Integrated simulations of fast ignition of inertial fusion targets

Javier Honrubia
School of Aerospace Engineering
Technical University of Madrid, Spain

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Inertial Confinement Fusion

Lasers or X-rays symmetrically irradiate pellet

1-2 mm radius
$10^{14}$-$10^{15}$ W/cm²
a few ns

Material is compressed to
$\sim 1000 \text{ gcm}^{-3}$

Hot plasma expands into vacuum causing shell to implode with high velocity

Hot spark formed at the centre of the fuel by convergence of accurately timed shock waves
National Ignition Facility (NIF)

- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm

NIF is 50 times more energetic than any previous laser
The NIF point design has a graded-doped, beryllium capsule in a hohlraum driven at 285 eV

- Laser Beams
  - (24 quads through each LEH arranged to illuminate two rings on the hohlraum wall)
- Cryo-cooling Ring
- Graded-doped Be Capsule (CH and Diamond are alternates)
- Solid DT fuel layer
- Aluminum assembly sleeve
- Capsule fill tube
- Hohlraum Wall:
  - $U$ or $U_{0.75}Au_{0.25}$
- Hohlraum Fill
  - $He_{0.8}H_{0.2}$ at 0.9 mg/cm$^3$
- Laser Entrance Hole (LEH) with window
Precision targets being developed for the NIF meet the ignition target requirements.
Central ignition vs. Fast ignition

Conventional ICF

(a)

Low-density central spot ignites a high-density cold shell
\( \rho T_{\text{hot}} \approx \rho T_{\text{cold}} \) (isobaric)

Fast Ignitor

(b)

Fast-heated side spot ignites a high-density fuel ball
\( \rho_{\text{hot}} \approx \rho_{\text{cold}} \) (isochoric)
Fast ignition can be achieved with lower drive energies

- Separation between implosion and ignition phases.

Courtesy of M. Key

Fast ignition schemes

Our simulation work

- The research projects carried out on Marenoustrum and Magerit HPC have been focused to analyse alternative ignition schemes of inertial confinement fusion capsules with the aim of lowering the ignition threshold.

- The following schemes have been explored so far:
  - **Electron-driven fast ignition** of inertial fusion targets, where an electron jet is generated by the interaction of an ultra-high intensity (UHI) laser with the cone tip. The electrons deposit their energy in the compressed core triggering the fusion reaction.
  - **Ion-driven fast ignition** the same but driven by UHI laser-accelerated ions.
  - **Magnetized inertial fusion targets.** Just started.

- The simulation codes used have been as follows:
  - The hybrid code **PETRA** [Honrubia et al., *Phys. Plasmas* **12**, 052708 (2005)].
The first integrated FI experiment was very successful


GEKKO laser
9 beams, 0.53 μm, 1.2 kJ / 1ns

0.5 PW

1000x increased DD neutrons
≈20% coupling efficiency to imploded CD
Beam collimation by density effects: Experiment on fast electron transport in high density plasmas

**Experimental setup**

- **4 long pulse beams**
  - 1ns – 40-50J each at $2\omega_0$
  - 160µm focal spots (1/e)

- **Gold shield**

- **Short pulse beam**
  - 12 ps – 160 J at $\omega_0$
  - 20µm FWHM spot
  - $4\times10^{18}$ W/cm²

- **Polyimide hollow cylinder** containing CH foam of 3 ≠ densities:
  - 0.1, 0.3 and 1g/cc

- **Ni foil to produce the hot electrons**

- **Copper foil**

- **Target description**
  - Polyimide shell 1.1g/cc, 20µm thick
  - CH foam $\rho_m$=0.1, 0.3 or 1g/cc
  - 200µm long
  - foam diameter = 180µm

Experiment carried out at RAL

Foams polymerized by W. Nazarov (Univ. St. Andrews)
Targets assembled at RAL (Ch. Spindloe et al.)
Simulation strategy

- **3-D radiation-hydrodynamics** for the cylinder implosion and compression.
- **2D PIC** simulations to characterize the fast electrons generated by the short pulse laser.
- **Hybrid** simulations for simulation of fast electron transport in the compressed cylinder including self-generated electromagnetic fields.

