National Academies Committee on the Prospects for Inertial Confinement Fusion Energy Systems

Tour of NRL laser fusion facilities
2 November 2011

hosted by
Laser Plasma Branch
Plasma Physics Division
U.S. Naval Research Laboratory

Research supported by the Department of Energy, NNSA

Presented by Steve Obenschain

The Naval Research Laboratory

Navy's Corporate Research Laboratory
2200 employees/ 750 PhDs/$800 M/yr

Advocated by Thomas Edison (1915)
Startup in 1923

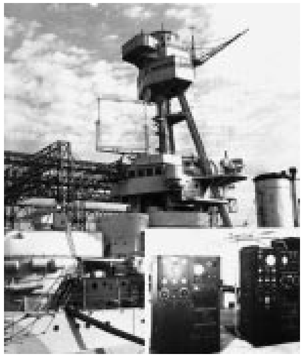
NRL Pioneered many advances:

- U.S. Radar (starting in early 1920's)

NRL developed radars "contributed to the victories of the U.S. Navy in the battles of the Coral Sea, Midway, and Guadalcanal."

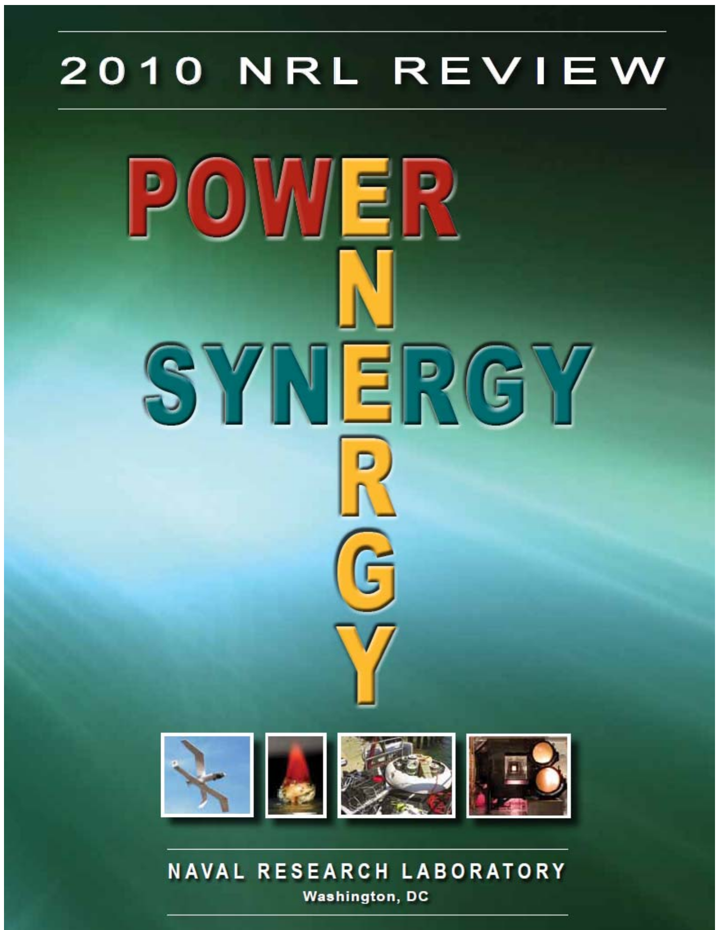
- GPS
- Vanguard rocket and scientific package (2nd U.S. satellite)
- 1st reconnaissance satellite

Under cover of scientific research: Galactic Radiation and Background (GRAB) satellite system.




NRL has a vigorous program in energy R&D

“The U.S. Department of Defense (DoD) consumed 889 trillion BTU of energy in FY08…..Although this is less than 1.5% of overall U.S. usage, it makes the DoD the single largest energy user in the country.”



Advances in
POWER AND ENERGY
Research at NRL

Energy Sources
- Laser Fusion
- Methane Hydrates

Energy Storage
- Nanoscale Electrode Materials for Batteries

Energy Conversion
- Photovoltaics

Power Delivery
- Superconductors

NRL Laser Fusion Energy Program

Energy Sources

(NRL 2010 Review, page 8)

NRL's Nike – the world's largest KrF laser facility.

LASER FUSION. Nuclear fusion has the promise to provide a clean, plentiful source of electrical power. Fusion energy does not produce greenhouse gases, and the fuel supply (lithium and deuterium feedstock) is sufficient for thousands of years. Fusion requires heating deuterium and tritium (D-T) to very high temperatures — on the order of 100 million °C — so they ignite and "burn" in a thermonuclear reaction. Two approaches are being pursued in international research efforts to harness fusion for power production. One approach is to confine the high-temperature D-T fuel by magnetic fields. The other approach is based on inertial confinement, where a pellet containing the D-T fuel mixture is compressed to very high density (~1000× solid) and then ignited; because the highly compressed fuel burns so rapidly, there is no need for external confinement. The technological and scientific challenges to inertial and magnetically confined fusion are quite different; pursuing both adds robustness to the fusion energy research effort.

NRL's long-established laser fusion program has concentrated on developing advanced laser technology and target designs for inertial fusion. The program has developed a krypton fluoride (KrF) laser technology that is predicted to greatly facilitate obtaining the high target gains (ratio of fusion energy output to laser energy input) needed for inertial fusion power. KrF lasers provide deeper UV ($\lambda = 248$ nm) and more uniform target illumination than any other high-energy laser technology. Simulations with NRL's FASTRAD3D hydro-code predict that the high target gains required for power plants can be attained with KrF laser energies of only 1 MJ. NRL has built the world's largest KrF laser facility, Nike, for target experiments, and uses its Electra KrF laser facility to develop the efficient and durable high-repetition-rate (5 Hz) technologies needed for fusion energy. In addition, NRL managed an external program (with researchers at universities, national labs, industries, and small businesses) that has advanced the other critical science and technologies needed to build a power plant, such as durable reaction chambers and low-cost target fabrication. This modular, KrF laser–based approach has the potential to put development of fusion energy on a faster track, possibly enabling the first fusion power plants to come on line in the 2030s.

History of NRL laser fusion program

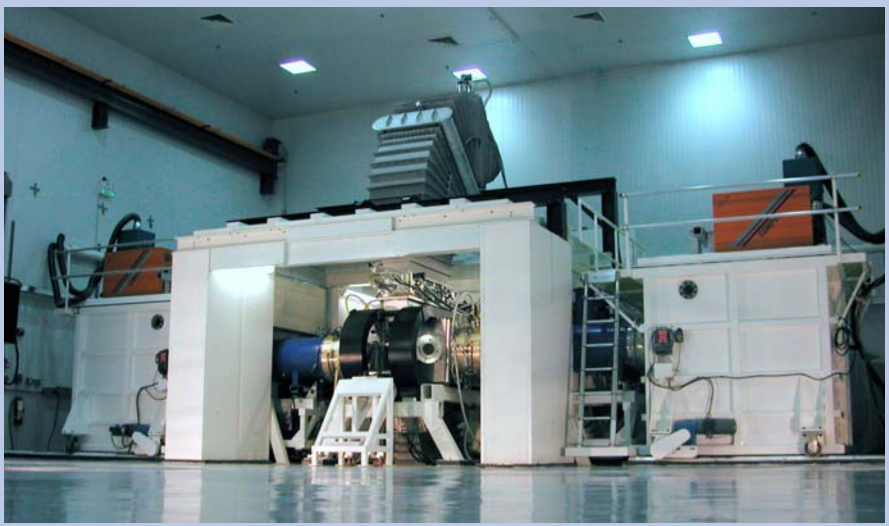
- **The first studies of laser produced plasmas at NRL began:** 1968.
- Laser fusion program funded by AEC: 1972
- **First successful flashlamp pumped Nd-glass disk amplifier** (tech. used in NIF)
- Team from NRL (John Emmet, et al.) assumed leadership of LLNL program
- **One of the first, and still the best, laser beam smoothing technology (ISI):** 1983
- **Switched to KrF lasers to exploit its physics advantages: 1987**
- NRL critique of early NIF indirect-drive designs led to improved designs: 1990's
- **1st radiation hydrocode 3-D simulations of RT in laser accelerated targets.**
- **Completed Nike the world's largest KrF laser:** 1995
- **Electra/HAPL program established (with LLNL):** 1998
- Developed high gain direct drive target designs that exploit the unique advantages of KrF – initially 60× gain at 500 kJ: 2005
- These designs led to new IFE development plan & Fusion Test Facility: 2006
- Still higher gains based on Univ. of Rochester's "shock ignition" concept: 2007.
- Added capability to do high intensity LPI target experiments on Nike: 2008.
- **Electra demonstrated high-rep KrF operation for > 90,000 shots:** 2009
- 11,000,000 continuous shots with 200 kV 5 kA solid state pulse power system: 2010

