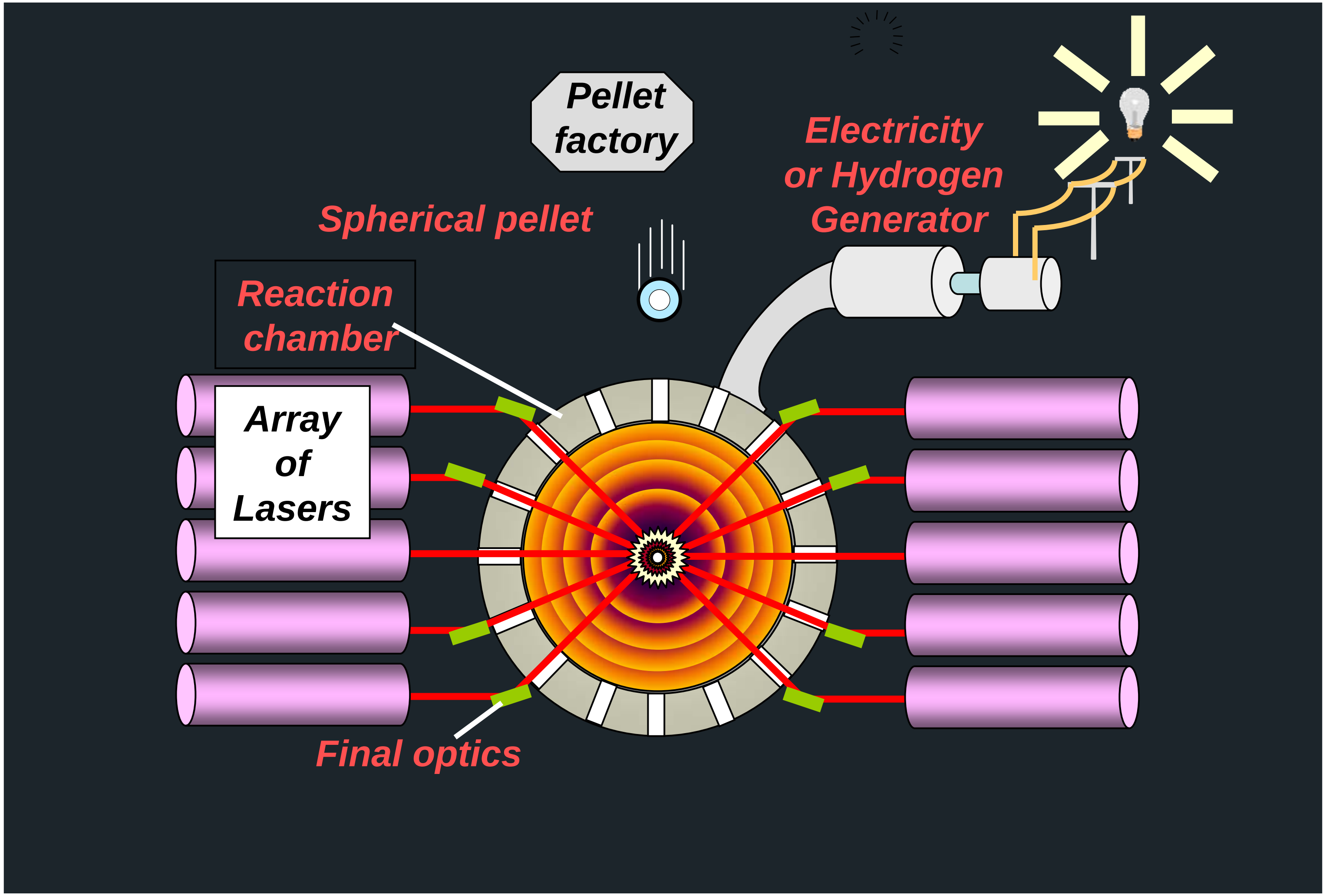
Laser Direct Drive:
Scientific Advances, Technical Achievements, and the Road To Fusion Energy

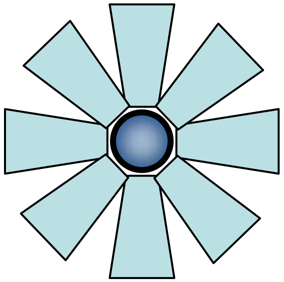
Presented by
John Sethian
Naval Research Laboratory

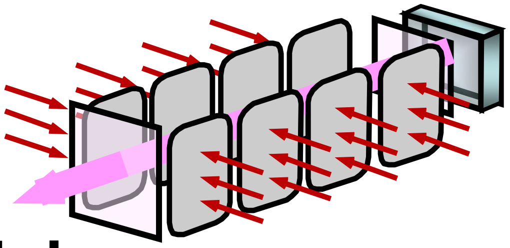
Fusion Energy with Lasers and Direct Drive



Why we believe direct drive with lasers can lead to an attractive power plant

1. Simplest target physics:

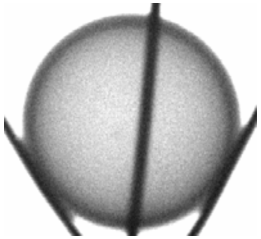




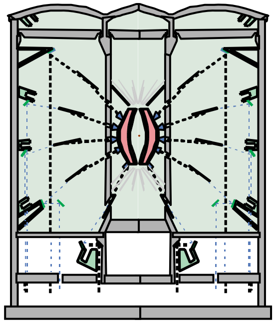
2. Laser (most costly component) is modular

3. Separate components lower cost of development

4. Simple spherical targets:
   facilitates mass produced “fuel"



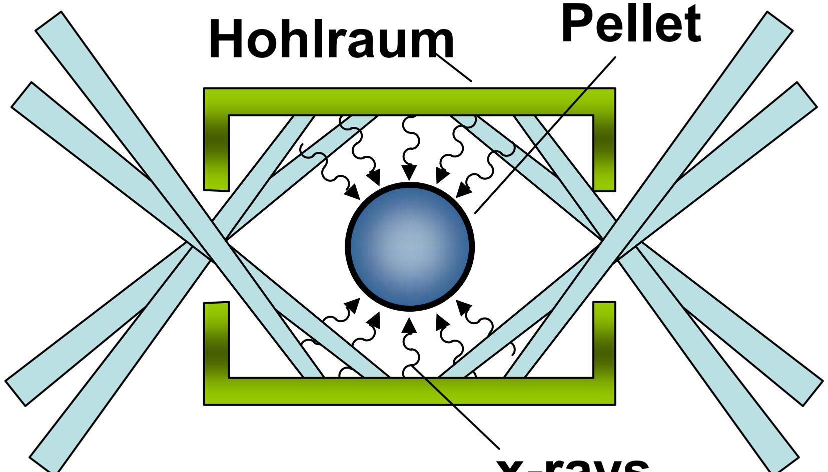
5. Power plant studies economically attractive



6. We have made a lot of progress!!

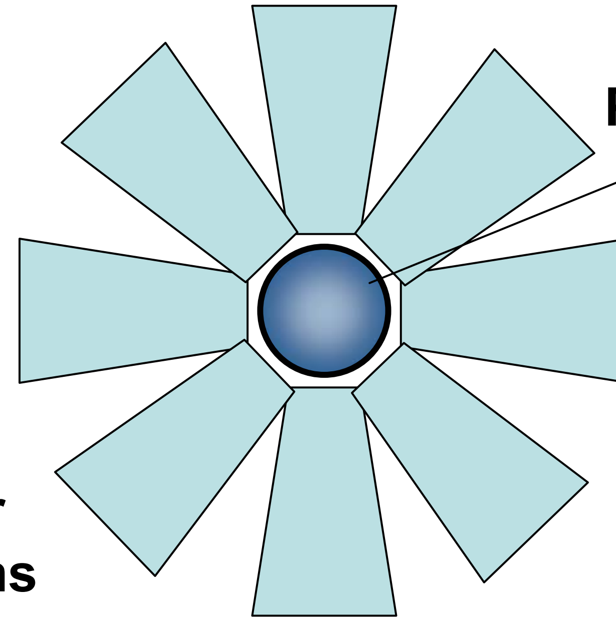
We are committed to Direct Drive for the Fusion Energy Mission

Indirect Drive (Chosen path for NIF)



- Relaxed laser uniformity requirements
- Complex targets & physics
- Predict moderate energy gain (≤ 40) at 1 MJ laser energy

Direct Drive (IFE)



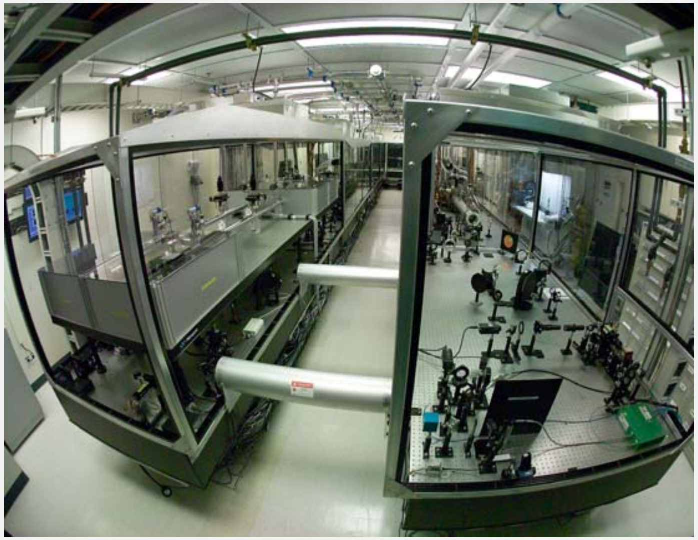
- Advanced lasers/ target designs overcome uniformity requirements
- Simpler targets & physics
- Predict Fusion Class Gains (> 140) at lower laser energy (500 kJ - 1 MJ)

Two laser options for Direct Drive:
KrF and DPPSL
Both have potential to meet the IFE requirements

Electra KrF Laser (NRL)
λ = 248 nm (fundamental)
Gas Laser

See talk by Frank Hegeler Thursday PM

Mercury DPPSL Laser (LLNL)
λ = 351 nm (tripled)
Solid State Laser



See talk by Chris Ebbers Thursday PM

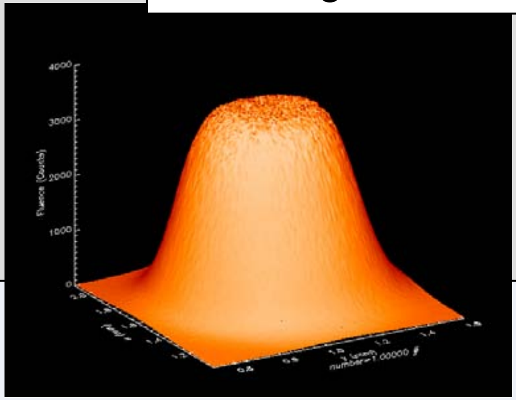
We encourage competition.
It leads to innovation and a better product.
And leads to it faster

KrF lasers have advantages for fusion energy

PHYSICS

- Deeper UV (248 nm vs 351 for glass):
  - -- Greater mass ablation rate and pressure at given intensity
  - -- Higher threshold for deleterious laser plasma instability (LPI) ~1.8x (so maximum ablation pressure is further increased)
- Focus of KrF beams can be readily "zoomed" to follow imploding pellet
  - -- increases coupling by 30%
- KrF has most uniform pellet illumination ➢.
  - -- 0.2% non-uniformity overlapped beams

Nike single beam focus



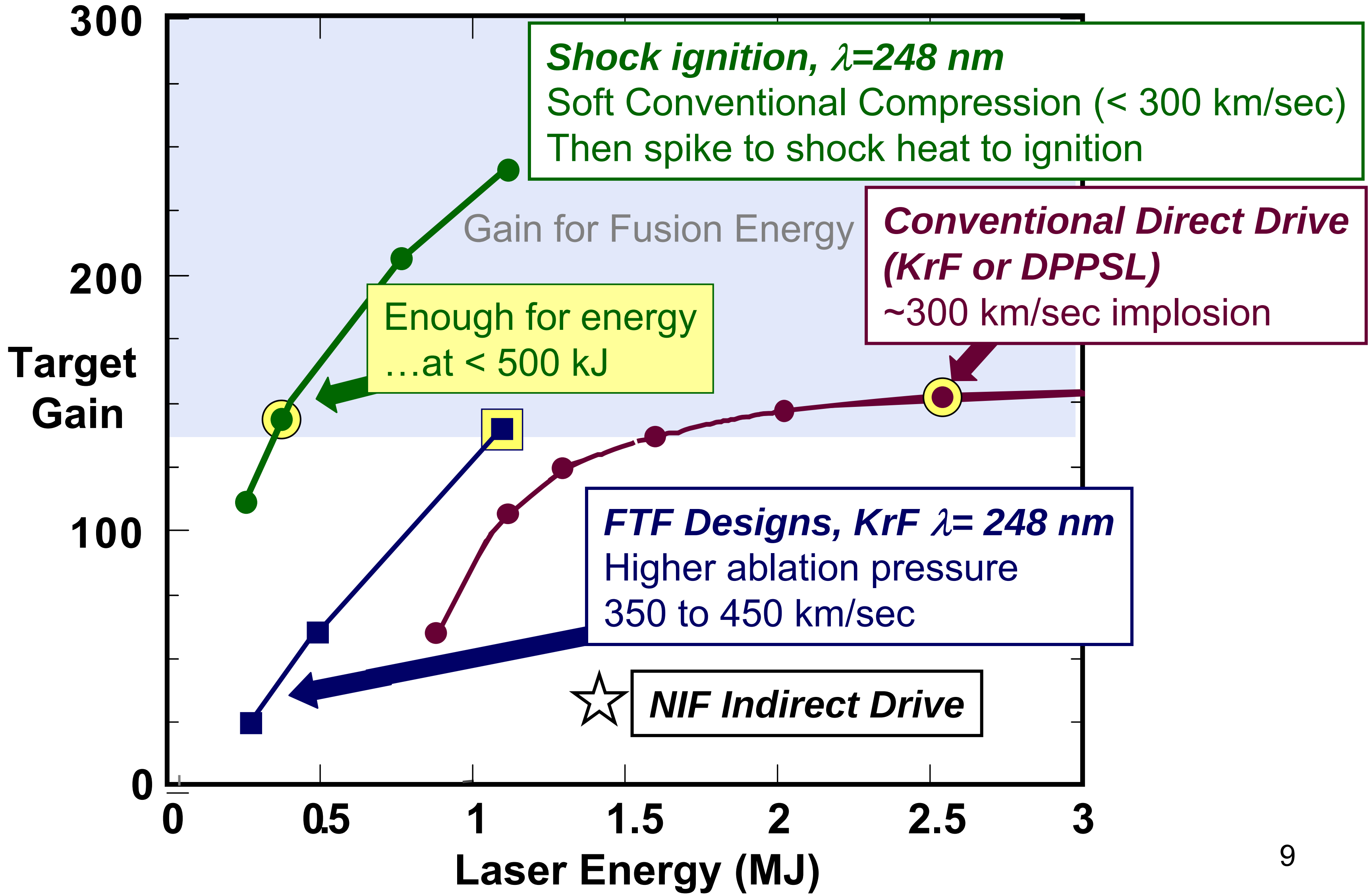
ENGINEERING

- Industrial robust technology (used in industry, medical applications)
- Gas laser medium is easy to cool (tough to break gas)

