Polar-Direct-Drive Experiments at the National Ignition Facility

M. Hohenberger
University of Rochester
Laboratory for Laser Energetics

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Summary

Polar-direct-drive (PDD) ignition is the alternative path to ignition at the National Ignition Facility (NIF)

• First integrated PDD implosion experiments explore the coupling of laser energy to the imploding CH shell in low-convergence experiments

• Radiography data of the imploding shell are in reasonable agreement with the simulations

• Hot-electron generation by the two-plasmon–decay (TPD) instability is reduced by using mid-Z ablators

• A Laser Path-Forward working group is actively engaged in adding beam-smoothing capabilities

Future focused experiments will examine laser–plasma and hydrodynamic instabilities.
Collaborators


University of Rochester
Laboratory for Laser Energetics


Lawrence Livermore National Laboratory

P. Fitzsimmons, J. D. Kilkenny, C. Kurz, and A. Nikroo

General Atomics

J. A. Frenje, R. D. Petrasso, and H. Rinderknecht

Massachusetts Institute of Technology

J. Bates, M. Karasik, S. Obenschain, A. Schmitt, and J. Weaver

Naval Research Laboratory
Outline

- Polar-direct-drive ignition on the NIF
- Early NIF experiments (12 shots to date)
  - trajectory
  - symmetry
  - laser–plasma interactions
- The path forward
- Conclusions
LLE is developing PDD:* a platform for direct-drive inertial confinement fusion (ICF) on the NIF using the x-ray-drive beam geometry

- Increasingly oblique irradiation near the equator
  - reduced absorption
  - reduced hydro-efficiency
  - lateral heat flow
  - cross-beam energy transfer (CBET)

The key physics areas for PDD are energy coupling, implosion symmetry, imprinting, and laser–plasma interactions (LPI’s)

Peak compression

- Stagnation + fuel–shell mix kinetic effects

Early time

- Fuel conditioning
- Plasma formation, imprinting, and drive uniformity
- Hydro-instability and mitigation, laser–plasma instabilities, preheat

Deceleration phase

- Rayleigh–Taylor growth

Acceleration phase: energy coupling

- Drive
- DT ice
- Shell
- DT gas
Early NIF implosions are using existing hardware to study implosion hydrodynamics and LPI at ignition-relevant conditions.

\[ R = 1.1 \text{ mm}, \text{ hard-sphere intensity distribution on current PDD implosions} \]

\[ E \sim 600 \text{ kJ}, \ I \sim 8 \times 10^{14} \text{ W/cm}^2 \]

A combination of beam-power balanced and beam pointing is used to optimize the implosion symmetry.

Current NIF beam smoothing precludes high-convergence implosion experiments.
A suite of diagnostics is used to measure the shell trajectory, symmetry, and plasma parameters.

- Additional diagnostics include:
  - scattered light—FABS/NBI
  - hard x-ray emission—FFLEX
  - soft x-ray emission—Dante
  - yield and n-bang time—nTOF’s, pTOF
  - areal density—WRF
Radiography data is used to extract the shell trajectory.

N140612

$t = 7.75$ ns

1500 $\mu$m

Backlit data
Two-dimensional DRACO simulations without cross-beam energy transfer (CBET) do not match the shell trajectory.

- **Backlit data**
- **DRACO without CBET**

Graph:
- Y-axis: Radius (mm)
- X-axis: Time (ns)
- Data points showing trajectory over time.
CBET redistributes energy between intercepting beams and reduces laser absorption near the equator

CBET causes rays from the beam tails to extract energy from high-intensity central rays.

Instantaneous deposited laser power at convergence ratio CR ~ 2

Laser deposition (W/cm³)

Collisional absorption only

$\text{Collisional absorption only } f_{\text{abs}} = 89\%$

CBET

$\text{CBET } f_{\text{abs}} = 67\%$

Target

Beam 1

Beam 2
Including CBET in the DRACO simulations improves the agreement with the measured trajectory.

- Discrepancy between simulations and data may indicate Rayleigh–Taylor (RT) growth.
Coronal self-emission imaging probes the region close to the ablation surface*

Self-emission imaging makes it possible to measure low-mode asymmetries without backlighting.

