Progress Towards High-gain Inertial Confinement Fusion with Lasers

A 1.3 MJ yield shot on the National Ignition Facility using 1.9 MJ of laser light demonstrated basic viability of inertial fusion. The NRL program is advancing a laser technology and approach that is projected to enable the higher gains (100+) needed for inertial fusion energy.

Presentation to APS Middle Atlantic Physicist Group

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Fusion powers the visible Universe

Can it provide clean plentiful energy on earth?
The basics of nuclear fusion: at a very high temperature atoms fuse together with the release of energy.

The fusion reaction with deuterium-tritium is the “easiest” to achieve – others require higher temperature.

\[ \text{Deuterium - D} \quad + \quad \text{Tritium - T} \quad \Rightarrow \quad \text{Helium - He}^4 (3.45 \text{ MeV}) + \text{neutron (14.1 MeV)} \]

1 MeV = 1 million electron volts – typical chemical reactions release a few electron volts of energy.
Paths to fusion on Earth: Magnetic Confinement

A strong magnetic field confines the hot burning plasma.

(from energy.gov)

Magnetic fusion ITER facility - under construction

https://www.iter.org/mach
Inertial Fusion (via central ignition)

Lasers or x-rays heat outside of pellet, ~100 Mbar pressure implodes fuel to velocities of ~300 km/sec.

Central portion of DT (spark plug) is heated to ignition. (~100 Gbar, ~10^8 °C)

Thermonuclear burn then propagates outward to the compressed DT fuel.

~ 3% of original target diamter

- Simple concept
- Potential for very high energy gains (>100)
- Requires high precision in physics & systems
- Need to understand & mitigate instabilities
A heavy fluid supported by a lighter fluid is subject to Rayleigh-Taylor Instability.

Example: A glass of water turned upside down..

Before

During

After

Glass of water
(Heavy Fluid)

Air
(Light Fluid)
An ICF pellet has a Rayleigh Taylor (RT) Instability: Pressure from the low density ablated material accelerates the high density shell.

\[ t_1 = t_0 + \Delta \]

Accelerated & compressed "Fuel"

\[ A_k(t) = A_{ko} e^{\gamma_k t} \]

Mitigation of RT instability.
Minimize \( A_0 \) (from target and drive imperfections)
Reduce growth: \( (\gamma t) \) -
Laser plasma instabilities (LPI) are a challenge to laser fusion

- LPI produced high energy electrons can preheat target impeding its compression.
- LPI induced laser scattering reduces laser drive and can spoil symmetry.
- LPI limits the maximum usable laser intensity and ablation pressure

Mitigation of laser plasma instabilities

- **Broad laser bandwidth** can disrupt the coherent wave-wave interactions that produce LPI
- **Short laser wavelength** increases the instability intensity thresholds of most instabilities
Two approaches to laser ICF

**Indirect Drive (ID)**– laser light converted to x-rays that drive the implosion – approach chosen for NIF.

- Mainline effort on NIF
- ID reduces laser uniformity requirements
- But is not efficient, only a small fraction of laser energy reaches target as x-rays

**Direct Laser Drive** – laser light directly illuminates the capsule

- Much more efficient than indirect drive
- But requires very uniform laser illumination of the target
- Potential for much higher gain and fusion yield

Illustration from https://lasers.llnl.gov/programs/nic/icf/
The National Ignition Facility (NIF) concentrates the energy from 192 laser beams energy in a football stadium-sized facility onto few-mm-size targets.

Matter temperature $>10^8$ K

Radiation temperature $>3.5 \times 10^6$ K

Densities $>10^3$ g/cm$^3$

Pressures $>10^{11}$ atm
NIF utilizes flashlamp-pumped Nd:glass amplifiers, the 1054 nm light is frequency tripled to 351 nm.

Near infrared $\lambda = 1054$ nm light from Nd:glass is frequency tripled to UV and directed to target.

Figure 1. The layout of NIF’s major components through which a pulse of laser light travels from injection to final focus on the target.