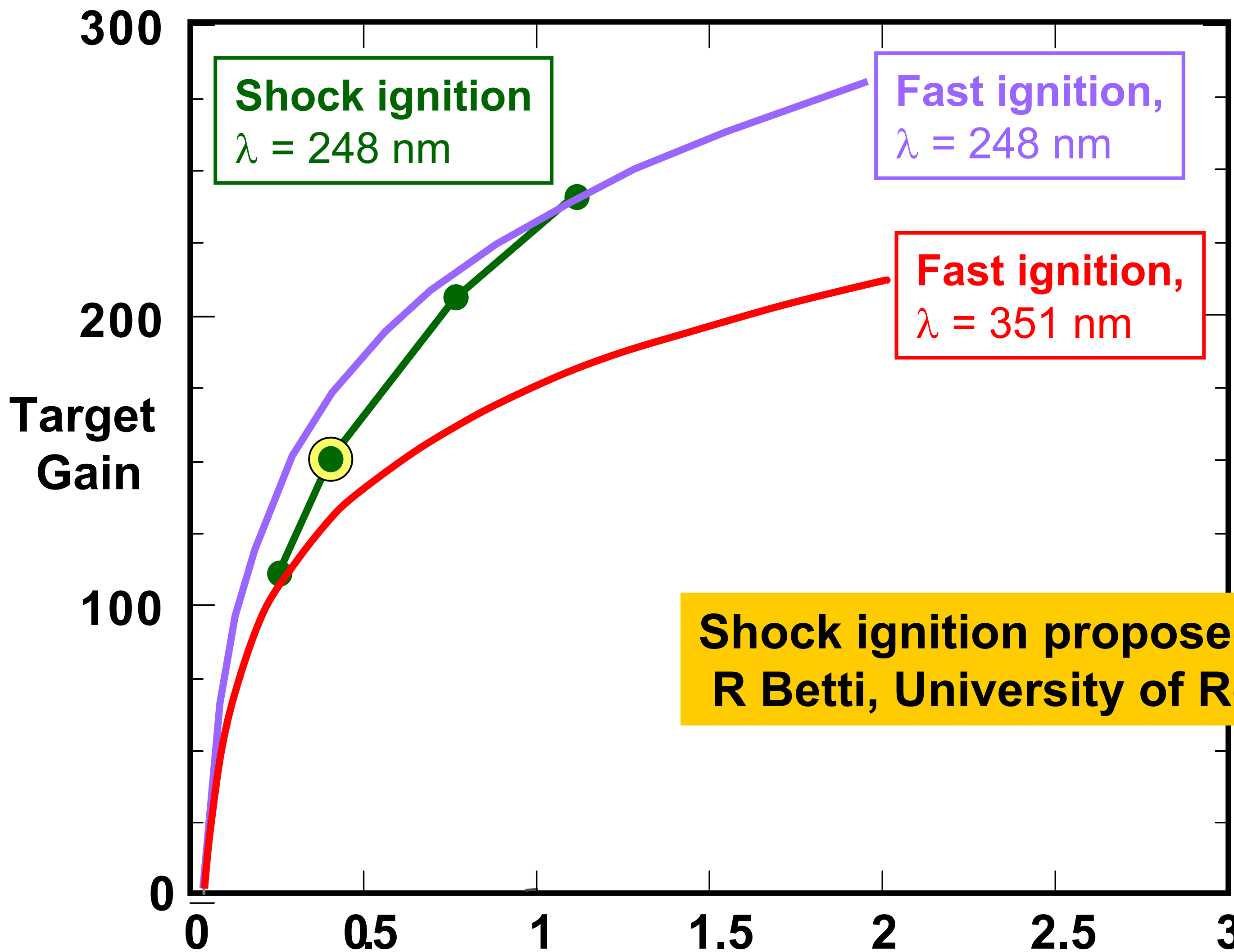
Advances and Achievements

- **target design**
- **lasers**
- **final optics**
- **target fabrication and engagement**
- **chamber**

New Direct Drive Designs:
Power plant class gains, much smaller laser



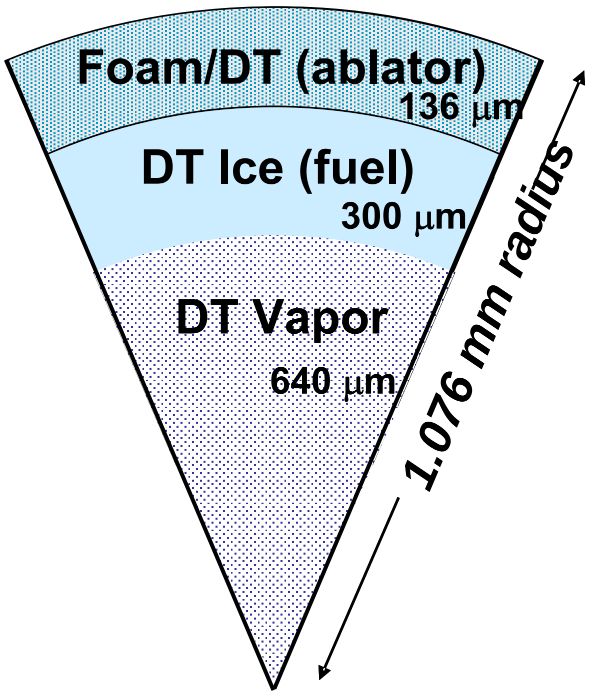
Shock Ignition predicts comparable gains as Fast Ignition… *without the complexities*

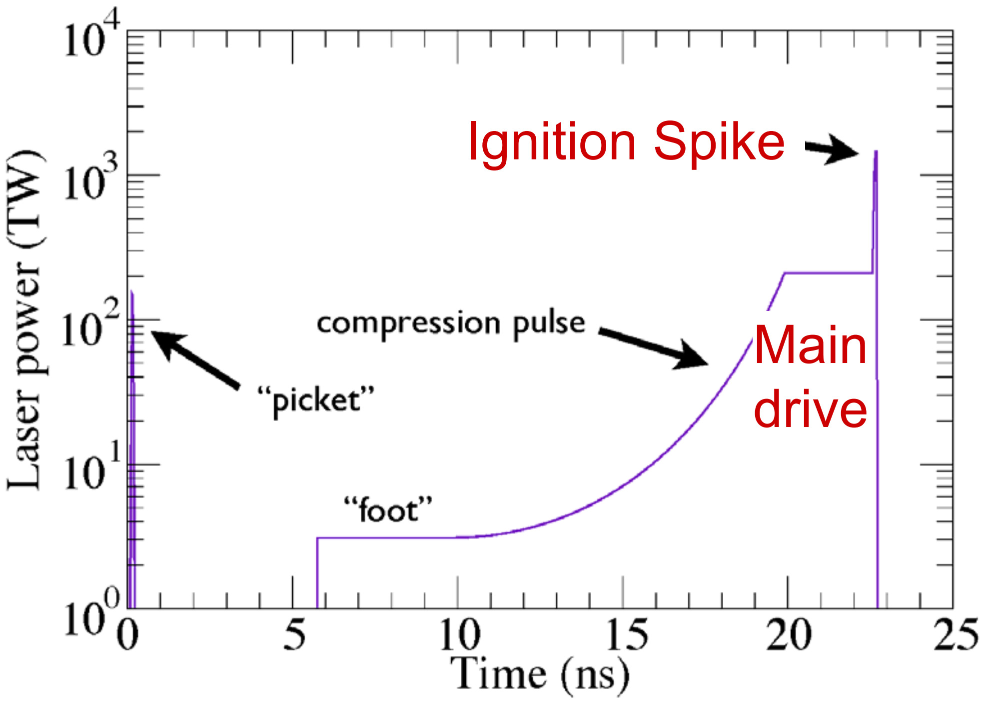


Shock ignition proposed by R Betti, University of Rochester

Shock Ignition:

Shell accelerated to sub-ignition velocity (<300 km/sec), Ignited by converging shock produced by high intensity spike





Low aspect ratio pellet helps mitigate hydro instability

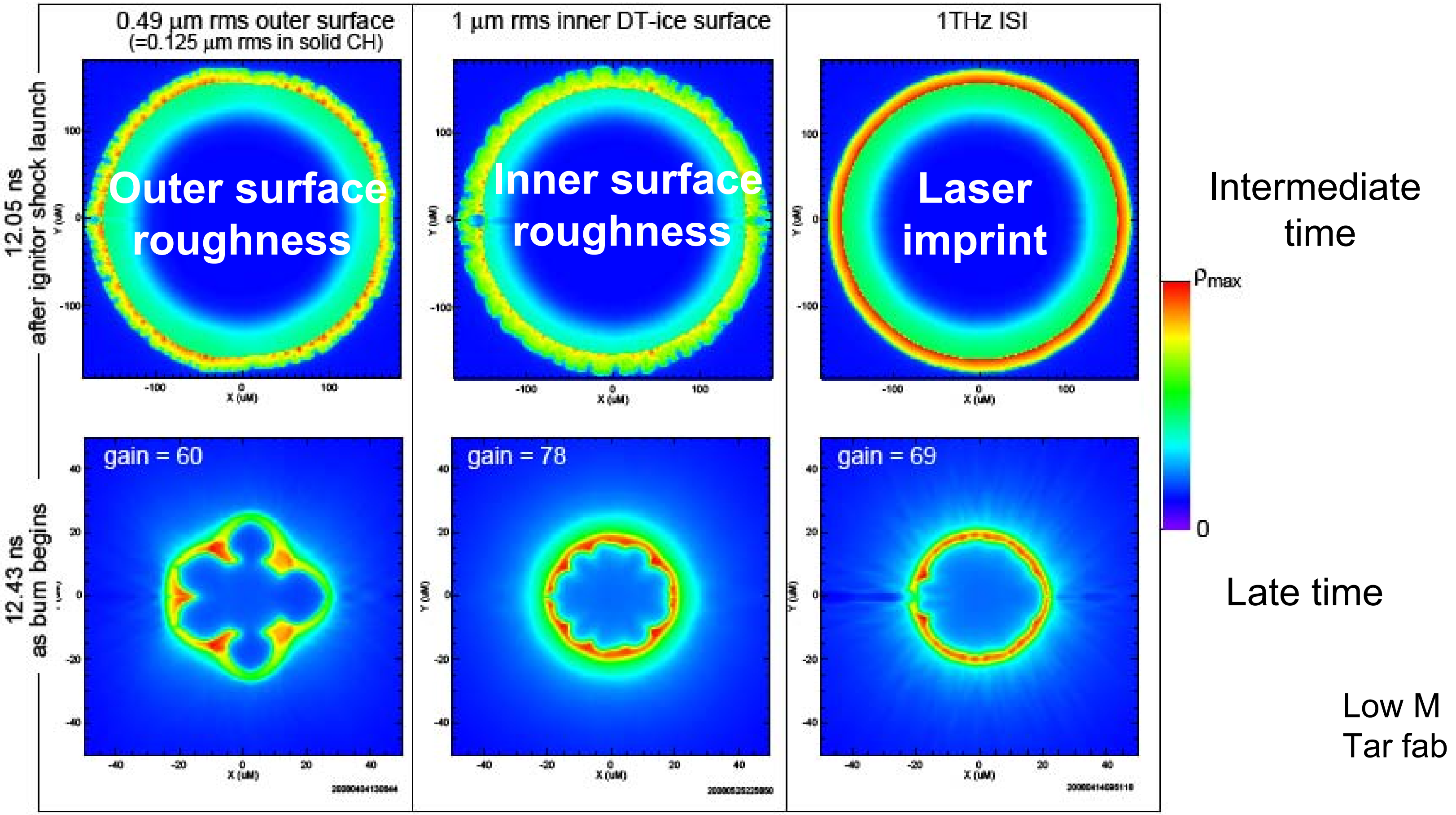
Laser Intensities

Peak main drive ~ 1.5×10^{15} W/cm^2

Igniter pulse is ~10^{16} W/cm^2

High resolution 2-D simulations show shock ignition designs are robust against hydro instabilities

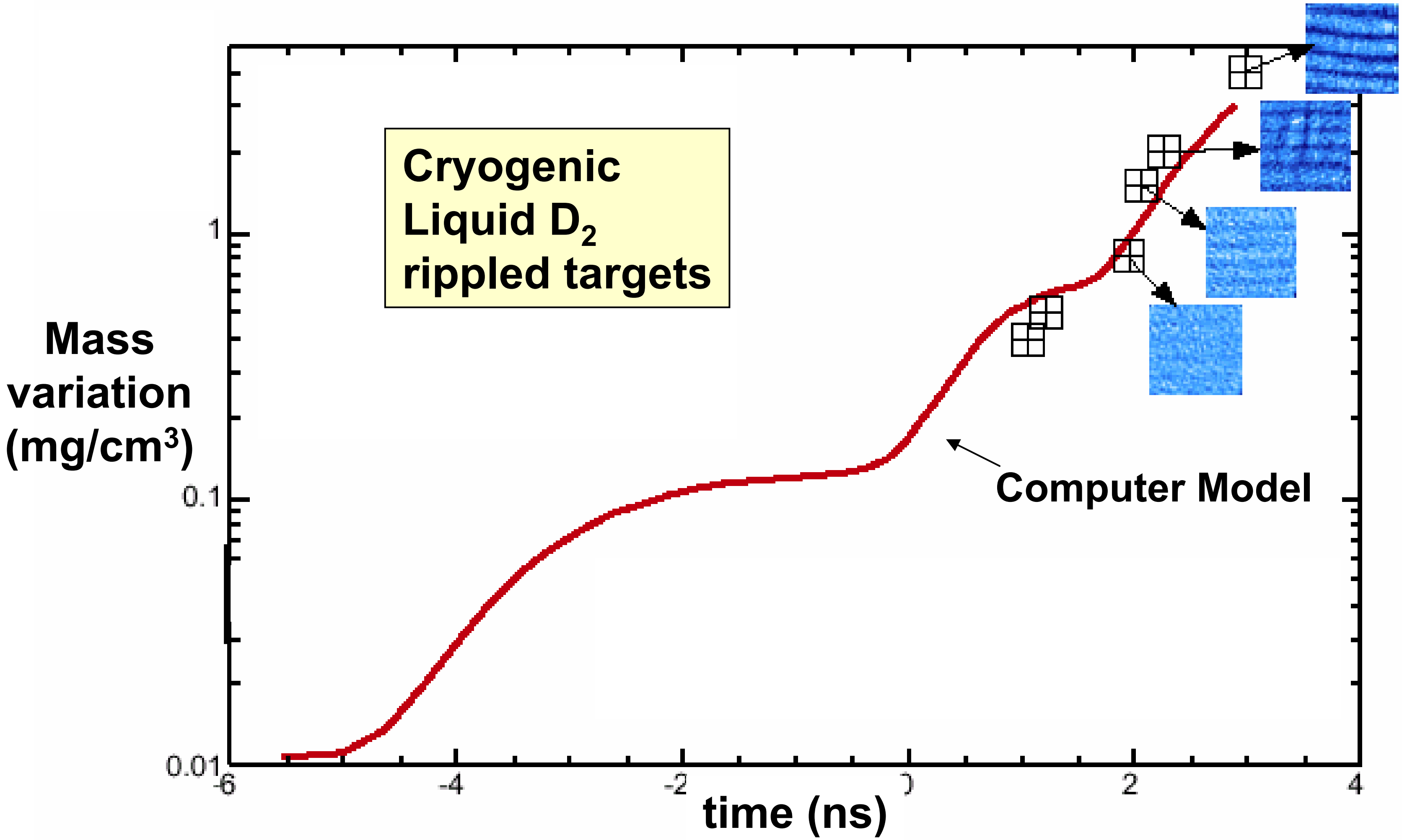
2-D Gain: 60× **2-D Gain: 78×** **2-D Gain: 69×**



