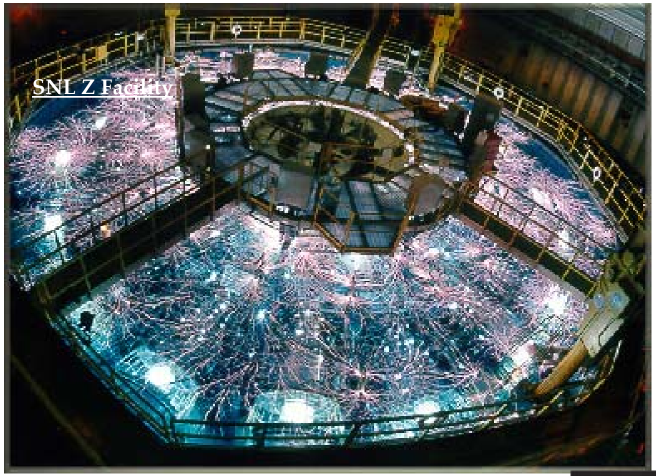
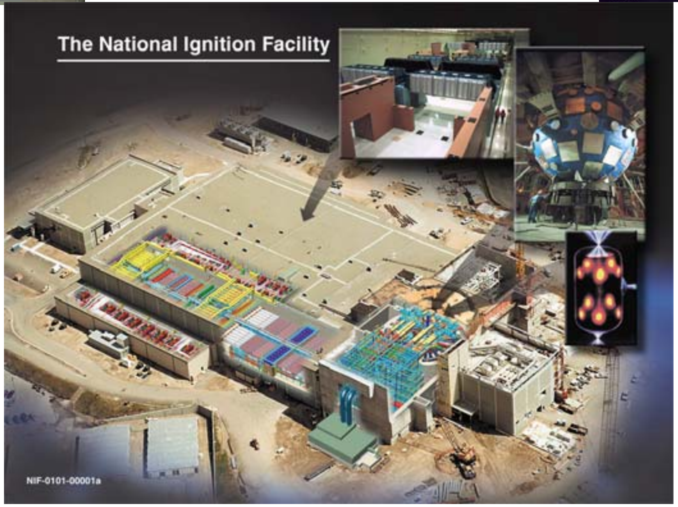
NNSA Defense Programs

Inertial Confinement Fusion Ignition and High Yield Campaign



National Nuclear Security Administration



Presented by:
Dr. Christopher J. Keane
Acting Assistant Deputy Administrator for
Inertial Confinement Fusion and the NIF Project

Presented at:
16th ANS Topical Meeting on
the Technology of Fusion Energy
September 14, 2004
Madison, Wisconsin

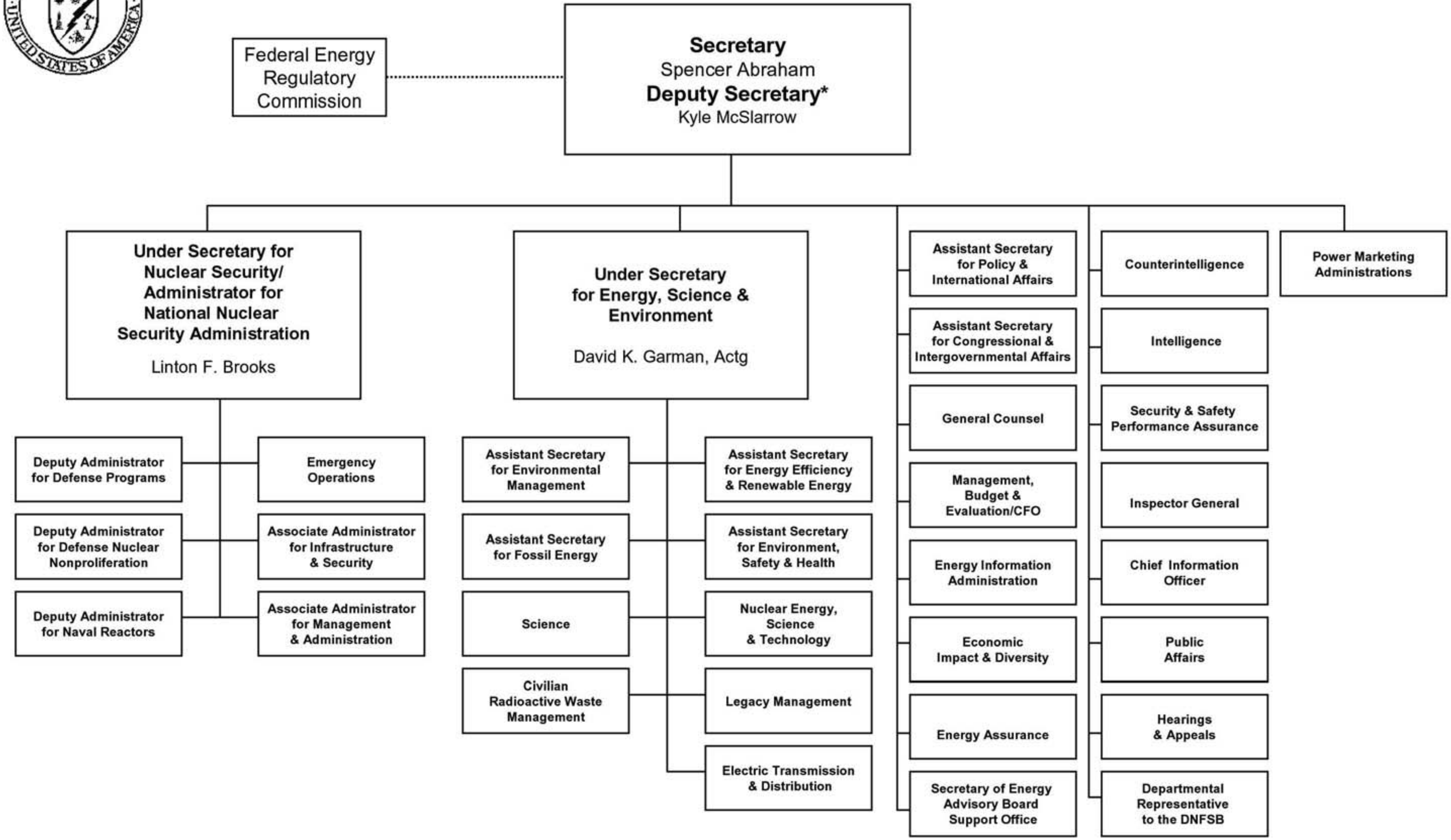
Outline

- National Nuclear Security Administration
- ICF Campaign and Stewardship overview
- Recent progress – NIF, OMEGA, Z, Nike
- Inertial Fusion Energy
- University activities

Summary- major points

- **ICF Program continues to make strong technical progress**
  - **NIF Project has made outstanding progress**
  - **Outstanding recent results at OMEGA, Z**
- **First experiments have been conducted at NIF**
  - **Detailed use planning is underway**
  - **Ignition 2010 is a major goal**
- **Pulsed power ICF shows promising results**
- **Petawatt lasers will significantly enhance capabilities**
- **ICF facilities (NIF, OMEGA,Z) are available to university and external users**
- **National Academy of Sciences recognizes High-Energy-Density Physics as an important scientific field**

DEPARTMENT OF ENERGY



- Federal Energy Regulatory Commission
- **Secretary**
  Spencer Abraham
  Deputy Secretary*
  Kyle McSlarrow
  - **Under Secretary for Nuclear Security/ Administrator for National Nuclear Security Administration**
    Linton F. Brooks
    - Deputy Administrator for Defense Programs
    - Deputy Administrator for Defense Nuclear Nonproliferation
    - Deputy Administrator for Naval Reactors
    - Emergency Operations
    - Associate Administrator for Infrastructure & Security
    - Associate Administrator for Management & Administration
  - **Under Secretary for Energy, Science & Environment**
    David K. Garman, Actg
    - Assistant Secretary for Environmental Management
    - Assistant Secretary for Fossil Energy
    - Science
    - Civilian Radioactive Waste Management
    - Assistant Secretary for Energy Efficiency & Renewable Energy
    - Assistant Secretary for Environment, Safety & Health
    - Nuclear Energy, Science & Technology
    - Legacy Management
    - Electric Transmission & Distribution
  - Assistant Secretary for Policy & International Affairs
  - Assistant Secretary for Congressional & Intergovernmental Affairs
  - General Counsel
  - Management, Budget & Evaluation/CFO
  - Energy Information Administration
  - Economic Impact & Diversity
  - Energy Assurance
  - Secretary of Energy Advisory Board Support Office
  - Counterintelligence
  - Intelligence
  - Security & Safety Performance Assurance
  - Inspector General
  - Chief Information Officer
  - Public Affairs
  - Hearings & Appeals
  - Departmental Representative to the DNFSB
  - Power Marketing Administrations

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* The Deputy Secretary also serves as the Chief Operating Officer

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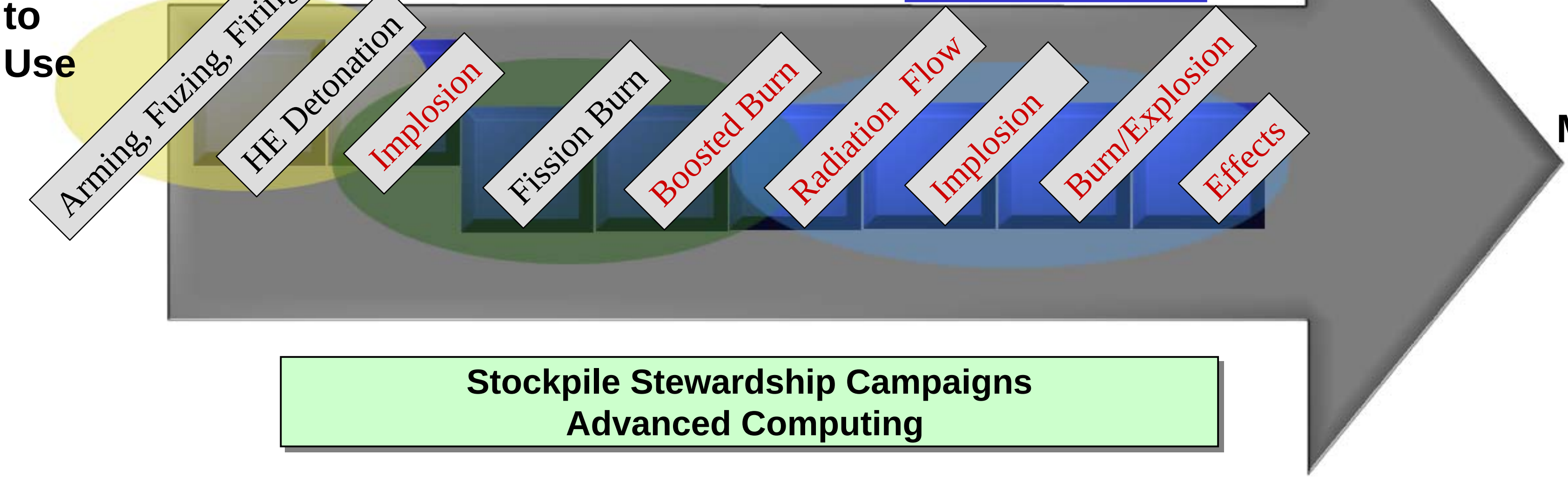
SSP Programs & Facilities Provide Necessary Research Capabilities

Adv. Hydro Capability

(DARHT)

ICF Facilities (NIF/OMEGA/Z)

Authority to Use



Militarily Effective Yield

Stockpile Stewardship Campaigns
Advanced Computing

Component Manufacturing (MESA)

(ASCI White)

ICF Campaign Strategic Goals

1. Execute high energy density physics experiments necessary to provide advanced assessment capabilities for stockpile stewardship

- Support stockpile refurbishment and assessment
- Address specific weapon issues, validate advanced ASCI simulations

2. Achieve ignition in the laboratory and develop it as a scientific tool for stockpile stewardship

- Provide thermonuclear burn capability for the SSP
- Key *integrated* test for validation of integrated ASCI simulations

3. Develop advanced technology capabilities that support the long-term needs of stockpile stewardship

- Pursue promising advanced concepts (pulsed power fusion, “fast ignition”, petawatt lasers)

4. Maintain robust national program infrastructure and attract scientific talent to the Stockpile Stewardship Program

- Support university programs and use of NIF, Omega, Z (~15% level)

