# Lasers and Inertial Confinement Fusion in the United States

From

Mike TN event (1952)

To

The National Ignition Facility (2009)

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Laboratory for Laser Energetics

NIF Technical Symposium
Livermore, CA
28 May 2009

Summary

# The understanding of inertial confinement fusion (ICF) has grown as successively larger lasers have been built

- The ICF era began with a successful thermonuclear test in 1952.
- The demonstration of the laser in 1960 began the quest to develop ICF and, eventually, create thermonuclear fusion ignition in the laboratory.
- ICF lasers have continued to become larger and more technically sophisticated.
- The NIF represents the next great leap in laser development
    - Congratulations to Ed Moses and the entire team!
- The improved understanding of ICF physics provides confidence for achieving ignition on the NIF
    - Nova technical contract
    - OMEGA cryogenic target implosions
- New laser and target physics concepts continue to advance the ICF program in the United States

**The LLNL/LLE collaboration in the development of ICF lasers and target physics has brought the U.S. to the next step—poised for ignition on the NIF.**

# The successful test of the 10-MT Mike thermonuclear device began the Inertial Confinement Fusion Era

- Stanislaw Ulam and Edward Teller developed the principle of a radiation implosion in January 1951.
- On 31 October 1952, Mike exploded with a yield of 10.4 megatons on the Enewetak Atoll.
- The island of Elugelap disappeared.
- This successful test ushered in the era of multimegaton nuclear weapons.
- It was the first step in developing ICF.

From http://www.lanl.gov/history/postwar/

# The demonstration of the laser spurred the development of ICF in the laboratory

- T. H. Maiman demonstrated a Ruby laser in 1960
- Almost immediately, people began thinking about laser-driven ICF
  - **1961:** Nuckolls suggested a laser-driven "thermonuclear engine"*
  - **1961:** Kidder "back of the envelope" calculations suggested sub-10-ns, >100-kJ laser required
  - **1962:** LLNL began exploratory ICF laser-development program
  - **throughout the 1960s:** classified discussions of ICF physics continued

**Until**

- **1972:** Declassification of compression and Nuckoll's *Nature* article predicted <1 kJ of laser light would be required
  - Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications, J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, *Nature* 239, 139 (1972)
- **1973:** Thermonuclear breakeven was predicted to occur by 31 December 1973 to KMS shareholders

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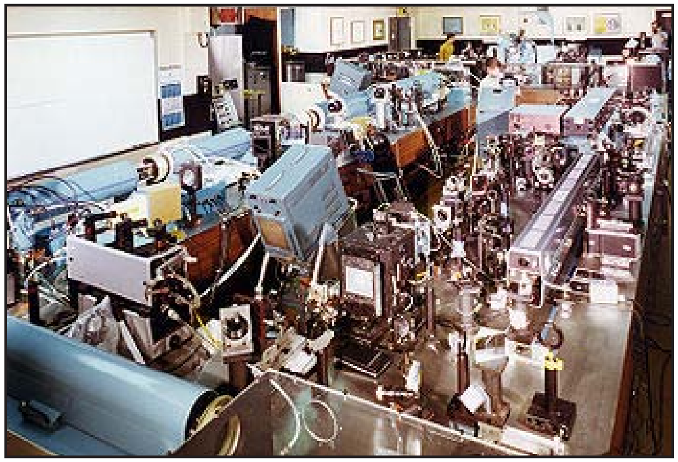
*J. H. Nuckolls, "Contributions to the Genesis and Progress of ICF," in *Inertial Confinement Fusion: A Historical Approach by Its Pioneers*, edited by G. Velarde and N. Carpintero–Santamaría (Foxwell & Davies Ltd., London, UK, 2007), Chap. 1, pp. 1–48.

# In the 1970s, a number of 1-$\mu$m-wavelength beam lasers were built to study target interactions and compression

DELTA – 4 beams, 500 J (LLE)
Nd:glass, 1 $\mu$m (1971)

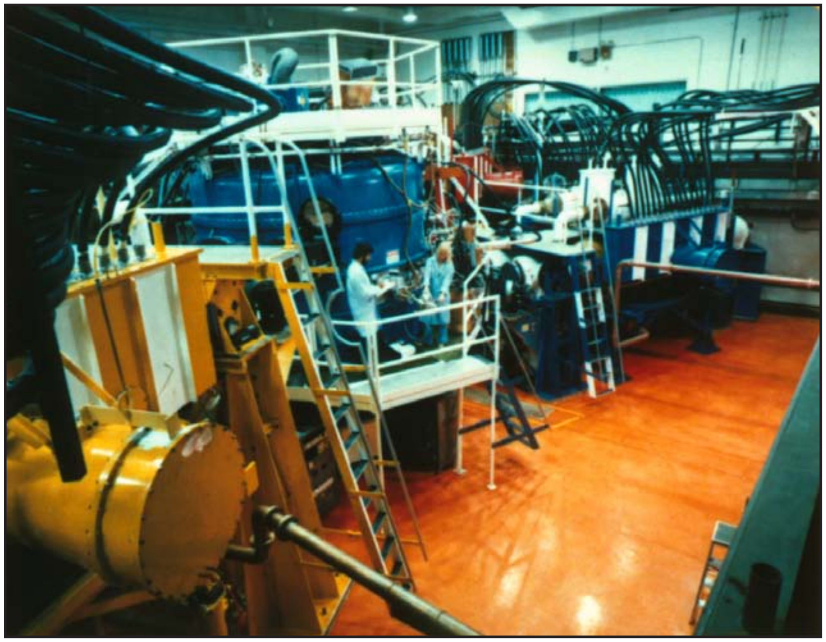
Pharos – 1 beam, 100 J, first disk amplifiers (NRL)
Nd:glass, 1 $\mu$m (1971)



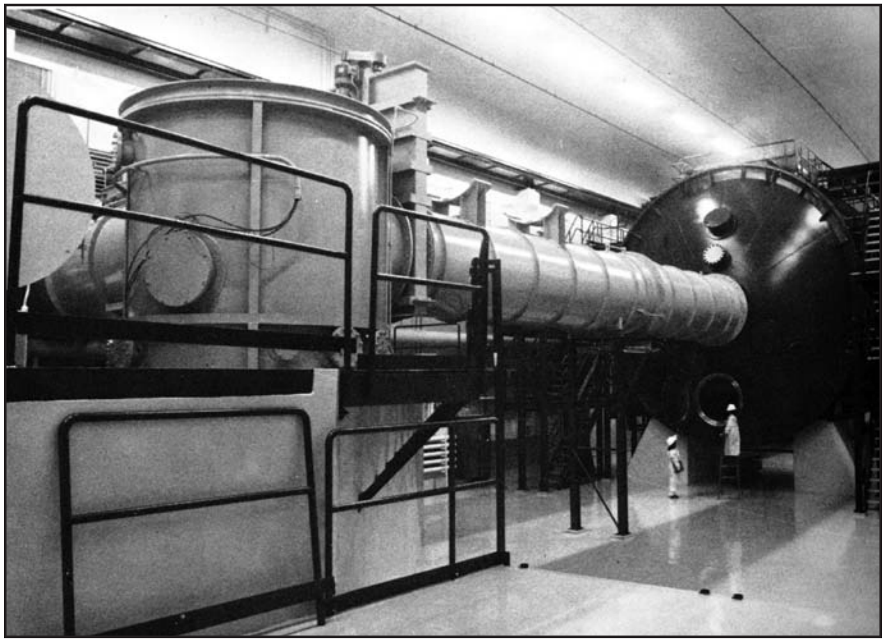
Janus – 2 beams, 40 J (LLNL)
Nd:glass, 1 $\mu$m (1975)

Argus – 2 beam, 2 kJ (LLNL)
Nd:glass, 1 $\mu$m (1976)

# From the mid 1970s to the early 1980s, 10.6-$\mu$m-wavelength $CO_2$ laser ICF experiments were conducted by LANL

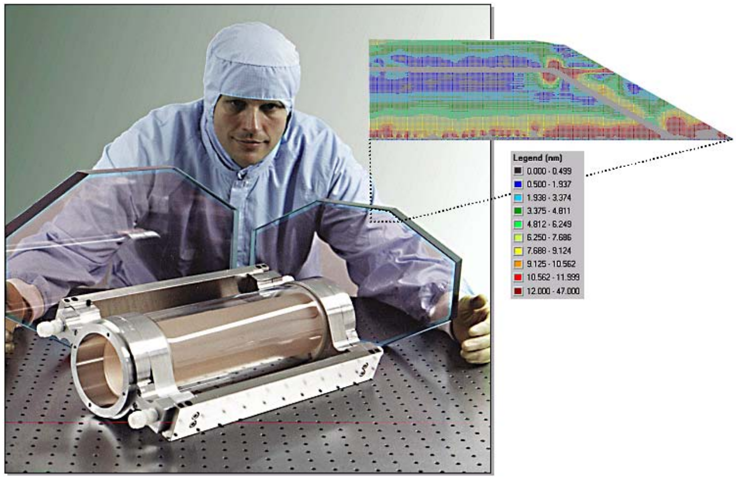


Helios – 10-kJ $CO_2$ laser (1978)



