Neutron and X-Ray Threat Modeling and Experiments for the Final Optic

Jeff Latkowski, Joel Speth, Steve Payne

Laser IFE Meeting

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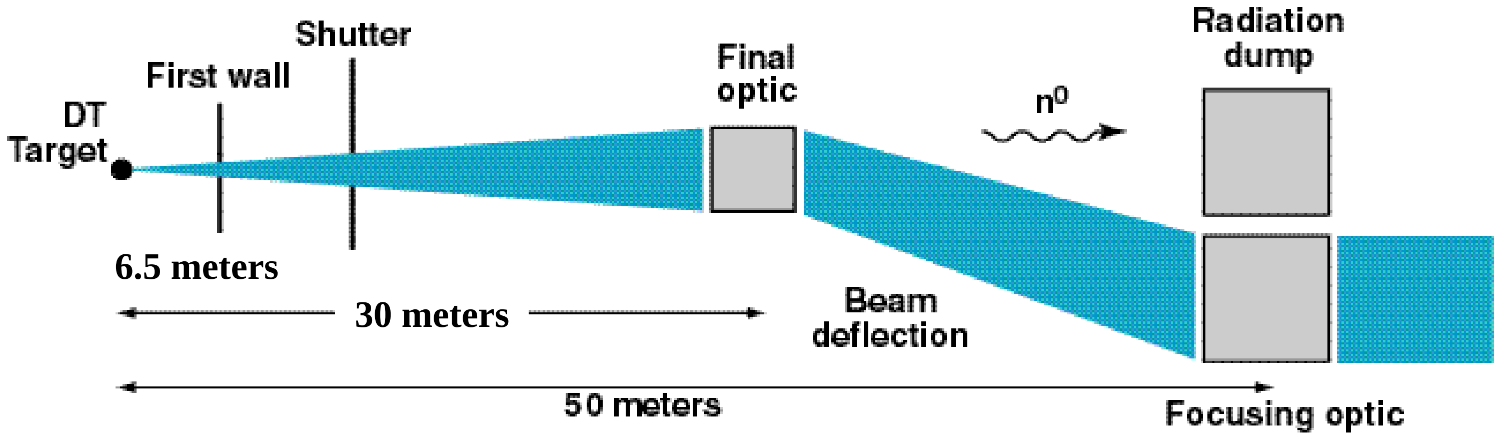
Updated "source term" for x-rays, neutrons, γ-rays, and ions: uses NRL target scaled up to 400 MJ/shot



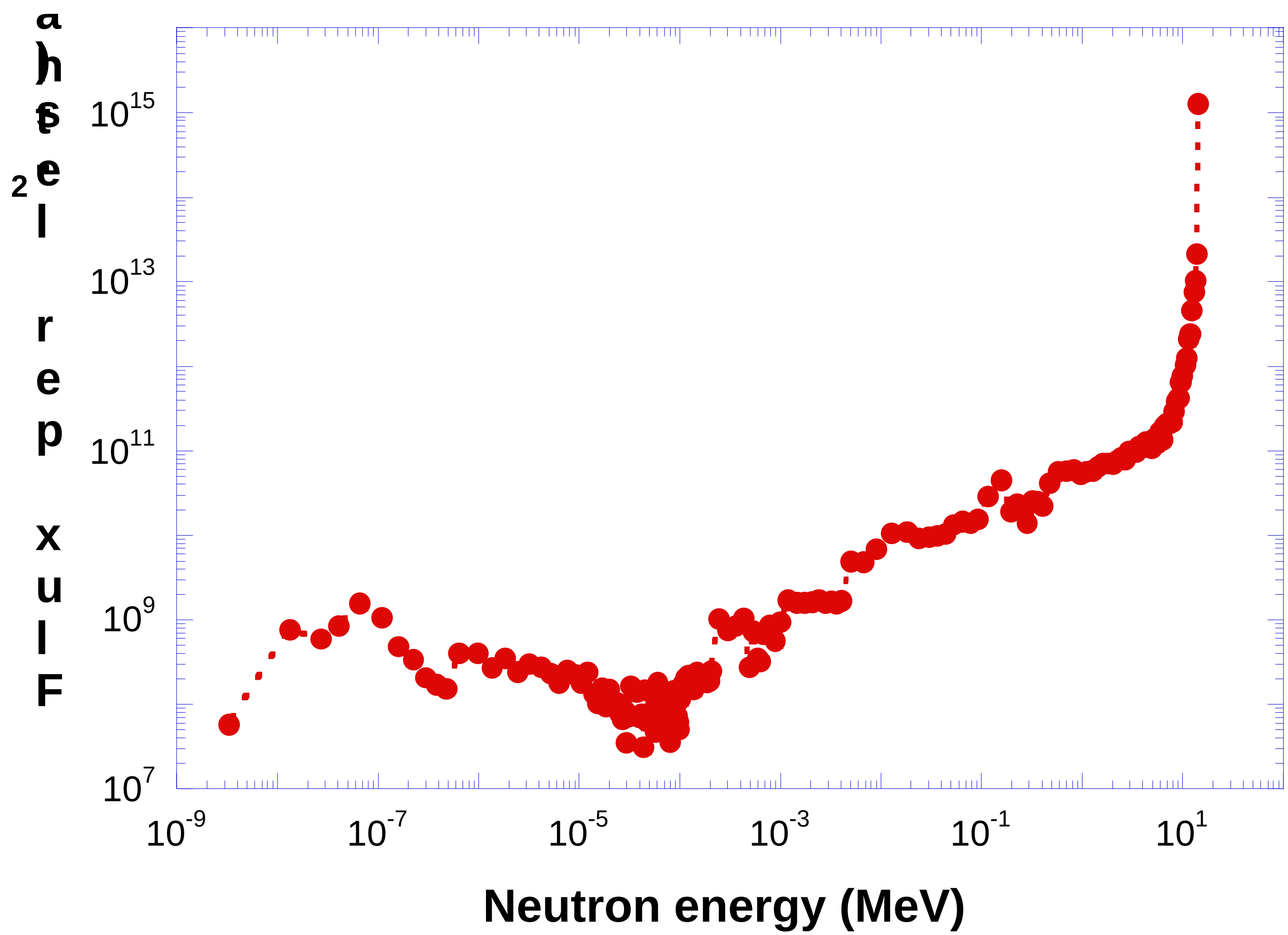
Threat	Target Emission	First Wall	Final Optic
X-rays	5.6 MJ/shot	1.1 J/cm^2 per shot (for vaccum; can be reduced with fill gas)	0.05 J/cm^2 (for vaccum; can be reduced with fill gas)
Neutrons	280 MJ/shot	190 krad/s; 3.5 MW/m^2; 9×10^{13} n^o/cm^2-s (14 MeV)	8.7 krad/s; 0.16 MW/m^2; 4.3×10^{12} n^o/cm^2-s (14 MeV)
γ-rays	<< 1 MJ/shot	--	1.4 krad/s
Ionic debris	110 MJ/shot	21 J/cm^2 per shot; 1.4 MW/m^2 (for vaccum; can be reduced with fill gas)	1 J/cm^2 per shot; 0.07 MW/m^2 (for vaccum; 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