ICF Campaign includes 6 major contractors and university participants

- Lawrence Livermore National Laboratory
  - *National Ignition Facility*
  - Glass laser technology development
  - Indirect drive ignition
  - Application of HED science to stockpile issues
  - Diode Pumped Solid State Laser

- Sandia National Laboratory
  - *Z/ZR pulsed power accelerator*
  - Physics of z-pinches and applications
  - Pulsed power technology development
  - High yield assessment

- Los Alamos National Laboratory
  - Trident glass laser
  - Indirect drive ignition
  - Application of HED science to stockpile issues

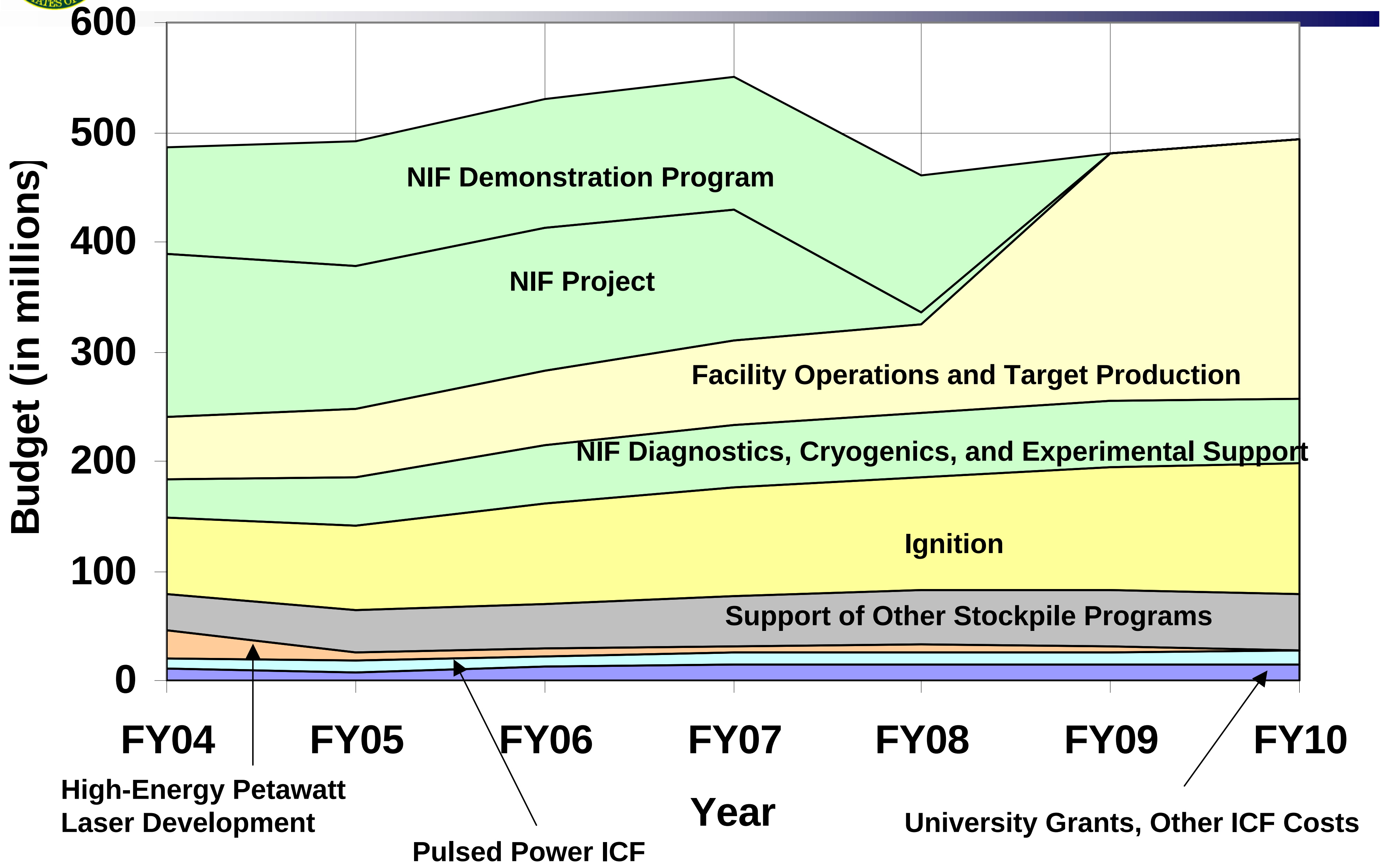
- University of Rochester / Laboratory for Laser Energetics
  - *Omega Upgrade glass laser*
  - *Application of HED science to stockpile issues (with LLNL/LANL)*
  - Direct drive physics assessment

- Naval Research Laboratory
  - Nike KrF laser
  - Use of smooth beams for physics
  - Direct drive target design
  - KrF laser technology development

- General Atomics
  - Target fabrication
  - Cryogenic technology target handling

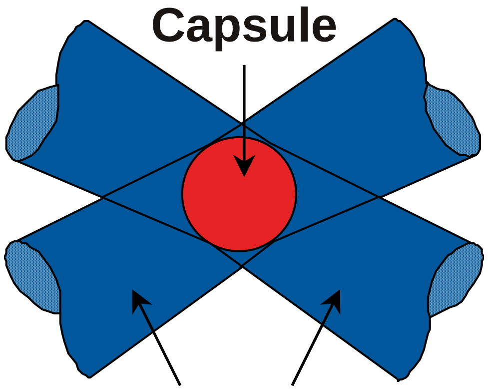
- Academic Alliances Program

ICF Budget by Major Category

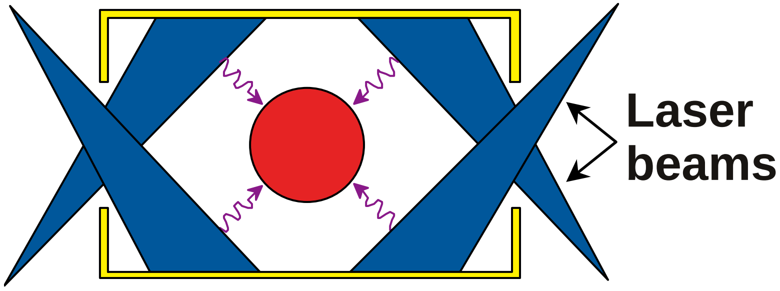


ICF implosions are carried out with both direct drive and x-ray drive

Direct-drive target (LLE,NRL)



X-ray-drive target (LLNL, LANL, SNL)

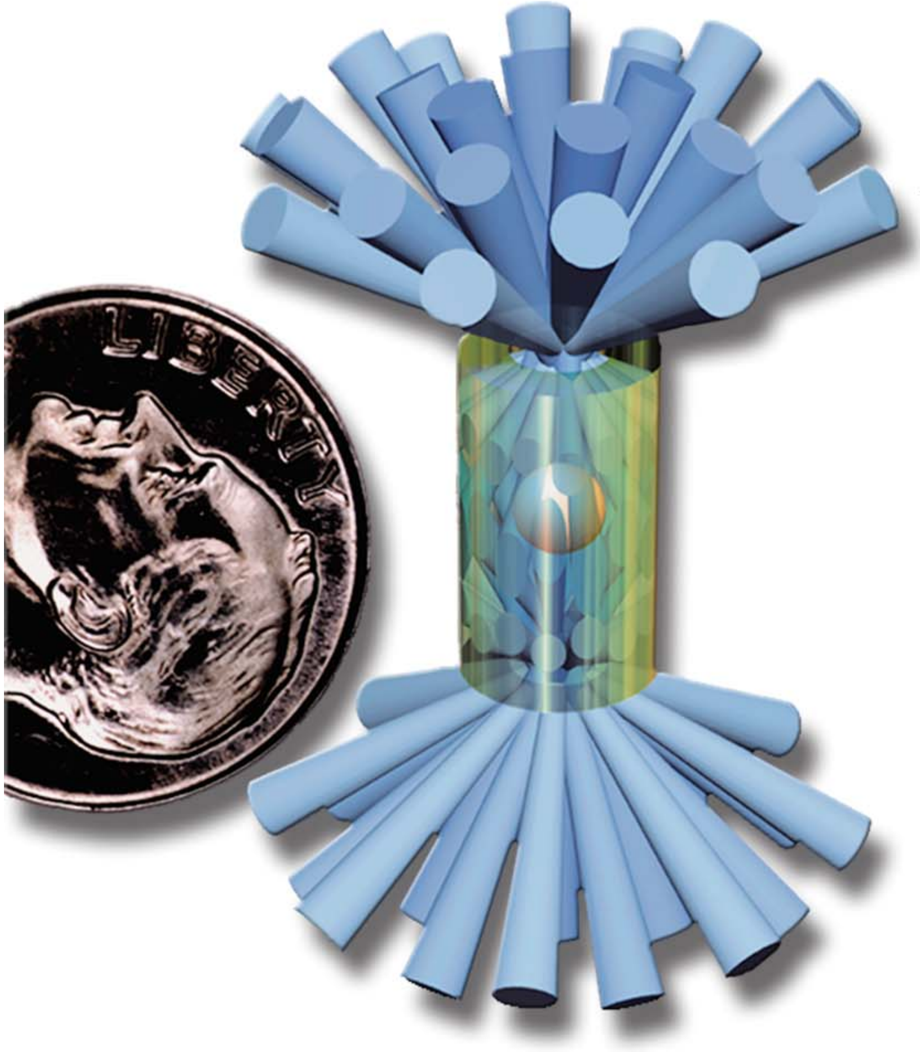


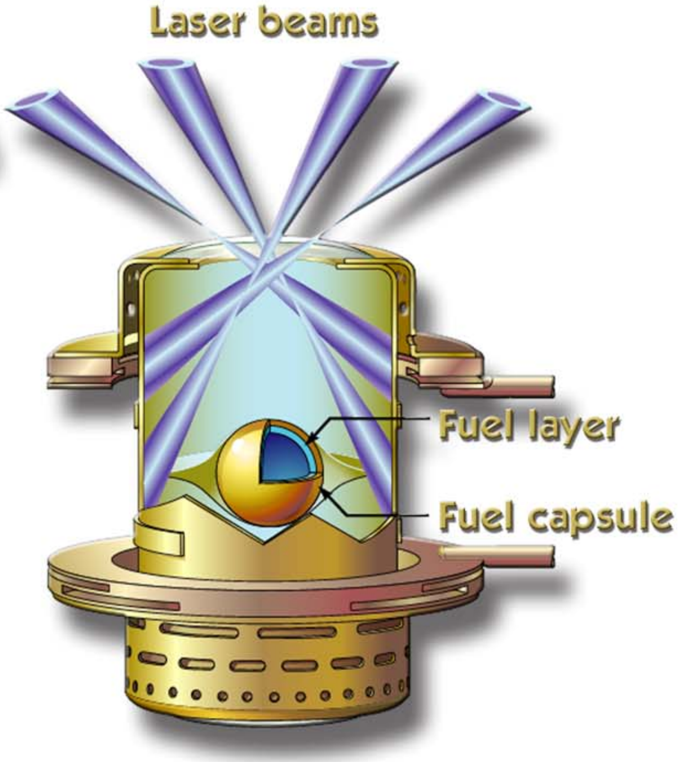
Hohlraum using
a cylindrical high-Z case

Key physics issues are common to both:

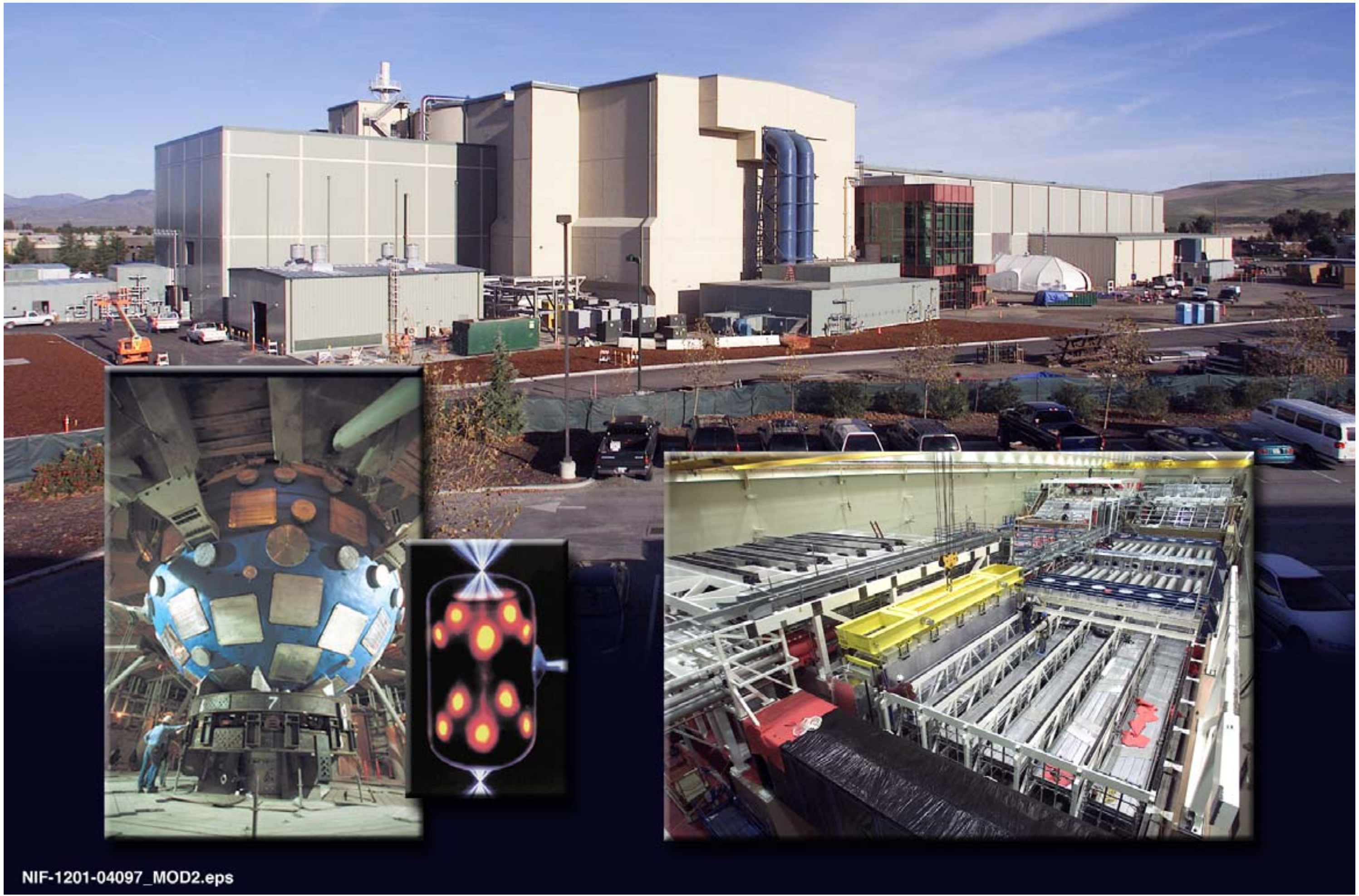
- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities

NIF Fusion Target





The National Ignition Facility

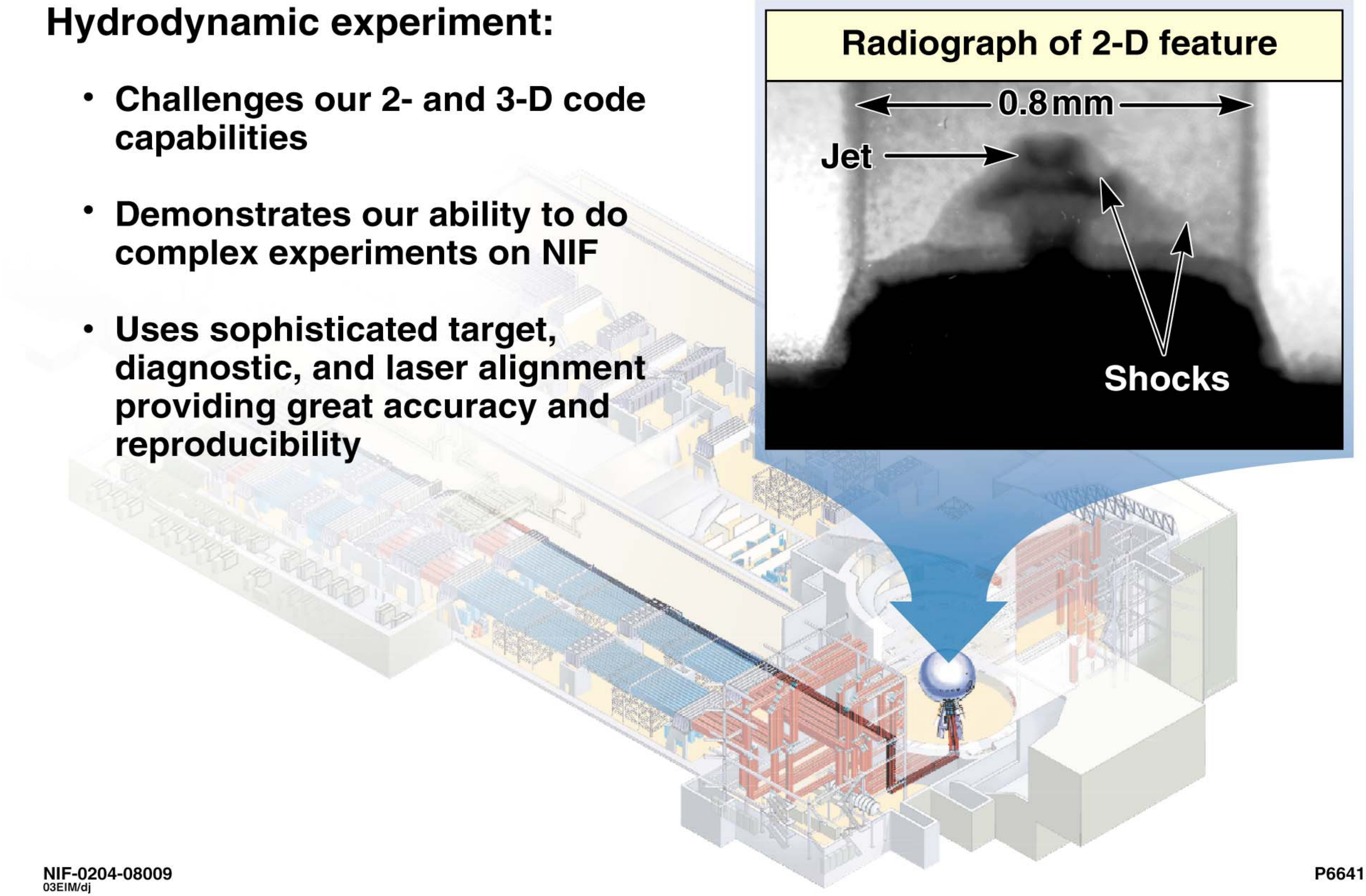


NIF concentrates 1.8 Mega Joules of energy into a mm^3 size target through the use of advanced laser technology

NIF is acquiring data for Stockpile Stewardship

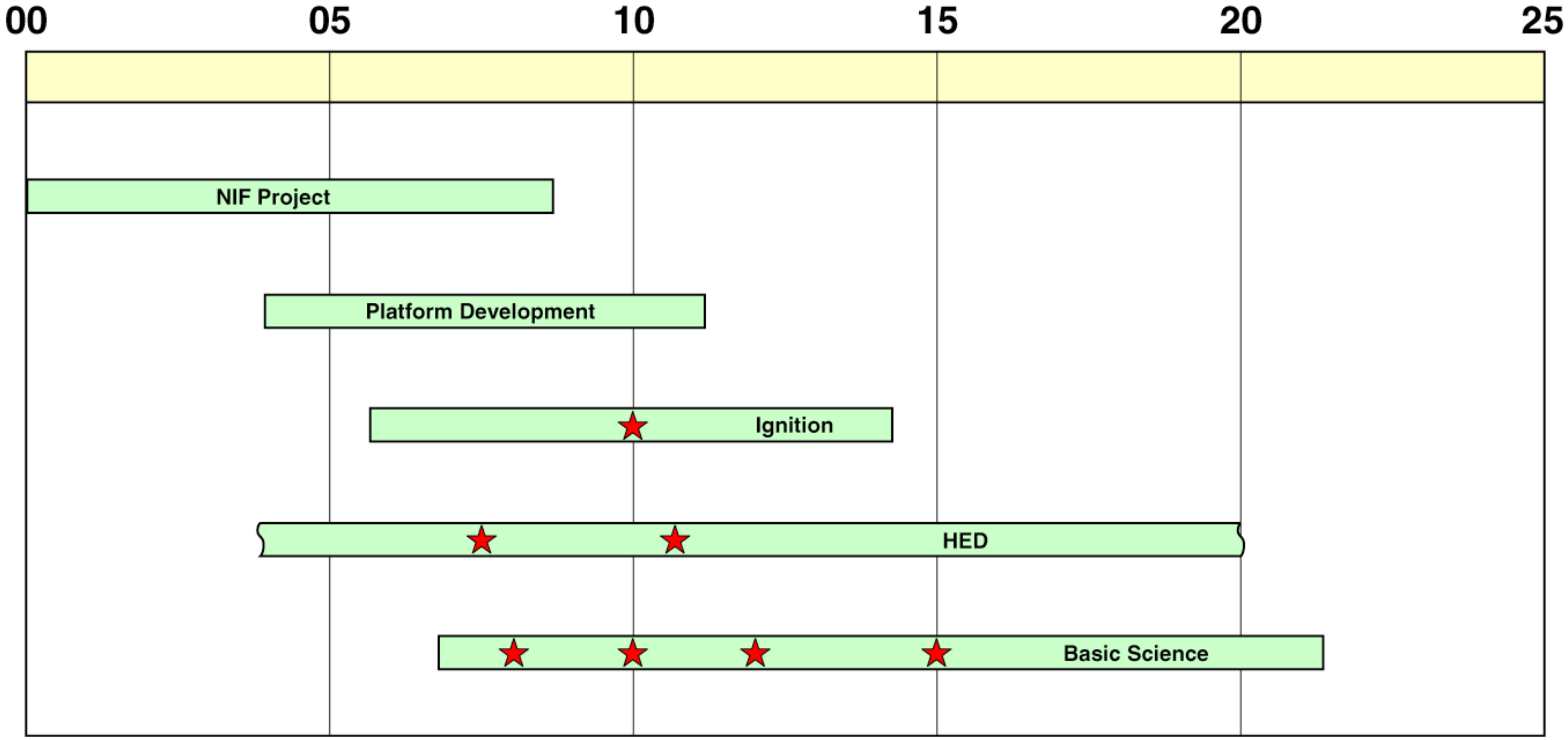
Hydrodynamic experiment:

- Challenges our 2- and 3-D code capabilities
- Demonstrates our ability to do complex experiments on NIF
- Uses sophisticated target, diagnostic, and laser alignment providing great accuracy and reproducibility