Antares – 40-kJ $CO_2$ laser (1983)

# Nd:phosphate glass overcame gain and self-focusing limitations of Nd:silicate glass for 1-$\mu$m lasers (mid 1970s)



- Early 1-$\mu$m laser systems used Nd:silicate laser glass
- LLE developed the high-gain phosphate laser glass LHG-8 with Hoya Corporation in 1978
- Phosphate laser rods
  - – high gain
  - – low nonlinear effects
  - – athermal

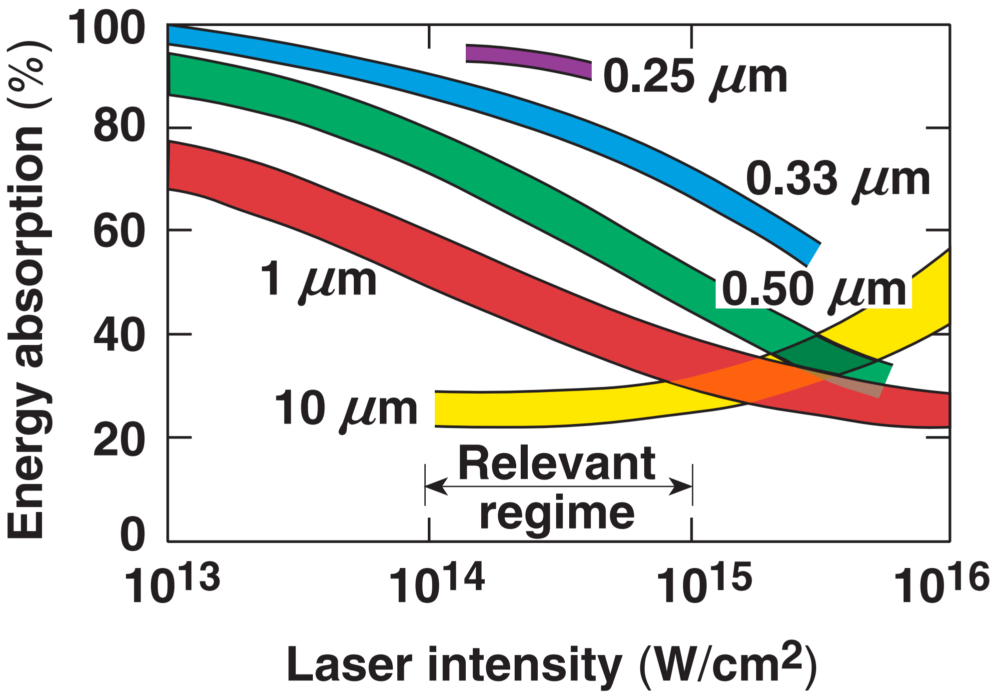
**LHG-8 is used throughout the world in all high-peak-power glass lasers including OMEGA and the NIF.**

# By 1980, multibeam, multiterawatt (TW), 1-$\mu$m laser facilities were conducting ICF implosion experiments

Shiva – 20 beams, 10 kJ, 20 TW
(LLNL 1977)

OMEGA – 24 beams, 4 kJ, 15 TW
(LLE 1980)

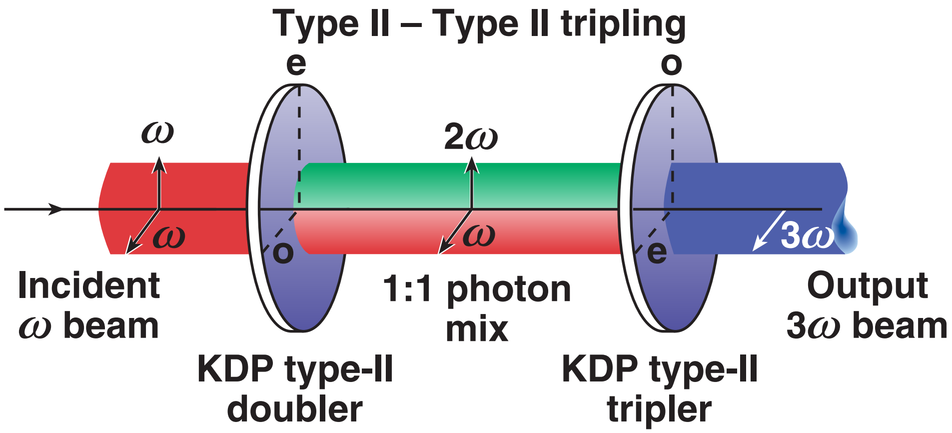
# By 1980, laser–plasma interaction experiments suggested that short-wavelength lasers (~1/3 $\mu$m) were required for ICF



- Short-wavelength lasers provide
  - higher laser absorption
  - reduced laser–plasma instabilities

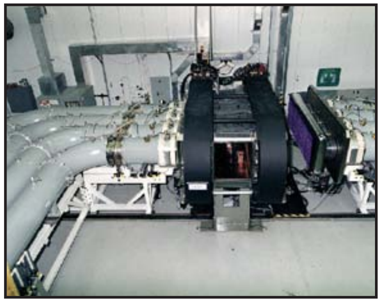
# Two primary paths were developed for short-wavelength ICF lasers

- **Efficient frequency tripling of 1-$\mu$m-wavelength light was developed at LLE in 1980***



**Conversion efficiency can be as high as 80%.**

- **Krypton Fluoride Lasers ($\lambda \sim 0.25\ \mu$m) were studied at LANL (Aurora) and NRL (Nike)**



Nike final amplifiers

Nike final mirrors

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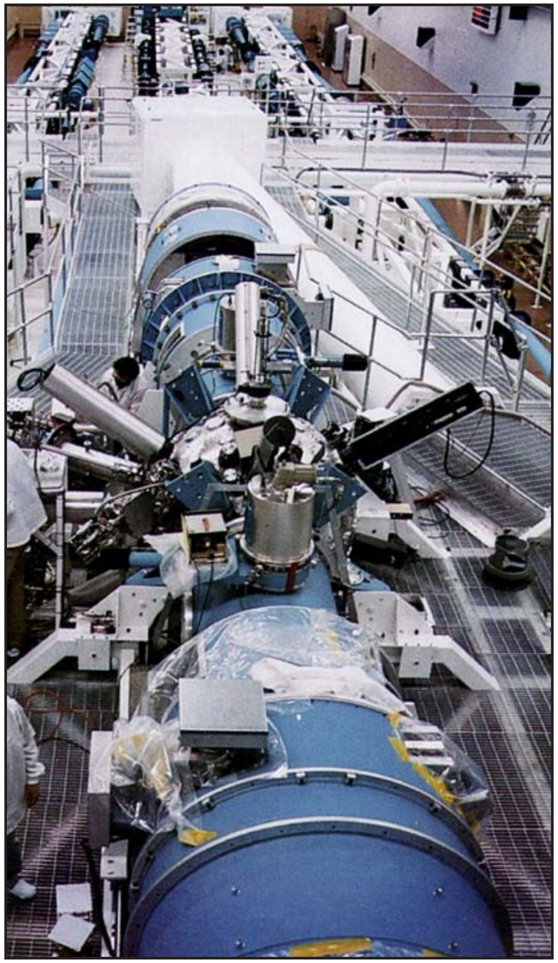
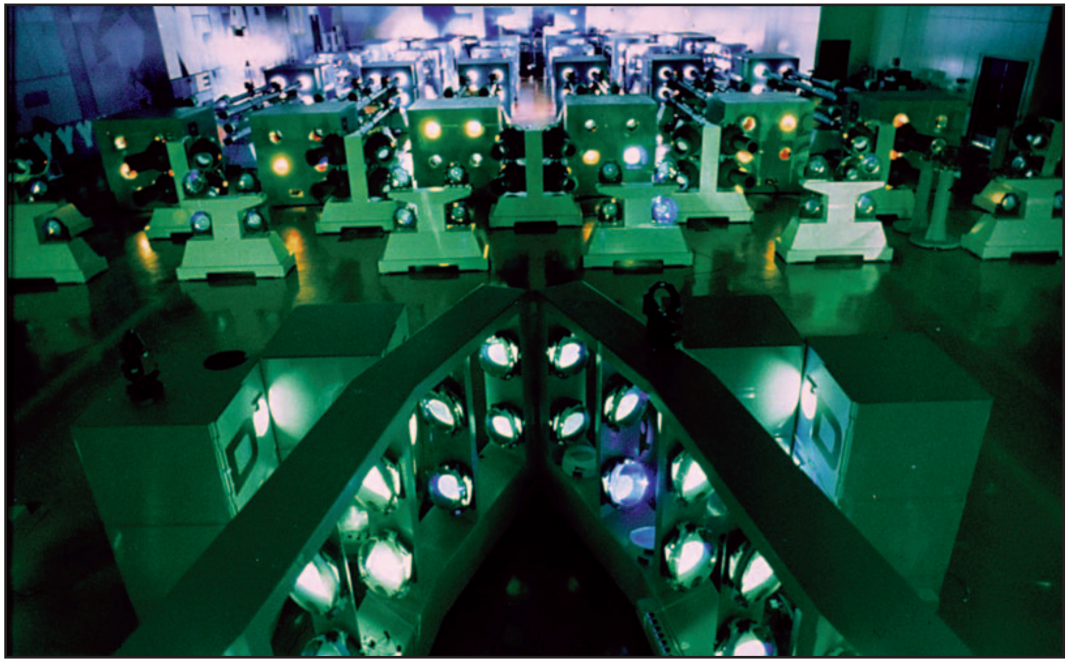
*R. S. Craxton, Opt. Commun. 34, 474 (1980).

