A Roadmap to
Laser Fusion Energy

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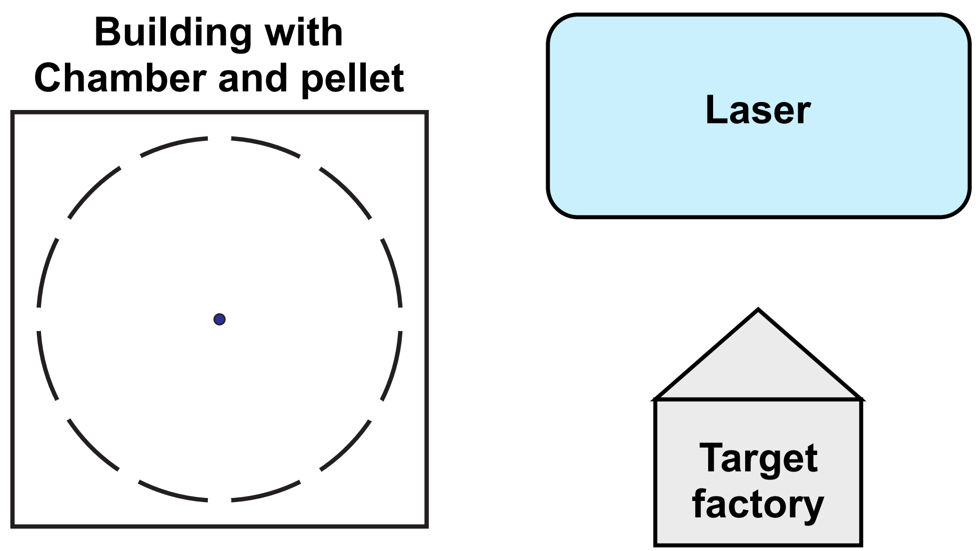
In 1971-1972 LLNL announced that they had an idea for laser fusion energy

- A little DT pellet in the middle of a large empty target chamber.
- The complex laser outside the radioactive environment, for easier maintenance.
- No ultra-high vacuum or superconducting magnets.



By 1975, several fundamental problems were discovered.

- **Laser beam nonuniformity:**
  Worse than expected, leading to a predicted large distortion of the pellet shell.

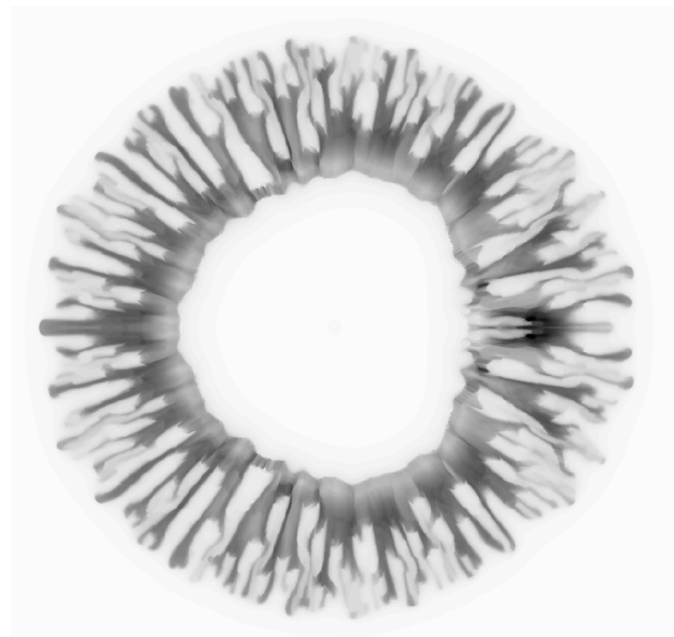
- **Raleigh-Taylor fluid instability:**
  Even with a smooth laser beam, new theory *(Bodner, NRL)* and modeling *(Lindl, LLNL)* predicted that the shell would break during the implosion.

- **Laser-plasma instabilities:**
  Measurements *(LANL)* found more suprathermal electrons than predicted; these electrons would preheat the DT fuel.

LLNL then switched to indirect drive.

NRL, Rochester, and some other labs, tried to solve the problems with direct-drive.

