Issues and Activities for Laser-IFE Optics

Snowmass, CO

July 10, 2002

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Threats to the optics vary for each step in our development plan

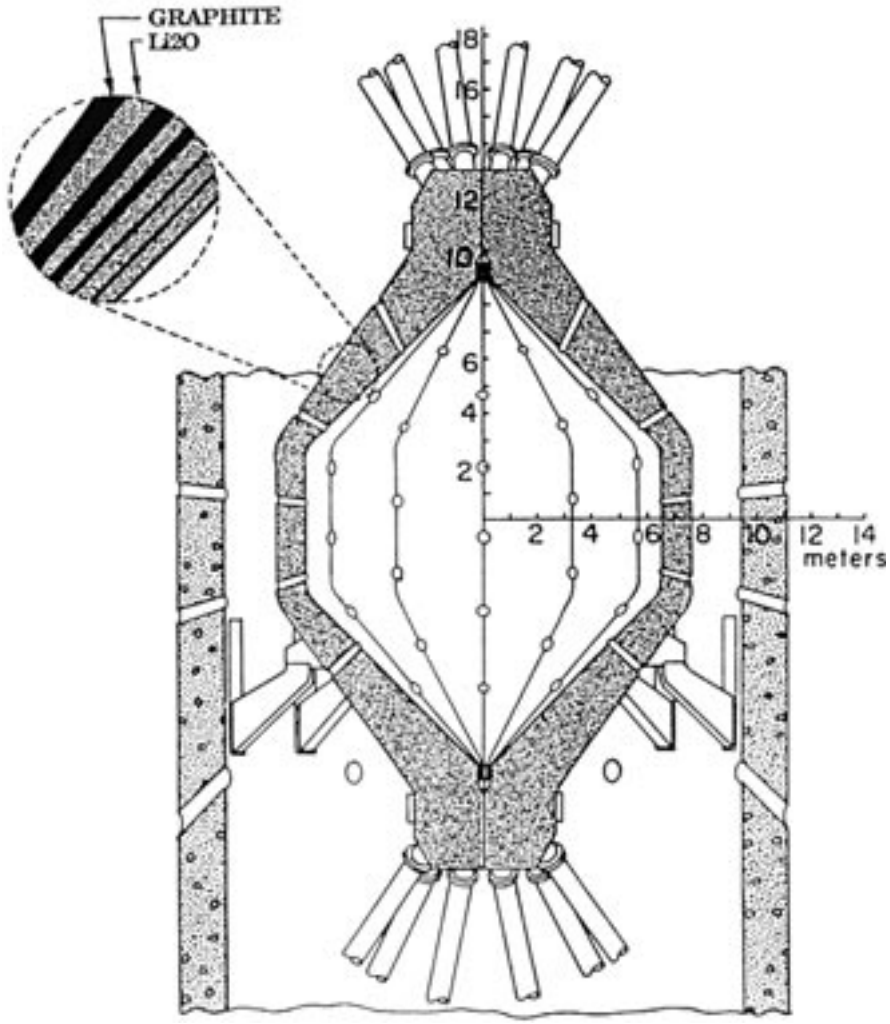
- Integrated Research Experiment—provides an integrated technology demonstration for laser, optics, and target injection & tracking at rep-rate

- Engineering Test Facility—puts all the pieces together for the first time on one facility; includes cryogenic targets and nuclear yield

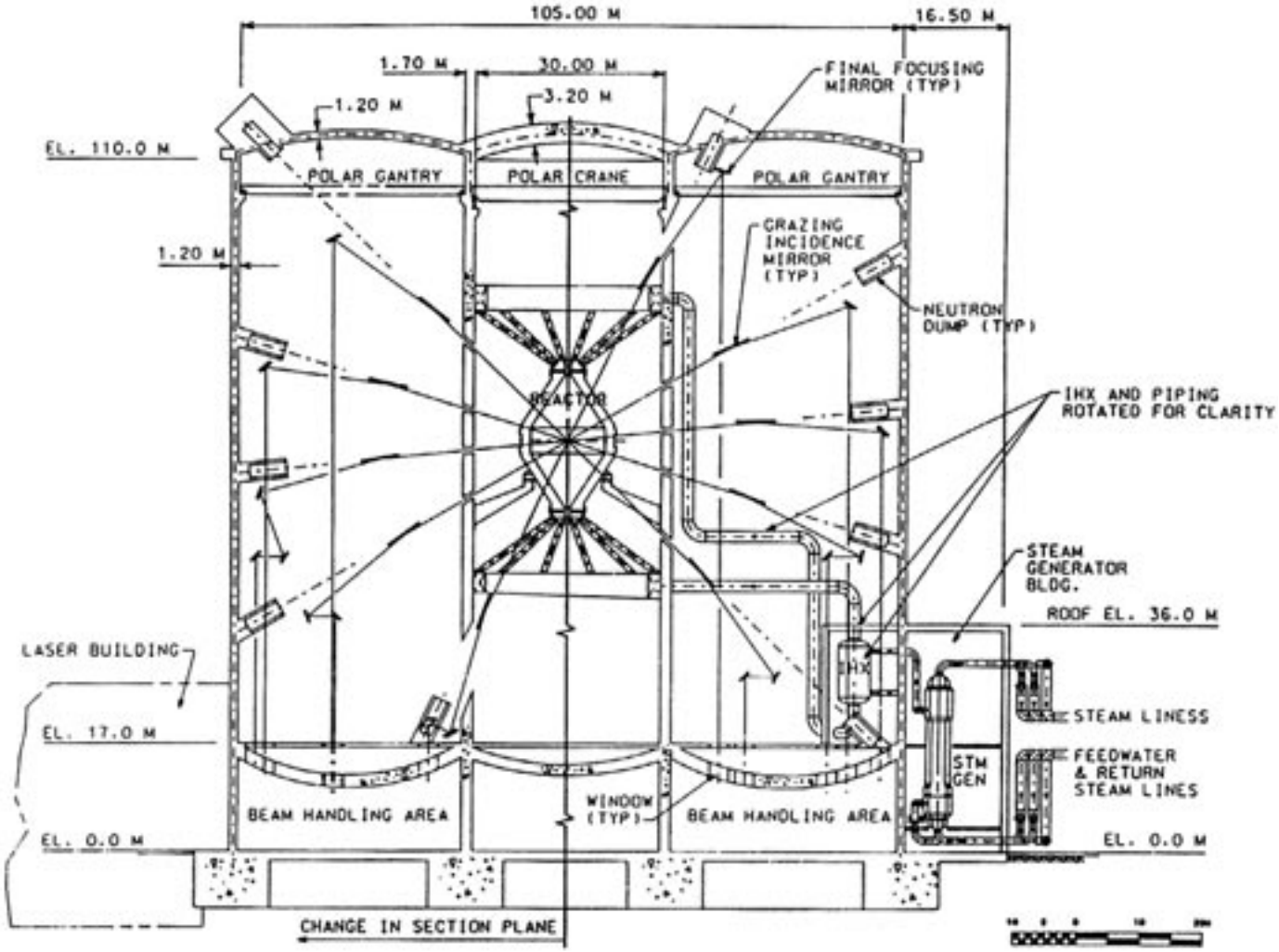
- Power Plant—threat spectra provided by John Perkins using LASNEX

