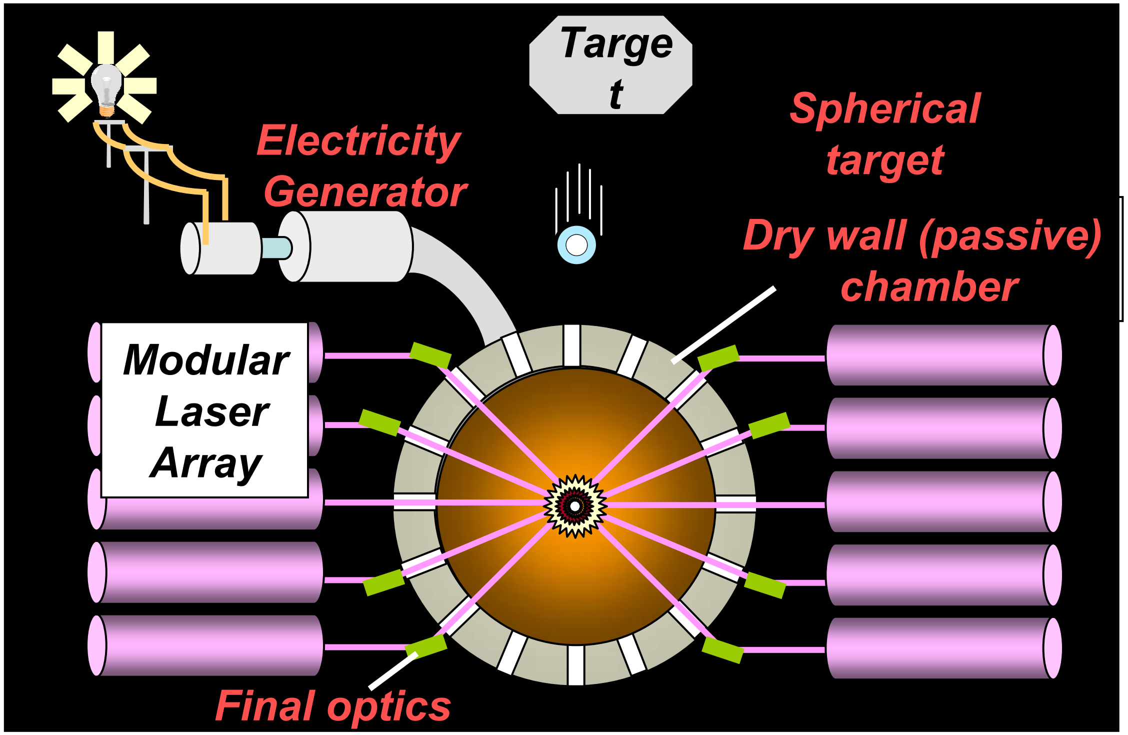
The Path to Develop Laser Fusion Energy

John Sethian
Naval Research Laboratory

plus the over 60 members
in the High Average Power Laser Program

Sep 14, 2004

Fusion Energy with Lasers, Direct Drive Targets, and Solid Wall Chambers



Capitalizes on large NNSA investment in laser-target physics and lasers

Inherent Engineering Advantages:

Separation of complex components from reaction chamber

Modular nature of the components

Reduced risk and cost of development: laser made of identical beam lines

Substantial technical advances since program started < 5 years ago

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

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

4. Contributor "emeritus": ARIES IFE study (OFES)

Farrokh Najmabadi, O-1-4.1 Tuesday 3:30

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, 14 Industries

HAPL - Madison, Wisconsin, Sept. 24-25, 2003

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. UNC
9. DELFT

Industry

1. General Atomics
2. Titan/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Technology
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

The Path to develop Laser Fusion Energy

Phase I:
1999- 2005

Basic Science and Technology

- 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
2006 - 2014

Develop Full Scale Components

- Power plant laser beam line
- Target fab/injection facility
- Materials evaluations
- Power Plant design

Ignition Physics Validation

- **MJ target implosions**
- **Calibrated 3D simulations**

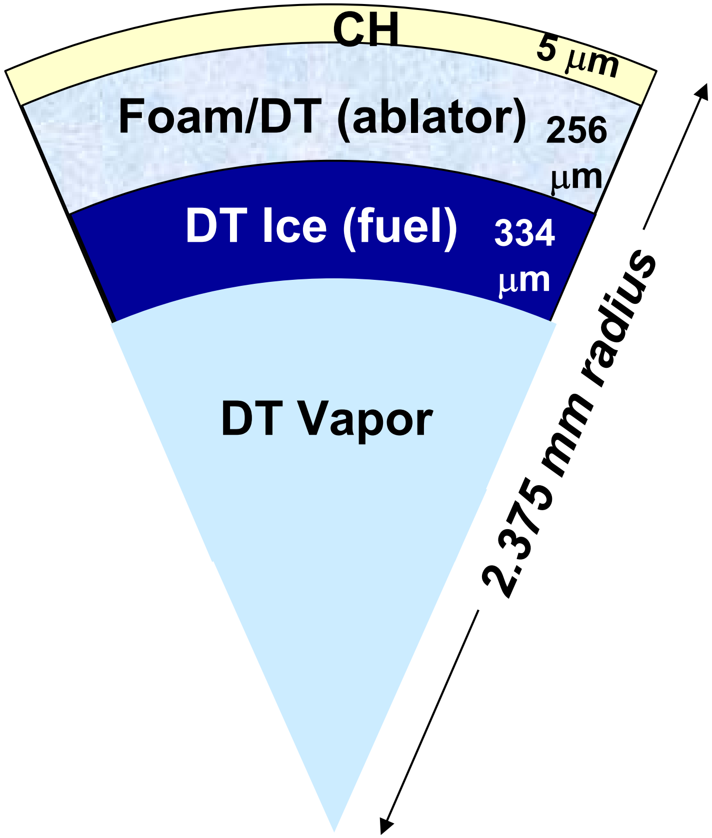
Phase III
Engineering
Test Facility
operating ~ 2020

Engineering Test Facility

- Full size laser: 2-3 MJ, 60 laser lines
- Optimize targets for high yield
- Optimize chamber materials and components.
- **~ 300-700 MW net electricity**

Current high gain target designs use a DT+ Foam Ablator

Sector of Spherical Target (NRL Design)

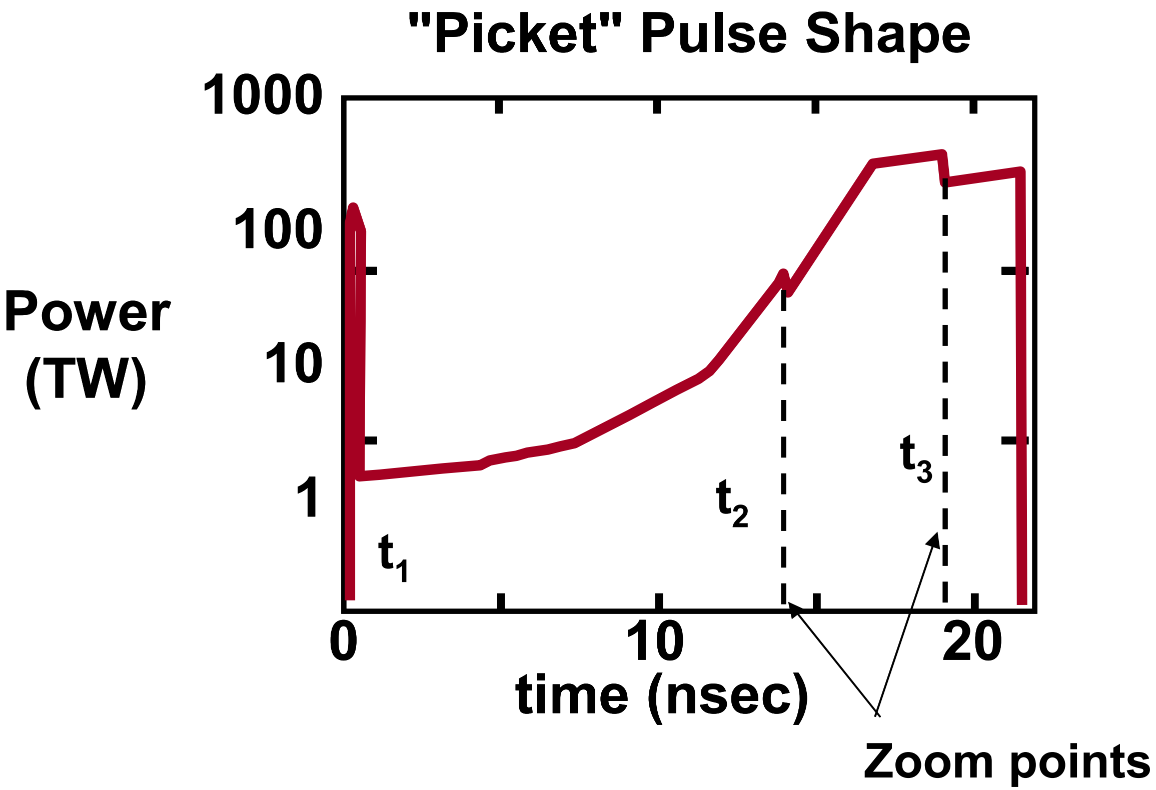


We need gains >100 for IFE because of modest (~7%) laser efficiency

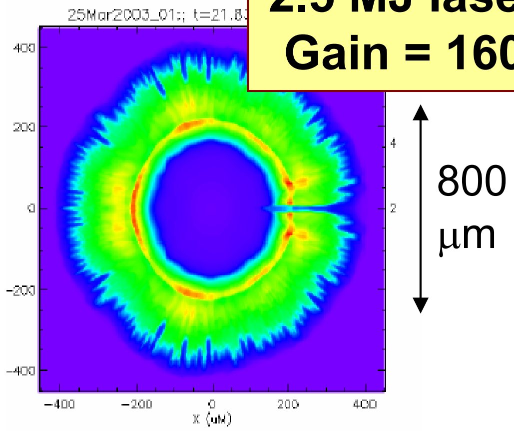
Current target designs have gains ~ 160 (2-D).
Include prepulse spike for adiabat control / imprint reduction
"Zoom" laser to maximize absorption

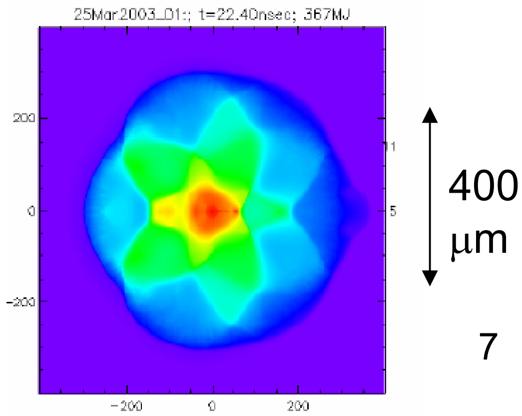
NRL FAST Code

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

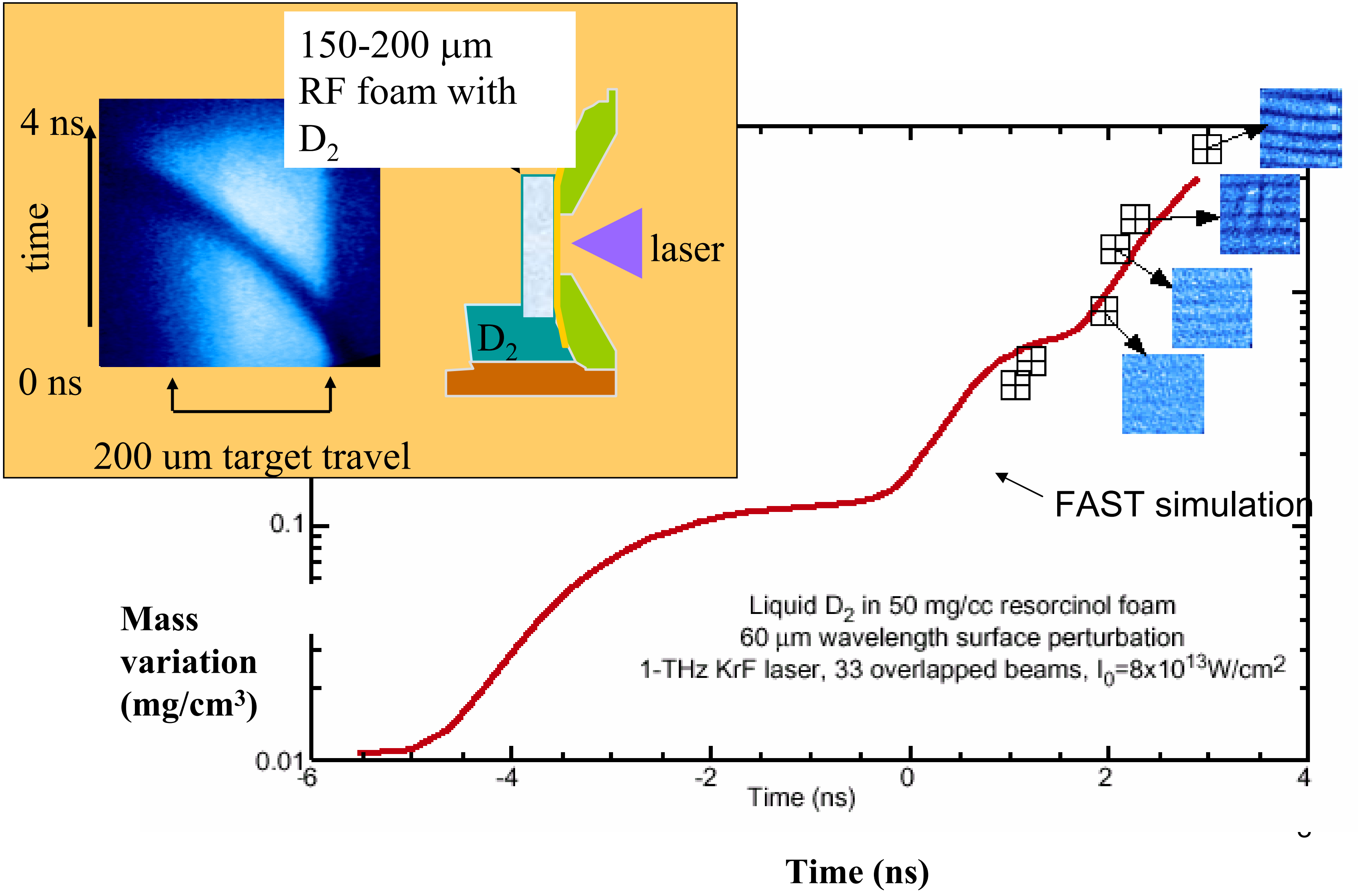


2.5 MJ laser
Gain = 160

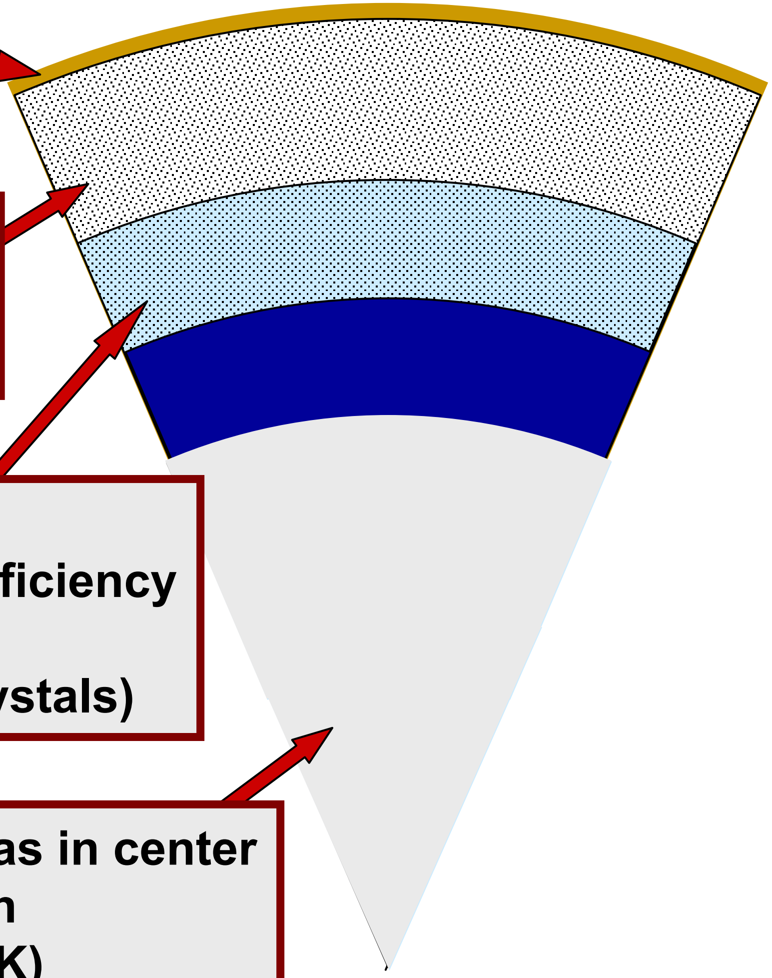




NRL FAST codes have been benchmarked with experiments



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



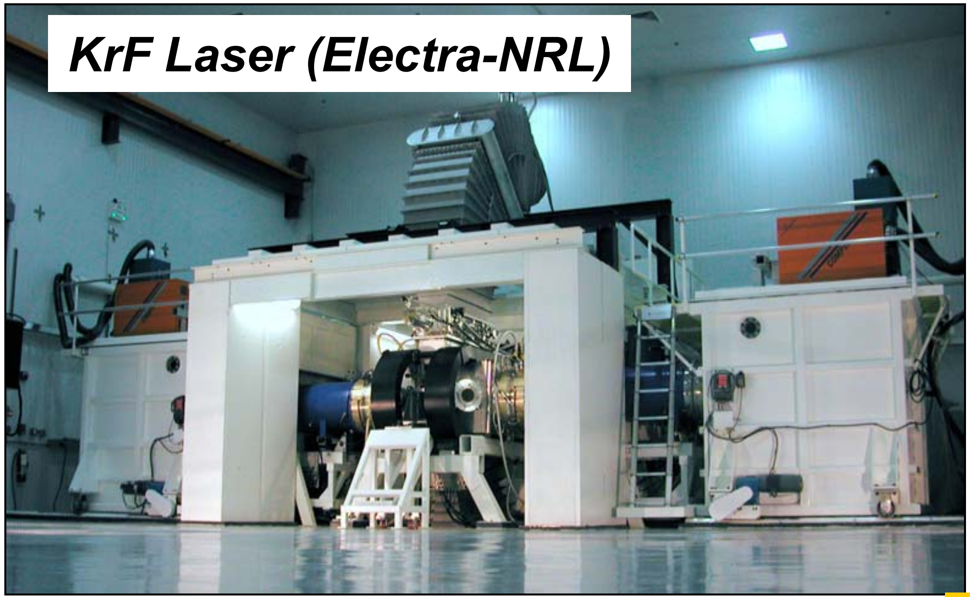
High Z (gold) outer layer
Reduces laser imprint-NRL exp't
Reflects IR during injection

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

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

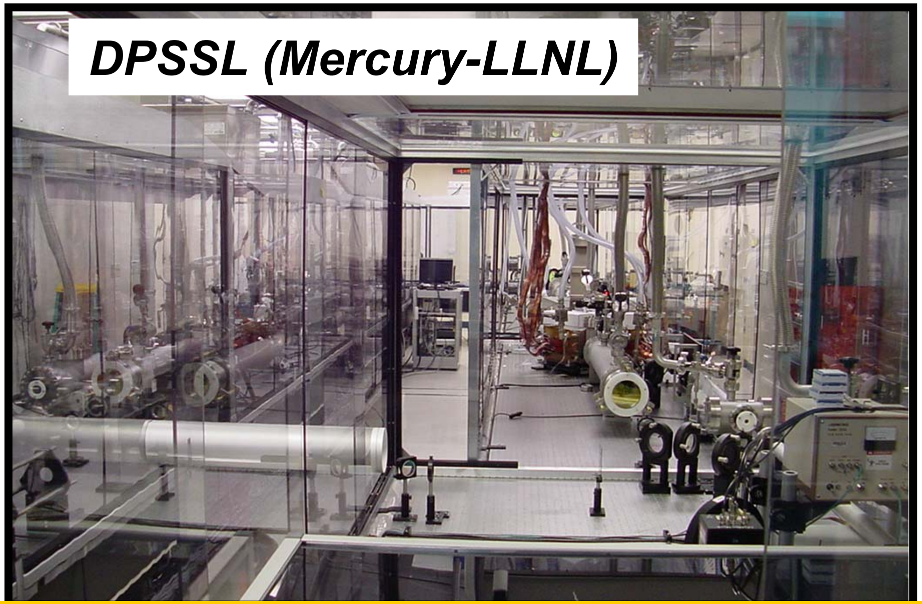
DT Ice fuel layer: can have no gas in center
Colder target helps injection
(1D calculations say gain OK)

The HAPL Program is developing two types of Lasers



KrF Laser (Electra-NRL)

Tom Jones, O-I-2.2 Tuesday 10:48



DPSSL (Mercury-LLNL)

Camille Bibeau, O-I-2.3 Tuesday 11:06

- Both lasers have potential for meeting IFE requirements
  - target interactions, rep-rate, cost, durability, efficiency

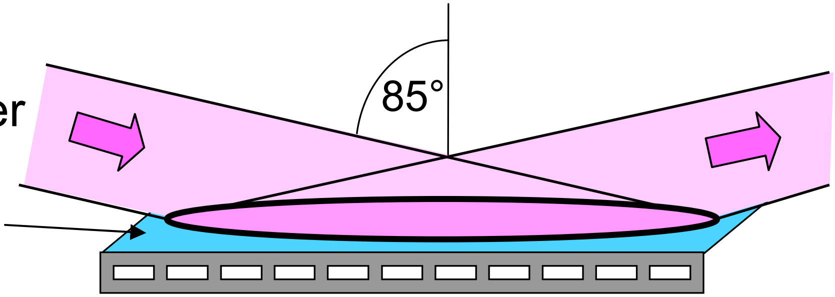
- Needed technologies are being developed and demonstrated on large (but subscale) systems.

- Technologies developed must scale to MJ systems

Final Optic Progress

Grazing Incidence Aluminum Mirror meets IFE requirements for reflectivity (>99% @ 85°) & damage threshold (5 J/cm^2)

Concept



Laser

Electroplated aluminum

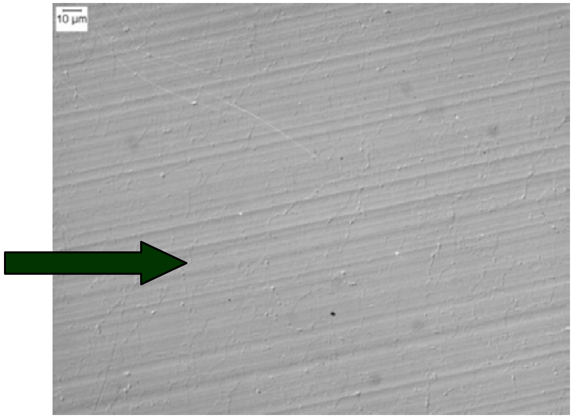
stiff, lightweight, cooled, neutron resistant substrate

Results

100,000 shots at 18 J/cm^2

No damage

Need ~ 5 J/cm^2



What's left: Large scale testing (happening on Electra)

Ion Mitigation (use magnetic fields)

Evaluate resistance to x-rays

Fabrication

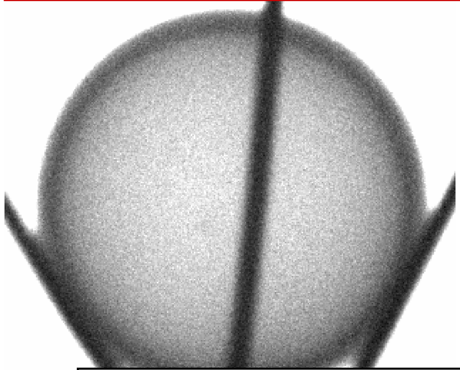
Jeff Latkowski, P-II-37 Wednesday PM Poster

Mark Tillack

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

Batch produced foam shells



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

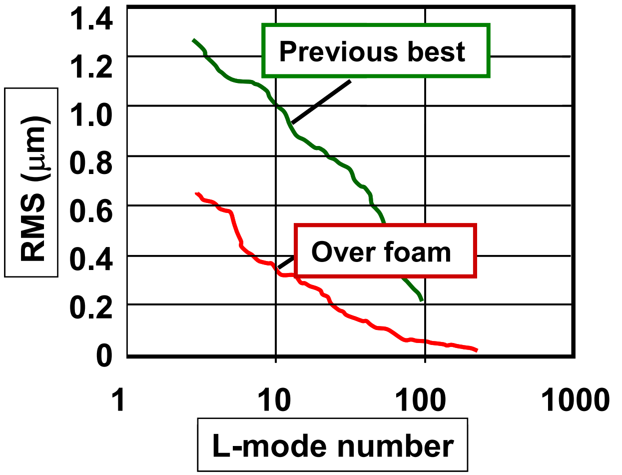
What's left: Overcoating

Jon Streit, O-II-2.5 Wednesday 11:42

Brian Vermillion, P-I-11 Tuesday PM Poster

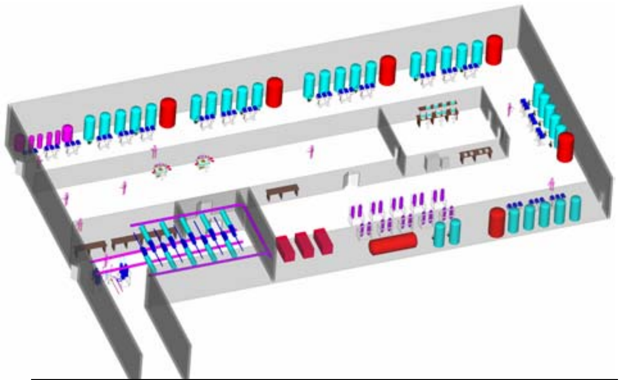
Produced very smooth (~ 0.6 µm RMS), robust DT ice layers over foam

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

What's left:
Target that meets all specs
Mass Production

Dan Goodin, O-II-2.1
Wednesday 10:38

Target Injector / Tracking Progress

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

Target Injection and Tracking system

Whats left: Better placement
Target Tracking

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

Ron Petzoldt, P-I-10 Tuesday PM Poster
D. Frey, P-I-12 Tuesday PM Poster

We have established a "chamber operating" window that simultaneously meets the requirements for efficiency, wall survival (> 1000's shots), and target injection

First wall is tungsten armor bonded to low activation steel

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

Chamber Physics:
What hits wall:
"threat spectra"

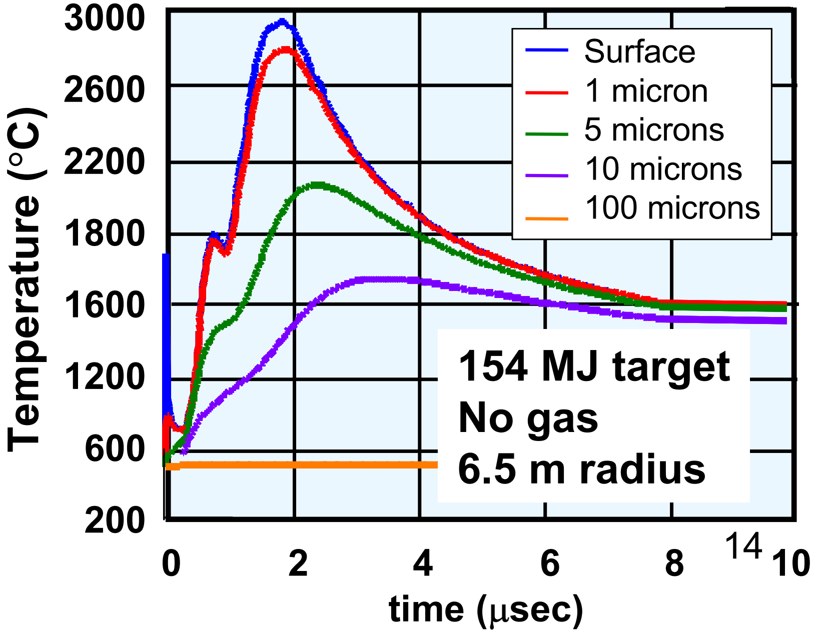
Materials:
How wall responds to
"threat spectra"

Greg Moses,
O-II-2.3 Wednesday 11:06

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

Brian Christensen, P-I-19 & 20
Tuesday PM Poster

Tungsten stays below 3410 °C melting point



154 MJ target
No gas
6.5 m radius

UCSD, Wisconsin, LLNL, LANL, GA

What's left in establishing a viable chamber concept?

1) Operating window for high yield (400 MJ) target

2) Chamber clearing

3) Long Term Wall Survival

   a) Helium retention
   b) Bonding W to Steel base
   c) Thermo-mechanical Fatigue

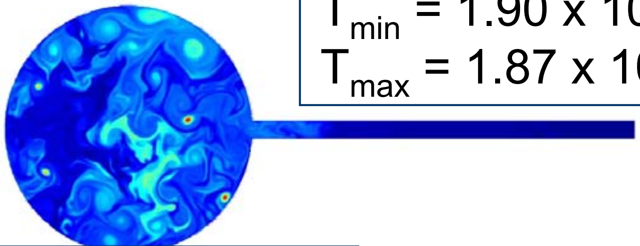
4) Chamber/Blanket interface

Igor Sviatoslavsky, P-I-30 Tuesday PM Poster

We are investigating how the chamber "clears itself" between shots with the SPARTAN code

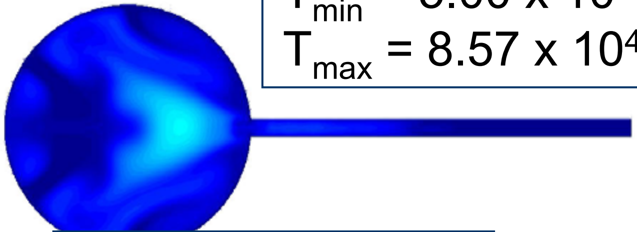
Example of SPARTAN output:

Diffusivity is important *in quieting chamber to reduce temperature between shots*



T_{min} = 1.90 x 10^4 K
T_{max} = 1.87 x 10^5 K

No Diffusive Terms



T_{min} = 5.00 x 10^3 K
T_{max} = 8.57 x 10^4 K

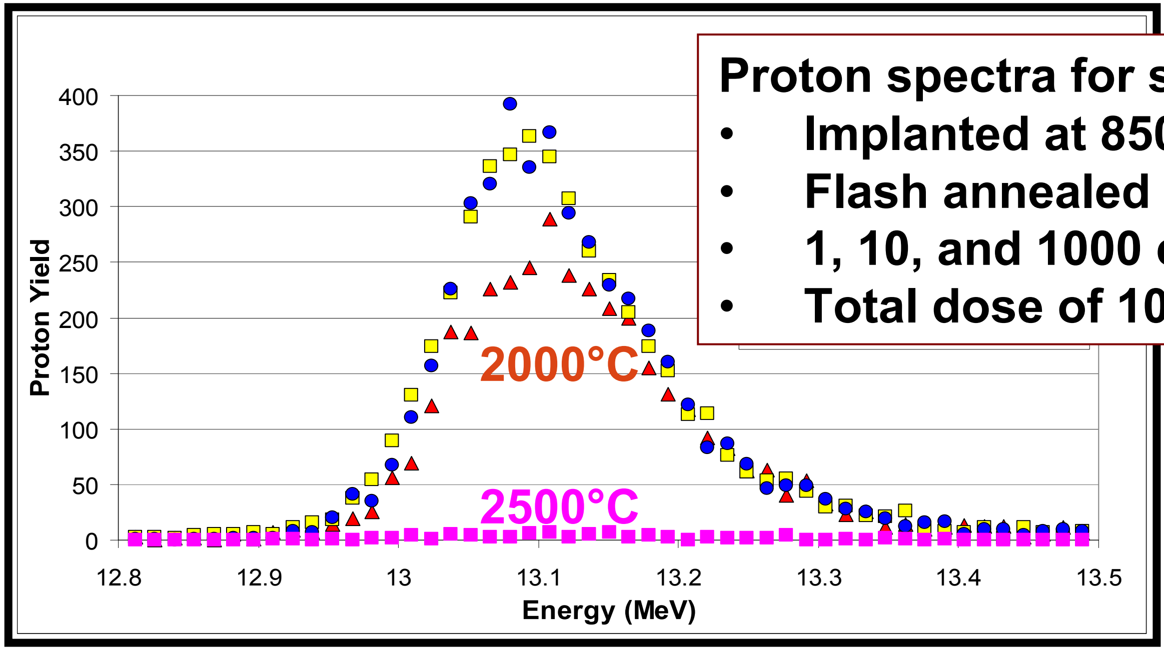
Full Navier-Stokes

Zoran Dragojlovic,
O-I-2.4 Tuesday 11:24

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

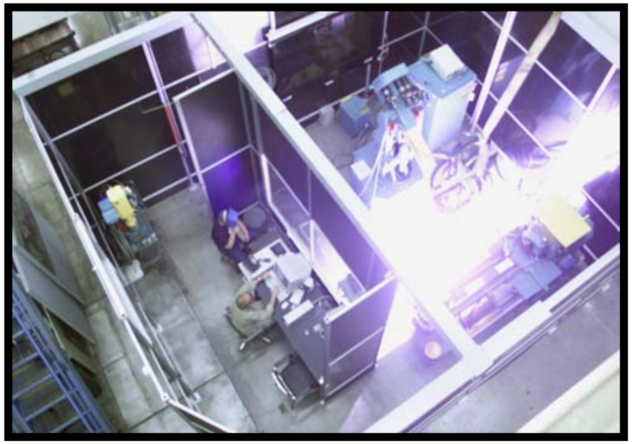
- **Implanted at 850°C**
- **Flash annealed to 2000°C (or 2500 °C)**
- **1, 10, and 1000 cycles**
- **Total dose of 10^{19} He/m^2.**

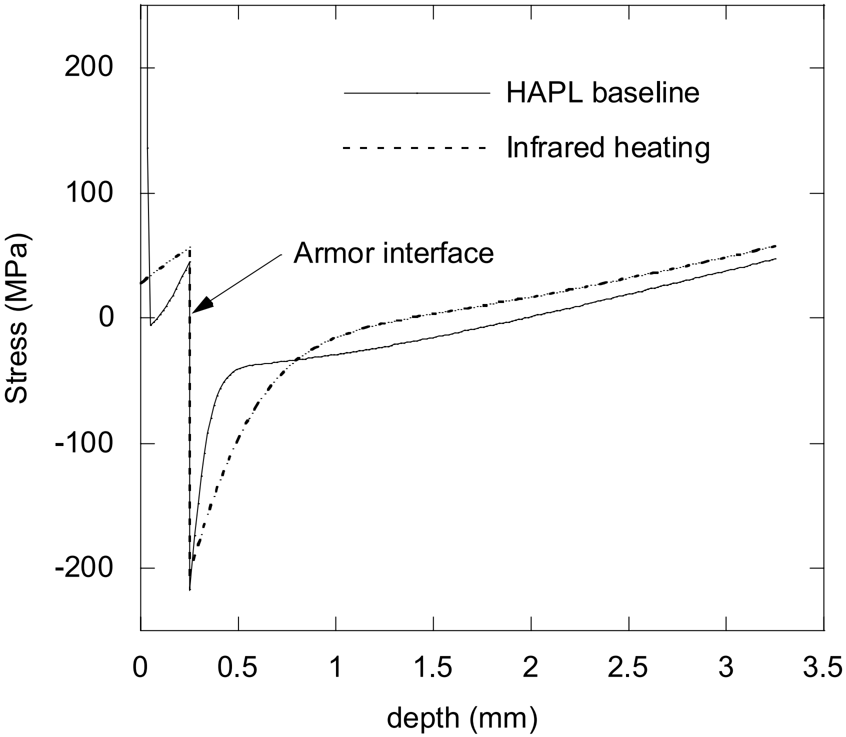
N. Hashimoto,
P-I-45 Tuesday PM Poster

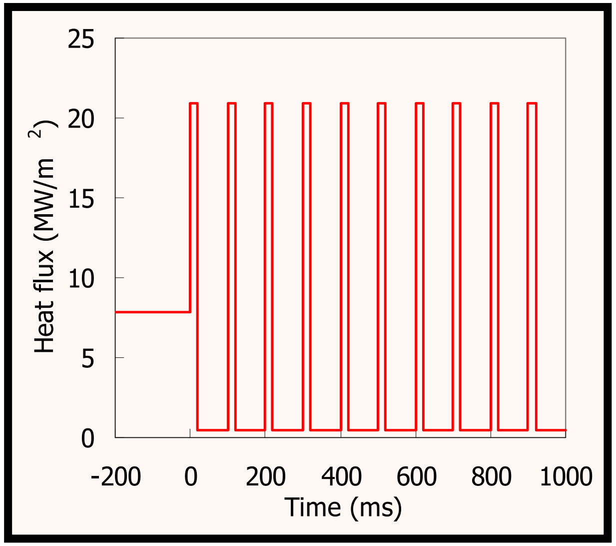
Effects of implantation studied with steady state IEC electrostatic trap

P. Radel, P-II-24 Wednesday PM Poster

Bond strength: We are using the Oak Ridge IR processing facility to study the long term integrity of the Tungsten-Steel bond







Lance Snead,
O-III-2.4 Thursday 9:00

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

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

X-rays:

Jeff Latkowski, P-II-37
Wednesday PM Poster

XAPPER

Latkowski (LLNL)

Z [*confirmation*]

Tanaka (SNL)

Ions:

Tim Renk, O-III-2.6
Thursday, 9:40

RHEPP

Renk (SNL)

Laser:

Dragonfire

Najmabadi (UCSD)

Experiments:

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

Modeling:

Jake Blanchard,
O-I-2.5 Tuesday 11:42

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

Blanchard (Wisc)

We are developing advanced, micro- engineered tungsten in case we have a problem

The concept: small feature size

Features less than He migration distance (~ 20-50 nm)

Small size allows tungsten to "breathe" under cyclic thermal stress

The Issues

Does it work?

Thermal conductivity

High integrity bond/structure

The approaches

Tungsten foam on ODS

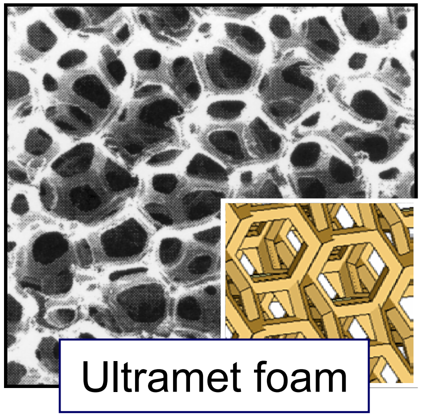
Sharafat (UCLA) +

Williams (Ultramet, Inc)

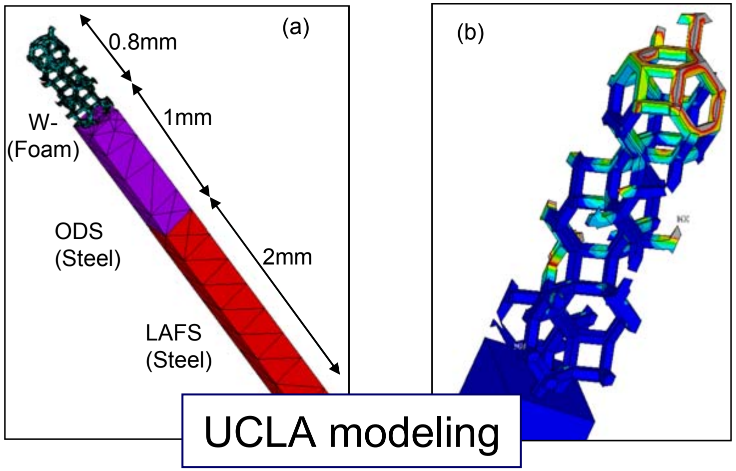
Vacuum Plasma Sprayed Tungsten

O'Dell (Plasma Processing, Inc) +

Raffray (UCSD)



Ultramet foam



UCLA modeling

We are nearing the goals for Phase I

Phase I:
1999- 2005

Basic Science and Technology

- 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
2006 - 2014

Develop Full Scale Components

- Power plant laser beam line
- Target fab/injection facility
- Materials evaluations
- Power Plant design

Ignition Physics Validation

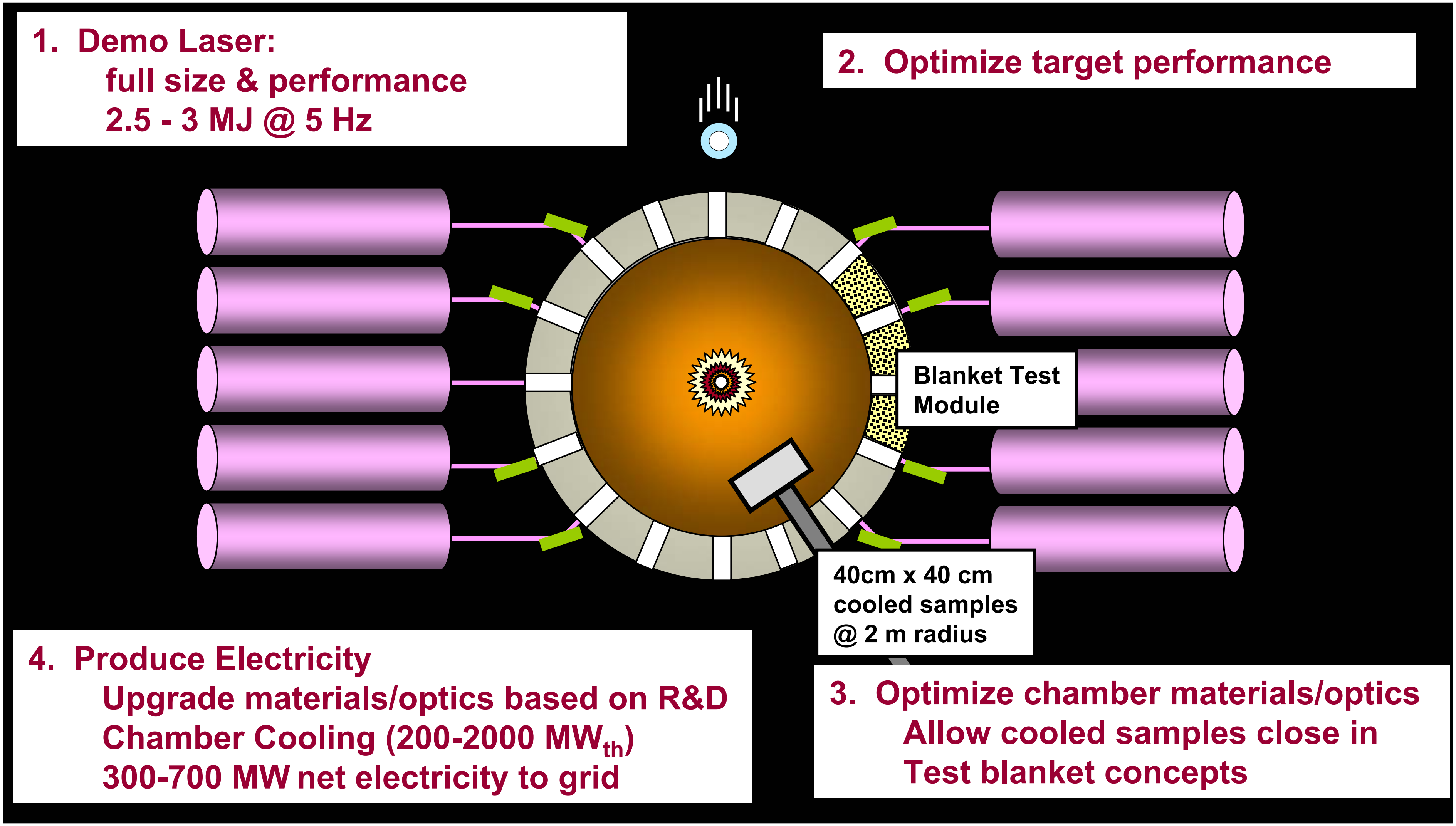
- **MJ target implosions**
- **Calibrated 3D simulations**

Phase III
Engineering Test Facility
operating ~ 2020

Engineering Test Facility

- Full size laser: 2-3 MJ, 60 laser lines
- Optimize targets for high yield
- Optimize chamber materials and components.
- **~ 300-700 MW net electricity**

The Engineering Test Facility (ETF) will have four goals, including upgrade to generate net electricity



1. Demo Laser:
full size & performance
2.5 - 3 MJ @ 5 Hz

2. Optimize target performance

Blanket Test Module

40cm x 40 cm cooled samples @ 2 m radius

3. Optimize chamber materials/optics
Allow cooled samples close in
Test blanket concepts

4. Produce Electricity
Upgrade materials/optics based on R&D
Chamber Cooling (200-2000 MW$_{th}$)
300-700 MW net electricity to grid