3-D hydrodynamic simulations of target compression

1 g/cm³ foam. 0.1 g/cm³ foam.
First experimental evidence of e-beam collimation


1 g/cc, \( \tau = 1.5 \) ns

1 g/cc, \( \tau = 2.0 \) ns

0.1 g/cc, \( \tau = 1.5 \) ns
Integrated simulations of ignition-scale targets
PIC simulations of electron acceleration in a double cone

- Cone parameters: $\theta = 15^\circ$, $d_{\text{int}} = 10\ \mu\text{m}$, $d_{\text{ext}} = 20\ \mu\text{m}$, $n_e = 80\ n_c$ and $Z^* = 40$ [Debayle, Honrubia et al., Phys. Rev. E 82, 036405 (2010)].

- Numerical parameters: $\Delta x = \Delta y = \lambda/50$, 40 electron/cell.

- 10 million cells, 400 million particles.

Laser beam

- $2 \times 10^{20}\ \text{W/cm}^2$
- $\text{p - polarized}$
- $\lambda = 1\ \mu\text{m}$
- Pulse length 1 ps
- Focal spot = 24 $\mu\text{m}$

Beam density $n_e$

Time integrated spectrum $f(\gamma)$

- $f(\gamma) = A\exp[-(\gamma-1)m_e c^2/kT_e]$ \text{[}\text{keV}]$
- $kT_e = 8.2\ \text{MeV}$

- $f(\gamma) = A (\gamma-1)^\alpha, \ \alpha \sim -1.2$

- $f(\theta) = A\exp\left(-\frac{\theta - \theta_0(y,t)}{\Delta\theta_0(y,t)}\right)^2$
Simulations with ‘standard’ injection

Electron injection without radial drift

- $E_{ig} = 36$ kJ
- $\langle E \rangle = 1.6$ MeV
- $\theta_{HWHM} = \Delta \theta_0 = 35^\circ$


Ion temperature and density

- $T_i$ / keV
- $\rho$ / $(100 \text{ g/cc})$

Resistive magnetic field

- $B_\theta$ / Tesla
- $\rho \geq 250 \text{ g/cm}^3$
- $\rho \geq 100 \text{ g/cm}^3$

Strong collimating magnetic field
Simulations with ‘PIC’ injection ($\theta_r \neq 0$)

electron injection with radial drift

- $E_{ig} = 40$ kJ
- $\langle E \rangle = 1$ MeV
- $\Delta \theta_0 = 22^\circ$, $\theta_r = 20^\circ$


Ion temperature and density

Resistive magnetic field

- $B_\theta / \text{Tesla}$
- $\rho \geq 250 \text{ g/cm}^3$

weak collimating magnetic field
Experimental evidence of fast electron collimation by external magnetic fields


Simulations by H. Nagatomo

Spectrum, angular distribution, image of x-rays are measured.
Ion-driven fast ignition
Generation extremely bright ion beams by the TNSA scheme

Target Normal Sheath Acceleration scheme [Snavely et al., PRL 85, 2945 (2000)]


\[ E_{\text{max}} = 2 T_{\text{hot}} \left[ \ln \left( + \left( \frac{t}{2} + 1 \right)^{1/2} \right) \right]^2 ; \]

\[ = \frac{\pi t_{\text{acc}}}{[2\exp(1)]^{1/2}} \]

\[ \rho_i = \frac{Z_i e^2 n_{e0}}{m_i} \]
“classical” proton FI scheme

Ion beam generation:
- Finite energy spread

Ion beam

standoff distance
cone end-cap to protect ion-source surface

Ignition hot spot

laser

Compressed fuel

(time spread)
Proton focusing in cone-targets has been demonstrated experimentally.