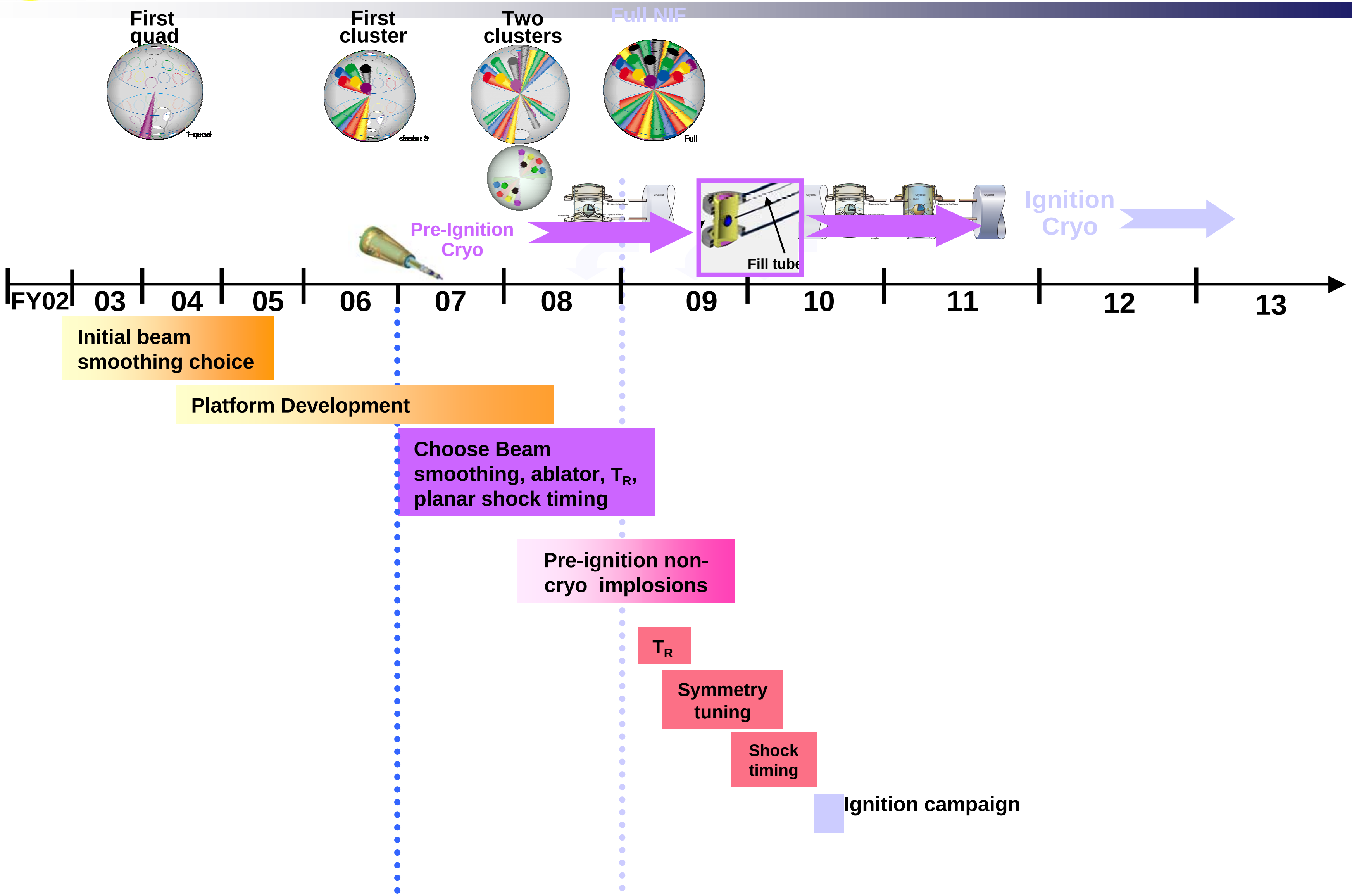


Radiograph of 2-D feature

Plans for Use of NIF reflect ICF Strategic Goals



Proposed fill tube target allows ignition experiments in 2010



Initial beam smoothing choice

Platform Development

Choose Beam smoothing, ablator, T_R, planar shock timing

Pre-ignition non-cryo implosions

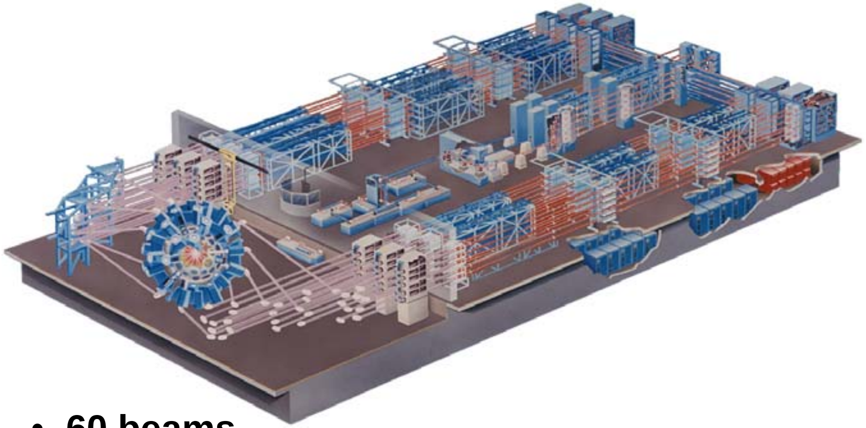
T_R

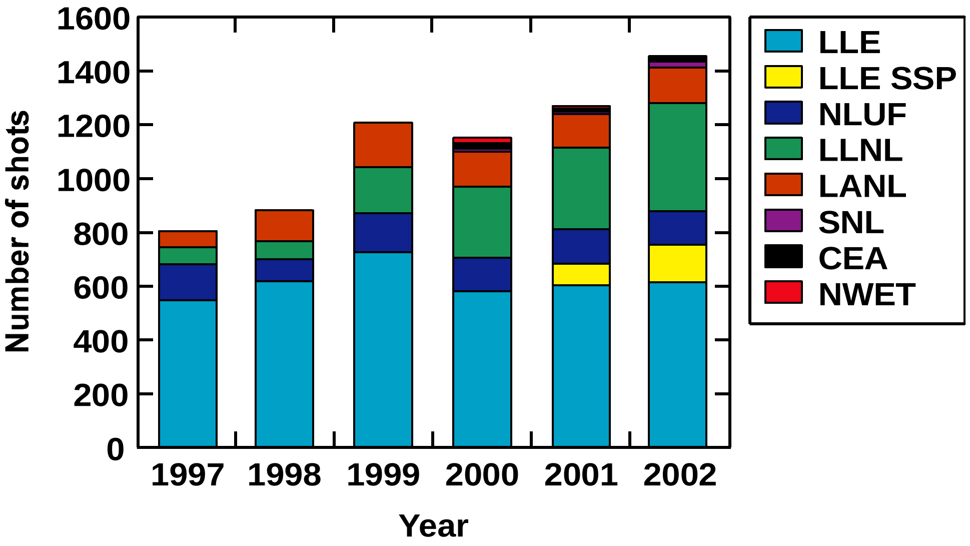
Symmetry tuning

Shock timing

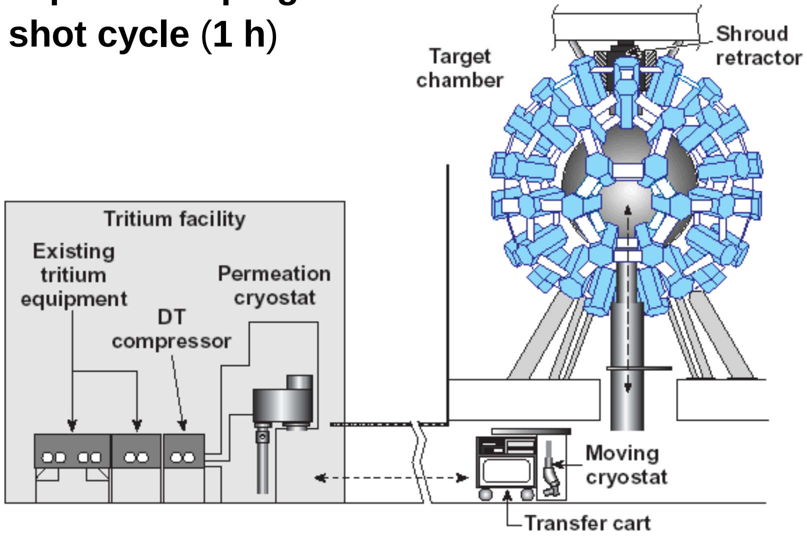
Ignition campaign

The OMEGA laser produces > 1400 target shots/year





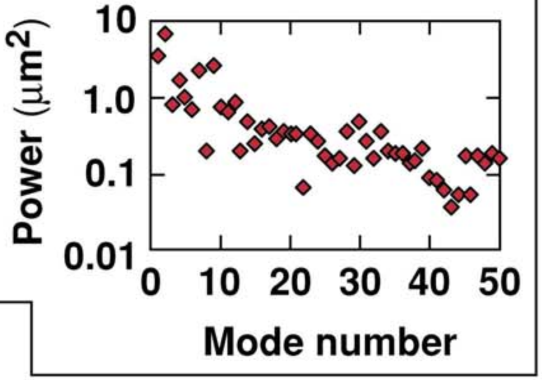
- 60 beams
- >30 kJ UV on target
- 1%-2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

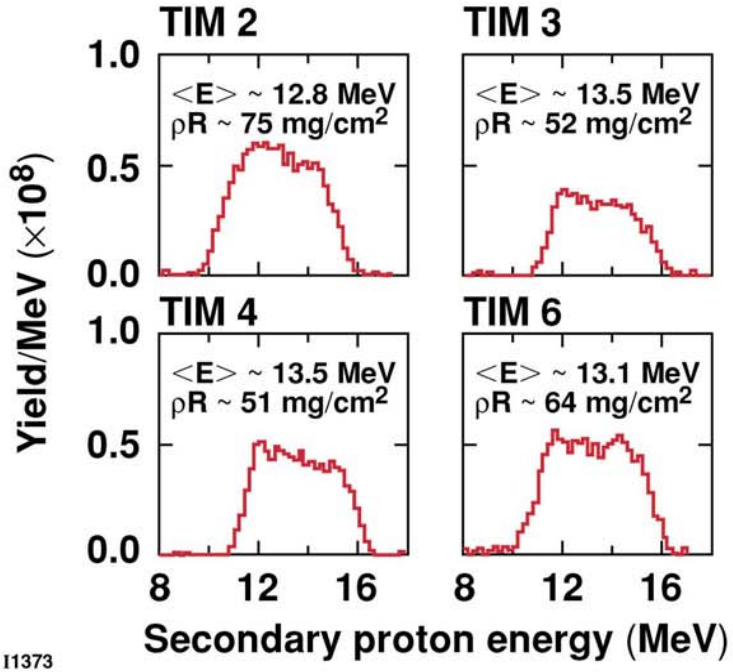


A well-centered, high-adiabat cryogenic target, even with an imperfect layer, can produce 1-D performance

Average ice + capsule rms smoothness is ~6 μm.

1-ns square
23.3 kJ
α = 25

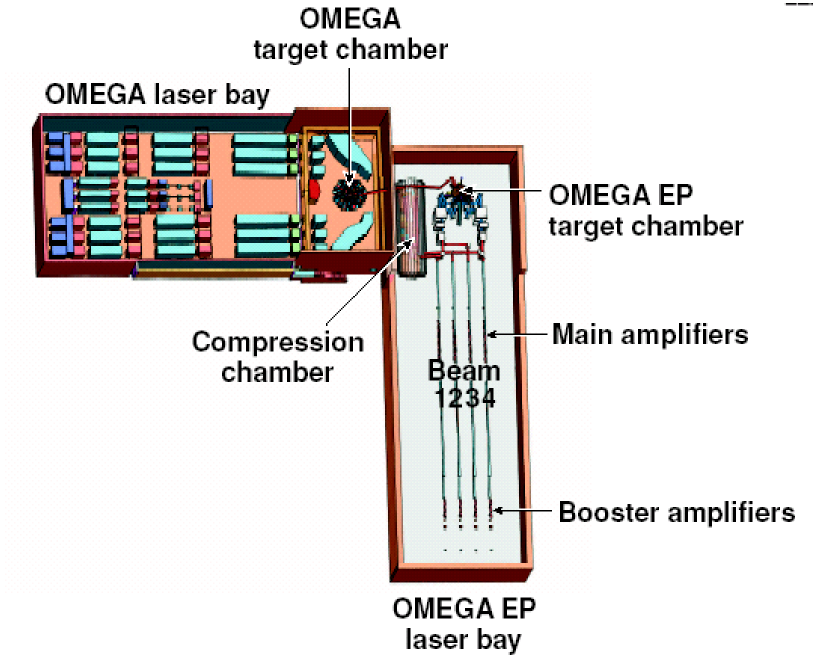




	Experimental	**1-D *LILAC***
Yield (1n):	**1.27×10^{11}**	**1.30×10^{11}**
Yield (2n):	**1.17×10^{9}**	**1.40×10^{9}**
Yield (2p):	**2.03×10^{8}**	**1.81×10^{8}**
<ρR>:	**61 mg/cm^2**	**45 mg/cm^2**
T_{ion}:	**3.6 keV**	**2.29 keV**