The agreement in equatorial shape between simulation and experiment improves when including CBET in the calculations.

- The difference between experimental data and simulations are likely a result of 3-D effects not captured by 2-D calculations.
The self-emission inferred shape evolution matches the radiography data very well.
The self-emission trajectory is delayed compared to simulations.

The discrepancy between backlit and self-emission trajectory is currently not fully understood.

P. B. Radha et al., JO4.00013, this conference.
Beam pointing, defocus, and energy balance have been used to control and improve symmetry. Framing-camera images (CR ~ 2) show the intensity (arbitrary units) distribution for different beam-spot profiles, with N130128 and N130731 labels. The graph on the right plots the ratio $P_6/P_0$ against $R$ (μm) for N130128 and N130731, highlighting the amplitude percentage. Further improvements in symmetry will require dedicated PDD phase plates and well-characterized beam-spot profiles.
The TPD instability is the dominant source of hot electrons in direct-drive ICF experiments

- Hot electrons can penetrate the ablator and preheat the fuel
- TPD gain scales as:
  - $\langle I \rangle$: overlapped beam intensity
  - $L_n$: plasma scale length
  - $T_e$: electron temperature

\[ G \sim \frac{\langle I \rangle L_n}{T_e} \]

- TPD signatures:
  - $\omega_L/2$ and $3/2 \omega_L$ emission
  - Hard x-ray emission $>20$ keV

$L_n^{\text{EP}} \sim 350 \mu\text{m}$  \hspace{1cm} $L_n^{\text{NIF}} \sim 500 \mu\text{m}$

$T_e^{\text{EP}} \sim 2 \text{ keV}$  \hspace{1cm} $T_e^{\text{NIF}} \geq 3 \text{ keV}$

$\omega/2$ emission is indicative of TPD in PDD implosions on the NIF*

Potential TPD interaction not yet diagnosed on the NIF

TPD on current NIF PDD implosions occurs in clearly delimited regions of the target.

*W. Seka et al., PO4.00011, this conference.
Hot electrons are generated predominantly during the main capsule drive

N131210: CH capsule, 600 kJ, $I = 8 \times 10^{14}$ W/cm$^2$

- Accumulated fraction of hot electrons versus deposited laser energy saturates at ~0.4% in CH ablators
- 0.4% or less conversion efficiency is required for ignition designs
TPD can be reduced by using mid-Z ablators*

The inferred preheat with the Si ablator is reduced by ~50%.

Future experiments will examine laser–plasma and hydrodynamic instabilities

• Cone-in-shell experiments will investigate laser imprint and Rayleigh-Taylor growth at NIF conditions
  – A. Shvydky et al., UO4.00008, this conference

• Planar experiments will approximate the interaction conditions at pole and equator of a PDD target
  – investigate beam angle of incidence on TPD hot-electron production in the absence of CBET

• CBET mitigation via hemispheric $\Delta \lambda$ detuning will be investigated by repointing the outer cones in one hemisphere to the equator
  – J. A. Marozas et al., NO4.00014, this conference
Polar-direct-drive ignition requires additional capabilities on the NIF

Future NIF Experiments

The NIF PDD Laser Path-Forward working group is actively engaged in adding beam smoothing, phase plates, polarization smoothing, and hemispheric $\Delta \lambda$. 

Hemispheric wavelength detuning

$\Delta \lambda \geq -6 \text{ Å (UV)}$ TBD
$\Delta \lambda \geq +6 \text{ Å (UV)}$ TBD

Current capability: $\Delta \lambda \sim \pm 2 \text{ Å (UV)}$

1. Add multi-FM fiber front end and combine with existing system
2. New PDD phase plates ($2\omega$) and polarization plates ($3\omega$) in final optics assembly
3. Add new SSD grating to 48 preamplifier modules (PAM’s)
4. New PDD ignition target insertion cryostat (PDD-ITIC)

The NIF PDD Laser Path-Forward working group is actively engaged in adding beam smoothing, phase plates, polarization smoothing, and hemispheric $\Delta \lambda$. 

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