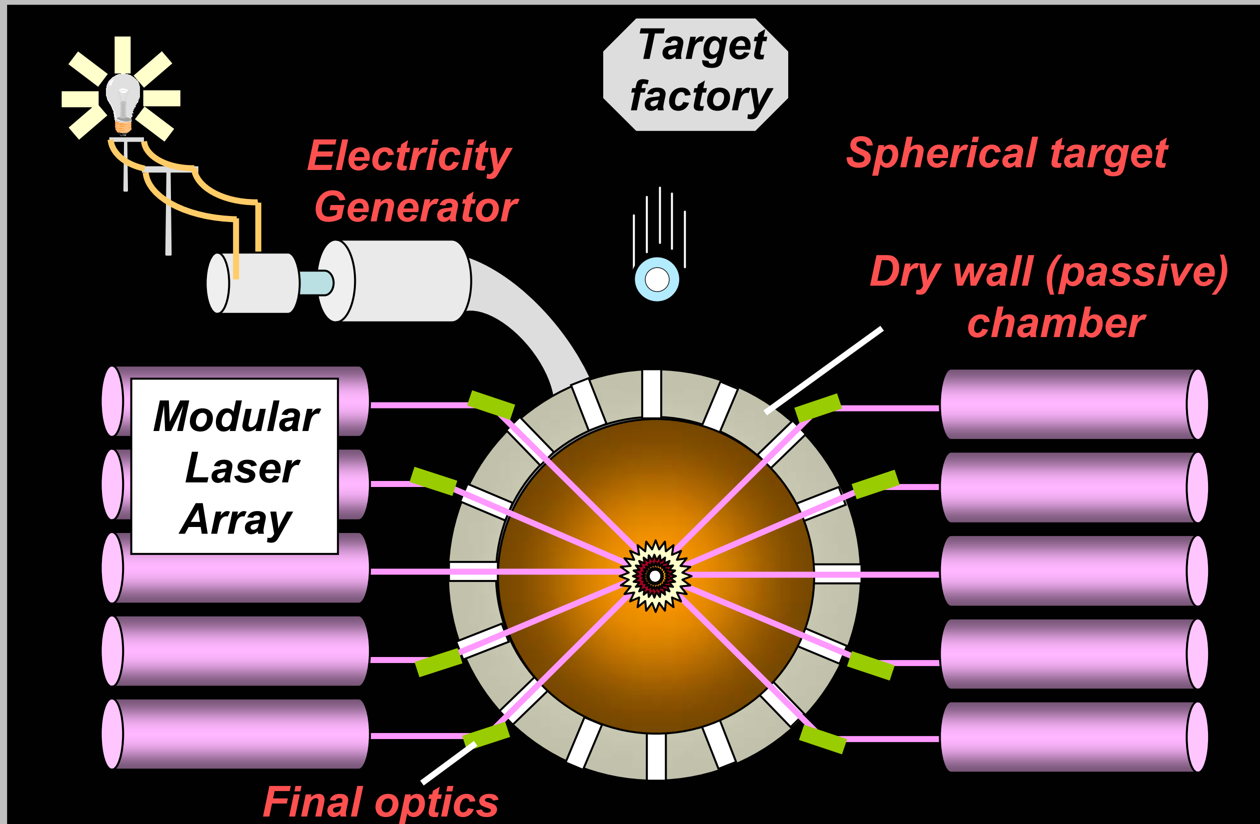
Fusion ENERGY with Lasers, Direct drive targets, and Solid wall chambers

John Sethian and Steve Obenschain
Naval Research Laboratory
Oct 28, 2003

Lasers + direct drive targets can lead to an attractive power plant



Modular, separable parts: lowers cost of development AND improvements

Targets are simple spherical shells: “fuel” lends itself to automated production

Solid wall (passive) chamber inherently simple

Past power plant studies have shown concept economically attractive

Programs contributing to the development of Laser Fusion Energy

1. NRL ICF Program (sponsored by DP/NNSA)
   - Direct Drive target physics with KrF laser
   - High Gain + NIF Target Designs

2. High Average Power Laser [HAPL] Program (DP/NNSA)
   - Science and Technology of other Laser IFE components
     1. Rep-rate, efficient, durable Lasers
     2. Final Optics
     3. Chambers
     4. Target fabrication and injection
     5. Some DD target design

3. Rochester LLE ICF Program (DP/NNSA)
   - Direct Drive target physics with glass laser
   - NIF + High Gain Target Designs

4. Contributor "emeritus": ARIES IFE study (OFES)
   - Chamber operating windows

Explicit energy mission gives an exciting, grand purpose...

1. Generates enthusiasm and opportunities
    a) Attracts the young, the best, and the brightest
    b) Attracts industry
    c) Attracts broad public support

2. The highest quality science results from having a defined mission
    a) True test of understanding is to make something work

3. Forces focus on the end product….a Power Plant
    a) Virtue of simplicity over complexity

4. Fusion should be developed as an integrated system
    a) Fusion science and technology is more than plasma physics
    b) Reach outside community to solve problems
    c) Balance between university, industry and national labs

5. Address key challenges first
    a) Justifies advancement to next phase

6. Maximize return on taxpayer investment: IT GETS THE JOB DONE!

HAPL/LASER IFE GUIDING PRINCIPLE

The fastest, most cost effective, 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 HAPL Program: 6 Government labs, 9 universities, 14 industries contribute to the development of Laser Fusion Energy

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
6. PPPL
7. UC Santa Barbara
8. UNC
9. DELFT

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
14. Plasma Processing, Inc

Entire group gets together 2-3 times/year
Small teams meet more frequently for specific tasks

Mult
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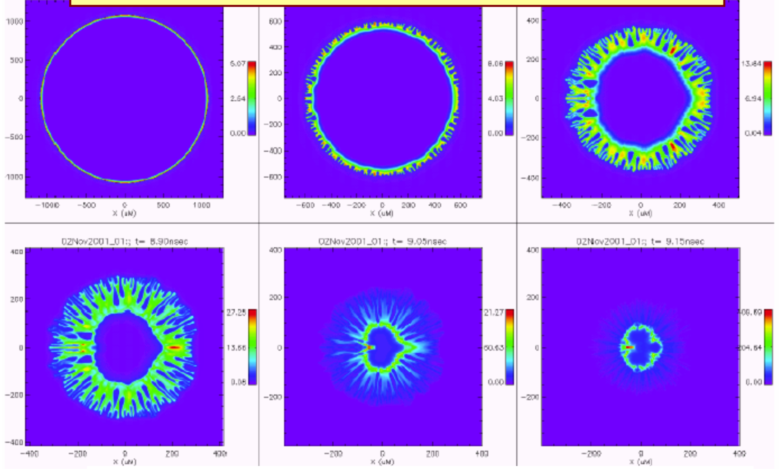
Progress in the Development of Laser Fusion Energy

Target design
Lasers
Final optics
Target Injection
Target Fabrication
Chamber Development