Capsule offset from TCC: ~14±7 μm

OMEGA Extended Performance (EP) Project

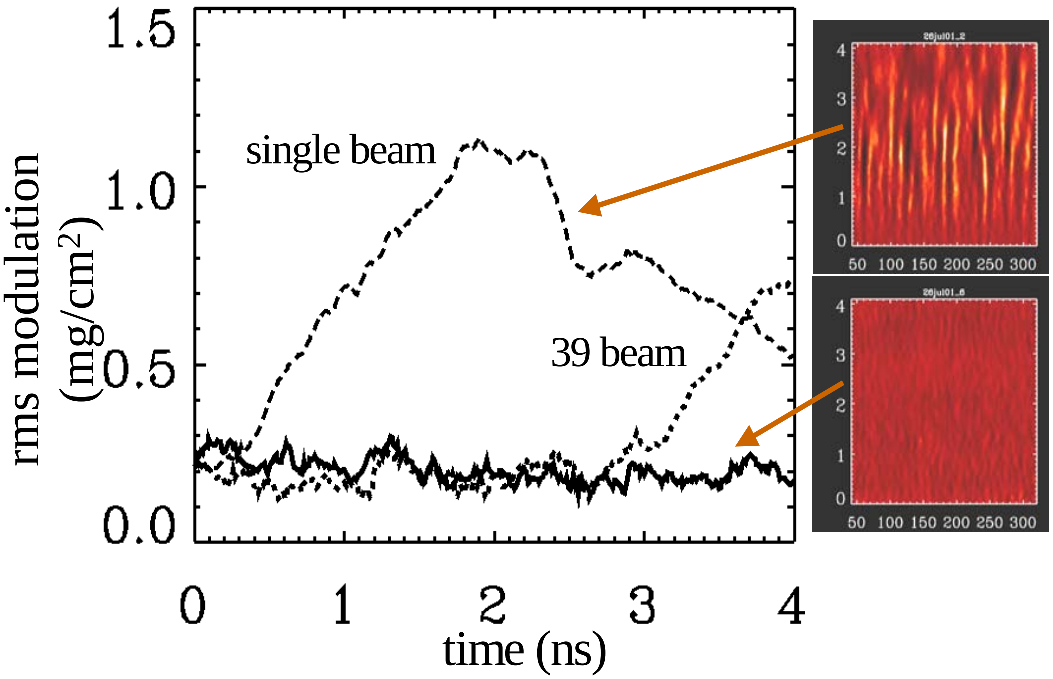


- Add two high-energy petawatt lasers for advanced backlighting and fast-ignition experiments
- $45-55M total estimated cost, 4-5 year schedule ($15M appropriated through FY03)
- University of Rochester to provide new $20M building, State of New York to fund $2M target chamber
- Construction started in May 2004

	Pulse duration	Pulse Energy	Power
Petawatt beams	**10^{-10}-10^{-12} sec**	**2500 joules**	**25 Terawatt-2.5 Petawatt**
Long pulse beams	**10^{-8}-10^{-9} sec**	**6000 joules**	**0.6 Terawatt-6 Terawatt**

Nike is examining issues central to defining the physics requirements for direct drive ICF

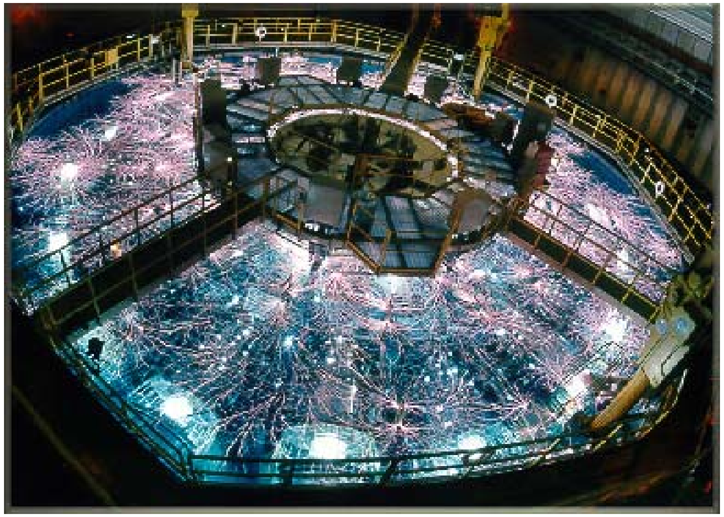
Example: thin high-Z layers substantially reduce the effects of laser non-uniformity

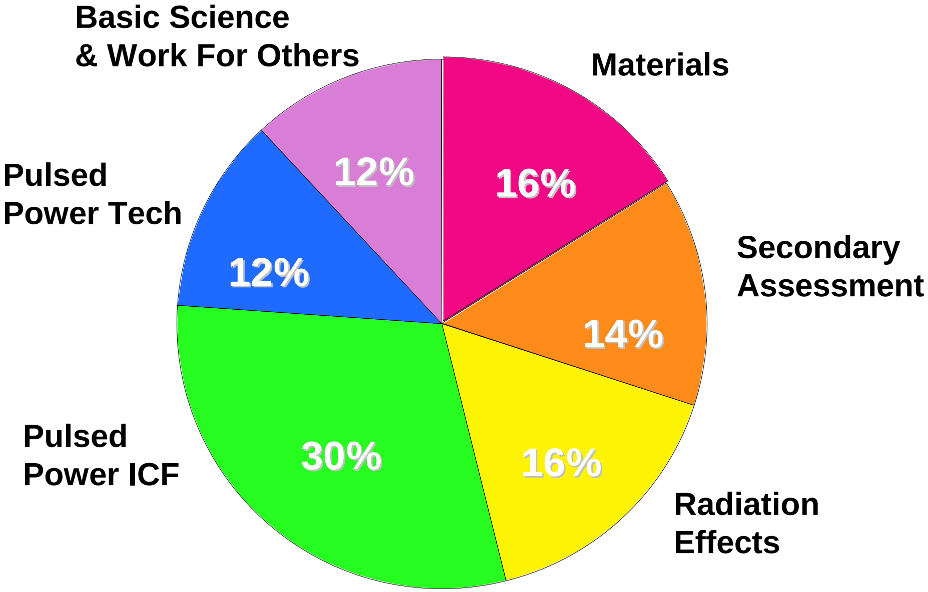


CH target
(single beam “foot”)

CH with 120 nm Pd
(single beam “foot’)

The Z machine at SNL provides critical capabilities for the SSP





Z is undergoing refurbishment (ZR Project)

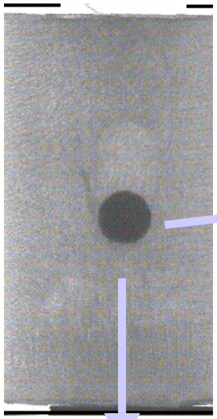
Distribution of Z Experiments (FY03)
Approximately 200 shot-days/year

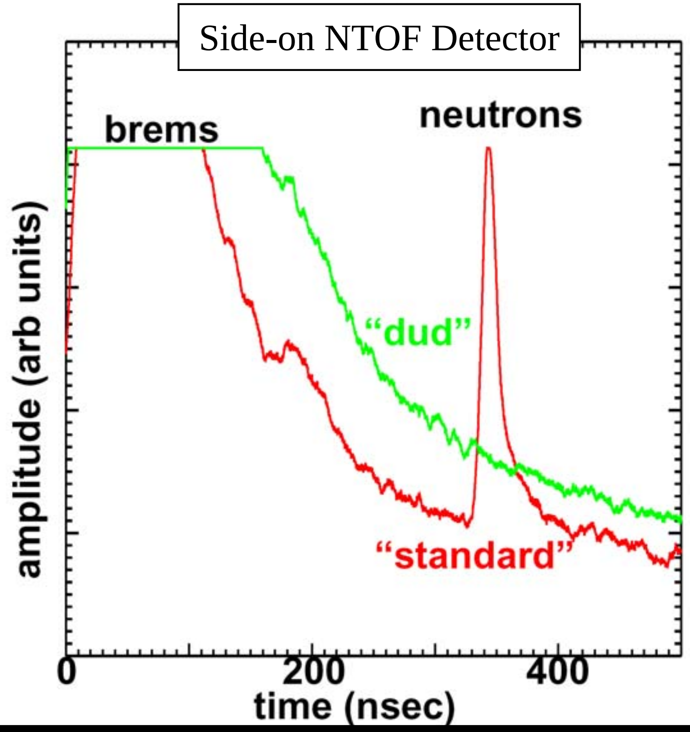
	Energy	Power
Z	1.6 MJ	230 TW
Z-R	2.7 MJ	350 TW

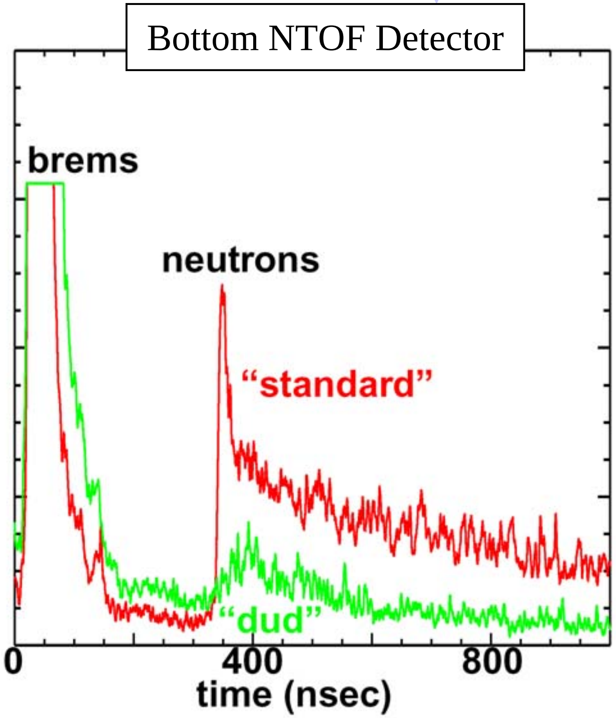
High levels of DD neutrons produced in a dynamic hohlraum experiments are thermonuclear

2.0 mm diameter
50 μm CH wall D_2-filled capsule
14 mg/cc CH_2 foam

Capsule absorbs
~ 24 kJ x-rays




Side-on NTOF Detector


Bottom NTOF Detector

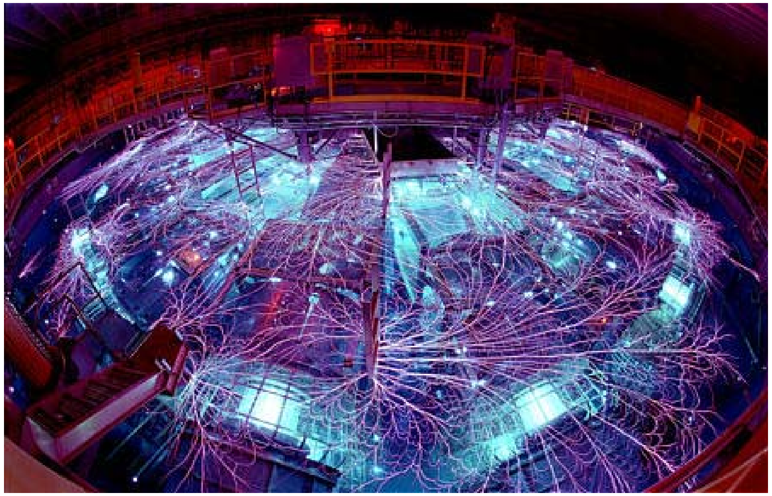
Neutron Time-of-flight both side and end-on shows 2.5 MeV D-D neutrons

- **Z1031: 24 atm D2 & 0.085 atm Ar**
  - **Activation yield ~ 3×10^{10}**
- **Z1032: 30 atm D2, 0.085 atm Ar & 0.6 atm Xe**
  - **Activation yield ~1×10^{9}**

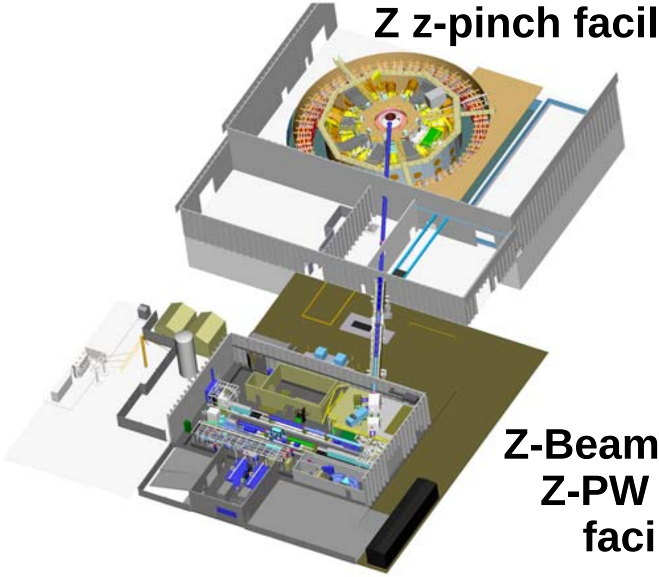
Z-Beamlet laser is being upgraded to provide a high energy PW laser for SNL's Z facility

- The Z-Beamlet laser is being upgraded to provide a 2-4 kJ, 1-10 psec short pulse laser for high energy radiography and fast ignitor experiments on Sandia's Z facility beginning in 2007.
- A stand alone 50-200 J, 0.5 - 10 psec prototype laser system will begin operation in 2004.