- Optic resides 30 m from target; target $\rho r = 3\ g/cm^2$
- Neutron dose is 8.7 krad/s → 2.8×10^{11} rad/FPY
- Gamma-ray dose is 1.4 krad/s → 4.4×10^{10} rad/FPY
- Neutron fluxes at final optic:
  - $\varphi_{tot} = 9.7 \times 10^{12}\ n/cm^2\text{-}s$
  - $\varphi_{n,fast} = 9.1 \times 10^{12}\ n/cm^2\text{-}s\ (E_n \geq 0.1\ MeV)$
  - $\varphi_{n,14MeV} = 4.3 \times 10^{12}\ n/cm^2\text{-}s$
- Transmutation of an SiO_2 final optic:
  - H = 28 appm/FPY; He = 69 appm/FPY
  - Mg = 15 appm/FPY; Al = 4 appm/FPY

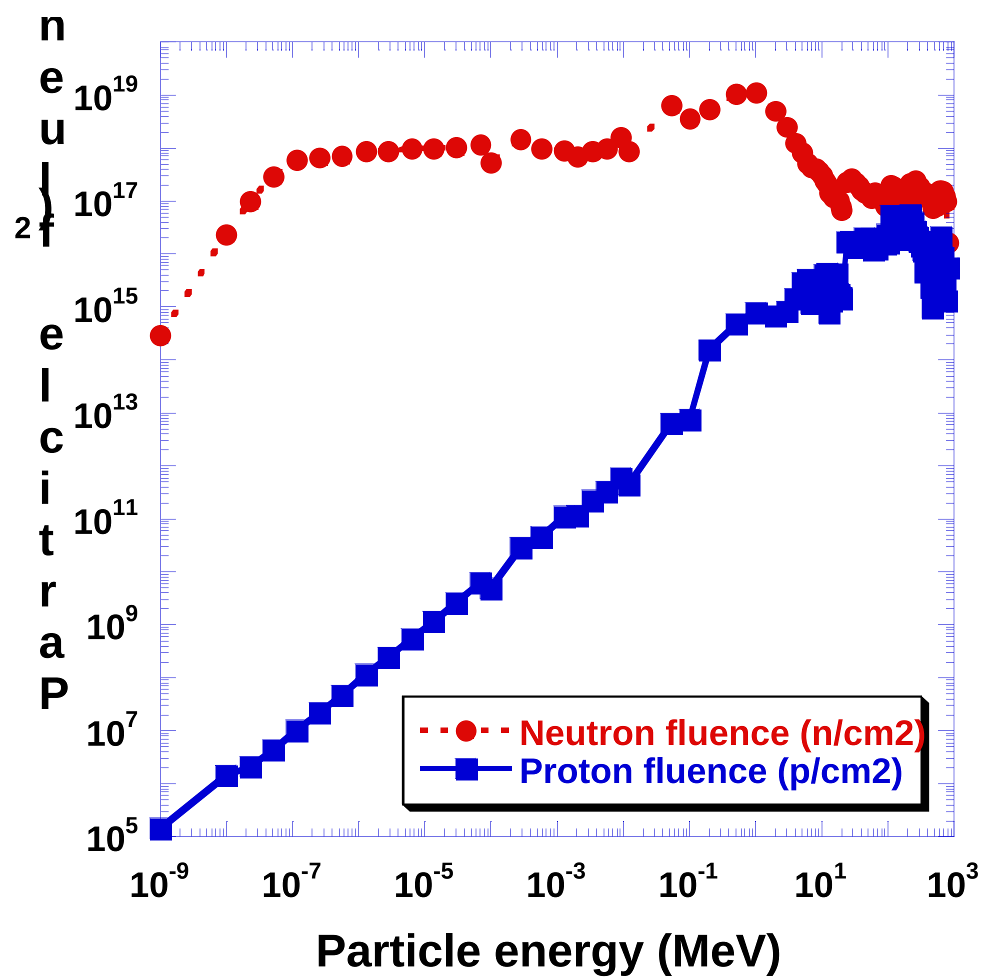
Neutron spectrum at the final optic



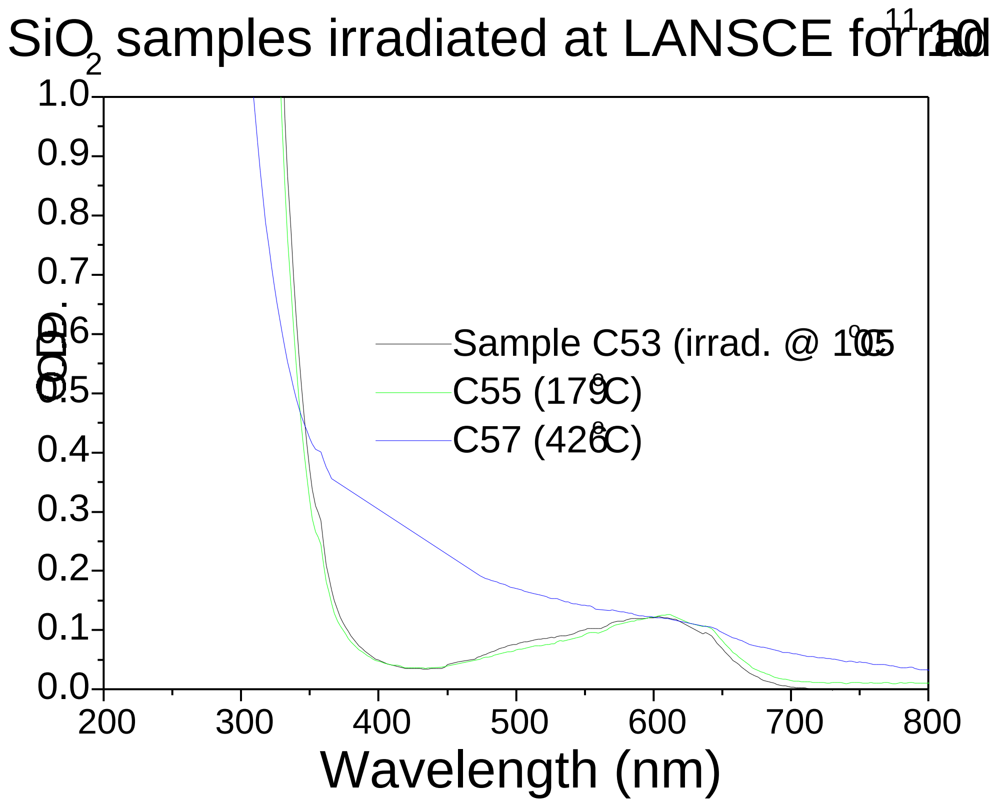
Note: Lethargy calculated with E_{max} = 14.1 MeV

