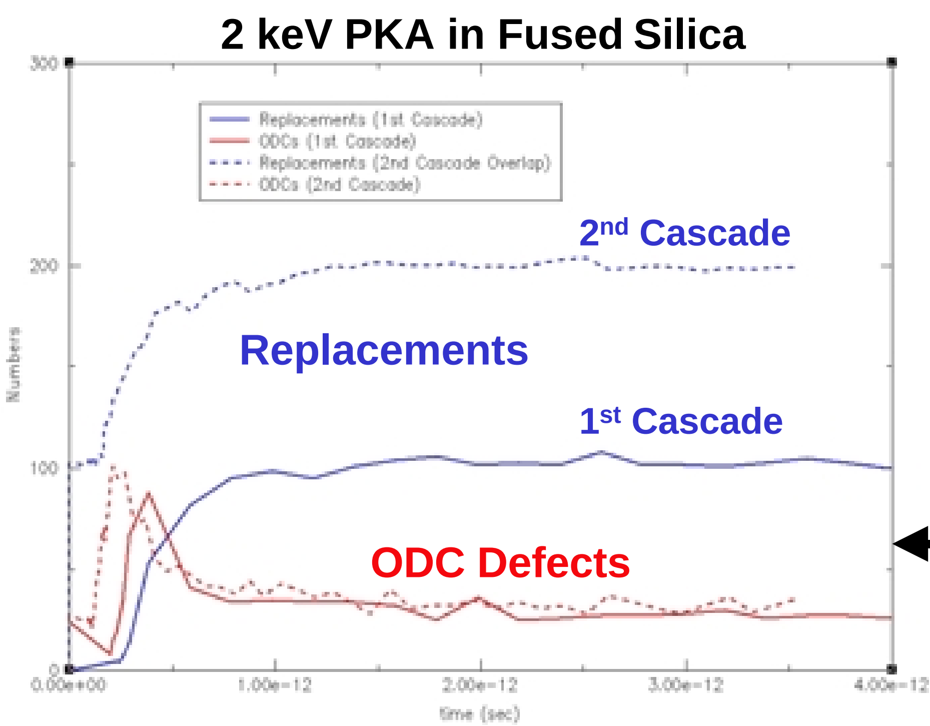
During the cascade, ODC and NBOHC defects are produced along the cascade tracks.

Most of the structural defects recombine and change partners. The remaining residual defects are precursors to electronic defects.

We are moving towards an understanding of the mechanisms of n^0 damage and radiation annealing

During single cascades, a large fraction of defects generated are annihilated. (Generation of Replacements).





Multiple cascades show that defects do not increase proportionally with additional overlapped cascades.

Optical absorption at λ=0.35 μm leads to heating of SiO_2 optic

- Optic is heated by:
  - Laser absorption (scales with thickness)
  - Attenuation of target emissions (e.g., neutrons)
  - Blackbody radiation from surroundings (e.g., chamber)

- Options for cooling:
  - Gas-cooling — requires >> 1 Mach flow, not possible
  - Thin channel of water — causes bowing of surfaces leading to strong lens, not possible
  - Use of ***thin*** optic to increase surface-to-volume ratio — requires diffractive optic and radiative cooling

Based upon radiative cooling, we estimate the final optic temperature

Total driver energy	3.7 MJ
Number of beams	345
Yield per target	281 MJ
Power plant repetition rate	11.1 Hz
Fusion power	3120.8 MW
Laser energy per beam	10.7 kJ

Fluence limit	1.46 J/cm^2
Final optic area	0.73 m^2
Final optic radius	48.2 cm
Final optic standoff	20.0 m
Half-angle per beam	1.38 deg
Solid-angle fraction per beam	1.45E-04
Total open solid-angle	5.0%

Chamber --> Optic view factor calculation:	
a =	13.5 m
R_1 =	1.16E-02
R_2 =	3.57E-02
X =	7.43E+03
F_{1-2} =	1.27E-03

Heating from chamber to optic:	
Q_{1-2} =	0.05 kW

Chamber radius	6.5 m
Penetration area	0.08 m^2
Penetration radius	15.7 cm
Chamber temperature	1723 K

