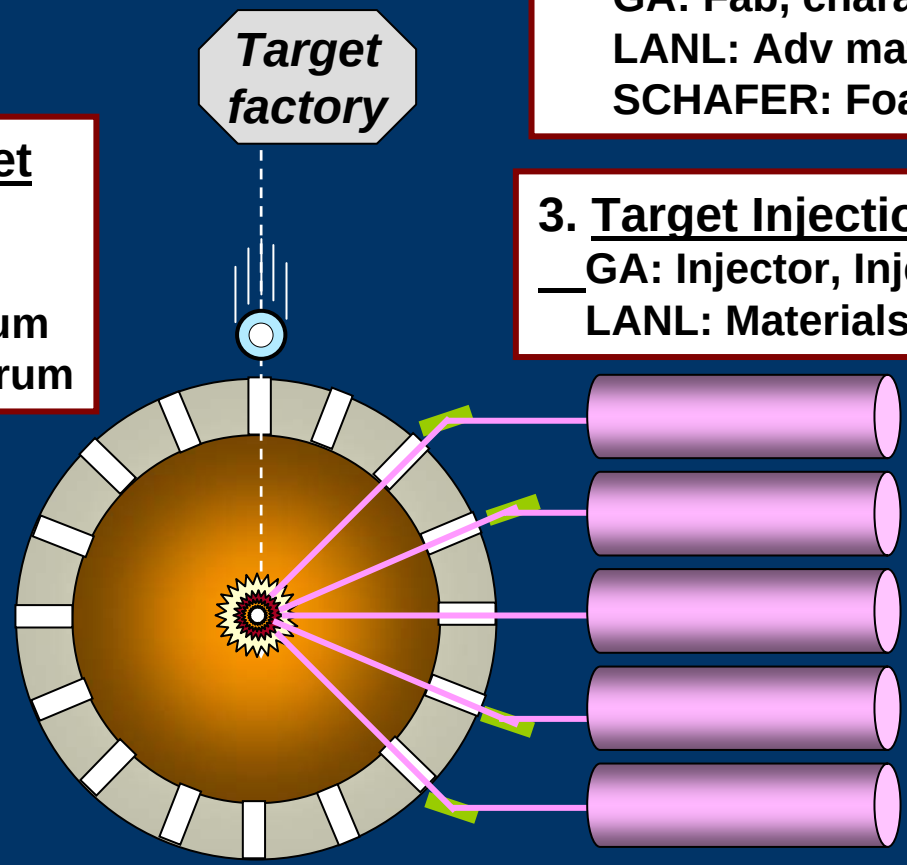
Program

1. Direct Drive Target Designs
NRL- target design
LLNL: Yield spectrum
WISCONSIN: spectrum

2. Target Fabrication
GA: Fab, charac, mass production
LANL: Adv mat, target fab, DT inv
SCHAFER: Foams, cryo layering

3. Target Injection
GA: Injector, Injection & Tracking
LANL: Materials prop, thermal resp.



4. Lasers
NRL: KrF
LLNL: DPSSL

5. Final Optics
LLNL: X-rays, ions, neutrons
UCSD: Laser, debris mitigation
LLNL/ORNL: Neutrons

6. Chambers and Chamber Materials
WISCONSIN: Dry wall, integrate design, Ion effects
UCSD: Chamber clearing, materials
UCLA : Fatigue Thermomechanics, Chambers
ORNL : Materials Development/Irrad. Evaluation

The Ten Year Plan

Research ⇒⇒⇒ Development

$ 25 M | $25 M | $30 M | $30 M | $30 M | $10 M

Point Design

| $1 M | $2 M | $1 M |

Integrated Research Expt

Design | *Construction* | *Test*

$30 M | $60 M | $60 M | $60 M | $60 M

Advanced Component Dev

$10 M | $10 M | $10 M | $10 M | $10 M

| FY 01 | FY 02 | FY 03 | FY 04 | FY 05 | FY 06 | FY 08 | FY 09 | FY 10 | FY 11 |

All dollar figures are preliminary estimates

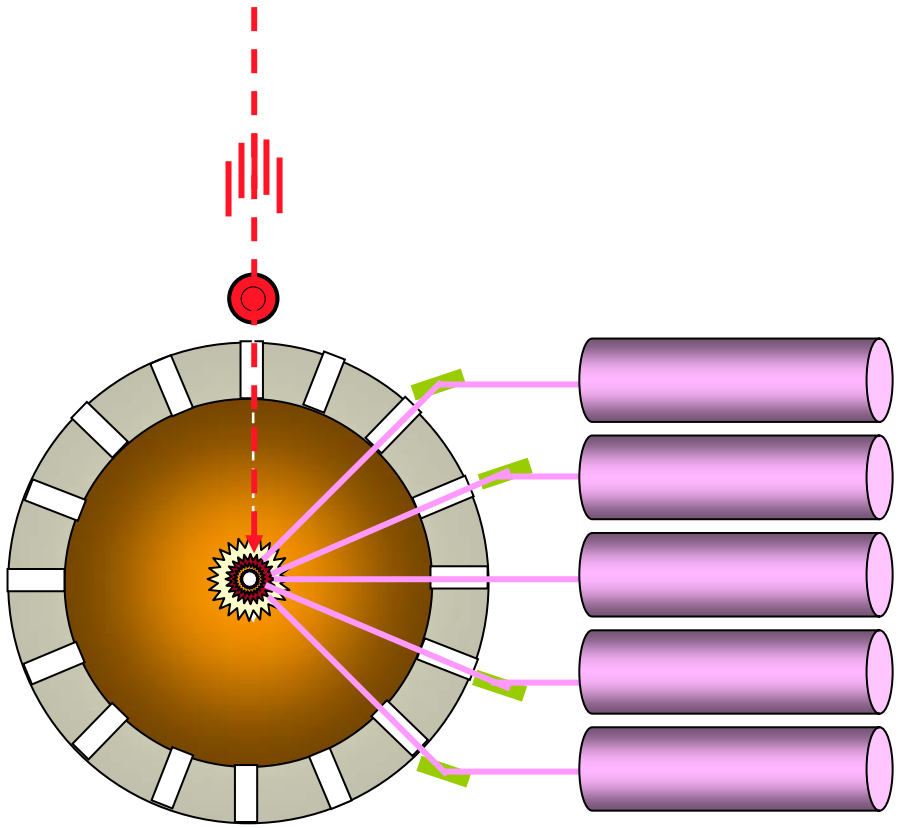
Philosophy for Approaching IFE Technology

Identify most critical issues (show stoppers) for the various designs and supporting systems. Carry out research to find a path forward or move away from the concept.

Modeling to direct experimental research

Materials budget ~ 3 M$

Materials Working Group
- Jake Blanchard
- Nasr Ghoniem
- Gene Lucas
- Lance Snead
- Steve Zinkle