Sombrero design was published in 1992

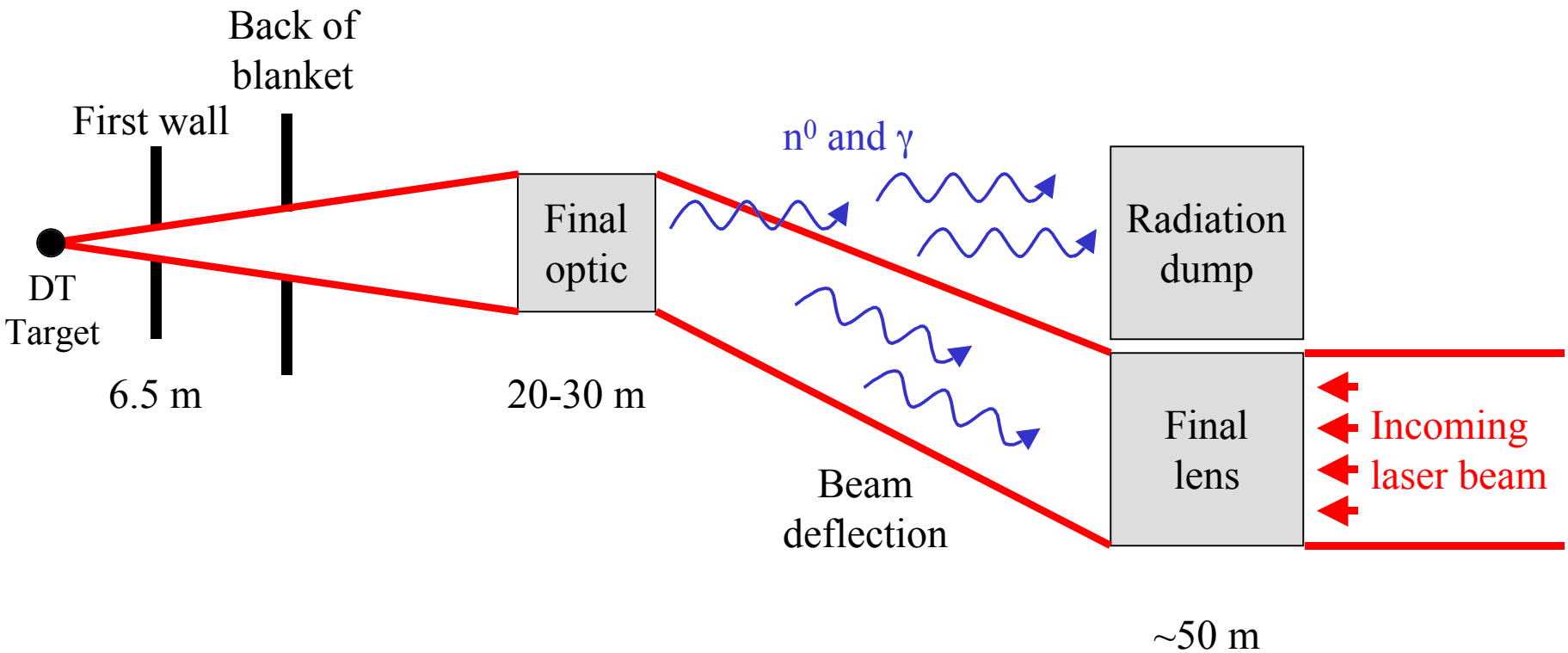
- Sombrero is a gas-protected, dry-wall laser-IFE power plant design:
  - Direct-drive targets illuminated over 4π
  - Final optic sits at 20-30 m
  - Low-density (0.5 Torr) Xe gas used to absorb x-rays and slow ions
  - Gas re-emits x-rays over longer timescale → spreads heat flux and allows conduction to avert ablation



Sombrero, (Cont'd.)



Definition of terms



The Integrated Research Experiment *will not* produce nuclear yield

- Driver energy likely to be ~100 kJ

- Laser fluence on optics:
  - Thermal stress limits 85º grazing incidence metal mirror (Al 7475 with 98.9% reflectivity) to ~2 J/cm^2 [1]
  - Final lens limit is ~5 J/cm^2 (equivalent normal fluence)

- Without cryogenic (or fusion) targets or higher driver energy, output will be mix of soft (~100 eV) x-rays and debris and/or shrapnel

[1] SOMBRERO Report, pg. 3-140.

The Engineering Test Facility *will* produce nuclear yield

- Driver energy likely to be 1-2 MJ
- Target output of 50-200 MJ is likely
- Breakdown should be similar to smaller NRL Radiation Pre-Heated Direct-Drive Target:

BUCKY Result	
Driver energy	1.3 MJ
Yield	195 MJ
Neutrons	150 MJ (76.8%)
X-rays	2.0 MJ (1.0%)
Ions	35.1 MJ (17.9%)

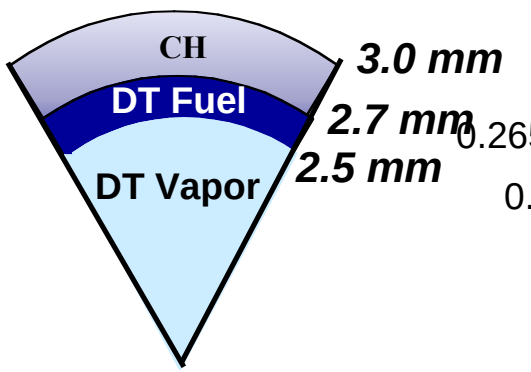
LASNEX Result	
Driver energy	1.3 MJ
Yield	154 MJ
Neutrons	109 MJ (70.8%)
X-rays	2.1 MJ (1.4%)
Ions	43.0 MJ (27.9%)

Presented at Laser-IFE Mtg, Feb. 2001.

Direct-Drive Targets Under Consideration Have Different Output

Direct-drive Laser Targets

SOMBRERO (1990)
Standard Direct-Drive

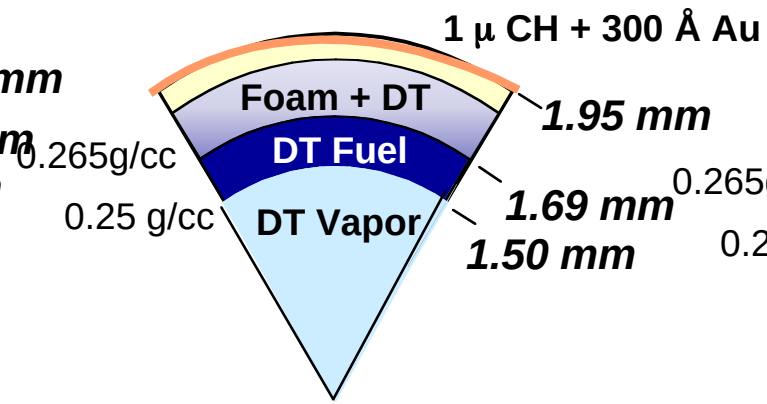


Laser Energy: 4 MJ
Laser Type: KrF
Gain: 100
Yield: 400 MJ

Debris Ions

94 keV D -	5.81 MJ
141 keV T -	8.72 MJ
138 keV H -	9.24 MJ
188 keV He -	4.49 MJ
1600 keV C -	55.24 MJ
Total -	83.24 MJ per shot