A calculation of a failed target implosion, showing the mix of DT fuel with the surrounding ablator



First breakthrough: switch to shorter laser wavelength

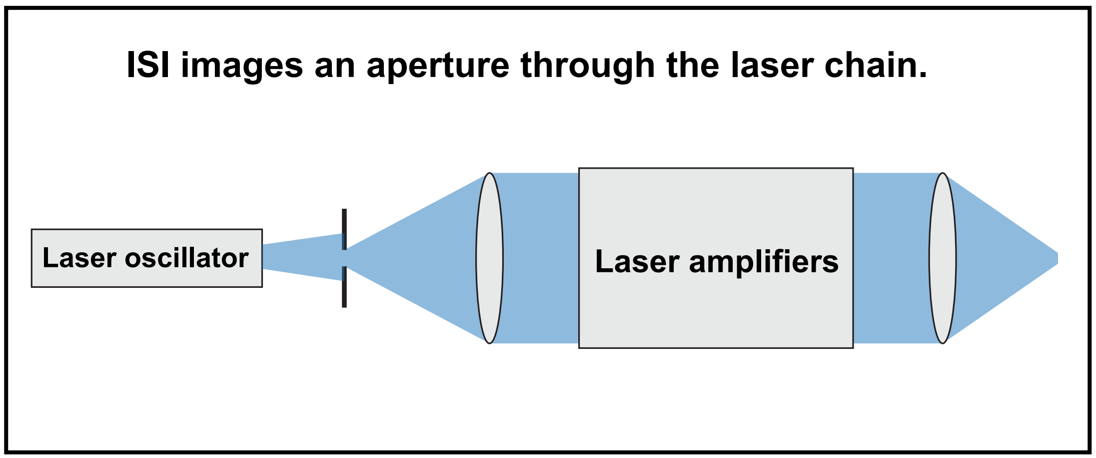
- French scientists show that tripling or quadrupling the laser frequency dramatically reduces the laser-plasma instabilities.

- Rochester scientist invents method of <u>efficiently</u> tripling the frequency of a glass laser.

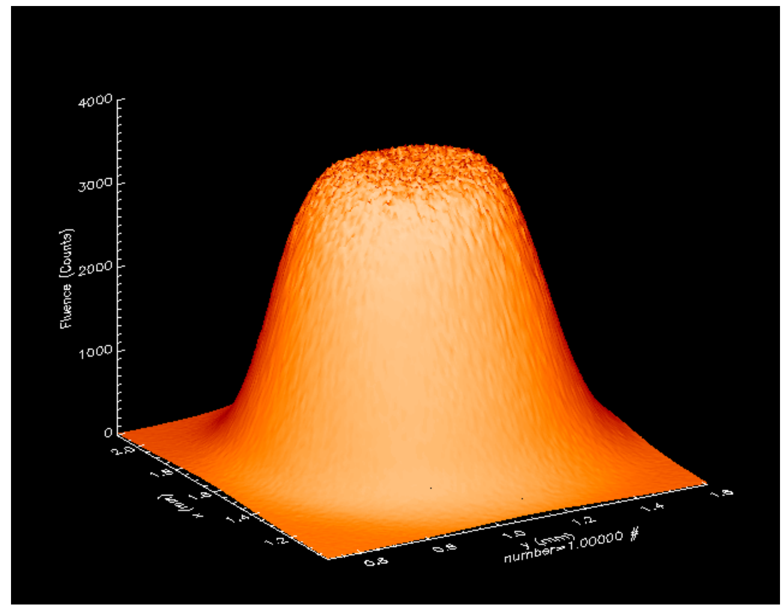
- Most laboratories adopt the Rochester technique.

What is the most uniform light source?

- **Not coherent laser light, but sunlight.**
- **Laser light can focus to a spot much smaller than needed for laser fusion (**μm vs mm**).**
- **Basic idea: trade off focusability and coherency for improved smoothness.**
- **Induced Spatial Incoherence (ISI), invented in 1982 by two NRL scientists (**Obenschain & Lehmberg**)**



Measured ISI focal spot profile using "Nike" KrF laser



ISI works best with a gas laser, such as KrF.

