High Power Lasers... Another approach to Fusion Energy

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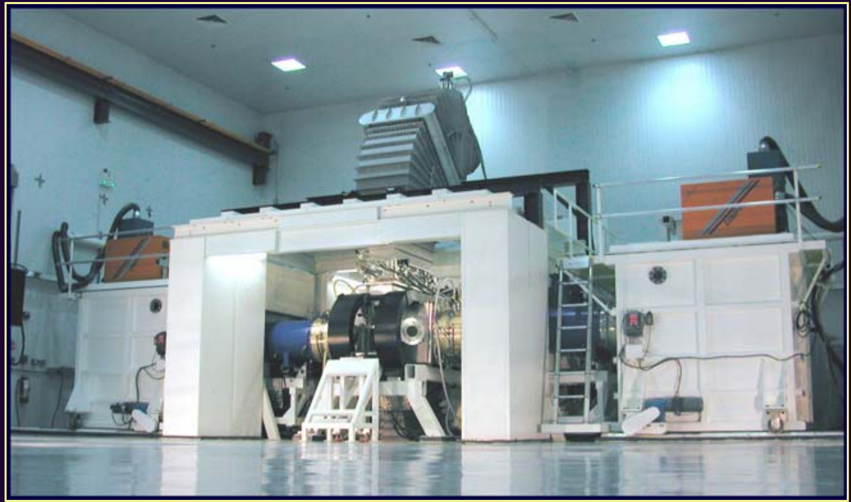


Main points of the talk

Fusion Energy based on lasers and direct drive targets

Can lead to an attractive electricity generating power plant

Developing Laser Fusion as an integrated system

Simultaneously addressing the science and engineering

Direct Drive Pellet Designs

Computer Models show target gain > 150
(need >100 for energy)
Underlying codes backed with experiments

KrF Lasers

Attributes : Beam uniformity, wavelength, cost, scaling to large systems
Technologies for rep-rate & efficiency look good,
Biggest challenge: durability of pressure foil

Progress made in the other Laser IFE components

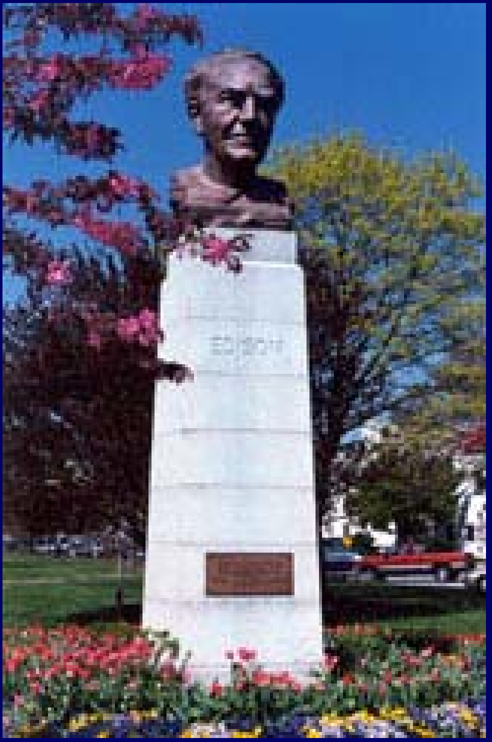
The Naval Research Laboratory (NRL)

- **NRL is the Navy's Corporate Research Laboratory**
  - **3000 employees, (900 PhDs + 400 MSc)**
  - **$800 M /year budget**

- **Field sites:**
  - **Washington DC (Main site)**
  - **Stennis, MS**
  - **Monterey, CA**
  - **Chesapeake Bay, MD**

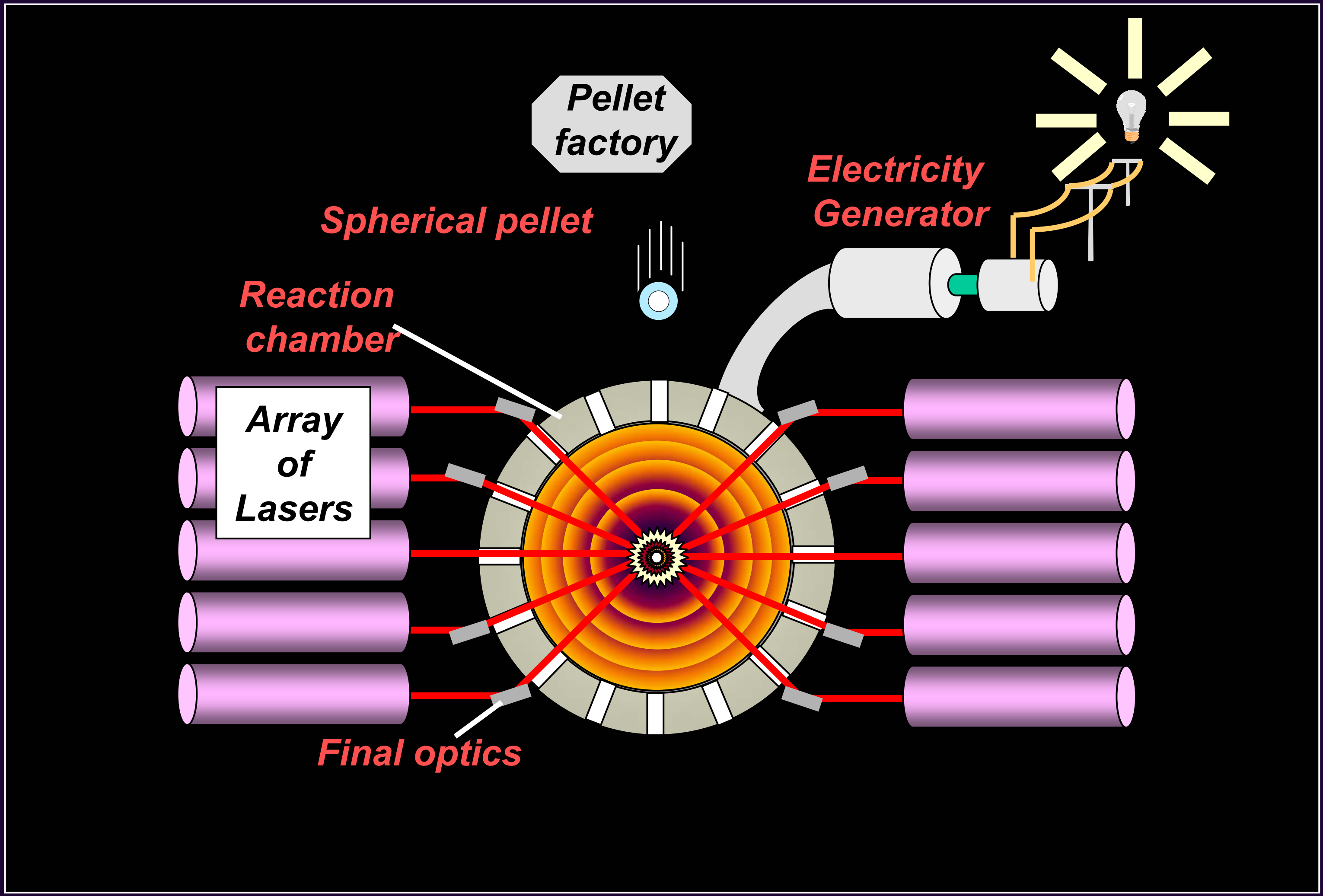
NRL conducts a broadly-based multidisciplinary program of scientific research and advanced technology

Radar
GPS
Viking (First useable satellite)



NRL Leads a National Program to develop the science and technologies for Laser Fusion Energy:
The NRL Nike Program and the High Average Power Laser (HAPL) Program

The laser fusion energy concept



Why we like fusion energy with lasers, direct drive targets and solid wall chambers

- **Physics and engineering looks good:**
  - Target simulations show high gains (>150) needed for energy
  - Lasers appear to be able to meet physics & engineering requirements

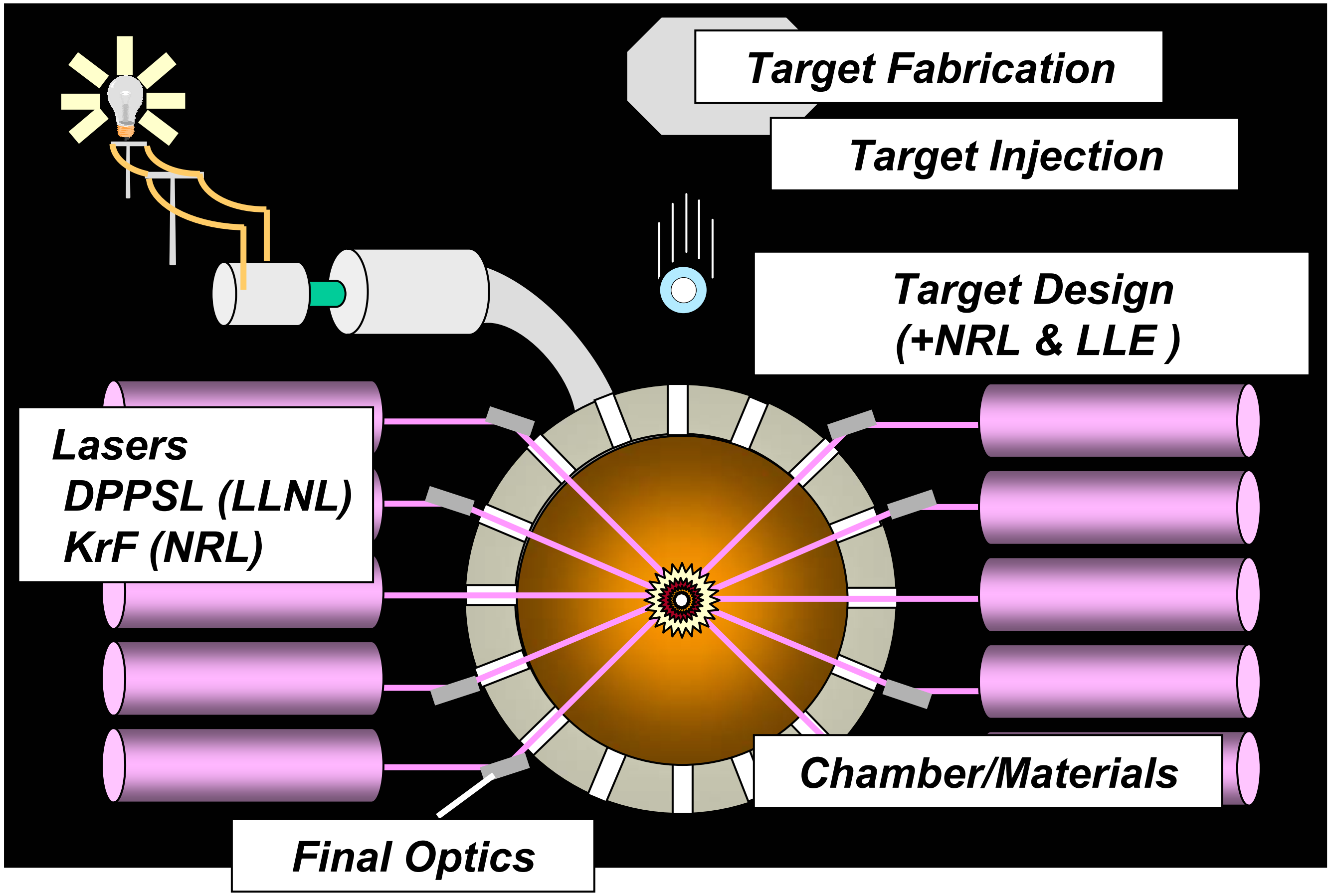
- **Inherent Engineering Advantages:**
  - Complex components (laser, target factory) are separated from the reaction chamber
  - Modular nature of the components

- **Reduced risk and cost of development:**
  - Laser made of identical beam lines

- **Substantial technical progress since program started 4 years ago**

The fastest, least expensive and least risky approach to develop fusion energy:

Develop the key science and technologies together, using the end goal of a practical power source as a guide



The High Average Power Laser (HAPL) Program:

An integrated program to develop the science and technology for Laser Fusion Energy

6 Government labs, 9 Universities, 13 Industries

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

Universities
1. UCSD
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. PPPL
7. UC Santa Barbara
8. U North Carolina
9. UC Berkeley

Industry
1. General Atomics
2. Titan/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Mission Research Corp
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. Optiswitch Technology

TARGET PHYSICS

Inertial Fusion Energy (IFE) with Lasers

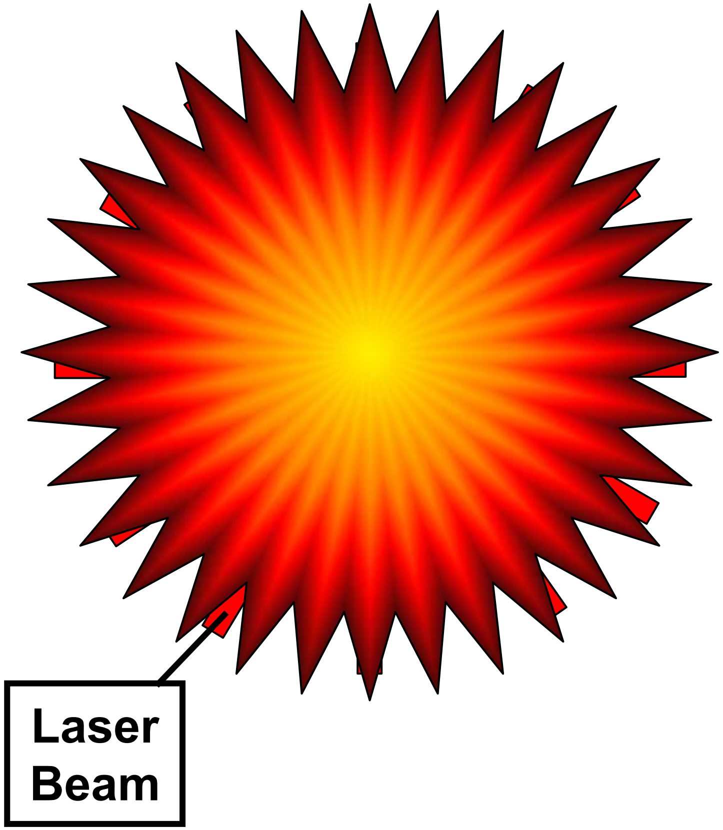
1. An array of laser beams symmetrically illuminate a spherical shell of DT fuel

2. Lasers *ablate* outer layer of pellet. Ablated material expands outward

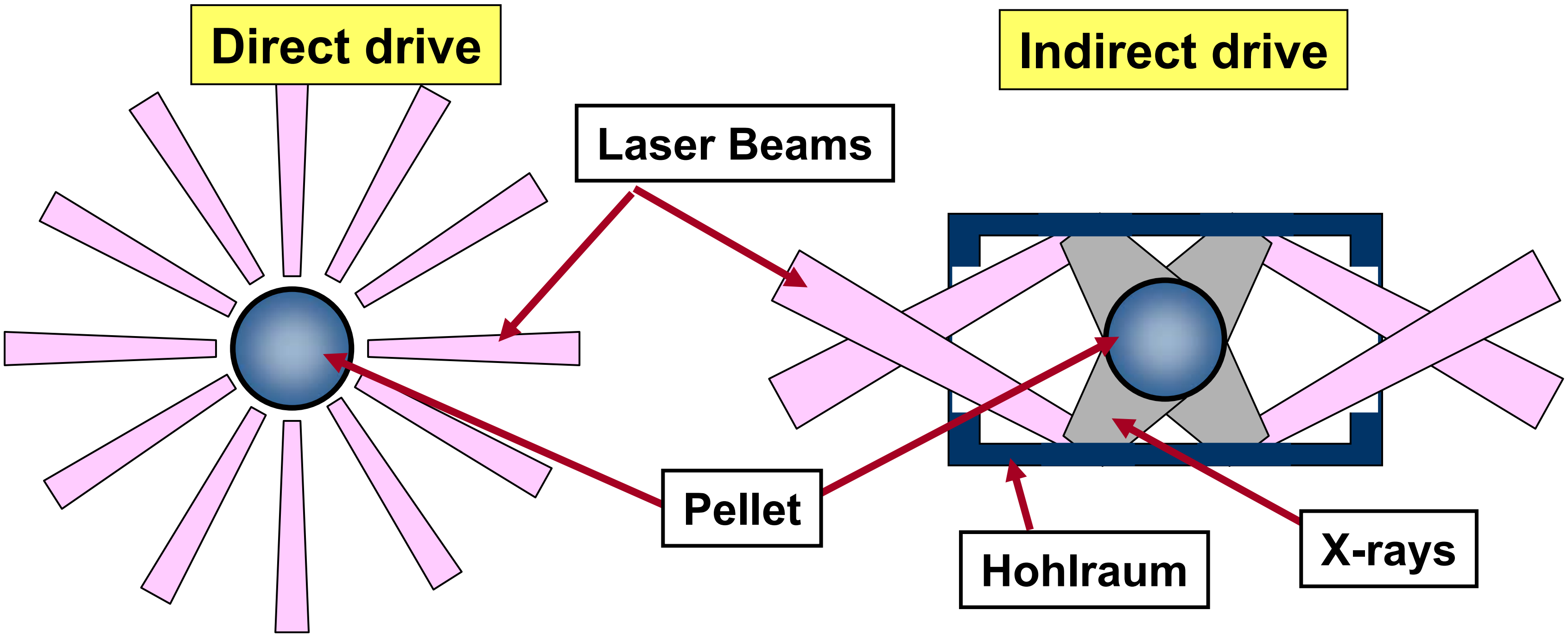
3. Core driven inward by rocket effect Compressed to very high density (1000 x solid)

4. Localized "hot spot" ignites

5. Fusion burn propagates through fuel



Why we like direct drive for laser fusion



Physics is simpler --key issue is hydrodynamic stability

Higher efficiency --better coupling of laser to fuel

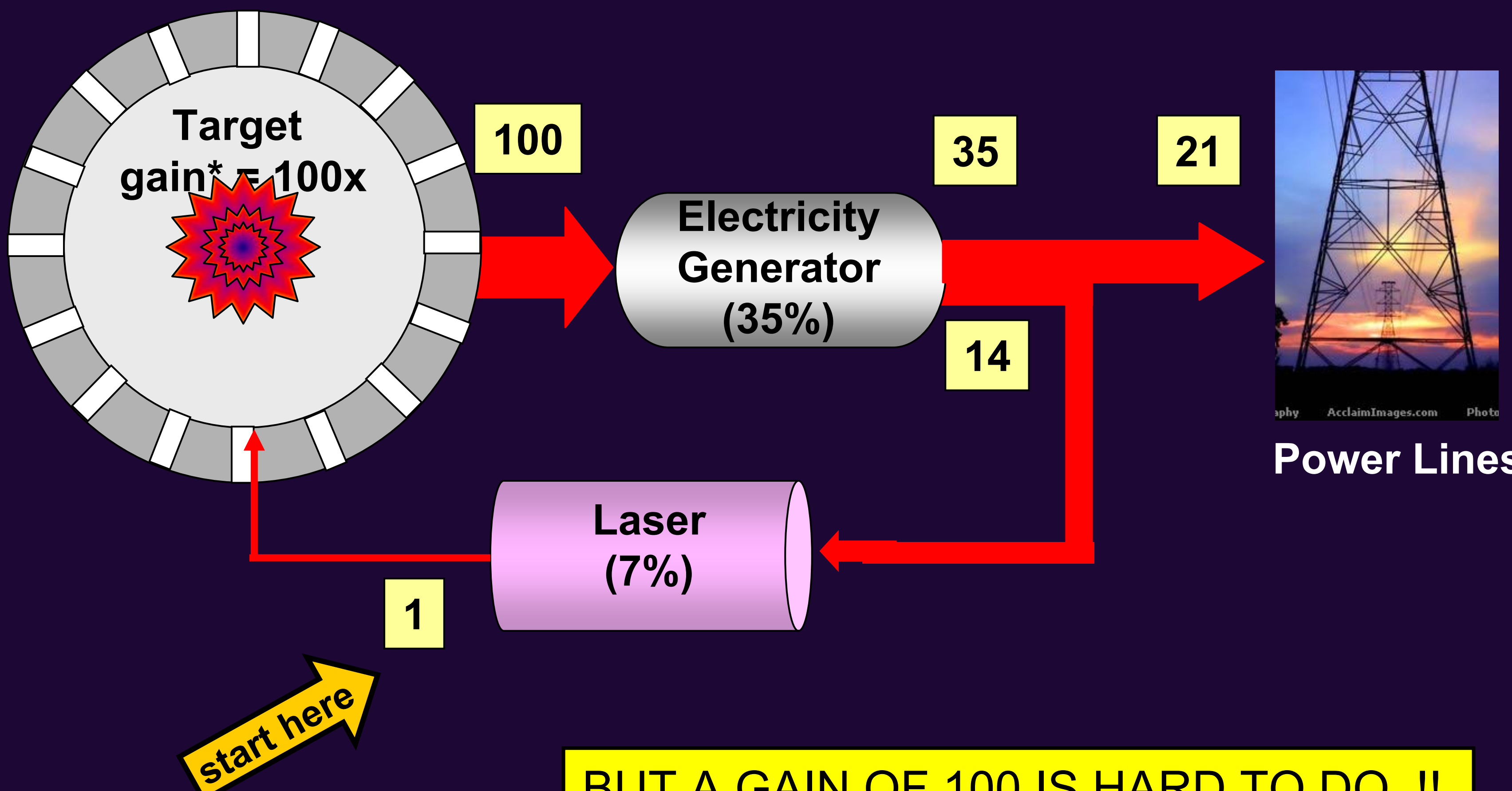
Targets relatively simple (cheap) to fabricate

No preferred illumination direction

Simpler operational issues: no hohlraum debris to recycle

The target has to make enough energy to run the power plant *and* have enough left over to produce electricity

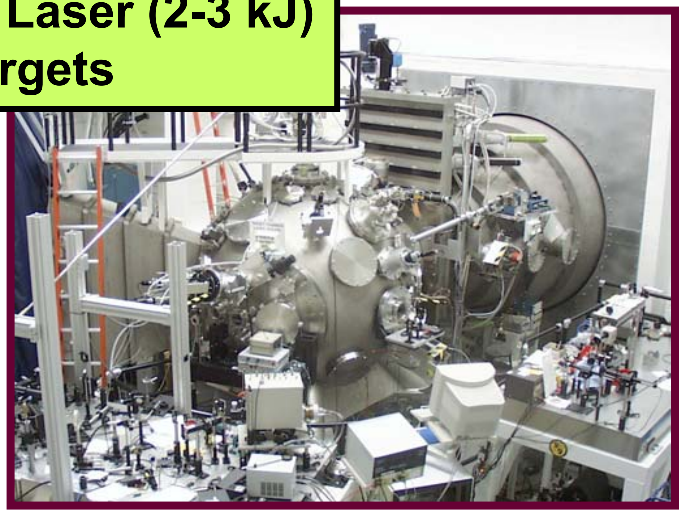
A Target "Gain" of > 100 x should be sufficient*



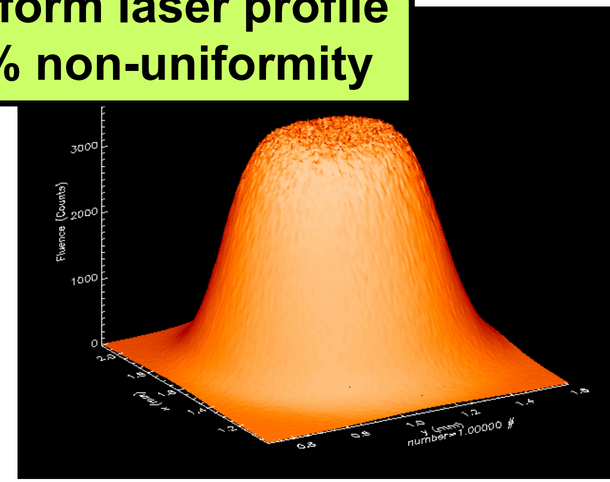
BUT A GAIN OF 100 IS HARD TO DO !!