# In the early 1980s, the principal Nd:glass fusion lasers were converted to 0.35-$\mu$m-wavelength operation



Novette – 2 beams, 6 kJ,
Nova prototype (LLNL 1977)



OMEGA – 24 beams, 2 to 4 $\text{kJ}_{\text{UV}}$,
converted to 0.35 $\mu$m (LLE 1985)

# A cryogenic fuel assembly was compressed to 20 to 40 g/cm$^3$ on the 24-beam, 0.35-$\mu$m wavelength, 2- to 4-kJ$_{UV}$ OMEGA laser in 1988

OMEGA UV, cryogenic fuel experiments demonstrated 200× liquid DT density. The OMEGA upgrade (30 kJ) was recommended by NAS review.

nature

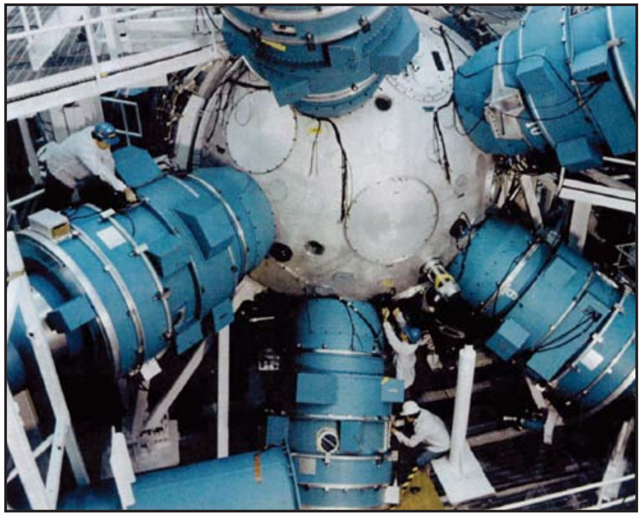
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 335 No. 6187 15 September 1988 $4.95

R. L. McCrory *et al*., Nature 335, 225 (1988).

# In the 1980s and 1990s, the Nova Laser System provided the physics understanding to justify construction of the NIF

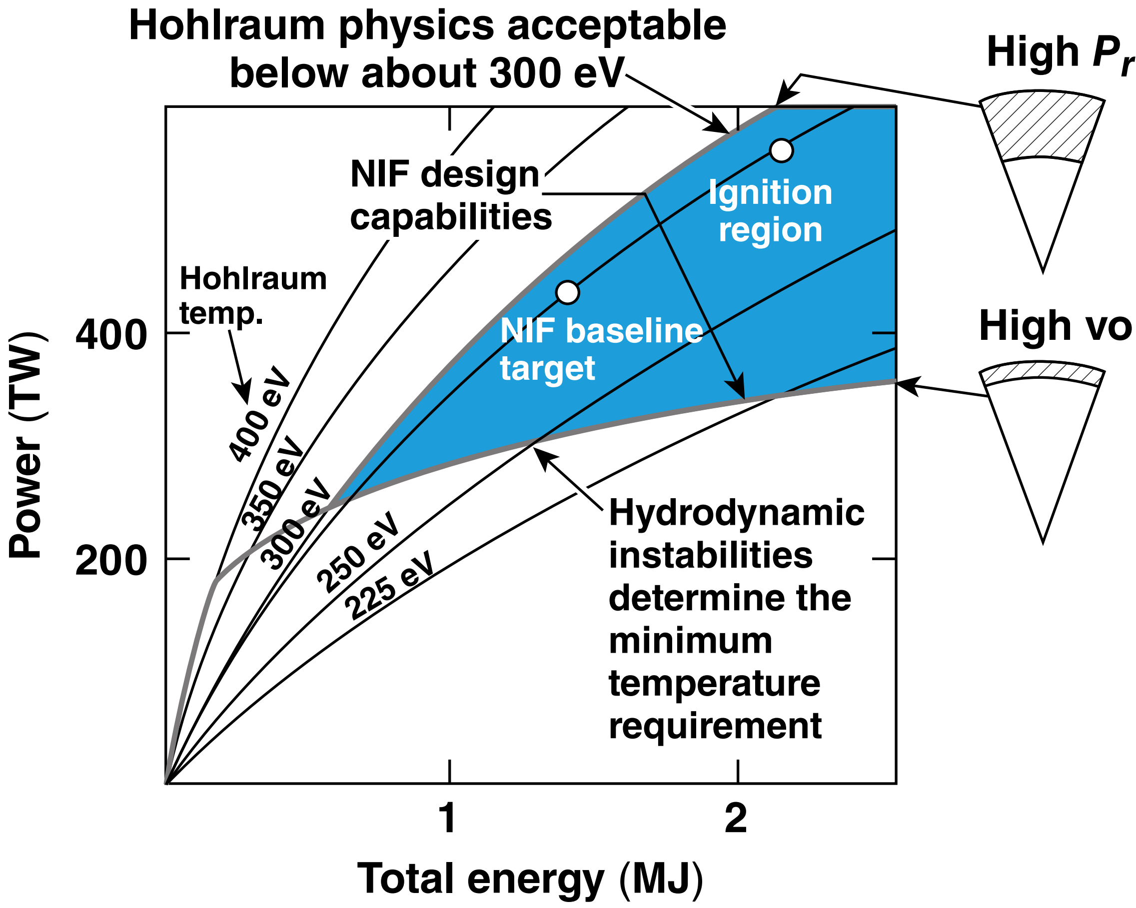
- **Nova laser at LLNL – 10 beams, ~30 $kJ_{UV}$ (1986–1999)**



- **The Nova technical contract (1990) required demonstration of precision control of laser-driven hohlraums to validate the ignition point design.**
- **After many reviews, DOE issued a record of decision on 19 Dec. 1996, paving the way for construction of the NIF.**

# Plasma physics issues and hydrodynamic instabilities constrain the hohlraum temperature

“Bird’s beak” plot from 1990



High $P_r$, $T_r$, $I_L$ ⇒ plasma instabilities

High vol ⇒ large $\frac{R_0}{R_{\text{final}}}$ ⇒ symmetry

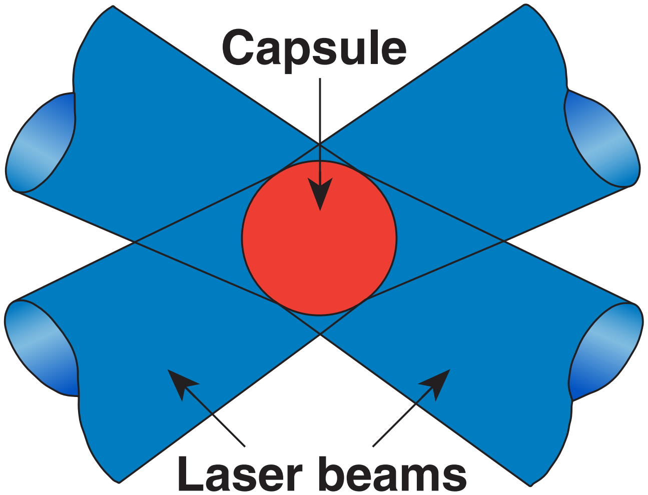
⇒ large $R/\Delta R$

⇒ hydroinstability

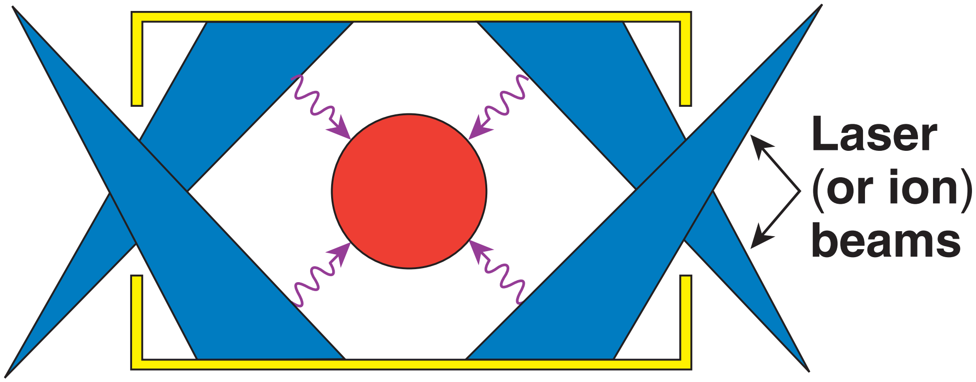
From J. Lindl, APS/DPP Maxwell Prize Address (2007).