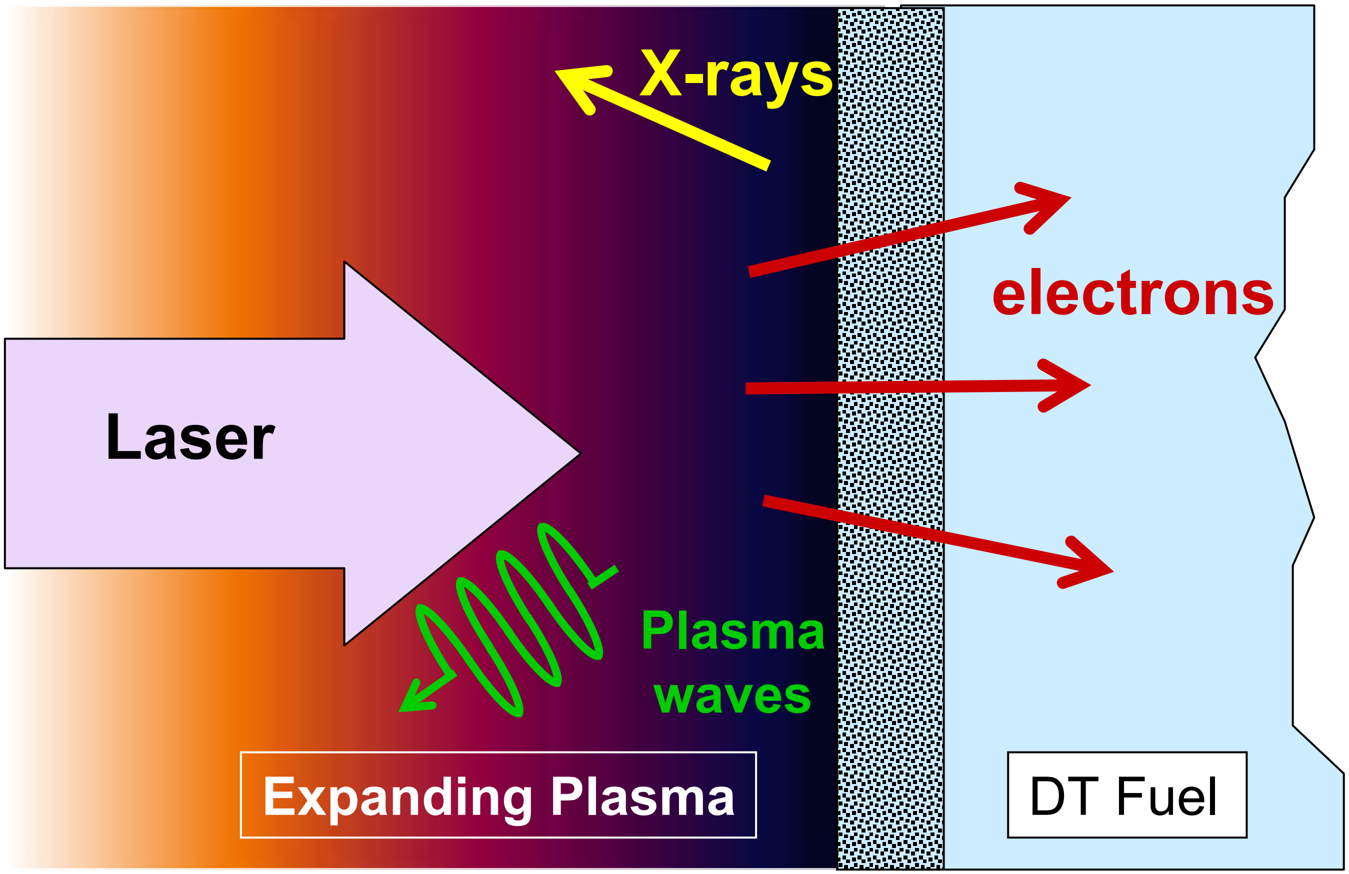
250 kJ shock ignited target – NRL FASTRAD3D simulations

Andy Schmitt NRL

Target physics codes have been benchmarked with experiments on Nike Laser



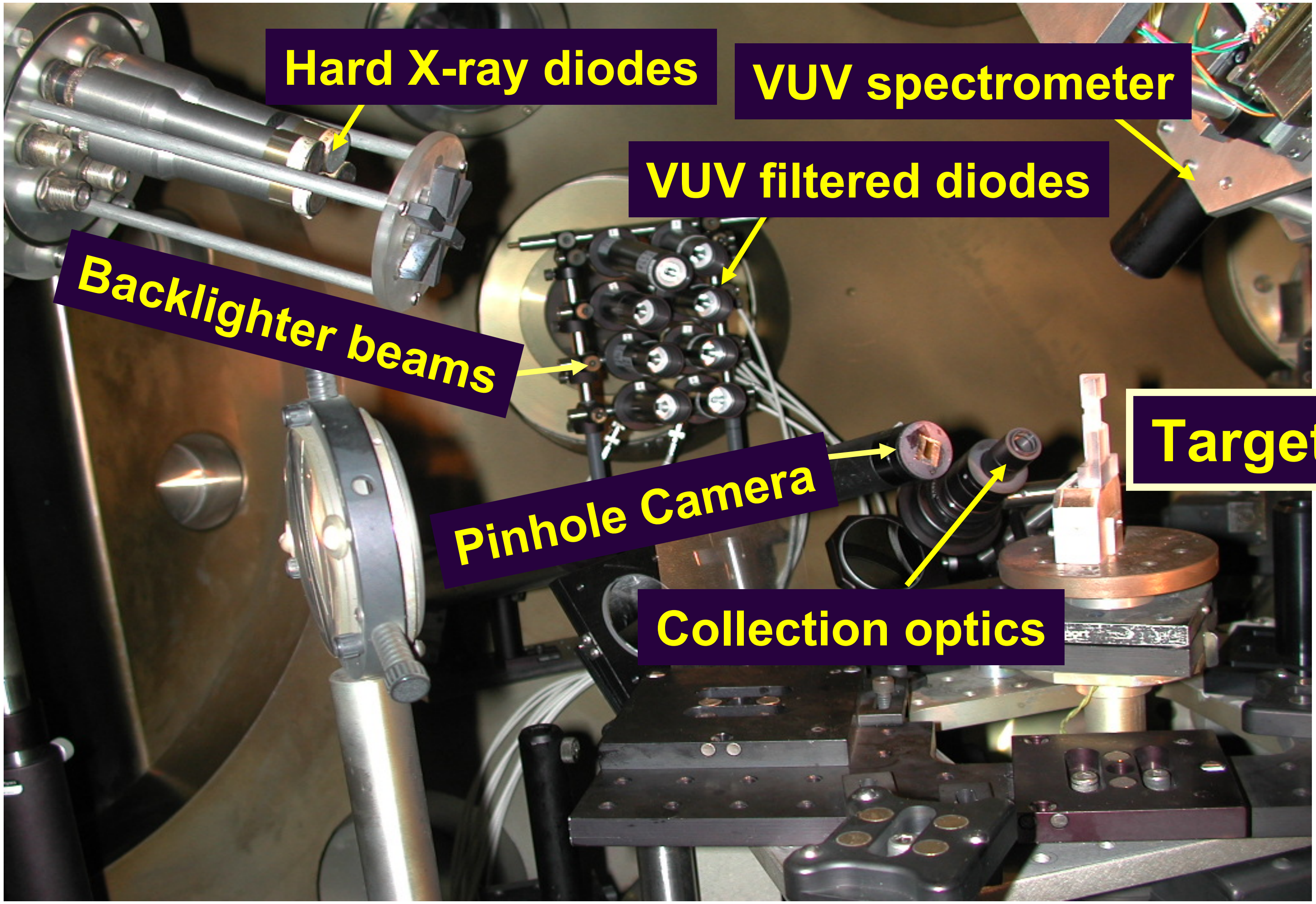
One challenge, in *any* laser target design --- Predicting Laser Plasma Instabilities (LPI)



Laser driven instabilities cause problems:

- Produces high energy electrons that preheat DT fuel
- Scatters laser beam, reducing drive efficiency

Nike experiment to study Laser Plasma Instability at prototypical intensities (up to 10^{16} W/cm^2)



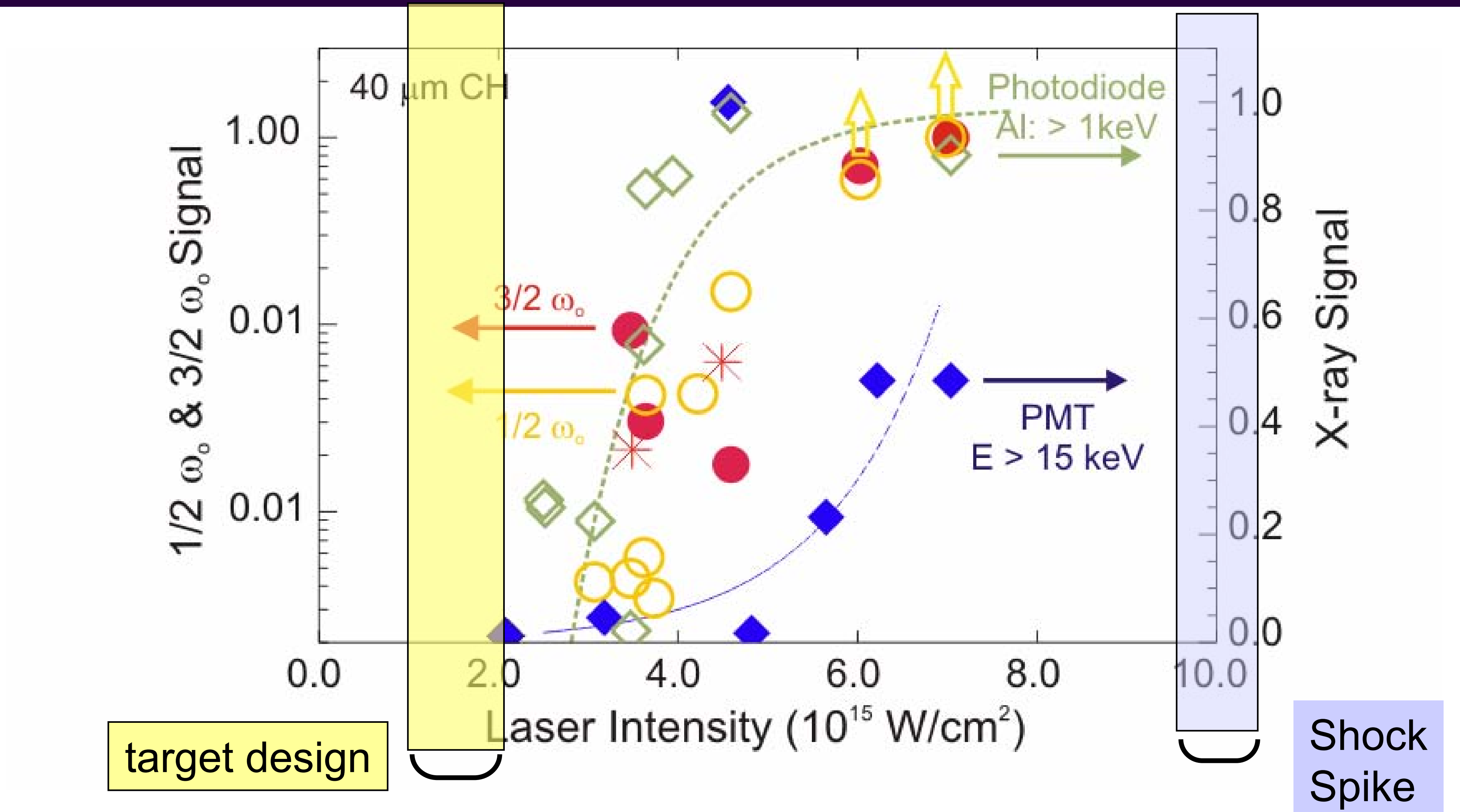
Targets can be cryogenic –e.g. liquid deuterium

Jim Weaver NRL

Nike Experiments are encouraging:

Higher threshold for KrF

Onset of LPI ~ 3 x 10^{15}, above target design point



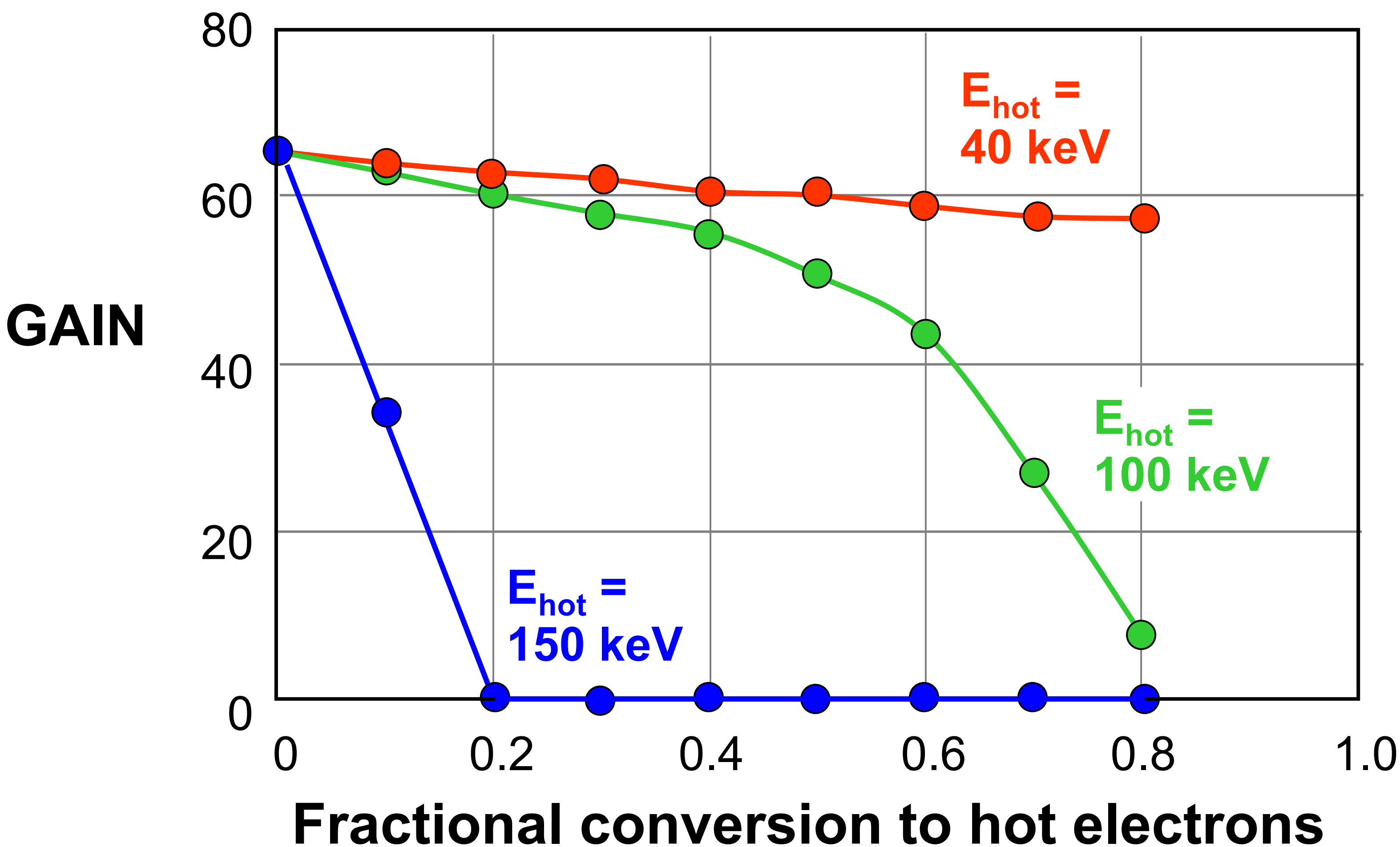
These experiments:12 Nike backlighter beams will be repeated @ 1 kJ with 44 Nike main beams

Jim Weaver NRL

brt

LLNL (LASNEX) simulations suggest hot electrons induced by spike may be *a <u>good</u> thing*