Laser direct drive has many advantages for Inertial Fusion Energy

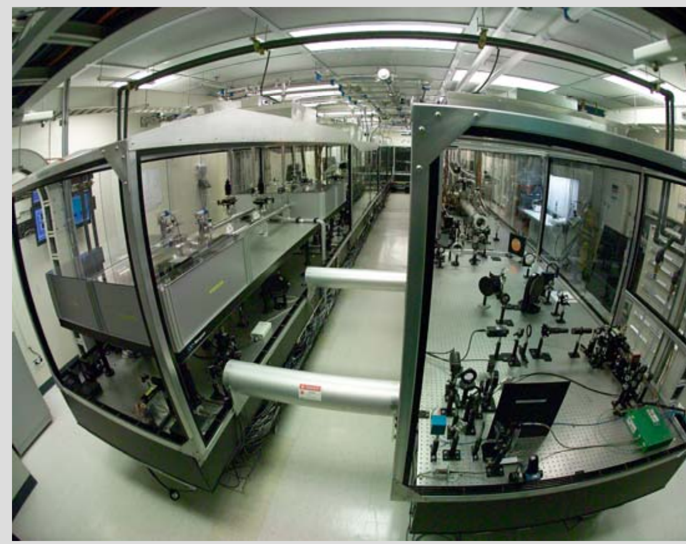
- Makes more efficient use of laser energy than indirect drive.
- Has potential for very high energy gains (>200).
- Simpler target physics.
- Simpler targets and less recycled material $\Rightarrow$ lower cost.
- Technologies developed for highly uniform target illumination.
- Large experimental, theoretical and computational data base on target physics.
- Ignition physics can be tested on the NIF.

Two laser options for Direct Drive.
Both have potential to meet the IFE requirements

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



Mercury DPSSL Laser (LLNL)
λ = 351 nm (tripled)
Diode-Pumped Solid State Laser



KrF is predicted to provide higher target performance

What is a Krypton Fluoride (KrF) Laser?

- **Gas Laser--Excimer (Excited Dimer) –** also Exciplex laser (Excited complex)

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

- **Discharge-pumped KrF and ArF (193 nm) lasers are used routinely for chip lithography..multi-billion shot capability**

Cymer ELS 7010

Repetition Rate 4 kHz
Pulse Energy 10 mJ
Average Power 40 W

Coherent LPXpro 305

Repetition rate 50 Hz
Pulse Energy 1.1 J
Average power 50 W

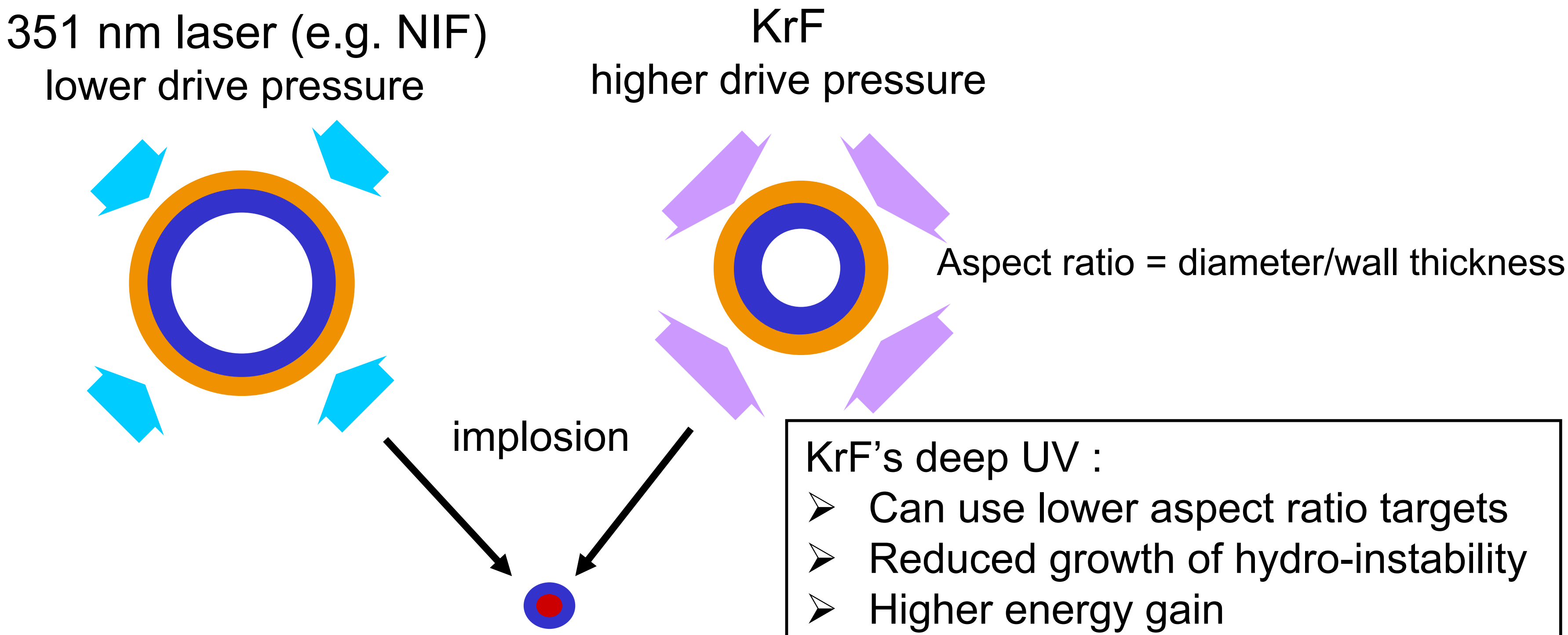
- **Large KrF amplifiers for IFE will be pumped with electron beams.**
  - **Not off the shelf, but do share several technologies with commercial systems.**
  - **Requires R&D for E-beam science & technology and larger size.**

KrF light helps Direct Drive target physics (1)

Provides the deepest UV light of all ICF lasers (λ=248 nm)

Deeper UV →

- Higher thresholds for laser-plasma instability
- Higher mass ablation rates and pressure
- Higher hydrodynamic efficiency
- Higher absorption fraction

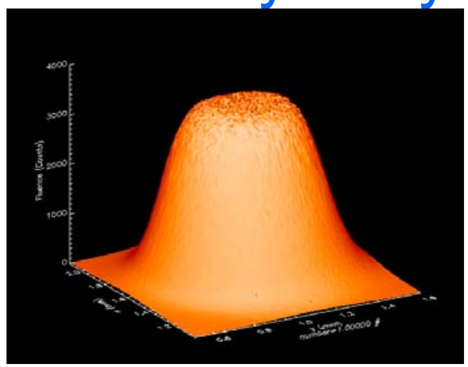


KrF's deep UV :

- Can use lower aspect ratio targets
- Reduced growth of hydro-instability
- Higher energy gain
- Less laser energy required

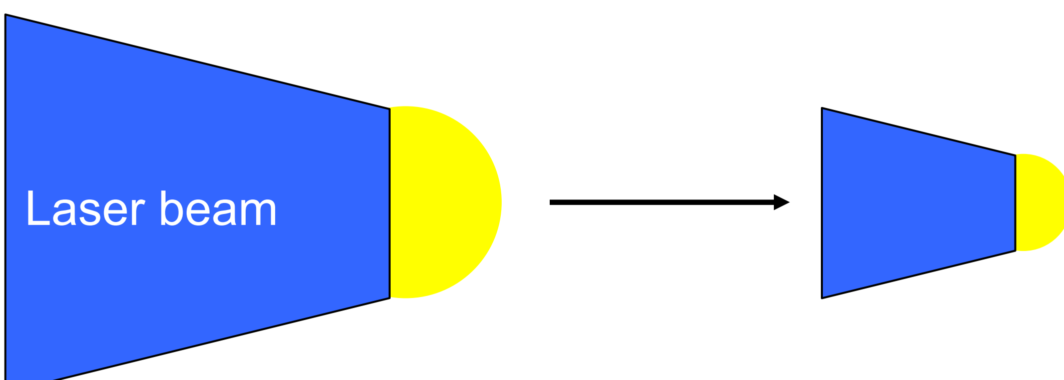
KrF Light helps the target physics (2)