# The fundamental physics of direct- and indirect-drive ICF implosions is the same

**Direct-drive target**



**X-ray-drive target**



Hohlraum using
a cylindrical high-Z case

**Key physics issues are common to both**

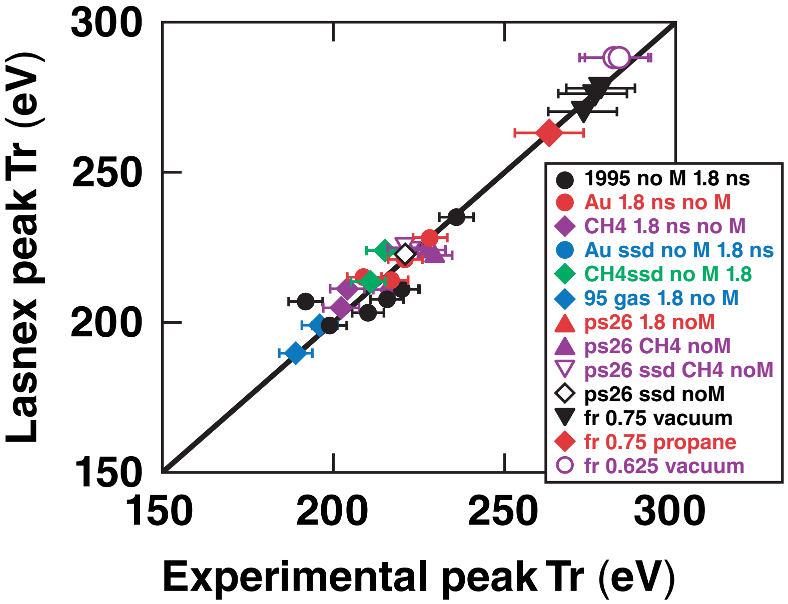
- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities
- Compressibility

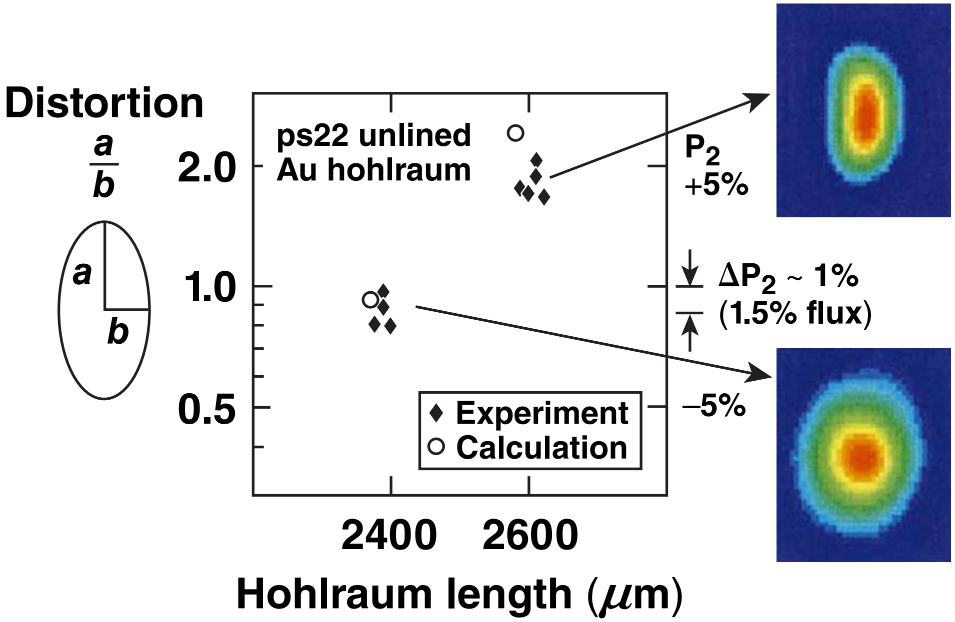
**Direct-drive cryogenic implosions provide essential information for ICF physics.**

# Experiments on the Nova laser demonstrated the key target physics required for ignition and satisfied the Nova technical contract

- **1985 to 1990: Nova experiments demonstrated the key physics requirements for laser-driven high gain**
- **1990: 300-eV hohlraum temperatures reduced the scale of an ignition facility from 5 to 10 MJ (LMF) to 1 to 2 MJ (NIF)**
- **1990s: Demonstration of precision control of laser-driven hohlraums, satisfying the Nova Technical Contract**

**Scaling of peak-drive temperature**



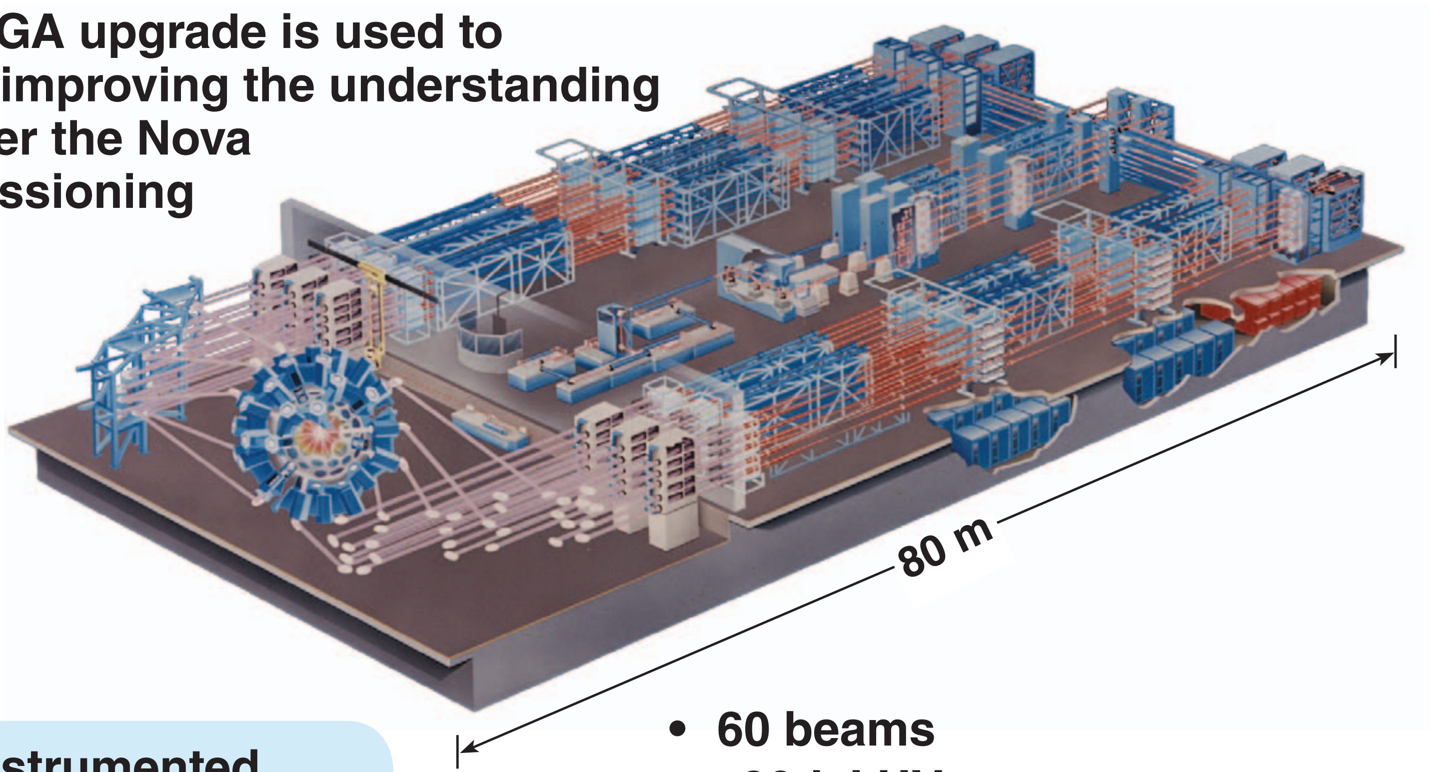


I1869

From J. Lindl, APS/DPP Maxwell Prize Address (2007).

# The OMEGA upgrade, completed in 1995, was designed to achieve high irradiation uniformity with flexible pulse-shaping capability

**The OMEGA upgrade is used to continue improving the understanding of ICF after the Nova decommissioning**



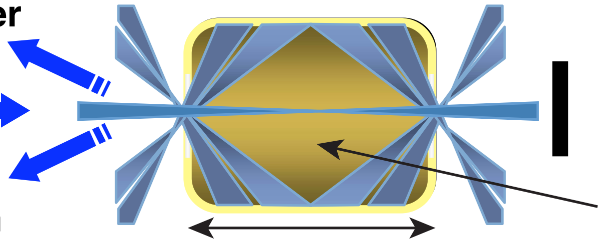
- 60 beams
- >30-kJ UV on target
- 1% to 2% irradiation nonuniformity
- Flexible pulse shaping
- Short shot cycle (1 h)

Fully instrumented

Successfully operated for 14 years with up to 1500 target shots/year

# 1995 to present: Experiments on the upgraded Omega Laser Facility further the understanding of ICF physics

## Well-characterized NIF-like plasmas are produced on the OMEGA laser.



Near backscatter imager (NBI)

Interaction beam

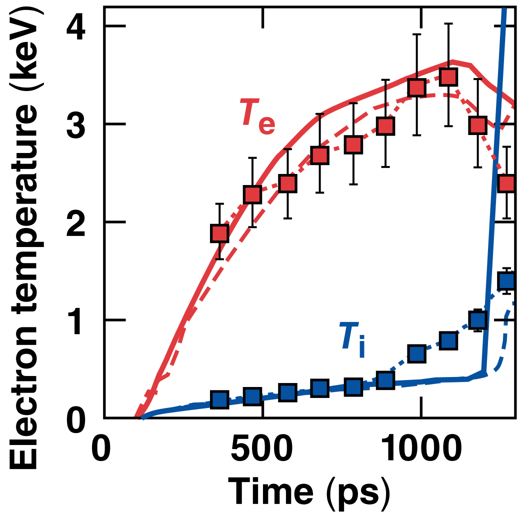
Full-aperture backscatter station (FABS)

$L$ = 2 mm and longer

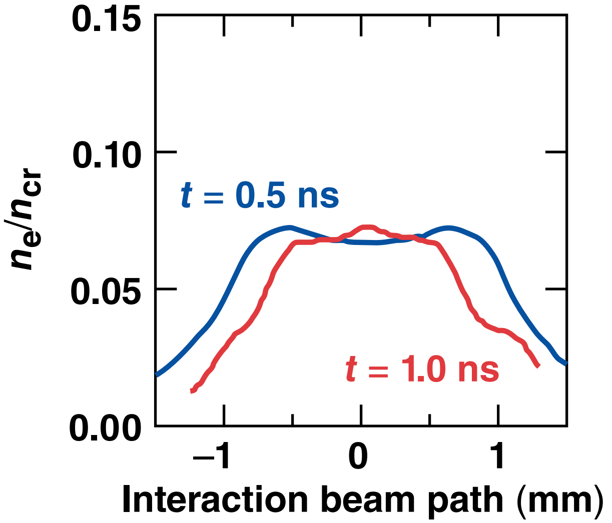
3$\omega$ transmitted beam diagnostic

CH gas fill produces a uniform electron density divided by the critical density ($n_e/n_{cr}$ = 6%)

**Plasma temperatures measured with Thomson scattering agree well with simulations**



**A uniform 6% $n_{cr}$ plateau is produced between 0.5 and 1.0 ns**



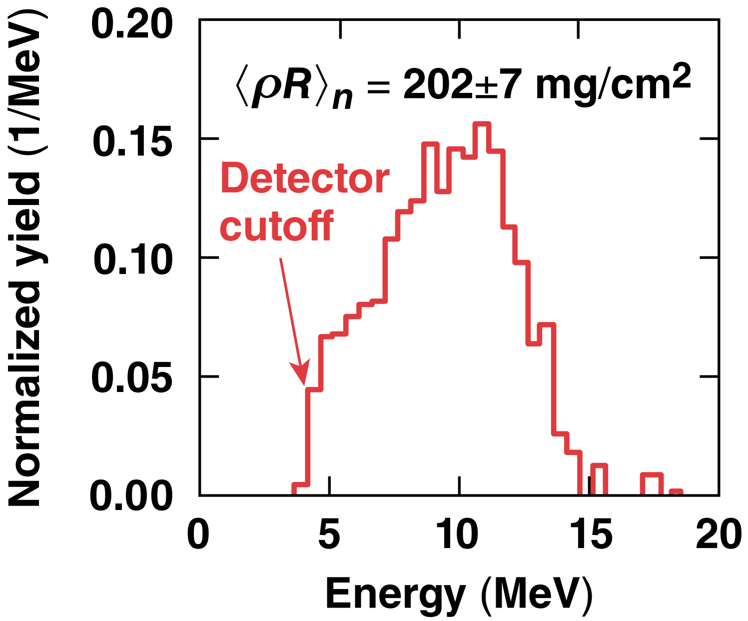
D. H. Froula *et al.*, Phys. Plasma 13, 052704 (2006).

From J. Lindl, APS/DPP Maxwell Prize Address (2007).

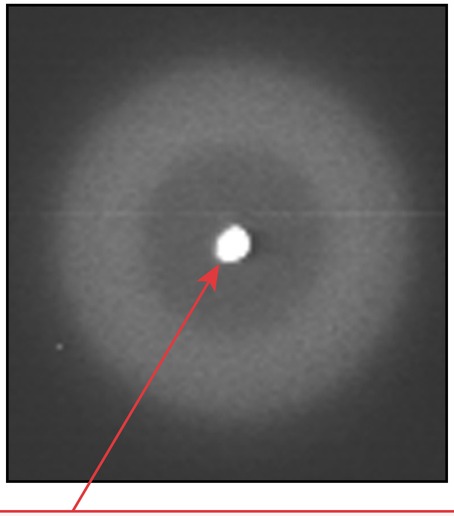
# Cryogenic target implosions on OMEGA have produced ignition-relevant areal densities (~200 mg/cm$^2$)

10-$\mu$m CD cryogenic implosion

Secondary D$^3$He proton spectrum



X-ray pinhole camera



D$_2$ fuel density reaches ~100 g/cc (500× liquid density)

**These are, by far, the highest areal densities measured in ignition-relevant laboratory implosions—very important for direct- and indirect-drive ignition.**

T. C. Sangster *et al.*, Phys. Rev. Lett. 100, 185006 (2008).

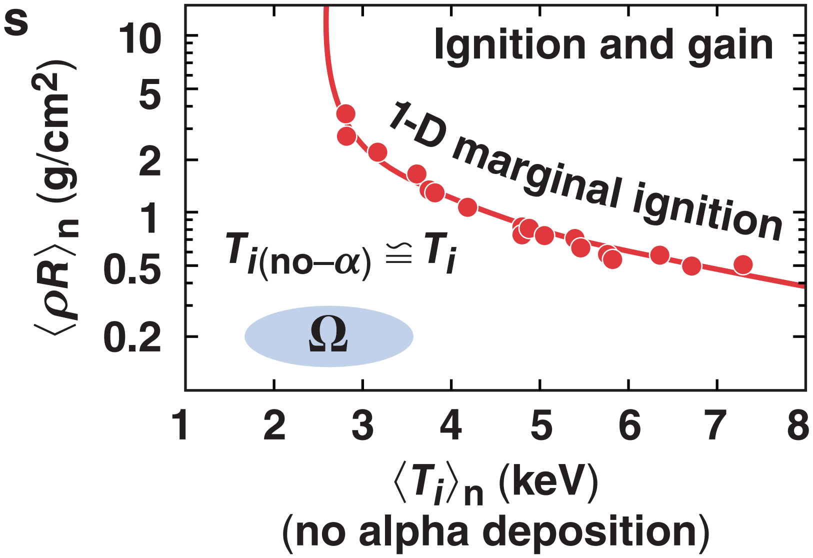
# A "Lawson's criterion" in terms of burn-averaged $\rho R$ and $T_i$ shows the requirements for ignition

- Simple scaling relations for ignition condition from Zhou *et al.** and Herrmann *et al.***

$$\langle \rho R \rangle_n > 1.3 \left( \frac{4}{\langle T_i \rangle_n (\mathrm{keV})} \right)^{2.4} \left(\mathrm{g/cm^2}\right)$$

- Fitting the results of 1-D simulations with Gain = 1 yields an ignition condition that depends on the burn-averaged $\rho R$ and ion temperature without alpha deposition.
- For sub-ignited implosions $T_{i(\text{no}-\alpha)} \cong T_i$