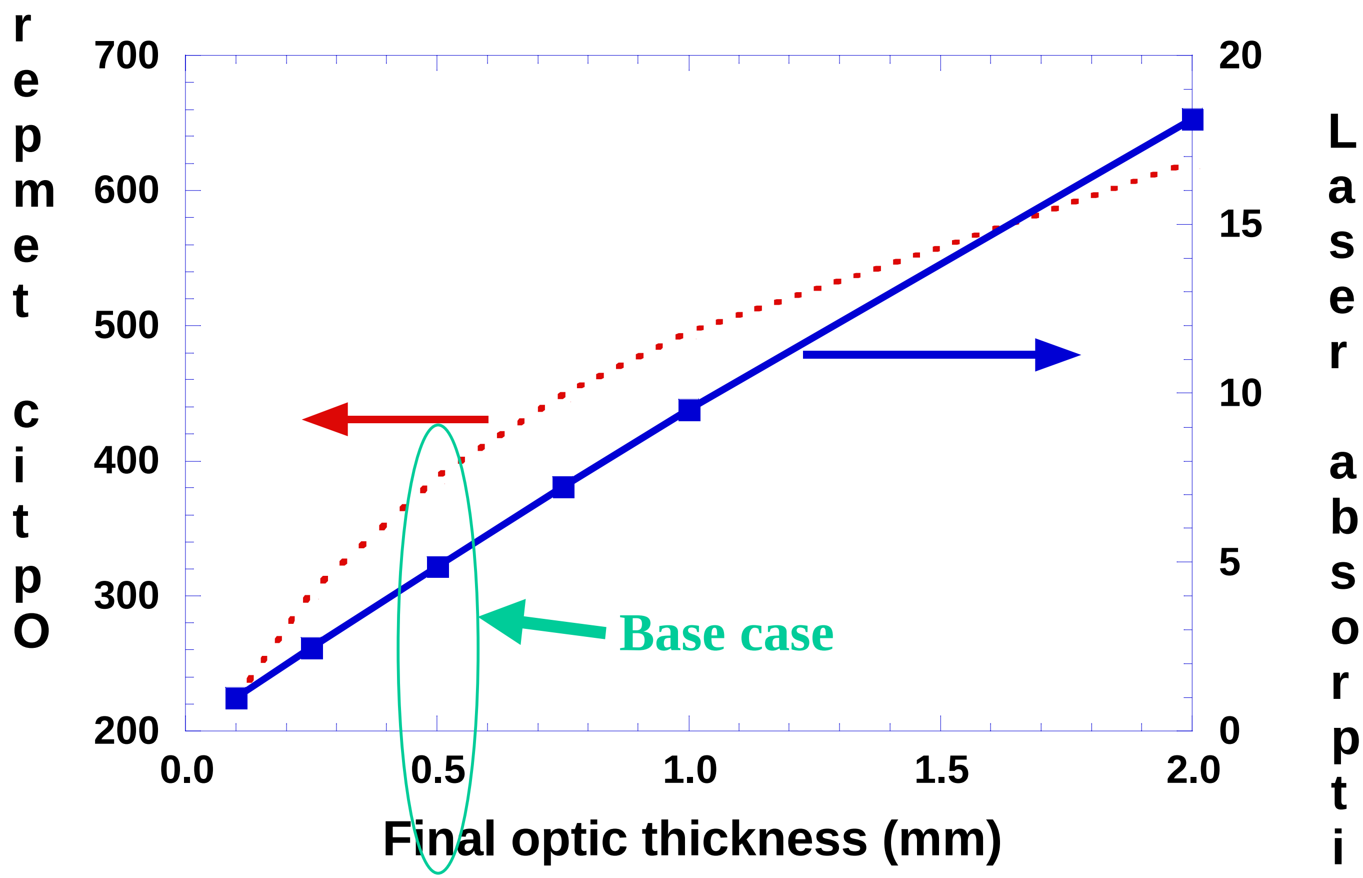
Neutron heating:	
Neutron power	2496.6 MW
Neutron loading @ optic	0.50 MW/m^2
Neutron mfp	8.23 cm
Average E_{dep} per collision	1.59 MeV
Neutrons colliding	0.6%
Neutron energy deposited	0.07%
Neutron heating	0.34 kW/m^2
Neutron heating	0.25 kW

Thickness of final optic	0.0500 cm
Absorption coefficient	1.0 cm^-1
Percent absorption	4.88%
Energy absorbed in optic	0.5 kJ
Laser absorption in optic	5.77 kW
Emissivity of optic (SiO_2)	0.88
Radiative power	6.07 kW
Temperature of surroundings	400 K