1 of 192 beams

https://str.llnl.gov/str/Powell.html
NIF 6-m diameter target chamber
The challenge — near spherical implosion by ~35X

DT shot N120716
Bang Time
(less than diameter of human hair)

~2 mm initial diameter
Hydrodynamic challenges to indirect drive ICF

Round, symmetric implosion → critical challenge for ICF

Hohlraum, capsule and tent

Highly efficient, highly symmetric simulated implosion

2 mm

tent

fill tube

0.07 mm

High-resolution postshot simulation of NIC experiment

Lawrence Livermore National Laboratory

Simulations by C. Weber
Near-vacuum and low-fill hohlraums offer a path to controllable, low-LPI environment

- 30-50% more efficient
- Minimal cross-beam energy transfer
- Symmetry control limited by filling → need shorter laser pulses

Helium $\rho \geq 0.96$ mg/cm$^3$  
Helium $\rho = 0.03 - 0.3$ mg/cm$^3$
Initial results from the HYBRID-E DT experiment N210808 with > 1.3 MJ yield

IFSA 2021
A. Kritcher

September, 2021
NIF diagnostics have provided key insight into our experiments and built understanding, here are some examples.

**DT Ion temperature, hot spot velocity, fuel density, yield**
- Five Neutron Time of Flight (nToF)'s and the Magnetic Recoil Spectrometer (MRS)

**DT Yield Map /Fuel uniformity**
- 48 Real-Time Nuclear Activation (NAD)'s read out in real-time 24/7

**DT Fuel uniformity: Compton Radiography**
- ~100keV x-rays produced by Advanced Radiography Source provide radiographs of DT fuel

**DT Neutron yield**
- Zirconium/Copper Nuclear activation

**Hot spot and Fuel Shape from Neutron Imagers**
- 3 Neutron Imaging (NIS) Lines of sight for 3D reconstruction of neutron hot-spot
- 2 NIS down-scatter lines of sight for fuel shape

**X-ray Imaging & Spectroscopy**
- 3 x-ray imaging lines of sight
- X-ray spectroscopy to characterize material mixed into the hotspot

**Gamma Spectroscopy**
- Neutron Burn-width, time of peak emission (Bang-time) and DT neutron yield

This is the best diagnosed HED plasma on the planet! -> developed over decades by the whole HED community
The August 8th shot (N210808) on NIF yielded more than 1.3 MJ and marks a significant advance in ICF research.

- Capsule gain > 5
- Laser gain ~ 0.7

The August 8th shot (N210808) on NIF yielded more than 1.3 MJ and marks a significant advance in ICF research.
The Hybrid-E target design that enabled the 1.3 MJ yield, involved increasing the diameter of the capsule which increased the % of x-rays driving the implosion.

High Yield Big Radius Implosion Design (HYBRID) strategy

- With fixed laser energy higher efficiency hohlraums to maintain velocity
  - Much more difficult for symmetry (long pulse, smaller case to capsule ratio (CCR))
  - Use data-driven models\(^3\) to guide design choices

The 1.3 MJ shot shows the basic viability of laser inertial fusion

But even with HYBRID-E only about 12% of the laser energy available to drive the target implosion via x-rays.

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1: O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019)
2: A.B. Zylstra et al., PRL 126, 025001 (2021); A.L. Kritcher et al., PoP 28, 072706 (2021)
Direct laser drive is a much more efficient approach

**Direct Laser Drive** – laser light directly illuminates the capsule

- Much more efficient than indirect drive (>5x)
- Potential to reach the high gains (100) required for the fusion energy application.