Gain 60 target may be able to withstand hot electrons up to 100 keV

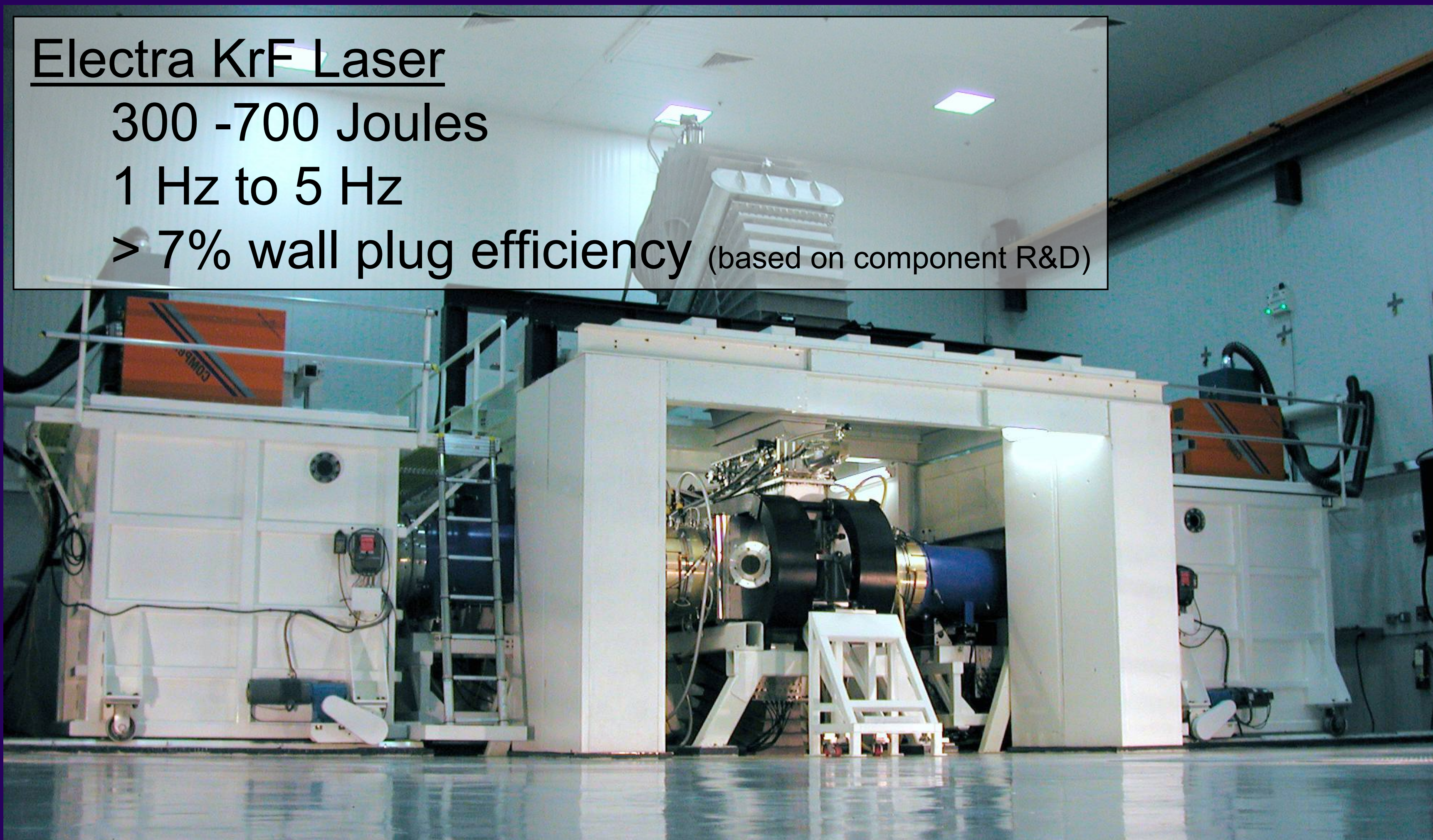


John Perkins LLNL

Advances and Achievements

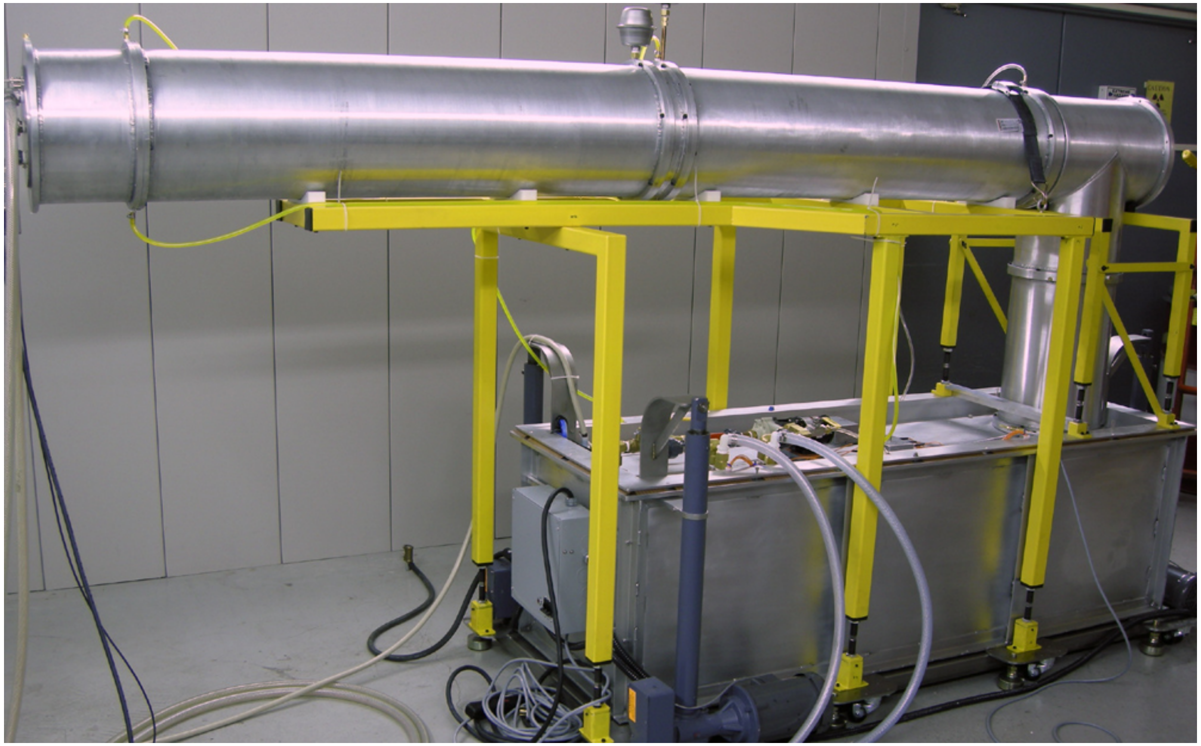
- **target design**
- **KrF lasers**
- **final optics**
- **target fabrication and engagement**
- **chamber**

Electra Krypton Fluoride (KrF) Laser
- electron beam pumped gas laser



see talk by Frank Hegeler (Thurs PM) for details

Advanced Solid State Pulsed Power Demo: 1 M shots at 5 Hz, 400,000 shots @ 10 Hz



- Based on Commercial switches (component life > 300 M shots)
- > 80% efficiency
- Attractive cost: < $ 2 M for Electra (15 kJ)

Malcom McGeoch (PLEX)
Steve GIdden (APP)

see talk by Frank Hegeler (Thurs PM) for details

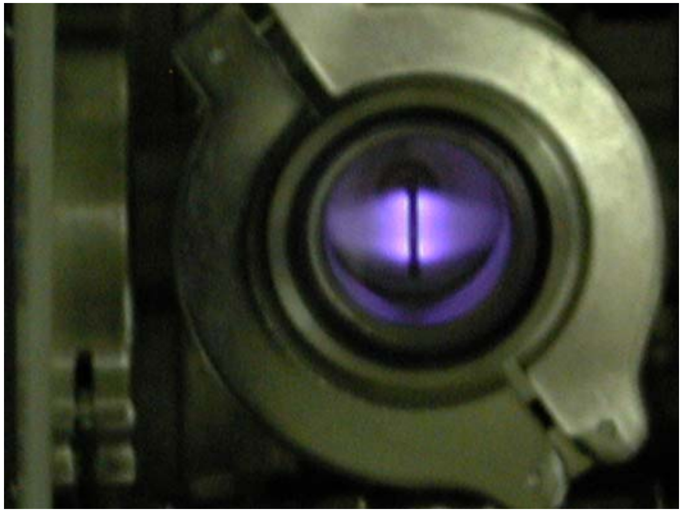
Hibachi foil durability has been a challenge

This ~~is~~ was a Hibachi Foil

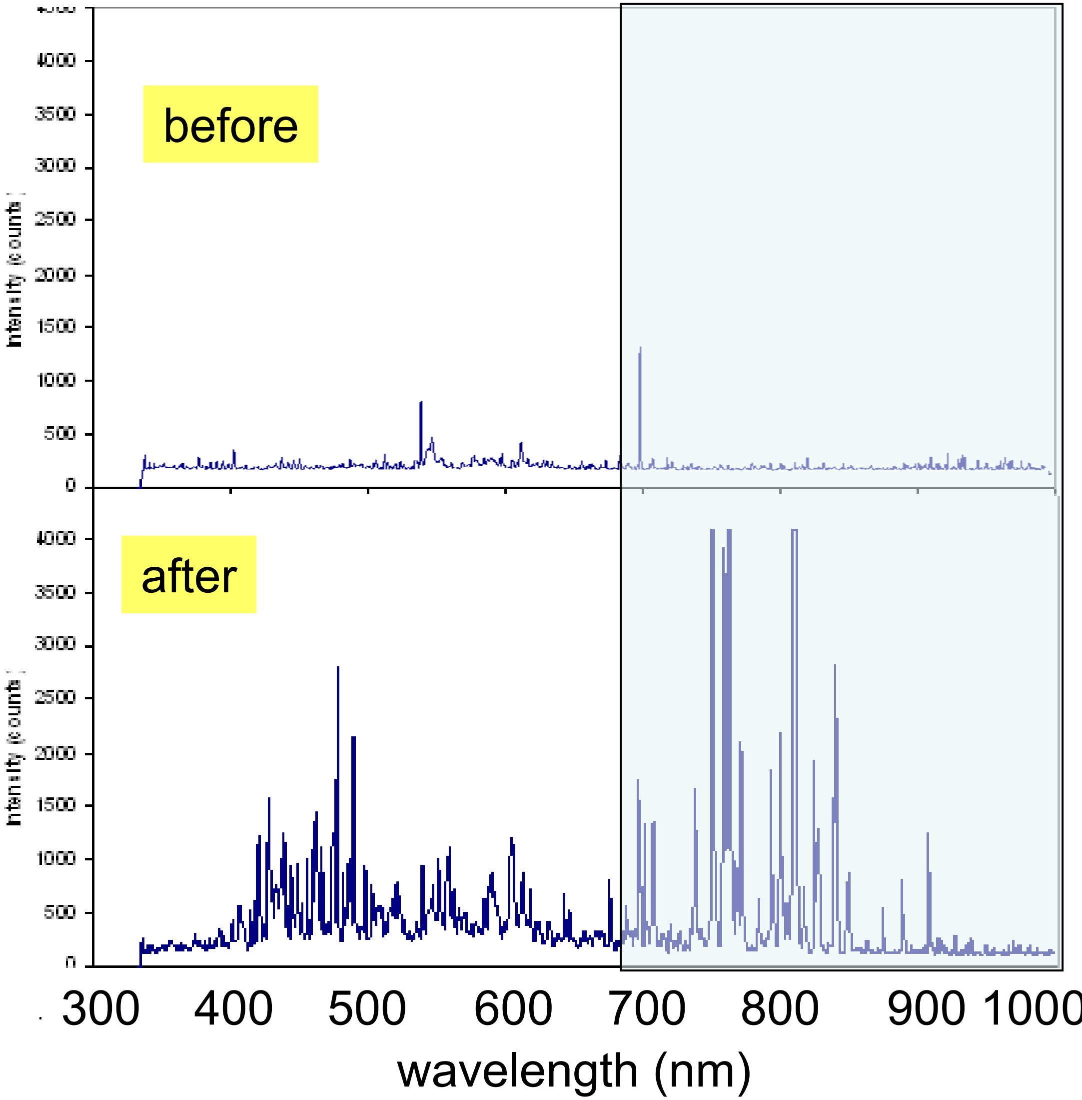
Typical Foil lifetime: 5,000 - 15,000 shots

Plasma Physics to the rescue

Penning Ionization Gauge

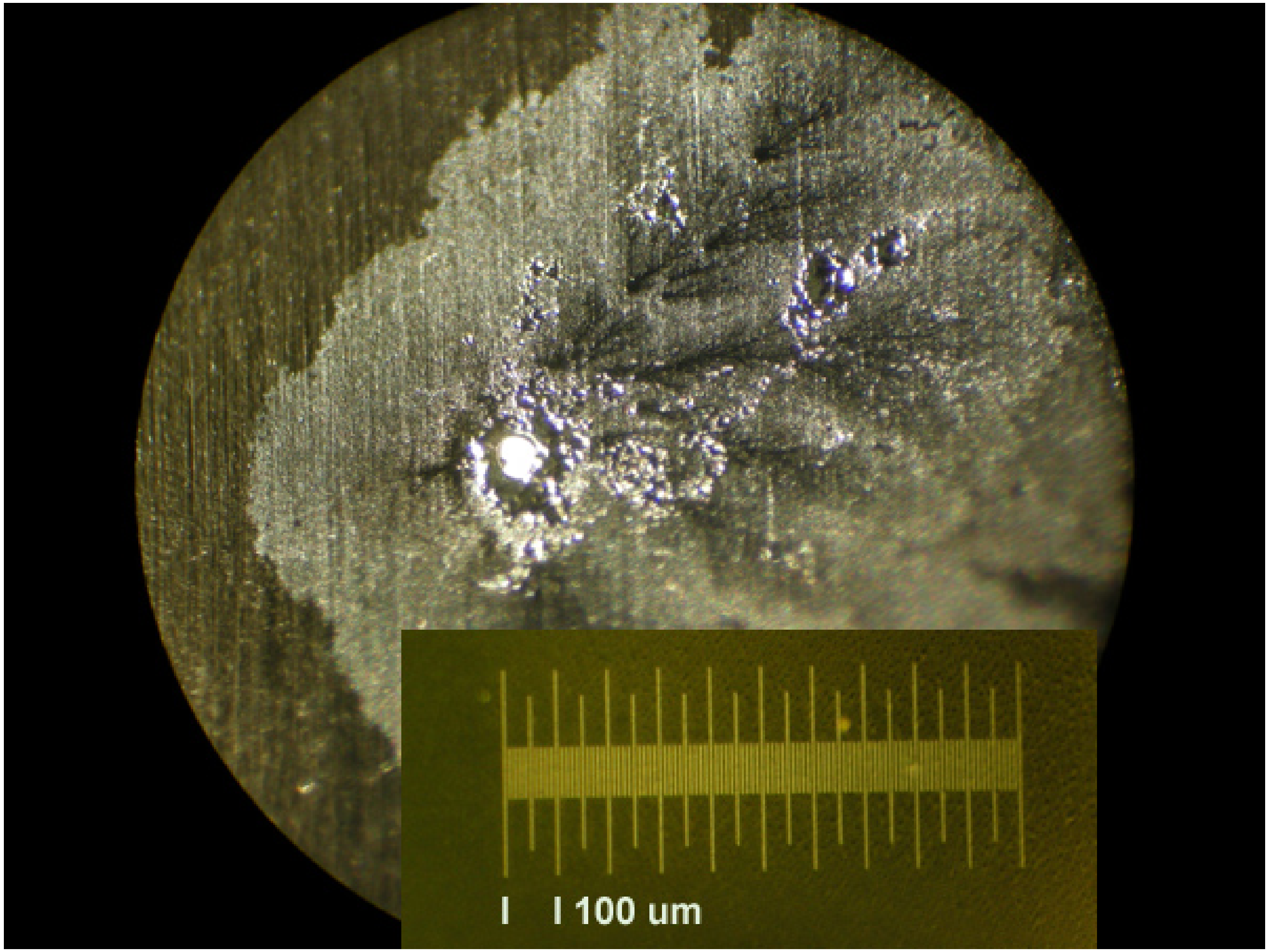


Spectrometer tuned to look at Ar emission (>700 nm: below Ar, above everything else)



J Giuliani & R Jaynes (NRL)