Z multimegajoule z-pinch facility



Z z-pinch facility



Z-Beamlet and Z-PW laser facility

Z-Beamlet multikilojoule laser facility

Total DOE Effort in IFE

- Office of Science
  - Heavy Ions
    - FY 04: $12.7 M (including $0.62 M IFE Technology)
    - FY 05: $11.9 M (President’s budget)
  - Fast Ignition
    - FY04: $1.8 M (including $1 M for Fusion Science Center at UR)
    - FY05: $1.8 M (President’s budget)

- Office of Defense Programs
  - High Average Power Lasers
    - FY 04: $24.5 M
    - FY 05: $25 M (House Mark)
  - Z- Pinch IFE
    - FY 04: $4.0 M
    - FY 05: TBD

RECENT PROGRESS IN THE HAPL PROGRAM

TARGET PHYSICS (NNSA ICF PROGRAM)

- Advances in laser, target fabrication, target design should allow highly symmetric implosions needed for high gain.
- Gains ~ 150 (above that needed for energy) are observed in high resolution simulations that account for realistic target and laser imperfections.
- Codes used in simulation are tested against experiments.

OTHER COMPONENTS & SYSTEMS

Target Fabrication:
- Mass produced foam shells that are close to target specs
- Study shows targets cost < $0.16 ea, meets requirements
- Grown ultra smooth cryogenic layers over foam underlay
- Smoothness maintained over wide range of temperatures

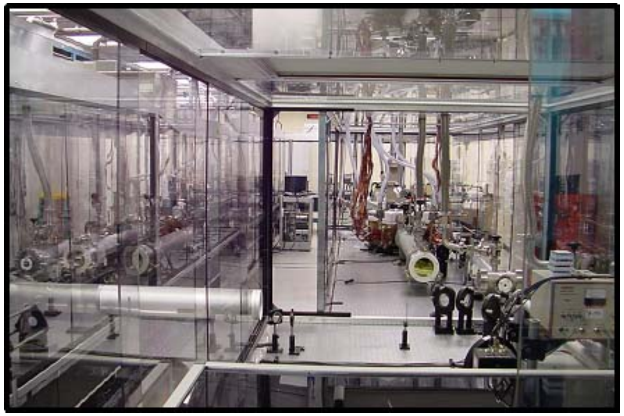
Target Injection
- New light gas gun target injector--achieves required velocity and repetition rate.
- Demonstrated separable sabot

Final Optic
- Demonstrated grazing incidence metal mirror meets reflectivity, exceeds laser damage threshold requirements

Reaction Chamber
- Established chamber operating window based on tungsten armored ferritic steel chamber first wall.
- Developing advanced materials for long term wall survival
- Three new materials testing facilities brought on line
- Experiments suggest He retention not as serious with IFE

MERCURY Diode Pumped Solid State Laser (LLNL)

- All new laser architecture: diodes, crystals, gas cooled amplifier head
- Produces 34 J single shot, 114 W at 5 Hz for > 10^4 shots

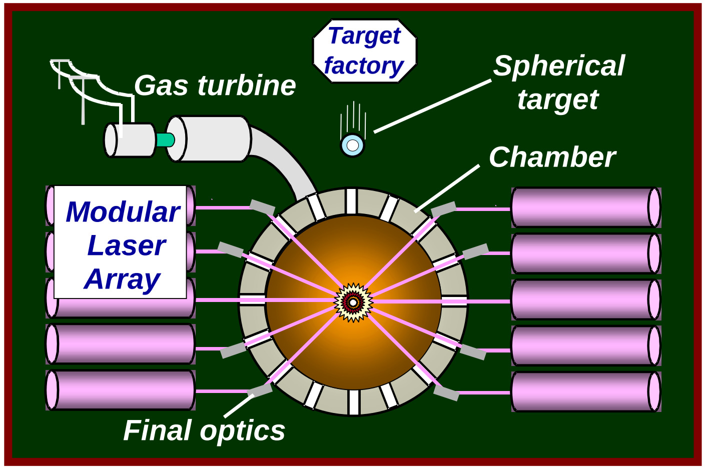


ELECTRA Krypton Fluoride Laser (NRL)

- Produces 400-700 J of laser light in 1 Hz & 5 Hz bursts
- Advances in KrF physics, e-beam transmission window and pulsed power predict overall efficiency > 7%. Meets IFE req

The HAPL PROGRAM
A multi-institution, integrated program to develop the science and technology for fusion energy with lasers and direct drive targets

The Concept



An array of high-energy laser beams illuminate a cryogenic target that has been injected into a chamber.

The deuterium-tritium fuel in the target undergoes thermonuclear burn, and the energy is used to generate electricity.

The Development of Laser Fusion Energy

Capitalizes on the substantial investment in lasers and laser-target physics by DOE/NNSA in support of defense applications.

Modular nature of the components and capability to separately develop the key components reduces risk and costs when compared to other fusion approaches.
(e.g: laser consists of many identical beam modules, the laser and target factory are separated from the reaction chamber)

HAPL PARTICIPANTS:

DoD/DoE Labs: Naval Research Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratory, Los Alamos National Laboratory, Oak Ridge National Lab, Princeton Plasma Physics Laboratory.
Industry: General Atomics, Titan-Pulse Sciences Division, Schafer Corp, Science Applications International Corp, Northrop, Onyx, DEI, Coherent, Inc. Commonwealth Technology, Inc.
University: UC San Diego, Univ. of Wisconsin, UCLA, UC Santa Barbara, UC Berkeley, Georgia Inst of Technology, Rochester Lab for Laser Energetics

Z-Pinch Inertial Fusion Energy

Goal: Develop an economically-attractive power plant using high-yield z-pinch driven targets (~3 GJ) at low rep-rate (~ 0.1 Hz) with recyclable transmission lines (RTLs)

Research Areas:

- RTL development
- Rep-rated pulsed power driver development (Linear Transformer Driver- LTD)
- Shock mitigation (from fusion capsule explosion)
- Proof-of-Principle experiment planning
- Targets for Z-Pinch IFE
- Power plant technologies for Z-Pinch IFE (thick liquid walls, etc.)

Z-Pinch IFE Workshop:

- Held at SNL on August 10-11, 2004 (64 participants)
- Initial results in all areas
- (see papers: P-I-13, P-I-16, P-1-25, P-1-32, O-II-2.1, O-II-2.3, O-II-6.1 O-III-3.2, O-III-3.5, O-III-3.6)

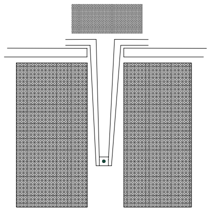
Funding: $4M in FY04 (began late in FY04)

Collaborators:

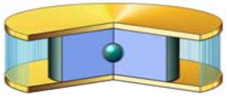
- LLNL, LANL, NRL, LBNL
- UCB, U. Wisconsin, UCD, UCLA, Georgia-Tech, U. Alabama, U. Missouri
- GA, MRC, FPA, Omicron
- Russia: Kurchatov, Tomsk (IHCE)

Synergy with ICF Program:

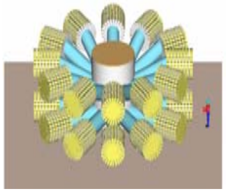
- RTLs, thick liquid walls, and LTD technology will enable higher shot rates and lower cost for the chamber and driver for a z-pinch high-yield facility



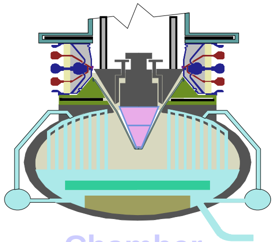
RTL



DH target



LTD driver



Chamber

The *long-term* goal of Z-Pinch IFE is to produce an economically attractive power plant using high-yield z-pinch-driven targets (~3 GJ) at low rep-rate per chamber (~0.1 Hz)

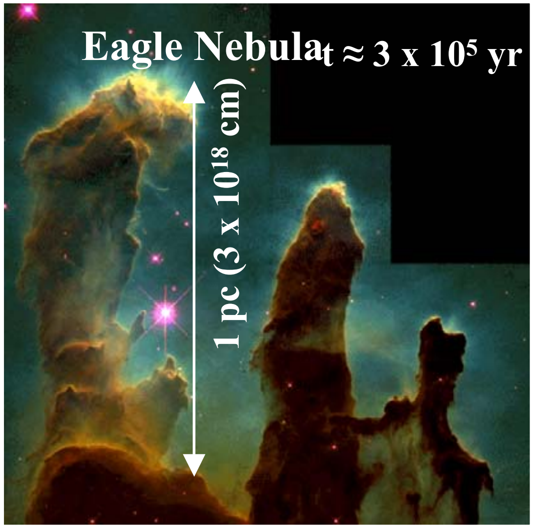
Z-Pinch IFE DEMO (ZP-3, the first study) used 12 chambers, each with 3 GJ at 0.1 Hz, to produce 1000 MWe

The *near-term* goal of Z-Pinch IFE is to address the science issues of repetitive pulsed power drivers, recyclable transmission lines, high-yield targets, and thick-liquid wall chamber power plants

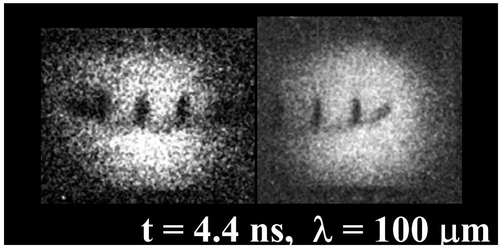
HEDP facilities allow astrophysics to be done “in the laboratory”

NNSA policy: A fraction of time on major facilities is allocated to basic HEDP science/university use

Can we generate an Eagle in the lab?

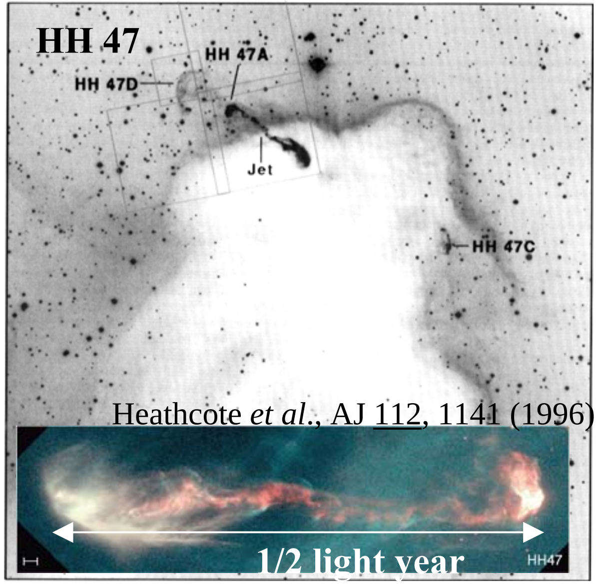


J.J. Hester *et al.*, A.J. 111, 2349 (1996)

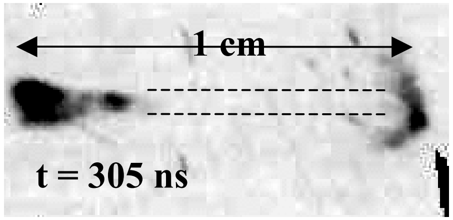


Remington *et al.*, Phys. Plasmas 4, 1997 (1994)

Can we generate a radiative MHD jet in the lab?



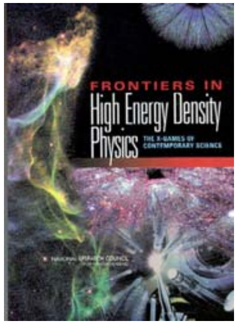
Heathcote *et al.*, AJ 112, 1141 (1996)



S. Lebedev *et al.*, Ap. J. 564, 113 (2002)

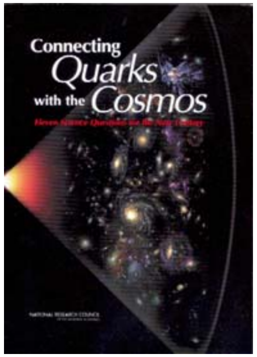
Natl. Academy reports state ICF/High Energy Density Physics is an exciting and rapidly evolving field

- **"Frontiers in High Energy Density Physics" (R. Davidson et al.)**



"..research opportunities in this crosscutting area of physics are of the highest intellectual caliber and are fully deserving of the consideration of support by the leading funding agencies of the physical sciences."