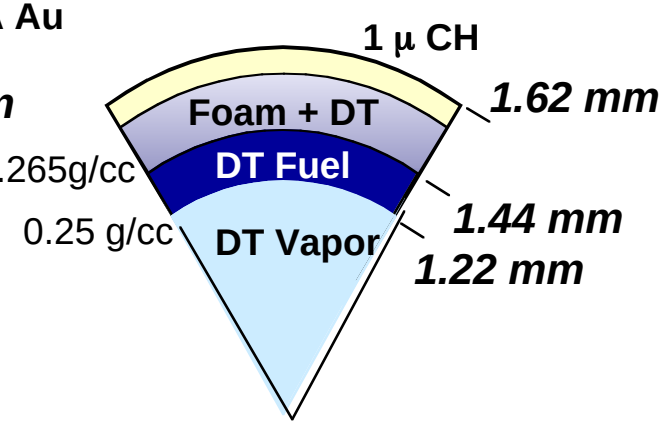
NRL (1999)
Radiation Tailored-Wetted Foam



Laser Energy: 1.3 MJ
Laser Type: KrF
Gain: 127
Yield: 165 MJ

Spectra:
- Calculated with BUCKY
- Calculated by NRL
- Calculated with Lasnex

NRL (1999)
Wetted Foam

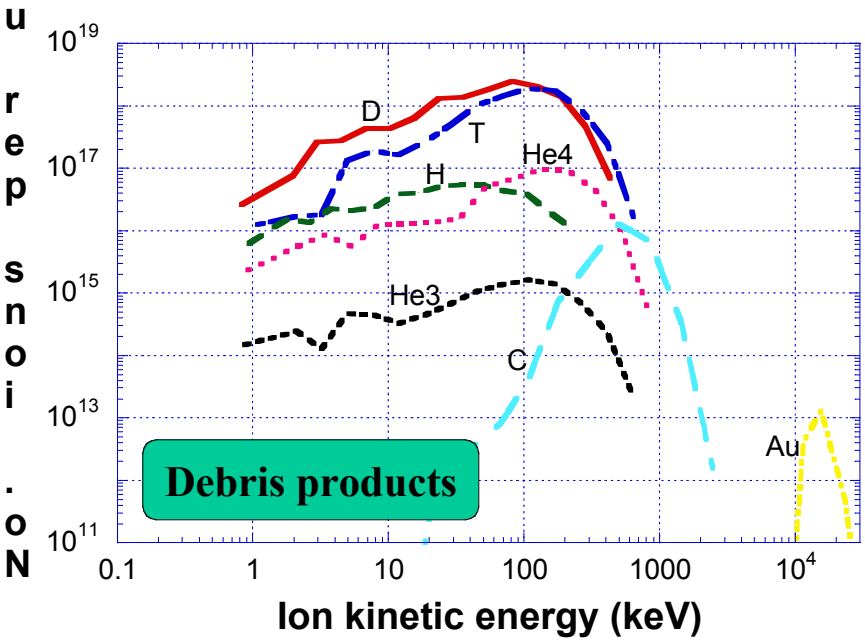


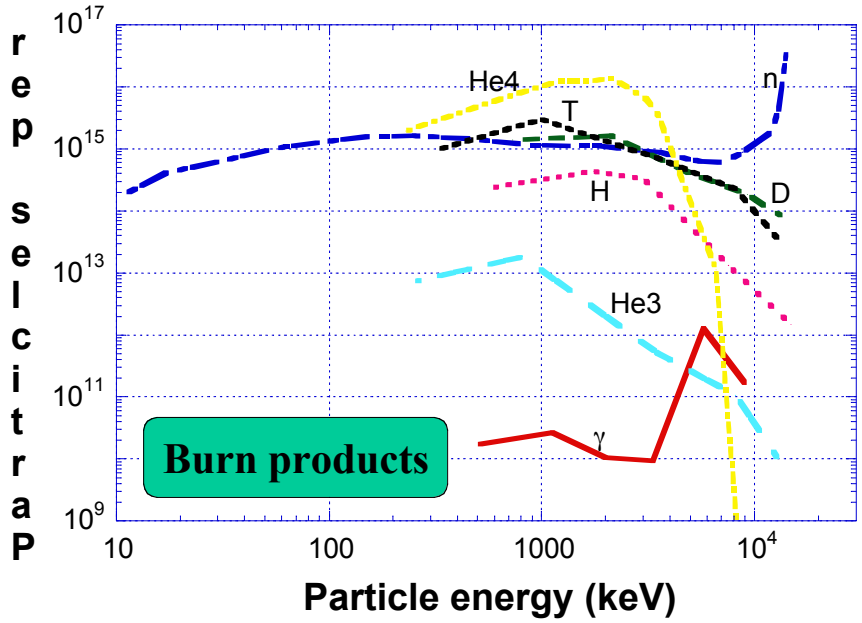
Laser Energy: 1.6 MJ
Laser Type: KrF
Gain: 108
Yield: 173 MJ

Spectra:
- Not Yet Calculated

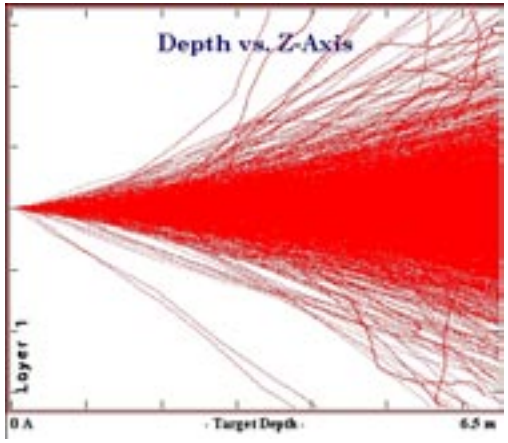
The energy partition and spectra for SOMBRERO were "legislated" by DOE.

NRL direct drive target output from John Perkins' Lasnex calculations

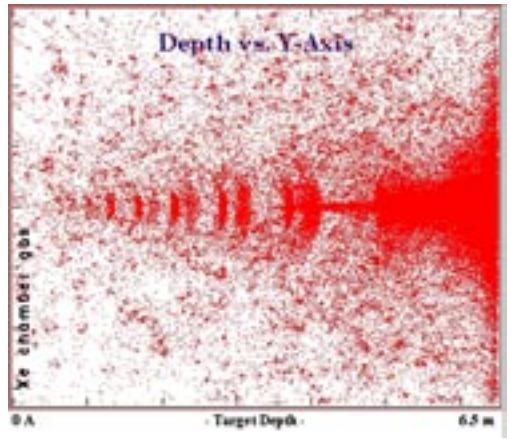




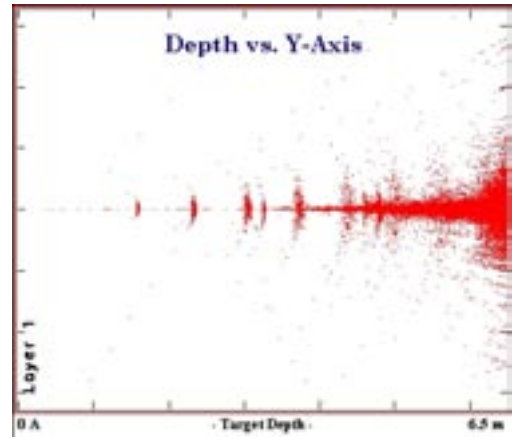
With less Xe gas, most charged particles make it to the wall and/or optics



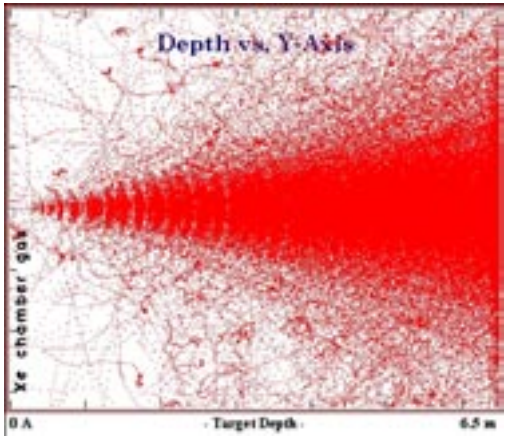
Debris Au ions



Debris D ions



Burn α ions



Debris C ions

- Plots show charged particle interactions with only 50 mTorr* (0.325 Torr-m) of Xe gas:
  - Ion output increased from ~20% in SOMBRERO study to 28% in NRL target
  - Harder ion spectra from the NRL target (Perkins' LASNEX results)

*Note: The target injection folks say that even 50 mTorr is too much gas.