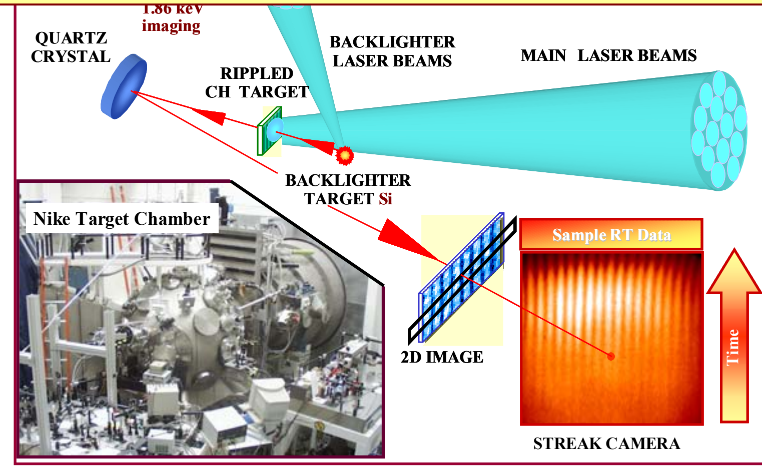
NRL Direct Drive Laser Fusion Program

Integrated High Resolution Target Designs



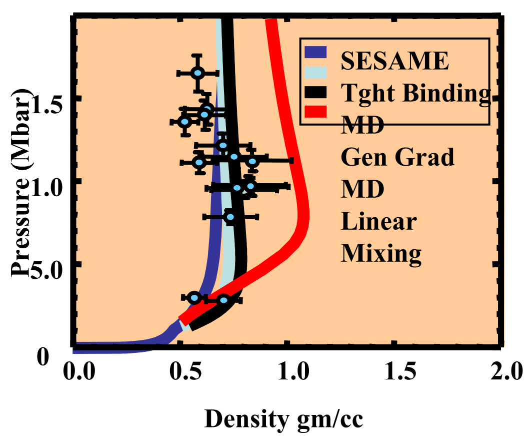
Snapshots of simulated pellet implosion

Nike KrF Laser: Experiments to probe needed physics & benchmark codes



Tests of Laser accelerated target stability

High Energy Density Physics

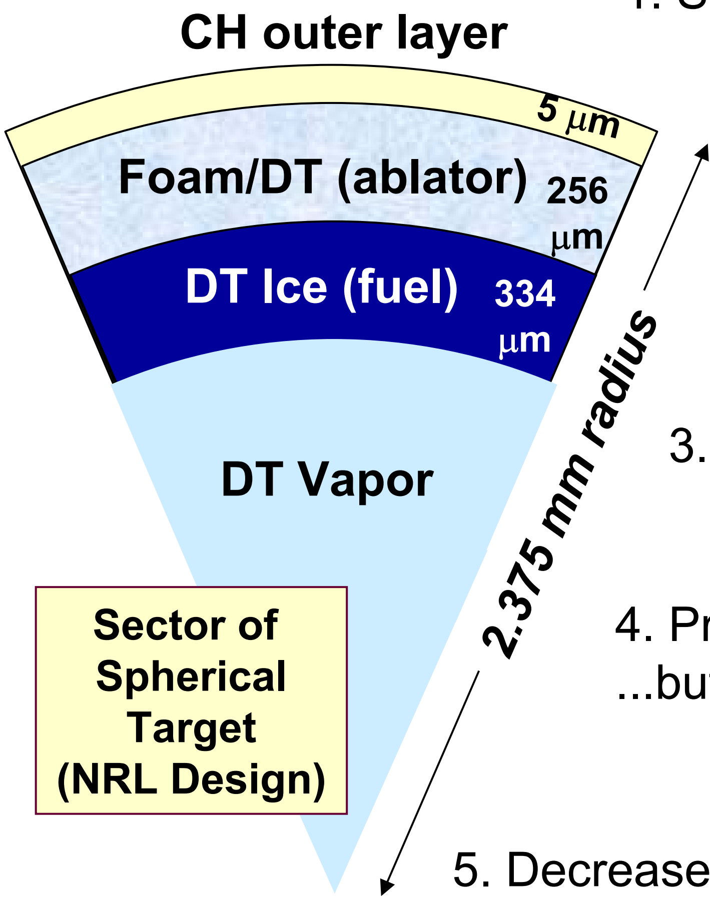


Deuterium Hugoniot EOS

Accomplishments

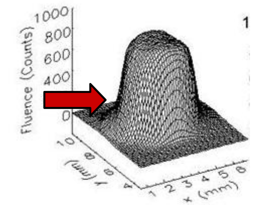
- Ultra-smooth large spot illumination.
- Planar RT data calibrate NRL codes
- Fundamental advances with RM & feedout experiments.
- Major EOS contributions.
- Discovery of high-Z target Imprint mitigation techniques.
- Advanced x-ray imaging and spectroscopic diagnostics.

For Direct Drive Laser IFE, Need gain > 100
- **The biggest physics challenge is hydrodynamic instability seeded by laser and target imperfections**
- **We have a recipe that can achieve these needs**



Sector of Spherical Target (NRL Design)

1. Smooth Laser beam--to reduce imprinting
   KrF: get it naturally (< 1.2% nonuniformity)
   DPPSL: apply smoothing techniques



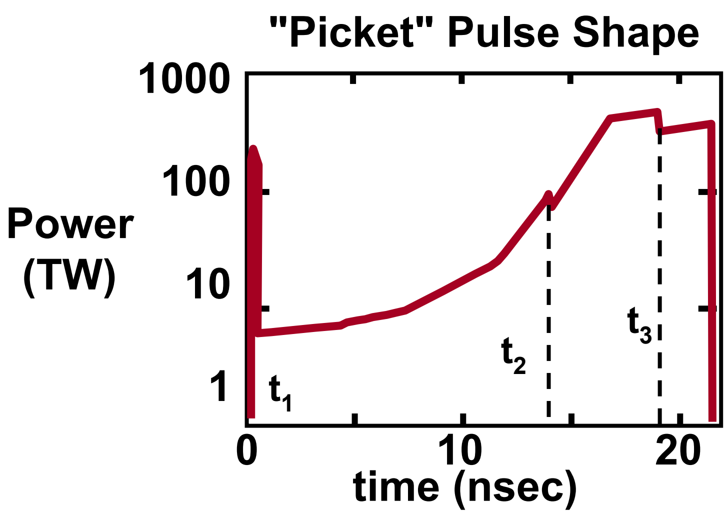
2. High Z coating outside target to further reduce imprint
   indirect drive in foot, direct drive in main
   demonstrated on NRL Nike experiments
3. Choose ablator to maximize absorption & efficiency
   Foam filled with DT
4. Preheat ablator to raise isentrope & reduce RT growth
   ...but keep fuel cold (dense) to maximize gain
   Can be done with shocks by shaping laser pulse
5. Decrease laser focal spot to follow imploding pellet
   "Zoom the laser beam"

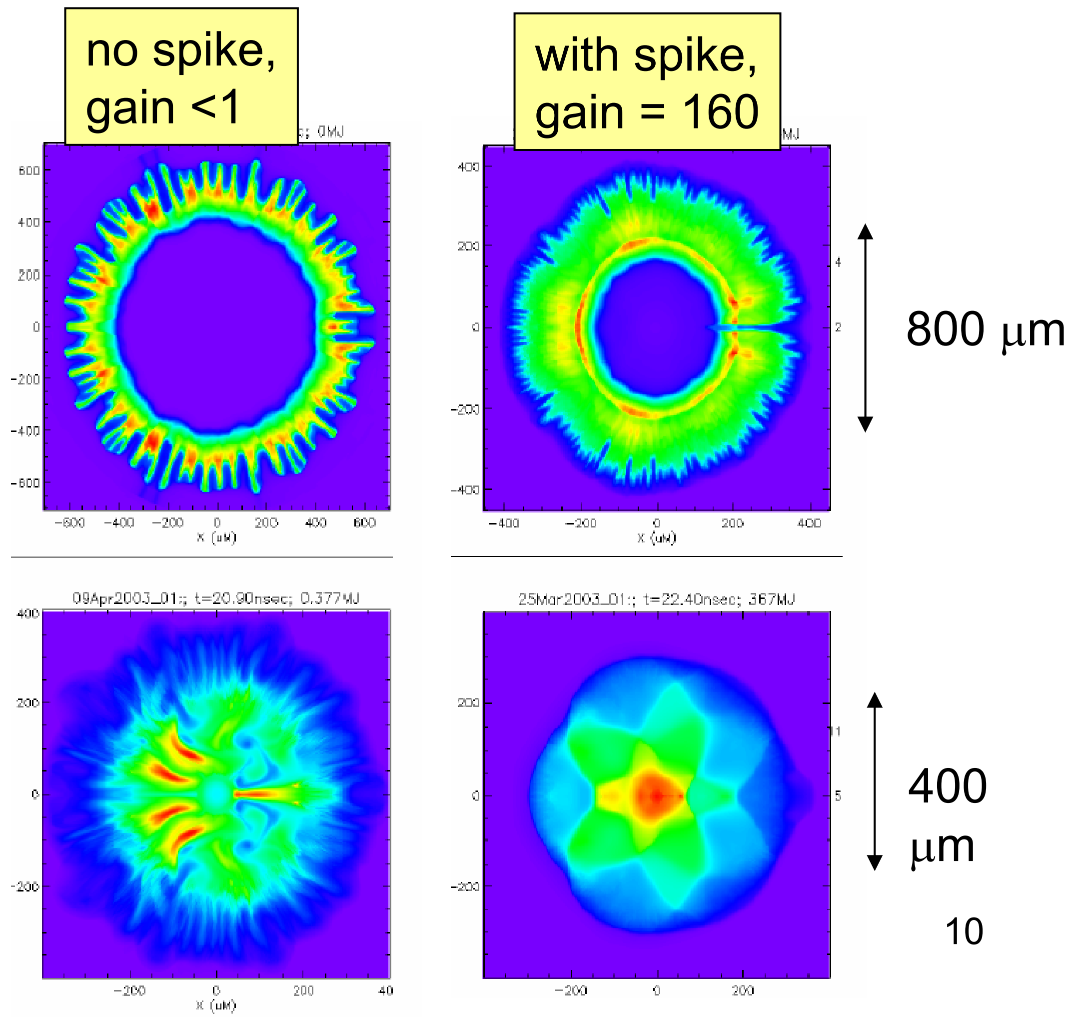
Current designs (LLE, LLNL & NRL) have gains > 100 (~2D). All use DT+ foam ablator, and prepulse spike for adiabat control / imprint reduction

NRL FAST Code (Benchmarked with experiments on Nike)

High resolution 2D calculations that account for both laser and target non-uniformity