The LANSCE neutron spectrum is quite *hard* and mixed with *protons*

- Samples exposed at LANSCE for several months
- Depending upon position, samples received a fluence of:
  - 5-8 × 10^{19} n/cm^2
  - 0.4-1.0 × 10^{18} p/cm^2
- For a total dose of:
  - 0.7-1.0 × 10^{11} rad n
  - 2-4 × 10^{10} rad p



We have irradiated SiO_2 samples (Corning 7980) for 10^{11}rads for several different temperatures

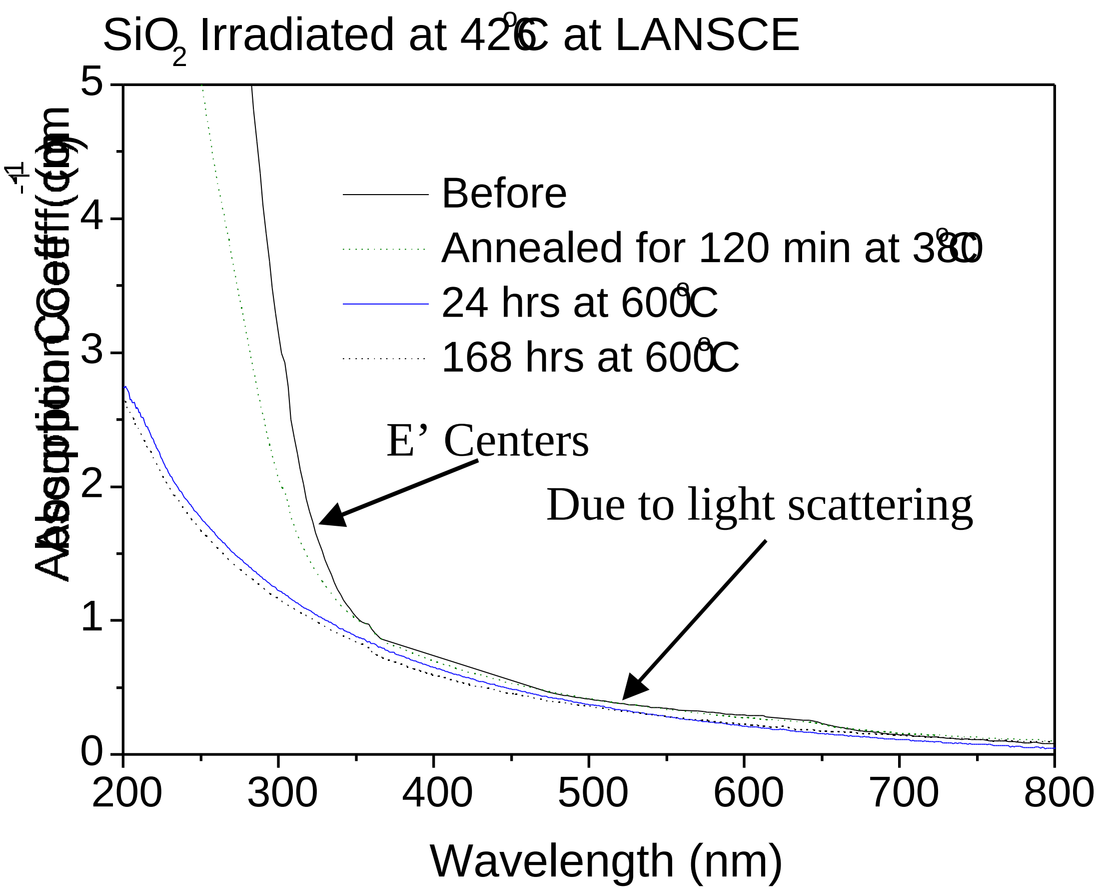


• The non-bridging oxygen hole center (NBOHC) evidences absorption at 620 nm, while the E' and oxygen deficient center (ODC) occurs in the UV

• NBOHC is apparent for samples irradiated at 105 ^{o}C and 179 ^{o}C, while the sample irradiated at 426 ^{o}C reveals a slow rise to shorter wavelength