- **"Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" (M. Turner et al.)**



"Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high energy density physics. The Committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field."

Summary- major points

- ICF Program continues to make strong technical progress
  - NIF Project has made outstanding progress
  - Outstanding recent results at OMEGA, Z
- First experiments have been conducted at NIF
  - Detailed use planning is underway
  - Ignition 2010 is a major goal
- Pulsed power ICF shows promising results
- Petawatt lasers will significantly enhance capabilities
- ICF facilities (NIF, OMEGA,Z) are available to university and external users
- National Academy of Sciences recognizes High-Energy-Density Physics as an important scientific field

Backups

High-Energy-Density Physics is the study of matter at extreme conditions similar to those in a weapon

- For the stewardship program ignition provides:
  - A means to evaluate weapon assessment issues involving “burn”
  - An integrated experiment to validate ASCI codes
  - A “grand challenge” to attract top talent

- “Non-ignition” high-energy-density experiments are required to provide understanding and validate computational models in key areas
  - Hydrodynamics- compression phenomena, instabilities
  - Material properties under extreme conditions
  - Radiation transport
  - X-ray sources for nuclear weapons effects

- Recent National Academy of Sciences reports have also recognized the importance of high-energy-density physics to US science overall

A detailed NIF use plan is under development

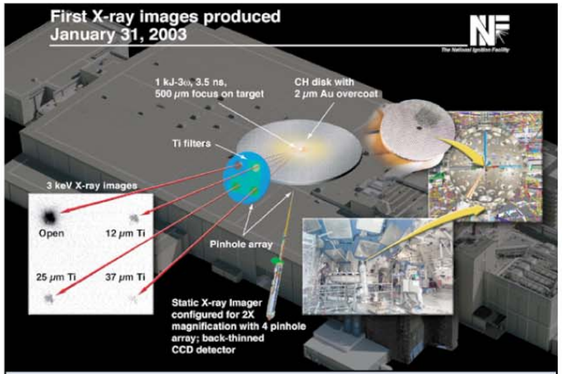
- **Technical/budget areas involved in planning**
  - **NIF Project construction/NIF activation**
  - **Weapon physics and effects**
  - **Ignition**
  - **Basic science**
  - **NIF diagnostics, cryogenics, and experimental support**
  - **Direct drive potential in this timeframe will be assessed**

- **Approximate NIF annual shot allocation:**
  - **Ignition: 40%**
  - **Weapon physics: 40%**
  - **Basic Science/IFE: 15%**
  - **Contingency: 5%**

- **Plan accelerates ignition experiments to 2010**

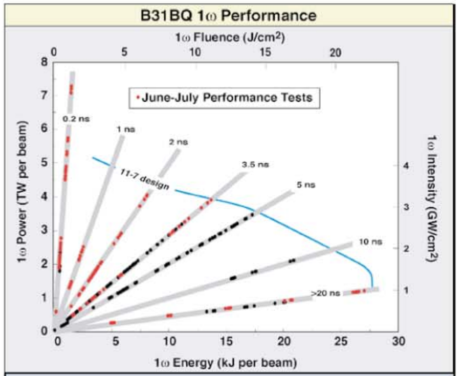
The first NIF lasers are functional

First four laser beams of NIF installed for commissioning beginning in November 2002



First X-ray images produced January 31, 2003

First light to target chamber center and first x-rays measured in January 2003



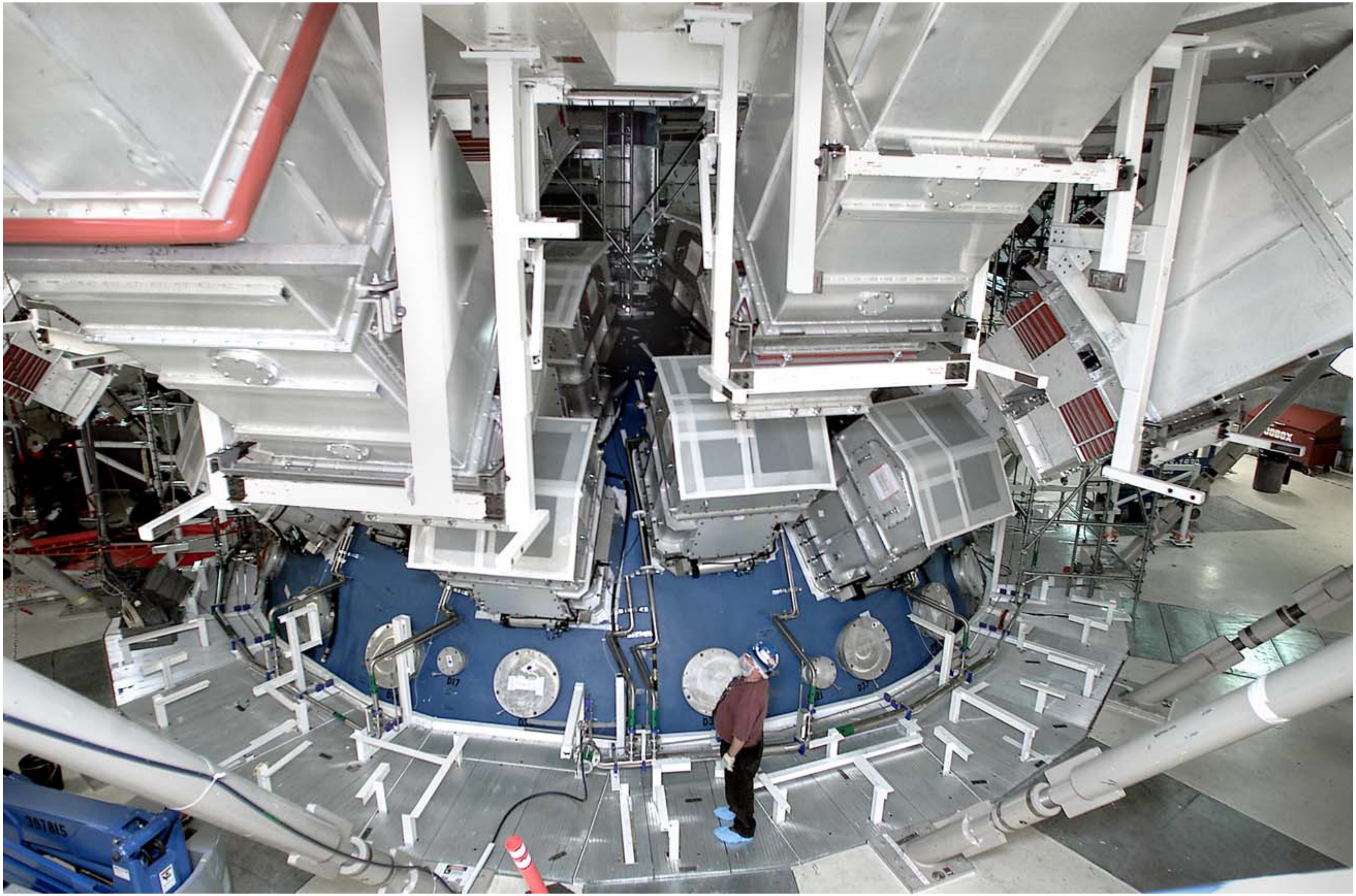
B31BQ 1ω Performance

1ω laser exceeds power & energy reqmt's for entire operational parameter space

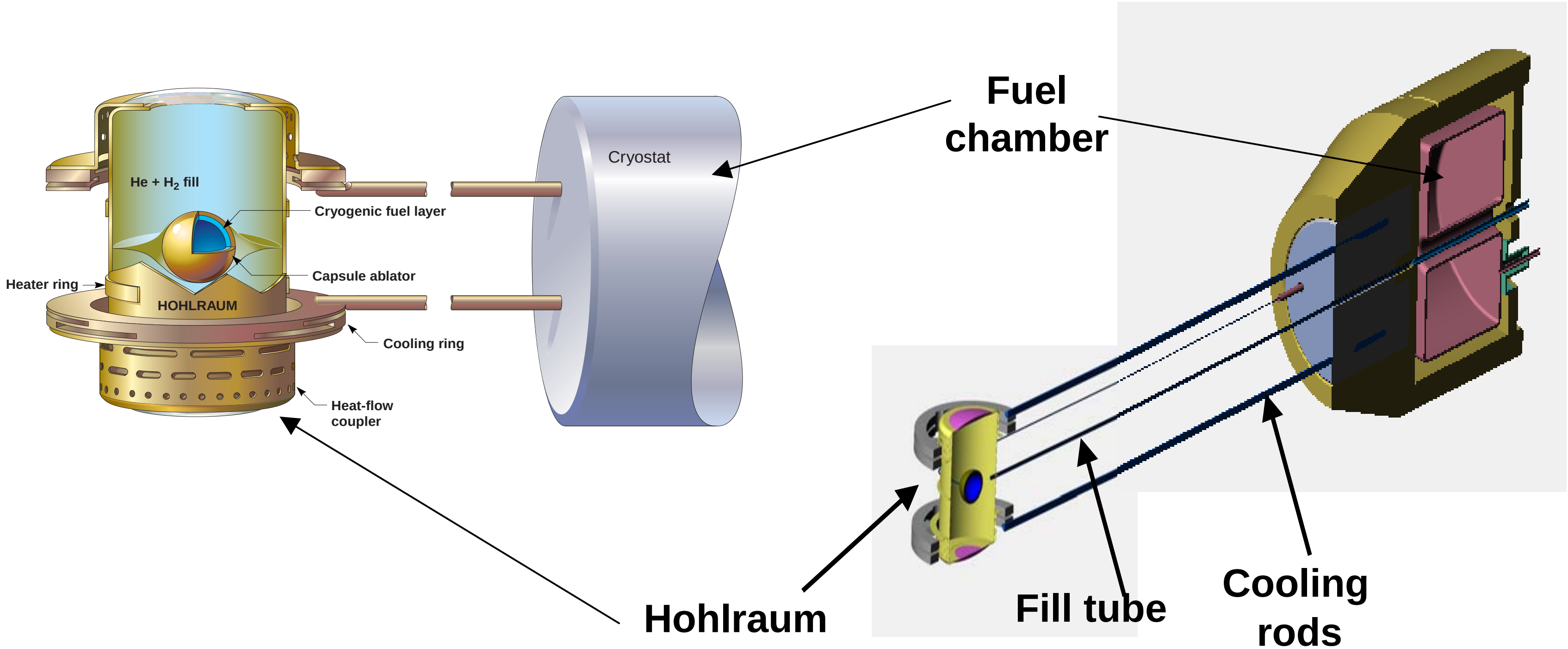
- **Single beam performance:**
  - — 26 kJ of 1ω light (Full NIF Equivalent = 5.0 MJoule)
  - — 11 kJ of 2ω light (Full NIF Equivalent = 2.2 MJoule)
  - — 10.4 kJ of 3ω light (Full NIF Equivalent = 2.0 MJoule)
    - – 106 kJ 4 beam 1ω energy delivered in a 23 ns shaped pulse
- **Better than 6% beam contrast (1ω); 1% beam energy balance; beam relative timing to 6 ps**
- **Static x-ray imager, streaked x-ray detector, x-ray framing camera and full aperture backscatter system are operational at the target chamber**

NIF has completed its first experiments on hohlraum energetics and hydrodynamics

NIF -- Target Chamber Exterior



Filling of ignition targets with deuterium-tritium gas may be done in two ways



Fuel chamber

Hohlraum

Fill tube

Cooling rods

High pressure permeation fill (complex cryogenic system- “NIF Cryogenic Target System- NCTS”)