$p$ deflected by an $E$-field $E_r \approx -\nabla p_{he}/n_{he}$

Fluence diameter

Expanded hot $e$ source

$D_{80} (> 9$ MeV$)$

Laser

Focusing radial \( E \)-field at the cone wall

$E_p > 3$ MeV

Au cone 20 $\mu$m!

Divergent beam
PIC simulation data

Open PIC code EPOCH-2D [Arber et al., PPCF 57, 113001 (2015)].

Target [Honrubia, Morace and Murakami, MRE 2, 28-36 (2017); submitted to Phys. Plasmas (2017)].

Length \( x \) = 130 \( \mu \text{m} \), width \( y \) = 90 \( \mu \text{m} \).

Pre-plasma: exponential profile with a scale-length = 2 \( \mu \text{m} \).

Grid: 15 million cells, 600 million particles.

Laser

Wavelength \( \lambda = 1.06 \mu \text{m} \).

Peak laser intensity \( I_0 = 10^{20} \text{ W/cm}^2 \).

Spatial profile: Super-Gaussian, FWHM = 55 \( \mu \text{m} \).

Temporal profile: Gaussian, FWHM = from 1 to 0.35 ps.

Boundary conditions for particles and fields

\( x \) : laser and thermal

\( y \) : periodic

\( n_e = 100 \ n_c \)
Proton beam defocusing by the B-field

- B-field generation at the cone wall by a surface current [Zou et al., Phys. Plasmas 22, 063103 (2015)].

- B-field is dragged by the quasi-neutral plasma of protons + co-moving electrons.

- B-field is amplified and compressed at the cone tip.

- The polarity of the B-field is such that protons are de-collimated, hollowing or even breaking the proton beam.
Experimental validation
Experiments carried out at ILE, Japan

- Free standing cone.
- Gold walls 15 μm thick.
- Hemispherical shell 350 μm radius.
- Pulse energy: 800 J.
- Pulse duration: 1.5 ps.
- Laser intensity on target $\approx 10^{19}$ Wcm$^{-2}$.

after A. Morace et al.
Confirmation of beam hollowing

The experimental results confirm the effect of B-fields on free standing cones with the protons being deflected in a ring-like shape by the B-fields.
Confirmation of beam hollowing

The experimental results confirm the effect of B-fields on free standing cones with the protons being deflected in a ring-like shape by the B-fields.
New cone design to mitigate the B-fields near the cone walls

- Double cone with a ‘second wall’ isolated from the laser-to-proton converter foil.

- No currents flow through the second wall because it is electrically isolated. Thus, the B-field is confined to the gap between the two cone walls.

- Only the B-field generated at the rear surface of the converter foil is dragged by the quasi-neutral plasma and amplified at the cone tip. This field is much lower than that generated by the surface currents,
Double wall cone design to "shield" the quasi-neutral plasma from the B-field

- B-field generated by the currents flowing along the cone outer wall are 'confined' in the gap between the two walls.
- The B-fields at the cone tip are reduced substantially compared with the single wall cones. Even the low energy protons are well collimated.
- The divergence half-angle in this case is about 10 - 15° (HWHM) depending on the proton energy.

Laser intensity $I_{l,max} = 10^{20}$ W/cm$^2$, carbon cone tip.
Summary

- PIC and hybrid simulations have proven to be very useful for experiment design and interpretation.
- *MareNostrum* and *Magerit* super-computers allowed us to carry out realistic simulations, competitive with those performed at the large scale laser facilities.
- We plan to study other alternative schemes to reduce the ignition energies. Some of those schemes are shock ignition and magnetized inertial confinement fusion.
- Those new schemes will be analyzed in close contact with experiments and within the context of the EUROPfusion projects ‘Towards inertial fusion energy’ and ‘Preparation and Realization of European Shock Ignition Experiments’ funded by Euratom.

Thanks for your attention!