Optics may be strongly affected by large charged particle fluences

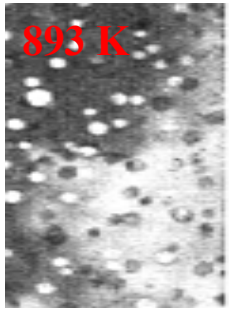
Fused Silica

- Sputtering: removal of 1.9 μm/y (**$5.5 \times \lambda_{DPSSL}$**) 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

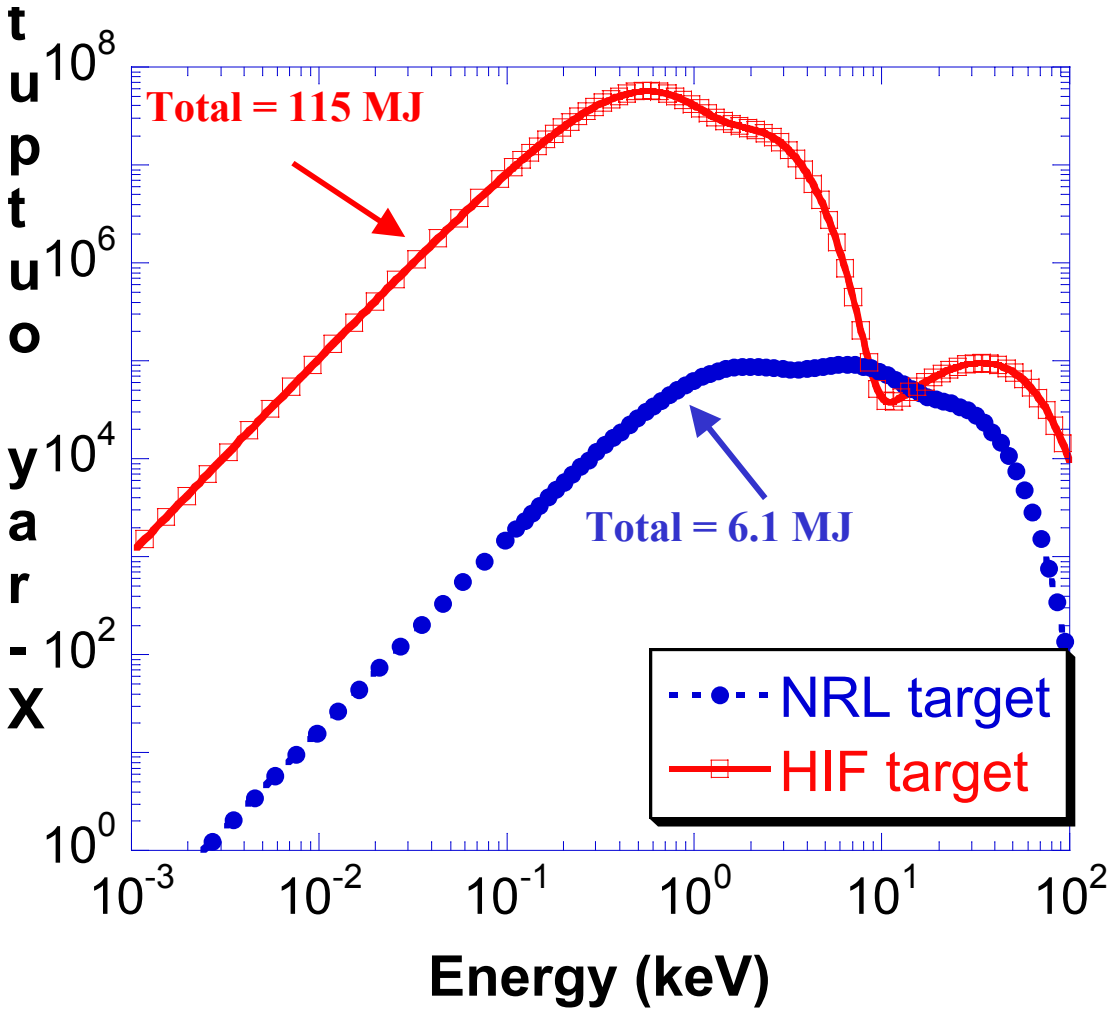
- Sputtering: removal of ~15 μm/y (**$59 \times \lambda_{KrF}$**) for Al GIMM (85º) at 30 m
- H_2^+ and He^+ irradiation produces dislocation loops and gas bubbles:
  - He bubbles keep spherical shape even after annealing at 893 K (see figure)
  - Bubbles near surface may affect reflectivity and/or beam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

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.

LASNEX x-ray spectra for NRL (direct-drive/401 MJ yield) and heavy-ion (indirect-drive/458 MJ) targets



Target output calculations (1-D LASNEX) courtesy of John Perkins, LLNL

Threats to the final optic —vacuum conditions assumed

	IRE	ETF	Power Plant
Driver energy	0.1 MJ	1-2 MJ	2-4 MJ
Yield	0	50-200 MJ	150-450 MJ
Repetition rate	Burst mode @ ~5 Hz?	5-10 Hz for hours at a time	5-15 Hz
Optic stand-off	10 m?	20 m?	30 m
Neutrons	0	ϕ_{14} = 2-8×10^{11} n/cm^2-shot	Φ_{14} = 5×10^{12} n/cm^2-s; Φ_{fast} = 9×10^{12} n/cm^2-s; Φ_{tot} = 10^{13} n/cm^2-s; D_n = 3×10^9 Gy/y; SiO_2 transmutation: He=69, H=28, C=54, Mg=15, Al=4 appm/y
Gamma-rays	0	0.7-3 Gy/shot	~10^9 Gy/y
X-rays*,**	6 mJ/cm^2	14-56 mJ/cm^2	19-76 mJ/cm^2
Ions**	2 mJ/cm^2	0.3-1.1 J/cm^2	0.4-1.1 J/cm^2

* For non-yield targets, I assume 70% conversion of laser energy to x-rays (value taken from NIF disk shot estimates)

** Emission is probably not isotropic; Lambertian?

Note: X-ray and ion fluences given on a per-shot-basis.

Threats to the penultimate optic —vacuum conditions assumed

	IRE	ETF	Power Plant
Driver energy	0.1 MJ	1-2 MJ	2-4 MJ
Yield	0	50-200 MJ	150-450 MJ
Repetition rate	Burst mode @ ~5 Hz?	5-10 Hz for hours at a time	5-15 Hz
Optic stand-off	15 m?	30 m?	50 m
Neutrons	0	$\phi_{fast} = 4\times10^{7}$ n/cm^2-shot	$\Phi_{fast} = 8\times10^{9}$-$1.5\times10^{11}$ n/cm^2-s D_n = 24-470 kGy/y (these scale with total Ω_{beam}; 0.25-5% used)
Gamma-rays	0	0.07-0.3 Gy/shot	~10^8 Gy/y
X-rays*,**	0	0	0
Ions**	0	0	0

* For non-yield targets, I assume 70% conversion of laser energy to x-rays (value taken from NIF disk shot estimates)
** Emission is probably not isotropic; Lambertian?
Note: X-ray and ion fluences given on a per-shot-basis.