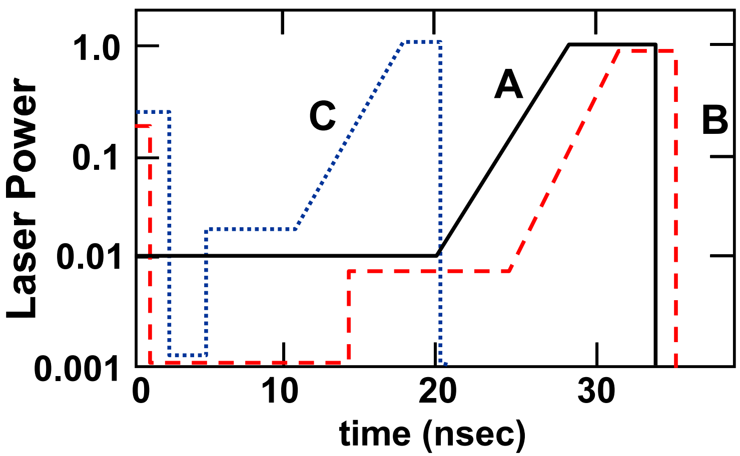
Laser 2.5 MJ



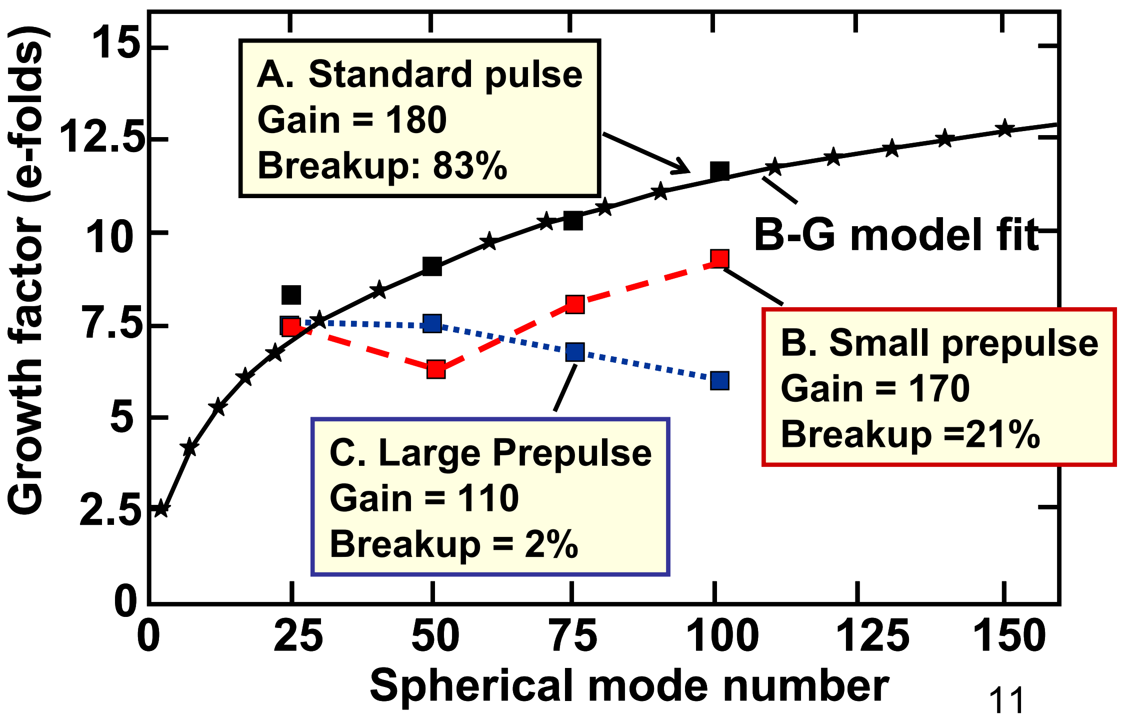


LLNL Lasnex has been used to perform 2-D single mode calculations of NRL target

pulse shape



2.4 MJ Laser, Gain 110-170



The design has sufficient flexibility to optimize the target physics along with the IFE requirements:

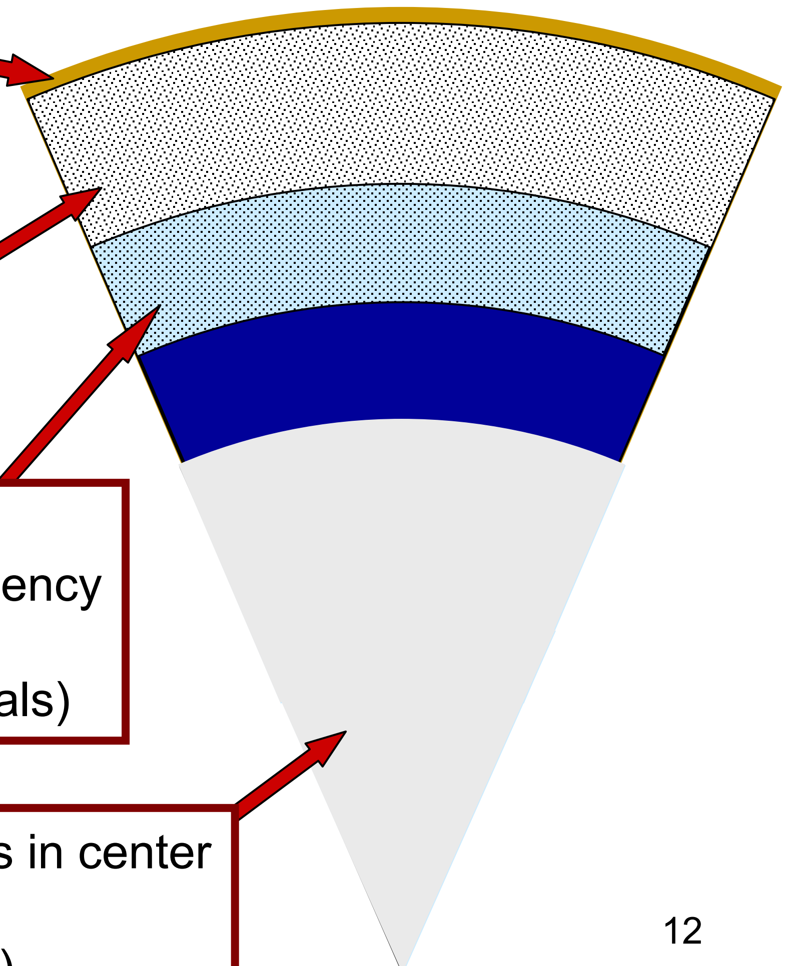
Target fabrication, target injection into the hot chamber, burn products, low cost, and power plant safety

High Z (gold) outer layer
- Reduces laser imprint-NRL exp't
- Reflects IR during injection

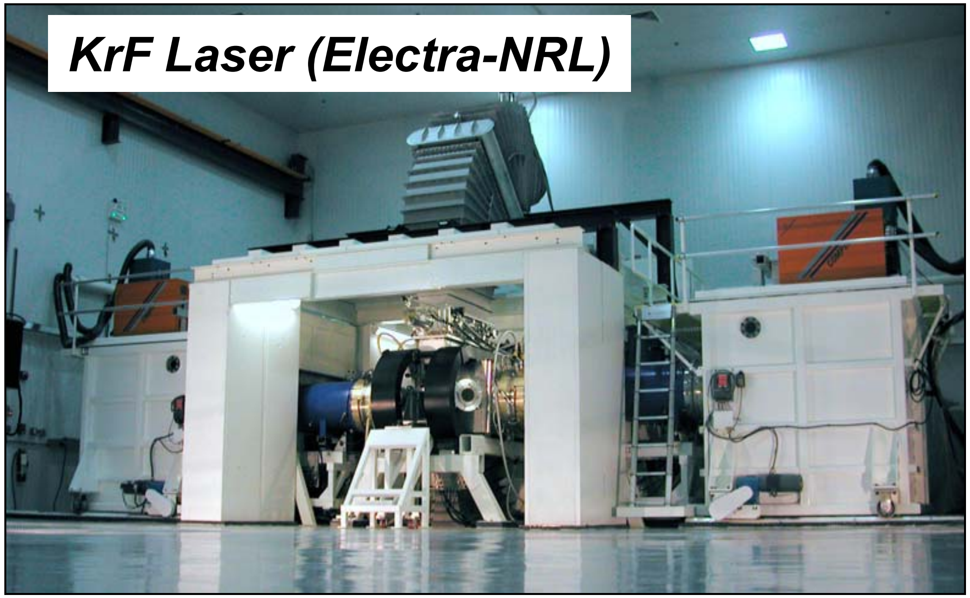
Empty foam outer layer
- Insulates target during injection
- (Preliminary 1D calculations say gain OK)

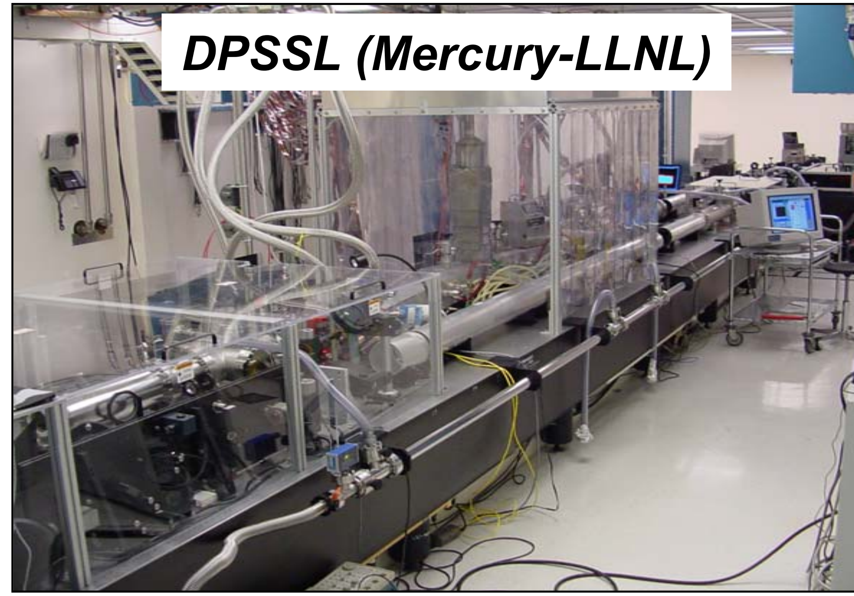
DT + Foam ablator
- Increased absorption and implosion efficiency
- Mechanically stronger target
- Improves inner ice surface (smaller crystals)