Smoothing by Spatial Dispersion (SSD), invented in 1988 at Rochester, is a superior match for glass lasers.

Short wavelength lasers

Reduced laser-plasma instabilities.

KrF laser: $1/4\ \mu$m

Glass laser: $1\ \mu\text{m} \Rightarrow 1/3\ \mu$m

Beam smoothing

ISI with KrF, SSD with glass.

- laser hot spots eliminated
- reduced laser plasma instabilities

In 1997, a method was proposed to control the other basic problem: Rayleigh-Taylor fluid instability.

Tailoring the adiabat

- Target gains of 125, and more, were finally possible.
- Gain was potentially sufficient for attractive fusion energy

High-Gain Direct-Drive Target Design For Laser Fusion

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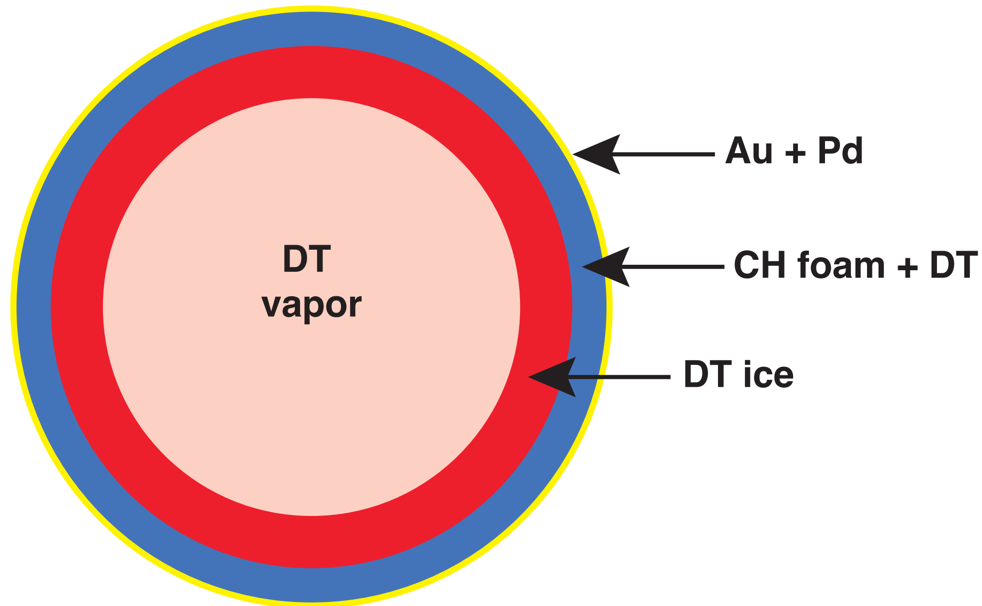
Abstract
A new laser fusion target concept is presented with a predicted energy gain of 125 using a 1.3 MJ KrF laser. This energy gain is sufficiently high for an economically attractive fusion reactor. X-rays from high- and low-Z materials are used in combination with a low-opacity ablator to spatially tune the isentrope, thereby providing both high fuel compression and a reduction of the ablative Rayleigh-Taylor instability.

The original attraction of laser fusion -- the target simplicity -- had been maintained!

The target physics problems were fixed by:

- Increasing the laser frequency
- Adding spatial & temporal smoothing to laser
- Modifying the temporal laser pulse shape
- Adding low-density CH foam to frozen DT, with a very thin Au/Pd overcoat



NRL direct-drive target design

The laser fusion community has a substantial laser-target experimental data base to support this simple concept.

With the development of a possibly successful fusion target design, the expected next step is a megajoule laser, to validate this approach to fusion energy.

But why spend a billion or more on a fusion demonstration, if there is some other simple flaw in the fusion energy concept?