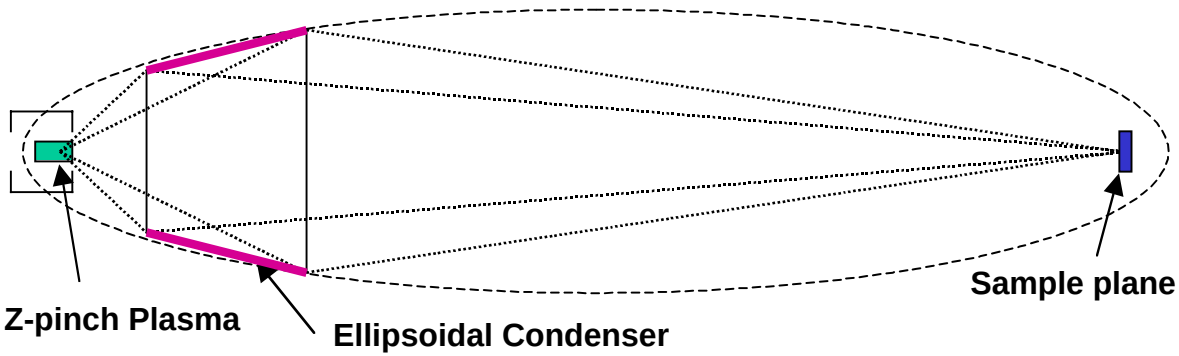
Current and future activities that address final optic questions

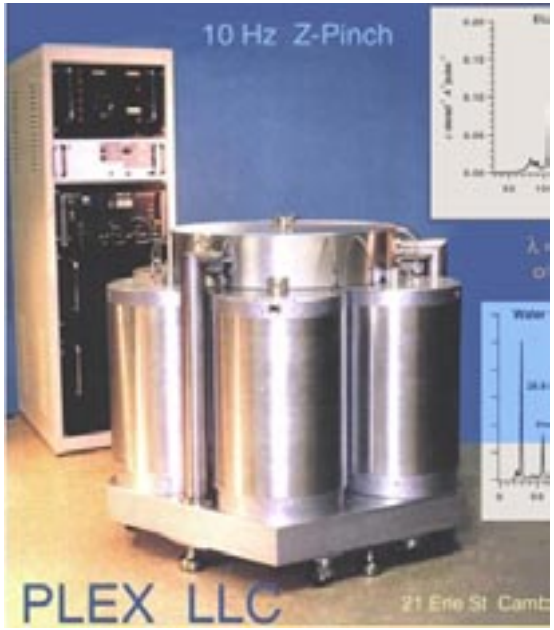
- USCD experiment for laser-induced damage threshold:
  - Saw LIDT fall from ~150 J/cm^2 (one shot) to >50 J/cm^2 for 10^4 shots with 99.999% pure Al optic
  - Not clear why it survives beyond 10 J/cm^2 (plastic deformation should happen at 8-10 J/cm^2)
  - Moving towards experiments with controlled surface contamination, coated mirrors, and MER-built mirrors

- Radiation damage was addressed for SiO_2 final optic:
  - Tested to IFE-relevant doses with hard neutron spectrum at LANSCE
  - Observed "radiation annealing" effect
  - Observed thermal annealing
  - Base case "design" is thin (500 μm) transmissive Fresnel lens that would be heated to ~500 C → leads to only 0.6% laser absorption
  - A variety of mirrors have been sent to ORNL for irradiation in HFIR

Activities that address final optic questions, (Cont'd.)

- XAPPER exposures for rep-rated x-ray damage:
  - RF-initiated z-pinch/ellipsoidal condenser collects x-rays and brings them to focus at sample/operation at up to 10 Hz (~4 _ 10^6 pulses before minor maintenance)
  - Soft x-rays: 113 eV with Xe; 250-300 eV with Ar; ~430 eV with N
  - Fluences up to 18 J/cm^2 with Xe
  - ***Specific energy matters more than fluence!***
  - Can surpass IFE specific energies at optics by >10^5

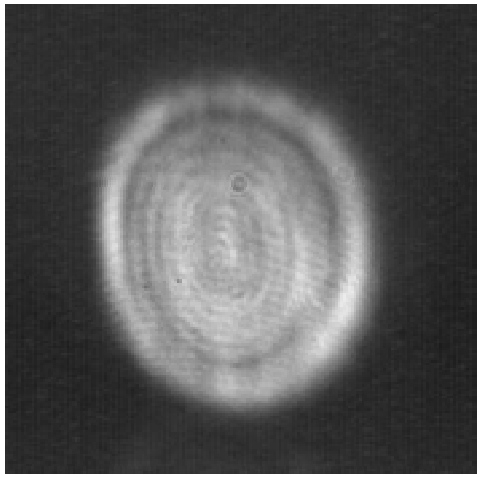


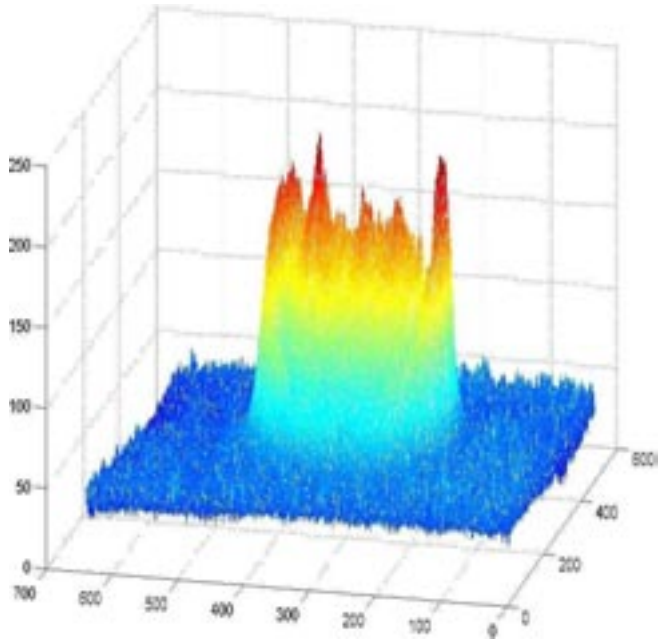


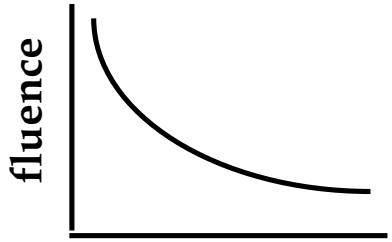
Activities that address final optic questions, (Cont'd.)

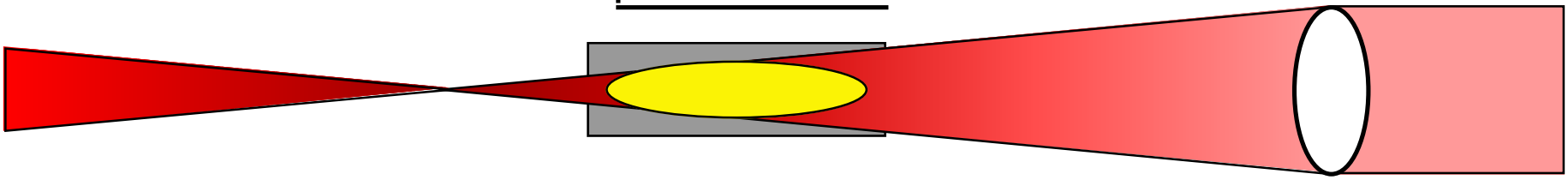
- Missing areas of research?
  - Charged particle effects on final optic?
  - Active mitigation:
    - Magnetic protection → hard to handle the gold
    - Gas puff → reasonable for gold but probably not others (10x higher range)
    - Others?