NRL Nike Program has the proper tools to develop and evaluate the physics of high gain target designs

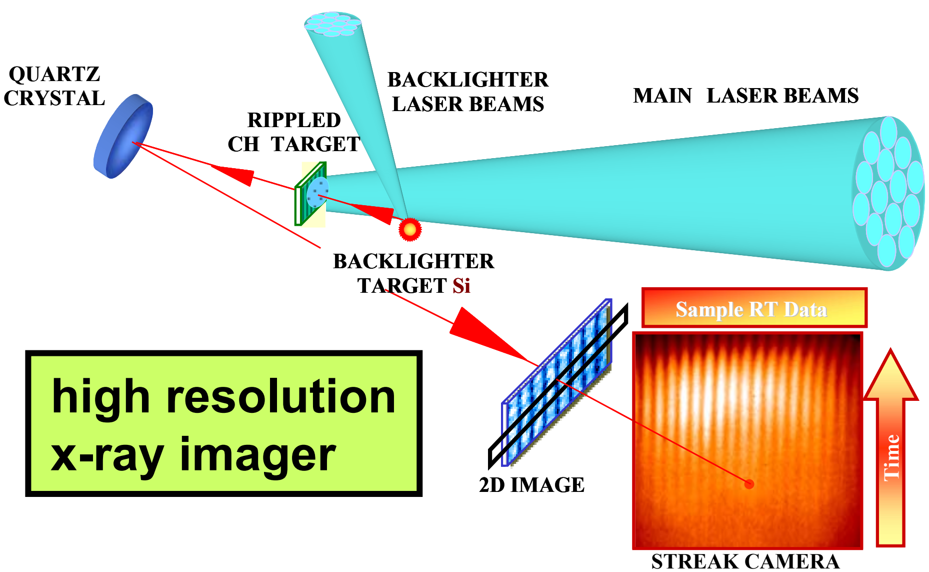
Nike KrF Laser (2-3 kJ)
Planar targets



Ultra uniform laser profile
0.3 - 1.3% non-uniformity

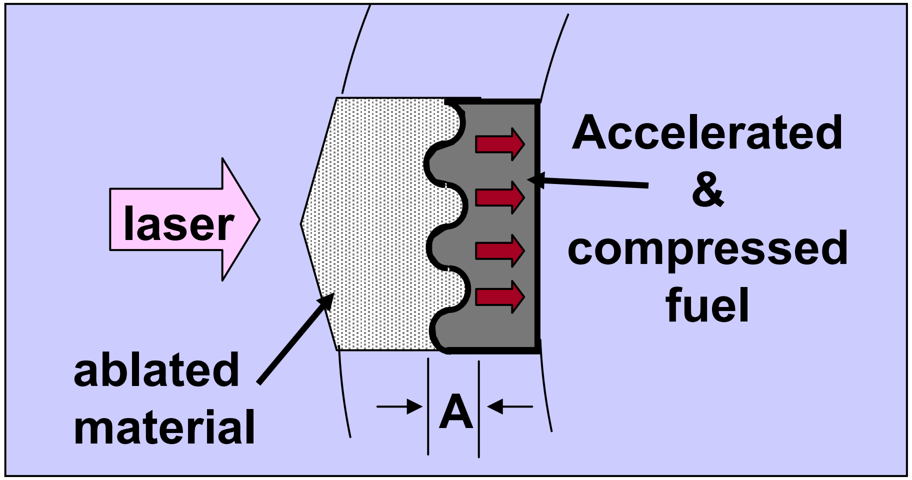


2 "self built" 256-Processor super-computers allow high resolution simulations of pellet implosions



high resolution x-ray imager

High Gain Direct drive requires control of Rayleigh Taylor Instability: Need to minimize both the initial mass modulations and the growth rate



Amplitude of mass modulations

Rayleigh Taylor growth factor

STEP #1:

a. Raise Isentrope (lower the density) of the ablator

$$A(t) = A_o e^{\gamma t}$$

Initial mass modulation

Laser non-uniformities

Target non-uniformities

STEP #2:

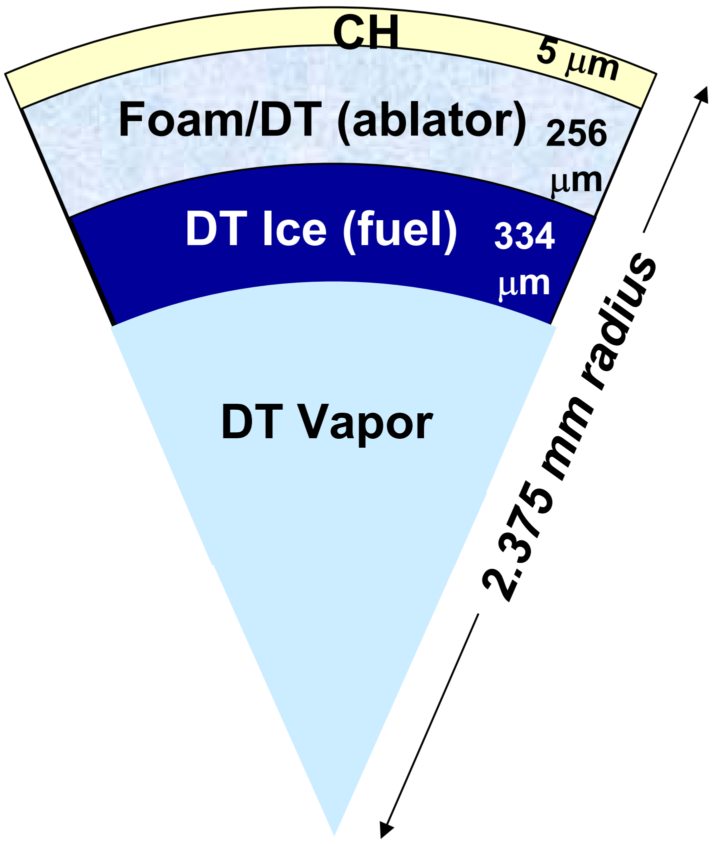
a. Use a Smooth Laser Beam

b. Reduce Laser Imprinting

c. Make target outer surface smooth

Current high gain target designs:
Ablator: DT+ Foam
Fuel: Pure DT

Sector of Spherical Target (NRL Design)



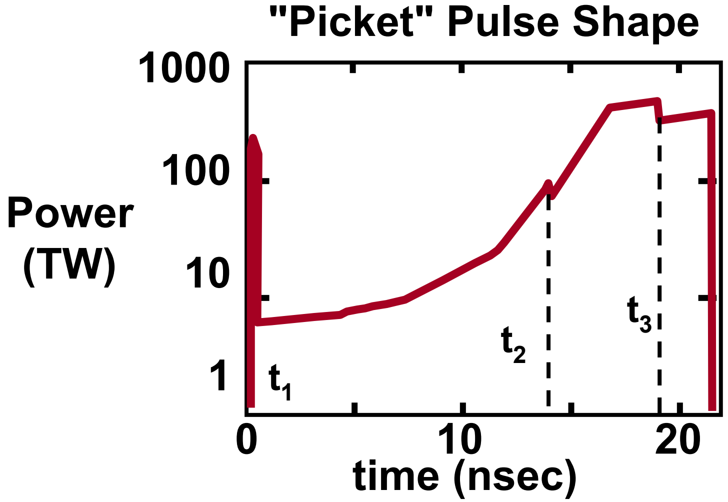
This design is very flexible.
It can (and has been) modified to meet the requirements for a power plant:

- **Fabrication**
- **Injection- acceleration**
- **Injection- survival**
- **Emissions**
- **Recycling**

Target gains > 160 are predicted with 2D computer simulations

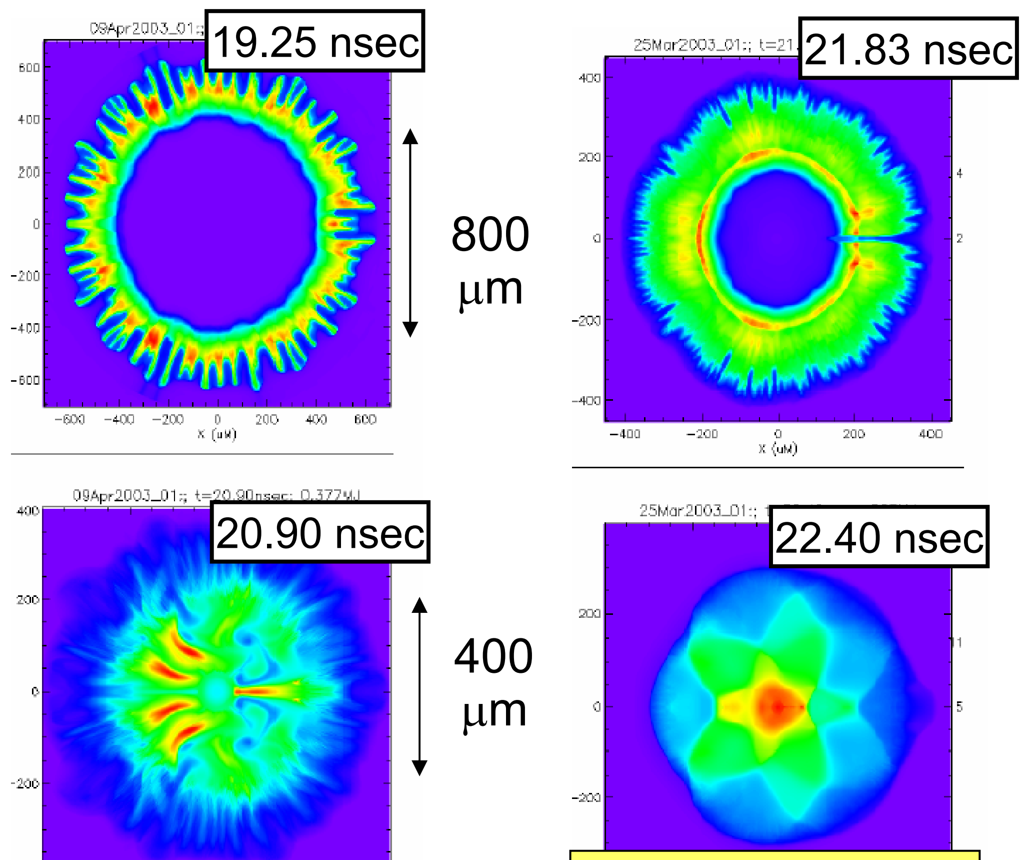
NRL FAST CODE: high precision 2D calculations that include all relevant modes and non-uniformities in the target and laser

Laser = 2.5 MJ



No Picket

With Picket

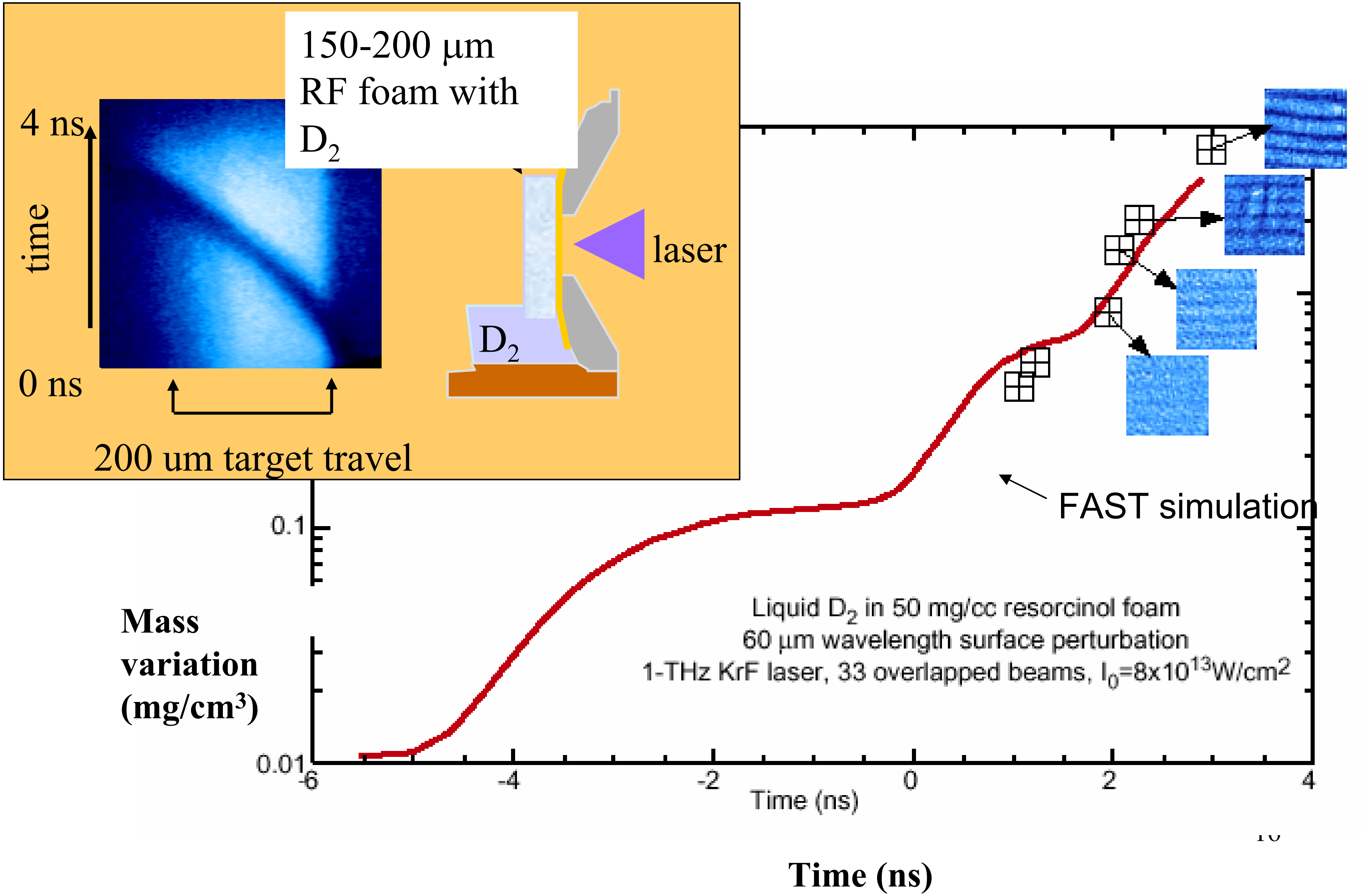


GAIN = 0.5 ☹

GAIN = 160 ☺

Similar predictions from University of Rochester, LLE and Lawrence Livermore National Lab

NRL target physics codes (aka FAST) have been benchmarked with experiments on Nike Laser



The Laser

What do we need for a Fusion Laser?

Can be repetitively pulsed (~ 5 pulses/second)
(means you have to be able to cool it easily)

Capable of High Energy per pulse (~50,000 Joules)

Short pulse length (4-8 nsec)

Very smooth laser beam (minimize A_0, seed for instability)

Ultra-violet (UV) wavelength (minimizes instabilities, maximizes coupling)

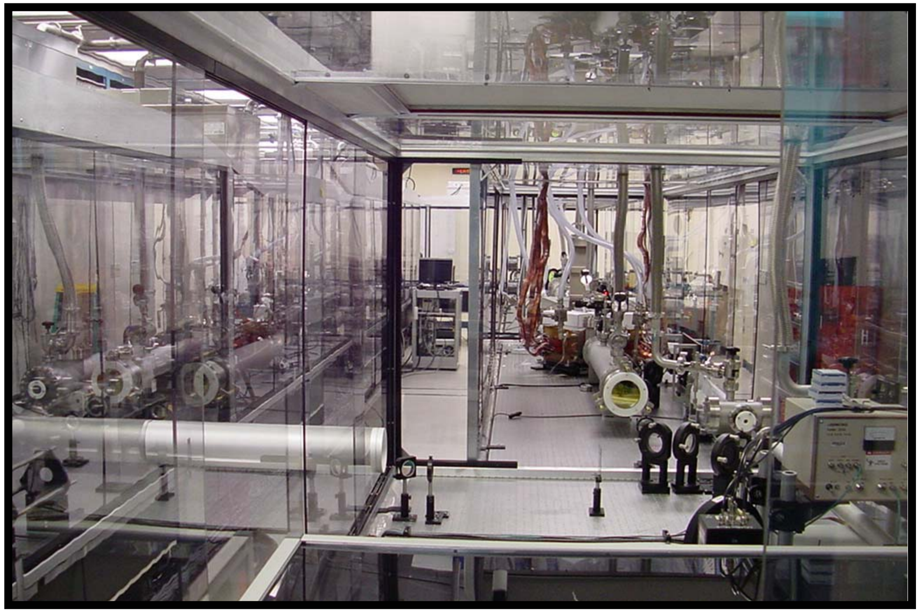
Low cost technology

Efficient (> 6% total)

Robust & Durable (2 years = 300,000,000 shots)

Two types of lasers are being developed for IFE:

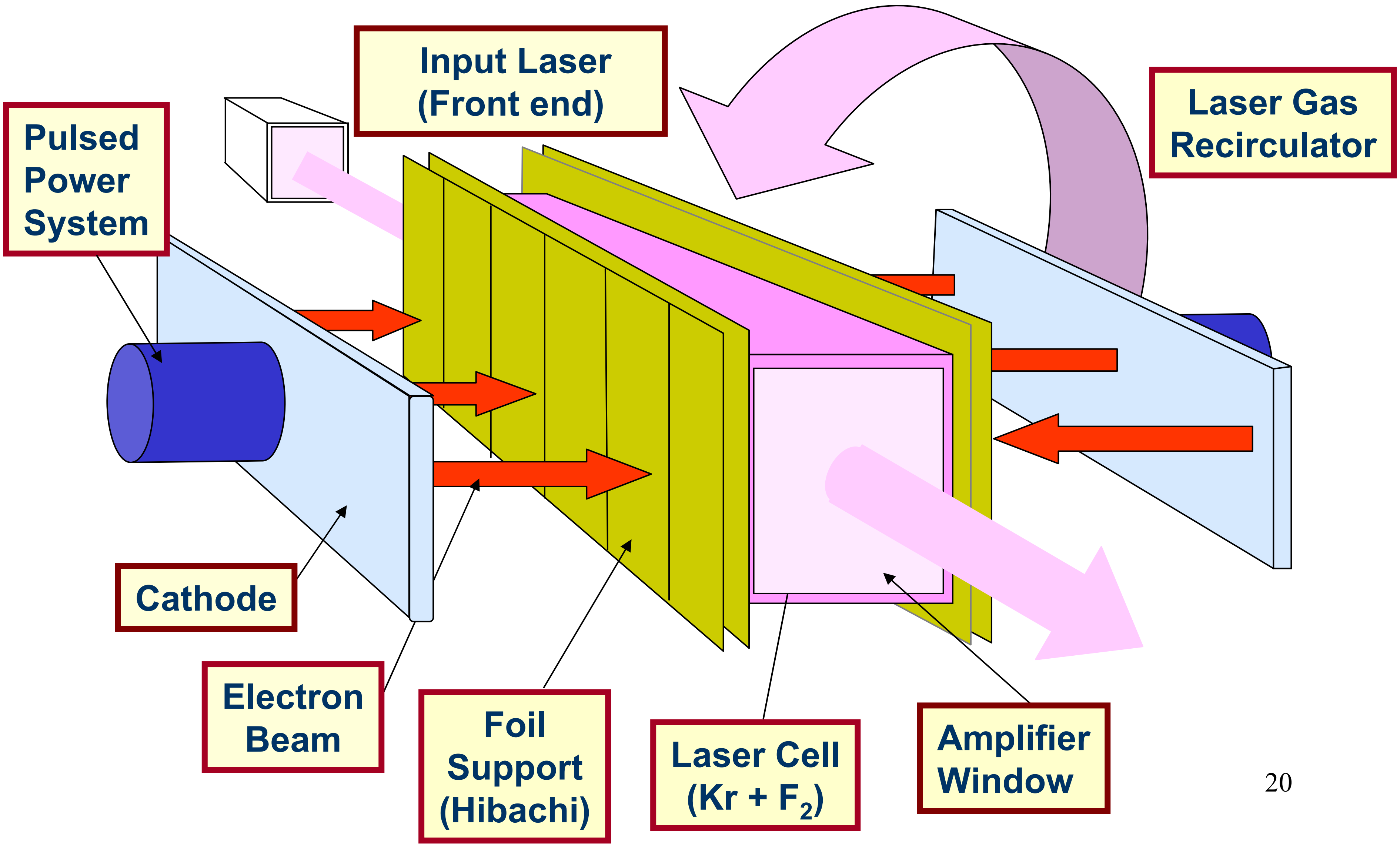
DPSSL (Mercury-LLNL)
Diode pumped solid state laser



KrF Laser (Electra-NRL):
electron beam pumped gas laser

Key Components of an electron-beam pumped KrF Laser

Energy + (Kr+ F_2) $\Rightarrow$ (KrF)* + F $\Rightarrow$ Kr + F_2 + hν (λ = 248 nm)



The advantages of a KrF laser

Can be repetitively pulsed (~ 5 pulses/second)

Capable of High Energy per pulse (~50,000 Joules)

Short pulse length (4-8 nsec)

Very smooth laser beam (minimize A_0, seed for instability)

Ultra-violet (UV) wavelength (minimizes instabilities, maximizes coupling)

Low cost technology (Industrial, pulsed power technology)

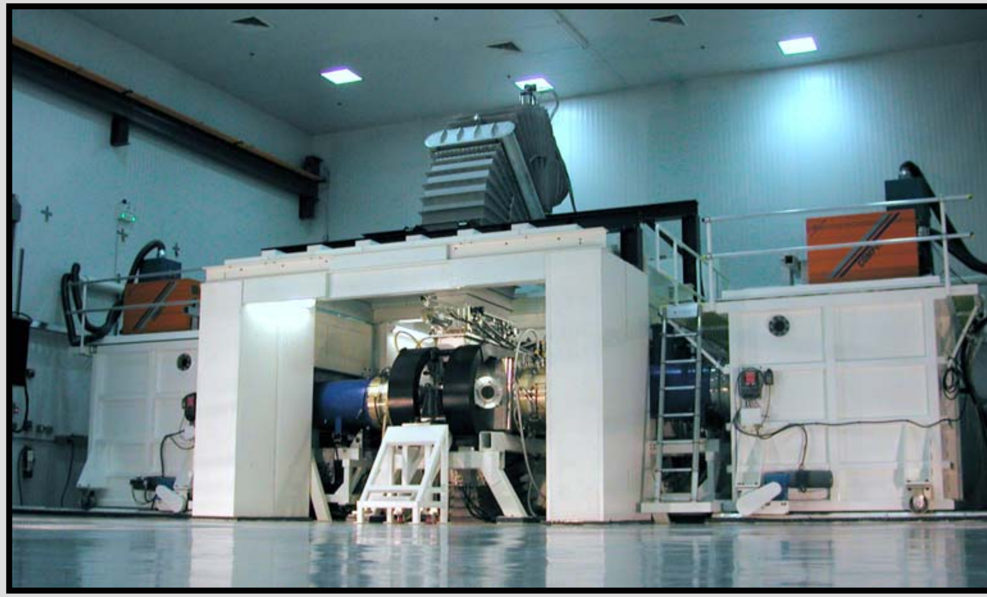
Efficient (> 6% total) (Predict 7%, based on recent R&D)

Robust & Durable (Good progress)

The key issues for KrF are being addressed with the Electra and Nike Lasers at NRL

Electra:
400-700 J laser light
500 keV/100 kA/100 nsec
up to 5 Hz

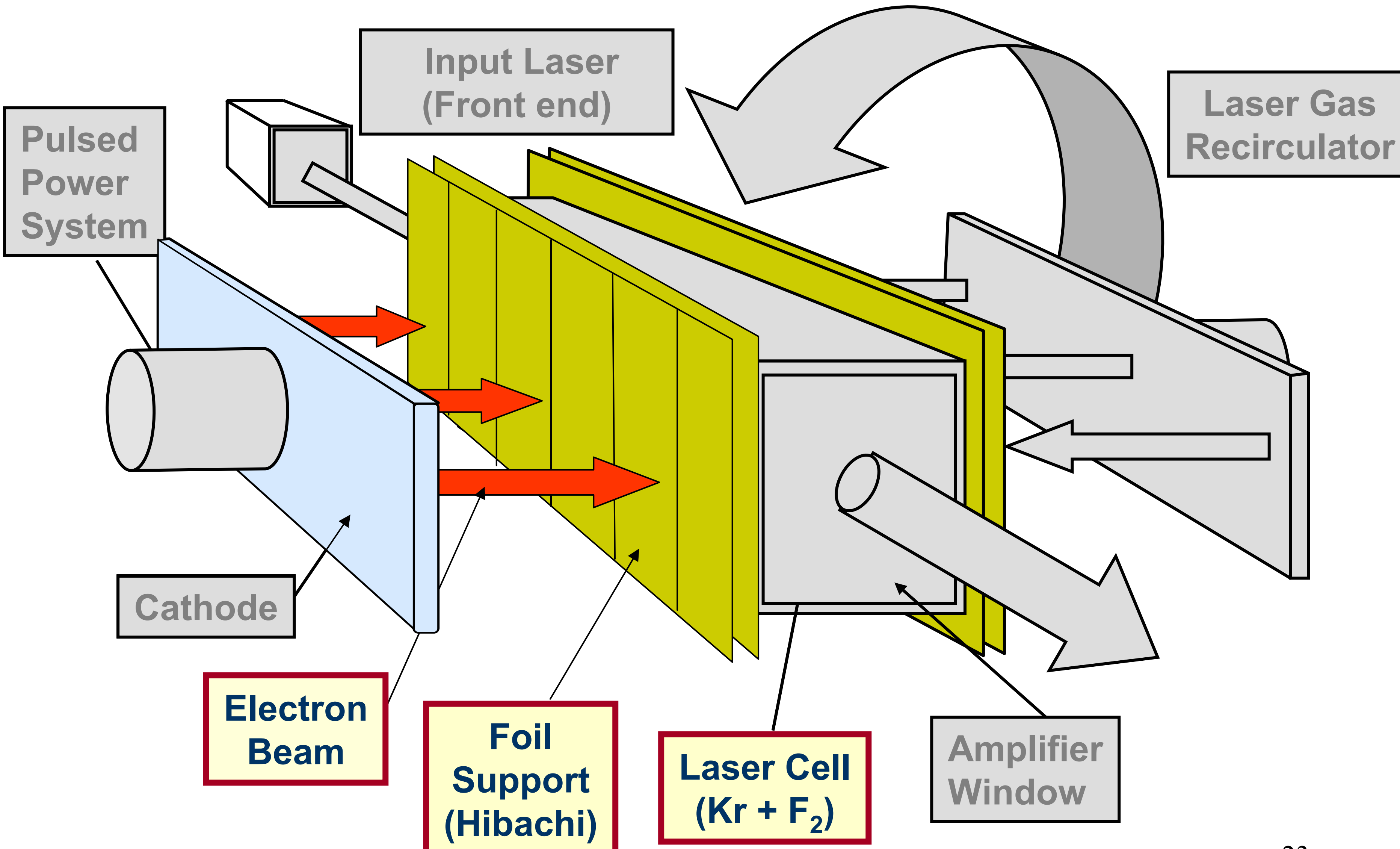
Develop technologies for:
Rep-Rate,
Durability,
Efficiency,
Cost



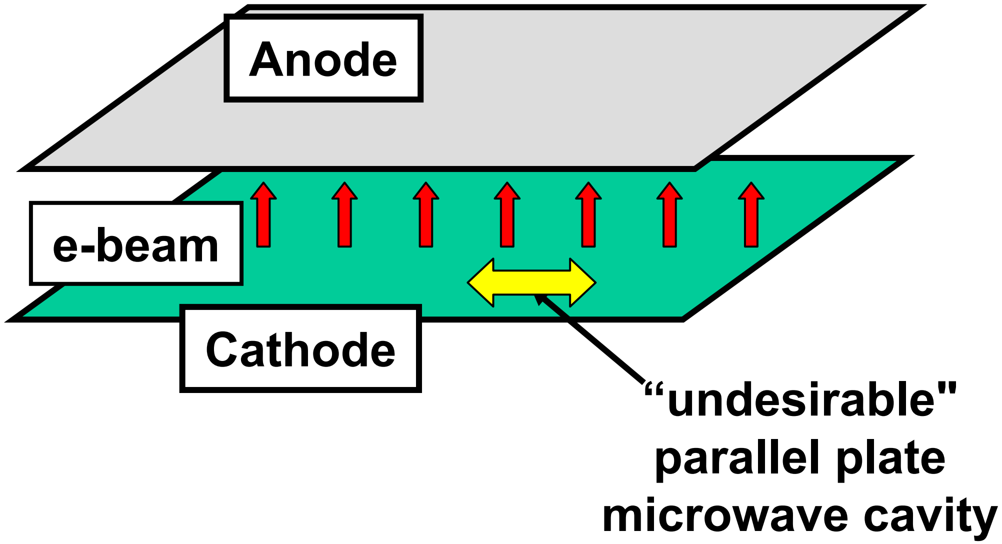
Nike:
3-5 kJ laser light
750 keV, 500 kA, 240 nsec
single shot

E-beam physics on full scale diode
Laser-target physics

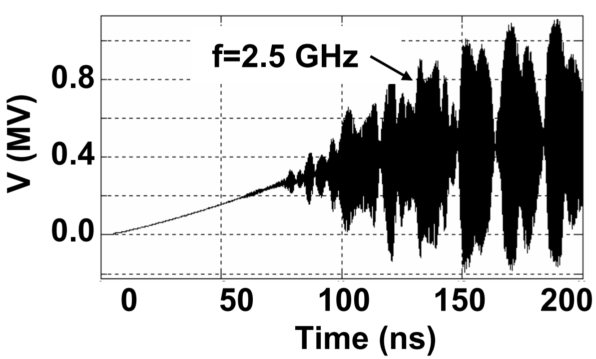
The electron beam, hibachi, and KrF physics

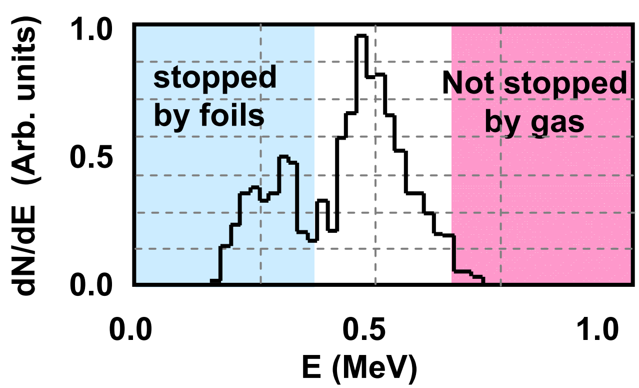


Experiments and 2-D models show "Transit Time" Instability in large area, low impedance diodes

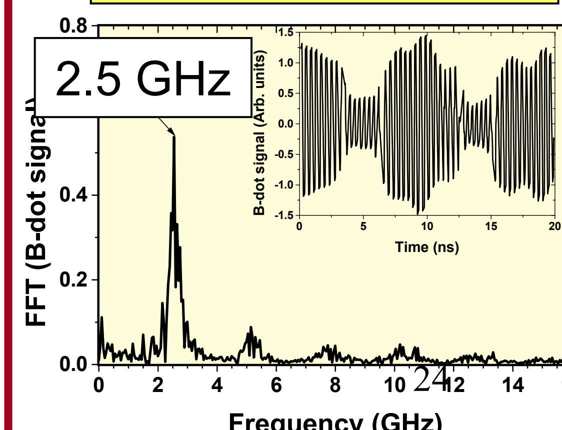


Theory

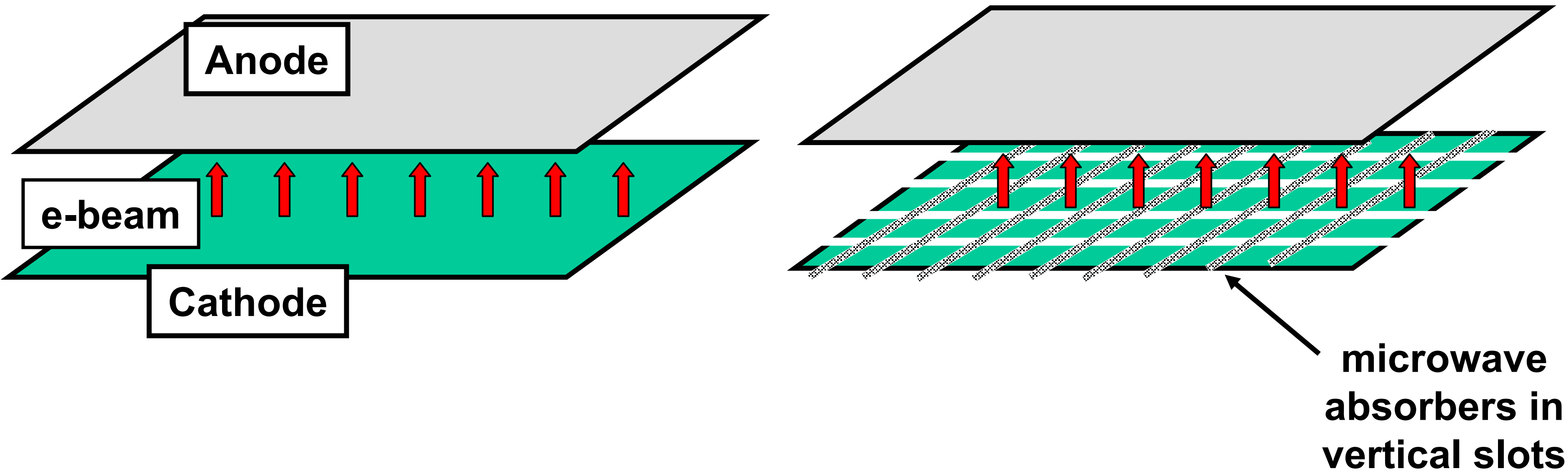




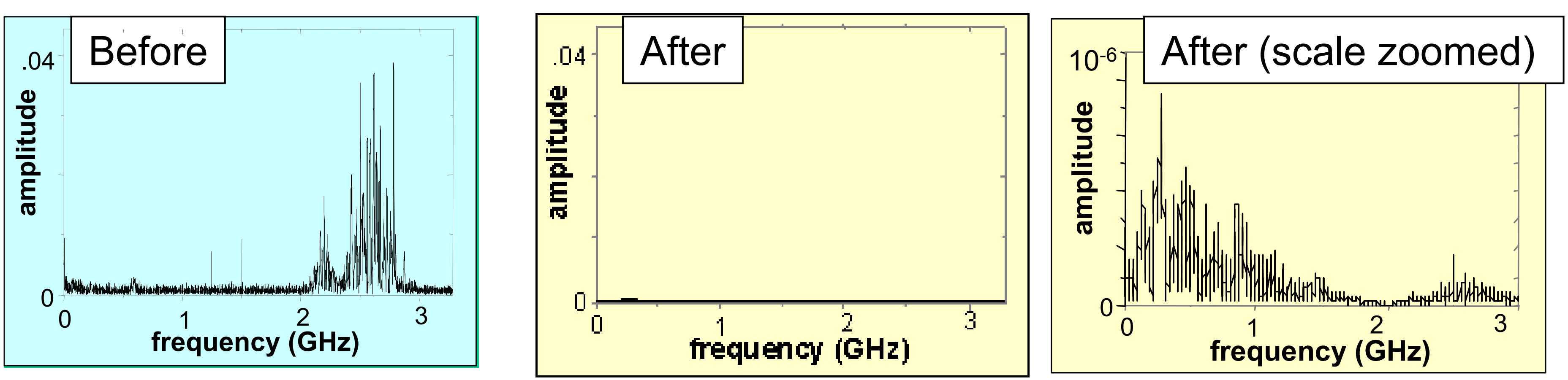
Experiment (Nike)



In accordance with theory, slotting the cathode and adding microwave absorbers eliminates the instability



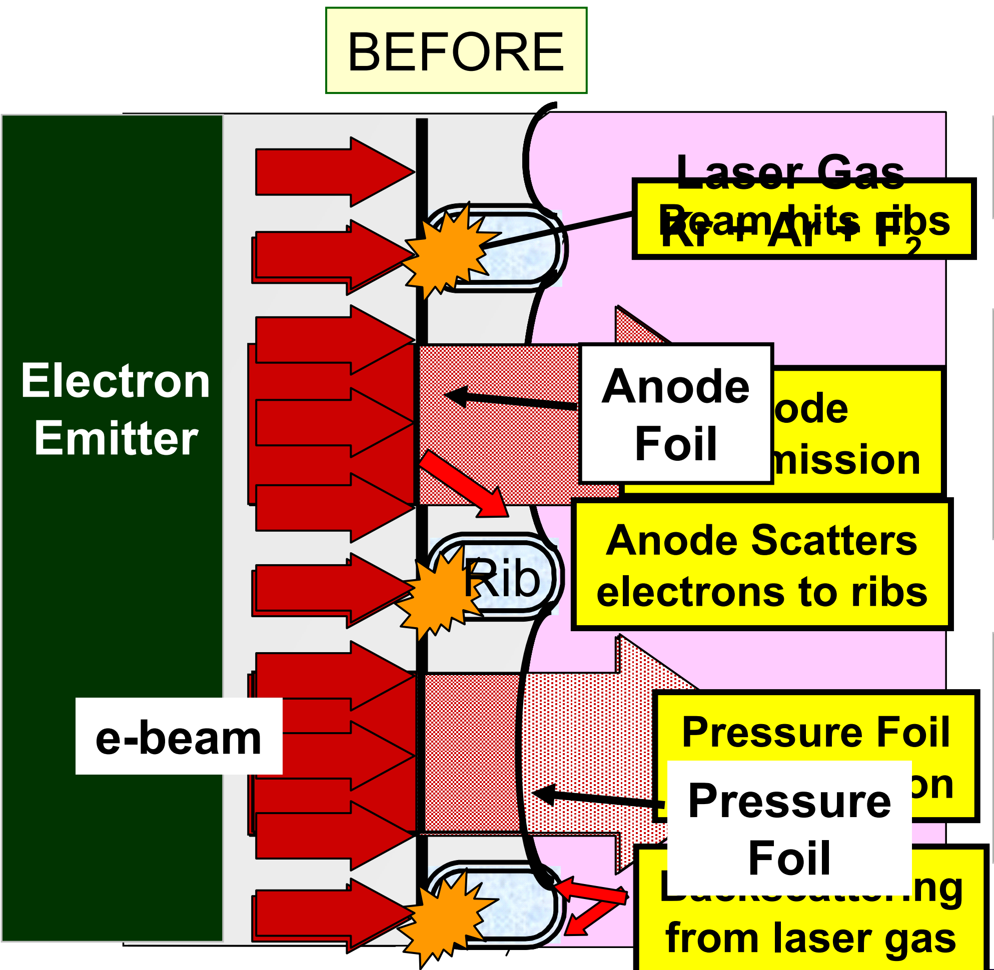
Experimental Fast Fourier transform of instability amplitude:

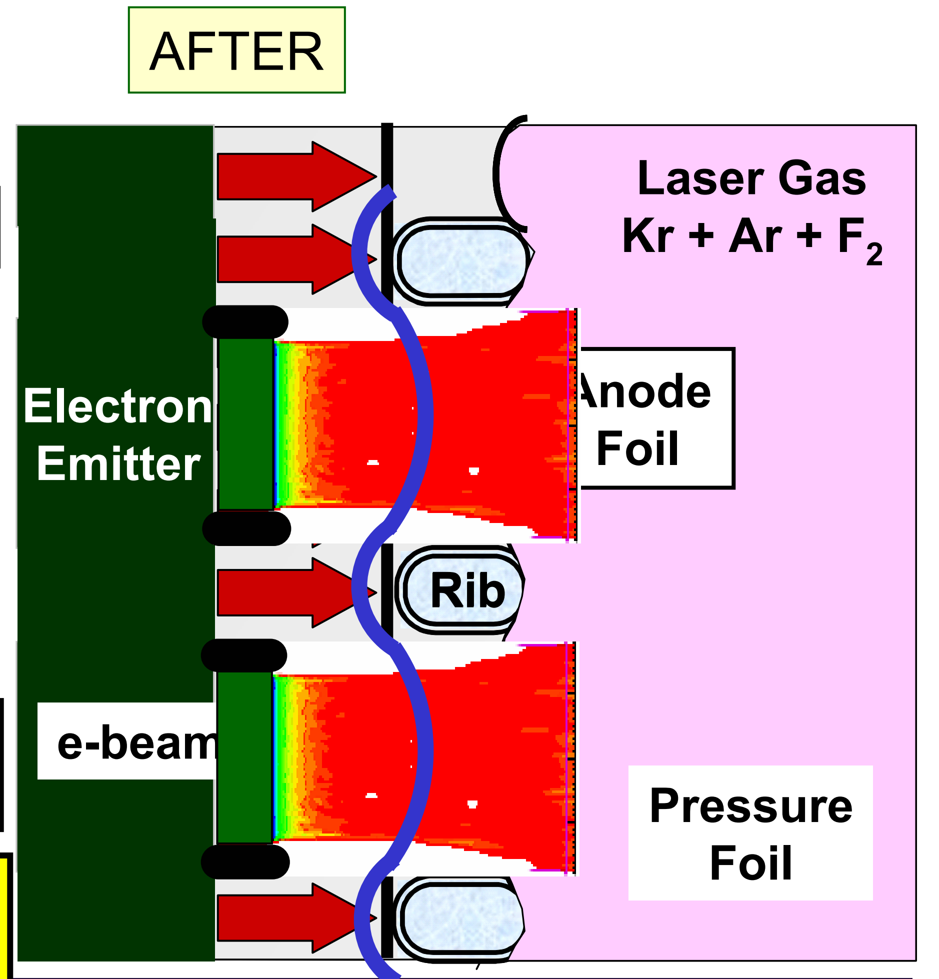


The Hibachi


.001" thick
Stainless Steel Foil
Ribs
(contain water
cooling channels)

We have increased the electron beam energy into the gas by eliminating the anode & patterning the electron beam





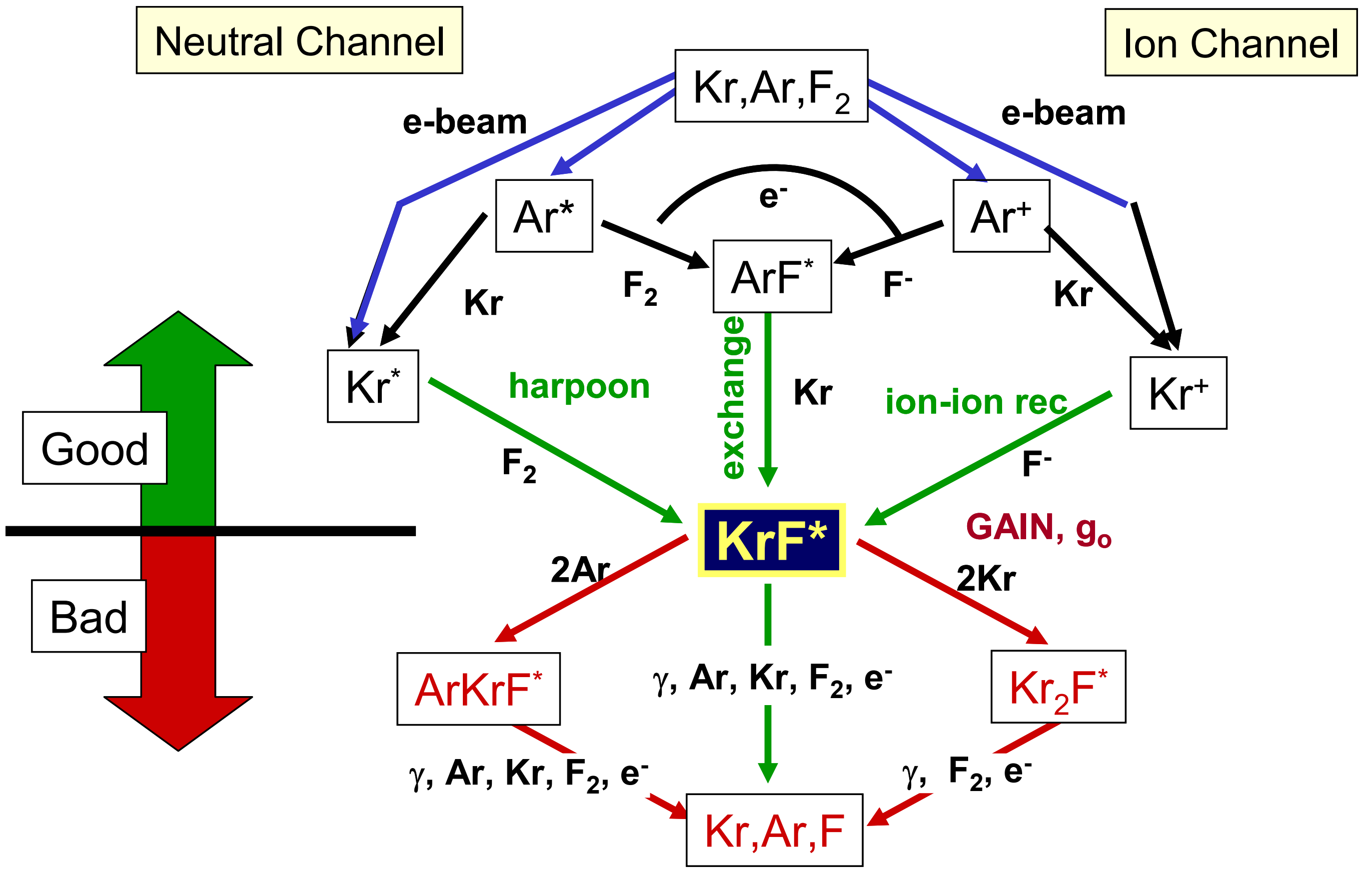
- 35% e-beam energy into gas

- 75% e-beam energy into gas
- Agrees with LSP models by MRC
- Expect ~ 82% @ 1,000 keV (IFE)

Orestes KrF Physics Code combines relevant physics into a single "first principles" code

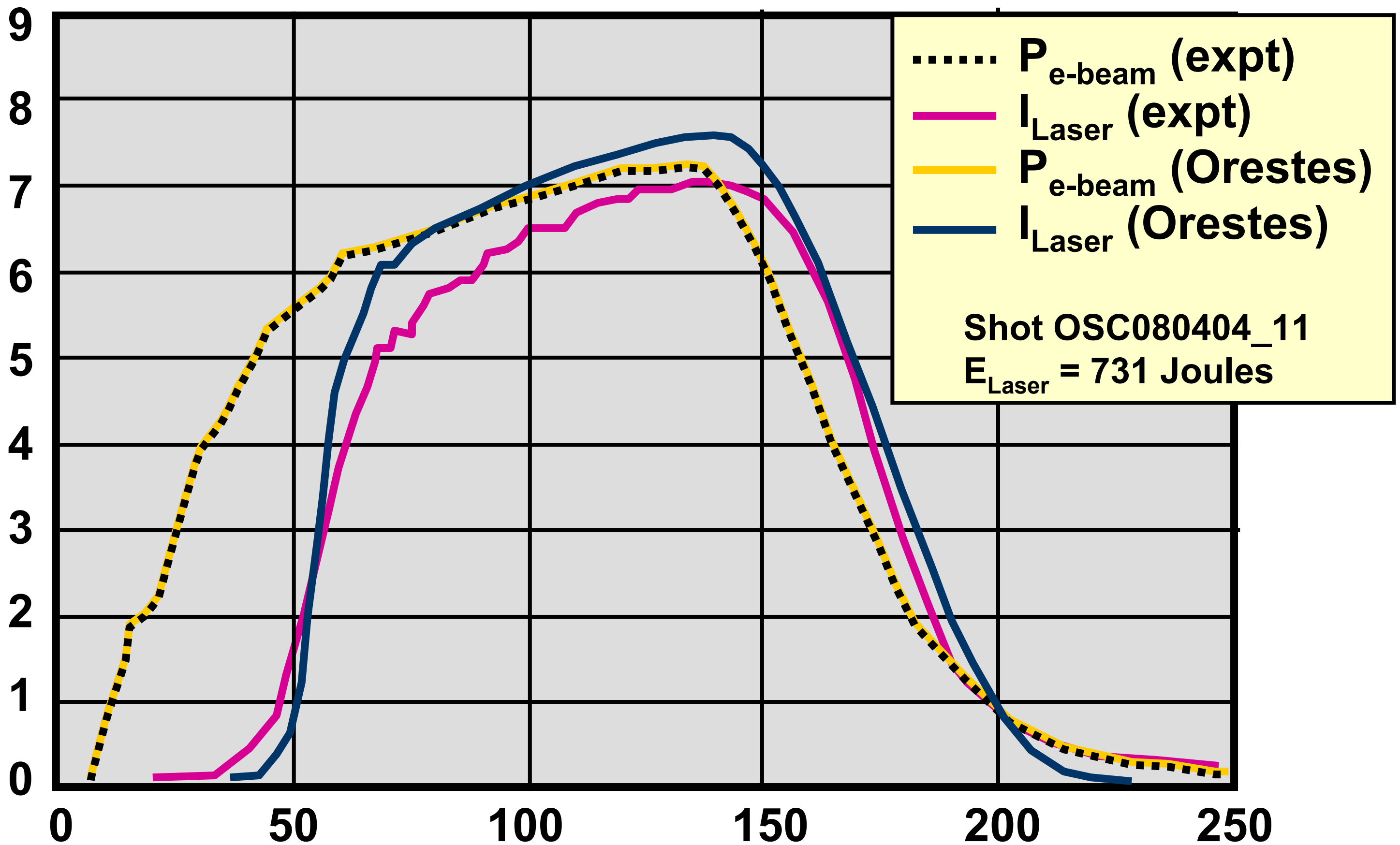
Electron Deposition	***Plasma Chemistry***
Laser Transport	***Amplified Spontaneous Emission***

24 species, 122 reactions



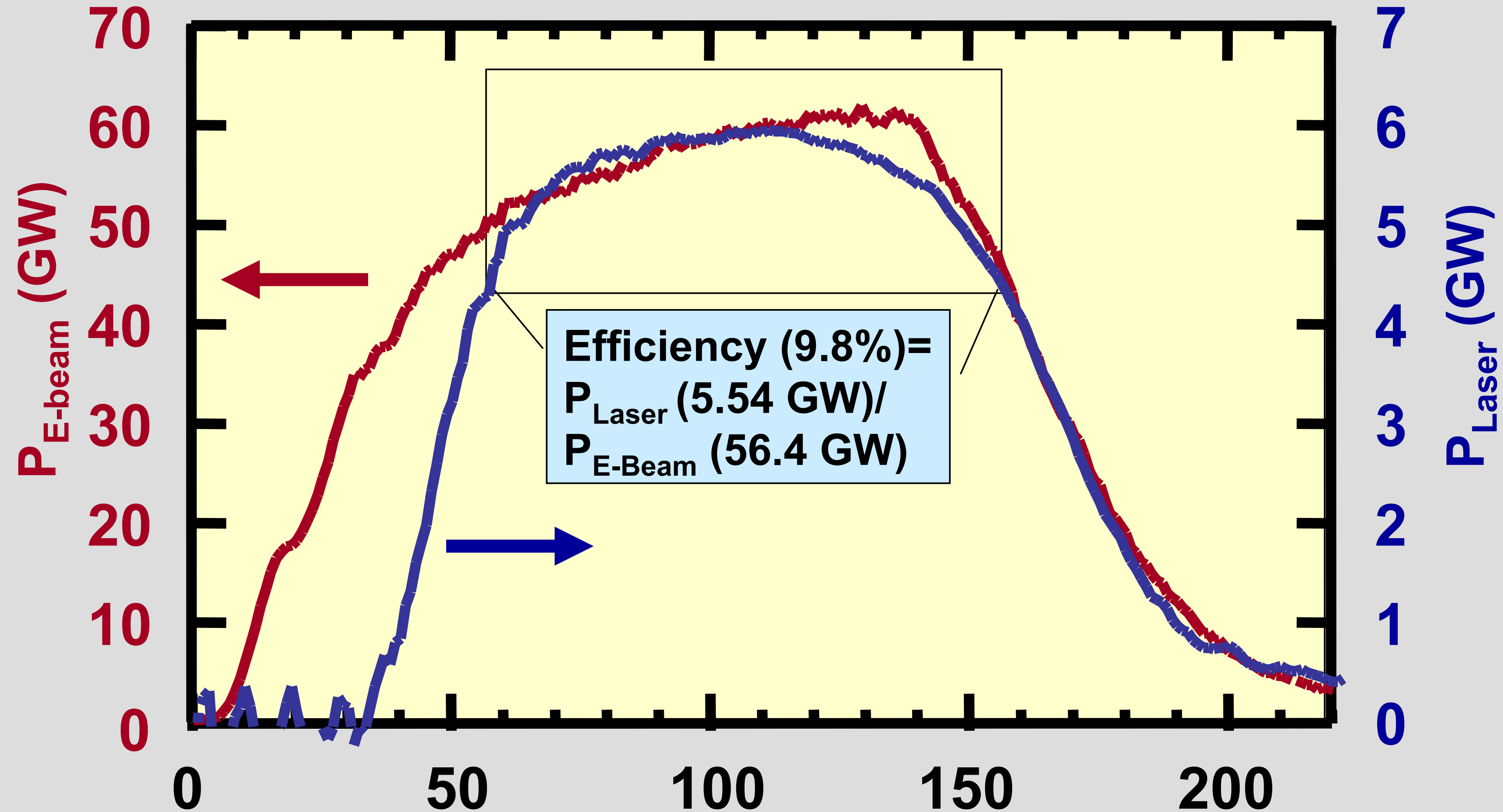
absorption, $\sigma = \sigma_{F2}\eta_{F2} + \sigma_{F-}\eta_{F-} + \sigma_{KrF2}\,\eta_{KrF2} + \sigma_{ArF2}\,\eta_{ArF2}$

Orestes becomes Electra



Apologies to both Socrates and Eugene O'Neil

Electra: ~ 10% intrinsic efficiency as an oscillator ...expect ~ 11 % as an amplifier



Why 11% as an amplifier? KrF grade windows with AR coating
Amplification from input laser

Based on our research, an IFE-sized KrF system is projected to have a wall plug efficiency of > 7% (meets goal)

Pulsed Power	Advanced Switch	87%
Hibachi Structure	No Anode, Pattern Beam	82%
KrF	Based on Electra exp'ts	11%
Optical train to target	Estimate	95%
Ancillaries	Pumps, recirculator	95%
Total		7.1%

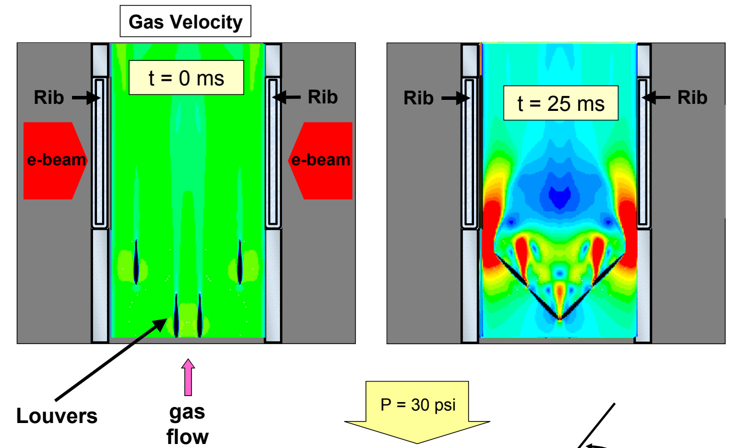
> 6 % is adequate for fusion target gains > 100...
...and latest designs have 2D gains ~ 160

We are developing three techniques to cool the foil

- **Convection cooling by the laser gas**

  Pro: Successful operation @ 1 Hz (foil temp < 200°C)

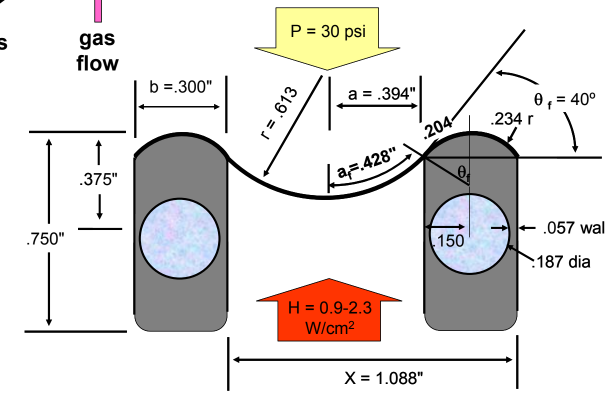
  Con: Foil temperature rises to 350-500°C @ 5 Hz operation



- **Conduction cooling to hibachi ribs**

  Pro: Simple, efficient cooling system

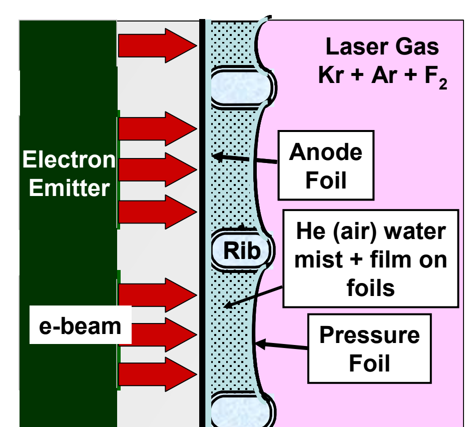
  Con: Requires close rib spacing which challenges e-beam transport through hibachi (may be reduced with advanced materials)



- **Mist cooling of the foil (developed by Georgia Tech)**

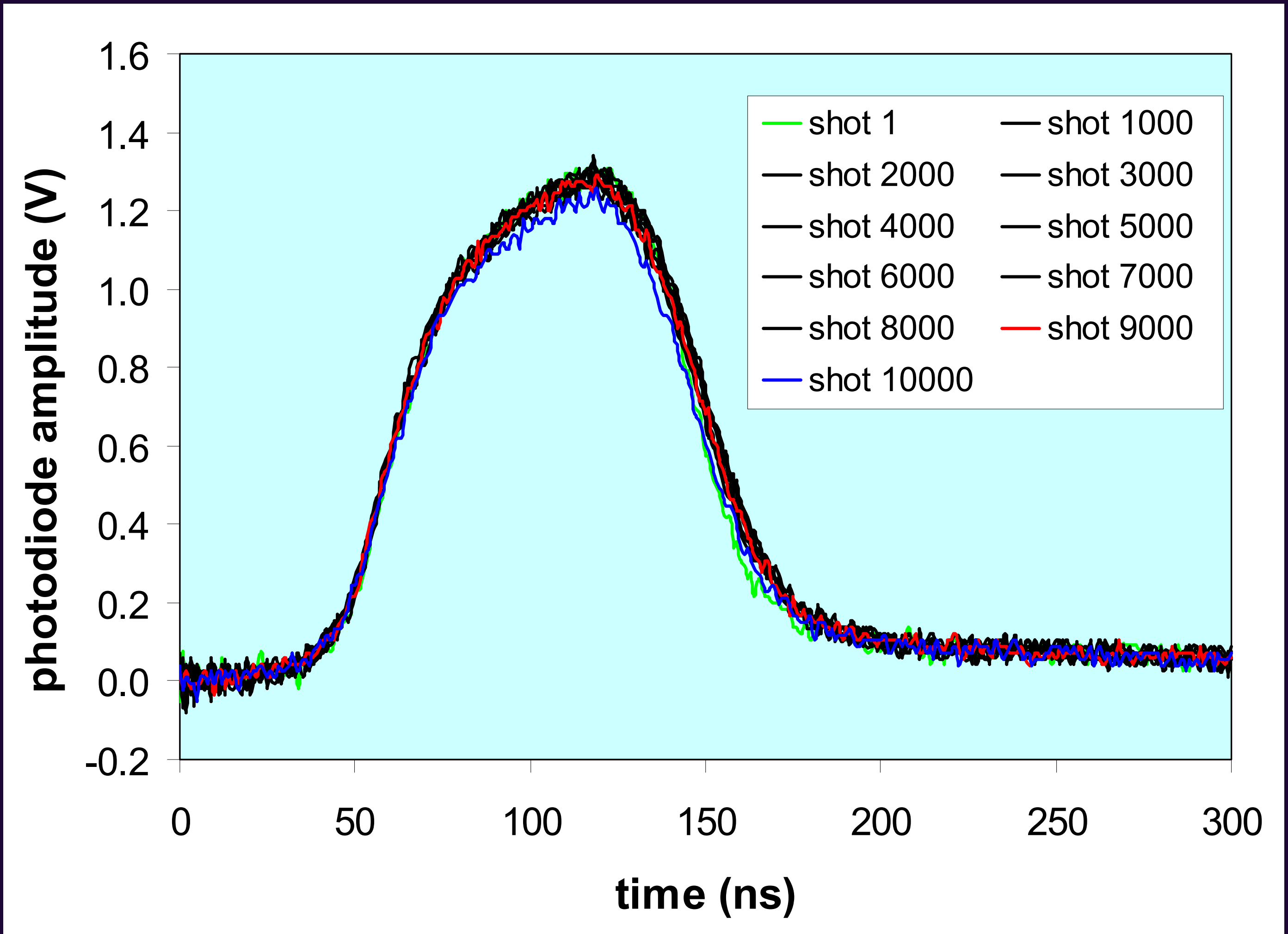
  Pro: Successful demonstration @5 Hz (foil temp < 140°C)