DT Ice fuel layer: can have no gas in center
- Colder target helps injection
- (1D calculations say gain OK)



The HAPL Program is developing two types of Lasers

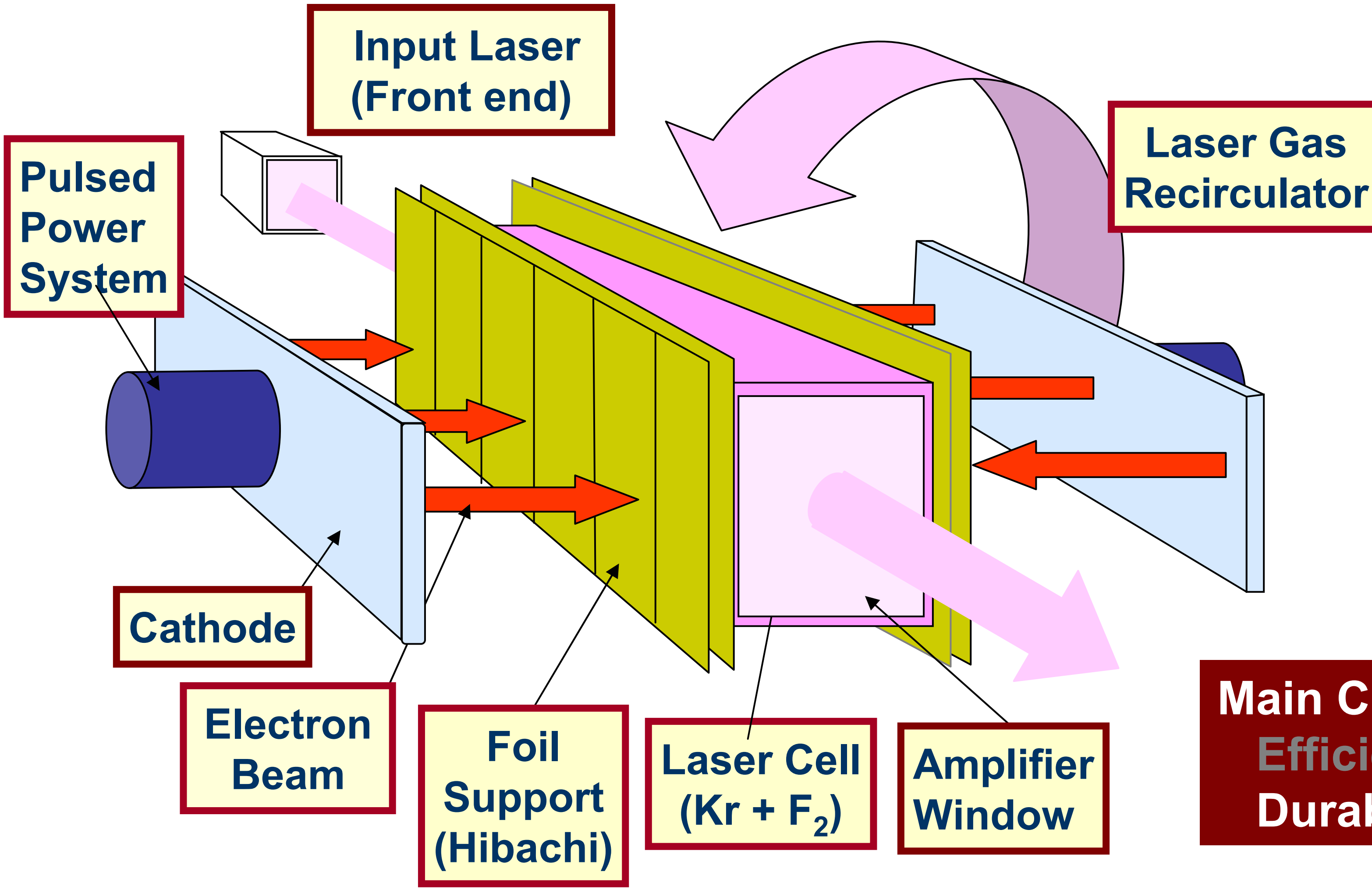




Goals

- Develop technologies for a laser with required efficiency (> 6%), rep-rate (5-10 Hz), durability (>100,000,000 shots), laser beam quality and pulse shaping.
- Needed technologies and system designs are being developed and demonstrated on large (but subscale) systems.
- Laser technologies must scale to full scale (2-3 MJ) systems

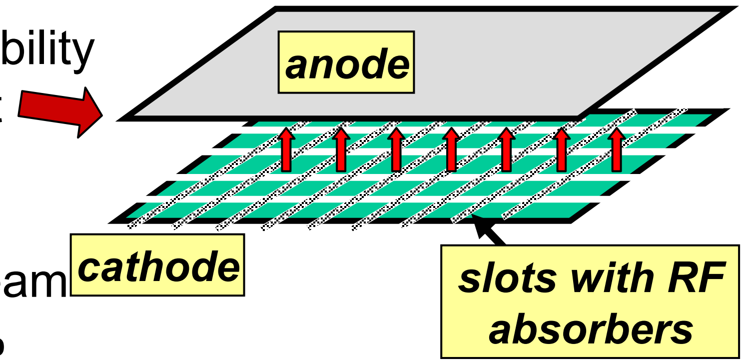
Key Components of an electron-beam pumped KrF Laser



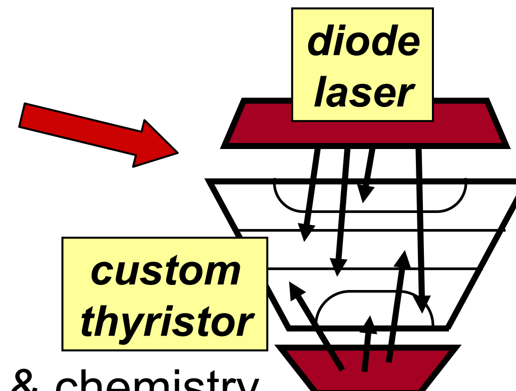
Main Challenges:
- **Efficiency**
- **Durability**

NRL has made fundamental, key advances in the science and technology of KrF lasers

1. Eliminated (fundamental) electron beam instability that compromised electron beam transport

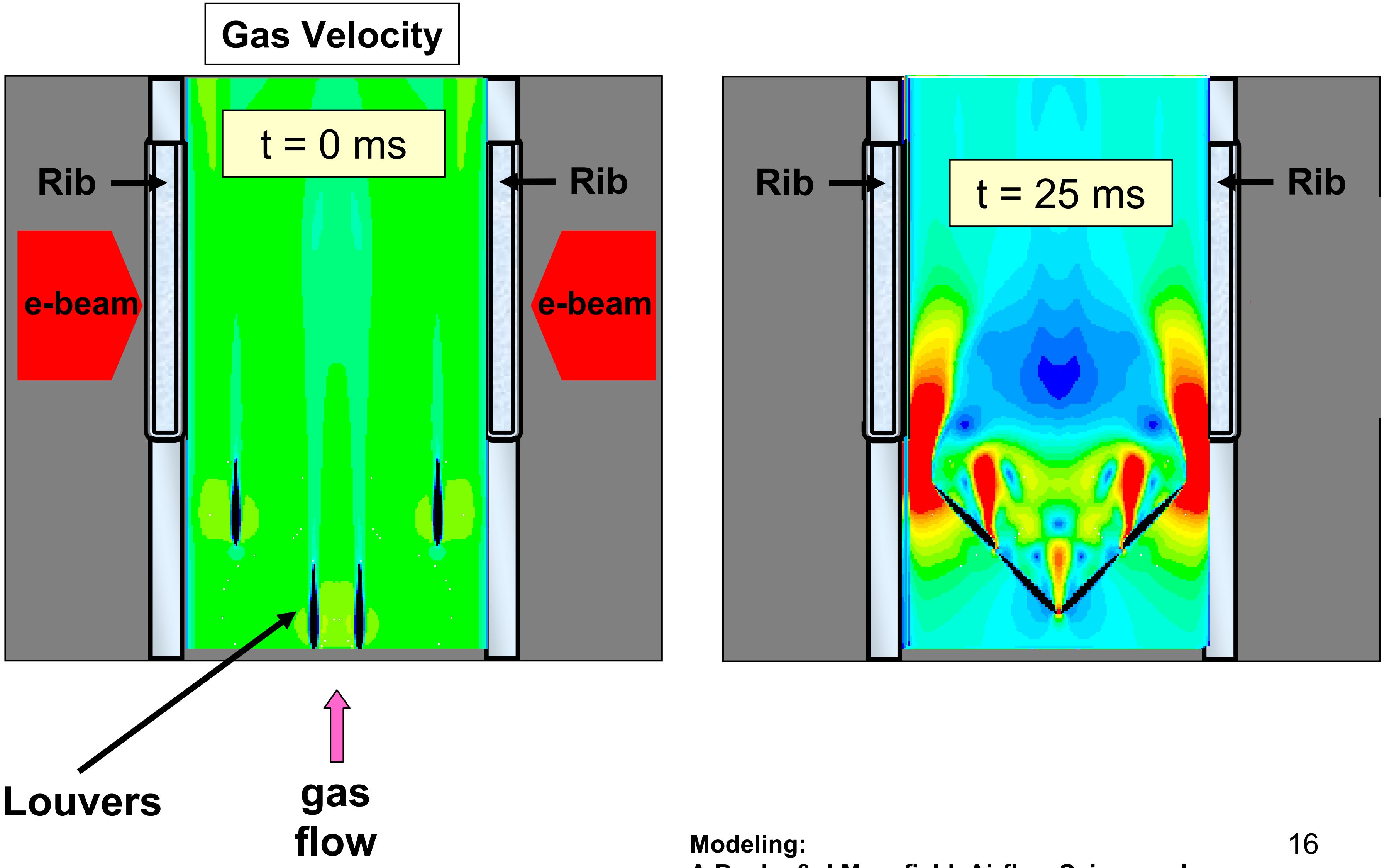


2. Demonstrated High Transmission Hibachi by eliminating anode foil and patterning beam
   Energy into the gas: **Old 35%, New > 75%**
   AGREES WITH MODELING
3. Developed Laser Gated and Pumped Thyristor:
   Solid State Switch that will be basis for efficient (>85%), low cost ($8.50/Joule) & durable pulsed power system



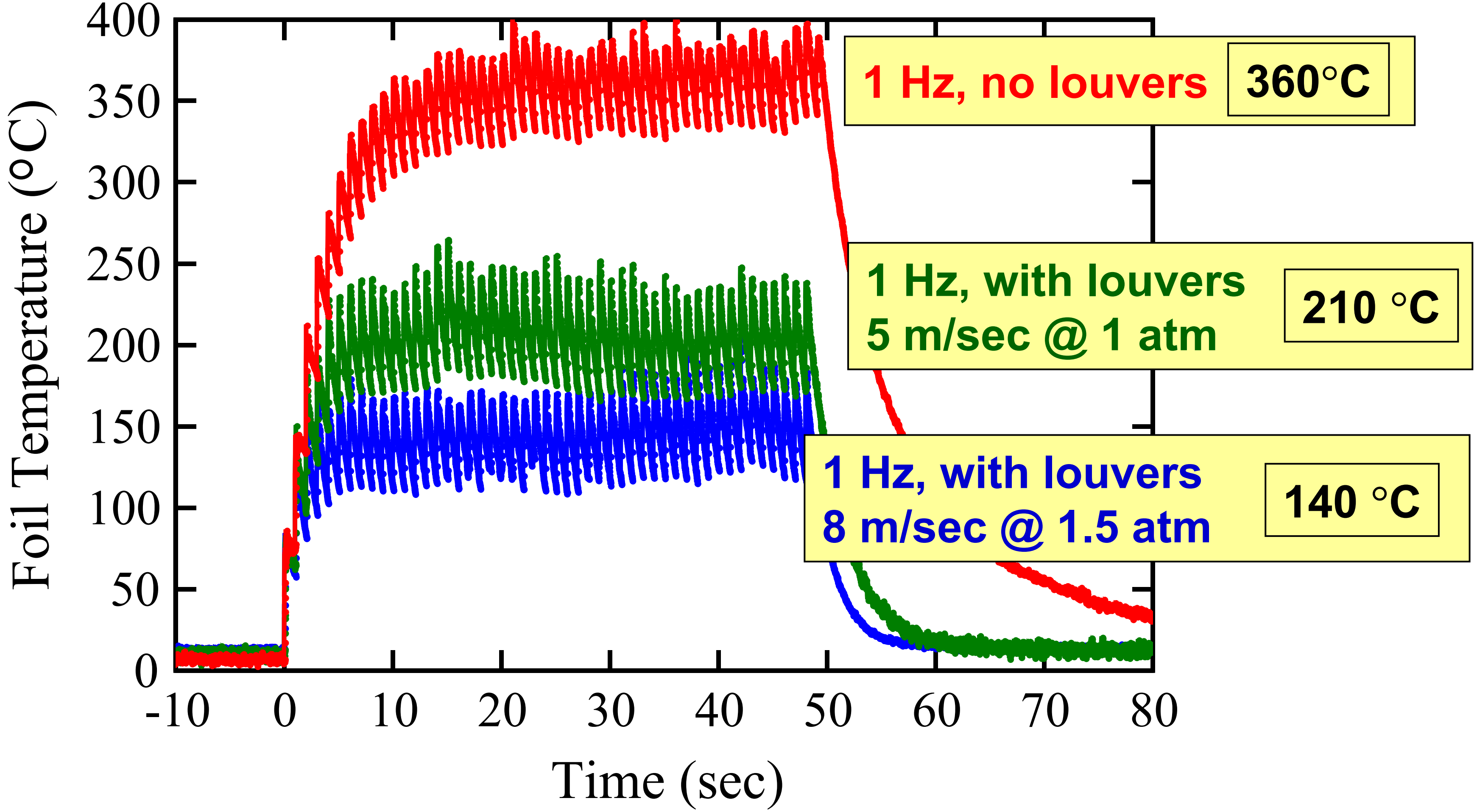
4. Electra produces 500 J laser light in 10 shot, 1Hz bursts
5. Developed "Orestes" code, combines relevant KrF physics & chemistry (24 species, 122 reactions) into a single "First Principles" code.
6. Electra achieved >8% intrinsic efficiency as an oscillator...
   We project >12% as an amplifier. **Kinetics looks good**
7. Demonstrated periodic deflection of laser gas cools hibachi

Periodically deflecting laser gas can cool hibachi foils



Modeling:
A.Banka & J.Mansfield, Airflow Sciences, Inc

Demonstrated periodic deflection of laser gas cools foils



Also: **Run 1600 shots continuous at 1 Hz (limit not reached)**
Run 169 shots continuous @ 5 Hz (cathode failure)

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

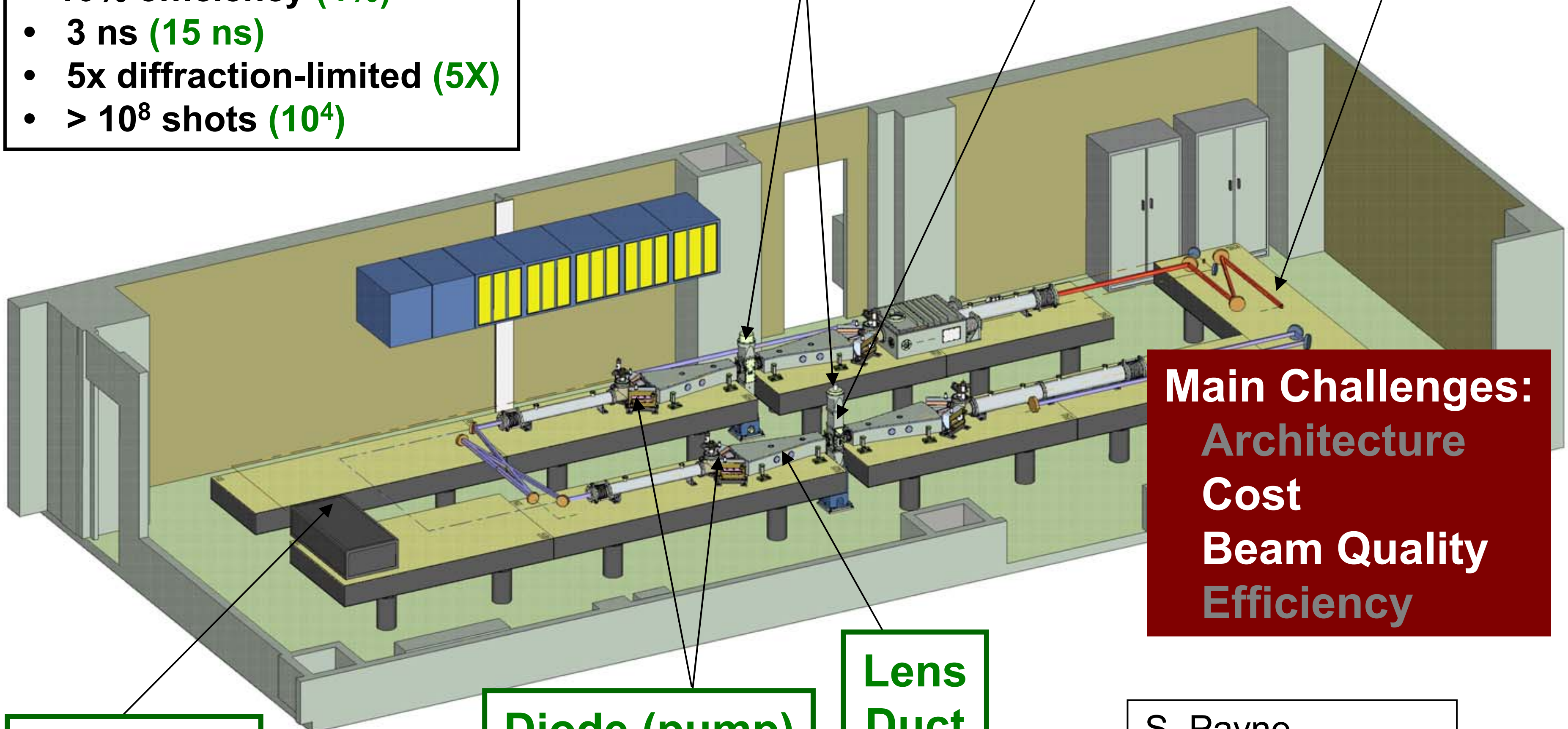
Pulsed Power	**Advanced Switch**	**85%**
Hibachi Structure	**No Anode, Pattern Beam**	**80%**
KrF	**Based on Electra exp'ts**	**12%**
Optics	**Estimate**	**95%**
Ancillaries	**Pumps, recirculator**	**95%**
Total		**7.4%**

