Proton Radiography of X-ray-Driven ICF Implosions

Proton radiographs

laser beams

58.8°
42.0°

protons

0
4×10^{14}\text{ W/cm}^2

Proton radiographs
0.9 ns 1.6 ns 2.2 ns 2.8 ns

\textit{Science (2010)}

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Summary

Proton radiography of x-ray-driven implosions have resulted in quantitative characterization of important aspects of indirect-drive ICF

- Several types of spontaneous electric fields and megaGauss magnetic fields
- Plasma flows and supersonic jets (~ Mach 4)
- Absence of the filamentary pattern and striations that generally found in laser-driven implosions
- Effects of gas fill impeding hohlraum plasma stagnation
- Extension of proton radiography to the NIF
Protons are inherently sensitive to the structures of plasma density and fields.

\[ D + ^3\text{He} \rightarrow ^4\text{He} + p \ (14.7 \text{ MeV}) \]

\[ D + D \rightarrow ^3\text{T} + p \ (3.0 \text{ MeV}) \]

Spatial resolution: \( \sim 40 \mu\text{m (FWHM)} \)

Energy resolution: \( \sim 3\% \)

Temporal resolution: \( \sim 80 \text{ ps} \)

PRL (2006)
For long-pulse, low-intensity laser light, the dominant source for $B$-field generation is $\nabla n_e \times \nabla T_e$, and the dominant source for $E$ fields is $\nabla P_e$.
The Lorentz force is used to identify and measure $E$ and $B$

(1) Proton trajectory bending is due to the Lorentz force

$$F = q \left( E + \frac{v \times B}{c} \right)$$

(2) Proton deflection angle $\Theta$ is proportional to

$$\propto E_p^{-1} \int E \times d\ell \quad \text{and/or} \quad \propto E_p^{-1/2} \int B \times d\ell$$

(3) Proton deflection due to collisional scattering is also proportional to

$$\propto E_p^{-1}$$

But this process always accompanies with energy loss

\[\begin{array}{c}
\text{Deflection (degree)} \\
\hline
\text{Energy (MeV)} \\
0 & 1 & 2 & 3 \\
0 & 10 & 20
\end{array}\]
Targets

- TIM 6 (P7)
- TIM 4 (P6)
- 100% LEH
- 30 μm Au wall
- ~ 0.6 mm diameter (~50 μm CH shell w/o gas fill)
- 1-atm C₅H₁₂ gas
- 0.6-μm polyimide window
- 58.8° beams
- 42.0° beam
- 4 × 10¹⁴ W/cm²
- 58.8° beams
- 42.0° beam
- ~0.6 mm diameter (~50 μm CH shell w/o gas fill)
The views of the spatial structure and temporal evolution of the laser drive in a hohlraum and implosion properties provide physics insight into x-ray-driven ICF

Vacuum with CH liner

D³He p

0.85 ns  1.60 ns  2.17 ns  2.79 ns

DD p

1.00 ns  1.75 ns  2.32 ns  2.94 ns

A striking feature shown in both fluence and energy images is a five-pronged, asterisk-like pattern surrounding the imploding capsule

Science (2010)
Plasma stagnation results in the hohlraum center and the regions between adjacent plasma bubbles $\Rightarrow E (\propto - \nabla P_e)$

$\beta \sim 10-100$
$C_s \sim 10^7 \text{ cm s}^{-1}$

$t \sim 0 \text{ ns}$

$t \sim 1 \text{ ns}$

Higher density

Supersonic plasma jet

Expanding plasma

Hohlraum wall
The measured hohlraum electric charging (potential) is shown to decay rapidly due to cavity discharge.
A peak $B$ field $\sim 10^6$ gauss is inferred in the proximity of the hohlraum wall.

The beamlets are squeezed ($\xi \sim -10 \ \mu m$) in the center region but expanded ($\xi \sim 100 \ \mu m$) in the out region.

$B \propto \xi \varepsilon_p^{0.5} L_B^{-1}$

Central region $\delta B \sim 0.02 \text{ MG} \rightarrow B \sim 0.2 \text{ MG}$

Outer region $\delta B \sim 0.1 \text{ MG} \rightarrow B \sim 1 \text{ MG}$ (assuming 10% asymmetry)

PRL (2009)
Proton fluence focusing and its reversal reveal a self-generated radial $E$ field and its direction change.

$E_r$ (V/m)

$P_e$ ne $\nabla P_e$

$t = 0.8$ ns

$t = 1.9$ ns

PRL (2008)
Experiments show the absence of the filamentary pattern and striations that generally found in laser-driven implosions.

Directly driven

Indirectly driven

To be submitted (2010)
Proton radiography is being extended to the NIF

In press, PPCF (2010)
Summary/Conclusion

• Proton radiography at OMEGA have provided important information about the hohlraum drive and capsule implosions

• Proton radiography will play an important role in diagnosing of indirect-drive ICF implosions at the NIF