  Con: More complex system, lowers e-beam transport efficiency (to ~77%)



Electra as a repetitively pulsed laser:

300 J/pulse @ 1 shot/second in a 10,000 second run (2 hrs, 45 min)



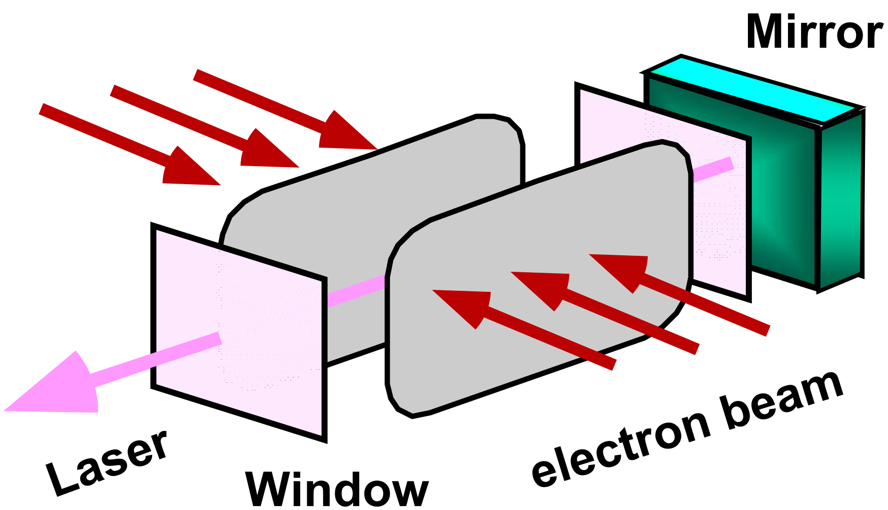
Also: 700 J/shot @ 1 shot/second (700 W) in 400 second bursts

400 J/pulse @ 5 shots/second (2,000 W) in 100 second bursts

Electra produces 700 Joules.
For Fusion we need 2,400,000 Joules
How do we get there from here?

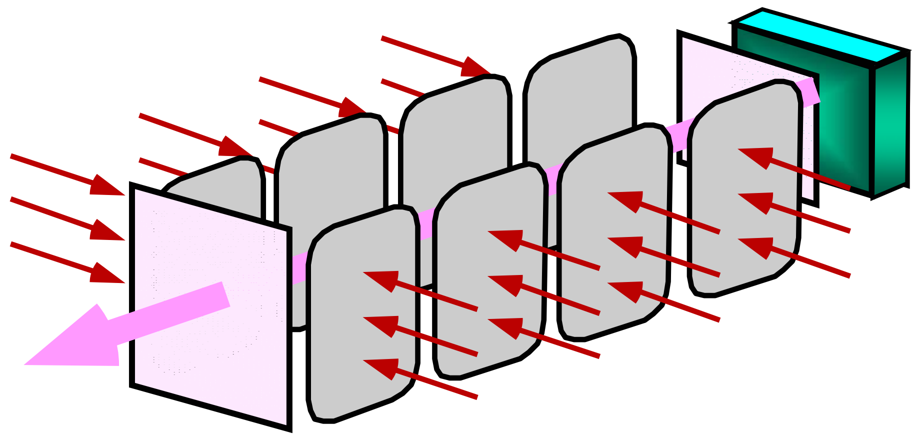
WHERE WE ARE NOW…..

Electra - 700 J output



WHERE WE WANT TO BE….

IFE-sized Amplifier- 50,000 J output



Two electron -beams:
500 keV, 100 kA, 140 nsec
30 cm x 100 cm each beam

Eight electron - beams:
1000 keV, 175 kA, 400 nsec
50 cm x 100 cm each beam

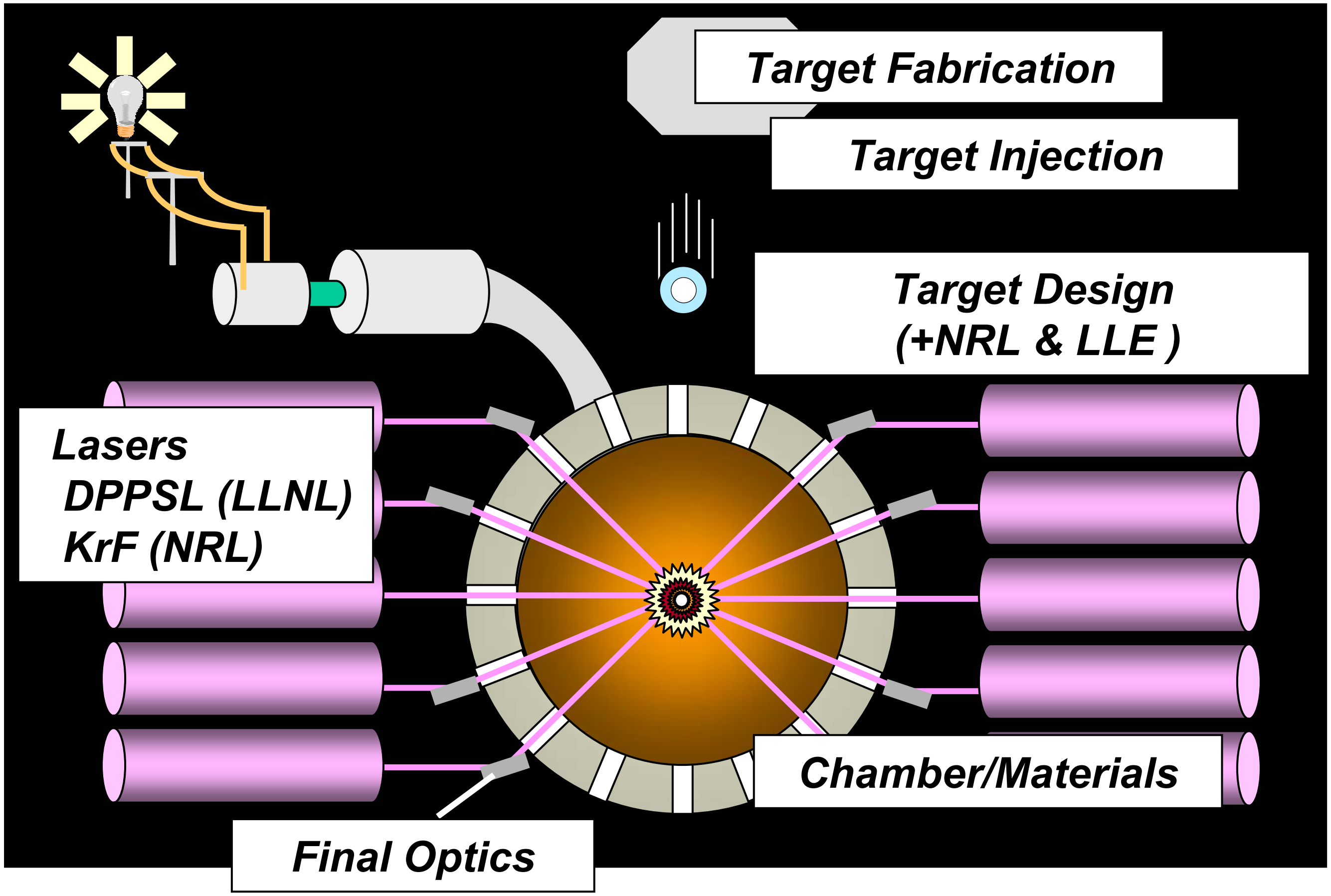
The other principal components:

Optics

Target Fabrication

Target Injection

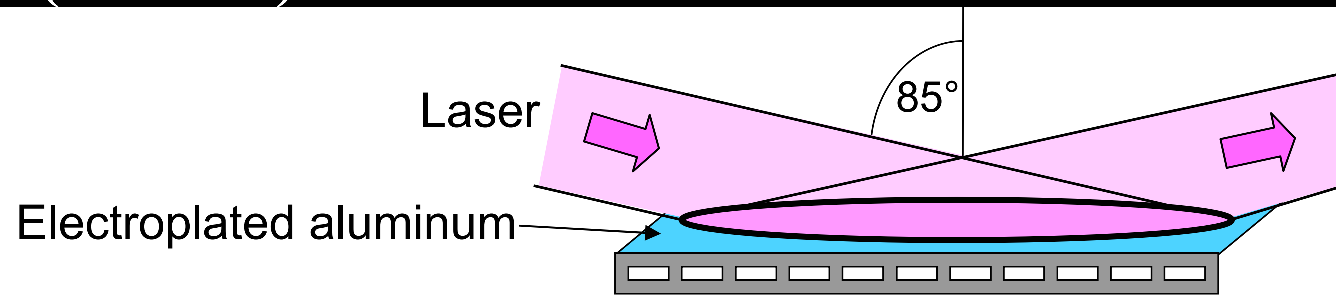
The First Wall



Final Optic:

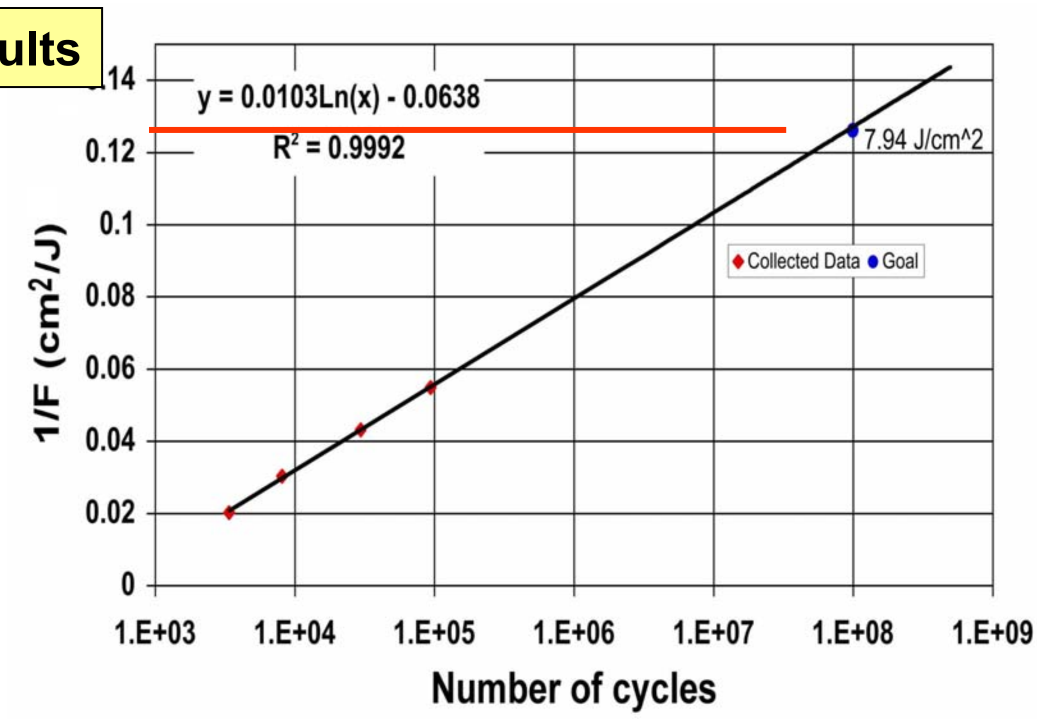
Grazing Incidence Aluminum Mirror meets IFE requirements for reflectivity (>99% @ 85°) and required long term damage threshold (8 J/cm^2)

Concept



stiff, lightweight, cooled, neutron resistant substrate

Results



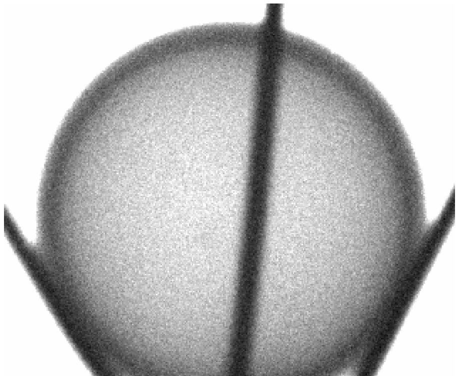
Improvements

Lifetime should be improved by using Al alloys that have high yield strength in their annealed state

Pure Al:	20MPa
Al 2024 (3% Cu)	97 MPa
Al 7075 (3% Zn)	147 MPa

Mark Tillack
UCSD

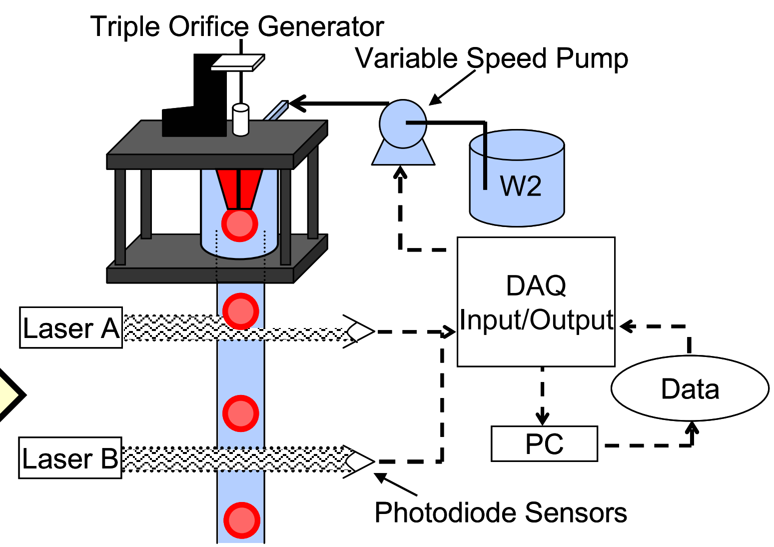
Target fabrication: We have mass-produced foam shells that *almost* meet all the specifications



X-Ray picture of batch produced foam shell 4 mm dia, 400 μ wall

- ✓ Diameter: 4-5(4.1*) mm ± 0.2 mm
- ✓ CH foam wall: 250-300(290*) μm
- ✓ High-Z coat: 500 Å
- ✓ Density: 20-120(100*) mg/cc
- ✓ Pore size: ~ 1 μm
- × CH full density overcoat: 1-5 μm
- × Non-concentricity: <1%*

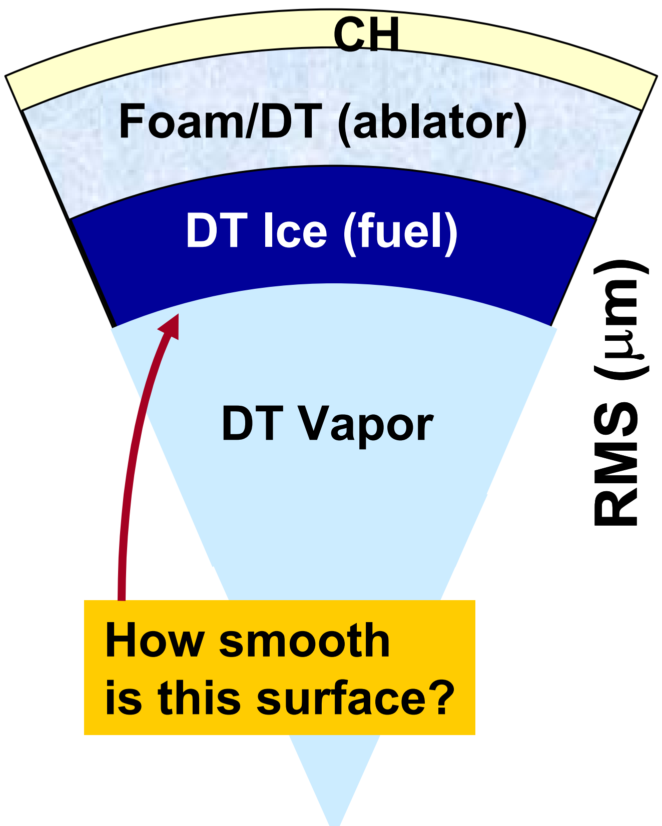
Produced 22 shells/min,
5 mm diameter, +/- 40 um (< 1 %)
Automatic feedback process controls shell diameter

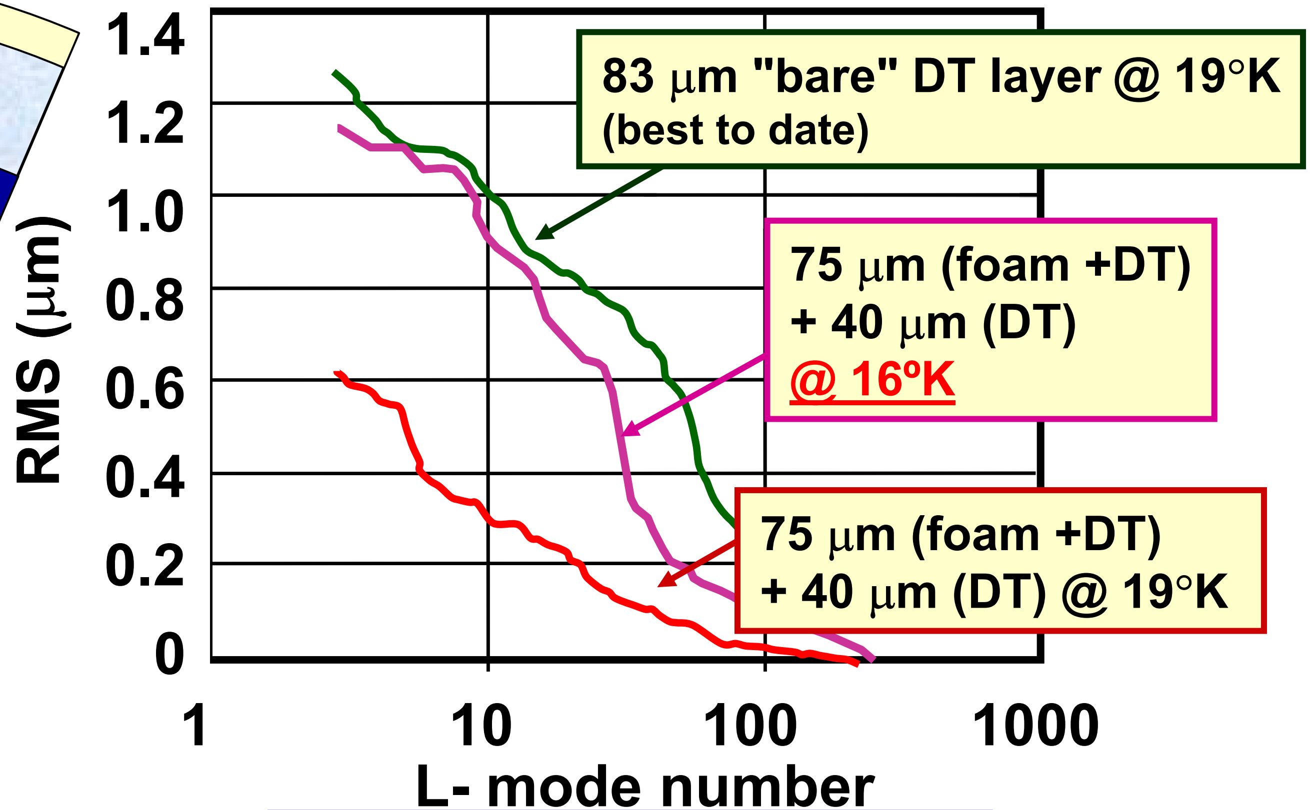


Not to scale

Brian Vermillion (GA)
Diana Schroen and Jon Streit (Schaffer)

DT ice grown over a foam underlay is smoother and thermally more robust than a pure DT layer... exceeds IFE specs of < ~ 1 um RMS