Testing up to 180 J/cm^2 has been completed by focusing the beam



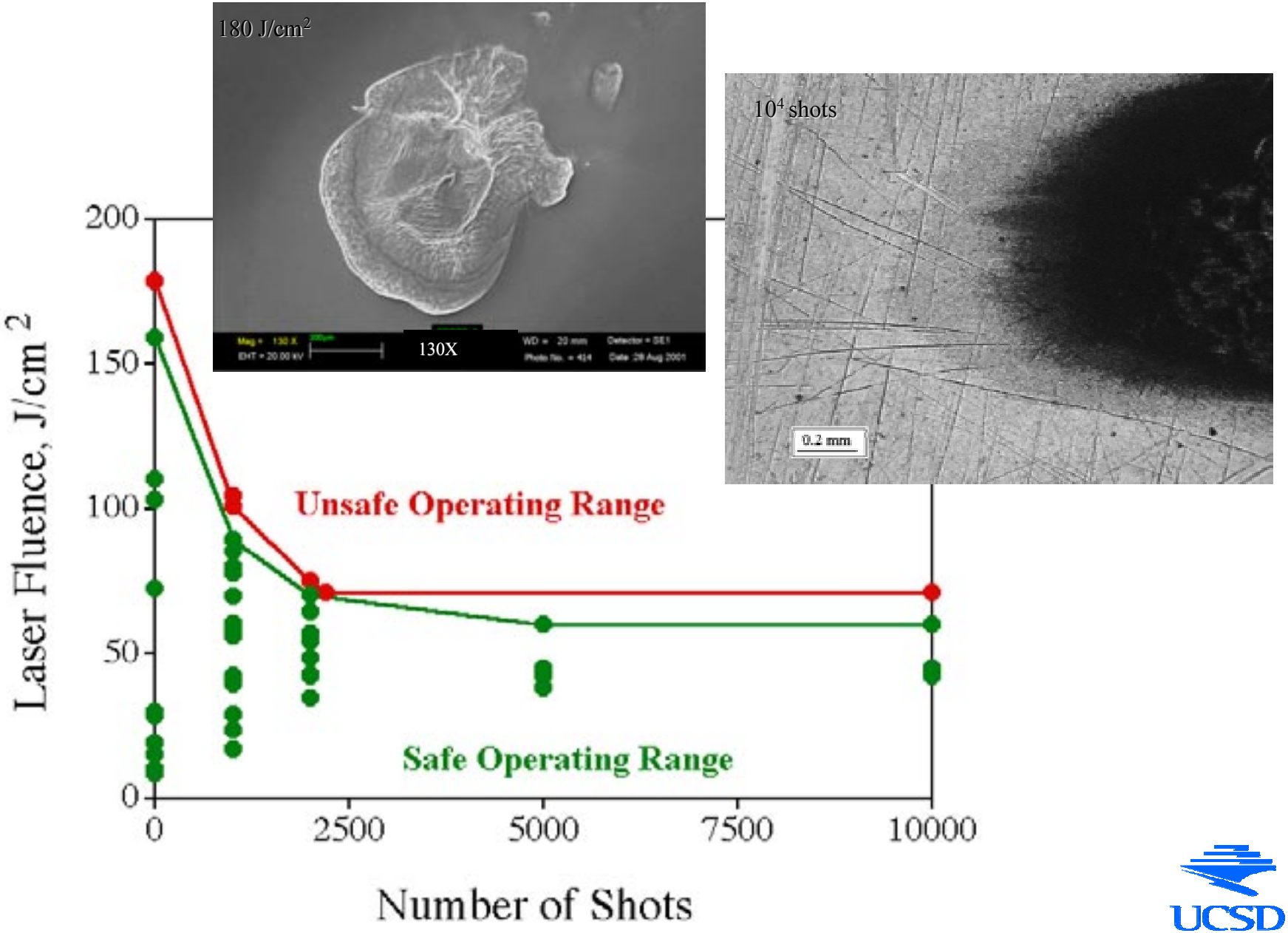






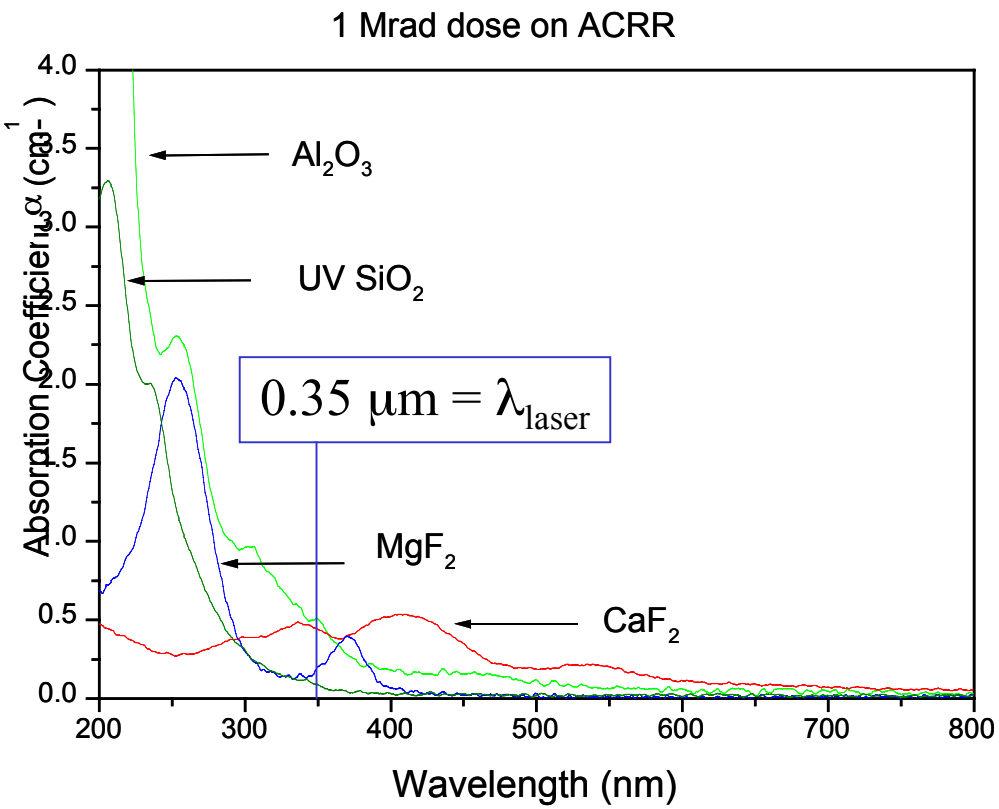
UCSD

Damage Regimes for 99.999% pure Al



UCSD

We have directly compared the absorption at 0.35 μm produced by 1 Mrad of neutrons for SiO_2, MgF_2, CaF_2 and Al_2O_3 (at ACRR, Sandia)