Laser

- **Repetition rate:** *from ~ 2 pulses/hour to ~ 5 pulses/sec*
- **Wall plug efficiency:** *from ≤ 2% to ≥ 7%*
- **Time between major maintenance:** *from 10^2 - 10^3 shots to > 10^8 shots*
- **Capital cost:** *from ~$5000/Joule to less than $500/Joule*

Target

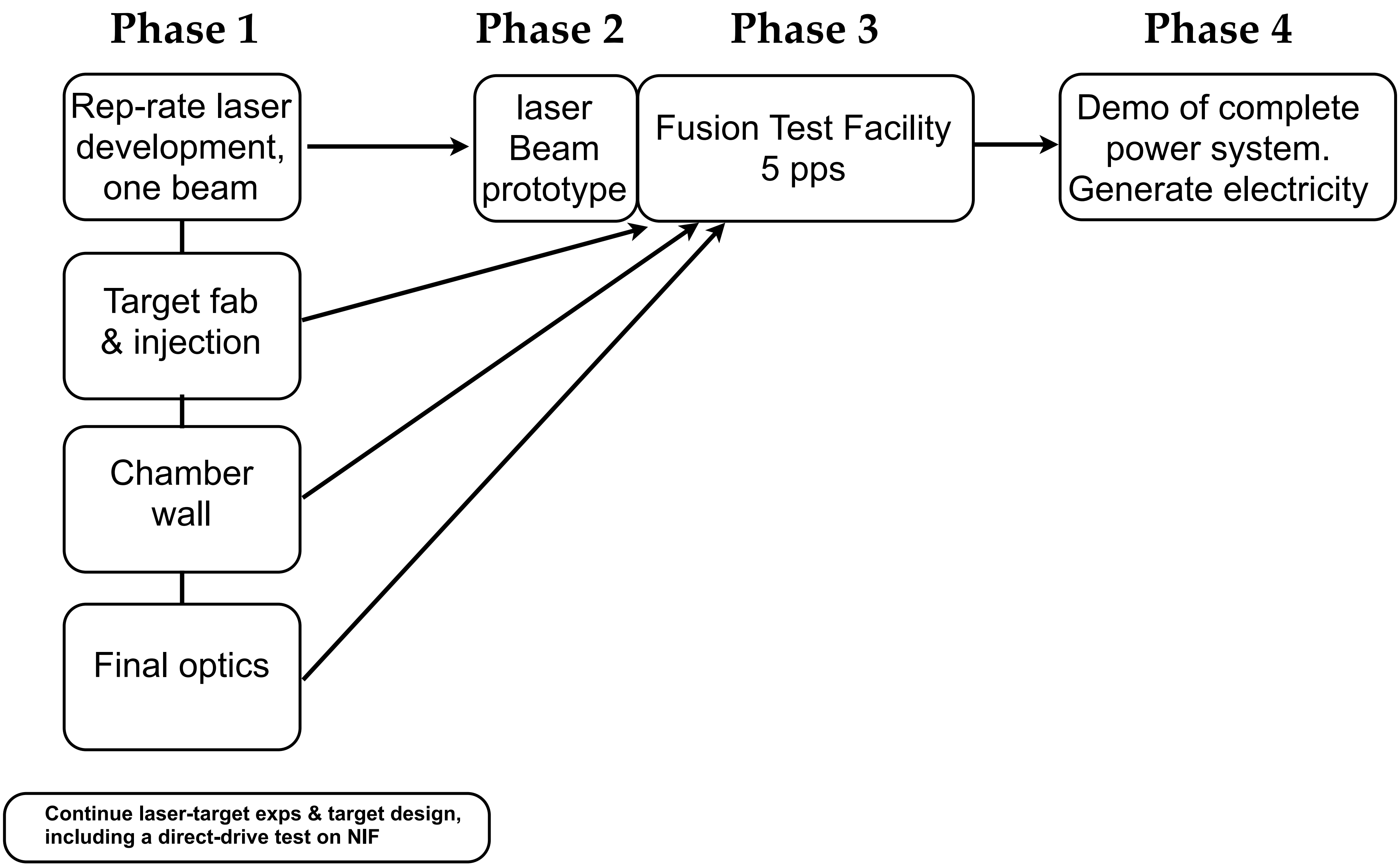
- **Cost:** *from thousands of dollars to less than 25¢ each*
- **Survivability:** *Injection into hot chamber without excessive heating of frozen DT*

Chamber

- **Chamber wall:** *Few-year survival from bombardment of x-rays, ion debris, neutrons*
- **Final optics that faces explosion:** *Survival from x-rays, ions, neutrons, and short-wavelength laser light*
- **Energy transfer:** *remove heat*
- **Tritium breeding; tritium extraction**

If <u>any</u> of these requirements couldn't be met, program should be cancelled

Simplified version of the laser-fusion roadmap that NRL developed in 1997



I collaborated with Mike Campbell (LLNL) to sell this roadmap to fusion energy.