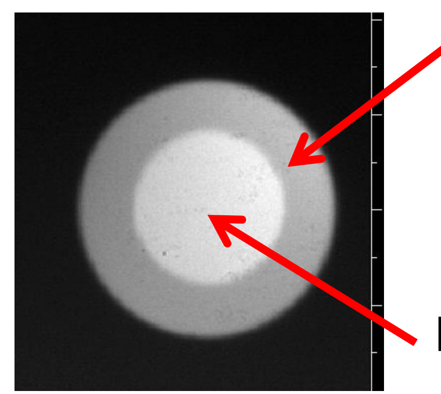
- KrF provides the most uniform target illumination of all ICF lasers.
  - Reduces seed for hydrodynamic instability



Nike KrF focal profile
Bandwidth up to 3 THz

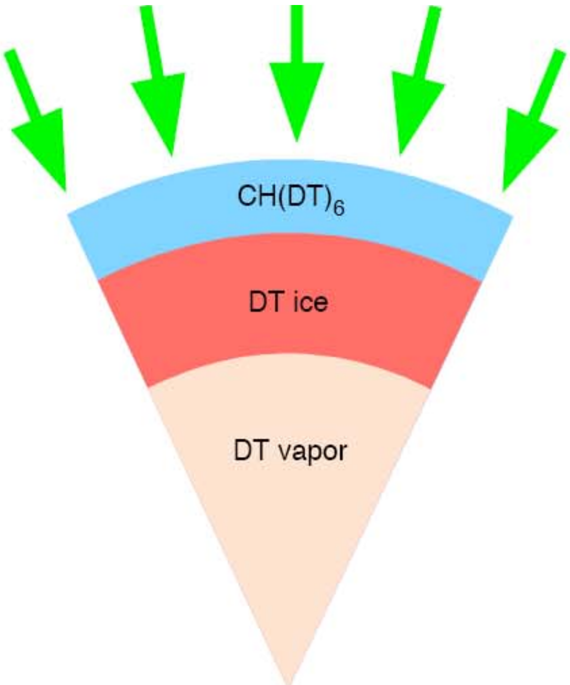
- KrF focal profile can zoom to "follow" an imploding pellet.
  - More laser absorbed, reduces required energy by 30%

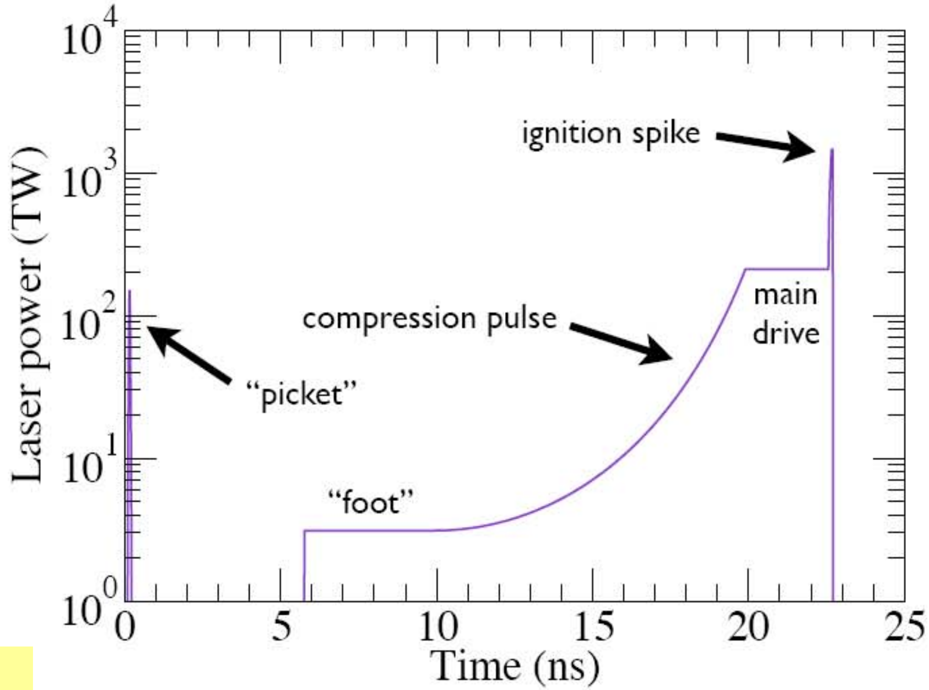




Shock Ignited (SI) direct drive targets

Pellet shell is accelerated to sub-ignition velocity (<300 km/sec), and ignited by a converging shock produced by high intensity spike in the laser pulse.





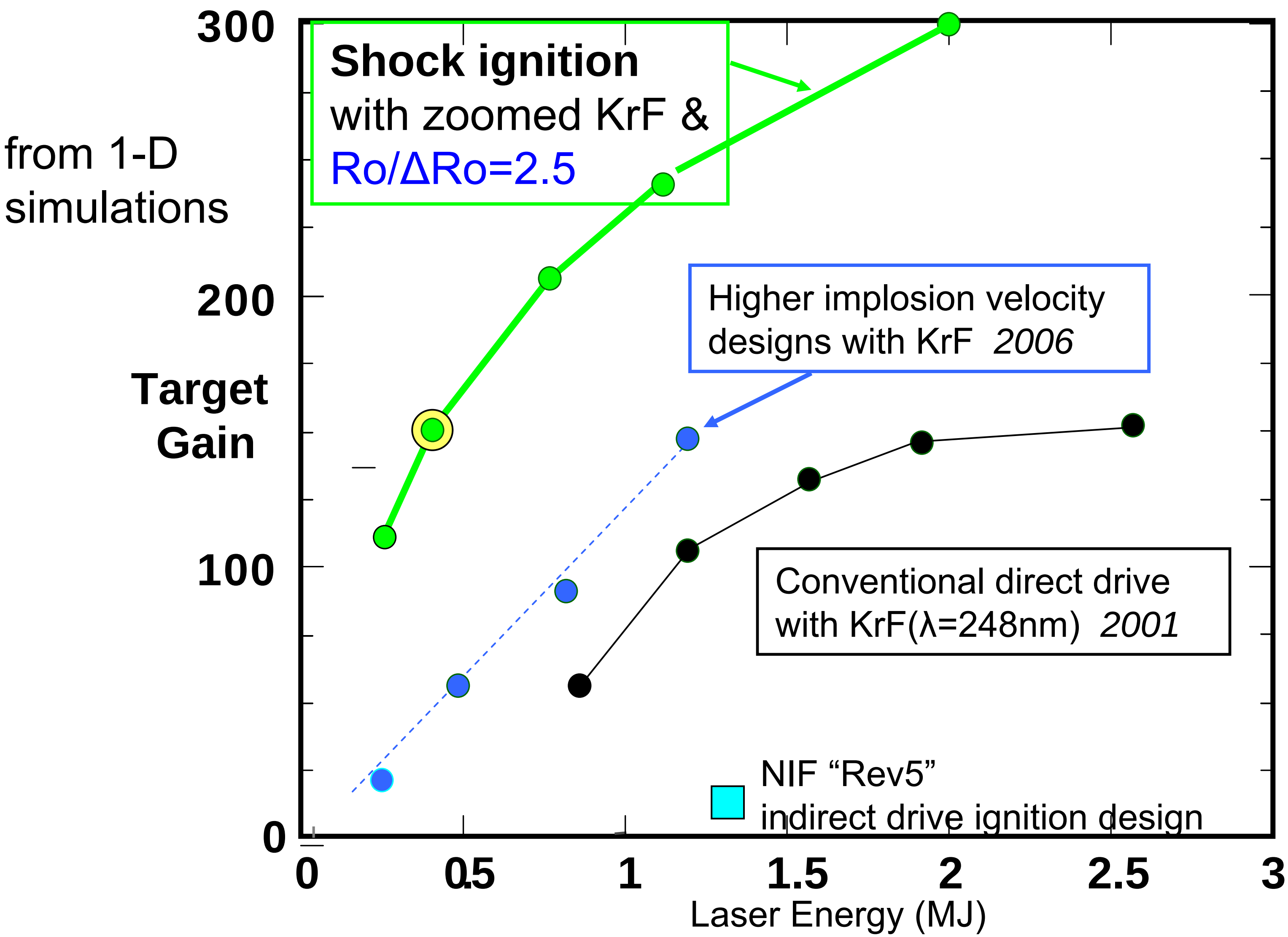
Low aspect ratio pellet helps mitigate hydro instability