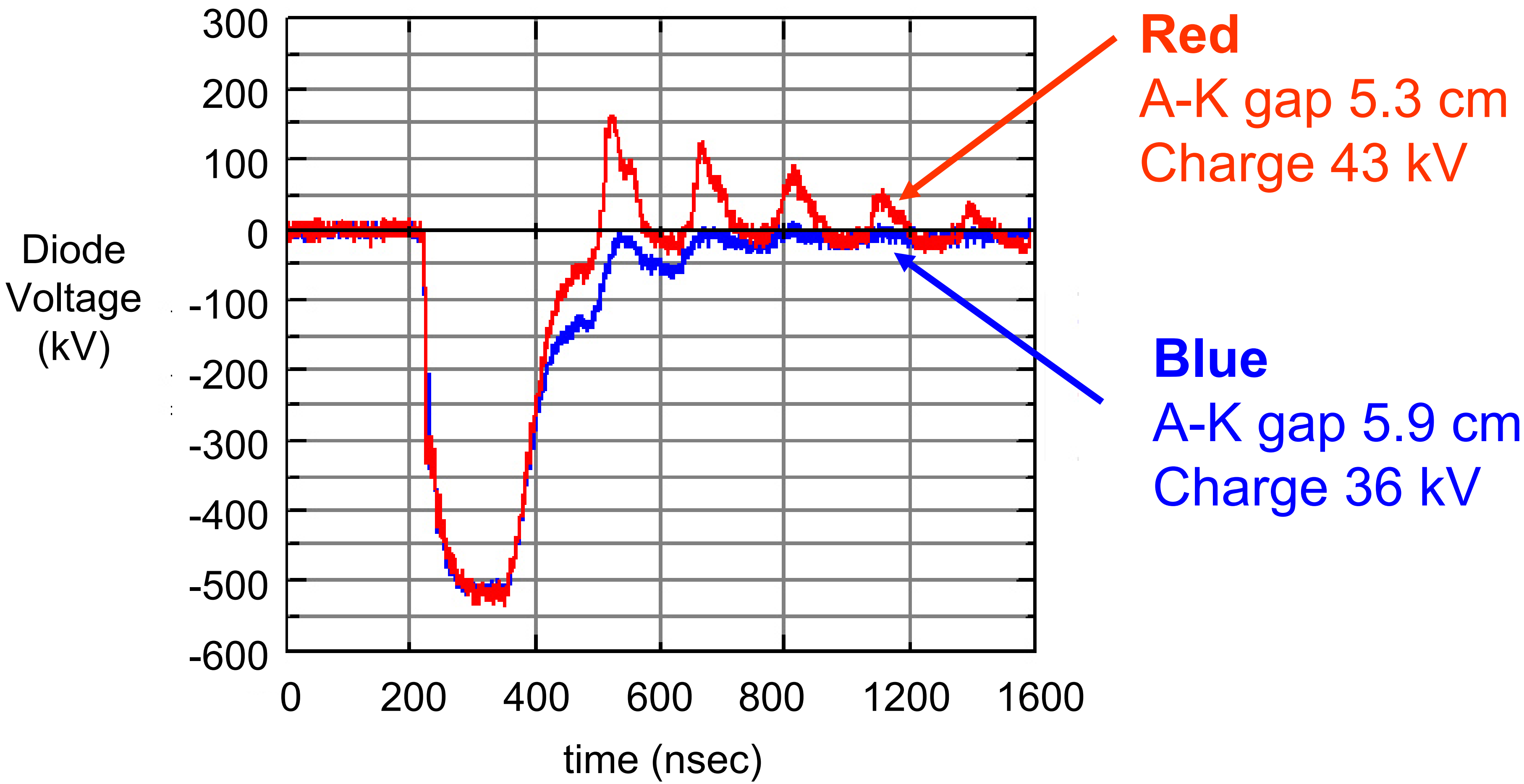
The Smoking Gun



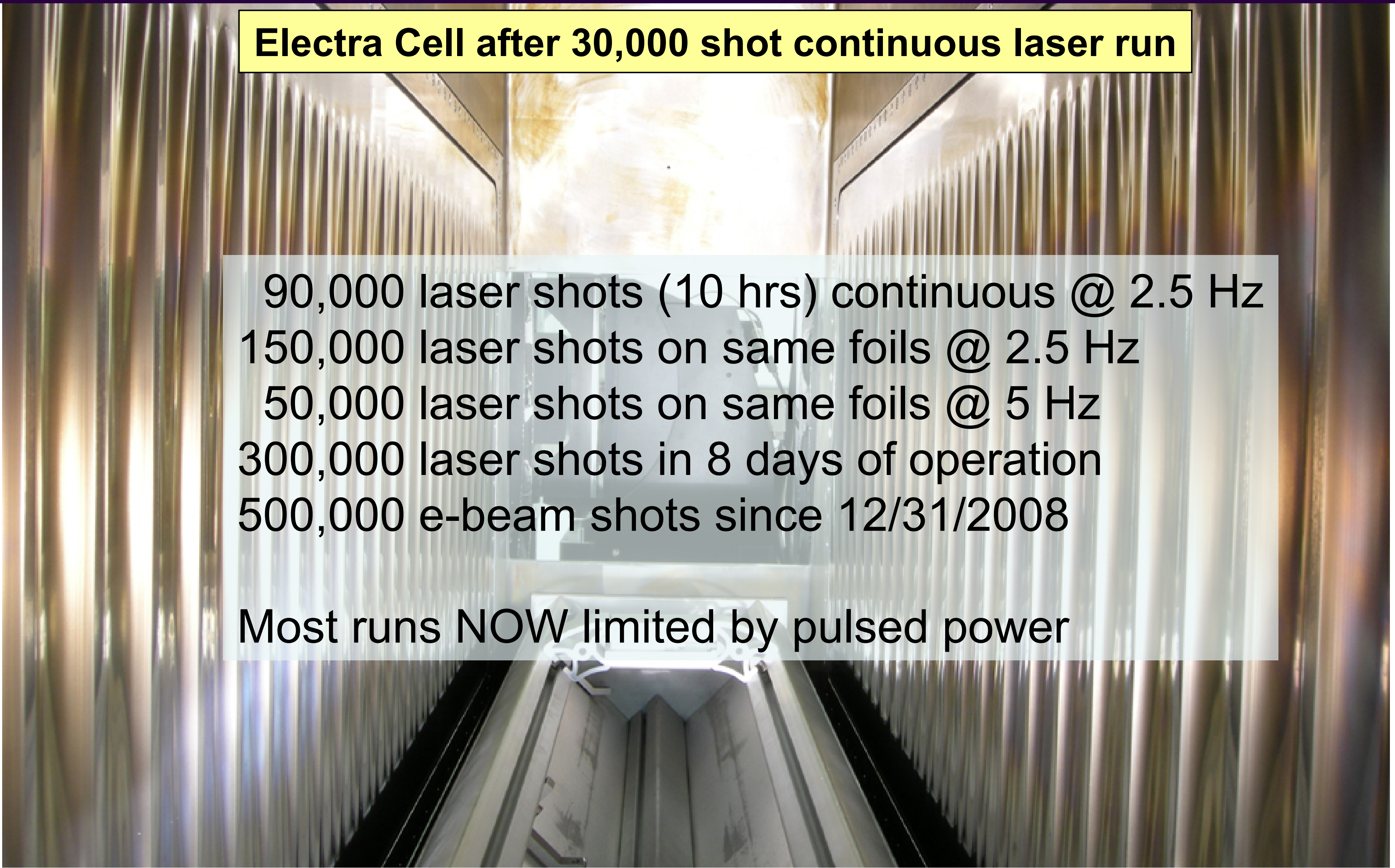
Penning
Ionization
Gauge
Pinhole
Early
Notification

SW-FL

Increasing A-K gap 10%, lowering charge volts 15%: Eliminated voltage reversal, *and hence foil emission*



Electra continuous durability has been extended to the 90,000 shot range

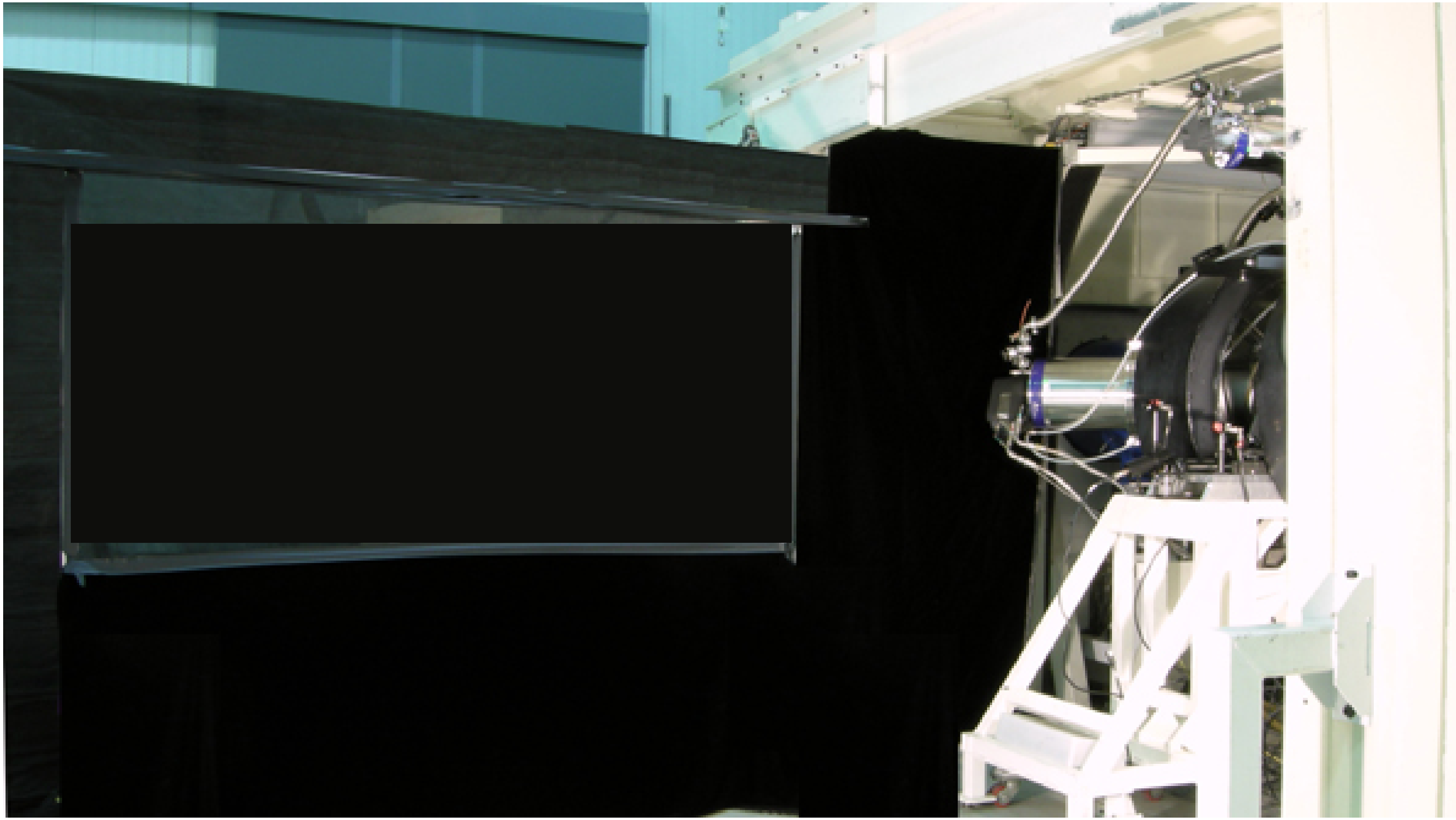


Electra Cell after 30,000 shot continuous laser run

90,000 laser shots (10 hrs) continuous @ 2.5 Hz
150,000 laser shots on same foils @ 2.5 Hz
50,000 laser shots on same foils @ 5 Hz
300,000 laser shots in 8 days of operation
500,000 e-beam shots since 12/31/2008

Most runs NOW limited by pulsed power

A video starring Electra

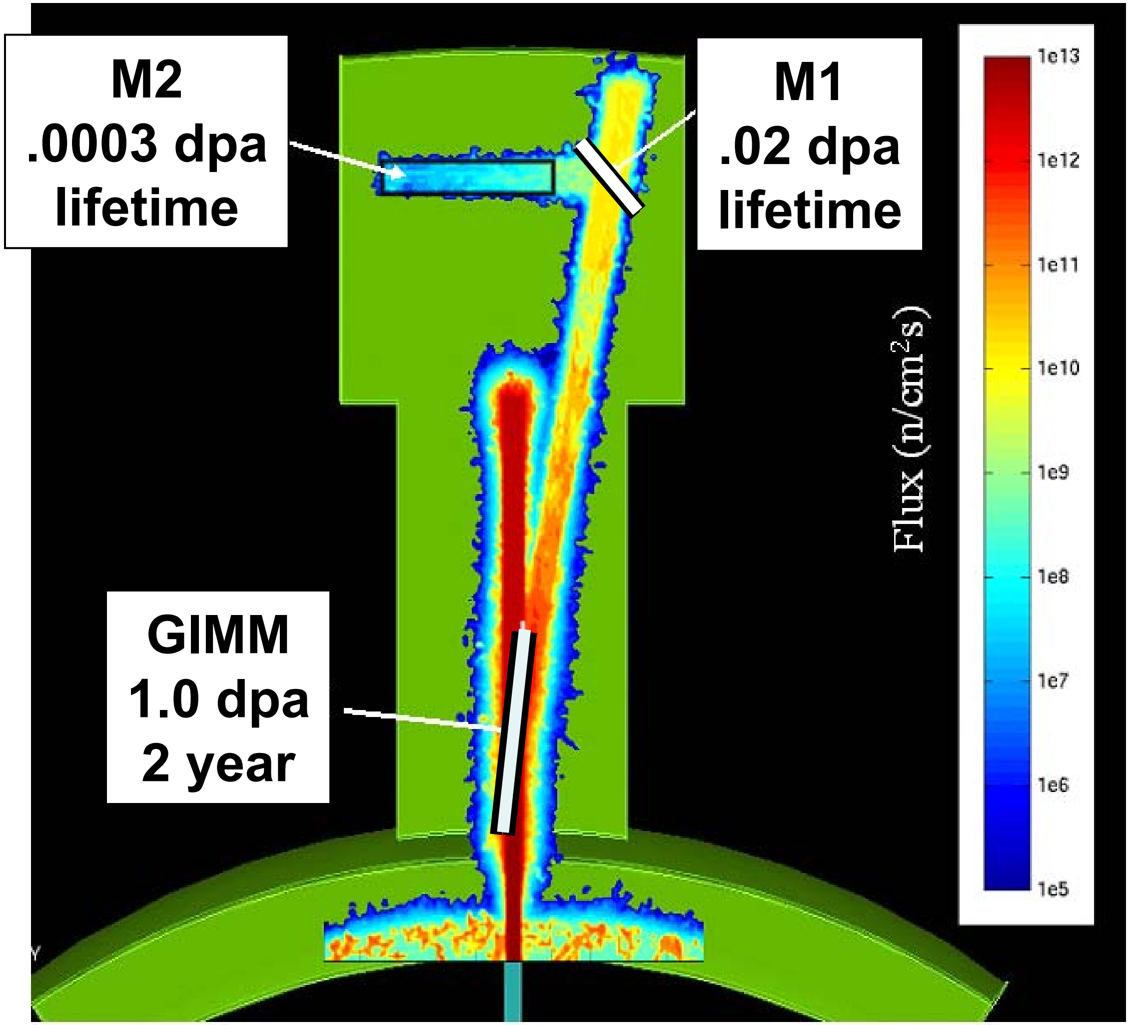


Advances and Achievements

- **target design**
- **lasers**
- **final optics**
- **target fabrication and engagement**
- **chamber**