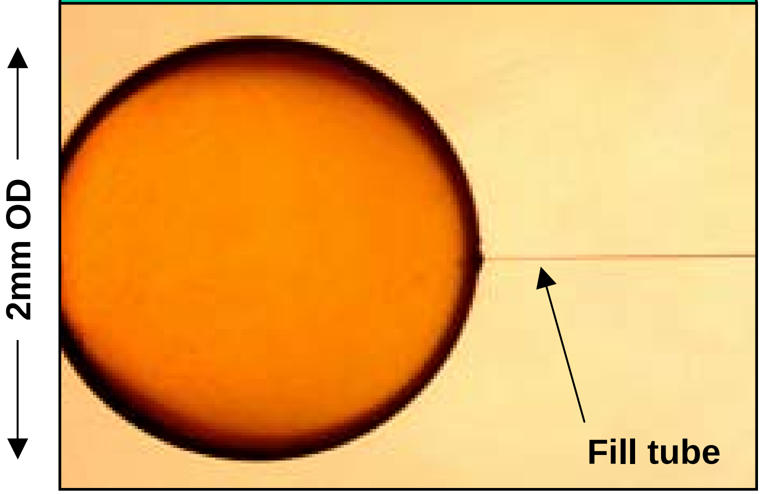
Fill tube- simpler cryogenic system

Attachment of 6-um fill tubes has been demonstrated

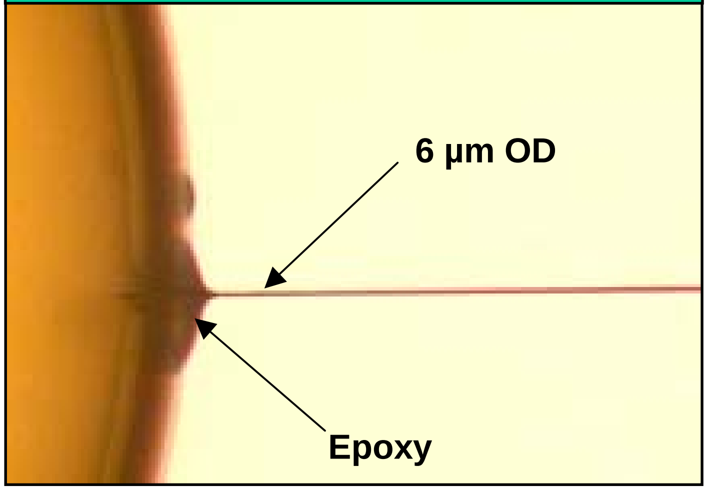
National Nuclear Security Administration

- Most work up to now has used 30 µm fill-tubes
- We are developing a ~10 µm fill-tube capacity.
  This could provide an alternative to permeation filling

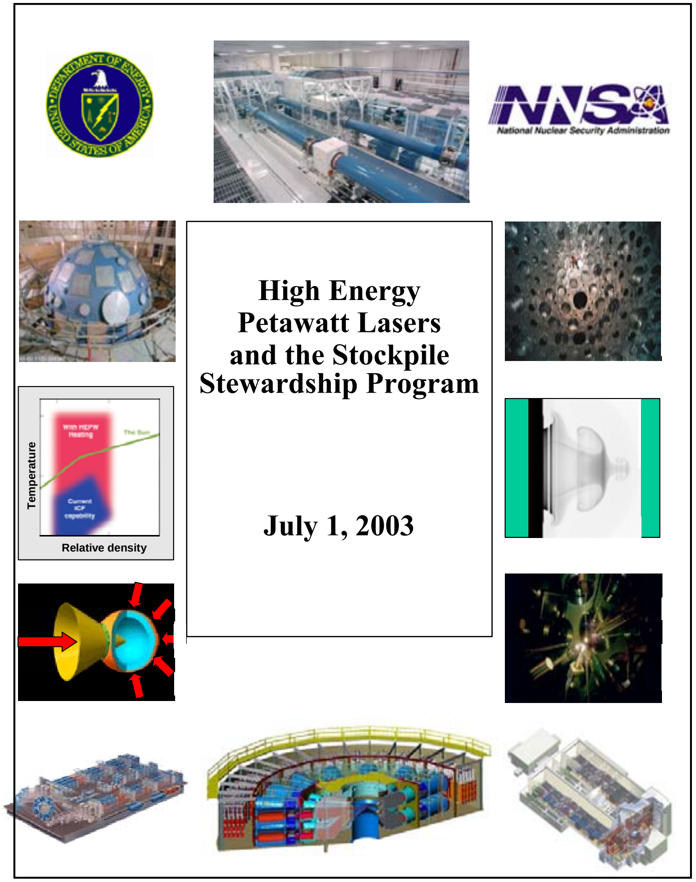
6 µm OD fill tube in 2 mm OD shell



Close-up of Shell/fiber glue joint



Petawatt lasers are important to the future of the ICF Campaign



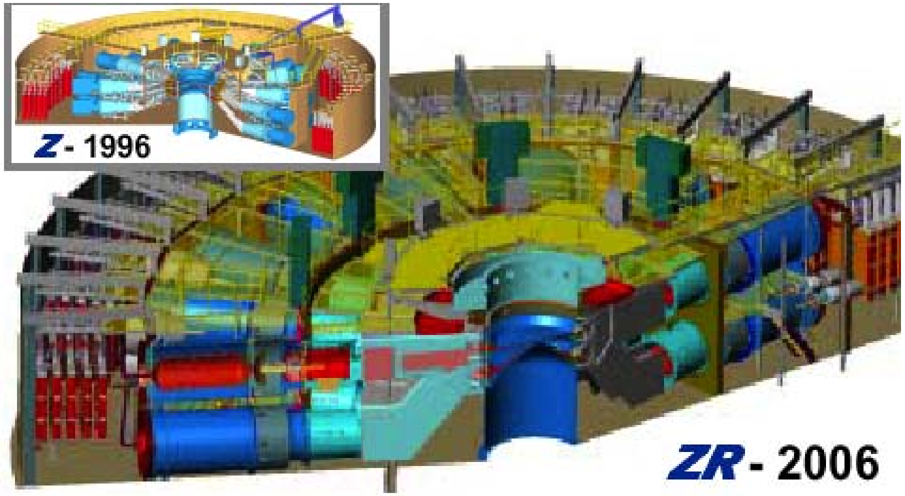
High Energy Petawatt Lasers and the Stockpile Stewardship Program

July 1, 2003

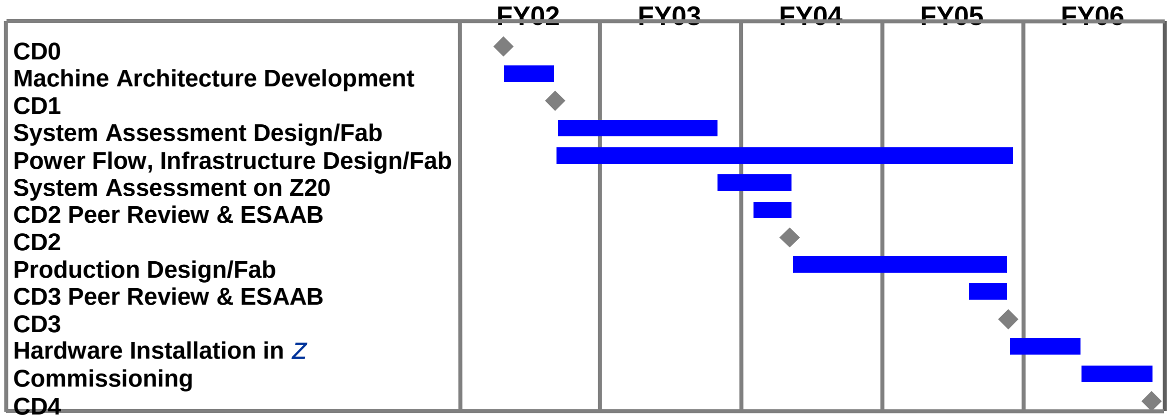
NNSA Plans

- *Why petawatts? Answer: <u>backlighting</u>, materials properties, fast ignition*
- **Develop HEPW grating technology**
- **Construct 2 HEPW lasers at OMEGA, with first beam available by 2006 and second no later than 2009**
- **Implement HEPW capabilities at Z & NIF (funding and schedule TBD)**
  - **Congressional plus-ups are funding HEPW at Z**
- **Support university involvement and adopt a user-facility approach to HEPW laser operations at ICF facilities**

The Z Refurbishment Project will enable z-pinch implosions to produce over 2.5 MJ and 300 TW of x rays



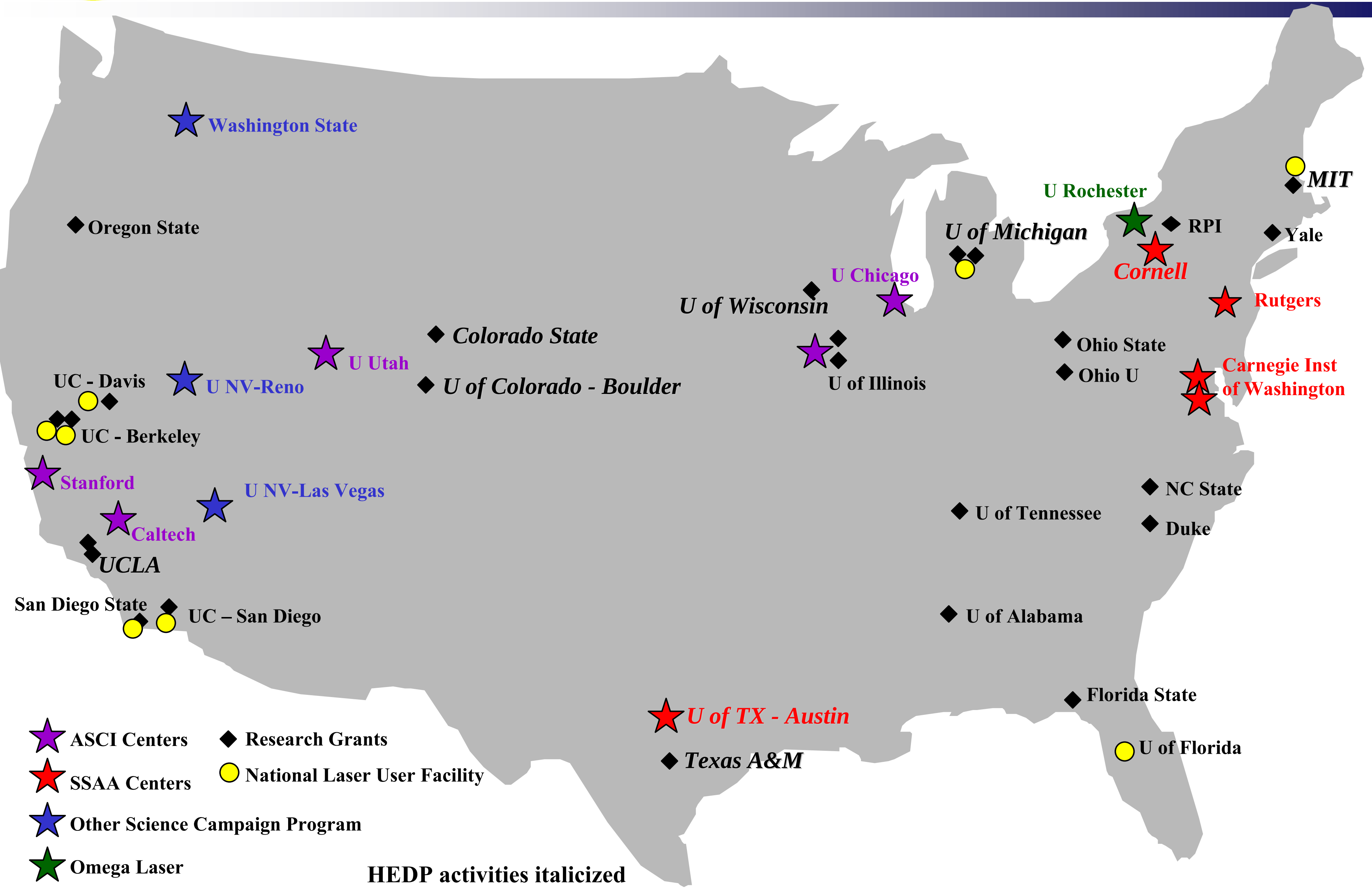
- ZR facility refurbishment in progress
- $57M total estimated cost, 4-5 year schedule
- Funded through Readiness in Technical Base and Facilities (RTBF)
- CD-0 approved 2/02
- CD-1 approved 8/02



ICF facilities are available to university and external users

- National Laser User Facility (NLUF/LLE)
  - ~100-150 shots year, $1M/yr
- 15% of NIF devoted to basic science, IFE, other external users
- Z also available but shots limited
- Ultra short pulse lasers at ICF facilities may also be available to external users in the future
- Advent of NIF requires a new paradigm for university participation – we are beginning to plan for university use on NIF

NNSA sponsors university research in variety of technical areas



HEDP activities italicized