Chamber Materials - overview and plans

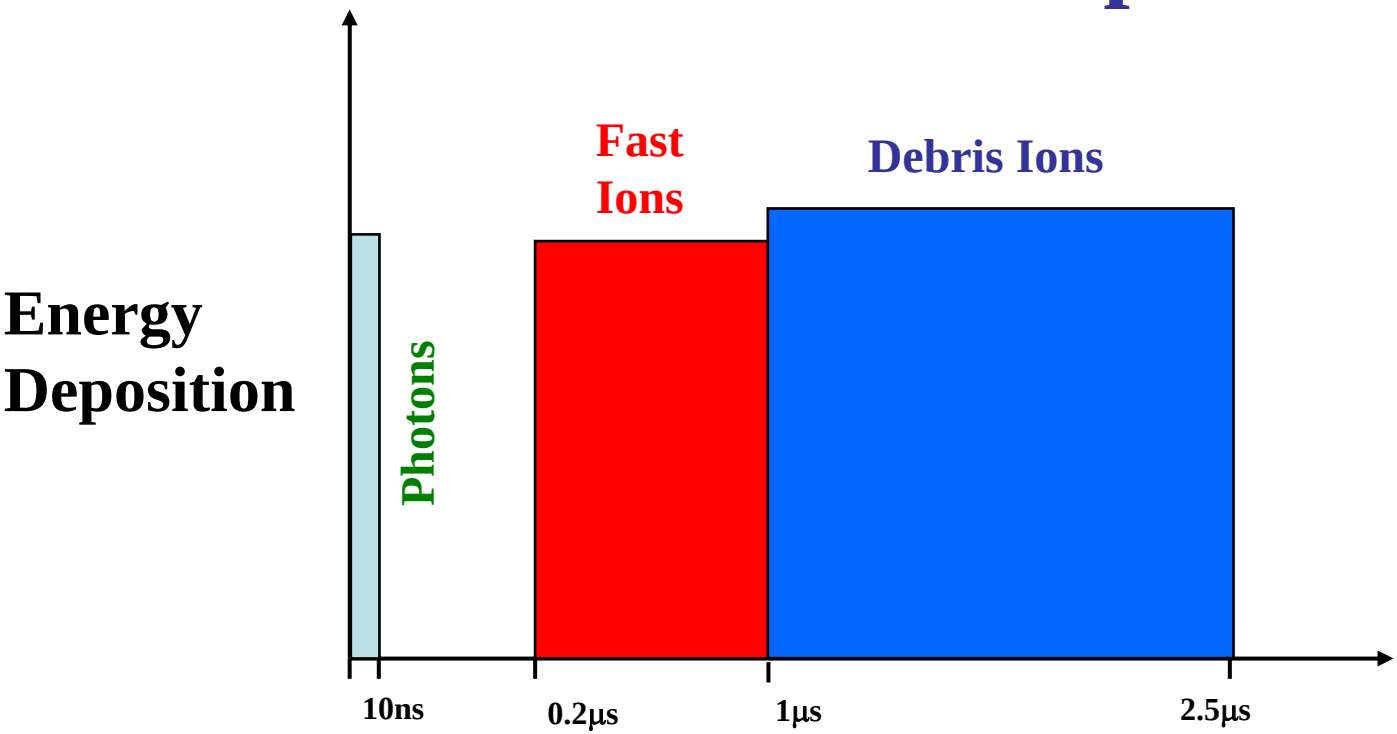
OFES Supported Materials Research

- Fatigue thermomechanics (UCLA)
- High temperature swelling of graphite fiber composite(ORNL)

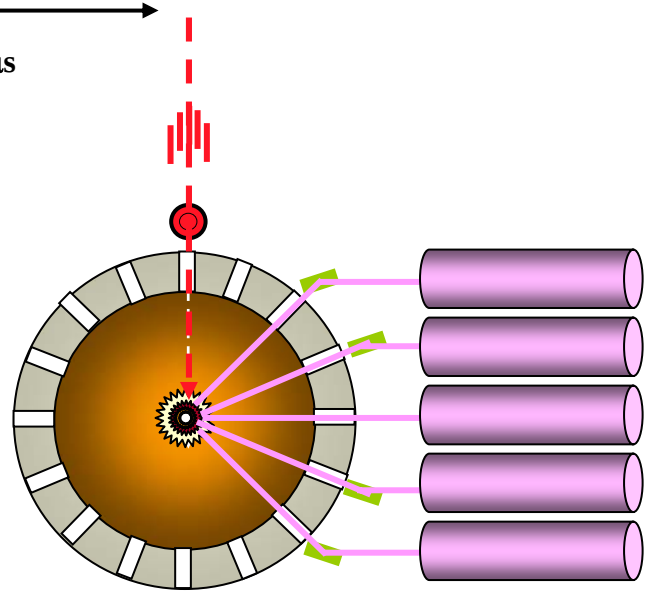
Critical issues from Chamber Materials Plan (HAPL)

- Transmissive Optics
  - Formation and annealing of absorption centers
- Reflective Optics
  - Neutron damage in dielectric mirrors
  - Laser induced damage threshold
  - Environmental effects (dust/debris)
  - Modeling surface modification under repetitive pulsing
- Structural Materials
  - Metallic structure - fatigue and pulsed irradiation effects
  - Composite System - CFC lifetime under high-temperature neutron irradiation
  - Refractory Armored Composites - basic fabrication and performance
  - Modeling - Defect formation and migration in graphite
- Safety
  - Tritium retention in graphite

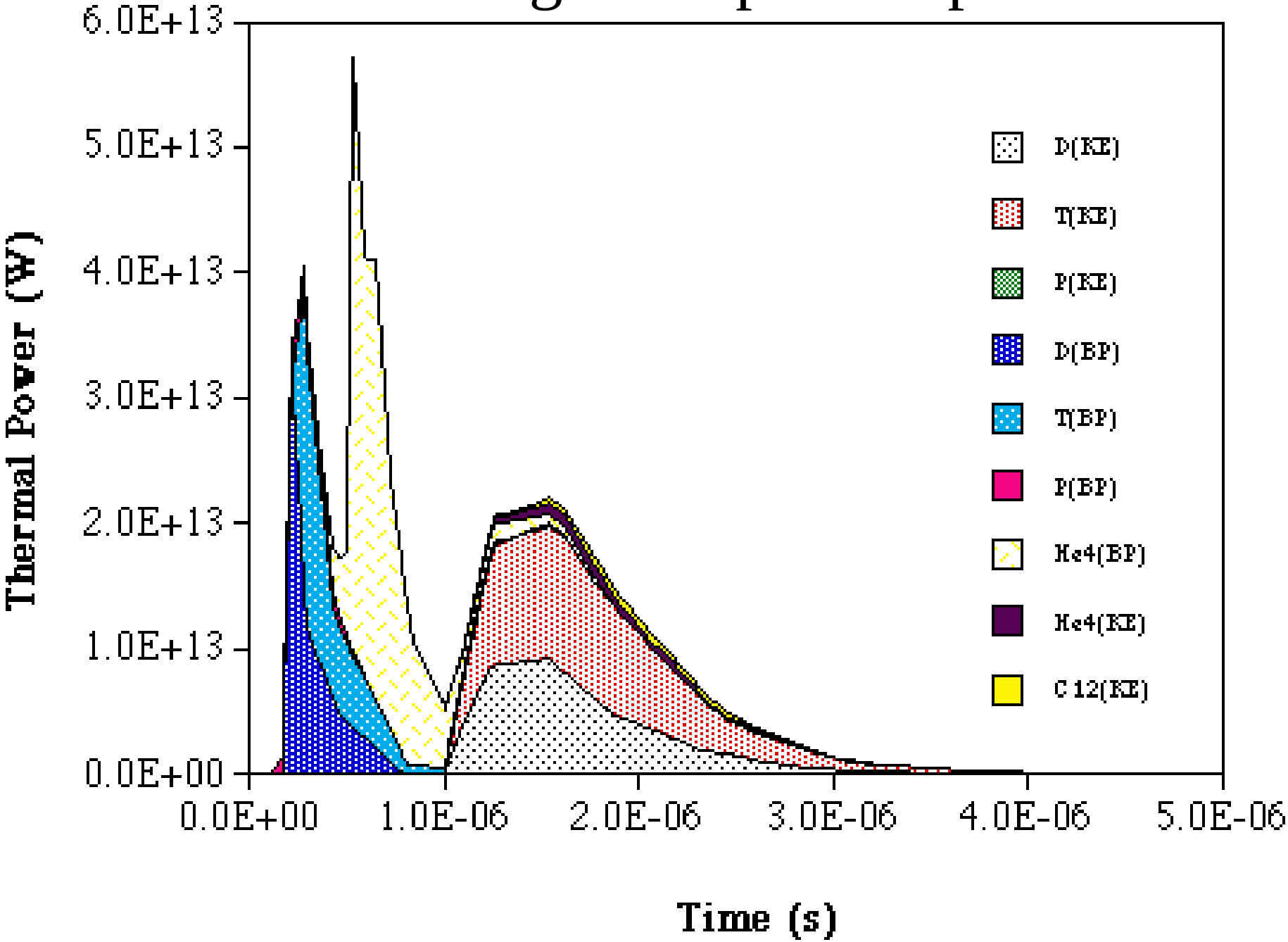
Critical Path Issue - Temporal Distribution



10 MW/m2 (MFE) = 10^4 MW/m2 (IFE)
10 dpa/yr (MFE) = 10^6 dpa/sec (IFE)



Time-of-flight ion power spread



Irradiation Damage in IFE

	IFE[1] (Li protected) (14 MeV neutrons)	IFE[3] (non-Li protected) (14 MeV neutrons)	Heavy Ion Accelerator (4 MeV nickel)	HFIR Fast Neutrons	HVEM (1 MeV electrons)	RHIC Injection Ring (BNL $P^+ \rightarrow Au$)
Peak Displacement Rate, dpa-s^{-1}	**0.1**	**1-10 (neutron only)**	**0.1-0.4$^{\dagger *}$**	**10^{-7}-10^{-6}**	**10^{-3}**	**10^{-7}-10^{-1}**
Average Displacement Rate, dpa-s^{-1}	10^{-7}-10^{-6}	10^{-6}- 2 x 10^{-5}	10^{-7}-10^{-3}	10^{-7}-10^{-6}	10^{-3}	10^{-8}-10^{-2}
Peak Particle Flux, $cm^{-2}s^{-1}$	~ 5 x 10^{20}	~ 5 x 10^{20}	10^{12}-10^{13}	10^{15}	10^{15}	10^{14}-10^{15}
Displacement Pulse Width, ns	10	10	2	continuous	continuous	100
Pulse Repetition Rate, HZ	10	10-20	dc to 10^7	dc	dc	?
Helium Production in Structure, appm-yr^{-1}	6*-300**	50†-7000††	available with dual beam injection	1-30	none	?