Average temperature of optic:		
T_{optic} =	662 K	389 C

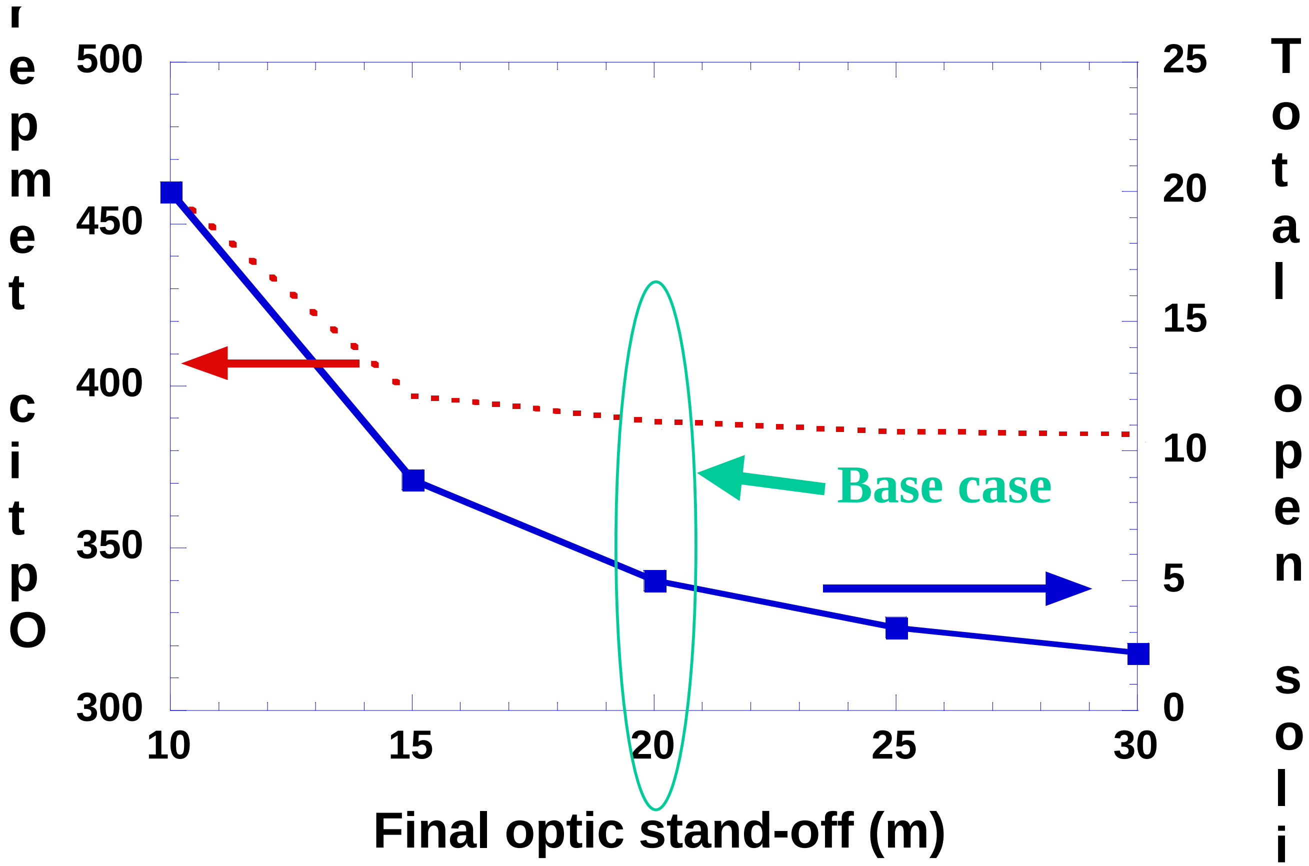
- Calculation begins with parameters from C. D. Orth, S. A. Payne, and W. F. Krupke, *Nucl. Fusion* **36** (Jan. 1996) 75-116:
  - E_{driver} = 3.68 MJ
  - Repetition rate = 11.1 Hz
  - G = 76
  - N_{beams} = 345

The final optic needs to be thinner than 1 mm to limit laser absorption



- Calculation assumes ϕ_{optic} = 1.5 J/cm^2
- A 500-μm thick optic would have an absorption of nearly 5% and equilibrium temperature of 389°C

The optic stand-off distance, R, must be >15 m to limit Ω to a reasonable value



- For R<15 m, radiative heating from chamber becomes important
- For R>20 m, little reduction in optic temperature with increasing stand-off as laser heating dominates