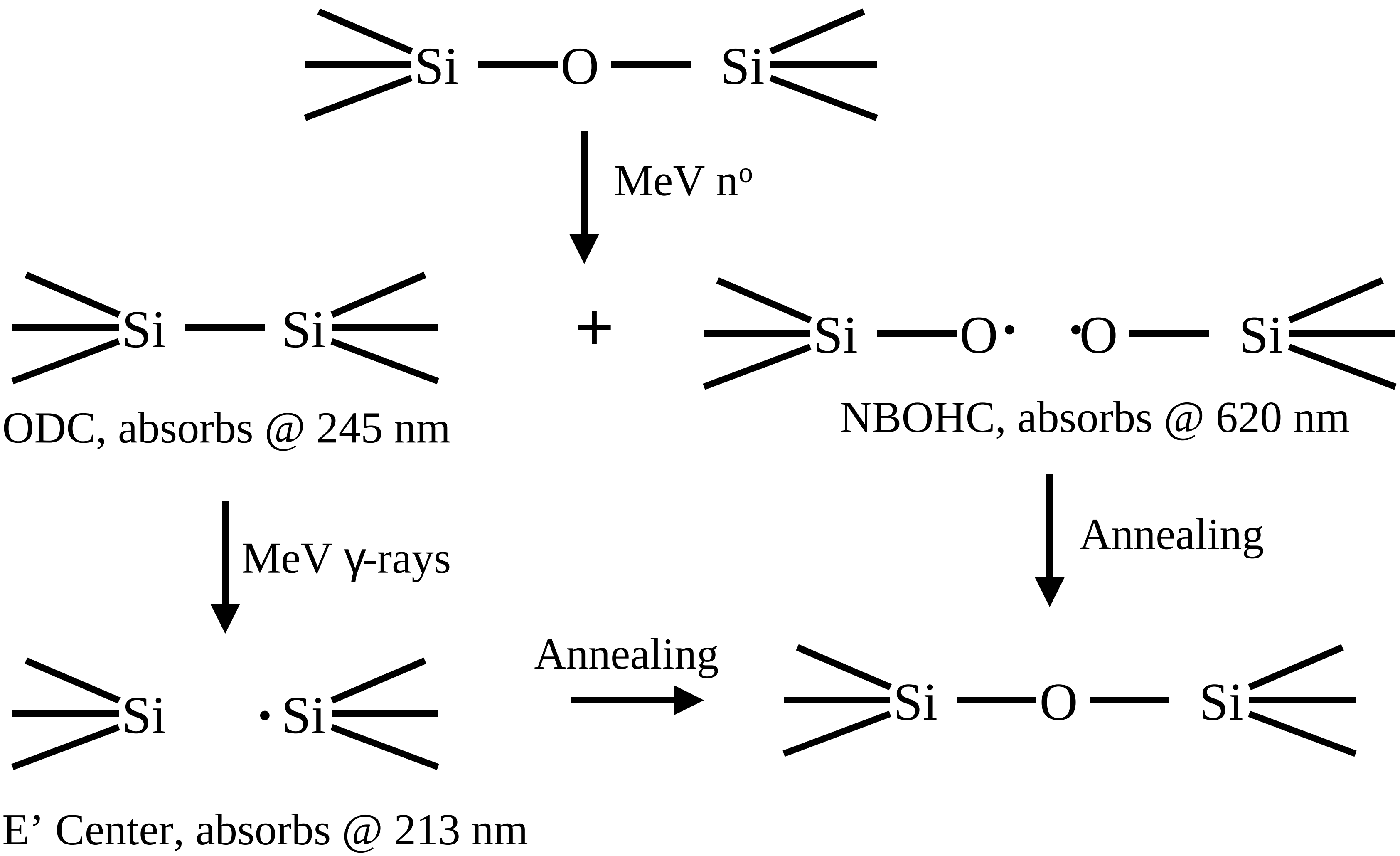
• Corning 7980 is a synthetic silica with ~1000 ppm water