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

Key Components of a DPPSL Laser

Goals (1st amplifier only):

- 100 J at 1ω (34 J)
- 10 Hz (5 Hz)
- 10% efficiency (4%)
- 3 ns (15 ns)
- 5x diffraction-limited (5X)
- > 10^8 shots (10^4)

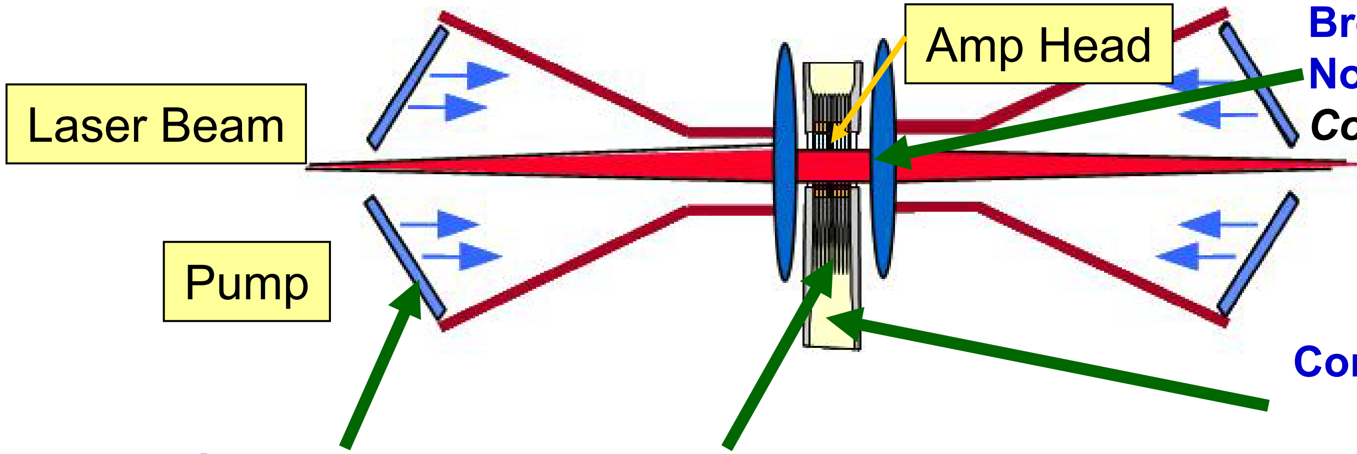


Main Challenges:

- Architecture
- Cost
- Beam Quality
- Efficiency

S..Payne,
C. Bibeau,
A. Baraymian et al
LLNL

The LLNL program has accomplished four major steps towards developing the DPPSL laser for IFE[57]

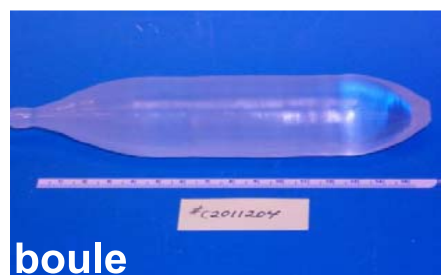


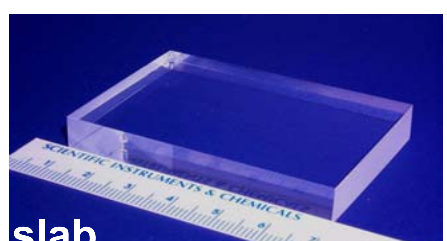
Brewster's angle → Normal incidence
Compact arrangement

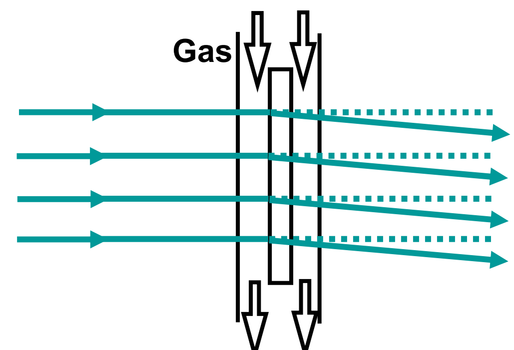
Convective cooling → Forced gas
Allows 10 Hz operation

Flash lamps → Laser diodes
Higher efficiency and reliability

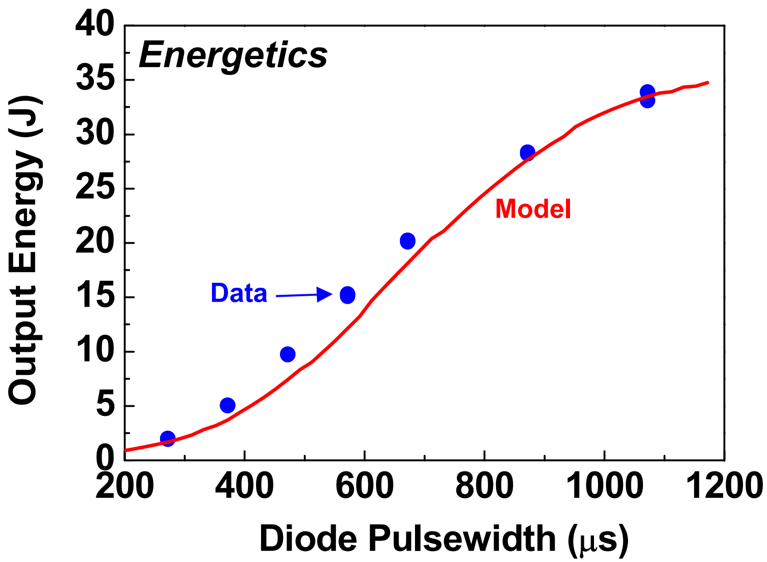
Nd:glass → Yb:crystals
Increased energy storage and efficiency

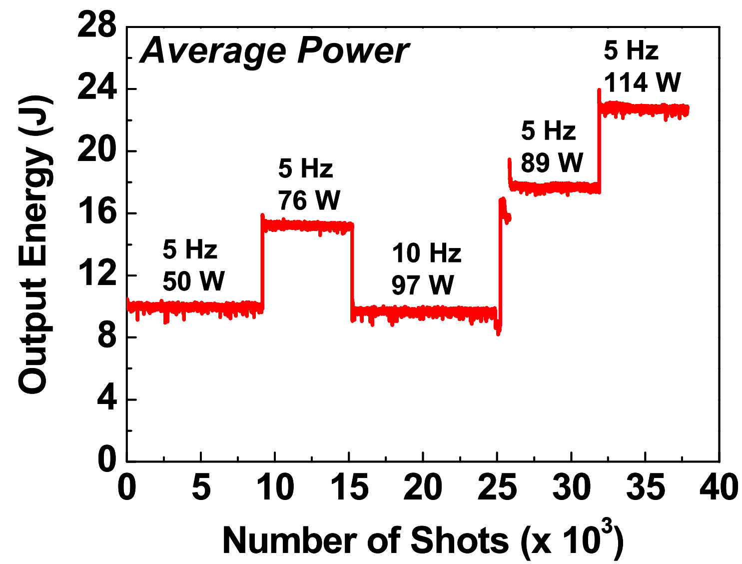


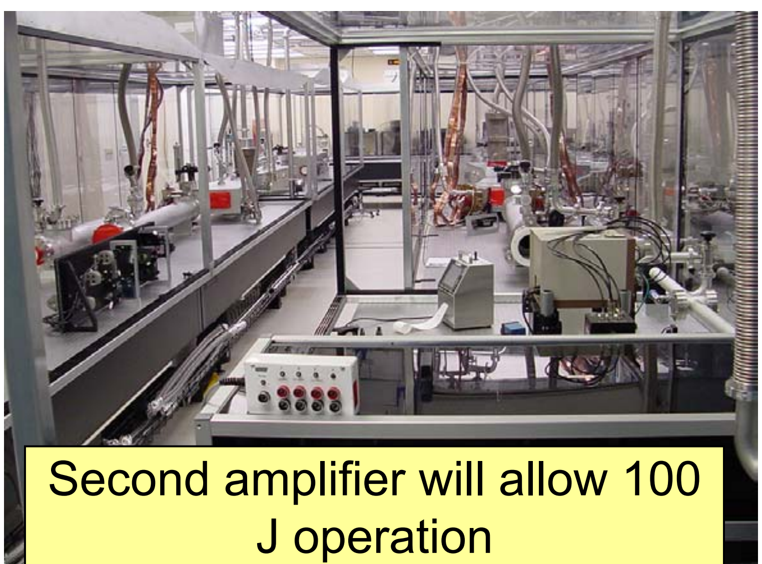


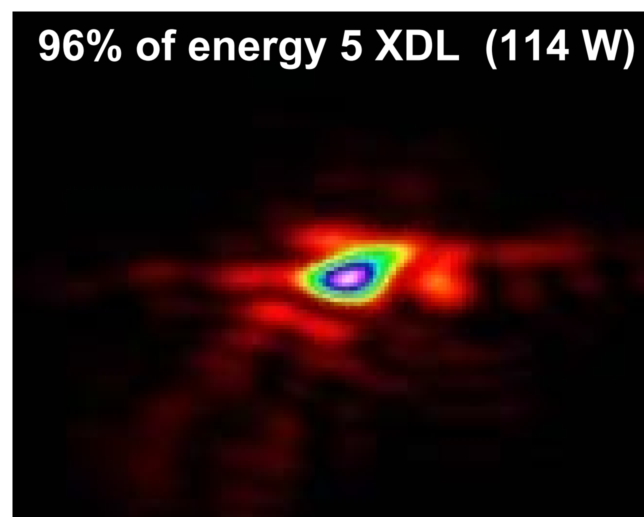


With a *single* amplifier, Mercury has produced up to 34 J single shot, and 114 W average power at 5 Hz..