*HYLIFE design.
**LASL wetted wall design.
†Dry metal wall.
††Graphite wall.
$^{\dagger *}$0.1 dpa/s corresponds to 1 μA beam focused to a 2 mm diameter beam of 25 μA/cm^2 and 0.4 dpa/s to a 1 mm diameter beam with density of 100 μA/cm^2.

Areas currently under study

Optics and Beam Handling

- Beam loss in transmissive optics (LLNL)
- Laser Induced Damage Threshold (UCSD, LLNL, UCLA)
- Damage due to surface “dust” (UCSD,UCLA)
- Reflective materials development (UCSD)

X-ray pulse effects (SNL, LLNL, UCLA, UW)

Pulsed ion effects (ORNL, SNL, UCSB)

Development of layered “first wall” structure (ORNL)

High-temperature swelling of CFC’s (ORNL)

Fatigue Thermomechanics (UCLA, UW)

Materials Systems:

- “Sombrero Design” Carbon Fiber Composites, SiC/SiC
- Refractory Armored Designs, W on SiC or W on RAF’s
- Refractory Walls

Ongoing Work - Temporal Distribution

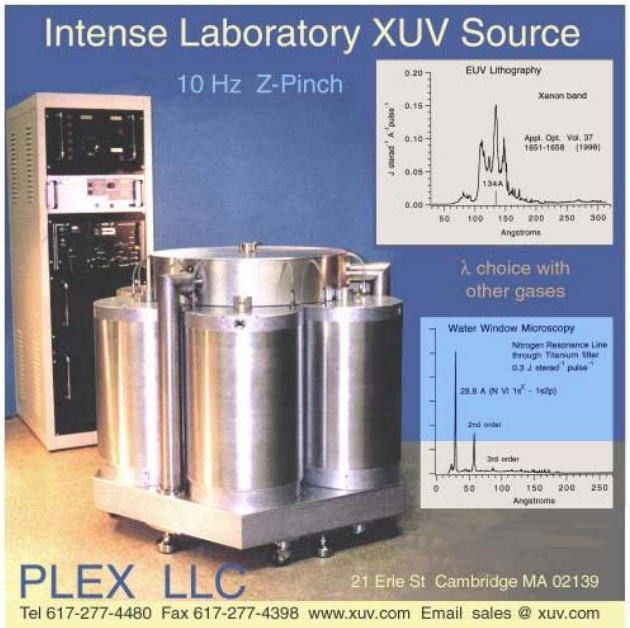
- PLEX facility, a high rep rate Z-pinch machine is being installed at LLNL for study of sub-threshold events in optics and structural materials.

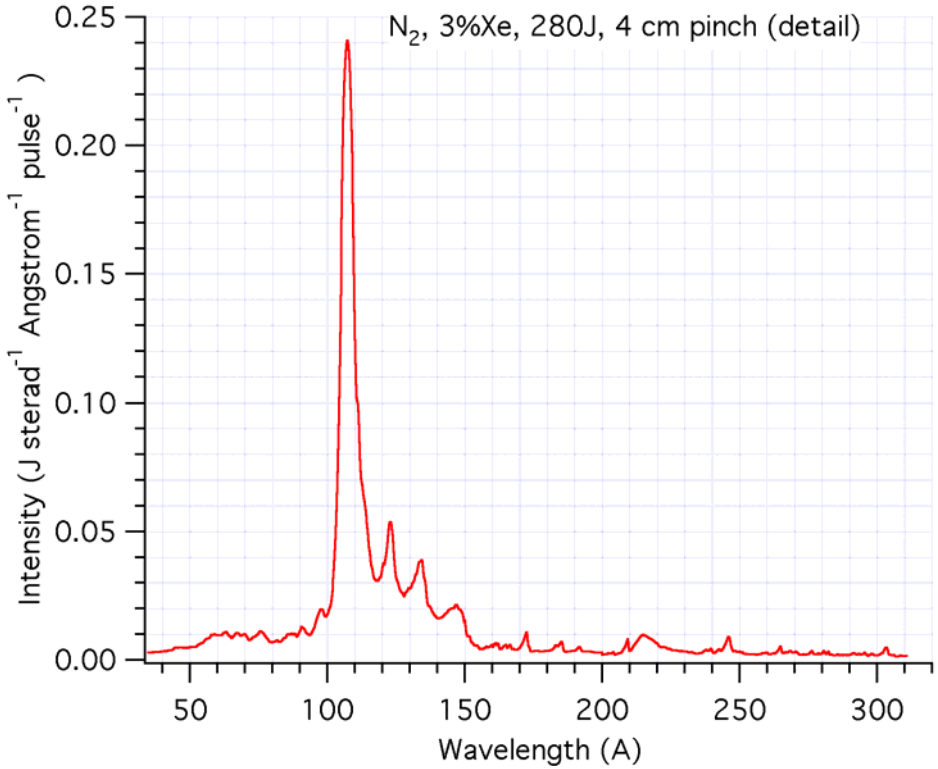
- Modeling is being pursued at UCLA and LLNL in support of upcoming PLEX experimental work.

- Sandia Z-pinch is being used for single blast surface effects

at near prototypic IFE conditions

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





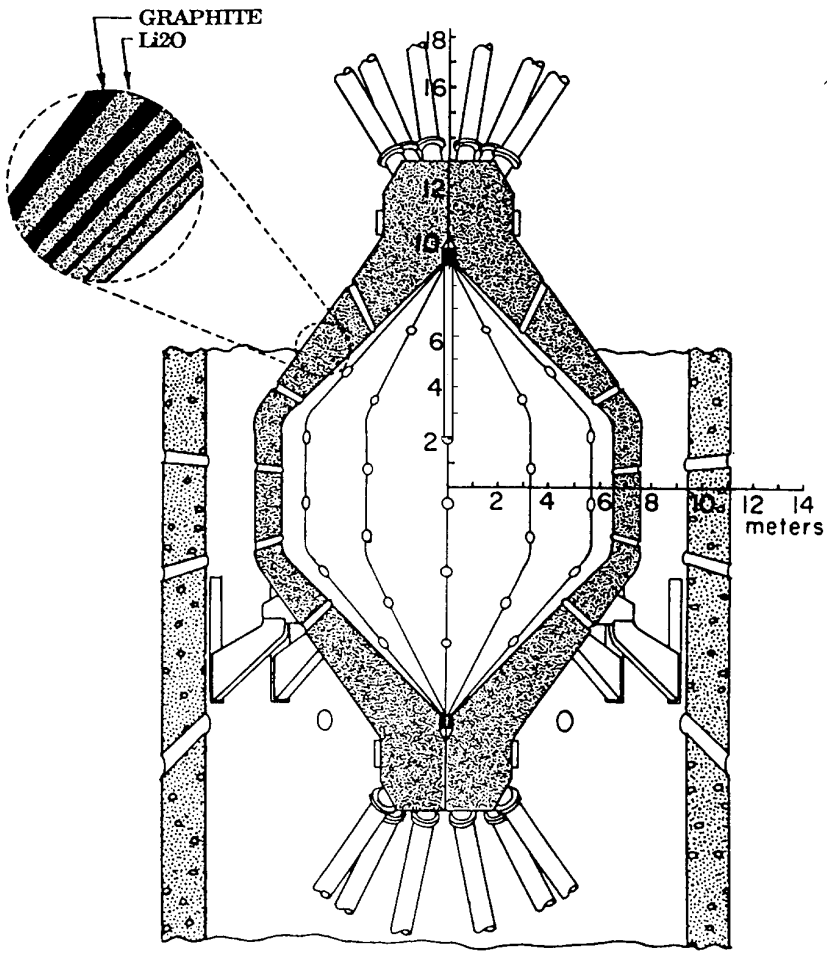
•10^6 pulse test at 240J stored energy @ 5Hz, with no change in 92.5eV transmission of test optic 50cm from plasma

• 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

- 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 ~ 10^8 shots/year
- To this point detailed modeled to suggest sub-threshold effects has not been done.