Peak main drive is 1 to 2 × 10^{15} W/cm^2

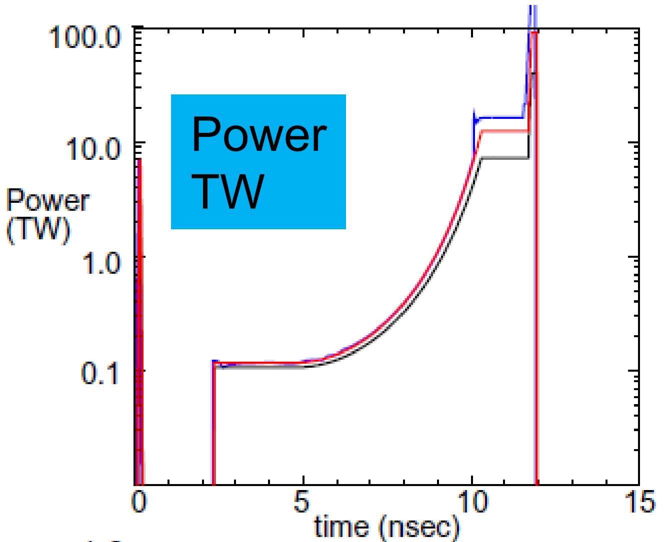
Igniter pulse is ~10^{16} W/cm^2

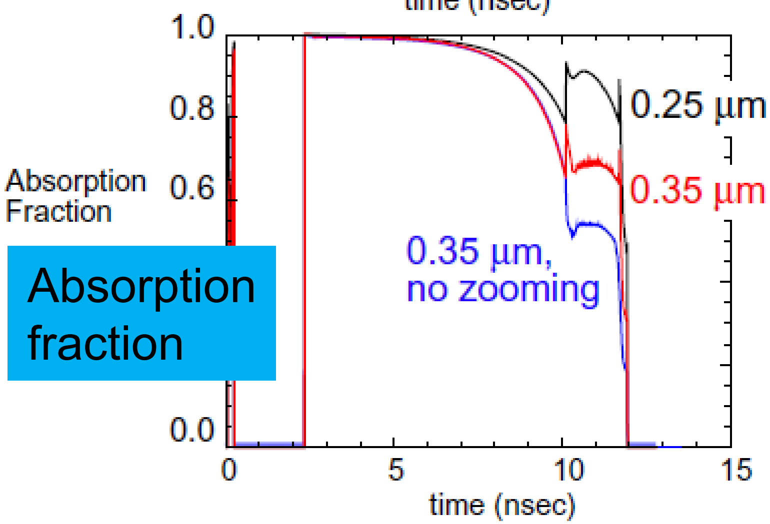
* *R. Betti et al., Phys.Rev.Lett.* ***98****, 155001 (2007)*

Gain curves show progress in direct-drive target designs



Shock ignition benefits from shorter λ and zooming



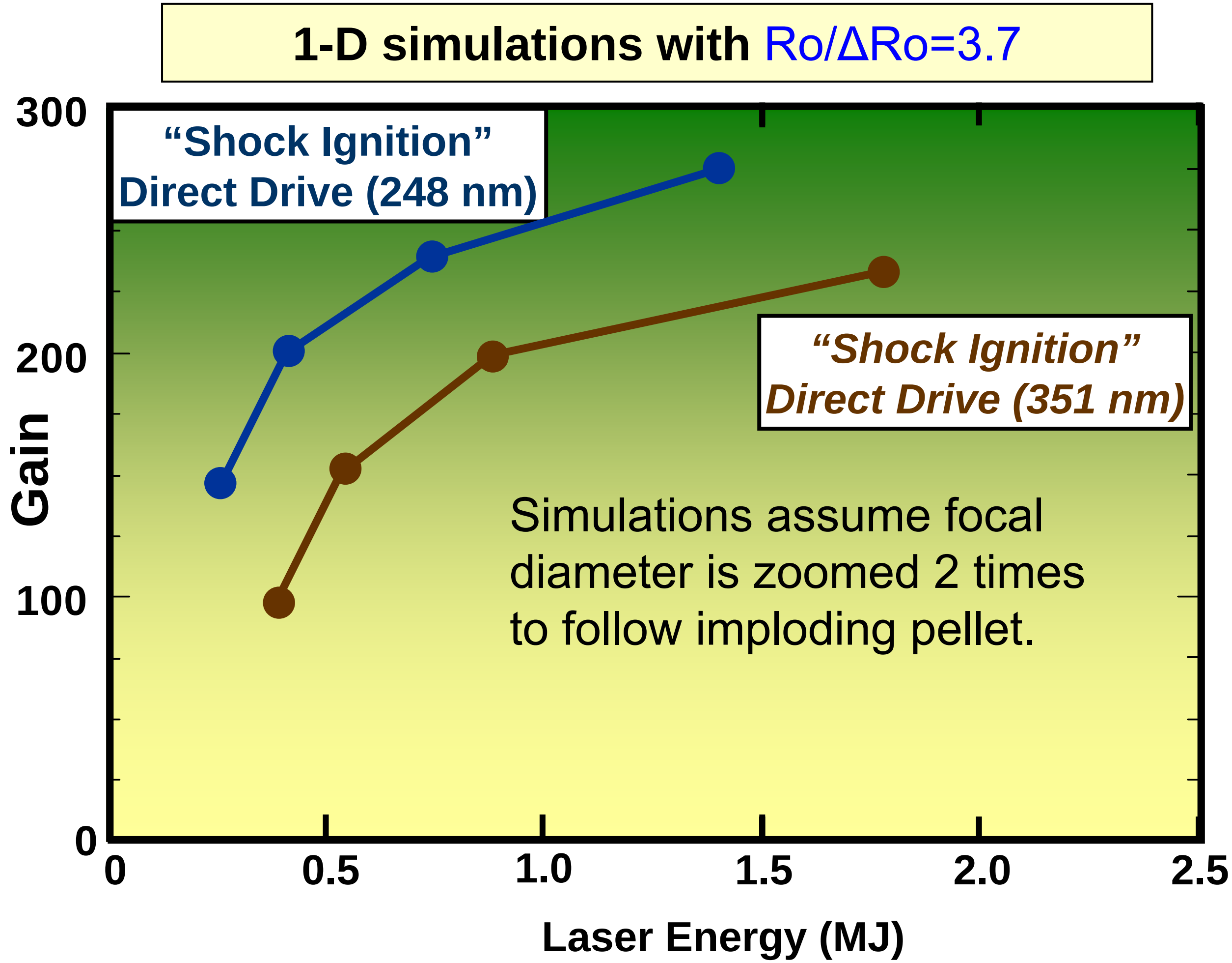


1-D Hydrocode simulations
Fixed low aspect ratio pellet (R/ΔR=2.5)

	KrF λ=248 nm with Zoom	**Nd:glass** λ=351 nm with Zoom	**Nd:glass** λ=351 nm no Zoom
Laser Energy	**230 kJ**	**430 kJ**	**645 kJ**
Yield	22 MJ	24 MJ	23 MJ
Gain	**97**	**56**	**35**
Peak compression intensity (W/cm²)	1.55×10^{15}	2.2×10^{15}	
Peak igniter intensity (W/cm²)	1.6×10^{16}	3.1×10^{16}	

- Significantly higher gain with 248 nm & zoom
- NIF has more than sufficient energy to test the physics