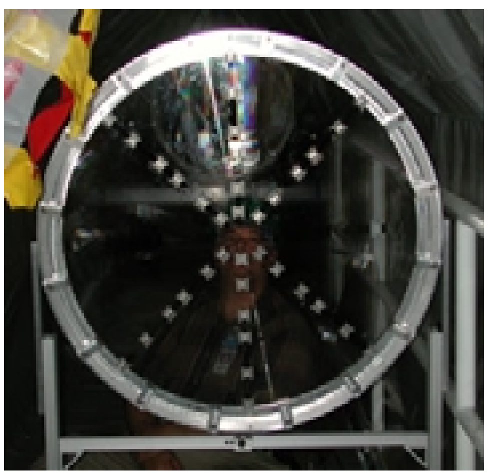
Fabrication of the final optic Fresnel lens is challenging

- Focus lens parameters:
  - Aperture 30 cm diameter
  - Focal length 20 m
  - Wavelength 351 nm
  - Optic thickness 500 μm (goal 200 μm)
  - Focusing efficiency >99%
  - Damage threshold >2 J/cm^2

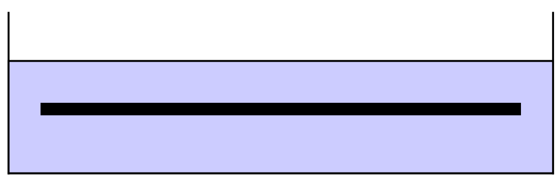
- Technical challenges:
  - Producing thin fused silica
  - Fabricating high-efficiency, off-axis Fresnel lens

Producing thin fused silica sheets is feasible

- Eyeglass Fresnel lens project has used 1 mm thick SiO_2 panels at 0.5 m sizes
- It is possible to polish SiO_2 down to ~500 μm
- 500 μm to 200 μm thinning can be performed by immersing the optic in a HF etch bath (~3 days @ 50 nm/min etch rate)
- If needed, further wavefront improvement of the thin sheets is possible with wet-etch figuring tools developed at LLNL