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

CFC as and IFE Structure



CROSS-SECTION OF SOMBRERO CHAMBER

- **SOMBRERO is the starting-point design, though the conceptual design effort currently underway may substantially alter the design point.**
- **Temperature range is currently assumed to be 600-1500°C.**
- **Chamber environment, hence surface particle flux and energy is unknown.**

Critical Path Issues - Graphite Composite

<u>Show Stoppers</u>

Tritium retention(for graphite)

Co-deposition

Swelling and Lifetime

<u>Crucial</u>

Fatigue Properties

Thermal conductivity (OFES)

RES (for graphite)

<u>Procrastinate</u>

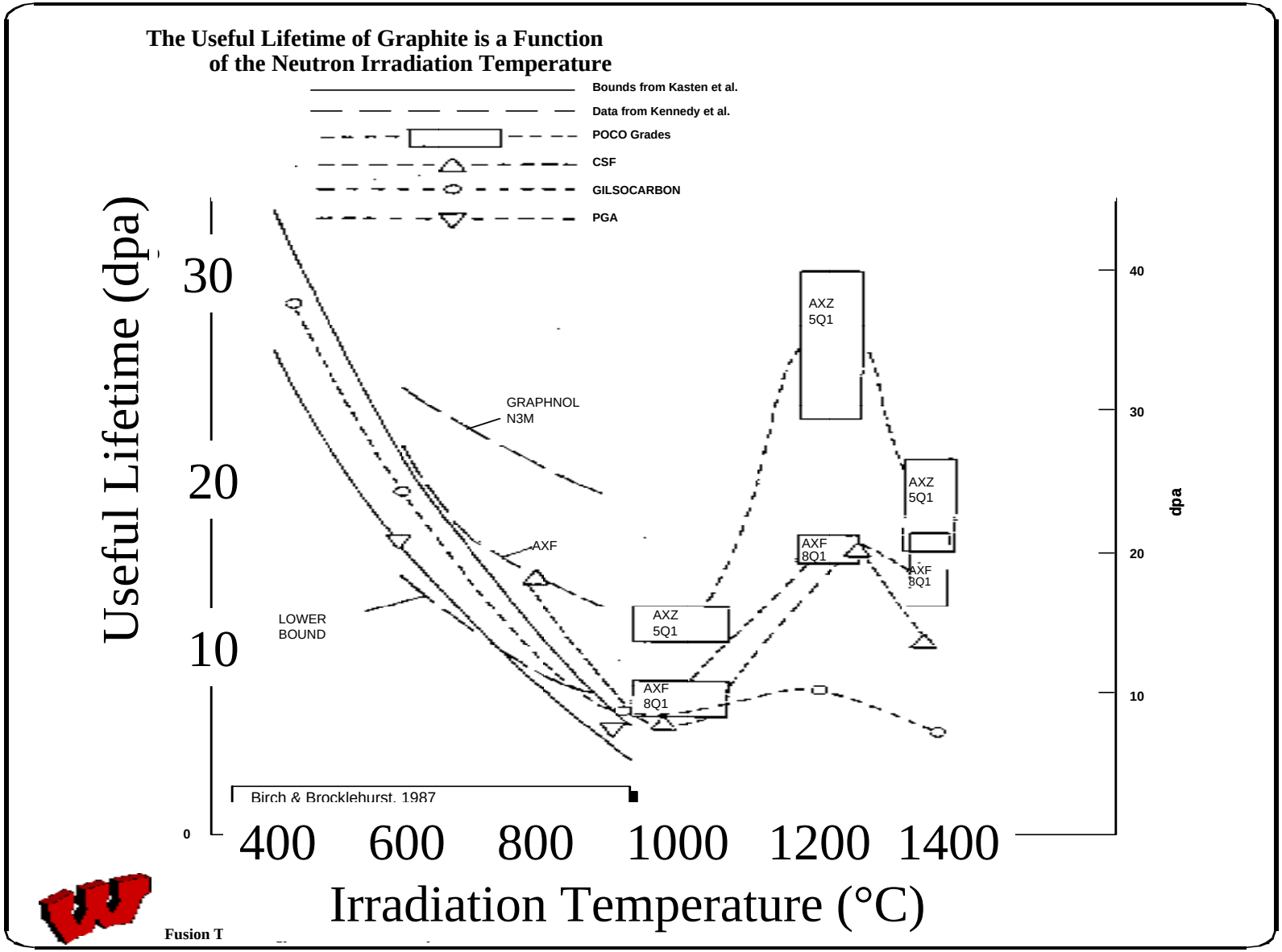
Design codes

Manufacturing large structures

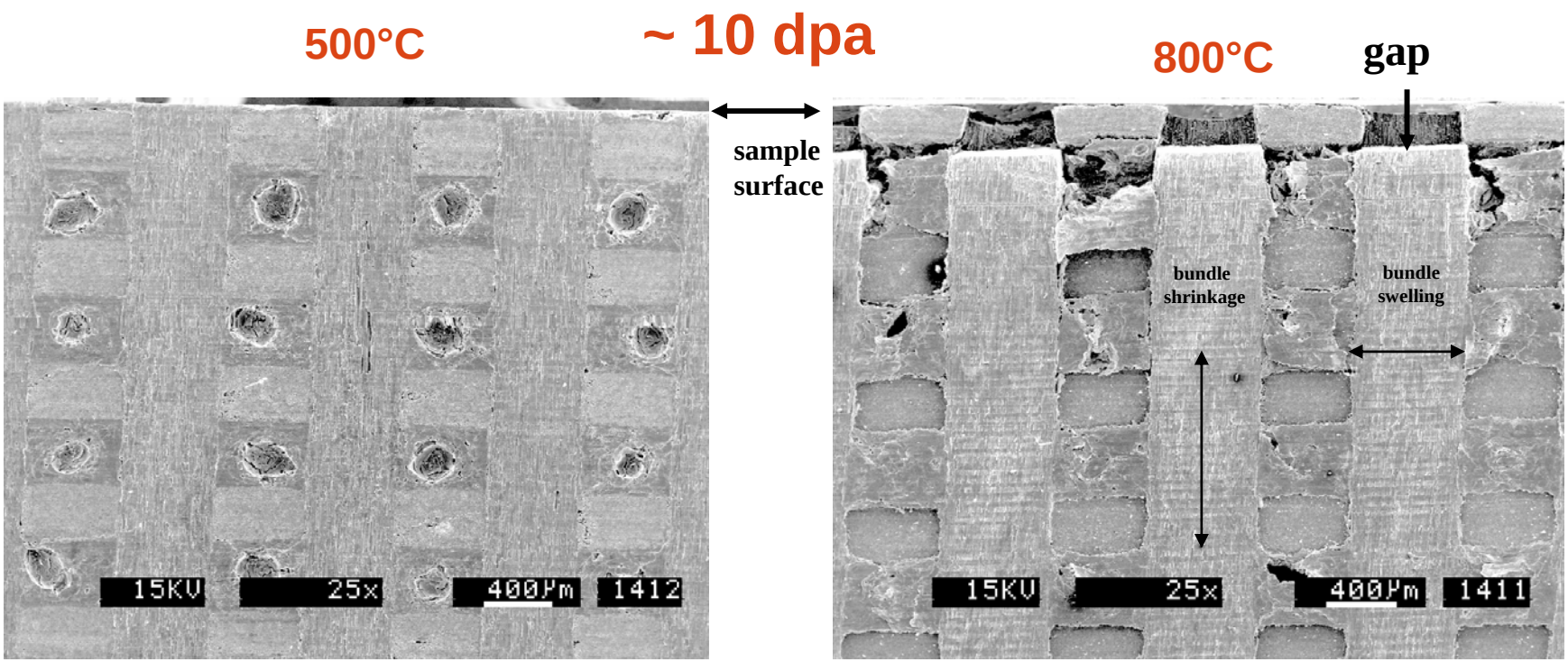
Designing 100% elevated temperature structure

Composite architectural design

Sombrero : Useful lifetime assumed based on existing graphite literature



- Sombrero assumed large extrapolations to future materials (thermal conductivity, mechanical properties) which have come about. Radiation performance is not known for the appropriate temperature range, though the lifetime assumptions are very aggressive.



OFES Swelling of CFC's

METS (Mapping Elevated Temperature Swelling) Experiment

Purpose : There is currently no high temperature irradiation data on the high quality graphite composites being considered for laser IFE. This program will yield data on swelling and thermal conductivity following neutron irradiation to high temperature and neutron fluence.