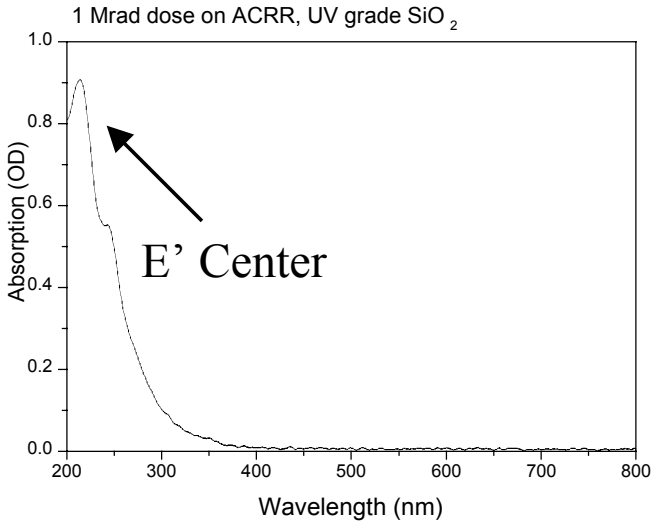


Optical Material	Absorption at 0.35 μm, $\alpha(cm^{-1})$
SiO_2	0.03
Al_2O_3	0.45
MgF_2	0.15
CaF_2	0.45

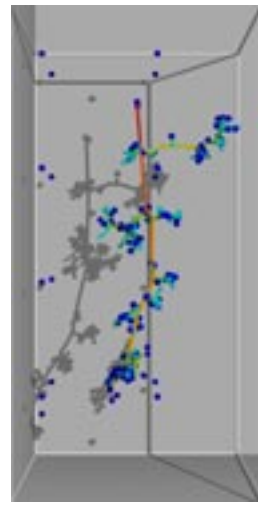
- SiO_2 yields *least absorption* at 0.35 μm for given neutron dose
- Number of defect created per MeV neutron:
  - $M_n = 35$ for SiO_2
  - $M_n = 13$ for Al_2O_3

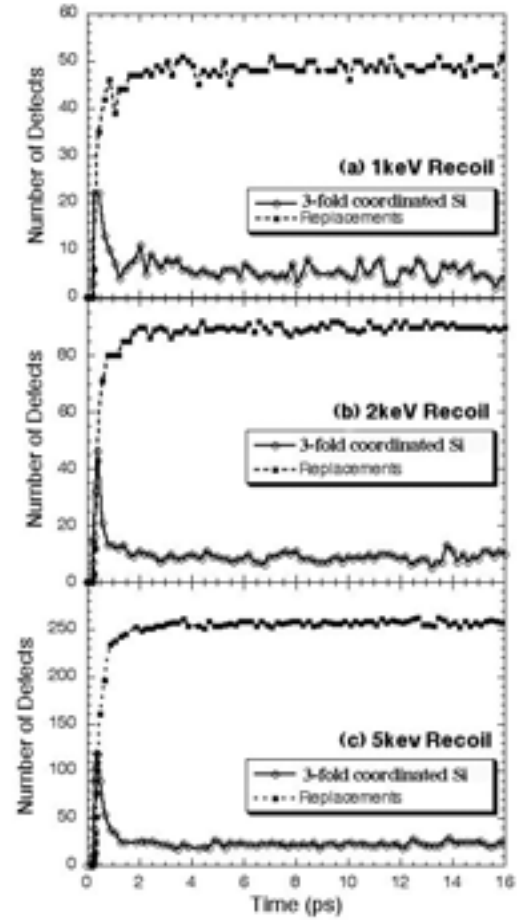
We have compared MDS theory with experiment for neutron-induced defects

Absorption spectrum (1 Mrad)



Collisional cascade

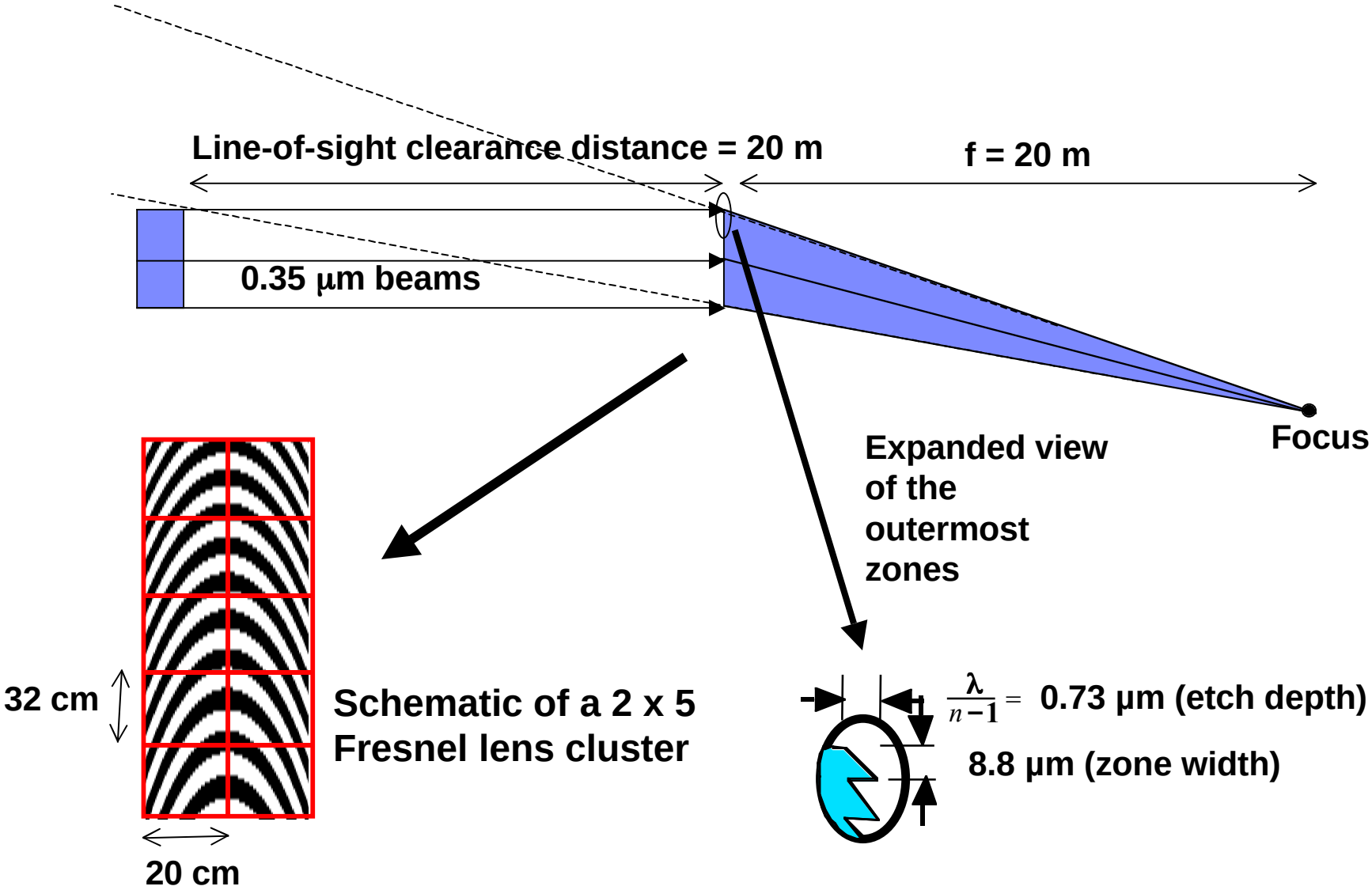




- Experimentally, 35 defects are created per 1 MeV neutron collision
- Based on *Molecular Dynamics Simulations* (MDS), ~ 400 are predicted
- Difference between measured vs calc'd values may be due to "slow" (>>psec) recombination