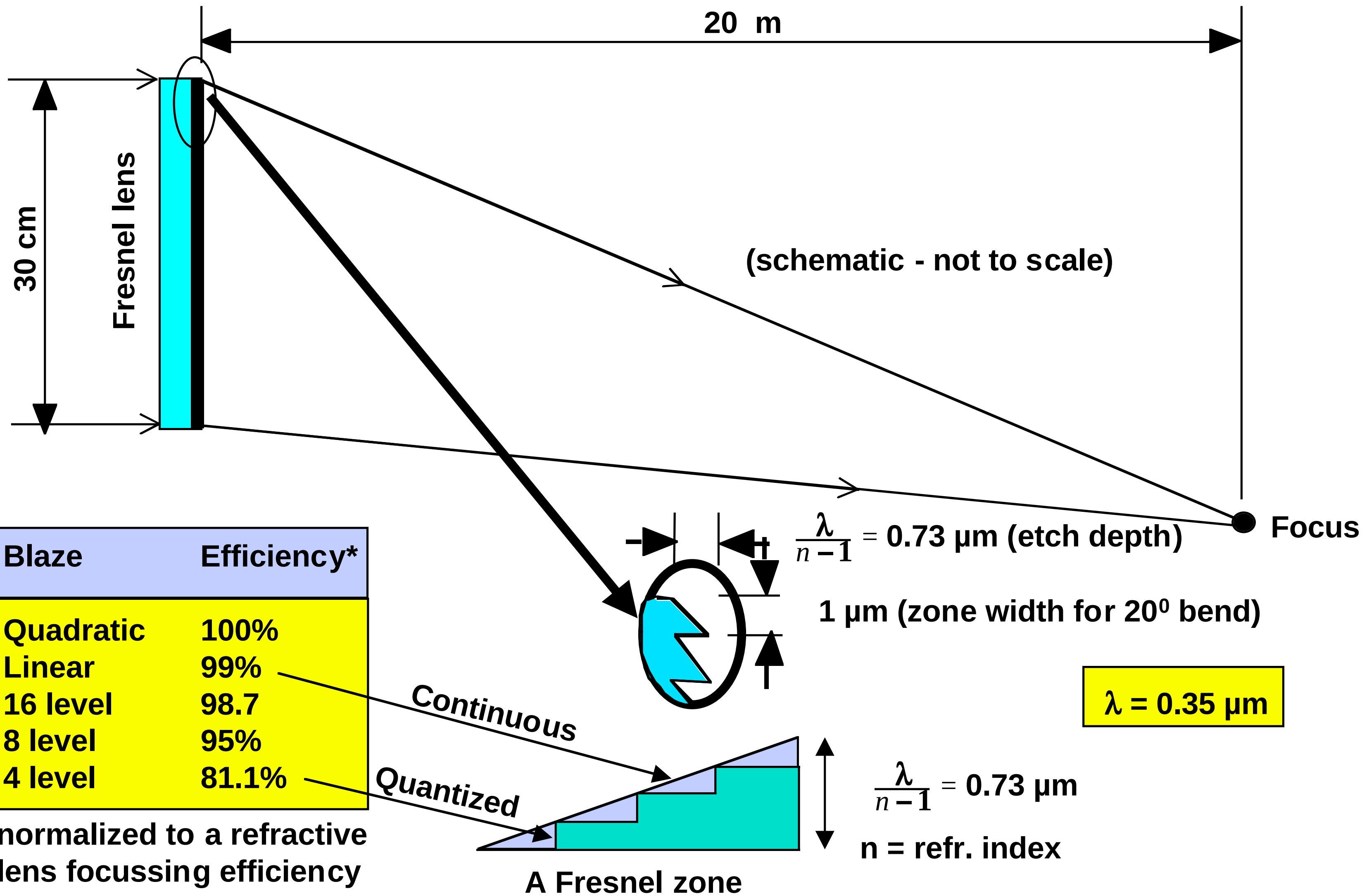


Fresnel lens in 1 mm thick FS



HF etch bath

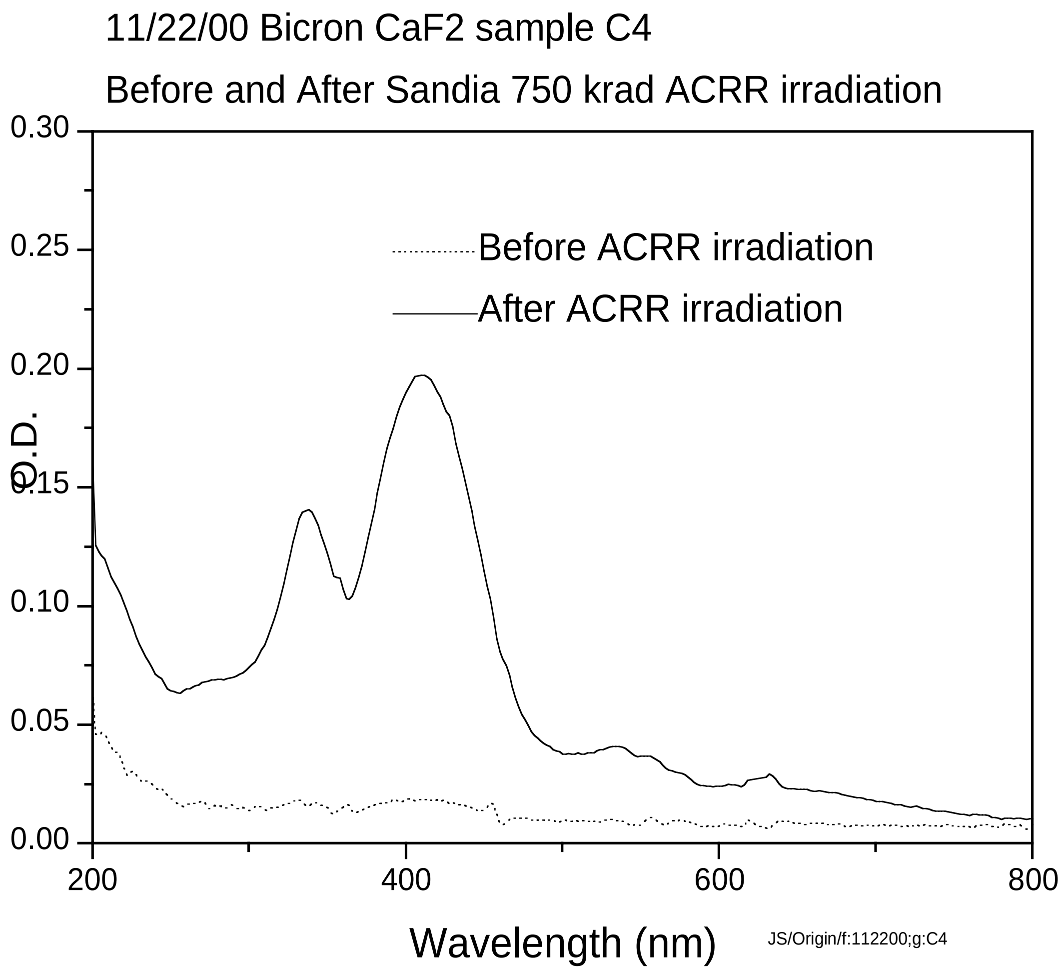
Characteristics of a diffractive Fresnel lens: 30-cm diameter example