Materials :	Kth(@RT) (W/m-K)	Kth(1000°C) (W/m-K)
A) Mitsubishi Kasei MKC 1PH (unidirectional CFC)	>700	~250
B) Fiber Material Inc. FMI-222 (balanced CFC)	>450	~220

Irradiation in HFIR Core Region		Temperature (°C)	Dose (dpa)
METS-1 Capsule	9 zones in range of	600-1500°C	2
METS-2 Capsule	"	600-1500°C	4
METS-3 Capsule	"	600-1500°C	10

Status:

- **All pre-irradiation measurements completed.**
- **Capsules fabricated and awaiting irradiation in HFIR**
- **Irradiation planned to begin this FY. Duration 1, 2 and ~7 months.**
- **Post-irradiation examination to include thermal conductivity and swelling.**

Critical Path Issues

Beam Handling and Optics

<u>Show Stoppers</u>

Transmissive

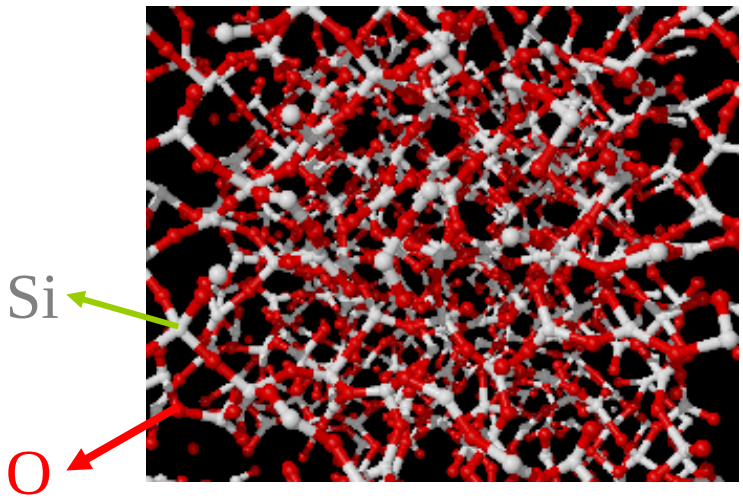
- **generation of optical absorption centers at DPSSL and KRF laser wavelength**

Reflective

- **Laser Induced Damage Threshold**
- **Effect of debris**
- **Fatigue thermomechanics**

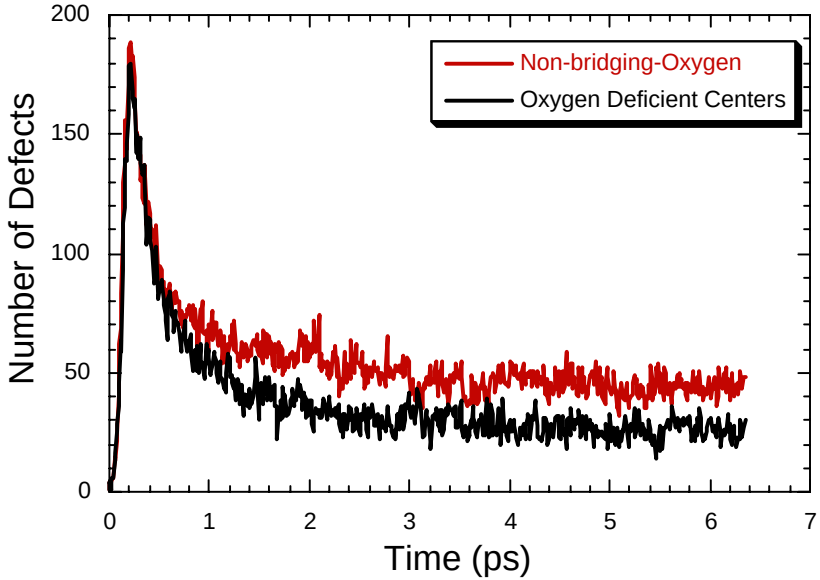
Molecular dynamics simulations of damage in SiO_2 glass

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



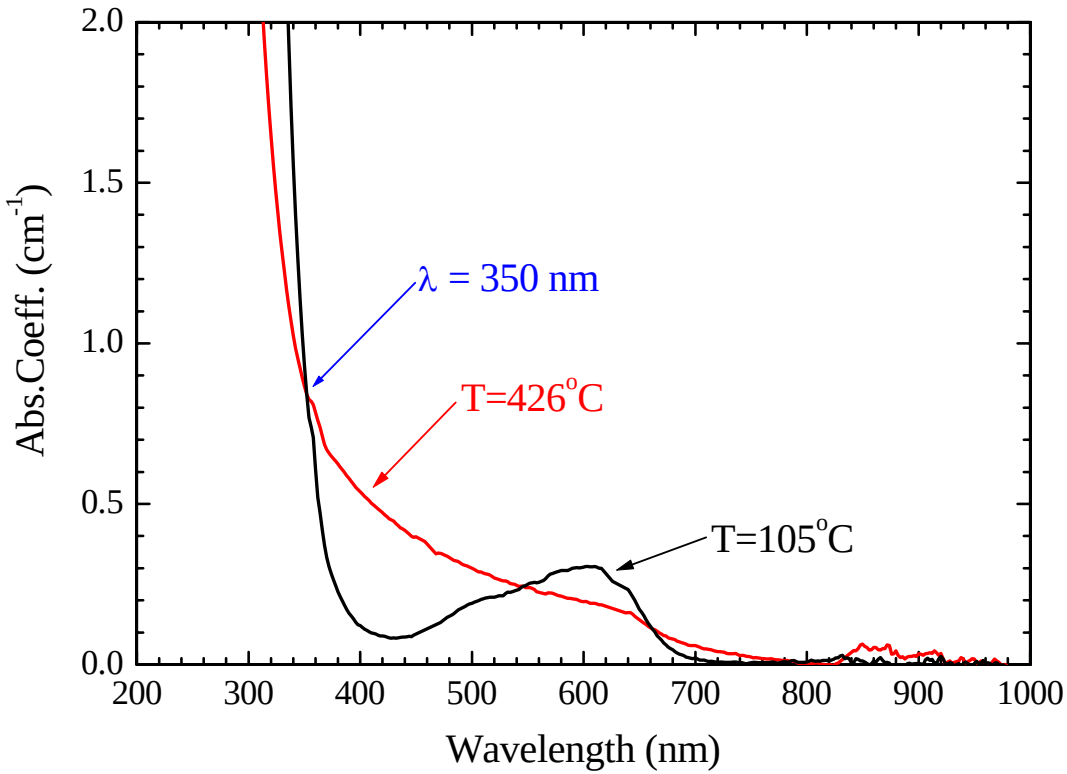
A database of damage in silica for recoils of energies of a few keV is being generated

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

A. Kubota, M.-J. Caturla

Residual defects that remain in SiO_2 following 10^{11} Rad irradiation depend on temperature

- 10^{11} Rads of neutrons corresponds to ~2 months irradiation in an IFE power plant



Study on glass optics suggest they will not work

Damage Threats- Reflective Optics

Two main concerns:

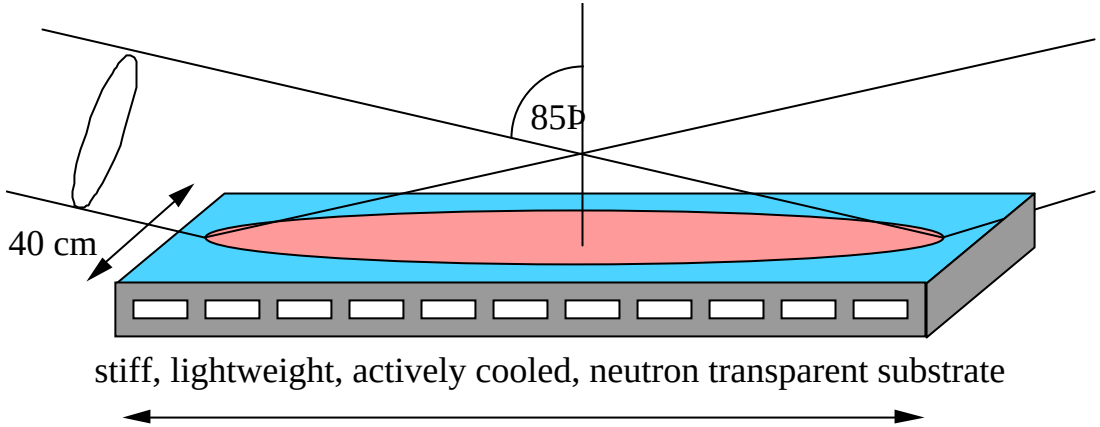
- Damage that increases absorption (<1%)
- Damage that modifies the wavefront –
  - spot size/position (200μm/20μm) and spatial uniformity (1%)