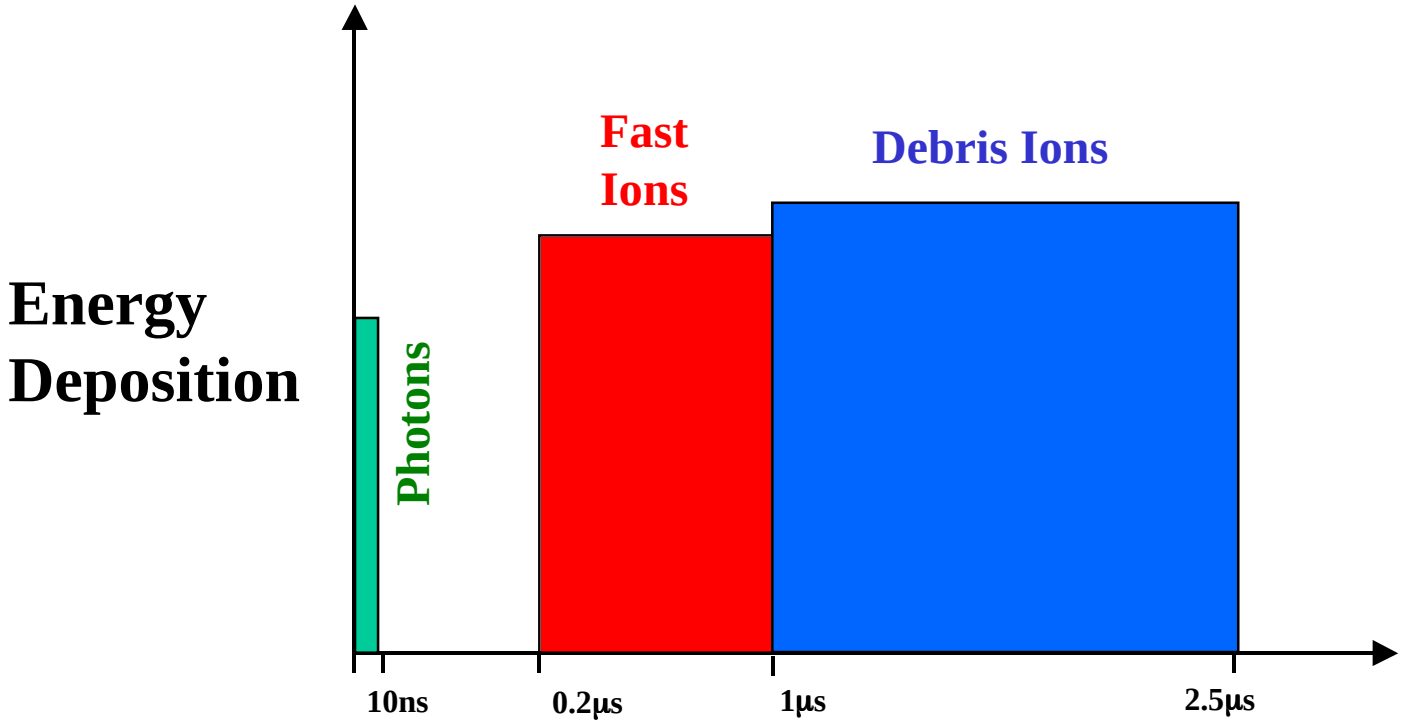
Defect formation and recovery (by MDS)

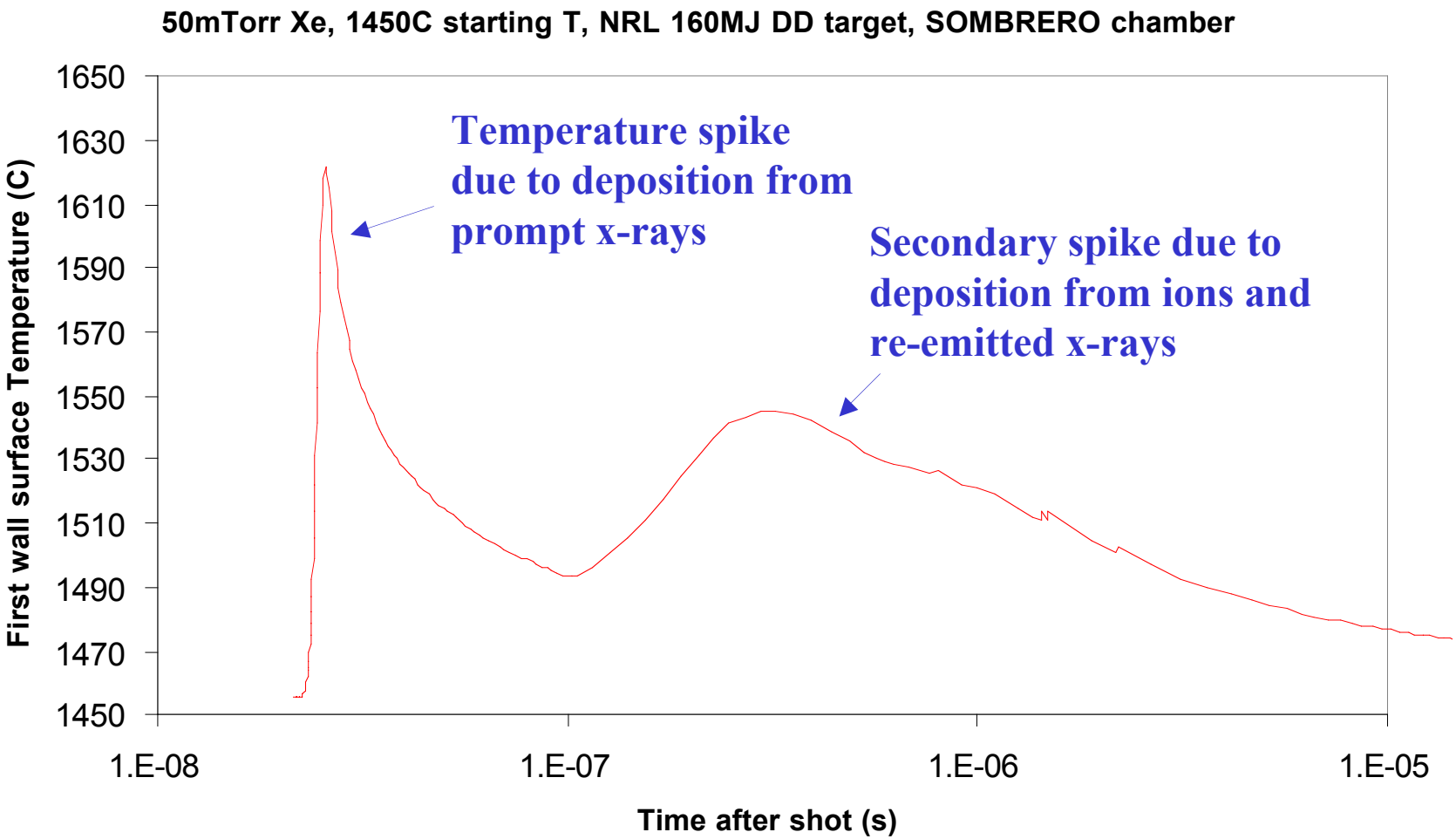
Final optic design is off-axis Fresnel lens for focusing and deflection



Backups

Temporal distribution for ions/photons based on LASNEX spectrum and 6.5 m chamber



Adapted from R. Raffray, March ARIES Meeting

Accounting for time-of-flight for a 6.5 m radius, the x-ray pulse dominates