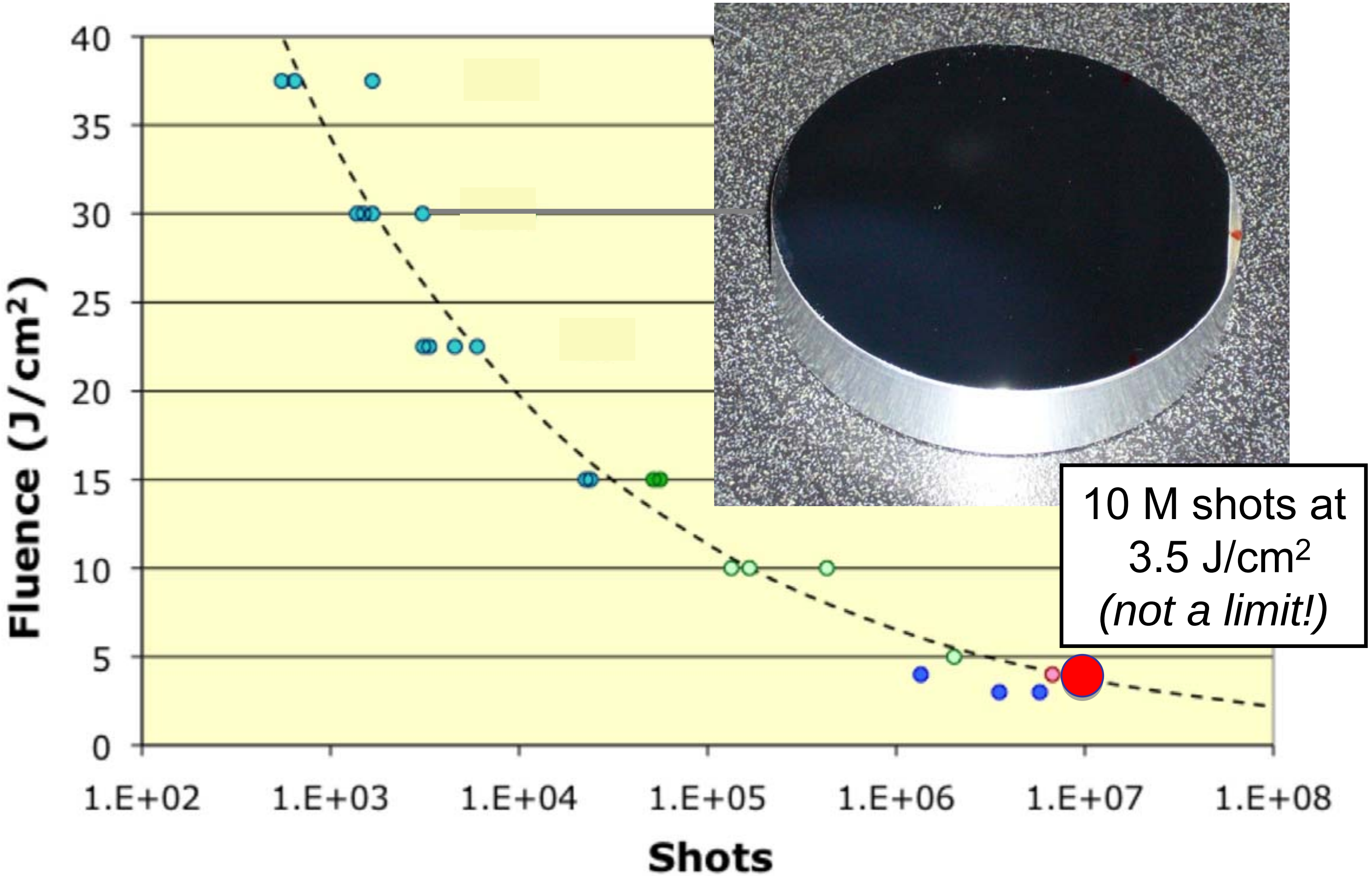
The final optics train

CAD Drawing of Final Optics, Coupled with MCNP simulation of Neutron flux



Mohamed Sawan (Wisconsin)
Malcolm McGeoch (PLEX)

GIMM laser damage threshold: > 3.5 J/cm² @ 10 M shots



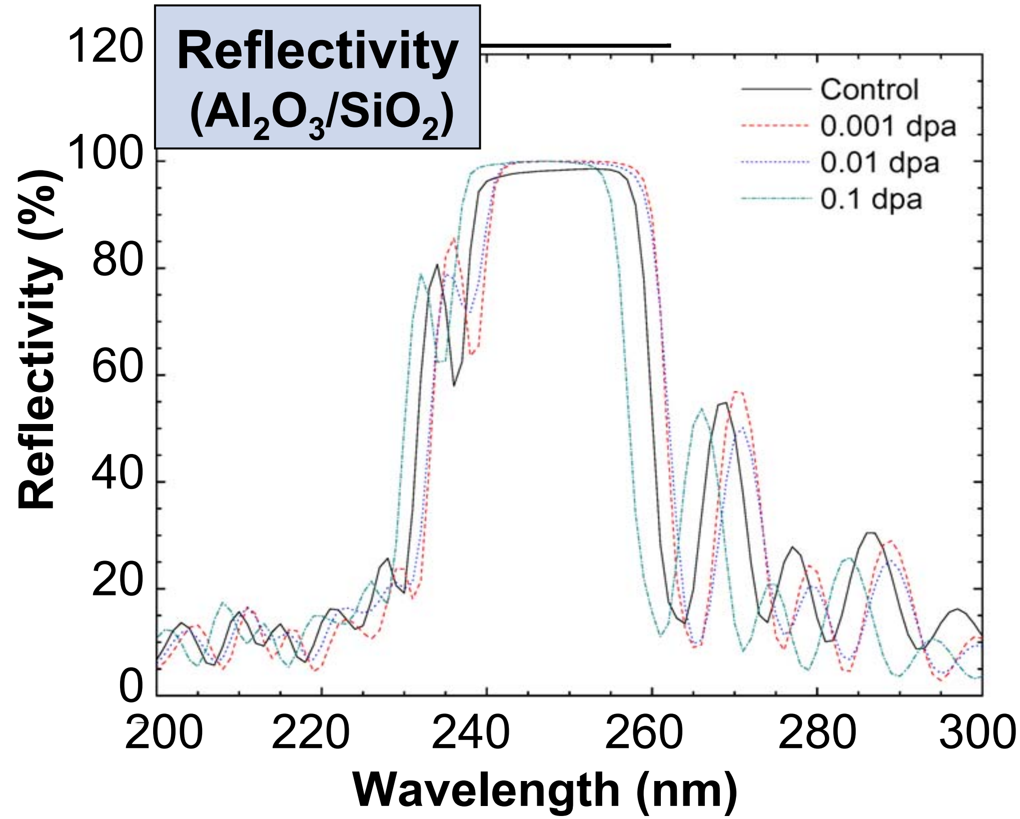
Mark Tillack (UCSD)

Dielectric mirror appears to resist predicted neutron fluence (0.02 dpa) on second mirror

The "key":
- **Match neutron-induced swelling in substrate and mirror layers**

Experiment:
- **Expose in HIFR (ORNL Reactor)**
- **Prototypical fluence, temperature**

Measurements:
- **Reflectivity**
- **Laser damage threshold**



Laser Damage Threshold (Al_2O_3/SiO_2)

No dpa	0.001 dpa	0.01dpa	0.1 dpa
86-87%	84-86%	78-83%	83-84%

Lance Snead (ORNL)
Tom Lehecka (Penn State)
Mohamed Sawan (Wisconsin)

Advances and Achievements

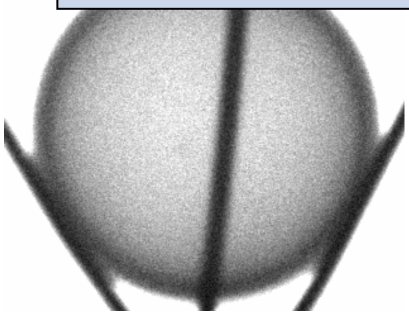
- **target design**
- **lasers**
- **final optics**
- **target fabrication and engagement**
- **chamber**

Target fabrication:

- **Mass produce foam shells that meet specs**
- **Fluidized bed for mass cryo layering**
- **Estimate Cost < $0.16 each**

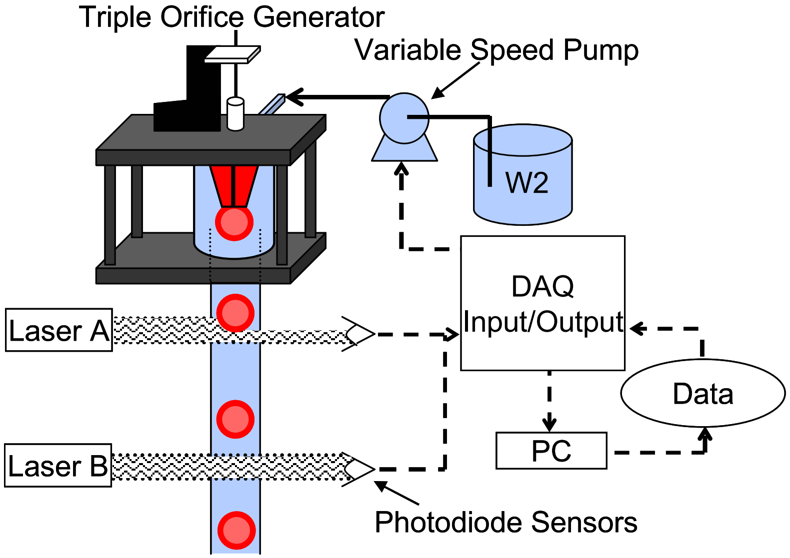
100 mg/cc foam shell

x-ray picture of 4mm foam



Mass Production: 22 shells/min

Cryogenic Fluidized bed to make smooth DT ice

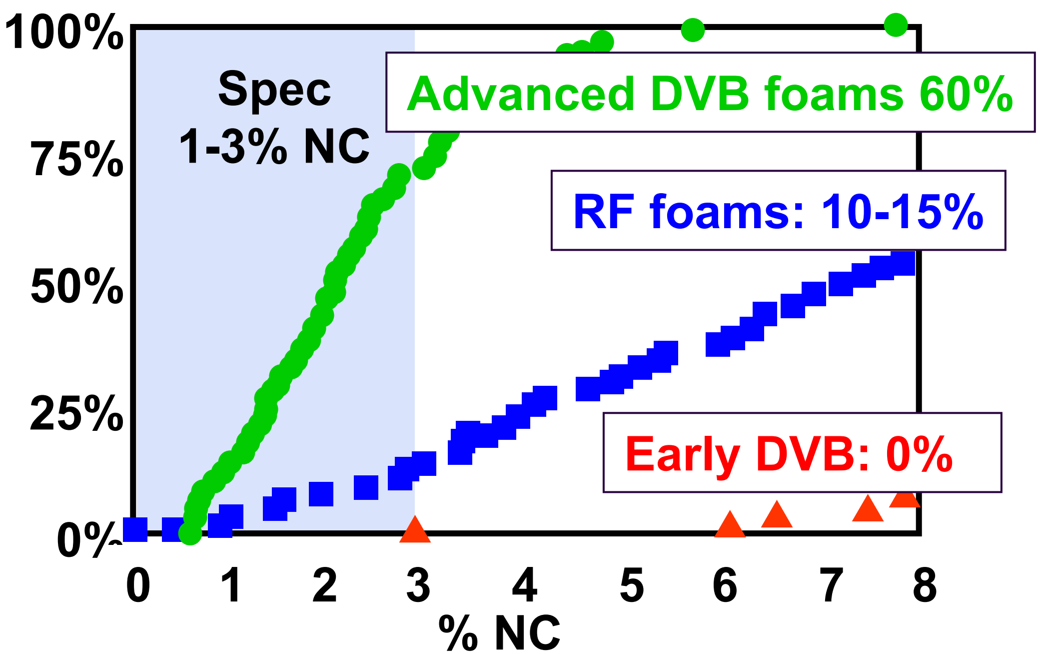


GA, Schaffer, UCSD

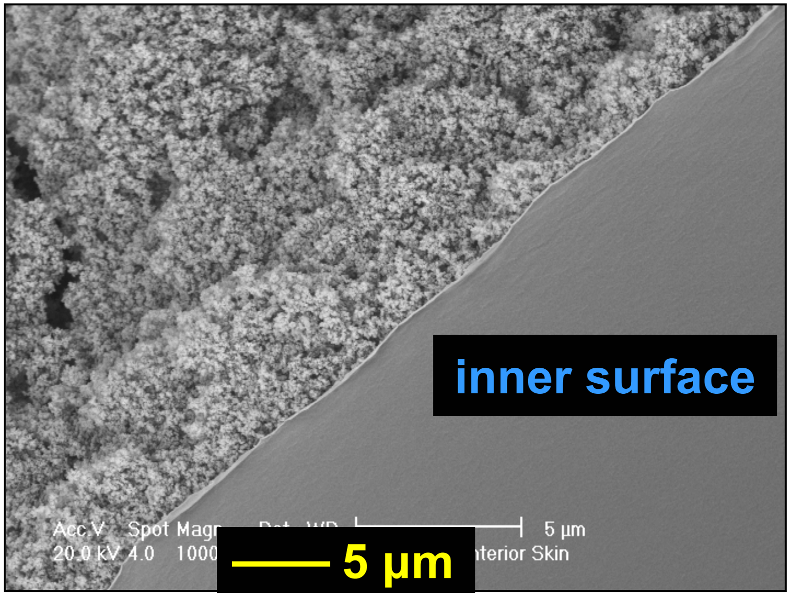
Recent target fabrication advances:

- ♦ Higher yield in non-concentricity
- ♦ Apply thin solid coat on foam during gellation

Higher percentage of shells that meet non concentricity (NC) specs



Proof of concept: Thin solid coating on Divinyl Benzine foam

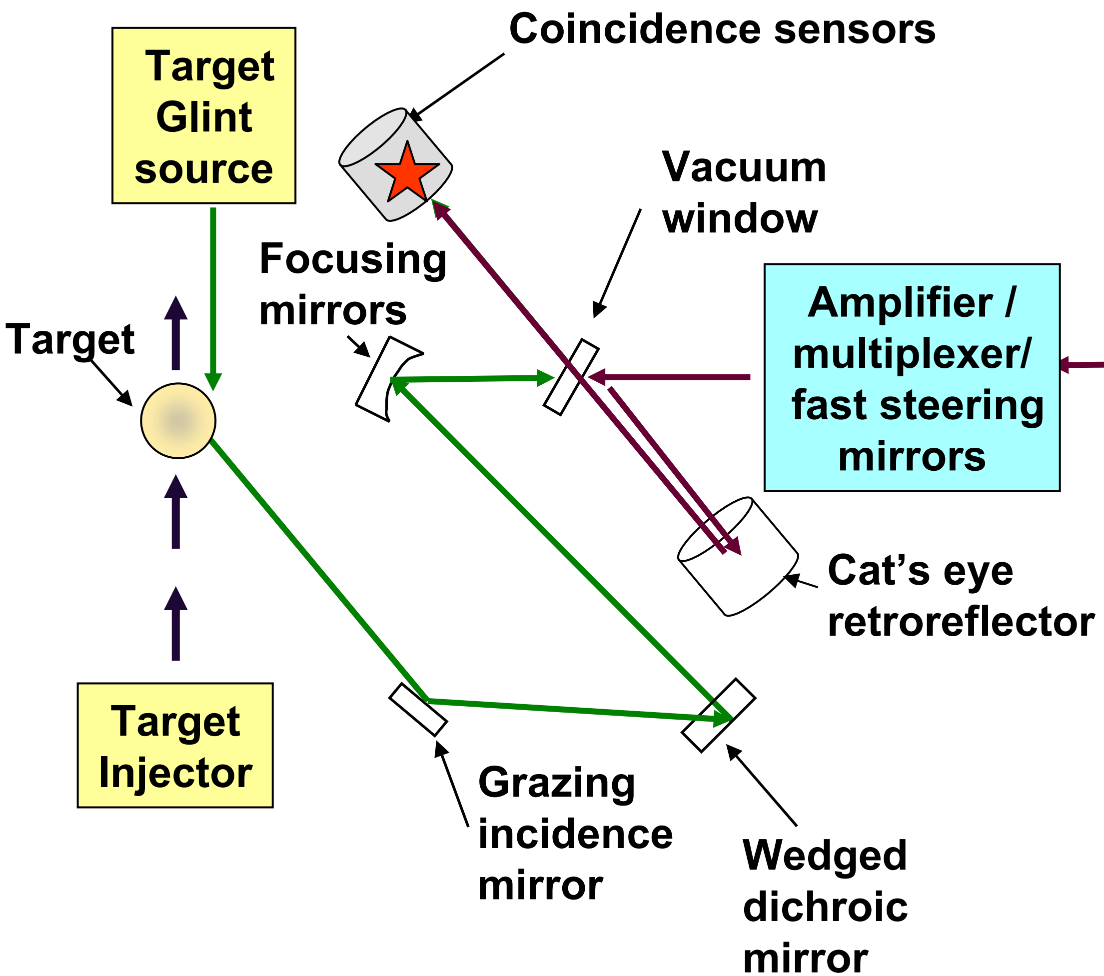


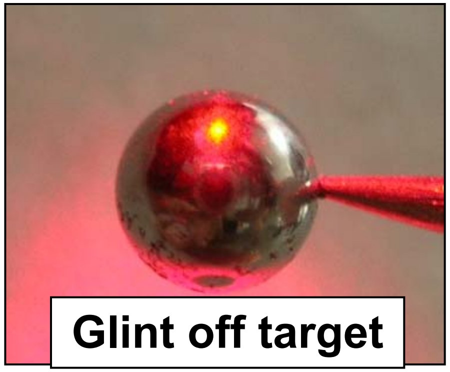
Schaffer Corp

General Atomics

Additional coating advances made at GA

Target Engagement:
Concept based on detecting "Glint" off the target.