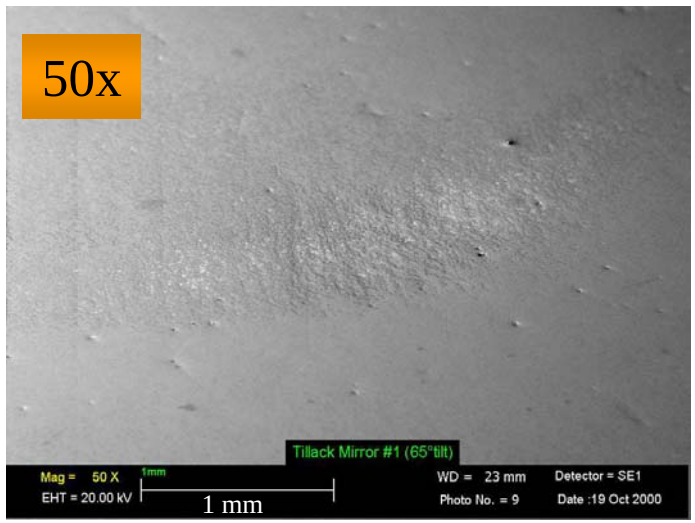
Final Optic Threat	Nominal Goal
Optical damage by laser	>5 J/cm^2 threshold (normal to beam)
Nonuniform ablation by x-rays Nonuniform sputtering by ions	Wavefront distortion of <λ/3 (~80 nm) (6x10^8 pulses in 2 FPY: 2.5x10^6 pulses/atom layer removed
Defects and swelling induced by γ-rays and neutrons	Absorption loss of <1% Wavefront distortion of < λ/3
Contamination from condensable materials (aerosol and dust)	Absorption loss of <1% >5 J/cm^2 threshold

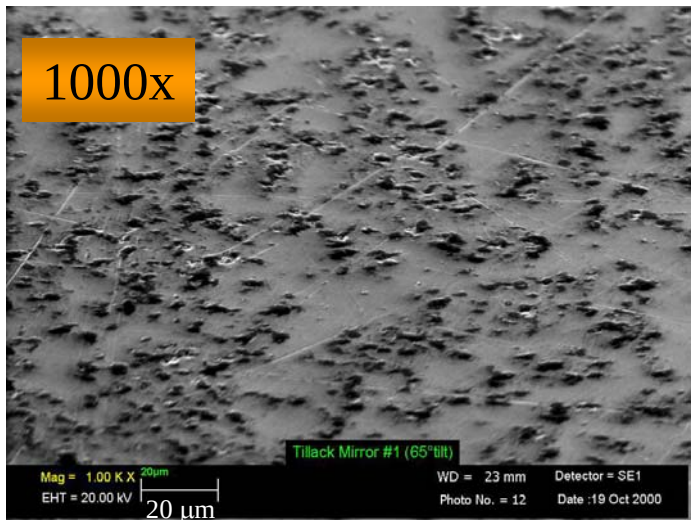
UCSD

Aluminum and Other Mirrors Being Studied

For 1.2 MJ driver w/ 60 beams @5 J/cm^2, each beam would be 0.4 m^2







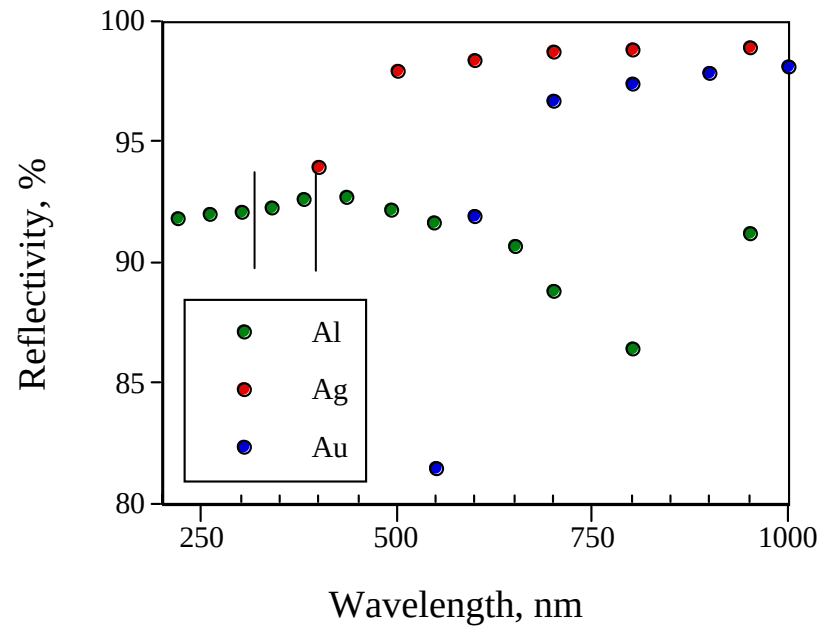
Aluminum is the 1st choice for the GIMM

Lifetime of multi-layer glass dielectric mirrors is unacceptably low due to rapid degradation by neutrons (HFIR rabbit irradiation with wider selection ofdielectric mirrors is underway)

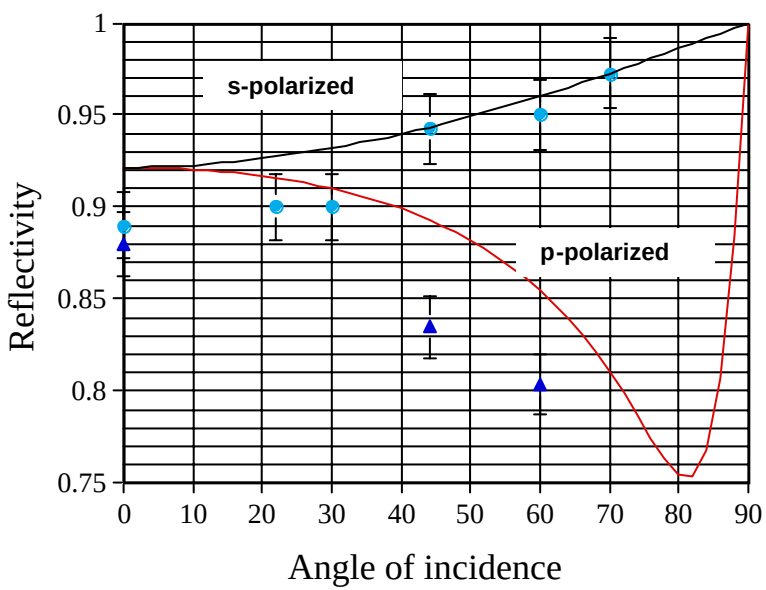
Al is a commonly used mirror material

- usually protected (Si_2O_3, MgF_2, CaF_2), but can be used "bare"

Normal incidence reflectivity of metals



Aluminum reflectivity at 532 nm



- Good reflectance into the UV
- Thin, protective, transparent oxide
- Normal incidence damage threshold ~0.2 J/cm^2 @532 nm, 10 ns