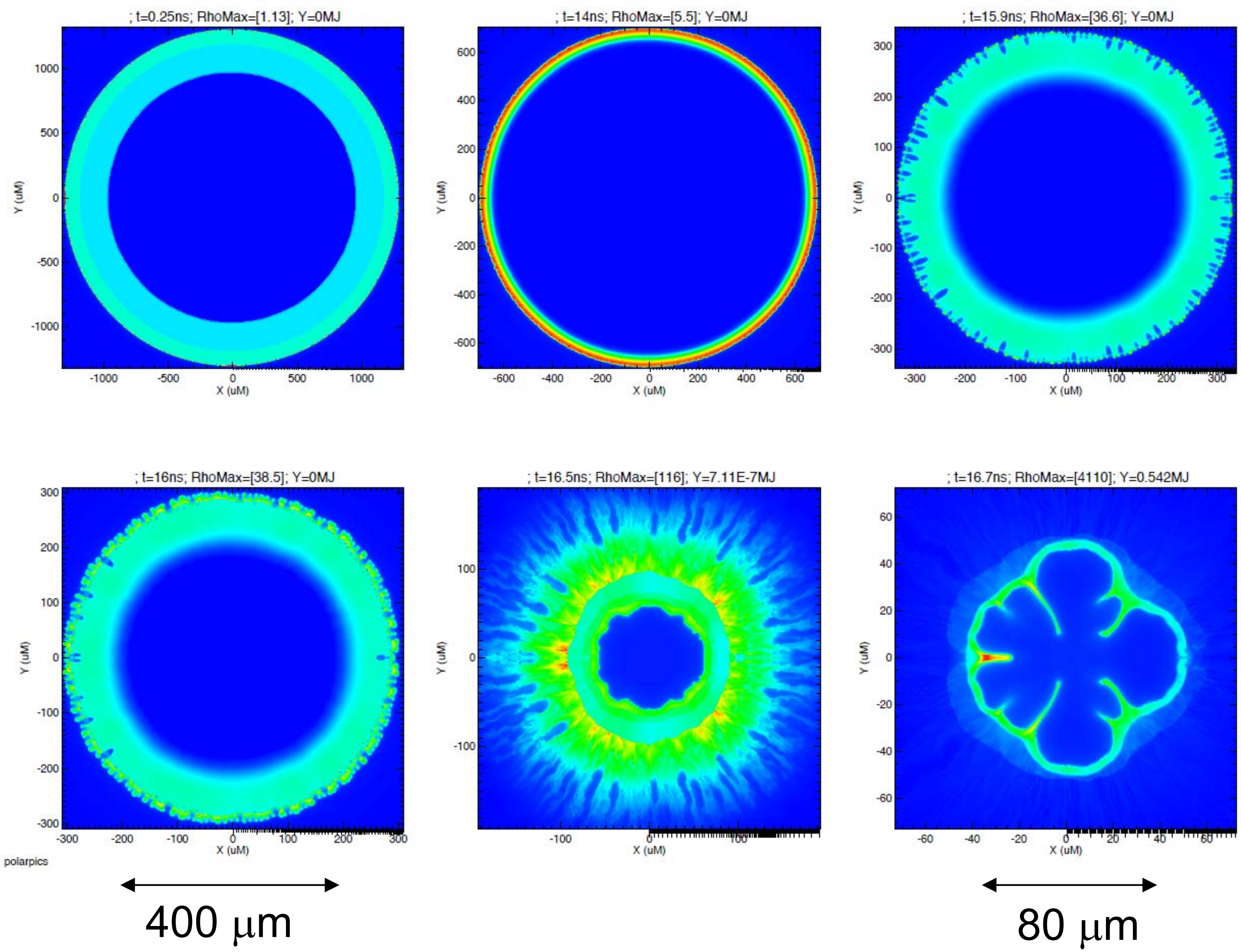
In simulations utilizing higher initial aspect ratio targets, high gain is obtained with both KrF (248 nm) and frequency tripled Nd:glass (351 nm) lasers.



Higher aspect ratio targets need less drive intensity for acceleration phase of SI

2-D simulations indicate that the larger 3.7 aspect ratio shock ignited targets can retain most of the 1-D gain.

Initial outer surface finish: 0.4 mg RMS (DT-foam), inner surface 1 μm RMS, 1 THz ISI



Laser: 529 kJ KrF

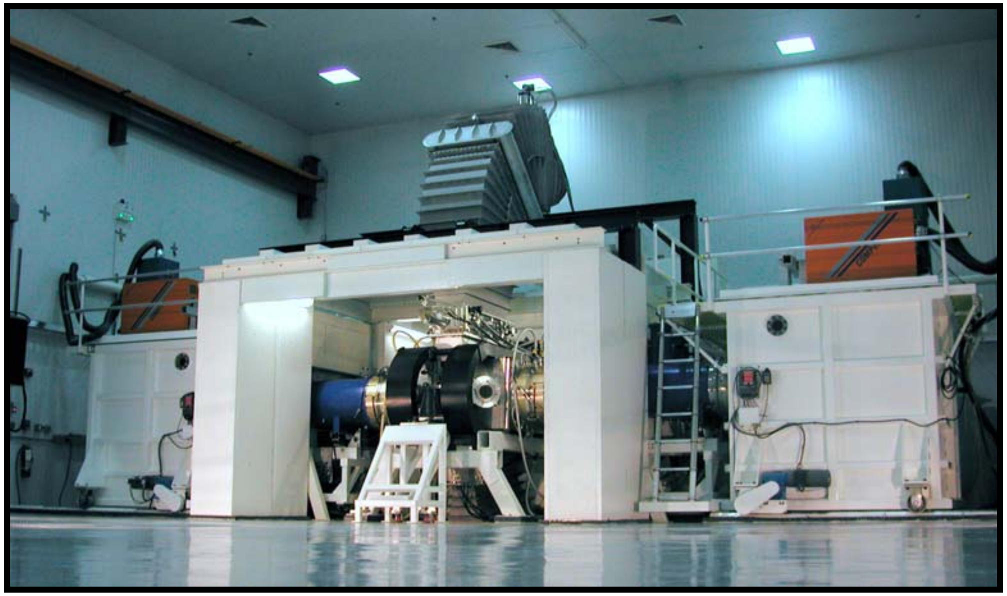
2-D yield: 72 MJ
2-D gain: 138×

1-D yield: 80.4 MJ
1-D gain: 187

KrF science and technology is being developed with the NRL Electra and Nike Lasers

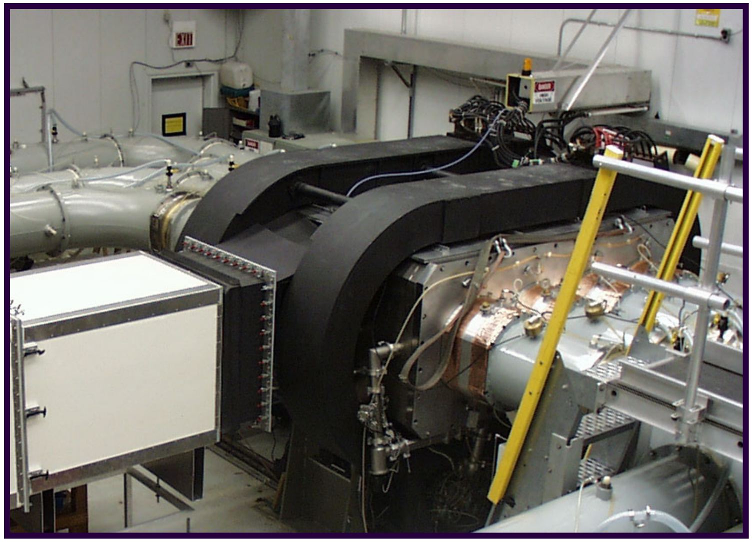
Electra: (5 Hz)
300-700 J laser light
500 keV/100 kA/100 nsec
30 cm x 100 cm e-beam