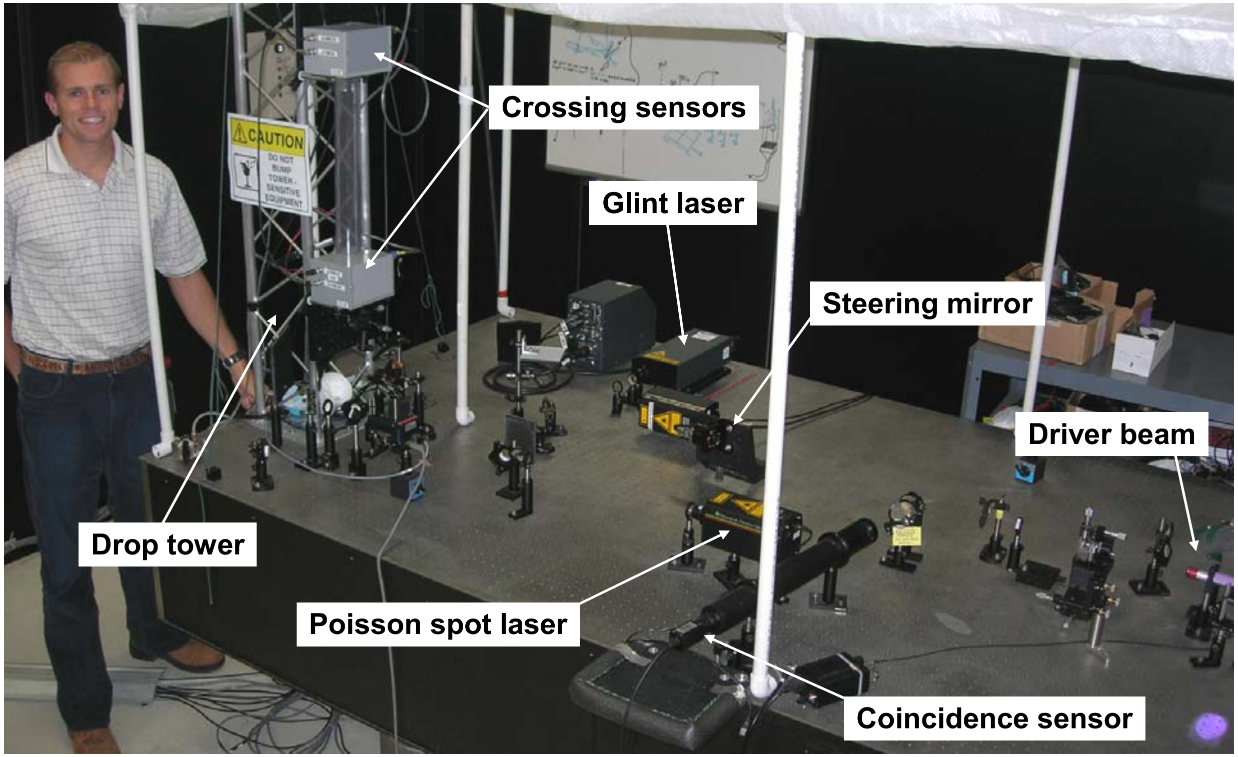


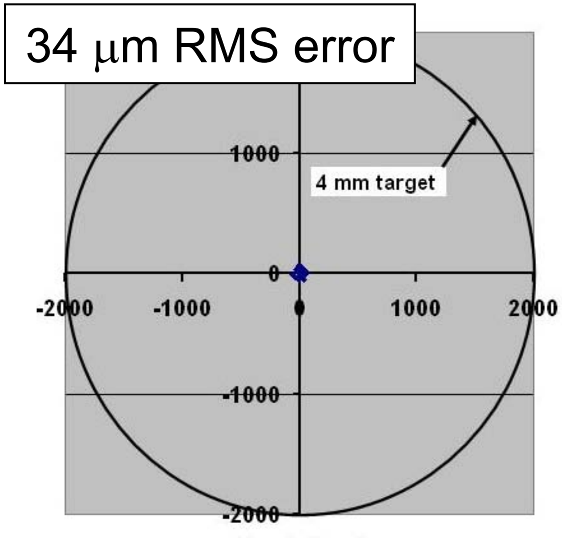


Glint off target

Lane Carlson (UCSD)

Target Engagement: Bench test: Mirror steers laser beam to target within 34 um. Need ~20



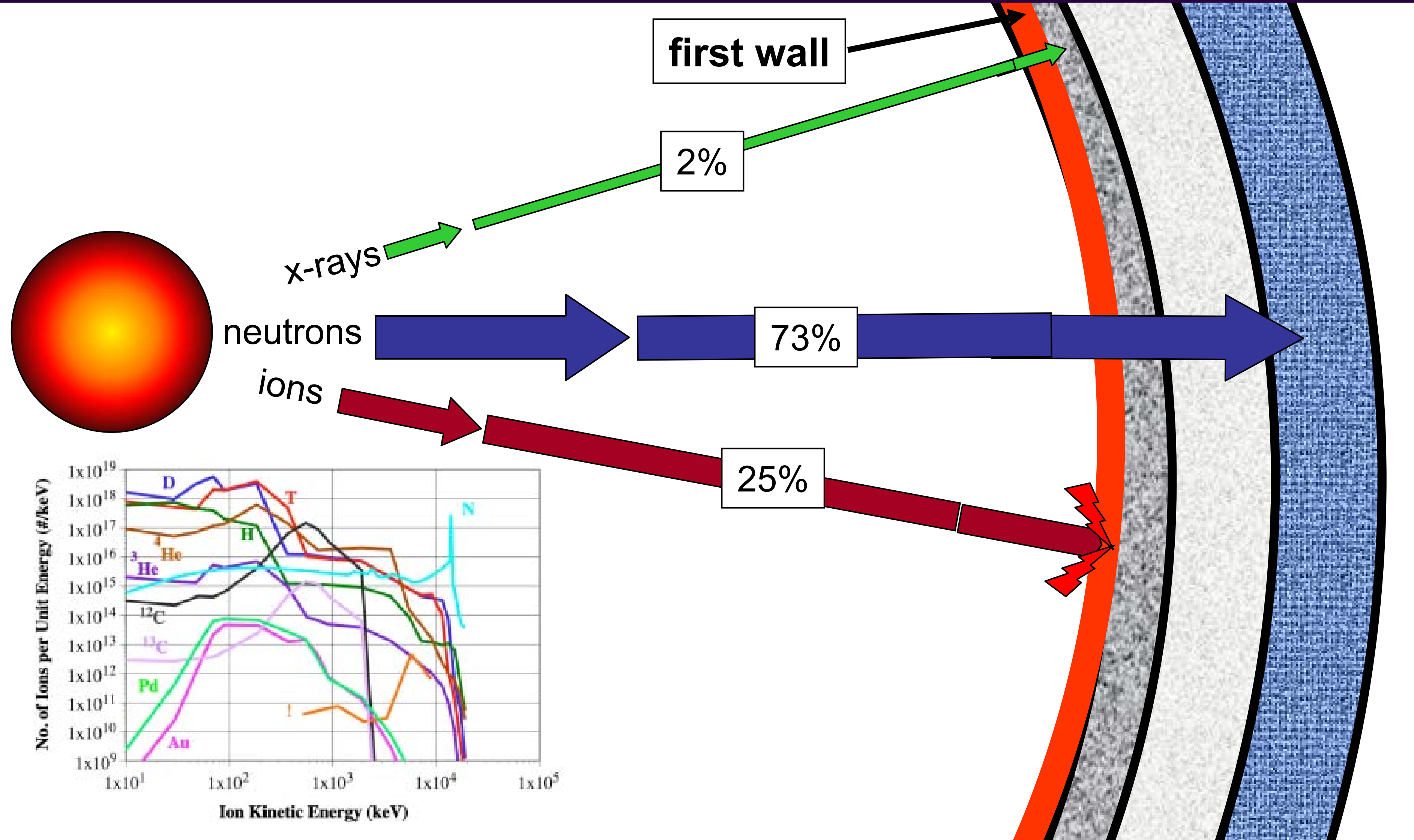


Lane Carlson (UCSD)

Advances and Achievements

- **target design**
- **lasers**
- **final optics**
- **target fabrication and engagement**
- **chamber**

The "first wall" of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.



Chamber options

Solid wall/vacuum	**Simplest** **Eases laser / target issues** ***Materials challenge***
Magnetic Intervention/vacuum	**Small chamber** **Really eases laser / target issues** ***The ion dumps***
Replaceable solid wall/vacuum Sawan, Wed SP3B-16	**Eases laser / target issues** ***Mechanical/operational complexity***
Gas in chamber Gentile, Wed SP3B-21	**Smaller chamber** ***Challenging laser / target issues*** ***Clearing Chamber (plasma)***
Thick liquid walls	**No materials issues (inc neutronics)** ***Challenging laser / target issues*** ***Droplet formation/ complexity***

combo

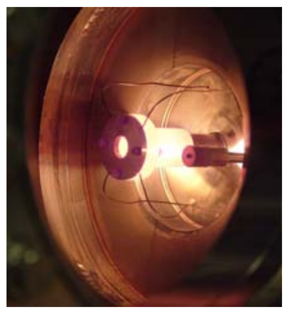
Solid Wall Chamber: Experiments/Modeling

Thermo-mechanical cyclic stress: *Mostly Solved*

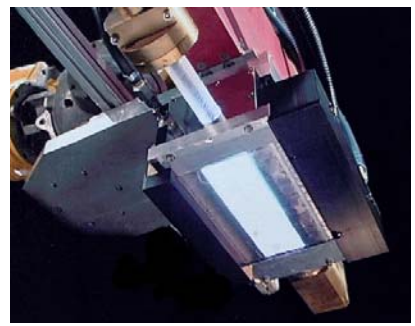
Surface & Interface

Ions:
RHEPP
(SNL)

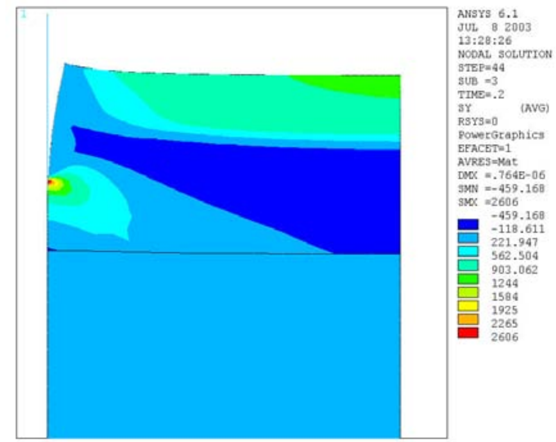
Laser:
Dragonfire
(UCSD)



Plasma Arc Lamp
(ORNL)

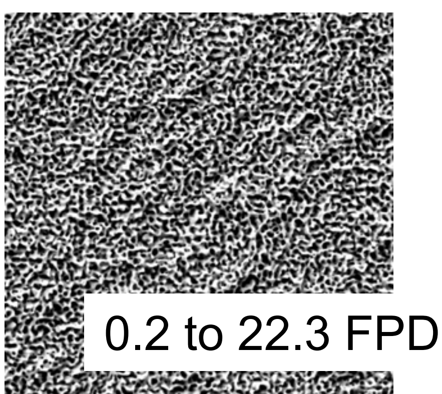


Modeling (Wisc/UCLA)



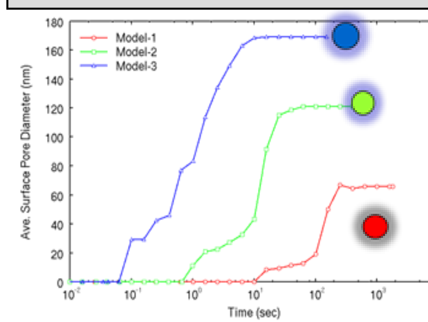
Helium Retention: *Remaining Major Challenge*

IEC (Wisconsin)

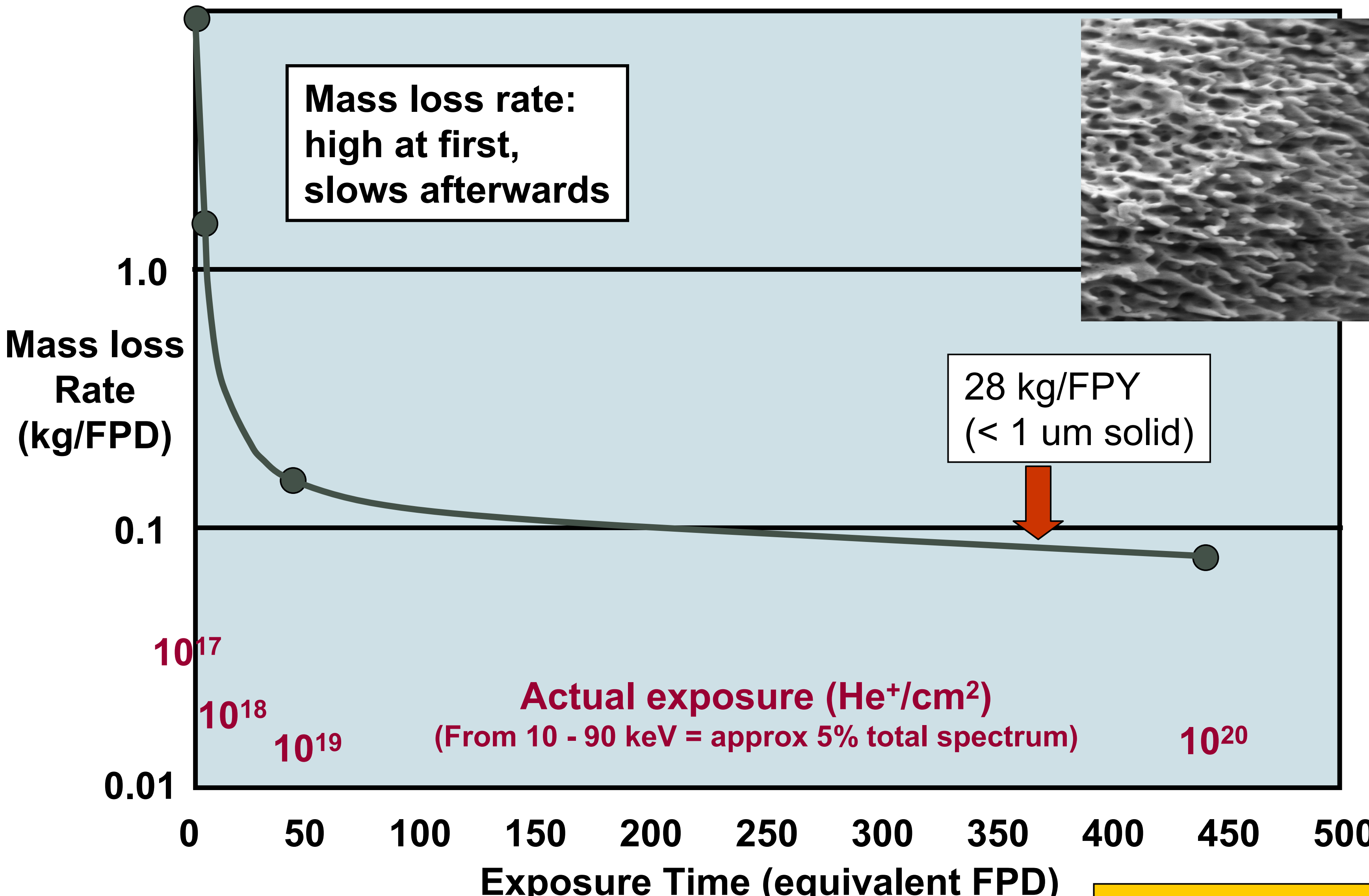


Van de Graff (UNC)

Modeling (UCLA/Wisc)