Cumulative Reverse Spectra RMS
Σ [L-mode (256-n)]
T = 19 °K

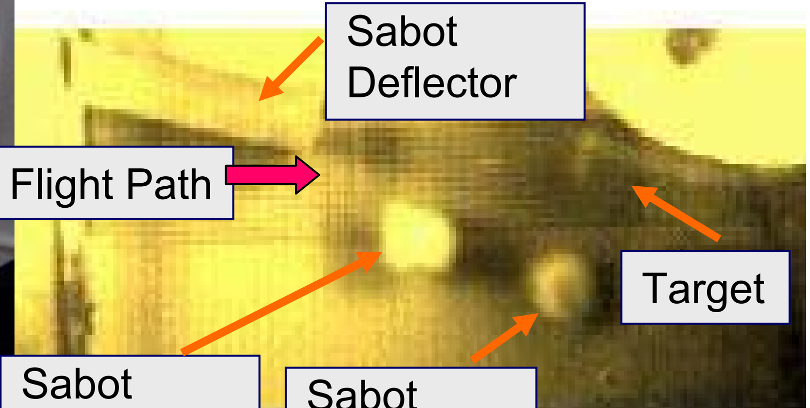
Jim Hoffer: LANL
Diana Schroen: Schaffer

Target Injector / Tracking Progress

- Light gas gun injector in ***rep-rate*** operation
- Achieved 400 m/sec (need 50-400 m/sec)
- Demonstrated separable sabot
- Target placement accuracy +/-10 mm (need ~5 x better)

Target Injection and Tracking system

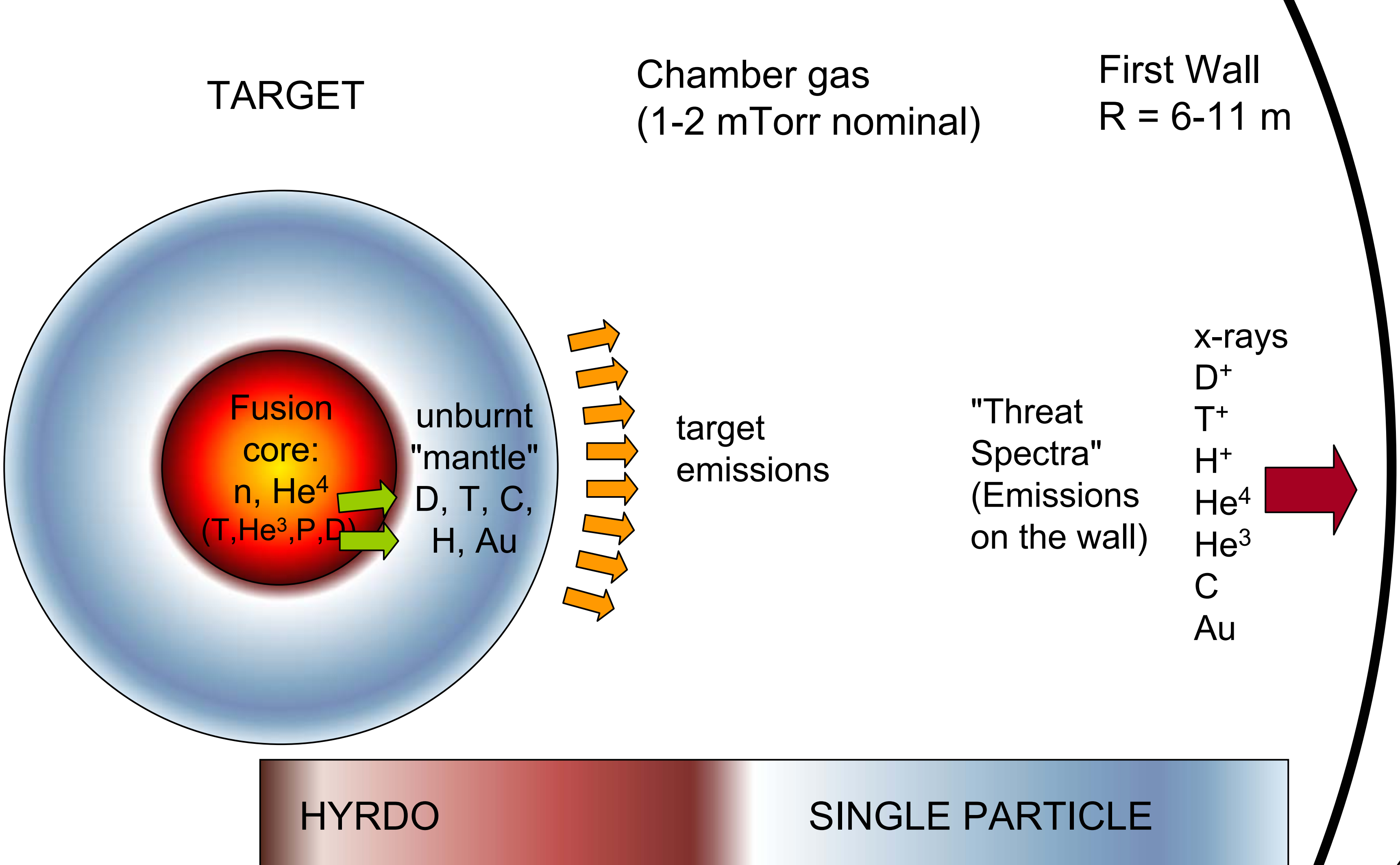
Demonstrated in flight sabot separation



Whats left:
Better placement
Target engagement

R..Petzoldt,
B. Vermillion,
D. Goodin,
G. Flint, et al
General Atomics

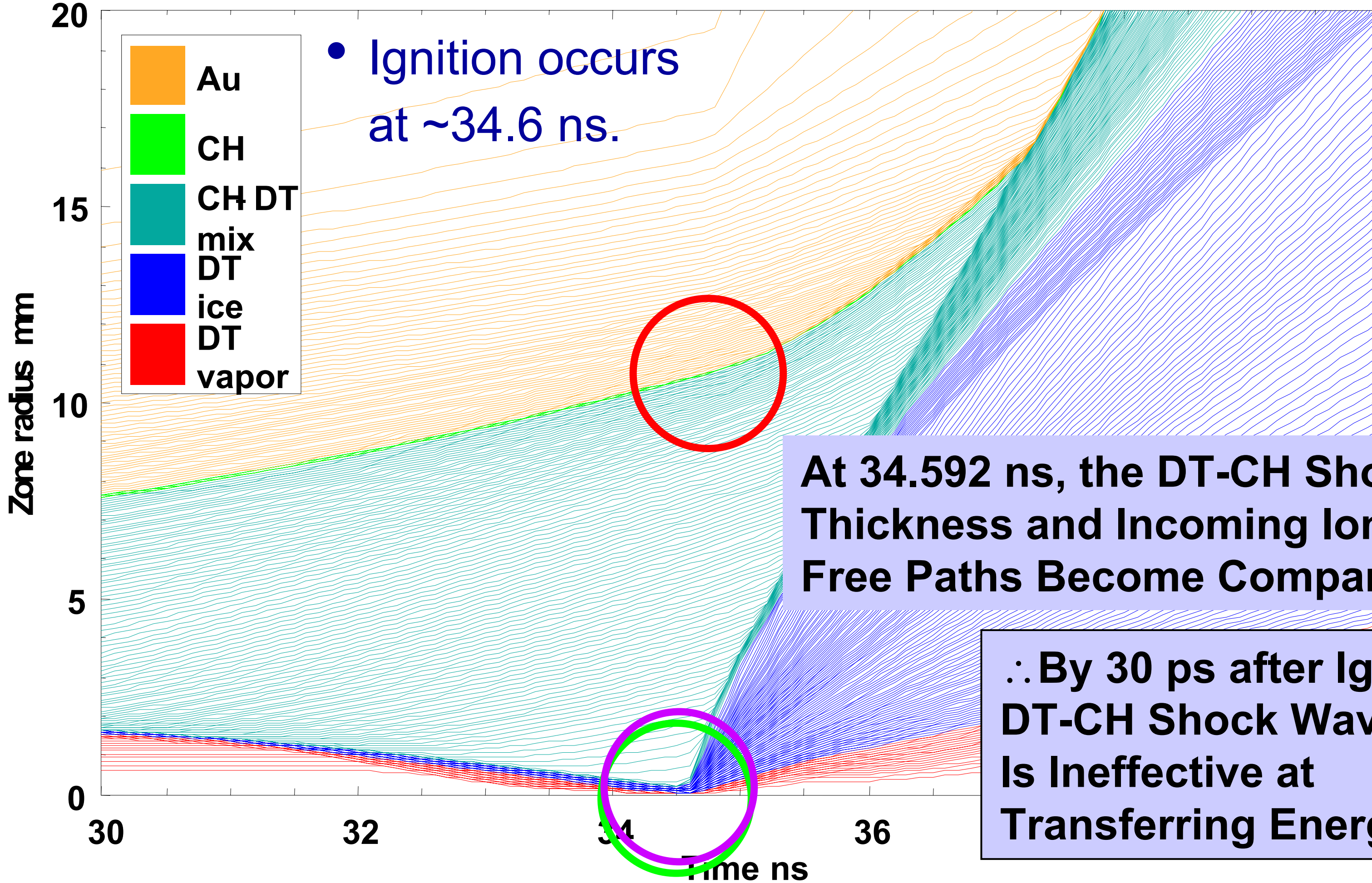
We need to predict the spectra, fluence and pulse shape of the target emissions incident on the first wall.. aka the "threat spectra"



the big unknown...where is this transition? Threat spectra may depend critically on this !!

Time near Ignition is the key to determining the threat spectra

Lagrangian constant-mass zones from BUCKY run of HAPL case

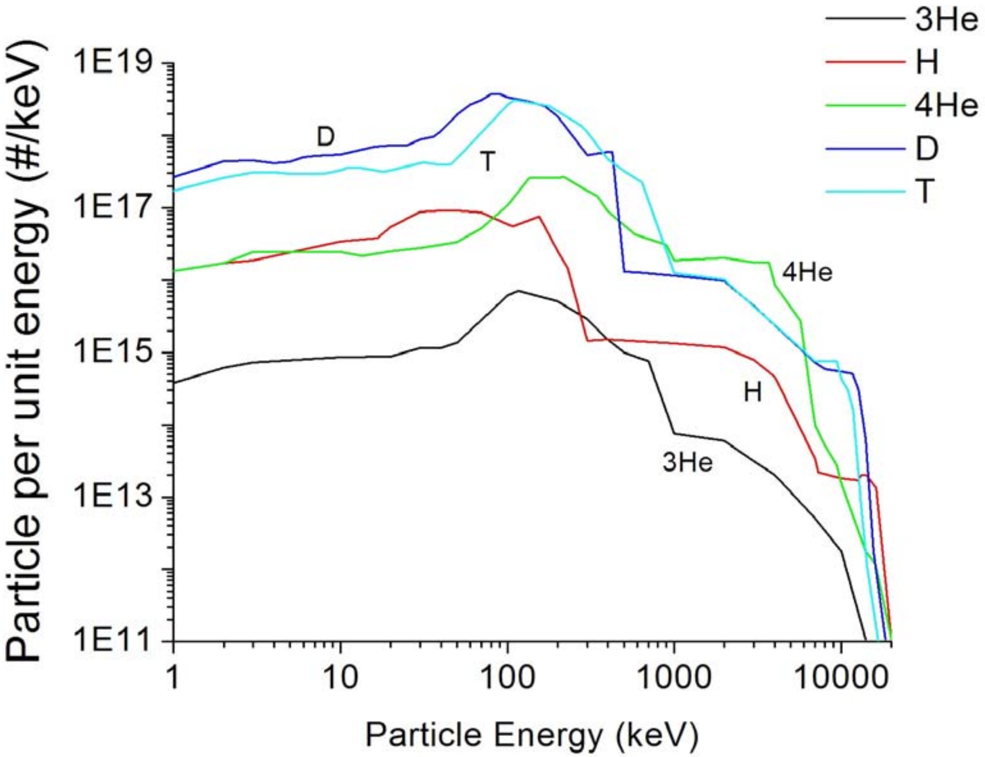


At 34.592 ns, the DT-CH Shock Thickness and Incoming Ion Mean Free Paths Become Comparable

∴By 30 ps after Ignition, DT-CH Shock Wave Is Ineffective at Transferring Energy

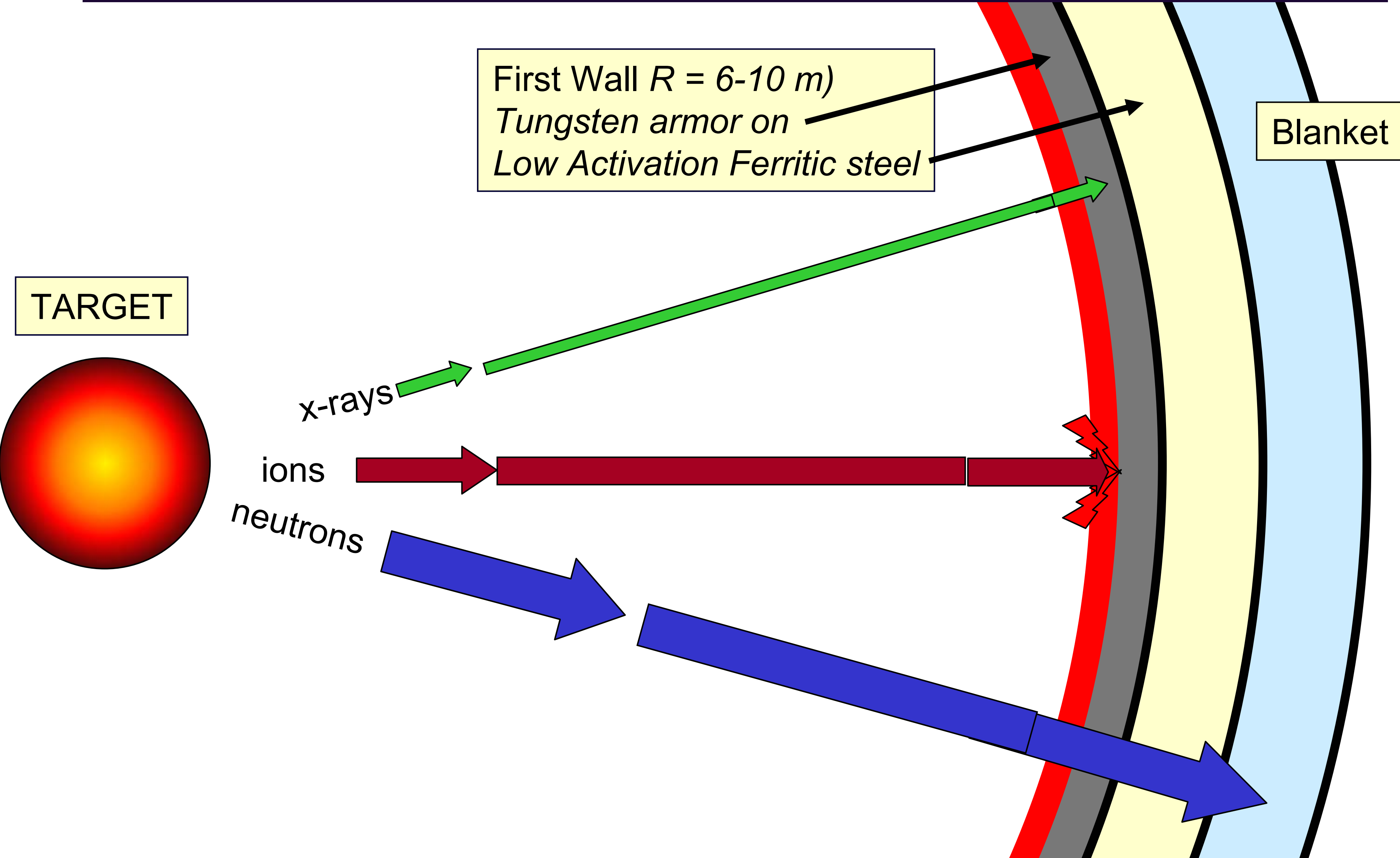
J. Santarius & G. Moses (Wisconsin)

We have been using a chamber threat spectra based on a pure hydro model



J. Perkins, LLNL

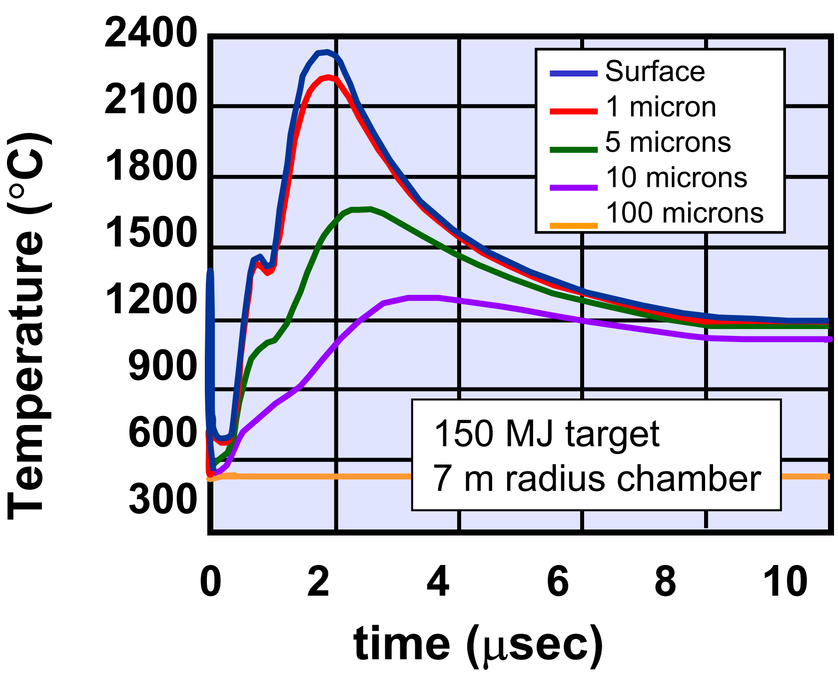
The ions pose the biggest threat to the first wall

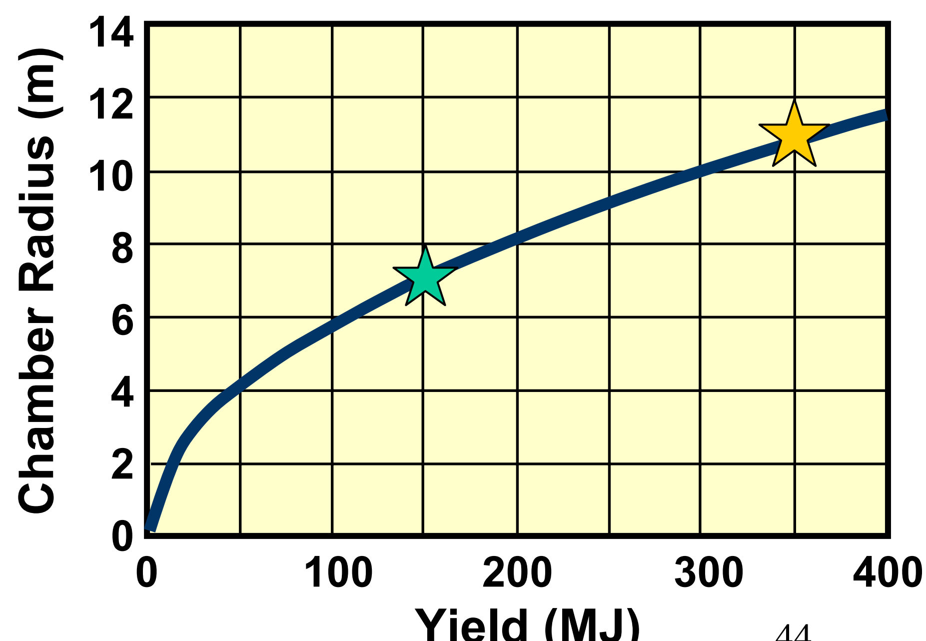


We have established a "chamber operating" window that simultaneously meets the requirements for efficiency, wall survival, and target injection:

First wall is tungsten armor bonded to low activation ferritic steel

1 mm W armor, 3.5 mm FS, $T_{coolant}$ = 575°C, Max Surface = 2400 °C





based on work by Rene Raffray, UCSD

Three issues for long term (3-5 year) survival of the first wall

1) **Helium retention**

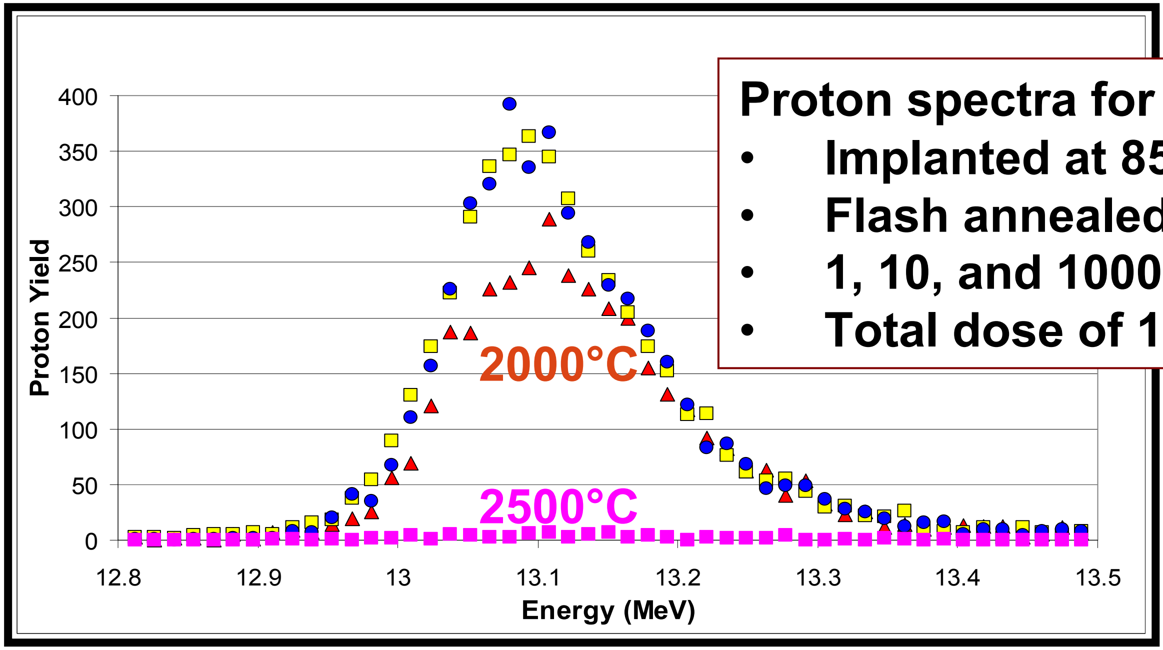
2) **Bonding W to Steel base**

3) **Thermo-mechanical Fatigue**

Helium Retention: Experiments show may be not be a problem at IFE Conditions

Amount of retained helium is lowered significantly when:

- Dose is spread out over large number of cycles
- Sample is flash annealed to prototypical temperatures

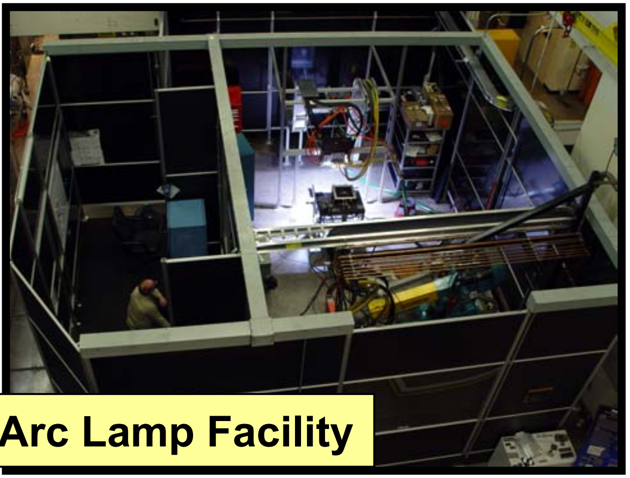


Proton spectra for single crystal tungsten

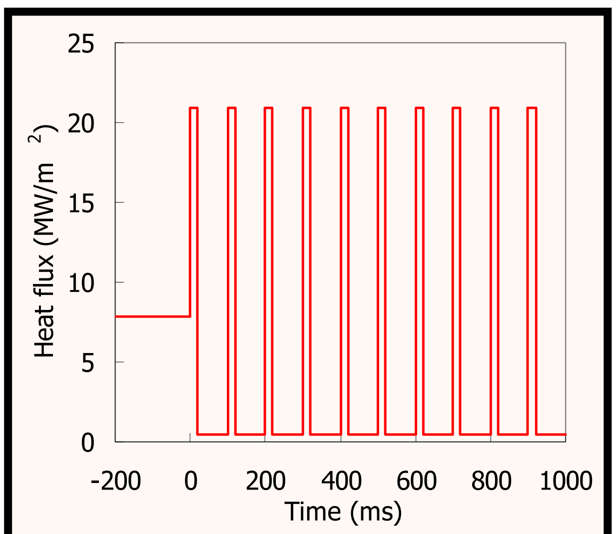
- **Implanted at 850°C**
- **Flash annealed to 2000°C (or 2500 °C)**
- **1, 10, and 1000 cycles**
- **Total dose of 10^{19} He/m^2.**

Expt's Lance Snead, ORNL
Modeling: S Sharafat, UCLA

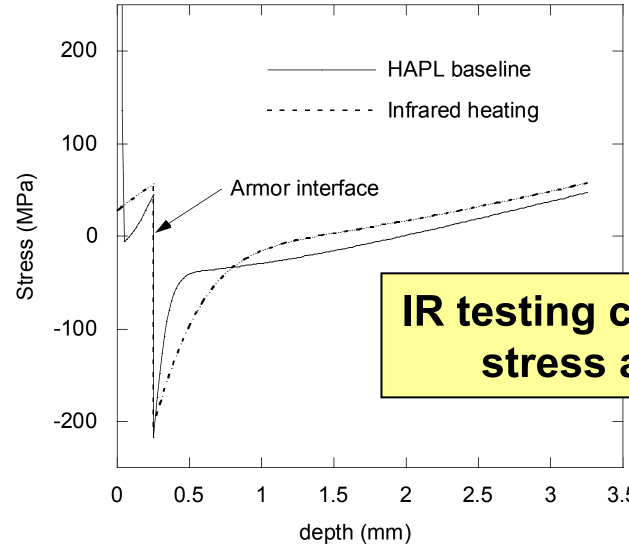
Bond strength: We are using the Oak Ridge High Intensity Infrared Arc Lamp to study the long term integrity of the Tungsten-Steel bond



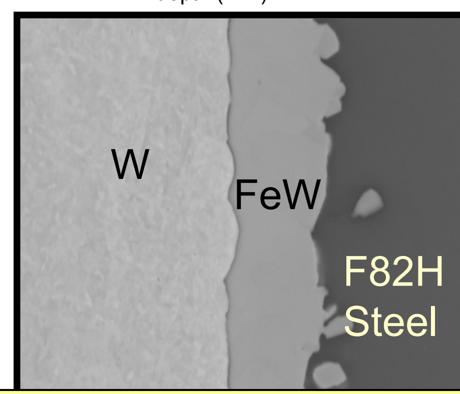
Arc Lamp Facility



Exposure cycles



IR testing closely matches stress at interface.



Lance Snead, ORNL

No degradation of bond after 10,000 shots but interface temperature was 900 °C, (lamp too intense)

Thermo-mechanical fatigue: We are using an array of facilities to expose FW materials to expected target emissions

BIG ISSUE...DOES OBSERVED ROUGHENING LEAD TO MASS LOSS?

X-rays:

XAPPER

Latkowski (LLNL)

Z [*confirmation*]

Tanaka (SNL)

Ions:

RHEPP

Renk (SNL)

Laser:

Dragonfire

Najmabadi (UCSD)

Experiments:

- Spectra
- Surface temperature
- TEM: sub-surface cracks

Modeling:

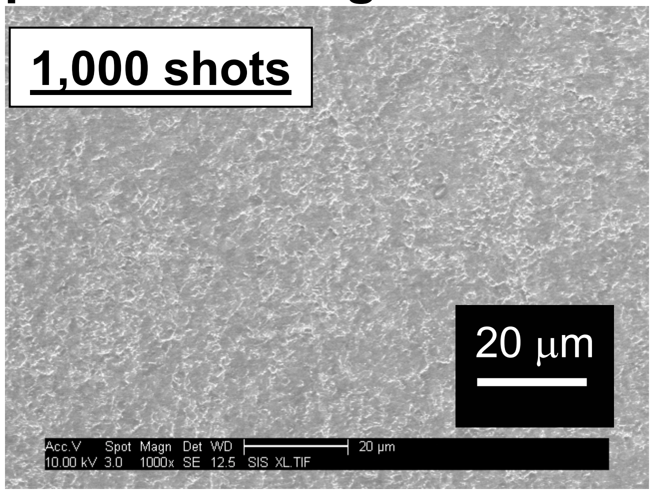
- Predict
  - Surface temperature
  - Sub surface cracks
- Stress modeling to get evolution of fatigue

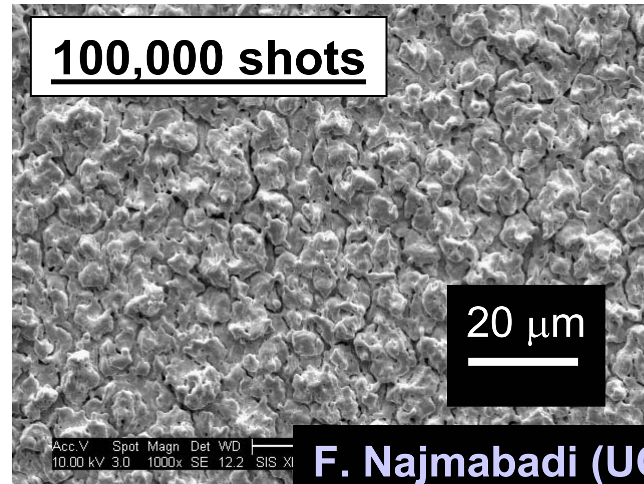
Blanchard (Wisc)

Thermo-mechanical fatigue experiments and modeling

Long term exposure of tungsten with shows surface will crack...

Laser
T_0 = 500 ºC
ΔT = 2000 ºC



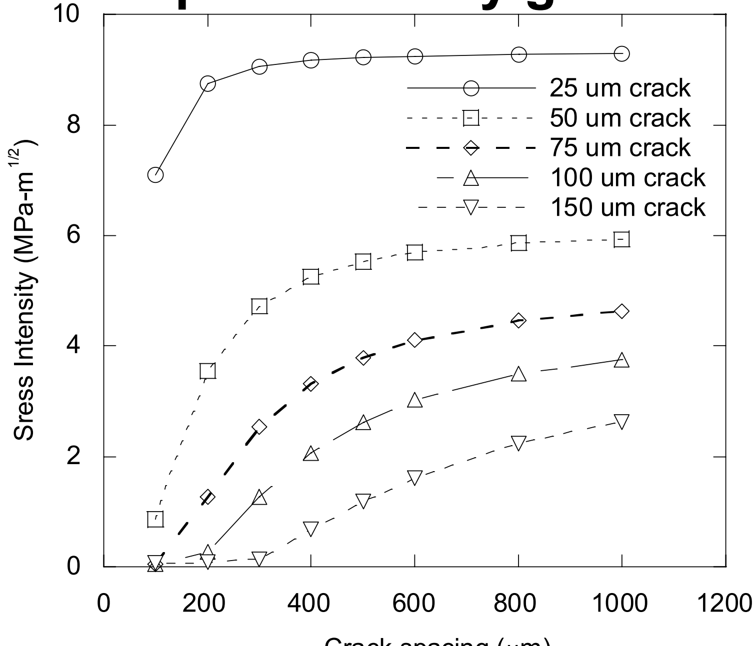


F. Najmabadi (UCSD)

But modeling shows cracks should stop before they get to the substrate:

Modeling also shows pre "castellating" the surface will arrest cracks at a shallower depth

J. Blanchard (Wisc)
N. Ghoneim (UCLA)



Main points of the talk

Fusion Energy based on lasers and direct drive targets

Can lead to an attractive electricity generating power plant

Developing Laser Fusion as an integrated system

Simultaneously addressing the science and engineering

Direct Drive Pellet Designs

Computer Models show target gain > 150
(need >100 for energy)

Underlying codes backed with experiments

KrF Lasers

Attributes : Beam uniformity, wavelength, cost, scaling to large systems

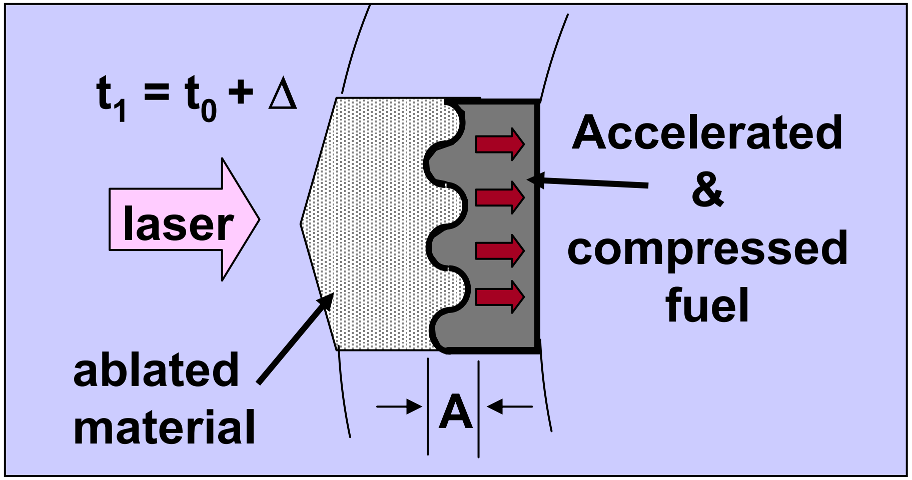
Technologies for rep-rate & efficiency look good,

Biggest challenge: durability of pressure foil

Progress made in the other Laser IFE components

TARGET PHYSICS- THE DETAILS

High Gain Direct drive requires control of Rayleigh Taylor Instability: Requires minimizing both the initial mass modulations & the growth rate



Amplitude of mass modulations

Rayleigh Taylor growth factor

STEP #1:

a. Raise Isentrope (lower the density) of the ablator

$$A\,(t) = A_o\, e^{\gamma t}$$

Initial mass modulation

Laser non-uniformities

Target non-uniformities

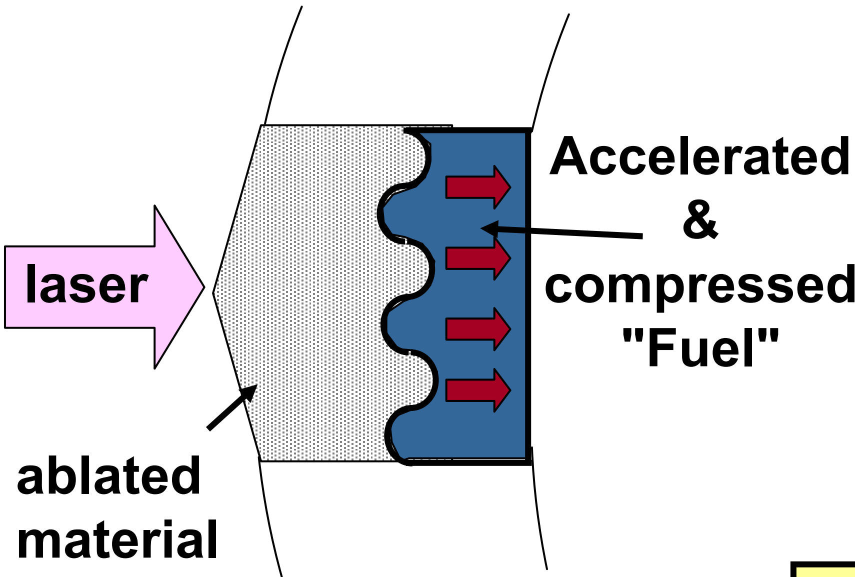
STEP #2:

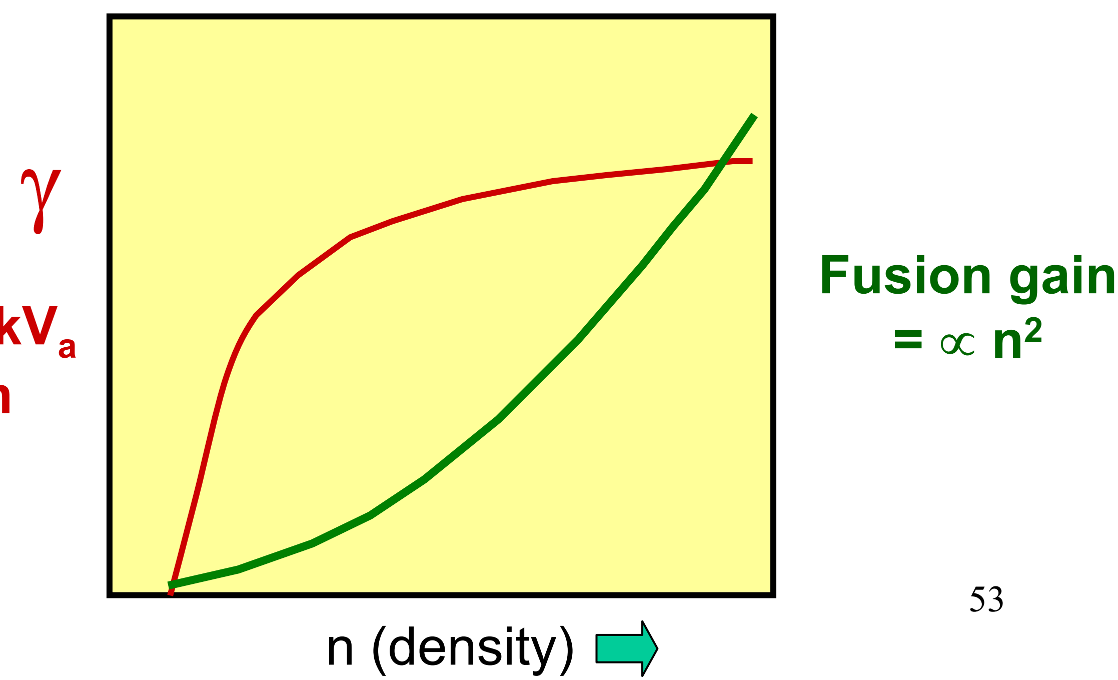
a. Use a Smooth Laser Beam

b. Reduce Laser Imprinting

c. Make target outer surface smooth

Step 1: Lower the growth rate by raising the isentrope of *just* the ablator.



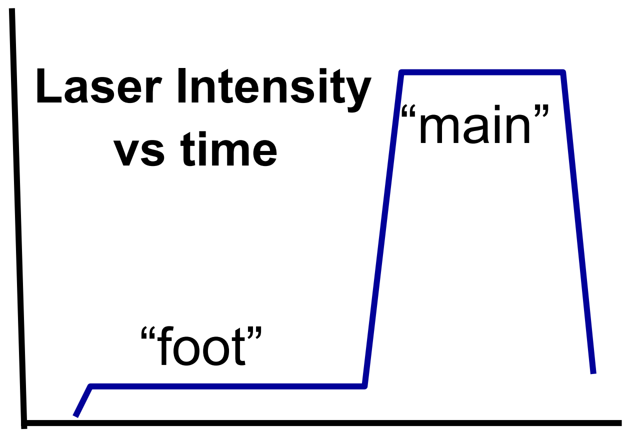


$\gamma \sim 0.9\,(kg)^{1/2} - 3\,kV_a$
where $V_a \propto 1/n$

Takabe H. and Bodner
1985 *Phys. Fluids* **28** 3676

How to raise Isentrope of just the Ablator

--preheat the ablator (decrease density), to mitigate Rayleigh Taylor growth,
--but keep the fuel cold (dense), to maximize gain



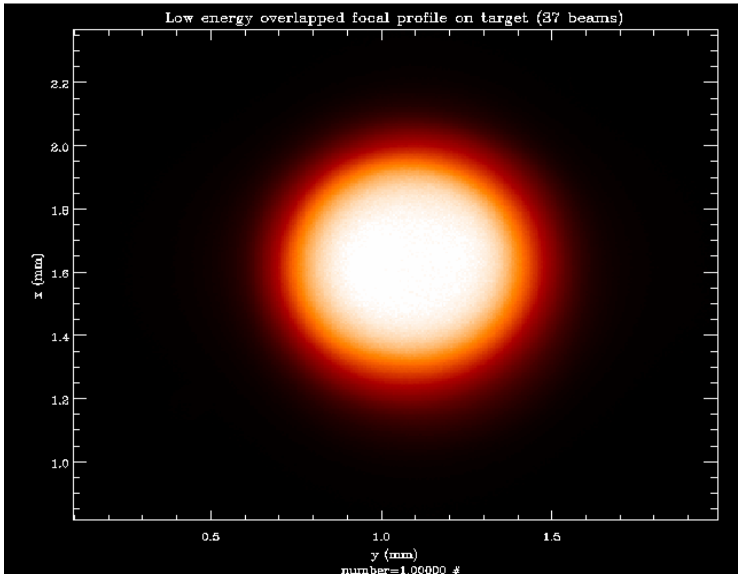
Can be done with radiation

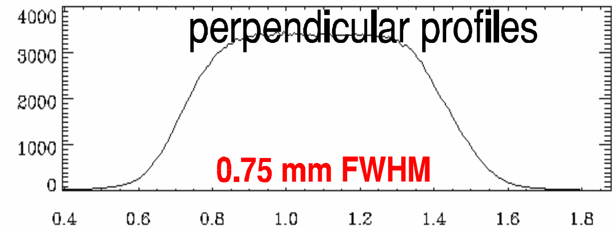
1. **Foot produces low energy x-rays from high Z layer outside target**
2. **Ablator made of CH Foam + DT (ablator)**
3. **Radiation stops in foam to heat ablator**
4. **Radiation does not get to pure DT so fuel stays cold**