- **Mike's one requirement: balanced funding between KrF and DPSSL. I accepted.**

- **Mike then made presentations at high level in Executive Branch, with my support. Audiences were polite, but it was not on their agendas.**

- **Congress then decided to support HAPL (High Average Power Laser).**

- **(*I then retire, in mid 1999*)**

- **From FY1999 through FY2008, Congress appropriated $190M to NNSA for HAPL. National program was managed by Naval Research Laboratory.**

- **A very successful program, but funding ended in FY2009.**

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The Science and Technologies for Fusion Energy With Lasers and Direct-Drive Targets

J. D. Sethian, D. G. Colombant, J. L. Giuliani, Jr., R. H. Lehmberg, M. C. Myers, S. P. Obenschain, A. J. Schmitt, J. Weaver, M. F. Wolford, F. Hegeler, M. Friedman, A. E. Robson, A. Bayramian, J. Caird, C. Ebbers, J. Latkowski, W. Hogan, W. R. Meier, L. J. Perkins, K. Schaffers, S. Abdel Kahlik, K. Schoonover, D. Sadowski, K. Boehm, L. Carlson, J. Pulsifer, F. Najmabadi, A. R. Raffray, M. S. Tillack, G. Kulcinski, J. P. Blanchard, T. Heltemes, A. Ibrahim, E. Marriott, G. Moses, R. Radell, M. Sawan, J. Santarius, G. Sviatoslavsky, S. Zenobia, N. M. Ghoniem, S. Sharafat, J. El-Awady, Q. Hu, C. Duty, K. Leonard, G. Romanoski, L. L. Snead, S. J. Zinkle, C. Gentile, W. Parsells, C. Prinksi, T. Kozub, T. Dodson, D. V. Rose, T. Renk, C. Olson, N. Alexander, A. Bozek, G. Flint, D. T. Goodin, J. Hund, R. Paguio, R. W. Petzoldt, D. G. Schroen, J. Sheliak, T. Bernat, D. Bittner, J. Karnes, N. Petta, J. Streit, D. Geller, J. K. Hoffer, M. W. McGeoch, S. C. Glidden, H. Sanders, D. Weidenheimer, D. Morton, I. D. Smith, M. Bobecia, D. Harding, T. Lehecka, S. B. Gilliam, S. M. Gidcumb, D. Forsythe, N. R. Parikh, S. O'Dell, and M. Gorensek

<u>Contributing Institutions</u>: Naval Research Laboratory; Commonwealth Technologies; Lawrence Livermore National Laboratory; Georgia Institute of Technologies; UC San Diego; University of Wisconsin - Madison; UC Los Angeles; Oak Ridge National Laboratory; Princeton Plasma Physics Laboratory; Sandia National Laboratories; General Atomics; Schafer Corporation; Los Alamos National Laboratory; PLEX Corporation; Applied Pulsed Power; L3 Pulse Sciences; University of Rochester; Penn State Electro-Optics Center; University of North Carolina - Chapel Hill; Plasma Processes Inc.; Savannah River National Laboratory