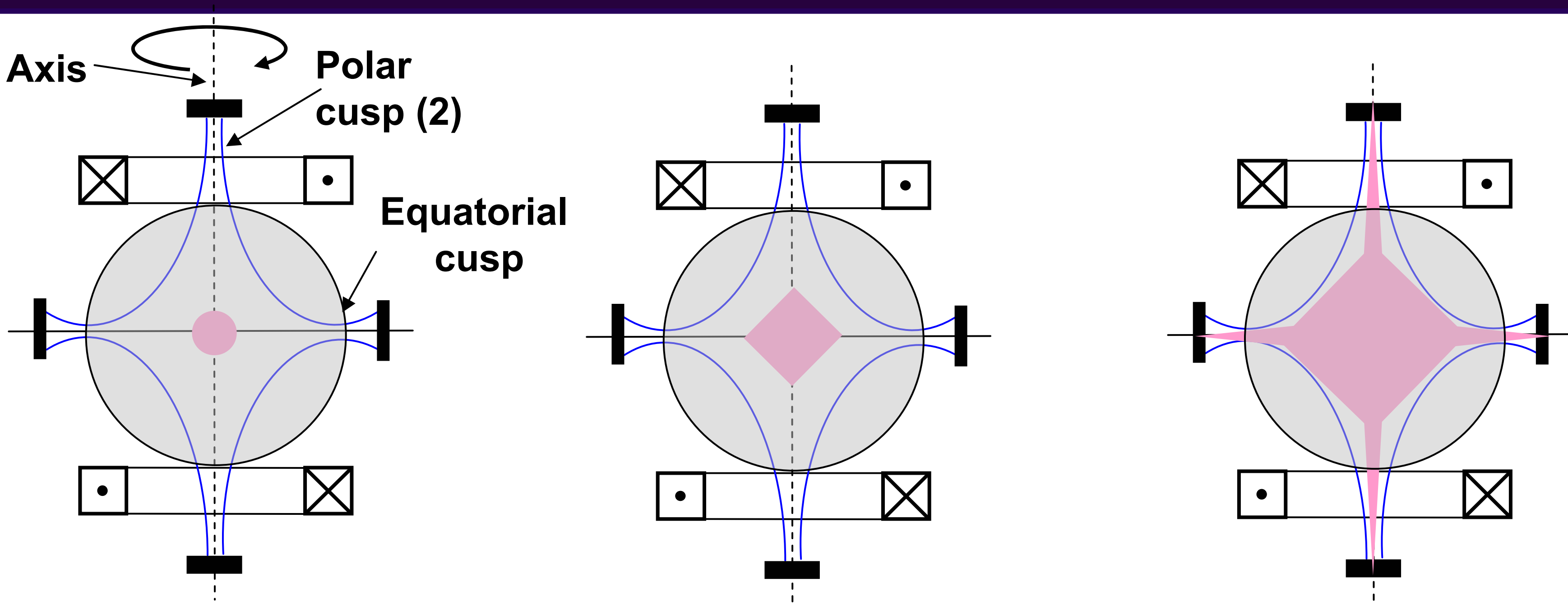


First "Nano-Engineered" Tungsten helium retention experiments are encouraging



Sam Zenobia (Wisconsin)

Magnetic Intervention:
Cusp magnetic field keeps ions off the wall
(in Plasma Physics terms: Conservation of $P_\theta = rA_\theta = 0$)

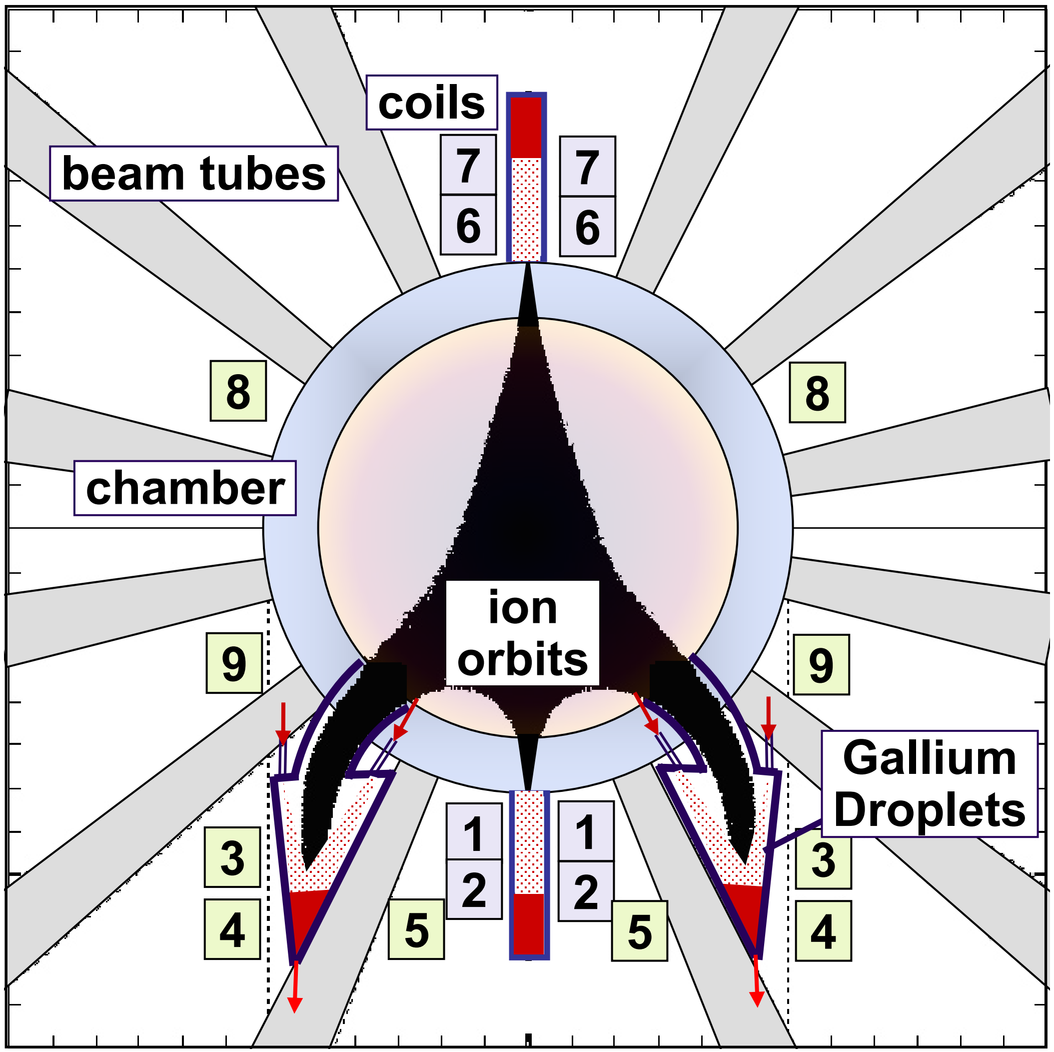


Plasma expansion initially spherical	**Ion cloud deforms as it encounters cusp**	**Ions, *at reduced power*, leak into external dumps**

1. **Physics demonstrated in 1979 NRL experiment:**
   R. E. Pechacek, et al., Phys. Rev. Lett. 45, 256 (1980).
2. **NRL experiment modeled by D. Rose at Voss Scientific (2006)**

An example of a Magnetic Intervention Chamber

Ions deflected downward by magnetic fields
Ion energy absorbed in Gallium Rain Ion Dissipaters™



Chamber radius: 5 m
Point cusps: 16 T
Main coils: 0.75 T

Energy absorption in Ga:
85% in first 10 mg/cm^2
15% in next 100 mg/cm^2

Only first layer evaporates

Gallium inventory enough so mean temp rise < 300°C

NB Vapor P of Ga = 10^{-6}T at 720 C

A.E. Robson, NRL (ret)

Objectives for next two years

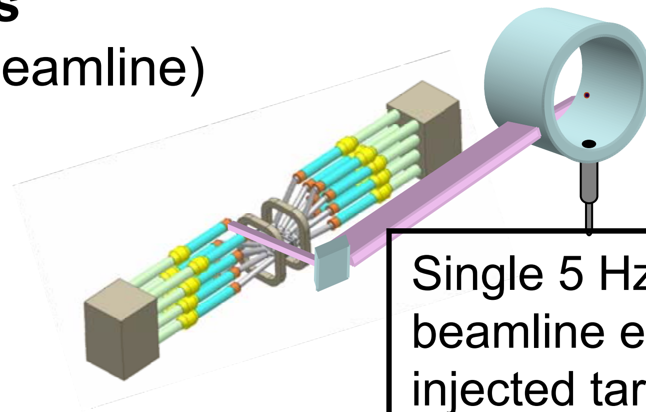
- Nike: Experiments/theory show physics advantages of KrF.
  - -- Refine/validate high gain designs
- Electra: Demonstrate >1 M shots continuous laser operation.
  - -- with technologies capable of 300 M shots (e.g. all solid state)
- Develop critical IFE technologies.
  - -- Mirrors, chamber concept(s), target fabrication / tracking, materials

If these are successful, next is a three stage program to IFE

A three stage plan for Laser Fusion Energy

<u>Stage I</u> : Develop full size components

- Laser module (e.g. 18 kJ 5 Hz KrF beamline)
- Target fabrication/injection/tracking
- Chamber design
- Refine basic pellet physics



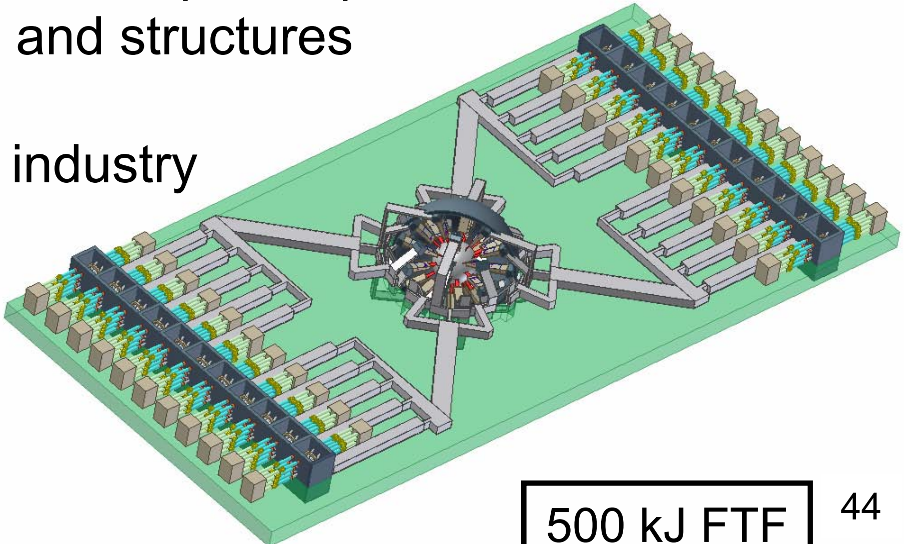
Single 5 Hz FTF beamline engages injected targets

<u>Stage II</u> Fusion Test Facility (FTF)

- Demonstrate physics / technologies for a power plant
- Develop/ validate fusion materials and structures
- Operating: ~2022
- Significant participation by private industry

<u>Stage III</u> Prototype Power plant(s)

- Electricity to the grid
- Transitioned to private industry



500 kJ FTF

What makes a credible fusion energy program?

fusion

The only function of ~~economic~~ forecasting is to make astrology look respectable.

John Kenneth Galbraith

What have we accomplished? (1 of 2)
or, the justification for pursuing an ***energy*** program

- **KrF based target designs show energy class gains < 1 MJ.**
  Designs backed with experimentally verified codes
  KrF advantages demonstrated (LPI, hydro, uniformity).
  - **Need experiments at higher energies, more robust designs**

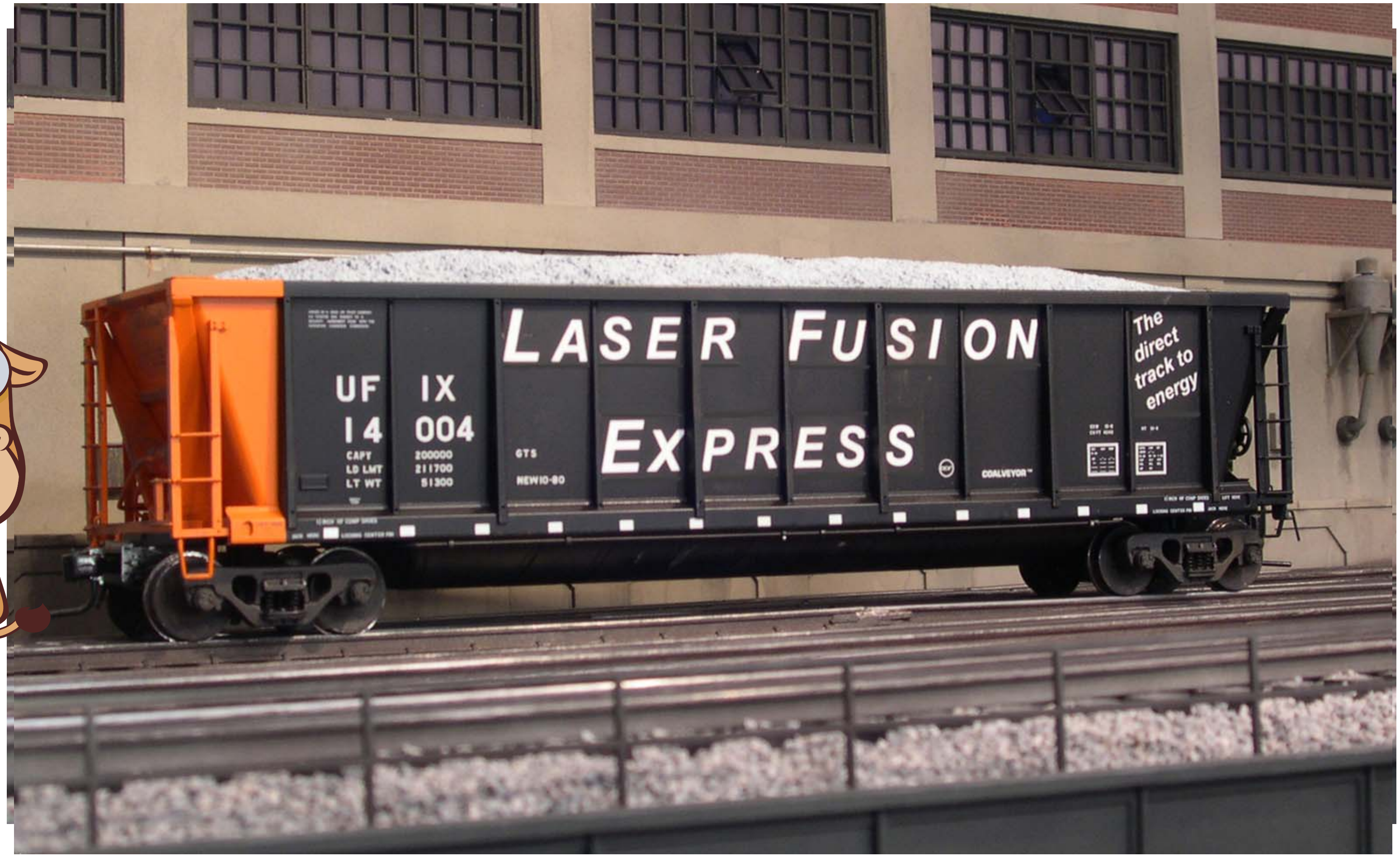
- **KrF lasers demonstrated, with scalable technologies:**
  Rep rate (2.5 - 5 Hz)
  Efficiency (> 7%) (with individual components)
  High energy rep-rate operation (250-700 J).
  Continuous operation (10 hr)
  Credible path to durability
  - **Need integrated 1 M shot continuous demonstration**

Continued on next slide....

What have we accomplished? (2 of 2)

- **Optics components resistant to prototypical neutrons, laser damage**
  - Need larger sizes, need extension to 300 M shots (from 10 M)
- **Can mass produce high precision foam shells for targets**
  - Need higher yield, Need gas tight coating
- **Demonstrated smooth DT ice over foam layer**
  - Need mass production layering demonstration (Fluidized bed)
- **Demonstrated target engagement using glint technique**
  - Need another 14 um pointing (now at 34, need 20)
- **Several viable chamber concepts, backed with experiments/theory**
  - Need refinement, integrated, economical design
- **Have conceptual designs for ancillary components:**
  - Blanket, tritium handling/processing, vacuum system, power conversion

The Vision…A plentiful, safe, clean energy source



A 100 ton (4200 Cu ft) ***COAL*** hopper runs a 1 GWe Power Plant for ***10 min***

Same hopper filled with ***IFE targets***: runs a 1 GWe Power Plant for ***7 years***

The Research Team

19th HAPL meeting
Oct 22-23, 2008
Madison WI
54 participants, 10 students

Government Labs
1. NRL
2. LLNL
3. SNL
4. LANL
5. ORNL
6. PPPL
7. SRNL

Universities
1. UCSD
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. UC Berkeley
7. UNC
8. Penn State Electro-optics

Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. APP
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI