Electron-driven fast ignition: current status and perspectives

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Outline

- Ignition-scale modelling.
- Divergence control methods.
- Electron guiding by external B-fields.
  - Experimental evidence of fast electron guiding at ILE.
  - Effects of B-fields on fast electron guiding in wires.
- Reduction of the cone – core standoff distance
- Conclusions
- What can be achieved with PETAL?
Ignition-scale simulations: ‘assumed’ FE source

\[ E_{\text{ig}} = 36 \text{ kJ} \]
\[ \langle E \rangle = 1.6 \text{ MeV} \]
\[ \theta_{\text{HWHM}} = 35^\circ \]

Honrubia&Meyer-ter-Vehn, PPCF 51, 014008 (2009)

Ion temperature and density

Resistive magnetic field

Chirsman et al., PoP 15, 056309 (2008)
Haines et al., PRL 102, 0450089 (2009)
Debayle et al., PRE 82, 036405 (2010)
Kluge et al., PRL 107, 205003 (2011)
FE source from PIC simulations

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

PIC simulations by Debayle et al., PRE 82, 036405 (2010)

Ion temperature and density

Resistive magnetic field

$T_i$ / keV
$\rho$ / (100 g/cc)

$B_\theta$ / Tesla

$\rho \geq 250 \text{ g/cm}^3$

weak collimating magnetic field
2D/3D PIC simulations of 1.3 PW, $1.4 \times 10^{20}$ W/cm$^2$ laser pulse up to $\sim 2$ ps

[Kemp and Divol, PRL 109, 195005 (2012)]

After $\sim 2$ ps the density profile and energy flux spectrum resemble the no-preplasma case.

Density of ‘hot’ electrons, laser- and electron energy flux

20µm diameter flat-top laser pulse $10^{20}$W/cm$^2$

Average angle vs. position

100 $n_c$

$L = 3.5 \, \mu m$

Line-out of Reference case

Line-out of ‘no-preplasma’

Spectrum of electron energy flux

energy-integrated angle spectrum

$\gamma = 2.5$

$< \theta > = 47^\circ$
Results shown by Strozzi et al. in PoP 19, 072711 (2012) based on PSC code simulations [Kemp and Divol, PRL, (2012)].

**One-dimensional factorization** of the fast electron source

\[ N(E, \theta) = N_0 f_E(E) f_\theta(\theta) \quad ; \quad \tan \theta = \left[ (v_x^2 + v_y^2)^{1/2} / v_z \right] \]

The energy spectrum \( f_E(E) \) is given by two temperatures

\[ f_E(E) = \frac{1}{\epsilon} \exp[-\epsilon / \tau_1] + 0.82 \exp[-\epsilon / \tau_2] \quad ; \quad \epsilon = \frac{E}{T_p} \quad ; \quad \tau_1 = 0.19 \quad \text{and} \quad \tau_1 = 1.3 \]

where \( T_p \) is the ponderomotive “temperature”.

The mean energy is \( \langle E \rangle = 1.02 \times T_p \) **Only 24% of the energy is carried out by electrons with energies lower than that given by the ponderomotive scaling.**

The angle spectrum is

\[ f_\theta(\theta) = 2\pi \sin \theta \exp\left[-(\theta / \Delta \theta)^4\right] \quad ; \quad \Delta \theta = 90^\circ \]

The mean divergence mean-angle is \( \langle \theta \rangle = 52^\circ \). Divergence is the same for all electrons, independently of their energy.
Ignition scale simulations by Strozzi et al.

- Target with 0.57 mg of DT, $\rho R = 3 \text{ g/cm}^2$.
- $r_{\text{spot}} = 18 \mu\text{m}$, $I_L = 1.4 \times 10^{21} \text{ W/cm}^2$, $\langle E \rangle = 8.2 \text{ MeV}$.
- **Artificially collimated** source $\Delta \theta_0 = 10^\circ$
- $E_{\text{ign}} = 132 \text{ kJ}$ of fast electrons.