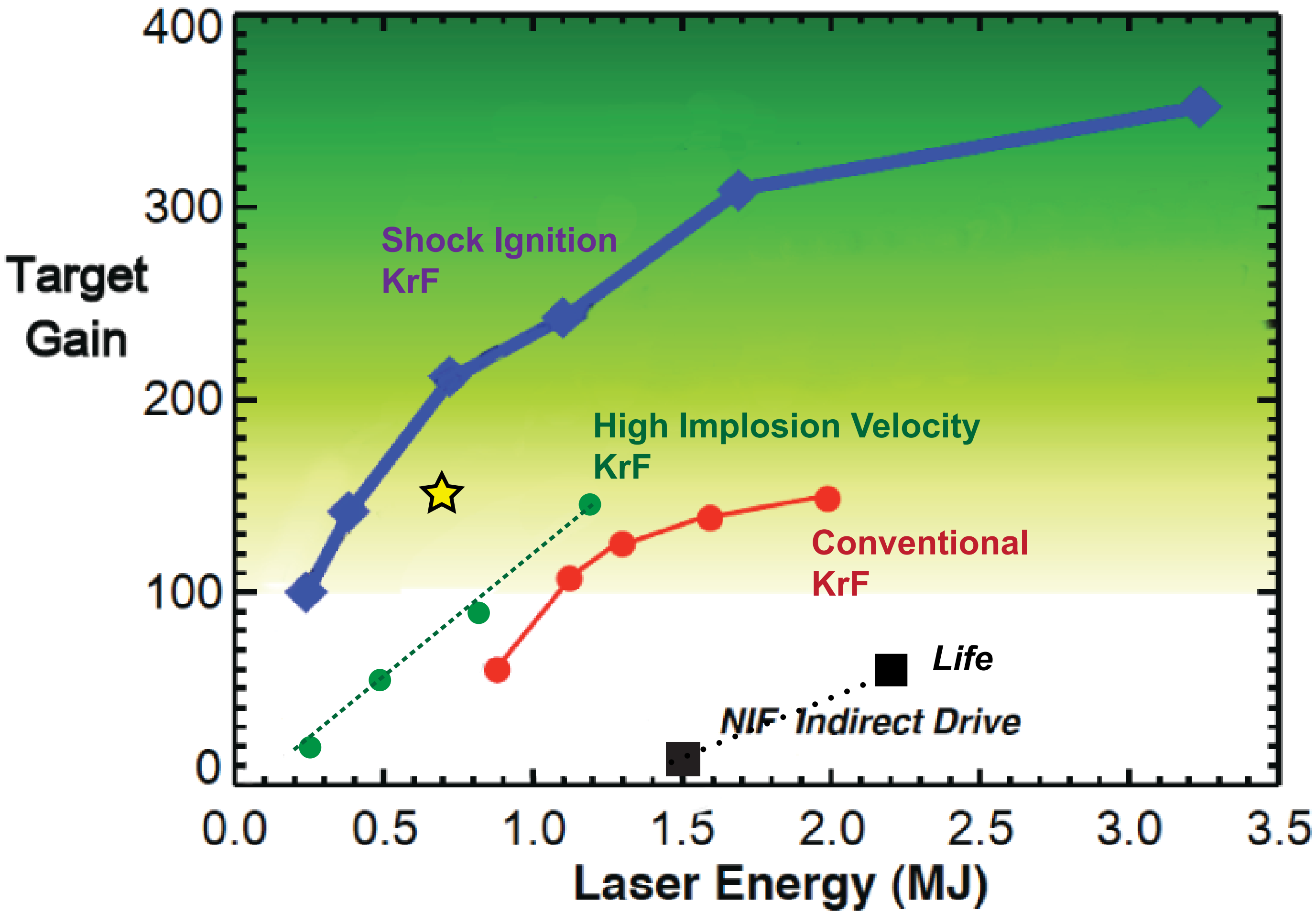
A few of the major accomplishments of HAPL program

- **"Electra" KrF laser:** achieved 300 - 700 J, with 90,000 shots at 2.5 Hz, and 50,000 shots at 5 Hz
- **"Mercury" DPSSL:** achieved 50 J (*at 1 μm*), with over 300,000 shots at 10 Hz
- **Final optics:** Material withstood 3.5 J/cm^2, no neutron damage
- **Target fabrication:** Foam shells fabricated, with cost estimate of $0.16 each in mass production. Methods developed for ultrasmooth DT layering
- **Target engagement:** Injection demonstrated with required accuracy and speed
- **Reaction chamber:** Dry wall with nanoengineered tungsten may meet requirements of x-ray, helium, and neutron irradiation

Accomplishments were close enough to full success, with no show stopper, to now justify a Fusion Test Facility

Contact John Sethian of NRL for more details

Direct-drive: High gain with low driver energy



☆ **~ 160 MWe net output**

KrF laser : 0.7 MJ, 7% efficiency, 5 pps

Target gain = 150

Thermal-to-electrical: 40%

Electricity recycling: 24%

Contact Andrew Schmitt of NRL for more details

KrF or DPSSL?