Blaze	Efficiency*
Quadratic	100%
Linear	99%
16 level	98.7
8 level	95%
4 level	81.1%

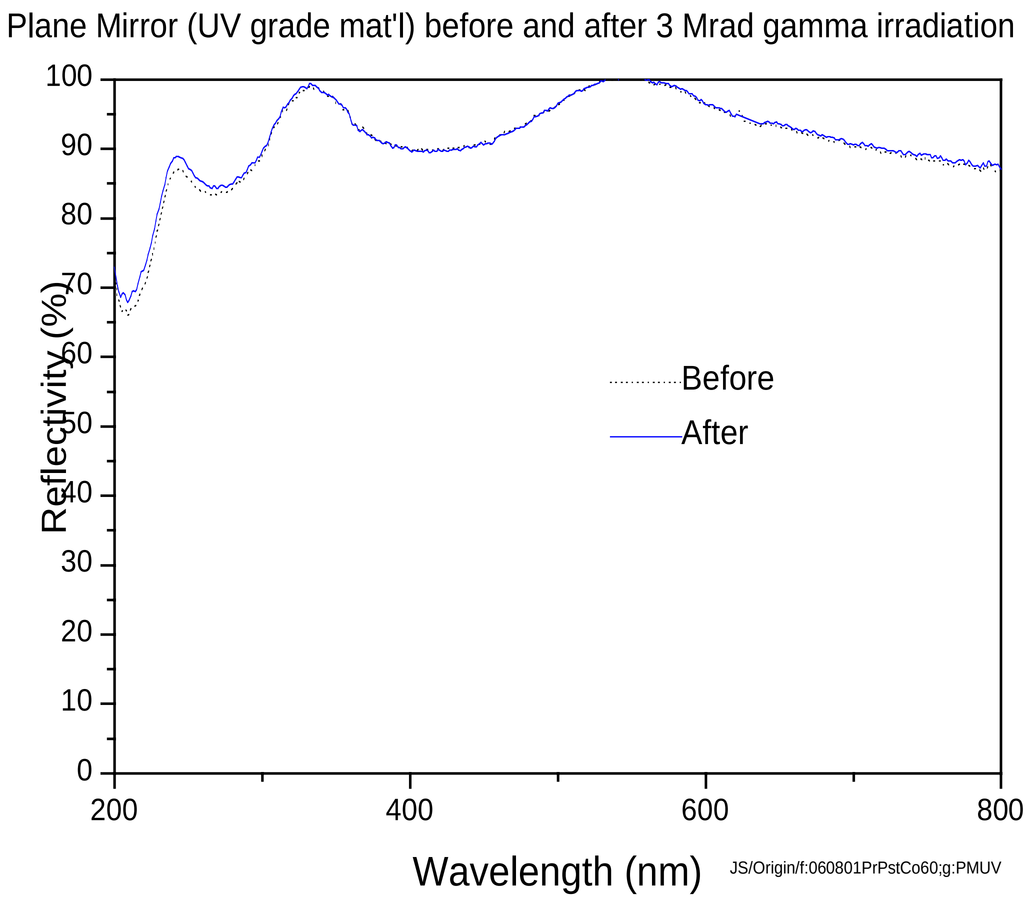
* normalized to a refractive lens focussing efficiency

CaF_2 incurs substantial absorption at 0.35 μm in response to n^0 irradiation (0.75 Mrad)