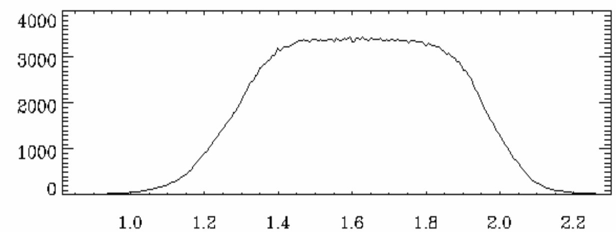
Can be done with shocks

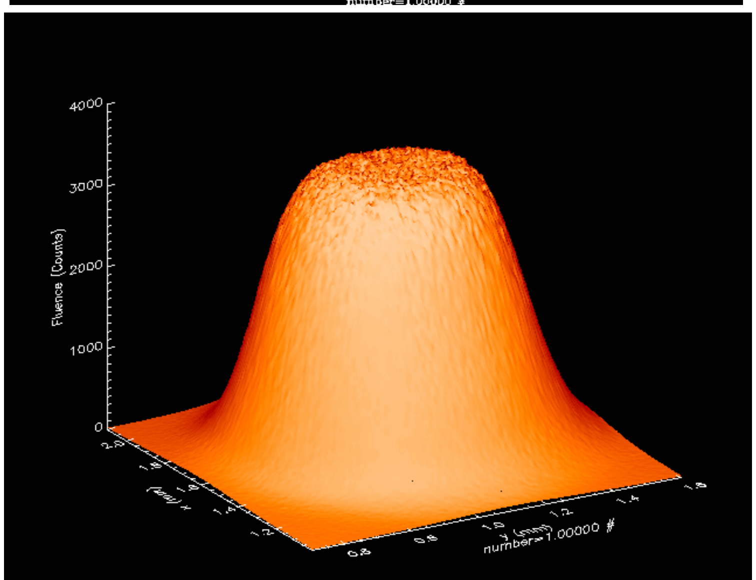
1. **Tailor laser pulse shape to launch low intensity shocks through ablator.**
2. **Time shocks to dissipate before getting into fuel**

STEP #2a Smooth Laser Beam:
The NRL Nike KrF laser produces very uniform laser beams









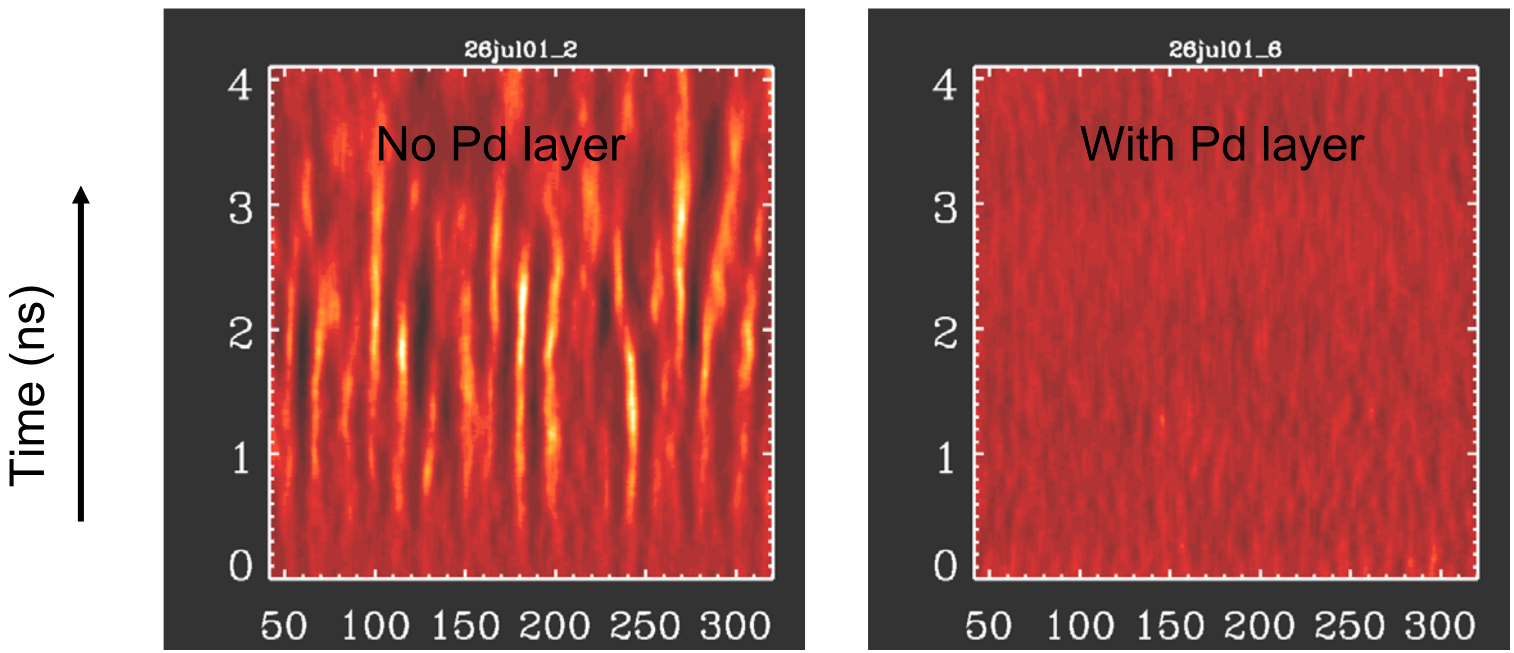
For 50% of the FWHM diameter:

- Power tilts < 2%
- Quadratic curvature : < 3%
- RMS speckle non- uniformity: 0.3 - 1.3% (*all modes*)

Step #2b Reduce "Imprinting" (Effectively smooth laser even further)

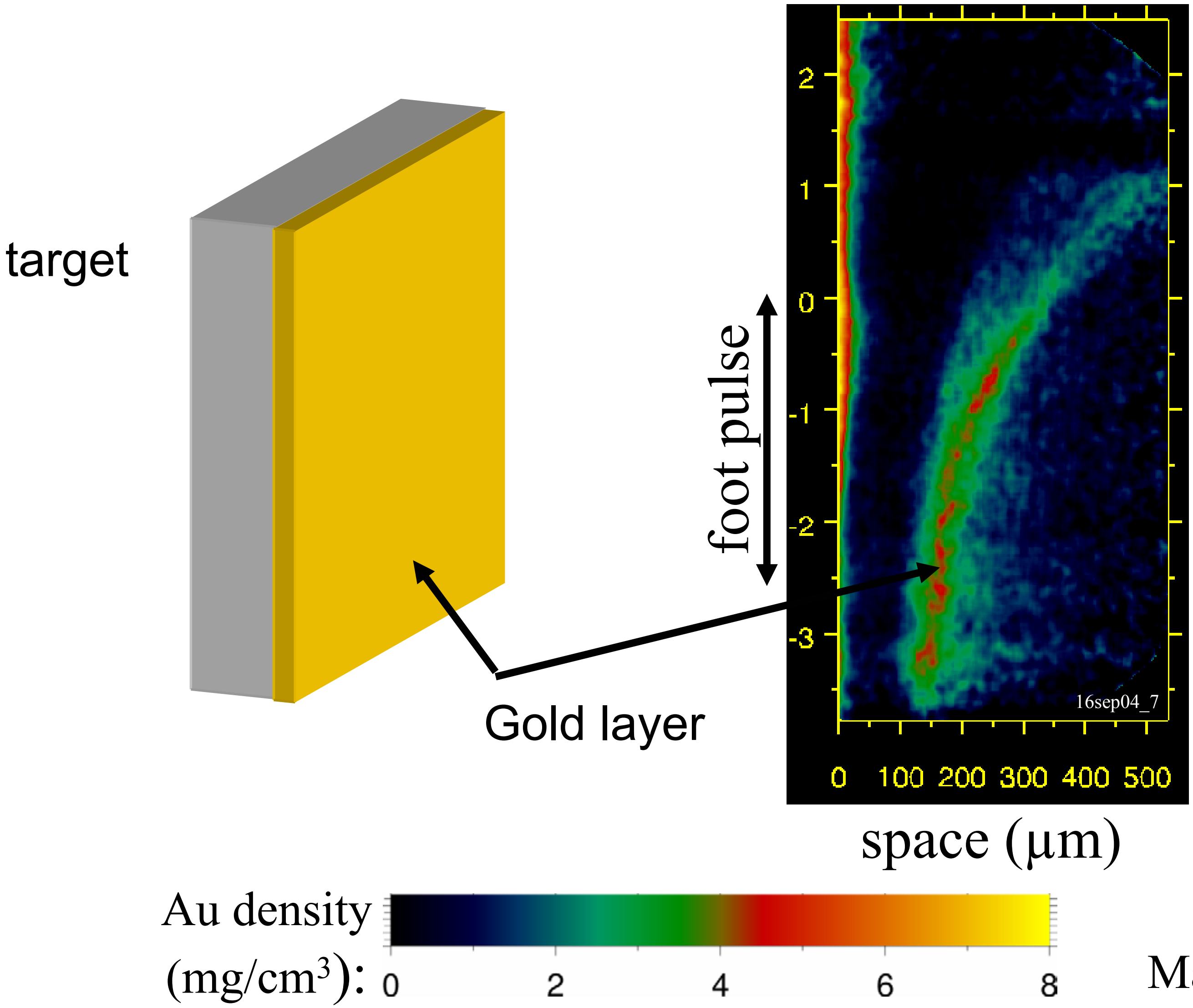
Experimental results show a thin high-Z outer layer (e.g. 1200 Å Pd) substantially reduces the effective laser non-uniformity….
I.E. reduces “seed” for instability

X-Ray Streak radiographs of ablatively accelerated planar targets



Distance across target (μm) Distance across target (μm)

High Z layer provides early time, very uniform, x-ray illumination of target



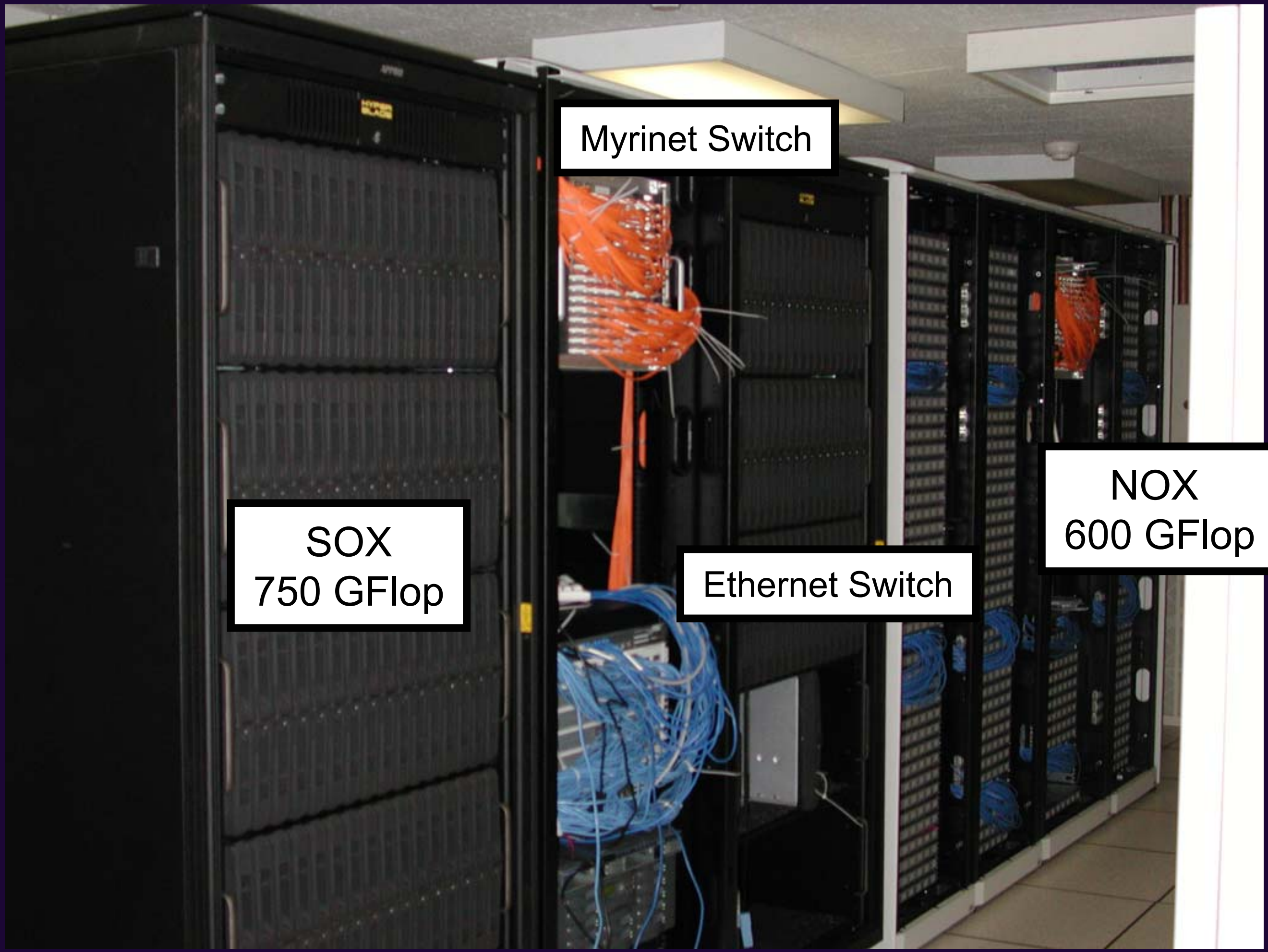
Max Karasik, et al.

Step 2c: Make target outer surface very smooth

Thin Au/Pd coatings with smooth surface finish: high DT permeability and high IR reflectivity.

General Atomics

NRL's large computer clusters allow routine high resolution simulations of pellet implosions.



2 "Self-built" 256-processor supercomputer clusters "NOX" and "SOX"

Processors: NOX 2.4 GHz Xeon, SOX 1.8 GHz Opteron

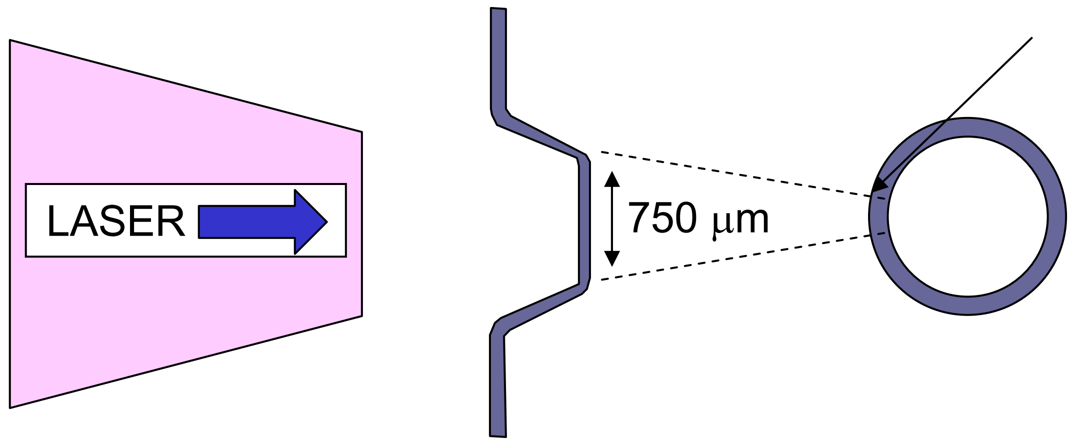
Interconnect: Switched Myrinet 2000

The Nike KrF laser accelerates planar targets at close to the same conditions as in a high gain target.

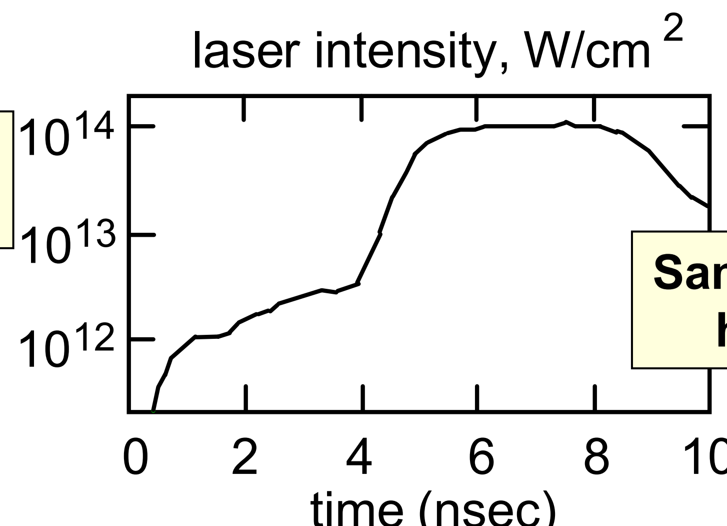
Laser 2-3 kJ
4 ns main pulse

Planar D2 + foam target...
(same material)

same arreal mass
as high gain target

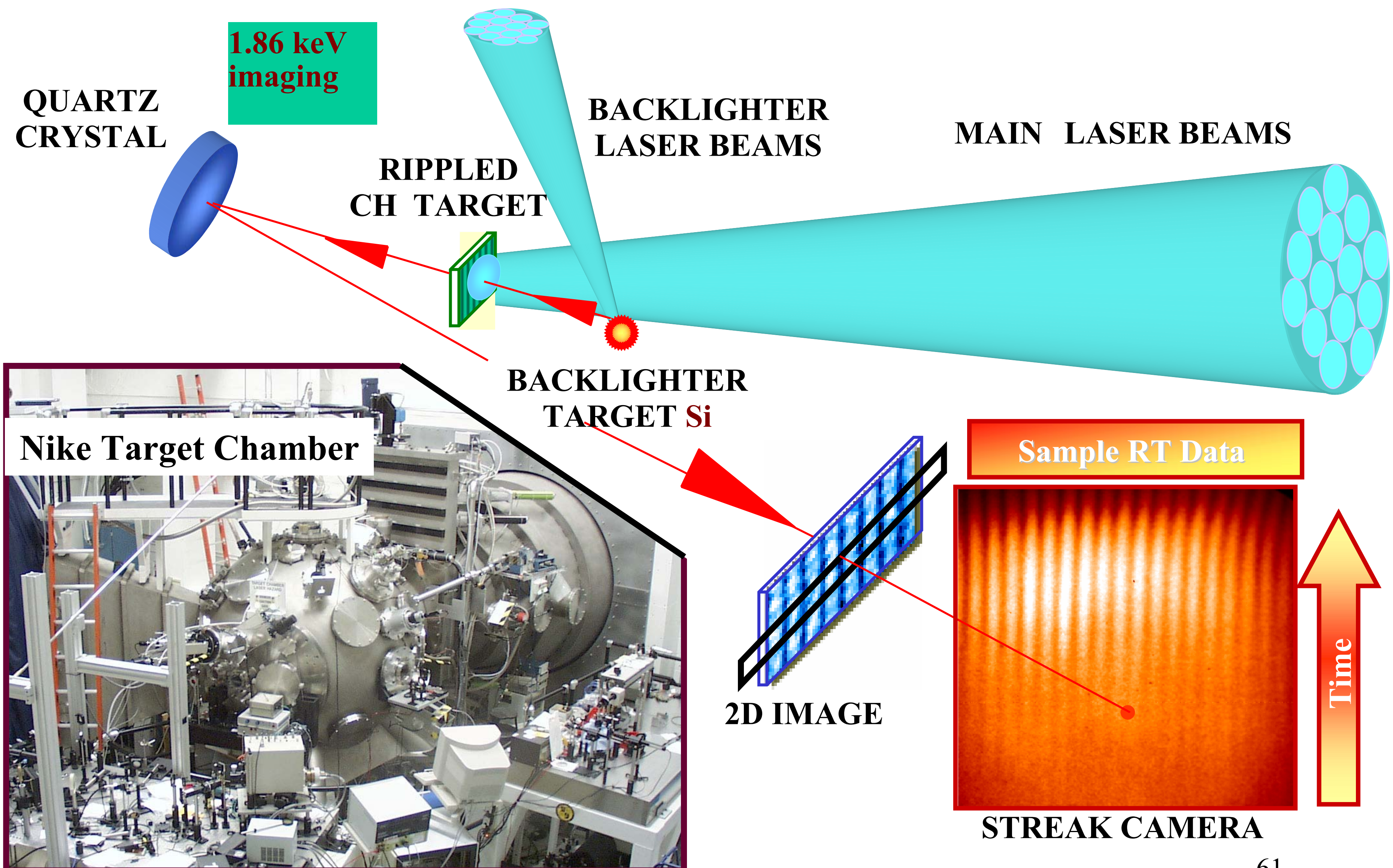


About same intensity
as high gain target



Same pulse shape as
high gain target

Nike is ideally suited to study hydrodynamics in planar geometry



Y. Aglitskiy, et al. , Phys. Rev. Letters, 86, 265001 (2001)

NRL target physics codes (aka FAST) have been benchmarked with experiments on Nike Laser