Very significant progress, and no show-stoppers yet.

Thus both lasers need to be further developed.

Advantages of KrF

- **Shorter laser wavelength has deeper plasma penetration, producing a higher rocket efficiency, and thus higher energy gains**
- **Zooming of focal spot during the implosion increases laser absorption, and thus produces still higher energy gains**
- **Lower risk of laser-plasma instabilities with shorter laser wavelength**
- **Superior low-mode laser beam smoothing with ISI vs SSD**
- **No delicate frequency converters or phase plates at end of laser chain**
- **Easier thermal management with gas laser**

Advantages of DPSSL

- **Less risk of optical damage to last mirror with longer laser wavelength**
- **Potential for higher wall plug efficiency** *(≥ 8% vs ~ 7%)*
- **Potential for higher durability with all solid-state components**

A Story:

The NIF had a test module, called "Beamlet" that had limited success.

Beamlet was never fired enough times, under realistic conditions, to discover the problems with optical damage and beam smoothing.

Premature decision to proceed with construction of NIF, because of:

- **lead-time for budget process**
- **expected limited window of political support in Washington**

NIF <u>had</u> to be completed by 2004!

The Moral of the Story:

KrF and DPSSL modules should be fully tested and fully reviewed before even <u>seeking</u> funds for a Fusion Test Facility! Goal should be a fixed-price contract for the rest of the modules.

Provide identical funding for KrF and DPSSL; same as used in HAPL program. Competition, then downselection, after full testing.

An Amusing Aside:

Funding to LLNL for DPSSL should be about the same, whether DOE proceeds with direct-drive or indirect-drive for fusion energy.

Summary evaluation of direct-drive laser fusion

- **Target**
  - Three high-gain target concepts, with detailed calculations and supporting experimental data
  - Potential for an attractive sub-GWe power plant.
  - NIF can test high-laser-intensity coupling in the "shock ignition" design.
  - The downside: an integrated direct-drive fusion test with NIF is unlikely, because SSD smoothing was optimized for indirect-drive.
- **Laser**
  - Demonstrated high rep-rate for significant duration, with both DPSSL & KrF !
  - Progress meeting all other laser requirements. No show stoppers, and clear path to possible success.
  - Progress sufficient to now justify next step: develop, and optimize, laser modules which could be duplicated, at fixed cost, for a fusion test facility.
- **Chamber & target factory systems**
  - Solutions proposed and partially developed that could meet all requirements.
  - Progress sufficient for next step: prepare for testing in a fusion test facility.

Recommended roadmap for a direct-drive fusion energy program

Now: Phase 2
Develop & optimize
~5 pps laser modules
for Fusion Test Facility

Phase 3
Build fusion Test Facility
to optimize chamber wall, etc
1 pulse & ~ 5 pps, 0.5 -1.0 MJ

Phase 4

KrF module
16 kJ

DPSSL module
Y kJ

Downselect

40 x 16 kJ
KrF modules
or
N x Y kJ
DPSSL modules

Prototype
Power
plant

Now: Further develop:
- Target fabrication
- Target injection & tracking
- Chamber system
- Final optics
- Heat and tritium handling

Now: Refine & further test:
- Target design (NIF, NRL, UR)

Contact Stephen Obenschain of NRL for more details

The NRL laser fusion program has strong Navy support, but it needs a political home.

1. **Unlike some other govenment agencies, the DOE has a strong institutional bias in favor of funding its own labs, versus say a Navy lab.**

2. **Some (not all) of the DOE lab leaders also have a strong bias to keep the most important work in-house, and they would probably try again to kill any new NRL laser fusion energy program. (*See HAPL*).**

3. **This is a reality that can not be changed.**

4. **One solution: a formal high-level Navy-DOE agreement that includes a lead role in KrF approach, KrF/DPSSL laser-development funding equality, etc.**

5. **IFE will only succeed if the best ideas and research efforts are properly acknowledged and supported, without bias in regard to the source. My concern about NRL also applies to participation by other outside institutions.**