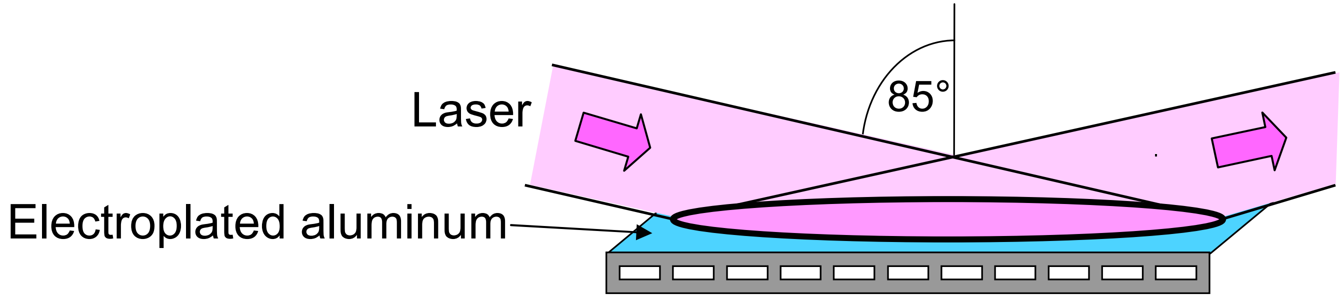




Final Optic Progress

Grazing Incidence Aluminum Mirror meets IFE requirements for reflectivity (>99% @ 85°) & damage threshold (5 J/cm²)

Concept

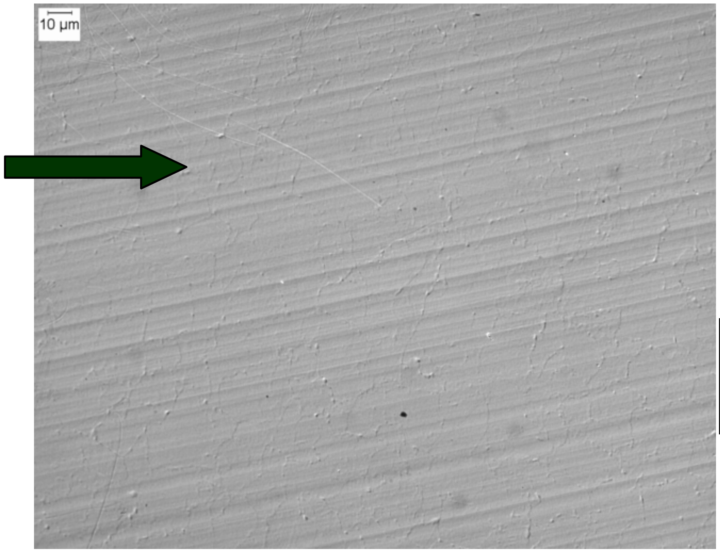


stiff, lightweight, cooled, neutron resistant substrate

Results

100,000 shots at 3-4 J/cm²
No discernable change to the surface

Surface finally showed change at 11 J/cm² @ 78,500 shots, may be due to initial surface imperfections

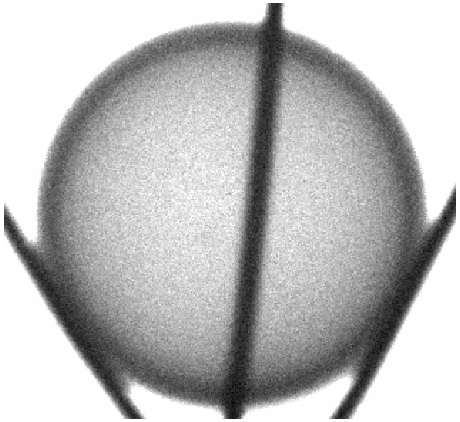


Mark Tillack
UCSD

Target Fabrication Progress

- ♦ Foam shells by batch production
- ♦ Cryo layers grown over foam are ultra smooth
- ♦ Chemical plant analysis >> direct drive targets < $0.16 ea

Established new foam chemistry. Batch produced foam shells

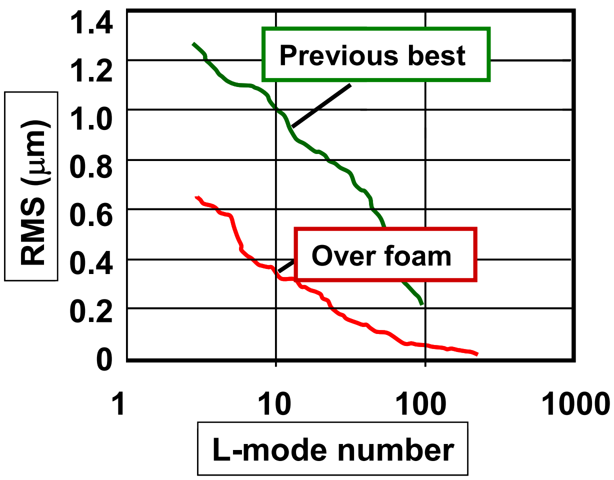


X-Ray picture of mass produced foam shell 4 mm dia, 400 μ wall

D. Schroen, Schafer Corp

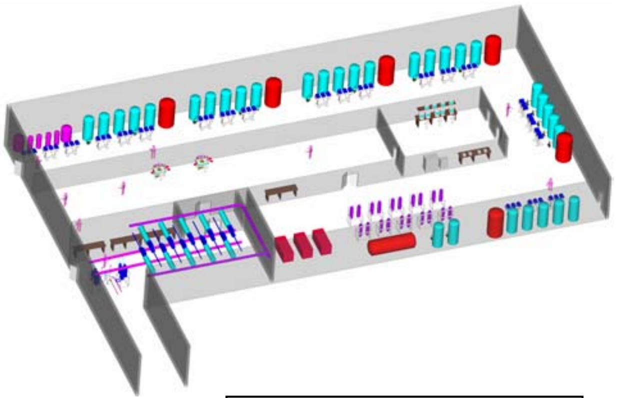
Produced very smooth (~ 0.6 μm RMS) DT ice layers over foam

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



J. Hoffer & D. Geller
LANL

Targets $0.16 each from chemical process plant methodology



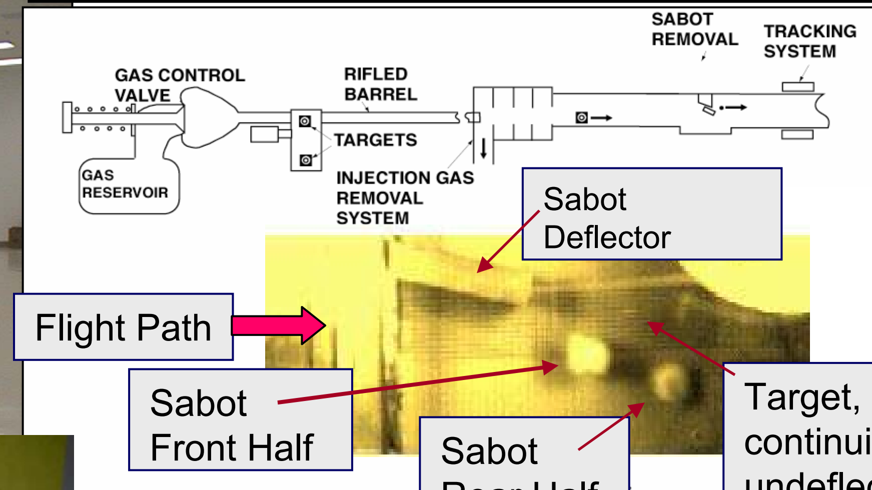
D. Goodin et al
General Atomics

Target Injector / Tracking Progress

- Light gas gun injector in operation
- Achieved required 400 m/sec
- Demonstrated separable sabot
- *Initial* Target placement accuracy +/-22 mm (need ~10 x better)

Target Injection and Tracking system

Demonstrated in flight sabot separation



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

Chamber Progress -1 Operating windows

Establishing Chamber operating windows is a multidisciplinary, simulation intensive, process......

.....Here is an example for a 154 MJ target.