- Compared to SiO_2, absorption at 0.35 μm is ~10× larger for same neutron dose

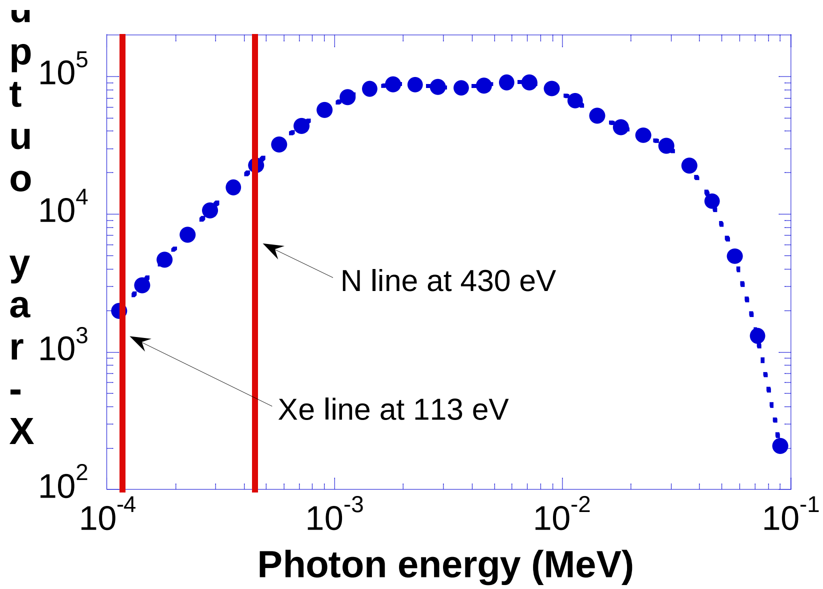
Aluminum mirror does not evidence any change in reflectivity in response to 3 Mrad of gammas



- Neutron irradiations have been completed, and will be evaluated shortly

IFE walls and optics may be exposed to significant fluences of soft x-rays

- NRL direct-drive target has a broad x-ray "peak" from ~0.5 to 30 keV; significant energies from ~20 eV to 100 keV
- Under vacuum, wall exposed to per shot fluence of >1 J/cm^2; optics exposed to ~0.1 J/cm^2
- Chamber wall can be designed to avert melting/vaporization



- With >10^8 shots/year and stringent requirements, ***sub-threshold*** effects may be important. Removal limits:
  - – Chamber wall: 10^{-2} – 10^{-1} monolayers/shot
  - – Optics: non-uniform removal <10^{-5} monolayers/shot

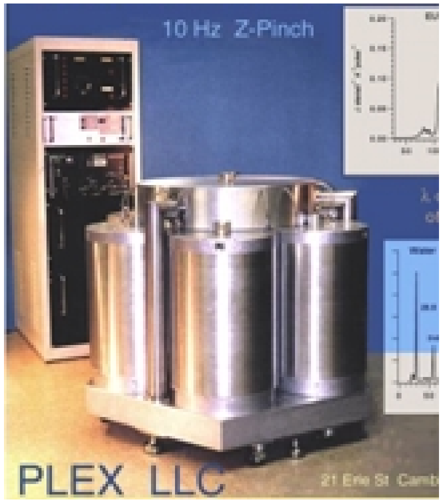
Mechanisms other than melting and vaporization may remove material, affect ability to reflect or transmit laser energy, etc.

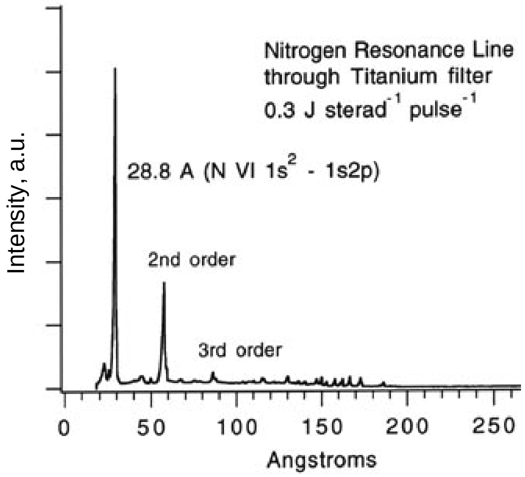
X-ray deposition produces different response than does corresponding levels of laser energy

- Primary distinction is depth of deposition (μm for x-rays vs. nm for laser)
- Longer x-ray deposition distances emphasize importance of hydrodynamics of interior material:
  - Rapid increase in internal energy due to x-ray deposition creates high pressures within the material
  - Pressure drives expansion (hydrodynamic motion) from surface layers away from bulk of the material
  - As expansion stops at end of pulse, rarefaction waves propagate from surface into bulk → these tensile stresses can be very important as mechanisms for ablation of heated material
- X-rays possess sufficient energy to break chemical bonds

PLEX can produce x-rays at energies, fluences, and repetition rates relevant to IFE conditions