- The electron-beam-pumped argon fluoride (ArF) laser provides this best light for this approach
  - Deeper UV light than other ICF lasers provides more efficient drive for implosions
  - Multi-THz bandwidth to suppress LPI
  - Good wallplug efficiency (10% predicted) for laser fusion energy application
NRL is the world leader in high-energy electron-beam pumped krypton fluoride (KrF) and argon fluoride (ArF) deep UV lasers

- Shorter wavelength enables higher drive pressure and more efficient implosions
- Capable of more uniform target illumination than other laser drivers
- Capable of zooming down the focal diameter to follow an imploding target, which further improves the drive efficiency

Nike 60-cm aperture KrF amplifier
2D LPSE simulations laser plasma Omega-size target show large increase in absorption with a broad bandwidth ArF driver

<table>
<thead>
<tr>
<th>Laser Driver</th>
<th>Wavelength $\lambda_0$ ((\mu m))</th>
<th>Approximate bandwidth $\Delta\nu$ (THz)</th>
<th>Time-averaged absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:glass</td>
<td>0.351</td>
<td>1</td>
<td>65</td>
</tr>
<tr>
<td>KrF</td>
<td>0.248</td>
<td>3</td>
<td>86</td>
</tr>
<tr>
<td>ArF</td>
<td>0.193</td>
<td>5</td>
<td>91</td>
</tr>
</tbody>
</table>

For the CH plasma corona in this example, $T_e = 3$ keV, $T_i = 1$ keV and $L_n = 200$ \(\mu m\). Increased absorption with ArF in this example is primarily due to suppress of CBET
NRL’s FASTRAD3D hydrocode simulations shows the expected increase in ablation pressure with decrease in laser wavelength.

5 ns square wave laser pulse incident on 2.6 mm diameter plastic sphere @ $10^{15}$ W/cm$^2$ (vacuum intensity)

![Graph showing max pressure over time for different laser wavelengths](image)
Hydrocode simulations show advantages of utilizing short wavelength light towards avoiding two-plasmon decay instability.

\[ I_{\text{threshold}} \left(10^{15}\ \text{W/cm}^2\right) = 8.06 \times T_e[\text{keV}] \times \frac{1}{(\text{laser\_wavelength}[\text{um}])} \times \frac{1}{\ln[\text{um}]} \] (Simon et al., Phys. Fluids 26, 3107 (1983).)

5 ns square wave laser pulse incident on 2.6 mm diameter plastic sphere @ \(10^{15}\ \text{W/cm}^2\) (vacuum intensity)

TPD is a laser plasma instability at quarter critical density that produces hot electrons.
NRL radiation hydrocode 1-dimensional simulations show that short wavelength enables the high gains required for the energy application (>100) at reduced laser energy.

High-resolution implosion simulations indicate ArF light can enable high gain and yield with laser energy less than that achieved on NIF.

**357 kJ ArF laser energy**
**109x energy gain**
**Yield of 39 MJ**

Laser energies near 1MJ are predicted to give >100 MJ yields.

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**Implosion simulation**
Shows effects of target and laser illumination defects.

See reference #1
kinetic simulations of a 30 kJ ArF amplifier show high intrinsic efficiency (>16%) over a broad operating regime with bandwidths of 4 and 10 THz

Intrinsic efficiency = laser power out/ E-beam pump power
With 16% intrinsic efficiency we project 10% wallplug efficiency

We expect 10% net electrical efficiency with a large ArF laser system
Energy application requires high target performance and operation at 5 to 10 pulses per second vs few shots per day on NIF.

- Pellets containing frozen or liquid DT fuel are injected and engaged by multiple laser beams.
- Neutrons heat a fluid containing lithium in the walls.
- Heat is used for conventional electric power generation.
- Neutrons produce more tritium from the lithium.

Major components are modular and separable.

See reference #7
Use of ArF’s broad bandwidth 193 nm light could enable construction of smaller lower cost IFE power plants with laser energy well below 1 MJ.

Power flow with 500 kJ 10% efficient ArF driver and 190 gain shock ignited target.
The NRL laser fusion program has a broad portfolio of experimental, laser development & simulation research efforts.

Laser target interaction experiments
Nike KrF laser facility

Simulation of a pellet implosion and of a laser-plasma instability

2 million MPH target speed!

Electra Argon Fluoride laser

Nike 56 laser beam optics
The NRL Nike KrF laser facility is used for basic hydrodynamic and laser-plasma interaction experiments in planar geometry.