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

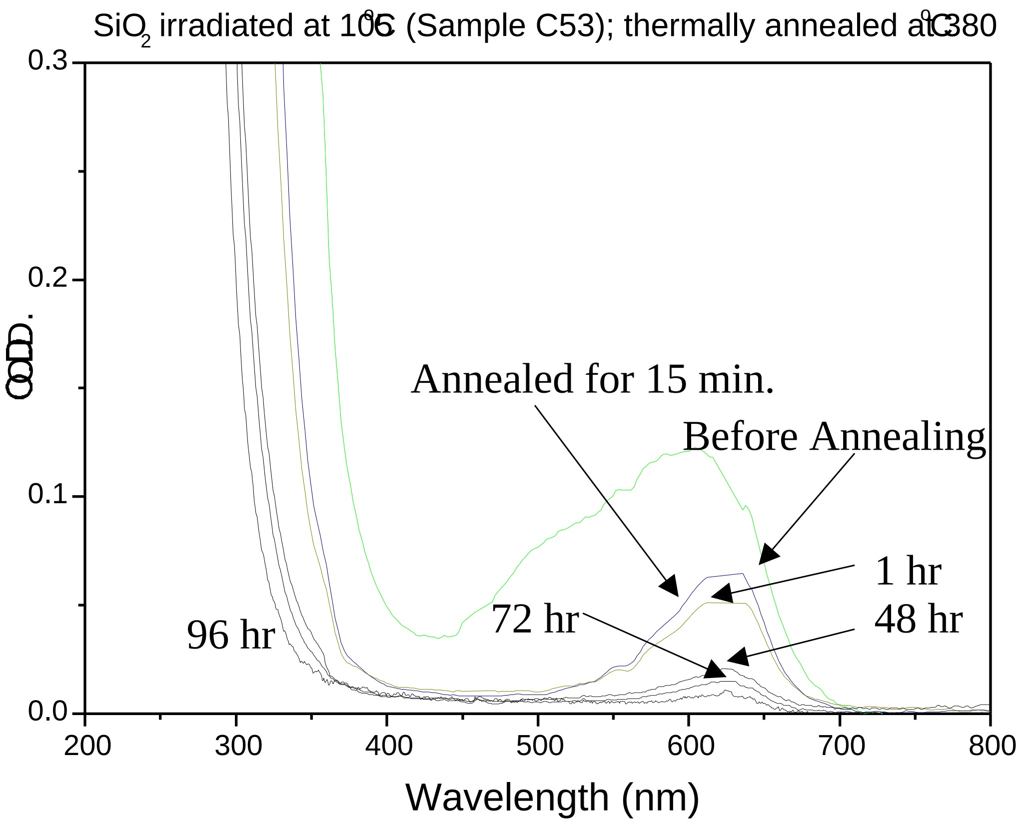


- Annealing at 380 °C reduces the E' defect population (for $\lambda < 350$ nm)
- Annealing at 600 °C completely eliminates the E' centers
- Slow rise in the baseline is due to scattering
- Scattering may be due to agglomeration of helium (25 appm predicted to form from n° irradiation)

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



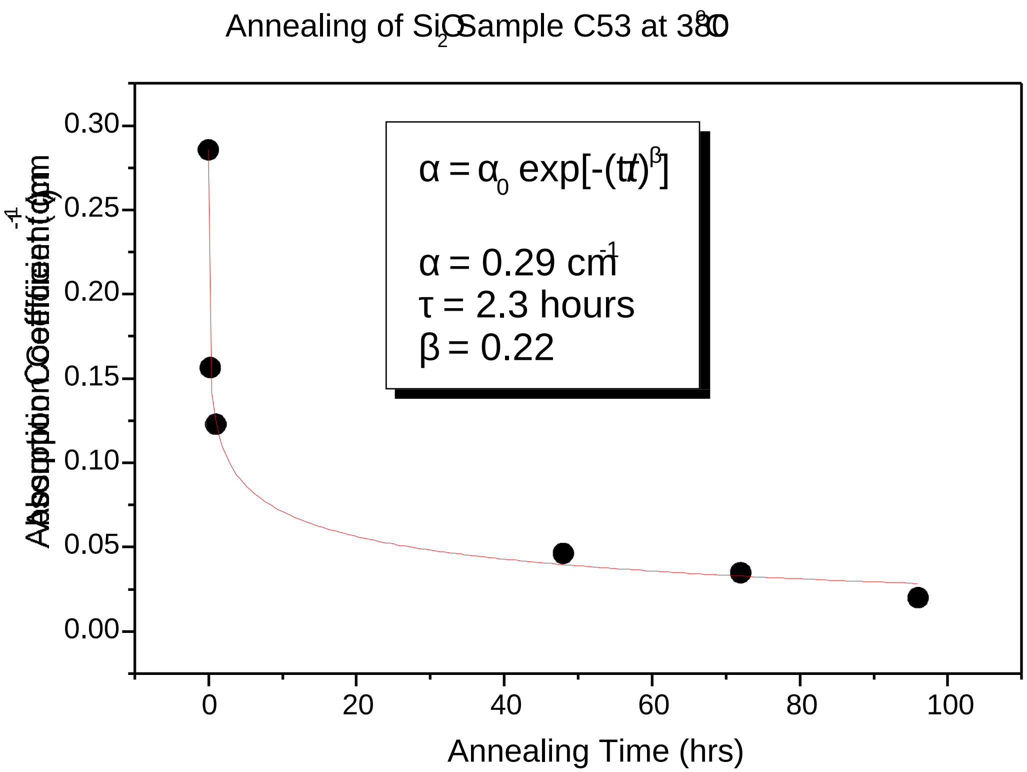
Following a dose of ~10^{11} rad n° at 105 °C, it is possible to anneal away the NBOHCs, ODCs, and E' Centers



- NBOHC absorbs at 620 nm, σ_{abs} = 1.6 x 10^{-19} cm^2 (from lit.)
- E' Center absorbs at 213 nm, σ_{abs} = 3.2 x 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

We have fit the decay of the NBOHC absorption at 620 nm to a "stretched exponential" function



- Fit to $\alpha = \alpha_0 \exp[-(t/\tau)^\beta]$
- Annealing of NBOHC at 380 °C yields
  - τ = 2.3 hrs
  - β = 0.22
- Annealing of E' Centers at 350 °C (from Marshall, et al.) yields
  - τ = 0.8 hr
  - β = 0.25

➢ Agreement between (new) NBOHC data and (previously published) E' data is reasonable (β is very close; τ is within factor of three)

➢ τ_{anneal} = 19 hrs (integral divided by initial value)

➢ $\tau_{anneal} = \tau_0 \exp(T_0/T)$ with T_0 = 10,400 K (Marshall et al.) gives $\tau_0 = 2.3 \times 10^{-6}$ hr

"Stretched exponential" form can be interpreted in a straightforward way

- Reference: Kakalios, PRL 59, 1037 (1987)

- Basic equation: $N = N_0 \exp[-(t / \tau)^{\beta}]$, $0 < \beta < 1$

- Dispersion in activation energy leads to slowing at later time:
  - $p(E) \propto \exp(-E/k\,T_{diff})$
  - $\beta = T / T_{diff}$
  - Implies $T_{diff} = 2970\ ^{o}K$ for SiO_2 annealed at 380 ^{o}C
  - Additional experiments at 300 ^{o}C are planned for confirmation