Critical Path Issues

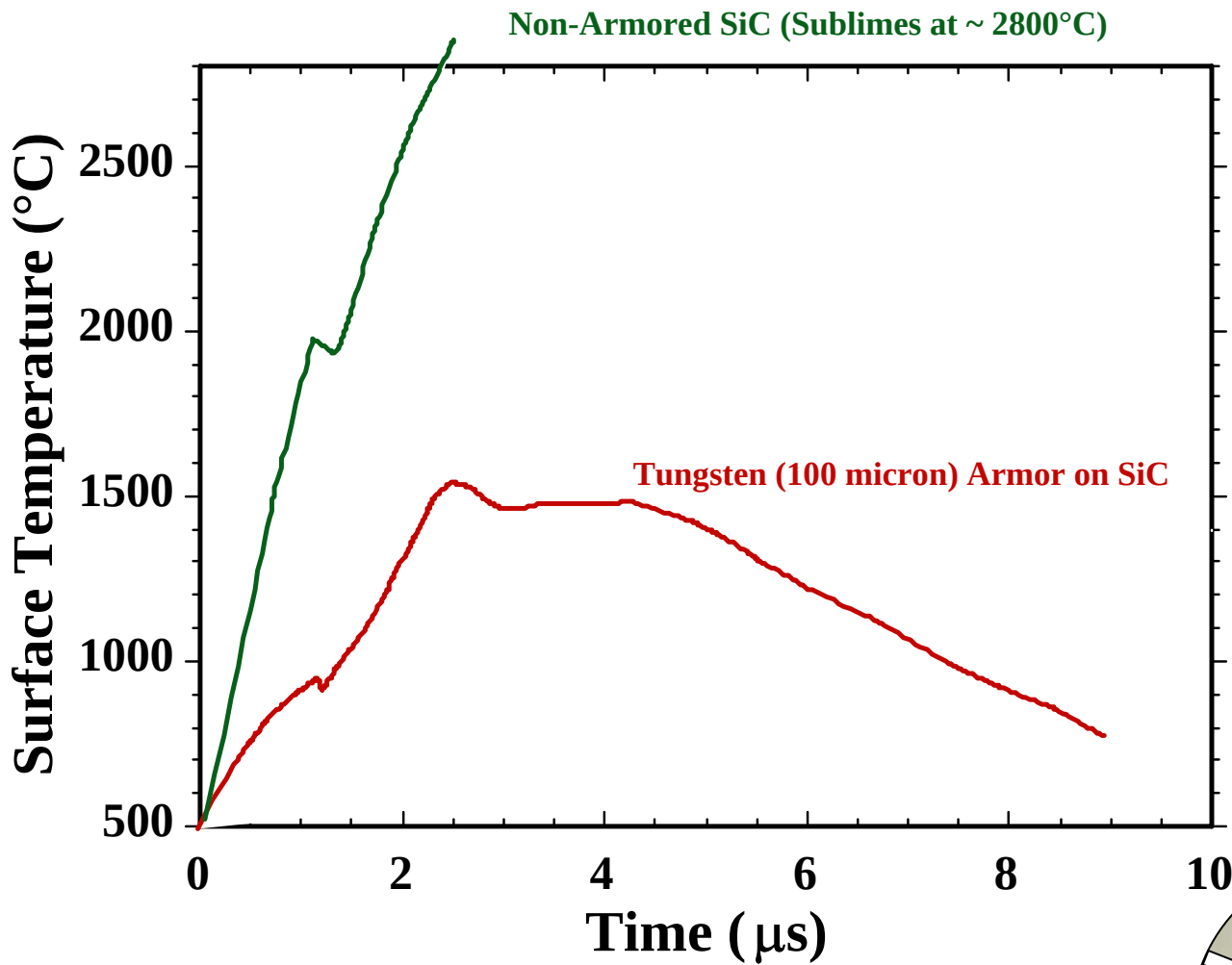
Refractory Armored Materials

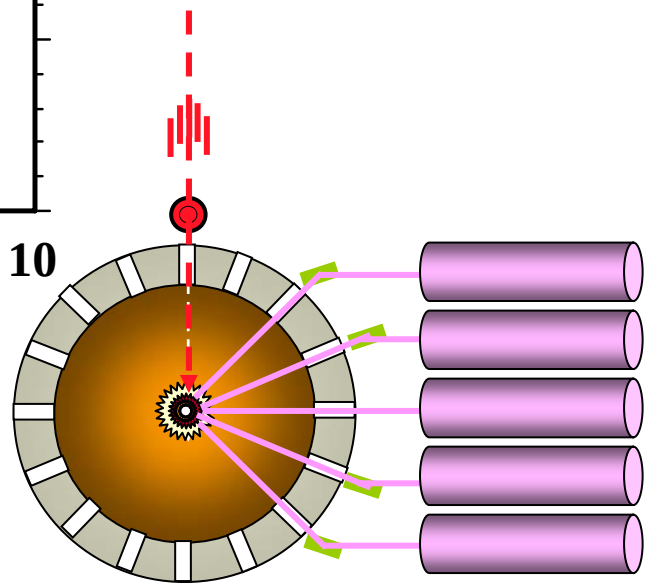
<u>Kiss of Death</u>
Material development
Fatigue Properties
Exfoliation due to ions
Issues relating to structural material

<u>Crucial</u>
Thermal contact resistance and thermal conductivity
Embrittlement (W grain growth, hydrogen effects, irradiation)
In-situ or ex-situ repair
Differential thermal and irradiation expansion

<u>Procrastinate</u>
Manufacturing large structures
Tungsten mobility/safety issues
???

Calculated Effect of W-Armor on SiC

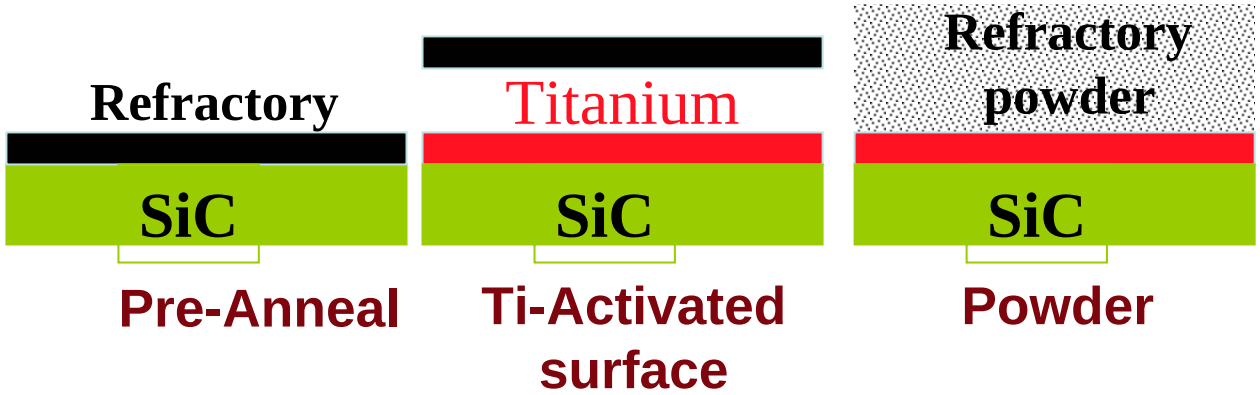


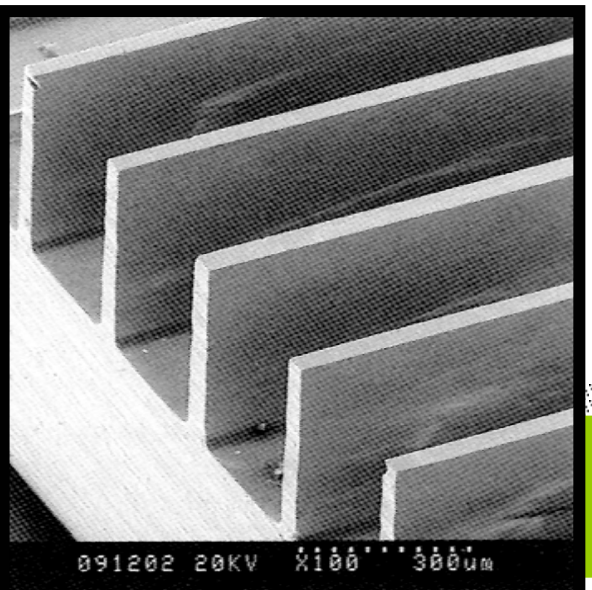


Refractory Transitions/Armors

- **Limited work on high-temperature refractory armor**
  - **refractory armored graphite fiber composites appear hopeless for IFE**
  - **W - SiC system unstable ~ above 1200°C**
  - **Mo - SiC system unstable ~ above 1400°C**

- **Development program underway**
  - **Refractory : Tungsten (W-Re), Moly**
  - **SiC : Hot Pressed alpha-SiC, CVD beta-SiC, SiC/SiC**

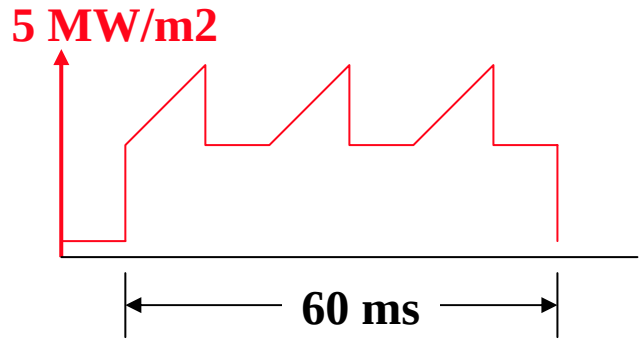


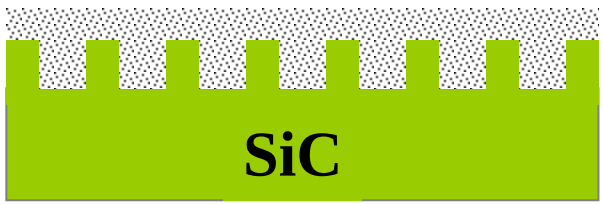


- **Castellated surface modeling underway (Blanchard U.W.)**

Substrate castellation:
200 μm deep x 200 μm wide

Infrared Rapid Melt Processing and Thermal Shock
--> Rapid melting of surface refractory, leaving substrate cool





QuickTime™ and a
decompressor
are needed to see this picture.