**Nike parameters:**
- Deep UV wavelength (248nm)
- 44 main beams for laser target interaction
- 12 "backlighter" beams
- 2-3 kJ on target long pulse (4ns)
- 1 kJ on target short pulse (300ps)
- ISI beam smoothing with up to 3 THz bandwidth
Nike target chamber

- Front end and beam 38 prop. bay spectrometer
- Beam 4 and beam 38 profile diagnostics
- 248 nm & broad half-omega spectrometers
- Filtered diodes, phototubes

GIR is a key diagnostic — information on target conditions are essential
Excimer angularly multiplexed laser optical systems provide high target illumination uniformity and easy implementation of focal zooming.

Nike KrF optical system with ISI smoothing
An ArF system would be similar

Time averaged laser spatial profile in target chamber
X-ray backlighting and sidelong lighting are employed to measure the motion and growth of hydrodynamic instability for laser accelerated targets.
Advancing the basic physics of multi-megabar shock propagation in low density foam targets on Nike

Foams are complex materials that will not behave exactly as uniformly distributed matter.

Near monochrome x-ray side-lighting @ 1.8 KeV

Yefim Aglitskiy
Nike experiment studding the hydrodynamics effects of isolated defects on laser accelerated targets which are compared with simulations

(a) Experiment from x-ray streak and (b) simulation of growth of areal density perturbations seeded by 20 µm x 25 µm groove

NRL FASTRAD 2D simulation of growth of two groove perturbations through RM and RT phases

From Fig. 1 of “Multi-mode hydrodynamic instability growth of pre-imposed isolated defects in ablatively driven foils,” C. Zulick et al., Phys. Rev. Lett. 125, 055001 – Published 28 July 2020
Nike KrF laser accelerates targets to greater than 1000 km/sec (0 to 2.2 million miles per hour in a billionth of a second!)

- Previous record of 700 km/s achieved on Gekko XII/HIPER glass (351nm) laser at Osaka
- Made possible by the high uniformity and high ablation pressure generated by the KrF laser

Joint experiment with Institute of Laser Engineering, Osaka University
NRL 6.1 and DoE ARPA-E and Office of Fusion Energy Science support advancing high-energy ArF development

Parametric experimental studies on Electra

Modify & validate NRL Orestes laser kinetics model for ArF

Notes
- 200 J obtained in oscillator mode (vs 96 J previous ArF record)
- Measuring gain, saturation flux and intrinsic efficiency & compare with simulations
- ArF lithographic industry has developed durable 193 nm optics – need to be scaled up in size for ICF
The high average power laser (HAPL) program managed by NRL advanced the broad range of technologies needed for a power plant.
The High Average Power Laser (HAPL) Program:
Integrated program to develop the science and technologies for Fusion
Energy with Laser Direct Drive (1999-2008)
HAPL generated, and in many cases, “bench tested” solutions for most key components (see http://qedfusion.org/HAPL/MEETINGS/0804HAPL/program.html)

**Neutron resistant final optics:**
High Laser Damage Threshold
Grazing Incidence Metal Mirror

10 M shots at 3.5 J/cm² (not a limit!)

**Low cost target fabrication:**

**Injected target engagement:**
Glint system: accuracy 28 microns

Estimated target cost $0.16 each

**Tritium handling and recovery**
The first wall of an IFE reactor must survive the “threat” spectrum from the target.

Alpha particles penetrate a few microns, form helium bubbles, and can cause the first wall surface to exfoliate.
Chamber concepts to prevent damage from alphas (pressure from helium bubbles exfoliates surface)

Tungsten “foam” with cell size small enough for helium to escape

Magnetic cusp field directs alphas away from the 1st wall and out of the reaction chamber
The Vision...A plentiful, safe, low-carbon energy source

A 100 ton (4200 Cu ft) COAL hopper runs a 1 GWe Power Plant for 10 min.

Same hopper filled with IFE targets: runs a 1 GWe Power Plant for 7 years.

Fig. by John Sethian
References