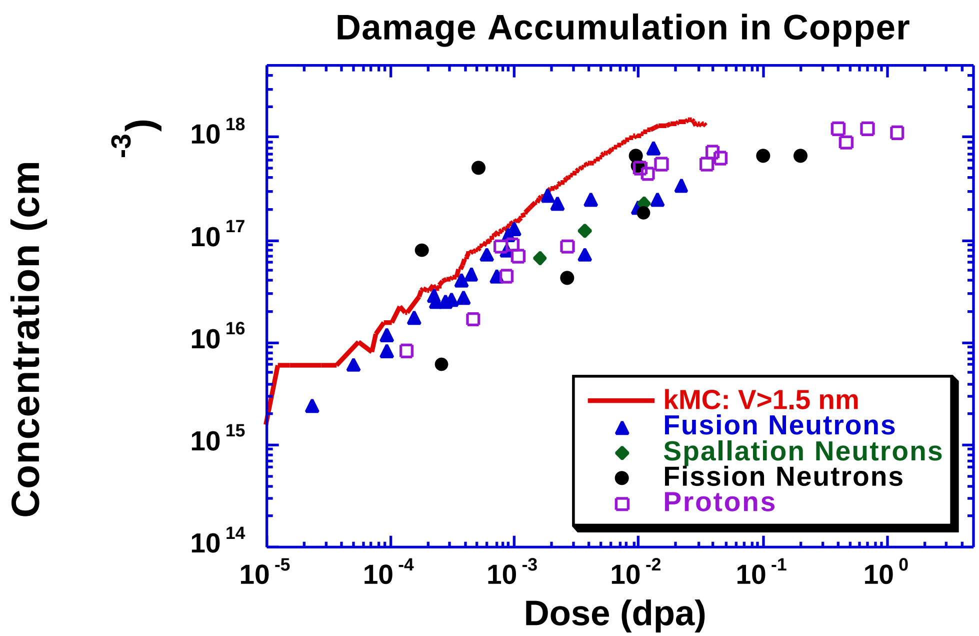
Defect generation by SPR III and LANSCE appear inconsistent with each other

- SPR III run – 3.2×10^5 rad @ ~1 MeV n^o (Marshall, et al.)
  - Produced 188 defects per 1 MeV collision
  - OR *1880 defects* per 10 MeV- equivalent collision
- LANSCE run – 1.0×10^{11} rad @ ~10 MeV n^o
  - Produced *0.35 defects* per 10 MeV- equivalent collision
- Defects may be experiencing "self-healing" due to "local melting" (preliminary theory)
  - Assume that atoms that reach 1000 ^{o}C are locally annealed (0.11 eV)
  - Then, 10 MeV n^o collision heats 10^7 atoms to 1000 ^{o}C (11% momentum transfer)
  - Therefore SiO_2 sample was "melted" 867× during the LANSCE irradiation, and only 0.003× during the SPR III run
- Hypothesis is that limiting defect concentration is:
  - [(6.6×10^{22} SiO_2-atoms/cm^3) / (10^7 melted-atoms/collision)] (1880 defects/collision) = 1.2×10^{19} defects/cm^3
  - Measured limiting concentration is 0.2×10^{19} defects/cm^3 (differs by factor of 6)

Self-healing due to "local melting" may be the mechanism limiting the defect population

Saturation of damage during irradiation

Copper irradiated with Neutrons and Protons show saturation of damage at ~ 10^{-2} dpa for T ~ 300 K



Experiments:

• *B. N. Singh, S. J. Zinkle, J. Nucl. Mat. 206 (1993) 212*

• *Y. Dai and M. Victoria, MRS V. 439 (1996) p. 319*

Kinetic Monte Carlo simulations reproduce the experimental measurements

In copper over 90% of the defects are vacancy clusters (forming Stacking fault tetrahedra)

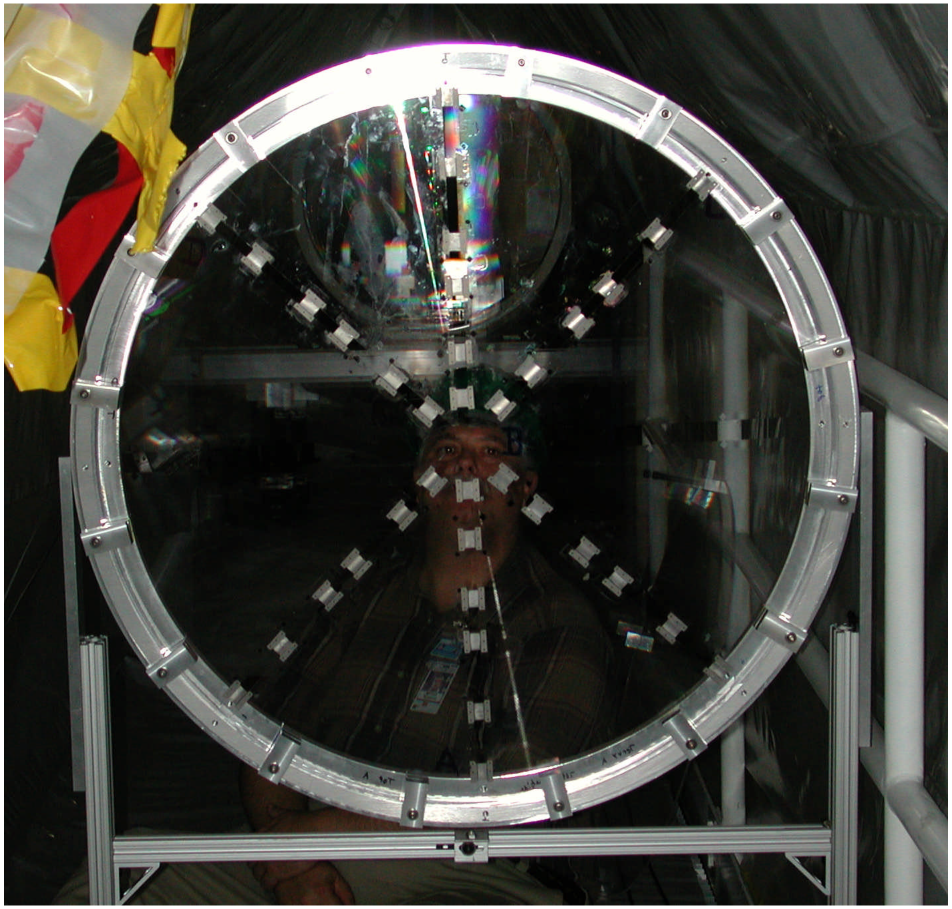
How might SiO_2 perform as the final optic for IFE?