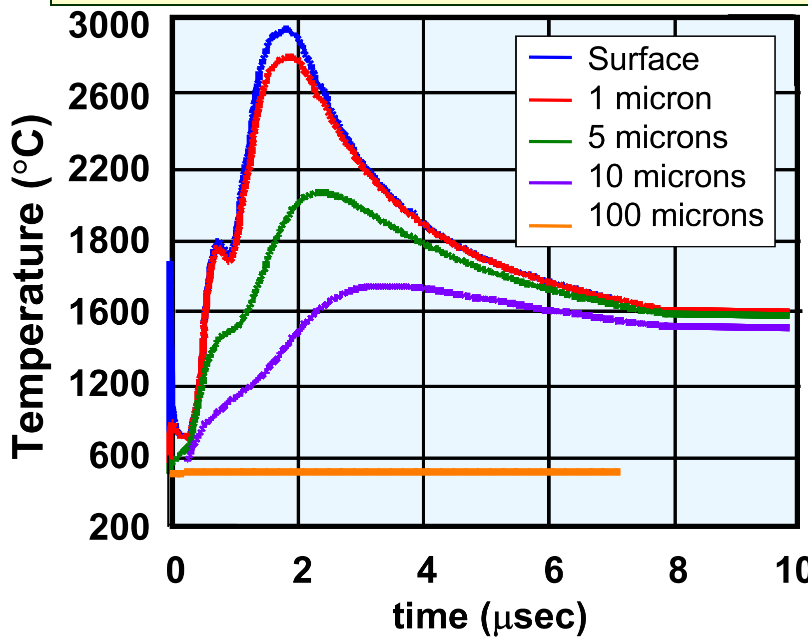
Target Physics:
gives target emissions (neutrons, x-rays, ions) →

Chamber Physics:
What hits wall: "threat spectra" →

Materials:
How wall responds to "threat spectra" →

Target Injection Survival:
allowed chamber conditions (gas, wall temperature) →

Tungsten first wall temperature stays below melting point (tungsten melts at 3410 °C)



154 MJ target
No gas
6.5 m radius

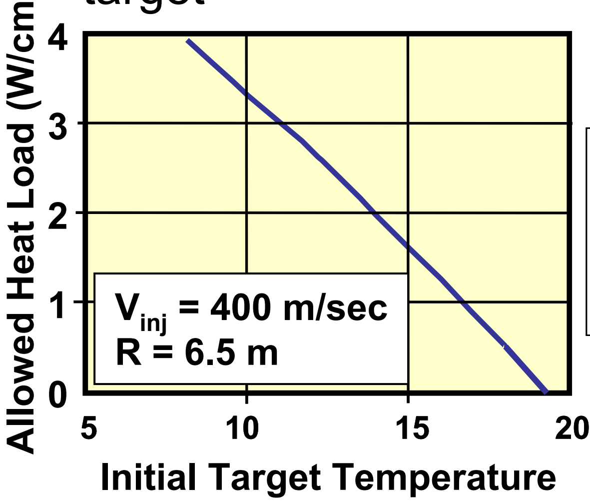
UCSD
Wisconsin
LLNL
GA

Chamber Progress -2 Operating windows

Establishing Chamber operating windows is a multidisciplinary INTERACTIVE process.

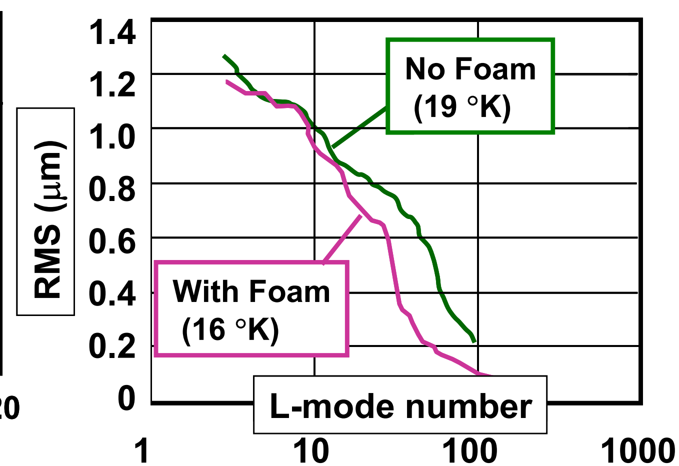
Problem:
Target won't survive in hot chamber

Solution:
Start with cooler target



Problem:
Can't make smooth DT ice at lower temp

Solution:
Can, *too!* --
if DT ice over foam



Problem:
Previous target designs needed gas in target

Solution:
Newer 1-D calculations:
Target OK with no gas

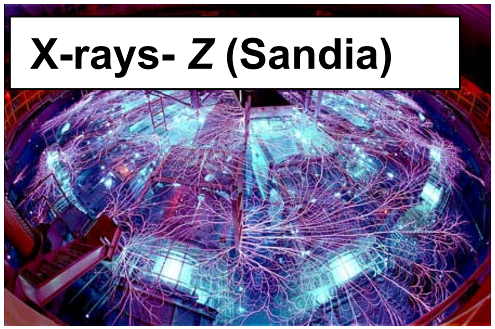
Note:
New foam insulated target opens operating window

HAPL team

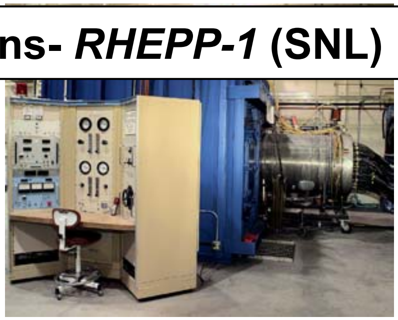
Materials Progress

- Long term material survival (Helium retention, thermo-mechanical fatigue) is still an issue.
- Using an array of facilities + modeling to address this

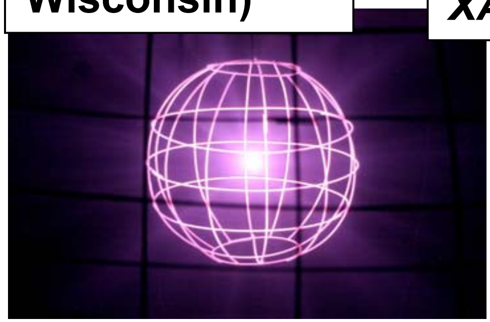
X-rays- *Z* (Sandia)



Ions- *RHEPP-1* (SNL)



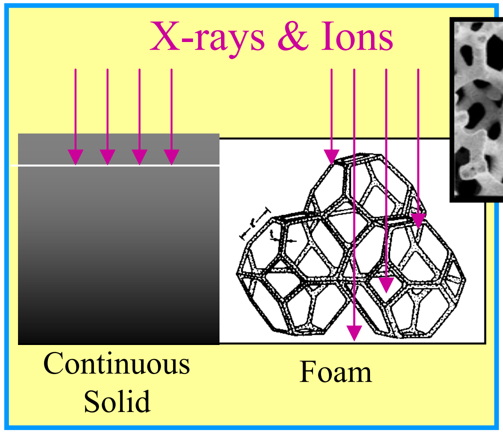
He^3 ions- *IEC* Wisconsin)

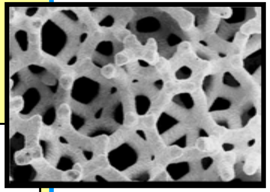


Rep-rate X-rays- *XAPPER* (LLNL)

1) Both Z and RHEPP are producing relevant threats.
2) Measured ablation/roughening thresholds close to the code predictions.

New materials & 3D modeling





"Engineered tungsten" (foam, fiber, plasma sprayed)

- **Allows Helium migration**
- **"Breathes" to mitigate fatigue**

SNL
LLNL
UCSD
ORNL
Wisconsin
UCLA

The Path to develop Laser Fusion Energy

Phase I:
Basic fusion science & technology
1999- 2005

Scalable Technologies

- Krypton fluoride laser
- Diode pumped solid state laser
- Target fabrication & injection
- Final optics
- Chambers materials/design

Target Design & Physics

- 2D/3D simulations
- 1-30 kJ laser-target expts

Phase II
Validate science & technology
2006 - 2014

Full Scale Components

- Power plant laser beamline
- Target fab/injection facility
- Power Plant design

Ignition Physics Validation

- MJ target implosions
- Calibrated 3D simulations

Phase III
Engineering Test Facility
operating ~ 2020

- *Full size laser: 2.4 MJ, 60 laser lines*
- *Optimize targets for high yield*
- *Develop materials and components.*
- *~ 300-700 MW net electricity*
- *Resolve basic issues by 2028*

Critical Issues that must be addressed to go to Phase II

Target Design:

Verify a robust family of target designs, using 2D and 3D modeling
Benchmark with experiments on Nike and Omega

Lasers (KrF)

Durability of hibachi foil and amplifier windows, efficiency in "real" system

Lasers (DPPSL)

Cost of diodes, large crystals, efficiency in "real" system, beam smoothing?

Chambers

Long Term materials: He retention and thermo-mechanical fatigue
Blanket and underlying neutron resistant structure

Final Optics:

Bonding to substrate (ok if Al, needs demo if SiC)
Resistant to target emissions (neutrons, x-rays, ions)

Target Fabrication

Mass produced shells that meet all IFE specs
Mass cryo-layering technique

Target Injection

Placement accuracy and tracking
Target survival in integrated scenario