*LILAC* fit



**Both $T_i$ and $\rho R$ can be measured experimentally.**

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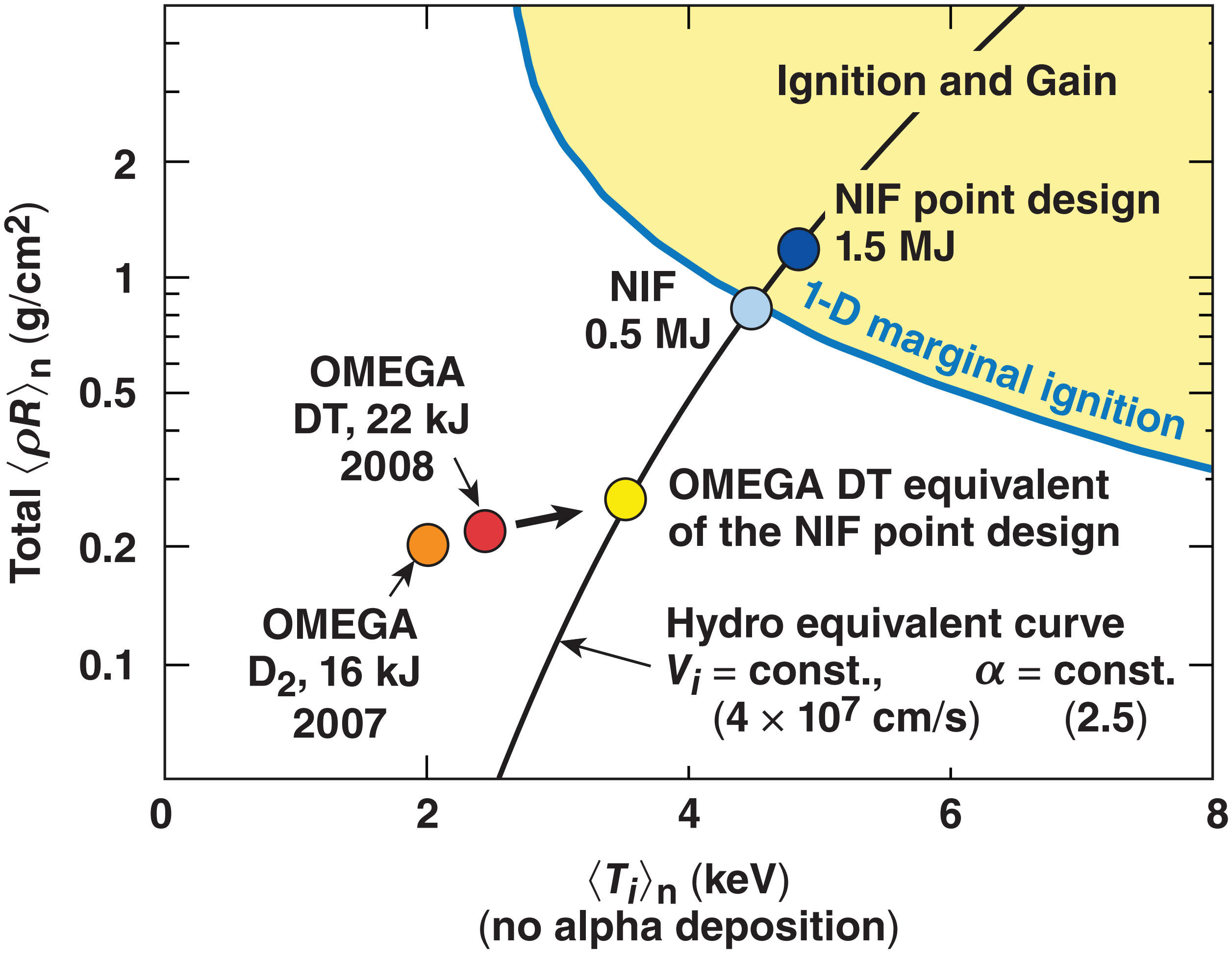
* C. Zhou and R. Betti, Phys. Plasmas 14, 072703 (2007).

** M. C. Herrmann, M. Tabak, and J. D. Lindl, Nucl. Fusion 41, 99 (2001).

# Cryogenic target implosions on OMEGA are approaching conditions that scale to ignition on the NIF

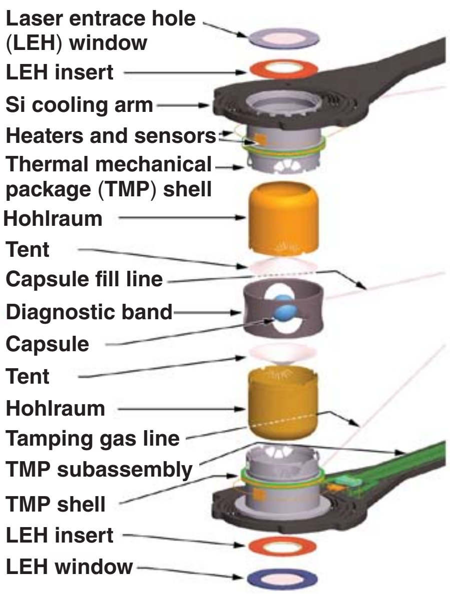
- Ignition-relevant areal densities have been achieved
- The next step is to increase $T_i$



# Targets, target diagnostics, and computational power have rapidly evolved from the early 1970s to today’s NIF ignition campaign requirements

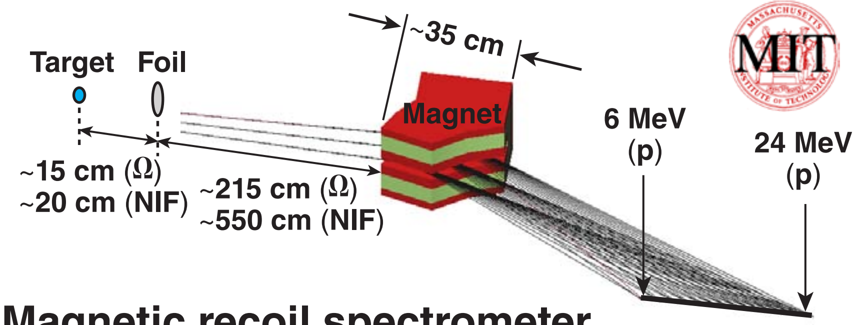
**Complexity of target**

**1970**

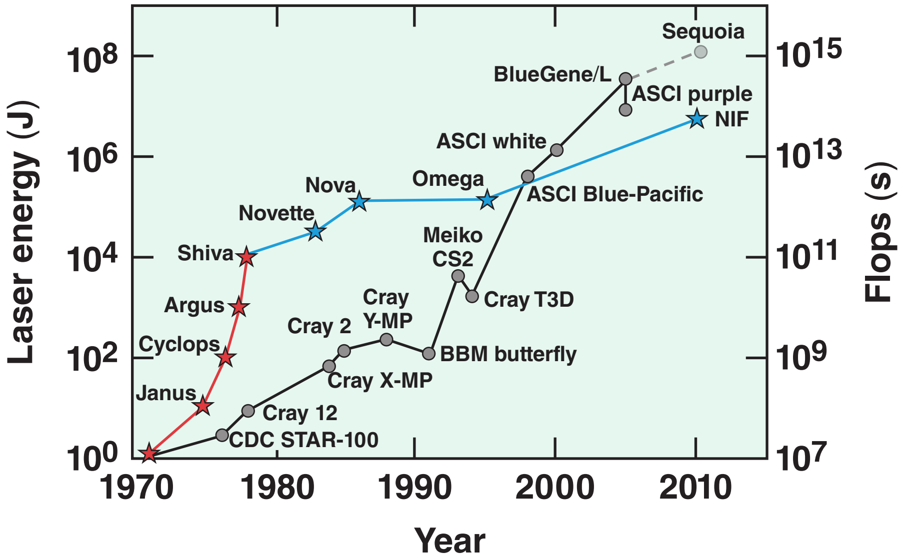


**Today**

**Lasers and computers have both experienced an explosive growth in capability**

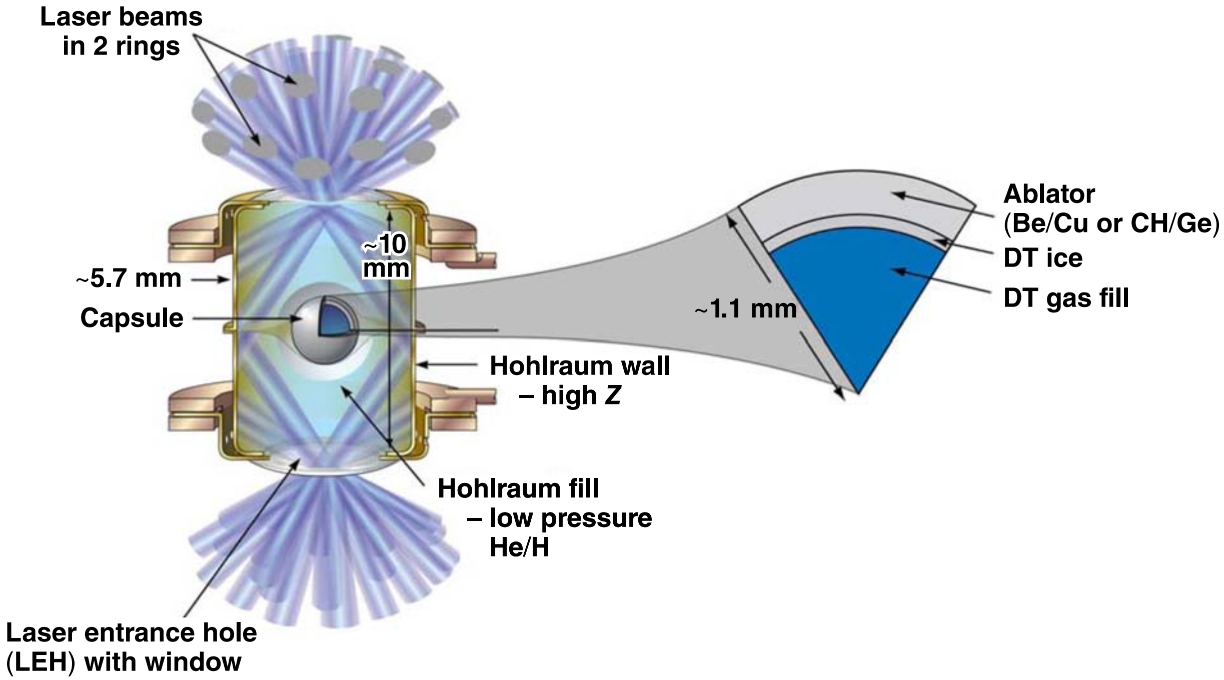


**Magnetic recoil spectrometer (MIT/LLE) for downscattered and primary neutrons on OMEGA and the NIF**



# Experiments on Nova, OMEGA, and other systems have led to the specifications for the NIF ignition target design

- The National Ignition Campaign (LLNL, LANL, GA, SNL, and LLE) has provided an understanding of the requirements for ignition on the NIF.