- Neutron dose rate of LANSCE (~10 krad/s) and IFE (8.7 krad/s) are comparable
- At 426 ^{0}C, α_{abs}(350 nm) = 0.14 cm^{-1}, but scatter is significant (α_{scatt} ~ 1 cm^{-1})
  - τ_{anneal}(426 ^{o}C) = 6.7 hr, serving to reduce E' center absorption
- At 105 ^{0}C, α(350 nm) = 1.0 cm^{-1}
  - Transmission = 90 % for a 1 mm thick diffractive optic
  - No scatter is observed in sample
  - τ_{anneal}(105 ^{o}C) = 2.0 × 10^{6} hr, so thermal annealing has no impact
- Self-healing of neutron-induced damage limits α(350 nm) to ~1 cm^{-1}, which offers 90% transmission for a 1 mm optic
  - Intermediate temperature (~200 – 300 ^{o}C) may be optimal
  - Transient absorption has not be evaluated in these experiments, and may be an issue
- Final optic may need to be cooled due to laser heating
  - n^{o} causes minor heating

1-mm-thick, SiO_2 diffractive optics can be constructed

- Fresnel lens fabricated in 80-cm diameter, 1-mm thick fused silica substrate:
  - using 2-mask lithography and HF etching for the Eyeglass project
  - tabs allow folding of the optic for transport into space

- Monolithic 80-cm diameter, 1 mm thick fused silica Fresnel lenses can also be fabricated using the same technology



S. Dixit 5/29/01

Several optical materials in addition to SiO_2 will be evaluated for their radiation hardness

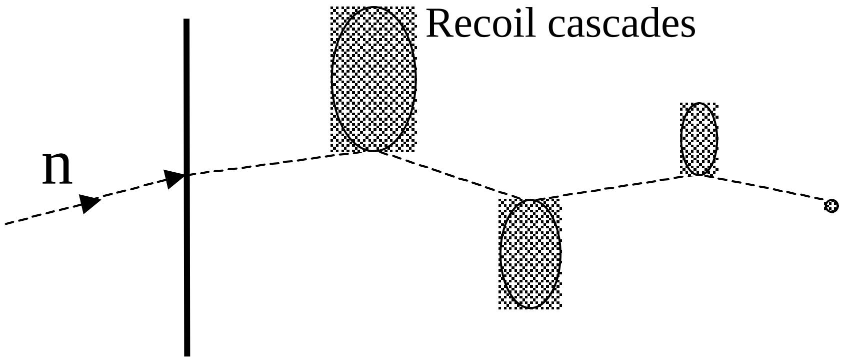
- Materials in-hand – Al mirrors, Al_2O_3, MgF_2, CaF_2

- Test procedures:
  - γ irradiate to test for impurities
  - n^o / γ irradiate at ACRR (SNL), in boron container
  - Investigate changes in optical properties
  - Consider use of elevated temperature for annealing
  - Develop theory of defects
  - Extrapolate to IFE-relevant doses

- These tasks are planned for the next few months

Modeling damage of laser optics due to neutron irradiation

Neutron irradiation of fused silica shows: (1) defect production (mostly oxygen-deficient centers) and (2) densification with irradiation dose



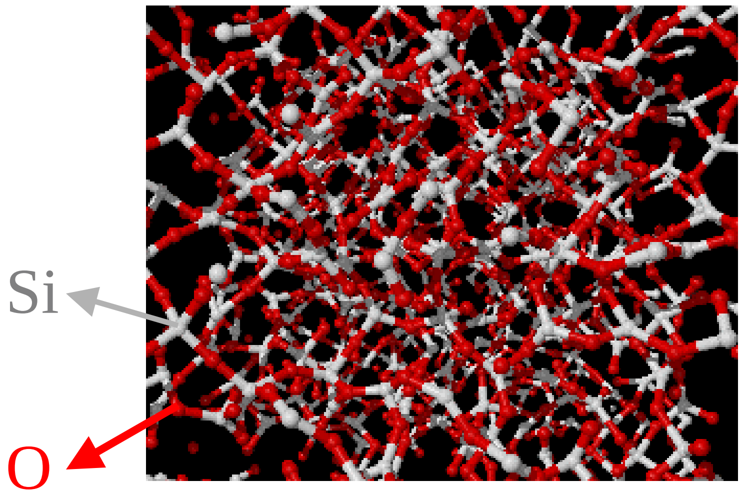
Neutron irradiation produces recoils with energies of several 10s of keV that result in damage of the target.

These phenomena occur at time scales of a few picoseconds, difficult to explore experimentally but ideal for molecular dynamics simulations.

Molecular dynamics simulations can be used to study structural changes such as densification and defect production in silica glass due to irradiation at energies of a few 10s of keV

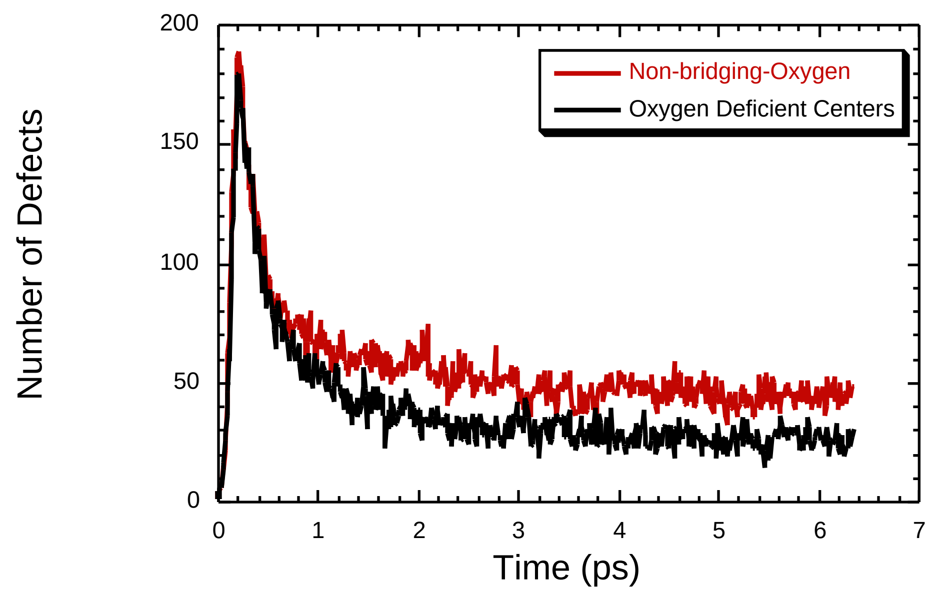
Molecular dynamics simulations of damage in SiO_2 glass