- PLEX uses a Z-pinch to produce x-rays:
  - 1 GHz radiofrequency pulse pre-ionizes low-pressure (~0.2 Torr) gas fill
  - Pinch initiated by 150 kA from thyratrons
  - Operation at repetition rates up to 10 Hz
- Can run at multiple wavelengths with multiple ellipsoidal collectors and different fill gases:
  - Xe @ 113 eV, 18 J/cm^2, 3.0 mm spot size, 12±5 ns
  - N @ 430 eV, 0.3 J/cm^2, 1.4 mm spot size, <30 ns
- With filters, can generate nearly pure line energies
- Minor pinch component replacement after ~10^7 shots; thyratrons good to >10^9 shots





PLEX will be used in conjunction with the *ABLATOR* code

- Diagnostics:
  - Continual monitoring of pinch electrical characteristics
  - Output characterization using an x-ray spectrometer and photo diodes
  - Measure surface height changes with Tencor alpha-step 200
  - Surface characterization using white light interferometry
  - Material removal mechanisms will be explored with optical and photon tunneling microscopy
  - For optics: pre- and post-shot characterization (collaborations with UCSD group and LLNL's LS&T group)
- *ABLATOR* x-ray deposition model will be upgraded
- First experiments will use filters to select line energies and benchmark *ABLATOR* for single-shot ablation as f(ϕ)
- Introduce additional materials; add capabilities to *ABLATOR*
- Repeat materials for multiple (10's), and eventually, many (1000+) shots

Proposed plans and strategy for x-ray ablation facility

- Facility will be used to test chamber wall and optics materials:
  - C/C composites, graphite, tungsten and tungsten alloys
  - SiO_2 and other transmissive optics; Al mirrors
- Pre- and post-irradiation analysis of erosion morphology
- Formation of a steering committee comprised of national members:
  - Will represent technical and institutional interests
  - Will set priorities and access national assets for post-irradiation analysis
- Ultimate facility goal is to develop and benchmark modeling tools to predict behavior

PLEX is a versatile x-ray source that could address IFE issues

- Key advantages are that PLEX would be very ***controllable***, ***rep-rated***, easy to diagnose, and ***dedicated***
- Could be used to explore effects that surface contamination and ion implantation have upon x-ray ablation
- In longer-term, could envision testing of neutron-irradiated materials
- PLEX can be modified for testing of mitigation methods:
  - Background fill gas such as Xe
  - Gas puffs at the optic
  - Liquid Xe droplets

Optics may be strongly affected by large charged particle fluences

Fused Silica

- Sputtering: removal of 1.9 μm/y (**5.5 × λ_{DPSSL}**) for lens at 30 m
- Ion irradiation on SiO_2 optics may cause significant changes in optical properties:
  - 3% absorption at 546 nm induced by 20 keV He^+ irradiation to fluence of 5×10^{15} cm^{-2}
  - 0.04% absorption at 200-600 nm from 1.2×10^{17} Au/cm^2 at 3 MeV (we expect 55× this per year)
  - Literature shows changes in refractive index as well

Aluminum

- Sputtering: removal of ~15 μm/y (**59 × λ_{KrF}**) for Al GIMM (85º) at 30 m
- H_2^+ and He^+ irradiation produces dislocation loops and gas bubbles:
  - He bubbles keep spherical shape even after annealing at 893 K (see figure)
  - Bubbles near surface may affect reflectivity and/or beam quality

893 K

He bubbles in aluminum after irradiation with 17 keV He^+ ions with a fluence of 1.2×10^{14} $ions/cm^2$ at 573 K.

K. Ono et al., J. Nucl. Mater. 183 (1991) 154.

Summary

- Radiation-annealing effect has been observed in SiO_2; limiting absorption at 0.35 μm is 0.1 mm^{-1} at <300°C

- 0.35 μm absorption can be reduced further by annealing near 400°C

- Collisional cascade theory and experimental results are in rough agreement

- Use of a thin (~0.5 mm) optic allows for acceptable absorption and scatter losses and operational temperature

Future work

- Samples of Al_2O_3 and MgF_2, as well as dielectric and aluminum mirrors have been irradiated at ACRR (1 Mrad neutrons) and will be analyzed for their IFE potential
- Determine optical damage limit for n^0-irradiated SiO_2
- MDS calculations will be extended:
  - Detailed understanding of radiation annealing
  - Understand cascade overlap and defect annihilation in SiO_2
  - Move to higher PKA energies
- Small off-axis Fresnel lens to be fabricated for optical testing
- Instantaneous n^0 irradiation response will be evaluated by LANL
- Next crucial element of final optic survivability is ablation and sub-threshold damage by x-rays