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

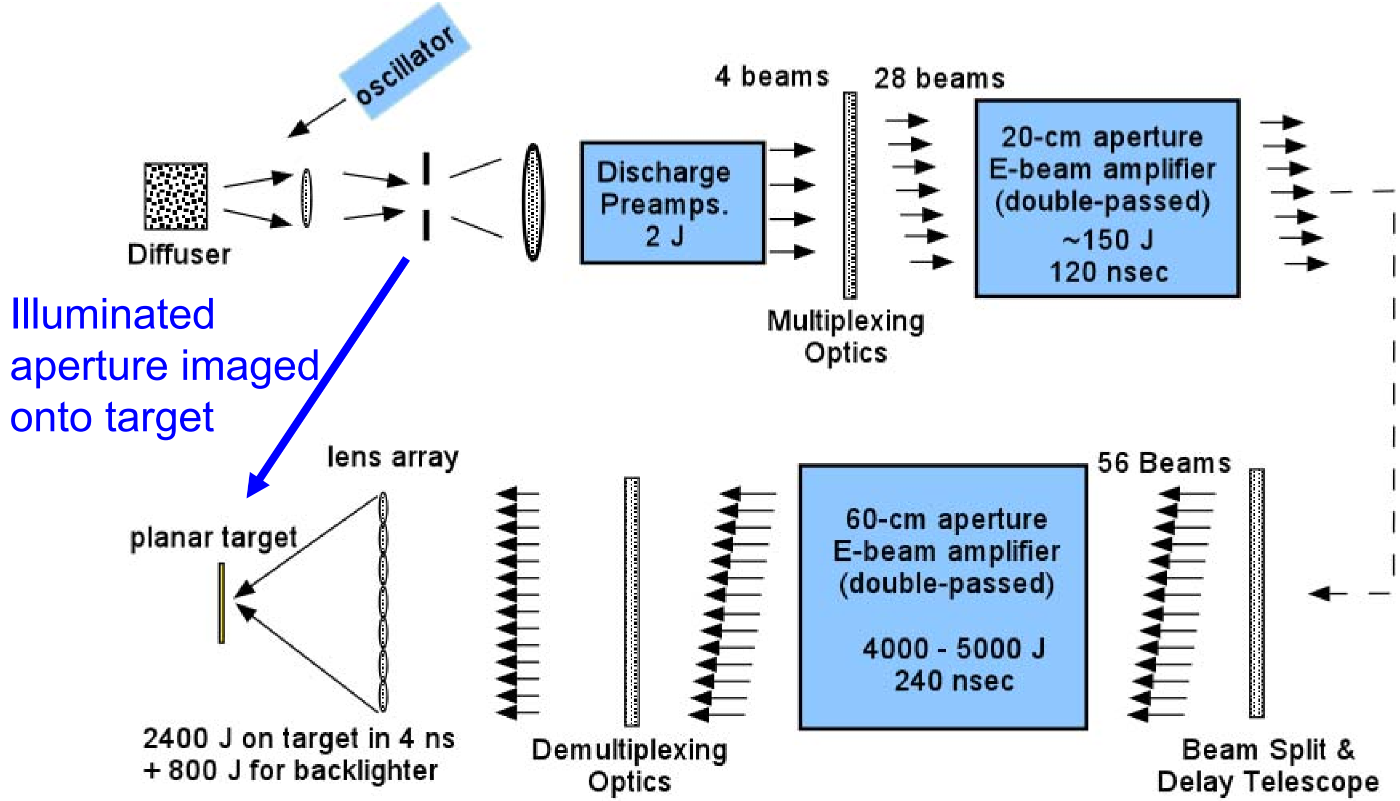


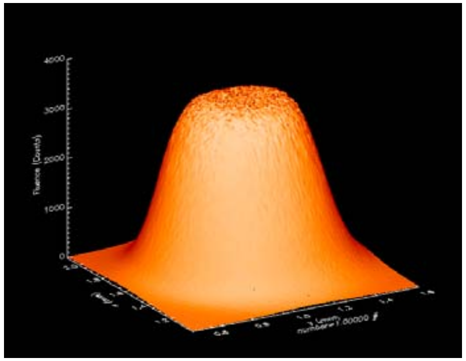
Nike: (Single Shot)
3-5 kJ laser light
650 keV, 500 kA, 240 nsec
60 cm x 200 cm e-beam

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



Nike laser Chain





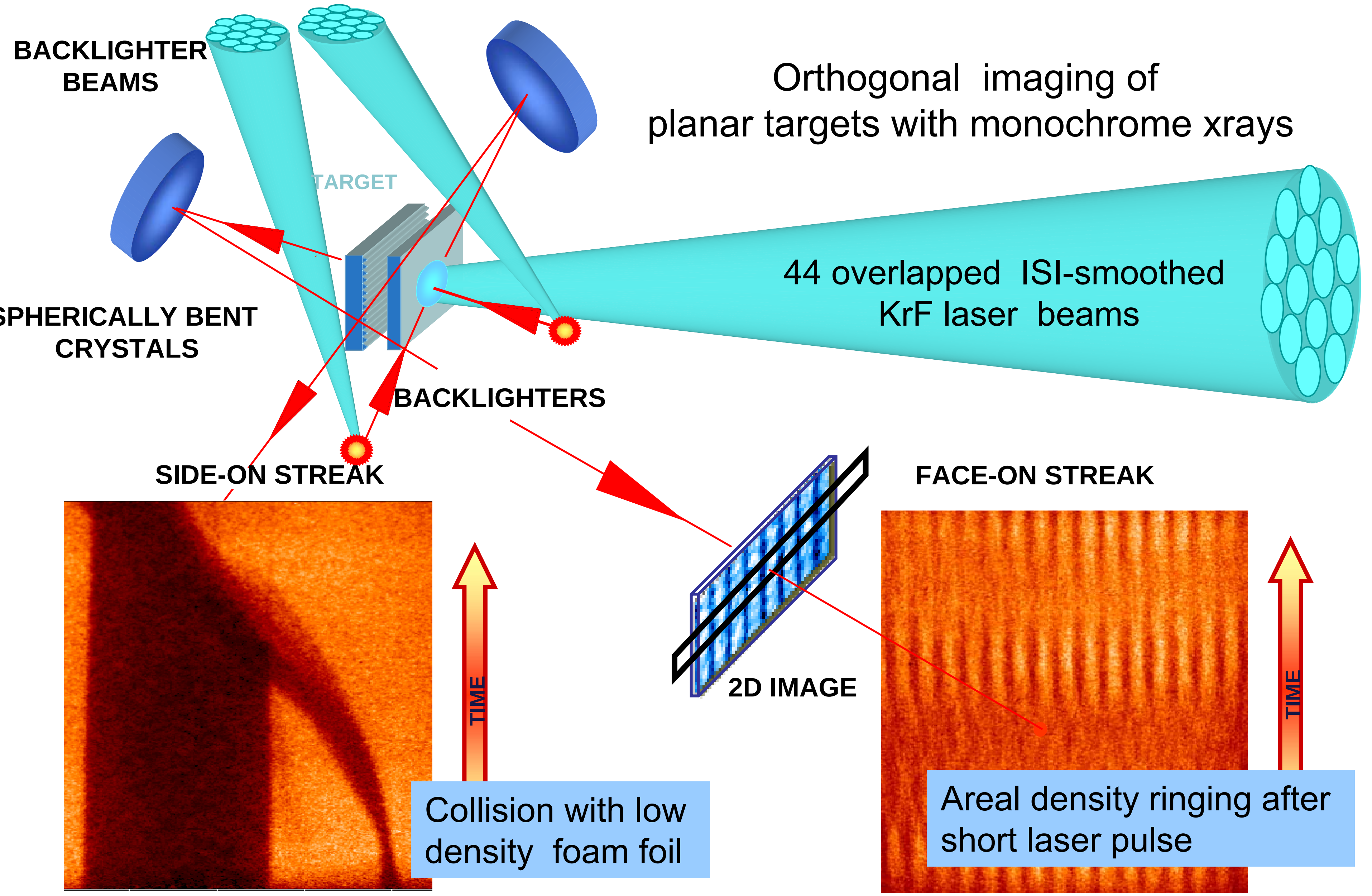
Laser profile in target chamber

Nike's angularly multiplexed optical system has been utilized for 16 years with many thousands of high energy shots on the beam transport optics.

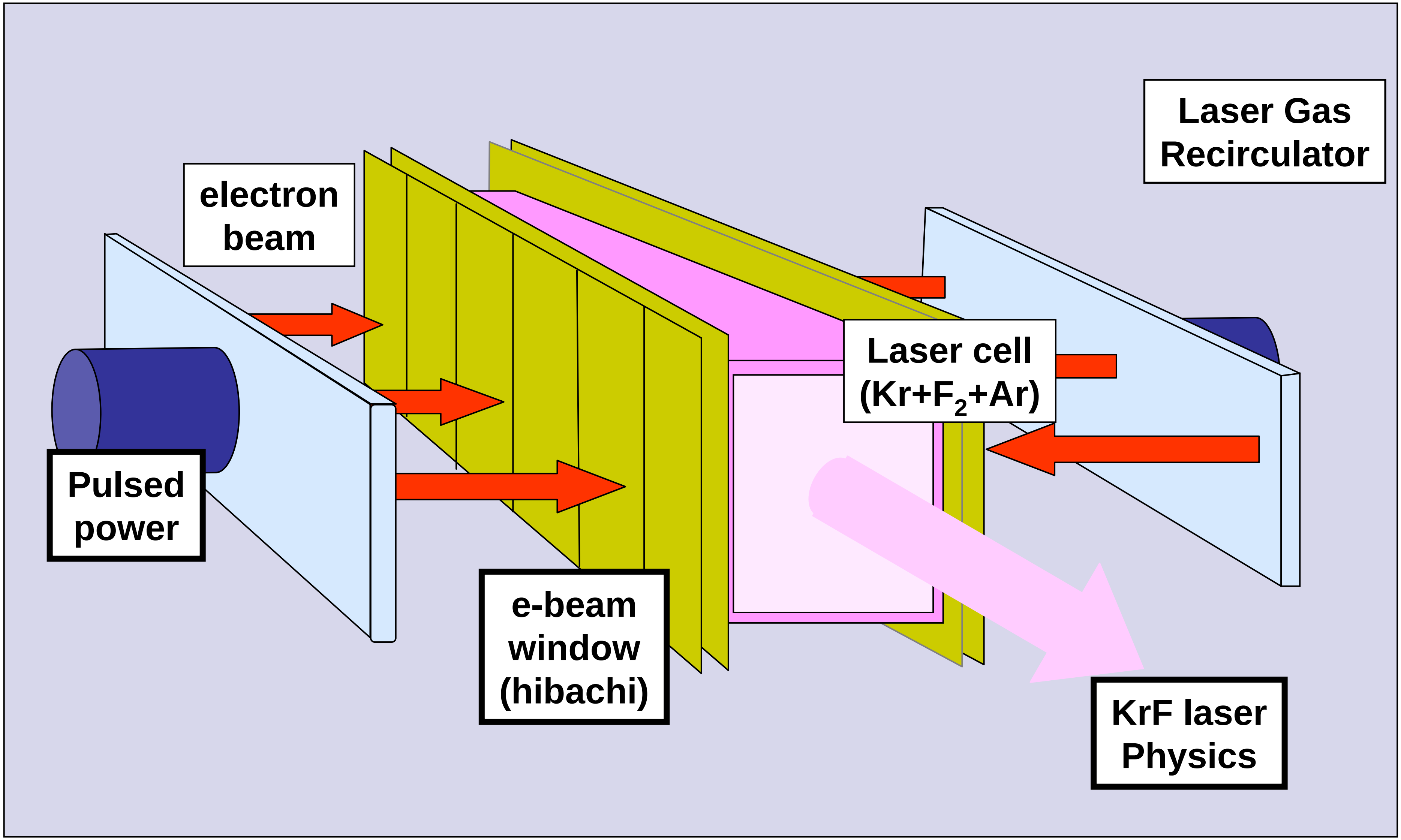
Changes for an IFE system:

- Utilize vacuum or He gas instead of air in the beam propagation paths.
- Utilize higher performance mirrors.
- Above changes would allow a more compact optical system (more energy and power per cm^2 of optic).

Nike is employed for studies of hydrodynamics and LPI



Elements of a Krypton Fluoride (KrF) electron beam pumped gas laser amplifier

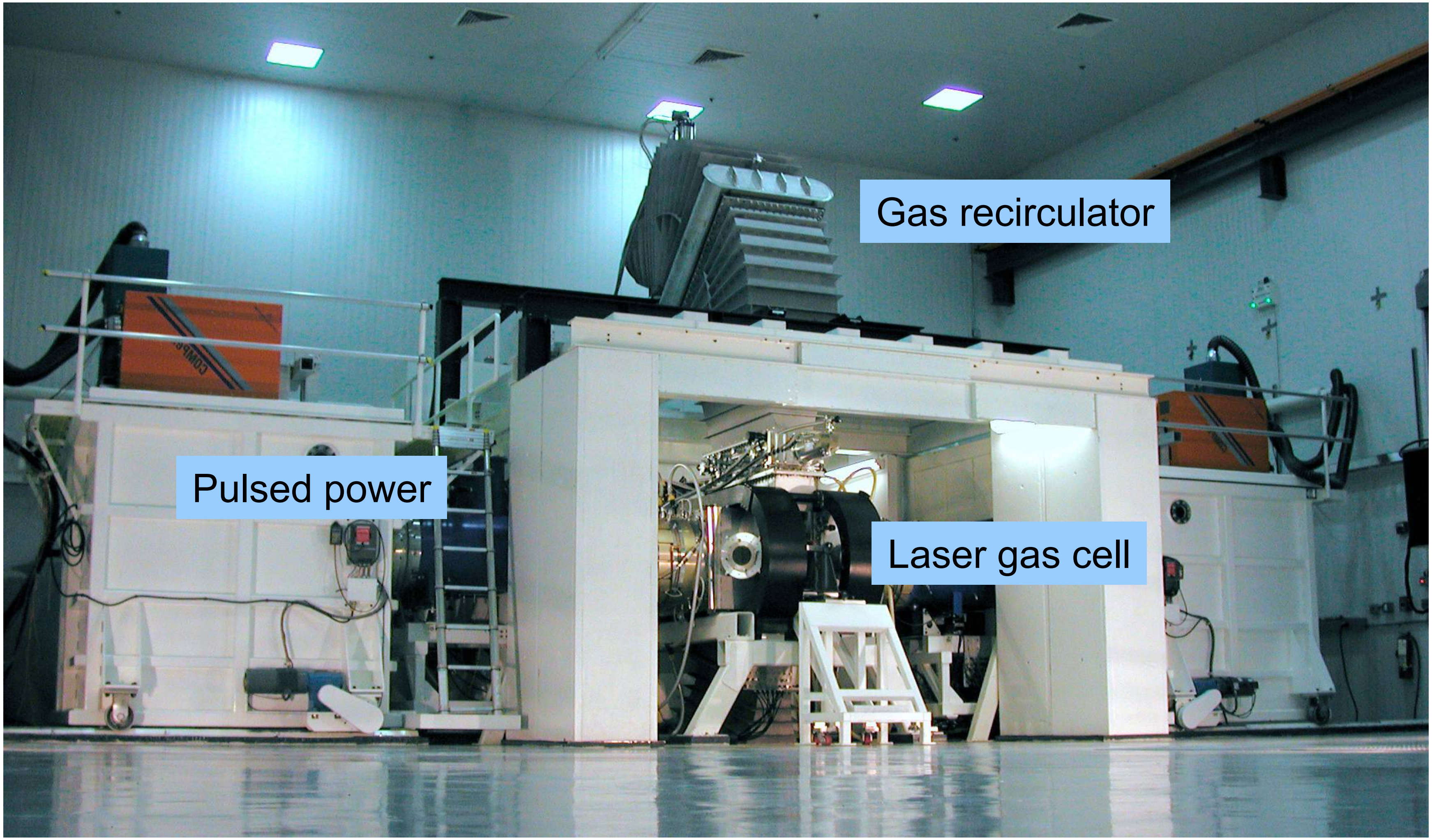


Electra Krypton Fluoride (KrF) Laser

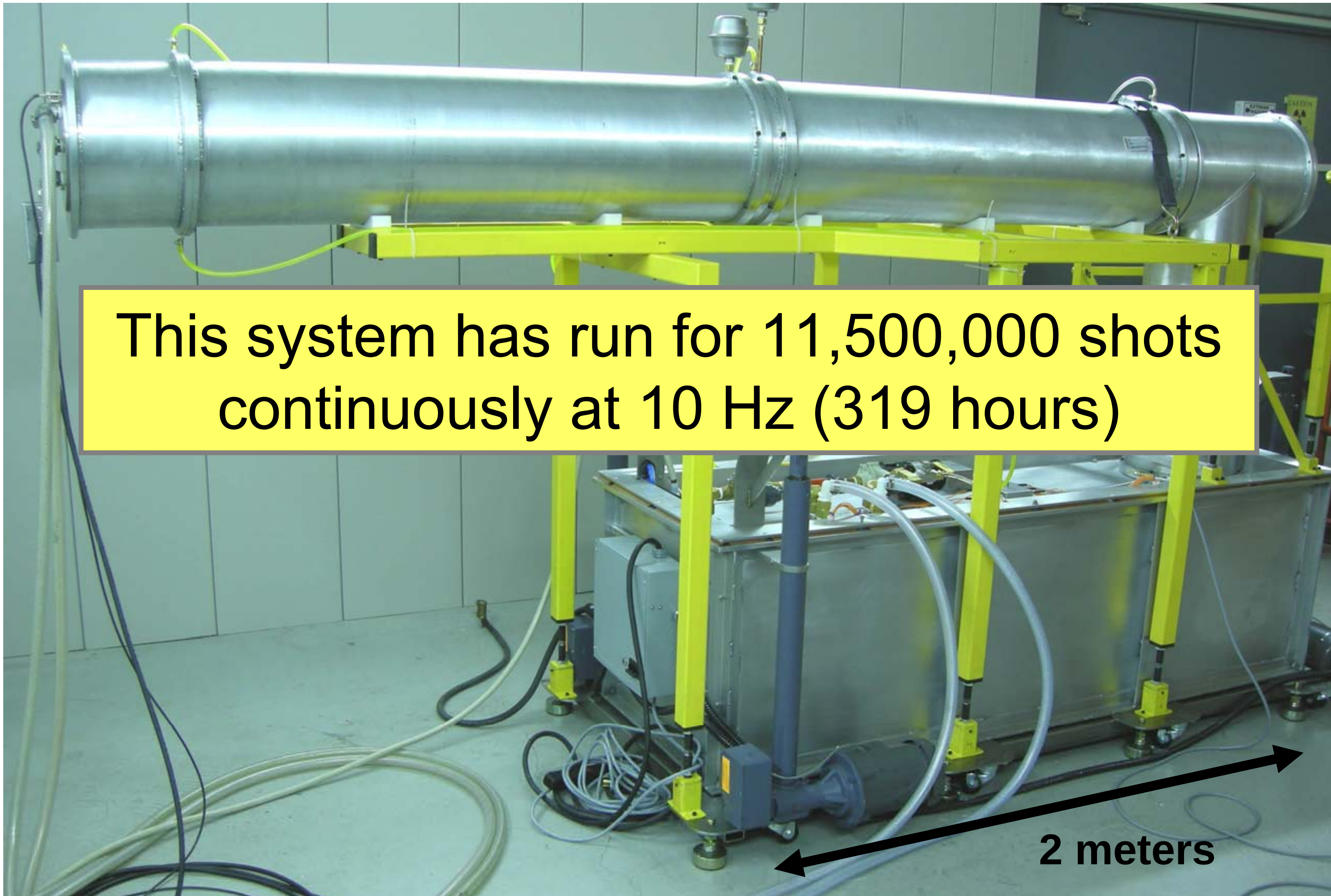
Laser Energy: 300 to 700 Joules

Repetition rate: up to 5 pulses per second

Continuous Runs: 10 hrs at 2.5 Hz (90,000 shots)