Initial conditions: Silica Glass



The initial glass generated by melting and quenching an initial crystalline structure

Preliminary simulations of damage in Silica glass at 5 keV show the production of Oxygen deficient centers and Non-bridging Oxygen defects



A database of damage in silica for recoils of energies of a few keV is being generated

First step to a complete model of damage and recovery of silica due to neutron irradiation

A. Kubota, M.-J. Caturla

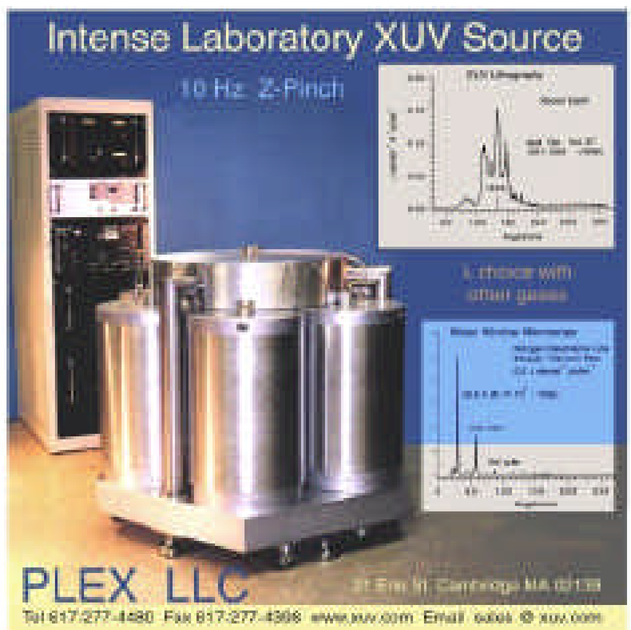
Molecular dynamics simulations of damage in SiO_2 glass: work in progress

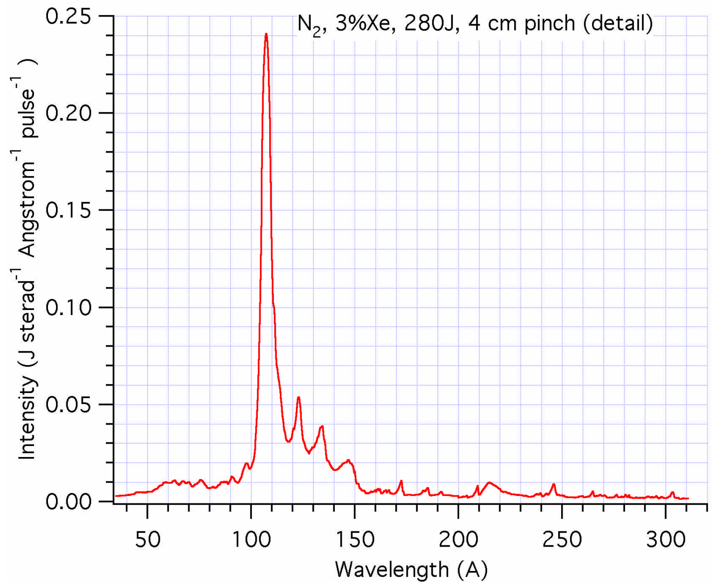
• Generate a database of number of defects and defect types vs. recoil energy

• Annealing: study damage evolution with temperature

• Damage accumulation: study the effects of cascade overlap

PLEX is able to produce an x-ray ablation source that might be useful for IFE-relevant testing of the first-wall and final optic





•10^6 pulse test at 240J stored energy @ 5Hz, with no change in 92.5eV transmission of test optic 50cm from plasma

• Parameters of system: \$320K; 1.5 J/ster/pulse; **up to 18 J/cm^2**; 113 eV; 3.0 mm source; uses ellipsoidal mirror for focus; 300J stored energy; 10 Hz; very low debris

The PLEX x-ray source may be extremely useful for IFE optics and chamber studies

- Capabilities are unmatched by other facilities:
  - 113 eV x-rays → baseline target emits significant x-rays at this energy
  - Fluence up to 18 J/cm^2 → IFE conditions are 1.1 J/cm^2 at chamber wall and 0.05 J/cm^2 at final optic (both vacuum)
  - 10 Hz repetition rate → mimics IFE conditions
- Previous work has studied x-ray ablation:
  - Anderson conducted Nova experiments up to 3 J/cm^2
  - Developed and benchmarked ABLATOR code
  - Only considered **vaporization** and **melting** as removal mechanisms
  - Only considered a few shots
- IFE optics and chambers must contend with ~ 108 shots/year

Removal of even 0.1 nm/shot is unacceptable → 1 cm/year!

Summary

- ➢ Fused silica evidences a limiting defect concentration
  - ✓LANSCE irradiations approximate IFE dose rate
  - ✓E'/ ODC and NBOHC are created and annihilated concurrently
  - ✓At 105 ^{o}C, transmission = 90 % for a 1 mm diffractive optic
  - ✓At 426 ^{o}C, absorption of E' centers are annealed away, but scattering centers form (may be due to helium bubbles)
  - ✓Based on "stretched exponential" fits, thermal annealing has no impact on the 105 ^{o}C and 179 ^{o}C irradiations
  - ✓Intermediate temperature may be optimal for FO
  - ✓Limiting defect population may be due to a self-healing effect ("local melting")
- ➢ Other FO candidate materials are on the docket to be tested and analyzed (Al mirrors, etc.)
- ➢ PLEX x-irradiation instrument may prove useful for ablation tests of FW and FO materials