Specifications: **Argon plasma (up to 1MW)**

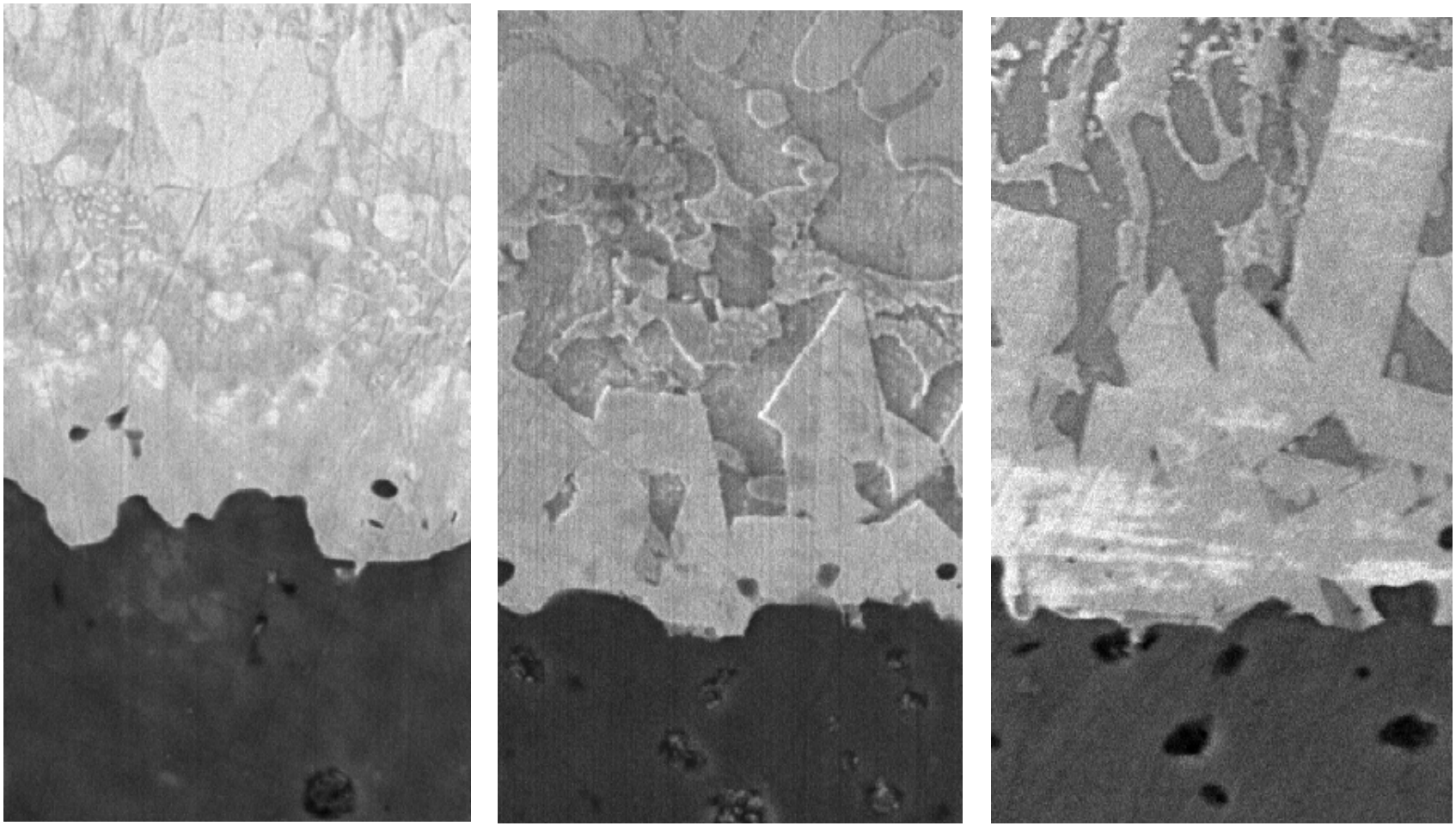
Pulse length : 10 ms (no shuttering)

Rep Rate : 5-10 Hz

Maximum heat flux at maximum area : 5 MW/m2 at 2.5 x 35 cm

Maximum heat flux attainable :12. 5 MW/m2 at 2.5 x 20 cm

Example : Infrared Processed Hexaloy SA / W powder



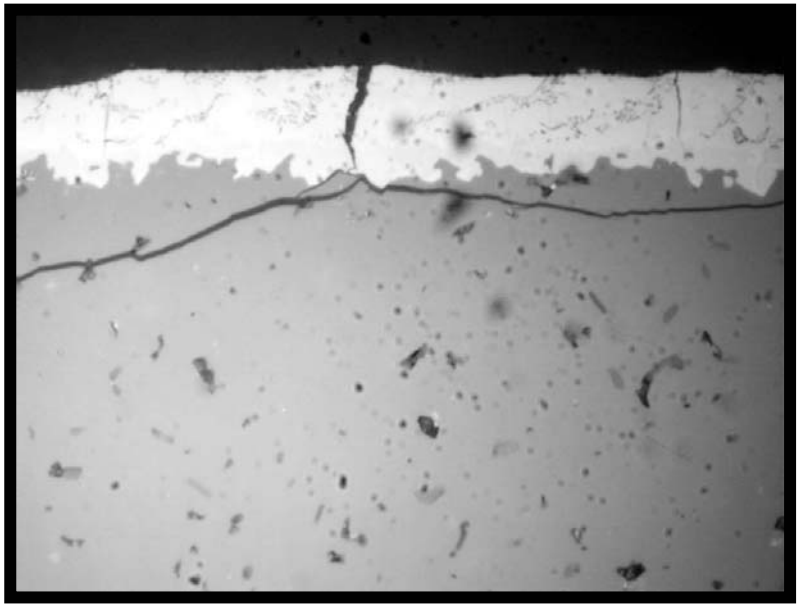
W powder

W deposition + W powder

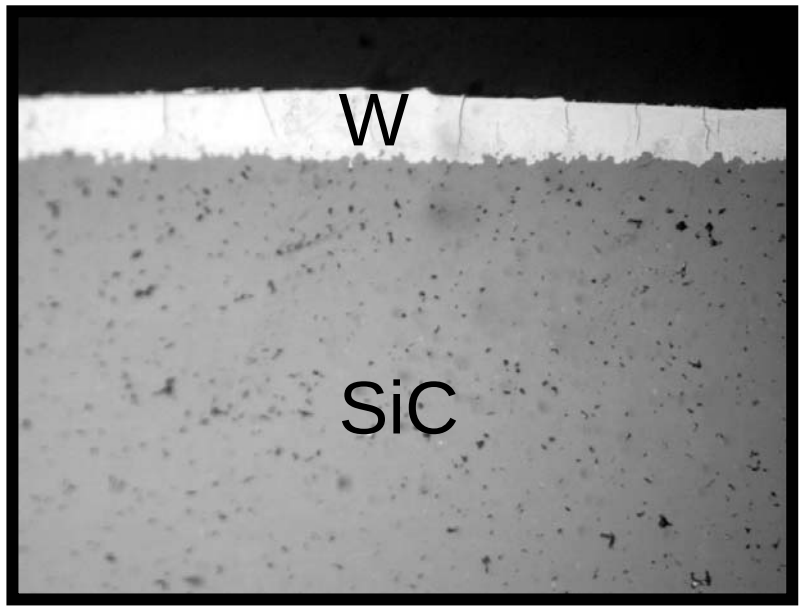
W deposition + annealing+ W powder

5μm

Crack formation



No preheating



Preheating

Initial processing resulted in cracking in tungsten which propagated across interface into substrate. This would cause spalling during fatigue loading. This has been controlled by preheating of the substrate prior to Infrared Processing.

Fatigue

Surfaces will be subjected to > 10^8 cycles per year with significant thermal and pressure pulses.

With certain designs surface layer is taken to melting temperature.

No experimental work in this area.

Exfoliation

- IFE first wall structures may be loaded by significant ion fluxes.
  - MeV to 10's of MeV (Pd, C, ^{3}He)
  - 0.1-1 MeV (He, D, T, H)

- Designs to date have ignored degradation to mechanical properties as well as sputtering (chemical and physical), blistering, and exfoliation. Lucas estimated 2-4 cm removal due to exfoliation per year (assuming no He/H migration)

- Currently, studies are underway to study the migration of helium implanted at low temperature (~600°C) followed by annealing to >1200°C using nuclear reaction analysis and TEM.