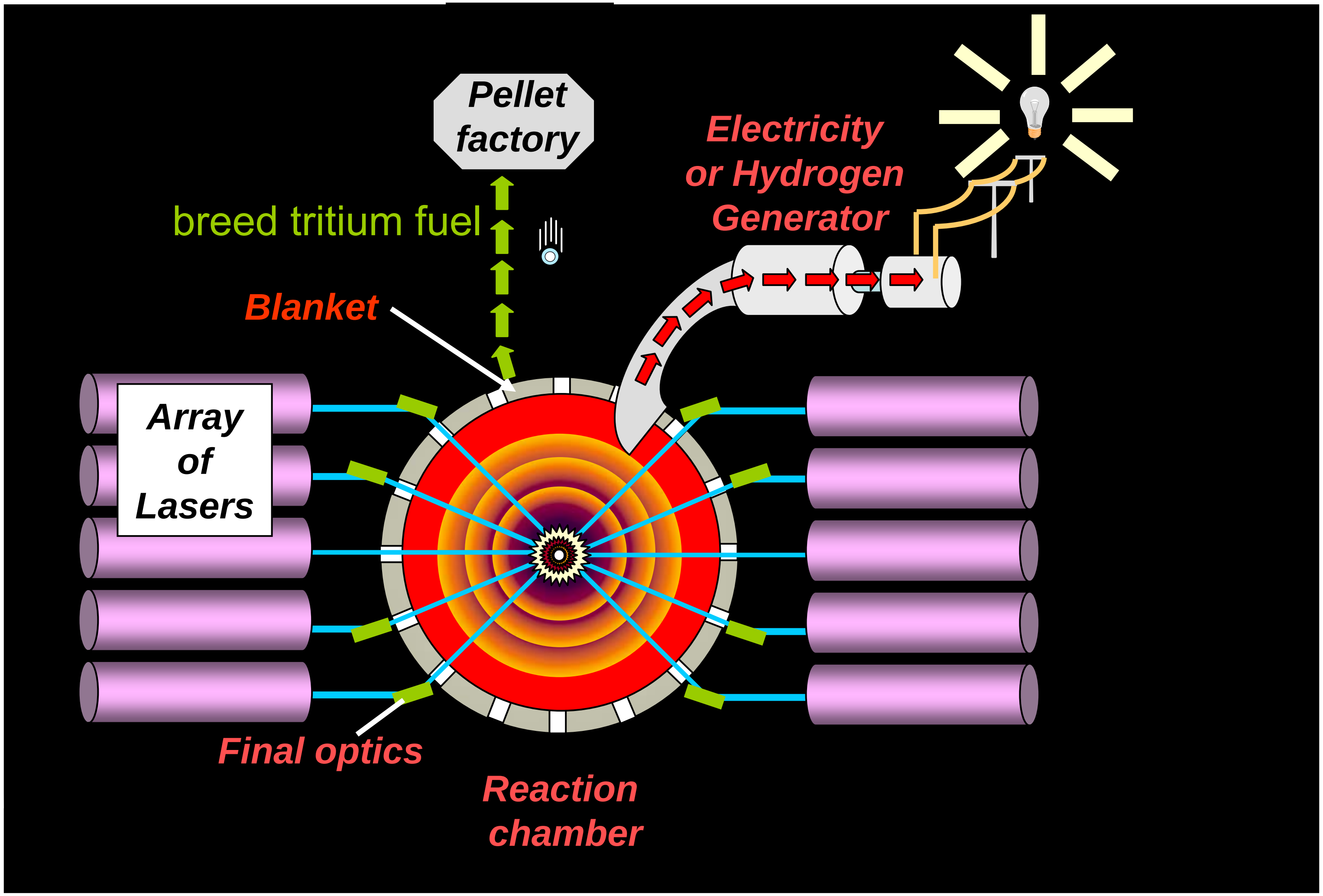


Compact 200 kV, 4.5 kA Solid State Pulse Generator Integrated Test of Components



PLEX LLC

A laser fusion energy power plant



Many components are modular and separable

Fusion should be developed as a phased program, with well defined gates to advance to the next phase

Phase I:

Basic IFE Science and Technology

Phase II:

Develop full size components

Phase III:

Fusion Test Facility

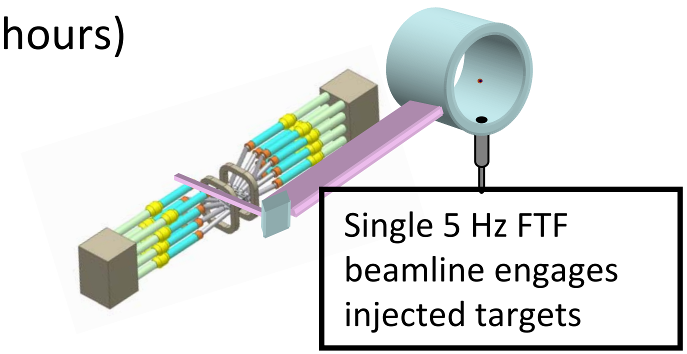
- Demonstrate integrated physics / technologies for a power plant.
- Tritium breeding, fusion power handling.
- Develop/ validate fusion materials and structures.
- **READY FOR PILOT POWER PLANT**

Increasing size
Increasing performance
Decreasing scientific risk
Increasing Industry Partnership

Some particulars of a Phased program with KrF

<u>Complete Phase I: (~3 years)</u>

- Install solid-state pulsed power on the Electra system
- Demonstrate long continuous runs (e.g. >500J, >100 hours)
- Complete auxiliary efforts begun by HAPL
- Design full scale beamline.
- Refine target design and physics

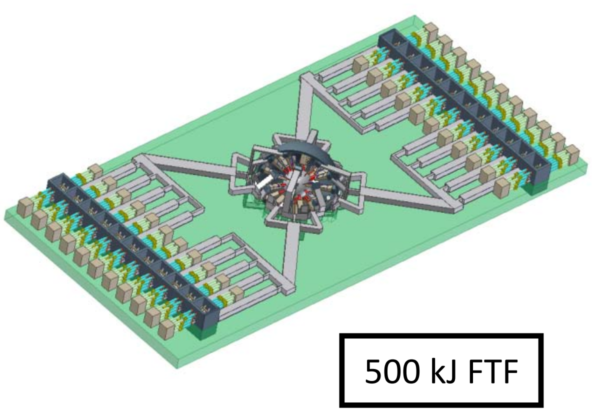


<u>Phase II</u> : Develop full size components (~5 years)

- Develop full scale KrF laser beamline (e.g. 18 to 30 kJ, 5 Hz KrF beamline)
- Engage injected targets with beamline.
- Increased efforts in all critical IFE technologies
- Develop high confidence in pellet designs & physics

<u>Phase III</u> Fusion Test Facility (FTF)

- 500 kJ 5 Hz KrF system utilizing shock ignition.
- ~250 MW fusion thermal power
- Develop/ validate fusion materials and structures
- Significant participation by private industry



NRL KrF laser facilities

Tour of Nike Target Facility
(Yefim Aglitskiy, Max Karasik, Jim Weaver)

Tour of Nike Laser Facility
(David Kehne, Bruce Jenkins)

Tour of Electra Facility
(Frank Hegeler, Matt Myers, Matt Wolford)

Discussion (& refreshments) Building 71 Conference Room

Bus back to hotel (11:45).

2 Tour Groups

John Sethian and Yung Chan – begin with Electra facility (A-L)'s

Victor Serlin and Steve Terrell – begin with Nike target facility (M-Z)'s