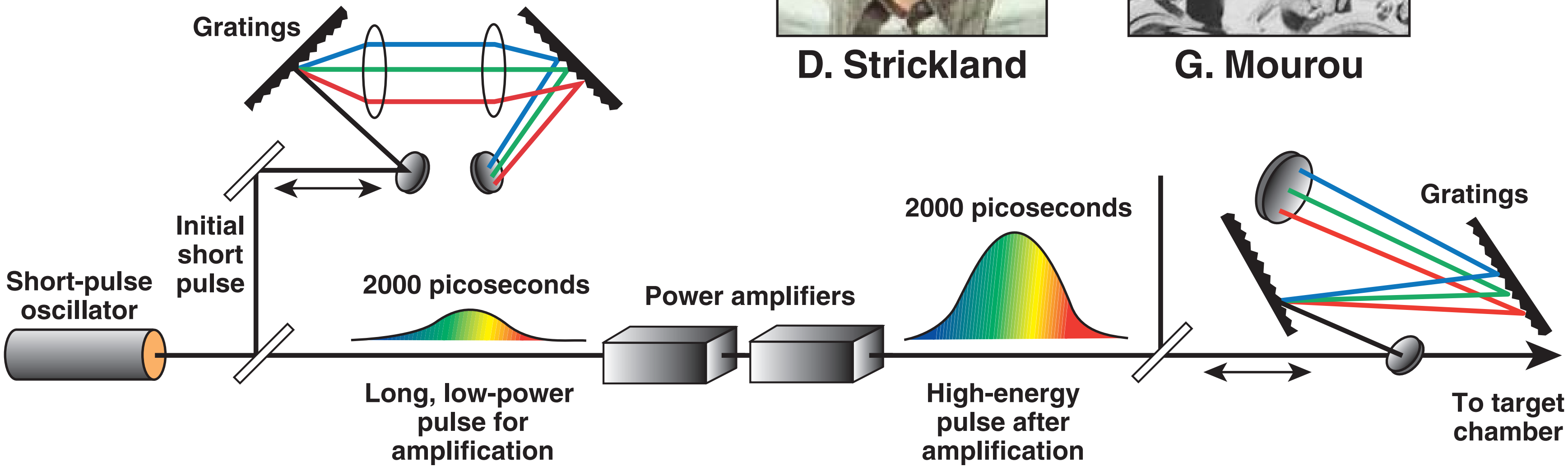


- A baseline target design is ready for testing.
- Ignition tuning experiments will begin this year with the first ignition attempt to be carried out in FY10.

# The development of chirped-pulse amplification (CPA) at LLE in 1985 led to a high-intensity revolution

D. Strickland

G. Mourou



Gratings

Initial
short
pulse

Short-pulse
oscillator

2000 picoseconds

Long, low-power
pulse for
amplification

Power amplifiers

2000 picoseconds

High-energy
pulse after
amplification

Gratings

To target
chamber

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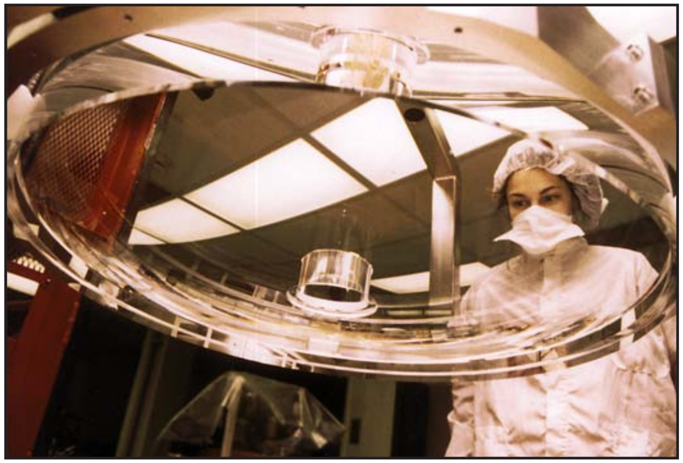
D. Strickland and G. Mourou, "Compression of Amplified Chirped Optical Pulses," Opt. Commun. 56, 210 (1985).

# The Nova Petawatt laser was completed a decade after the invention of CPA

- **CPA was invented in 1985**
- **Initial LLNL LDRD for Nova PW (M. Perry, M. Campbell *et al*.) in 1988**
- **Initial Nova PW operations in Dec. 1994 – 500 J, 500 fs**
- **Similar PW lasers have been built around the world**

**Grating chamber of the Nova PW**

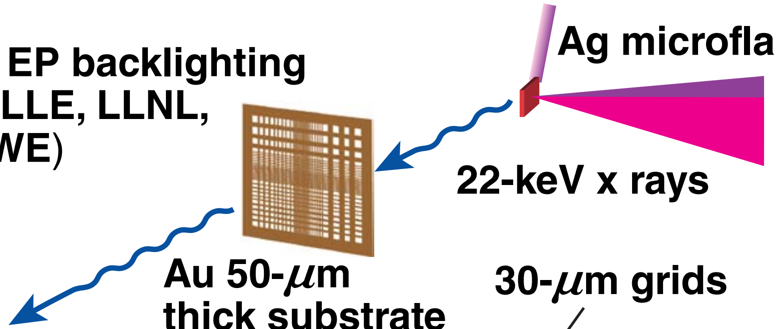


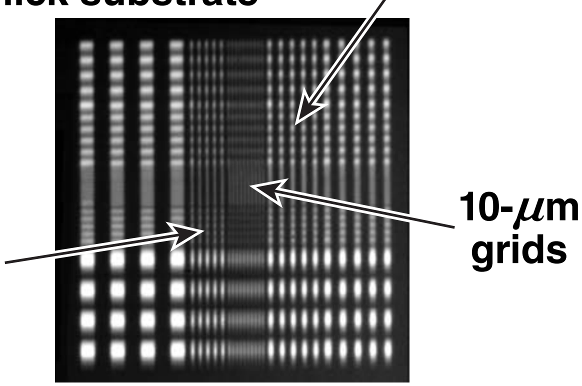
**The Nova Petawatt parabola was coated at LLE**

# The next generation of high-energy petawatt lasers will allow a wide range of high-energy-density conditions to be explored

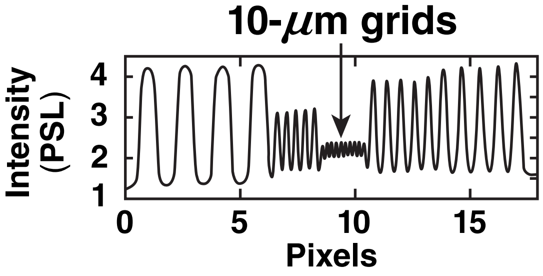
- High-energy petawatt laser–target interactions produce copious amounts of electrons, ions, and photons used to create and diagnose high-energy-density conditions

Initial OMEGA EP backlighting development (LLE, LLNL, LANL, CEA, AWE)





Lineouts along the grid pattern

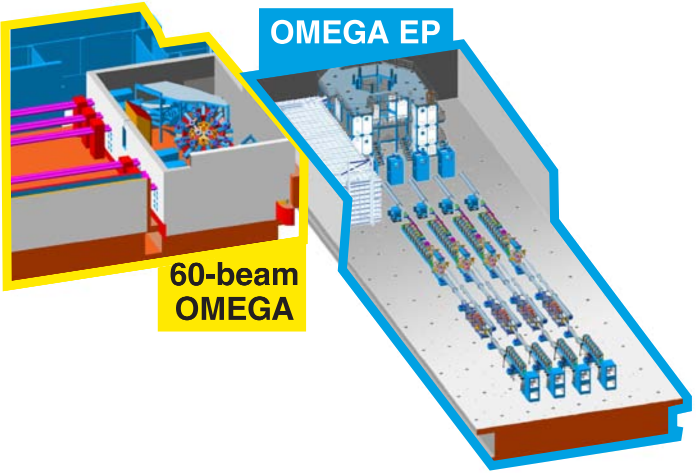


OMEGA EP: Completed 2008, first user experiments in Q1 FY09

# Today’s high-energy petawatt lasers extend ignition capabilities

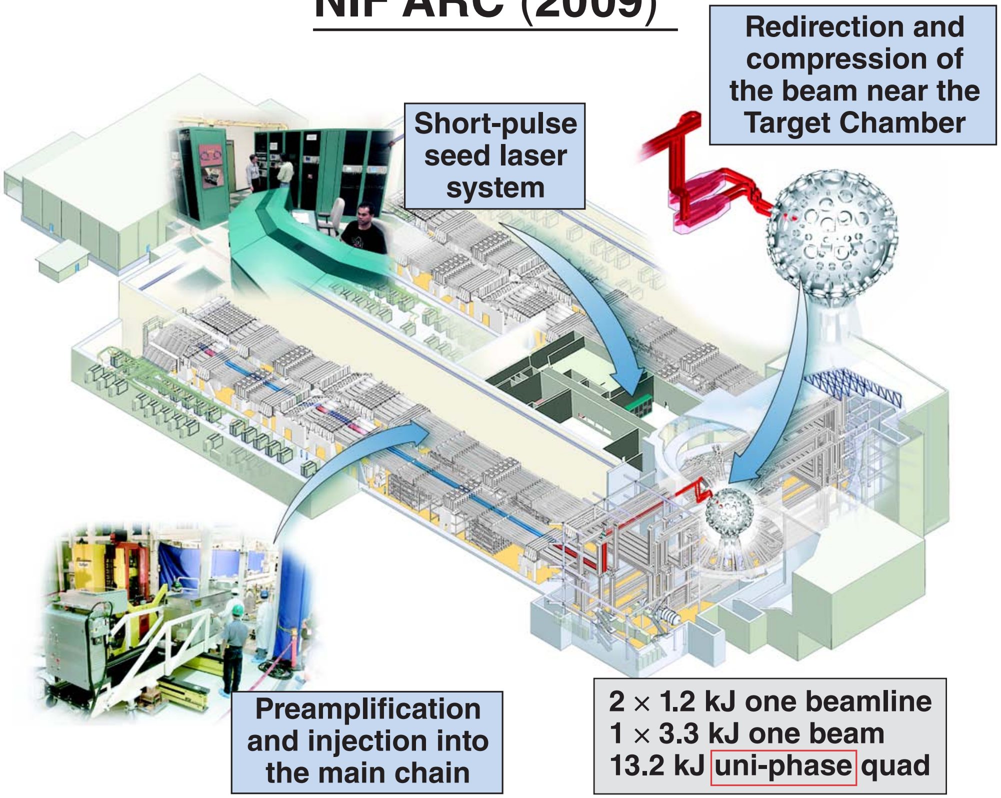
- Backlighting of target implosions
- Fast ignition

## OMEGA EP (2008)



2 HEPW beamlines
2.6 $kJ_{IR}$ each in 10 ps

## NIF ARC (2009)*



Redirection and compression of the beam near the Target Chamber

Short-pulse seed laser system

Preamplification and injection into the main chain

2 × 1.2 kJ one beamline
1 × 3.3 kJ one beam
13.2 kJ uni-phase quad

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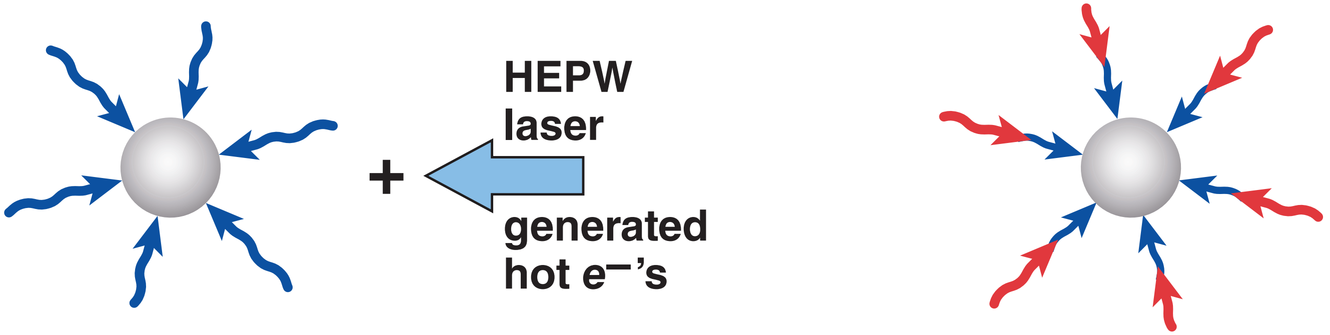
*M. Key, ECLIM (2006).

# New ignition concepts separate compression ($\rho R$) and heating ($T_i$)—two-step ignition

- In the current hot-spot ignition, the driver provides both compression ($\rho R$) and heating ($T_i$).
- Both fast ignition and shock ignition use a second drive to provide heating ($T_i$).



**Fast Ignition**

Compression

+

HEPW laser

generated hot $e^-$'s

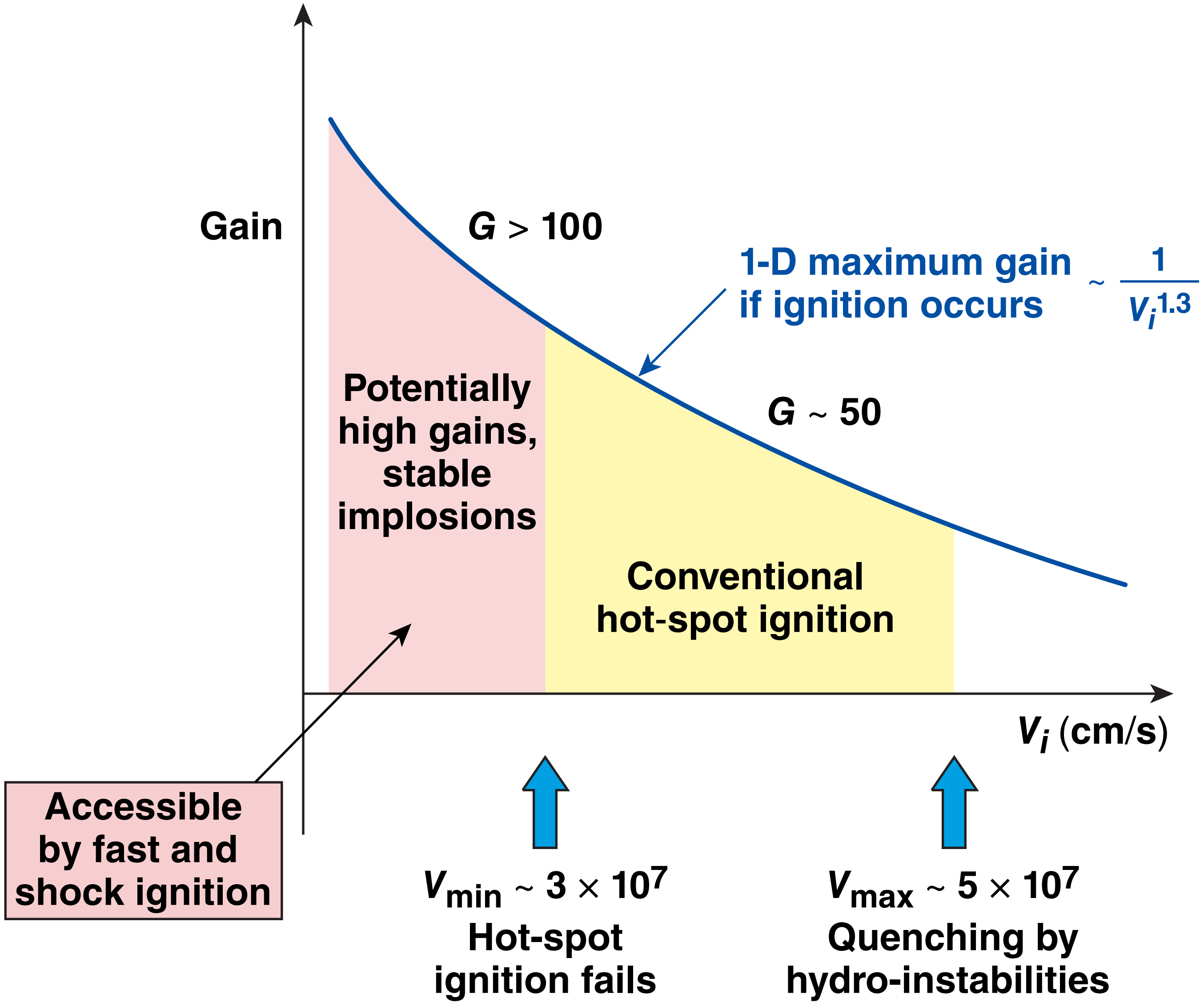
**Shock Ignition**

Compression + shock pulse

- Measured cryogenic target areal densities are relevant to these schemes.

**Two-step ignition offers lower driver energies with the possibility of higher gain.**

# Fast and shock ignition can trigger ignition in massive (slow) targets leading to high gains



Summary/Conclusions

# The understanding of inertial confinement fusion (ICF) has grown as successively larger lasers have been built

- The ICF era began with a successful thermonuclear test in 1952.
- The demonstration of the laser in 1960 began the quest to develop ICF and, eventually, create thermonuclear fusion ignition in the laboratory.
- ICF lasers have continued to become larger and more technically sophisticated.
- The NIF represents the next great leap in laser development
  - Congratulations to Ed Moses and the entire team!
- The improved understanding of ICF physics provides confidence for achieving ignition on the NIF
  - Nova technical contract
  - OMEGA cryogenic target implosions
- New laser and target physics concepts continue to advance the ICF program in the United States

**We are ready for the next step:
The demonstration of ignition on the NIF!**