<table>
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<tr>
<th>Density [g/cm$^3$]</th>
<th>Energy density [J/cm$^3$]</th>
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- Black squares for 10 $\mu$m radius, red circles for 14 $\mu$m, blue triangles for 18 $\mu$m and green crosses for 23 $\mu$m.

$E_{\text{fast}} = \text{fast e}^-\text{ energy [kJ]}$
- Two beam pulses [R.H.H. Scott et al., PRL 109, 015001 (2012)]

- Resistivity gradients [Robinson, Sherlock, and Norreys, PRL 100, 025002 (2008); Cai et al., PoP 18, 023106 (2011)]

- Magnetic switchyard [Robinson, Key and Tabak, PRL 108, 125004 (2012)].

- Decreasing density filaments [Debayle et al., PoP 20, 013109 (2013)].

- Parabolic resistivity mirror at the cone tip. [Robinson and Schmitz, PoP 20, 072704 (2013)]

- External B-fields.
Guiding of e-beams by strong B-fields
Divergence, energy distribution and flux of e-beam by using x-ray convertor attached target.

Collimating E-beam by strong-$B_z$

Spectrum, angular distribution, image of x-rays are measured.

Simulations by H. Nagatomo

ILE, Osaka
Angular distribution of bremsstrahlung x-ray indicates collimation of electron beams by external B-field.

**Collimating E-beam by strong-$B_z$**

Standard Au cone

Ext. B-field

Current

LFEX → GXII

20.9 deg.

69.0 deg.

77.6 deg.

Low $h\nu$ → high $h\nu$
Effects of resistive fields $B_\theta$ and external $B_z$-fields on fast electron energy deposition

Energy deposition

Coulomb collisions only

Coulomb collisions + resistive fields

Coulomb collisions + resistive fields + $B_{z,ext}$

Deposition is enhanced in high resistivity zones

Beam collimation and energy deposition are strongly enhanced by the $B_z$ field.
Effect of the external B-fields on fast electron guiding in wires
Fast electron guiding in wires with external B-fields

Solodov, FSC workshop on electron divergence in fast ignition (2010)

- UHI laser
- DLC, Al, Cu, Au
- e-beam
- \( \langle E \rangle = 3.5 \text{ MeV} \)
- \( \theta_{\text{HWHM}} = 55^\circ \)
- \( E_{\text{beam}} = 50 \text{ kJ} \)

- DT peak density = 450 g/cm\(^3\)
- DT fuel
- \( d_{\text{tip}} = 40 \mu\text{m} \)
- \( t_{\text{tip}} = 20 \mu\text{m} \)
- \( L_{\text{wire}} = 50 \mu\text{m} \)

- \( I_{\text{coil}} = 2, 5 \text{ and } 10 \text{ MA} \)

- "hot spot" 30×40 \( \mu\text{m} \)
e-guiding by wires and external B-fields

Energy deposition

$B_{z,\text{ext}} = 0$

uniform $B_{z,\text{ext}} = 1 \, \text{kT}$

$I_{\text{coil}} = 10 \, \text{MA}$

- DLC tip + wire

- Energy deposition

- $J_{\text{cm}^3}$
Coupling efficiencies with wires and external B-fields

(*) Coil current generating the external magnetic field.
Electron kinetic energy and beam divergence are critical issues for electron driven fast ignition.

PIC simulations show that even with a small pre-plasma, beam divergence is important and may hamper the magnetic collimation by resistive fields, leading to high ignition energies.

Electron guiding by external B-fields may be a solution.

kTesla magnetic field generation has been demonstrated experimentally.

Preliminary experiments and simulations show that external magnetic may help to improve the laser-core coupling substantially.

External B-fields improve fast electron guiding in wires, specially for low or intermediate Z wires.

Thanks for your attention!
What can be achieved with PETAL?

- Full characterization of the fast electron source in the fast ignition scenario, including electron energies, beam divergences, role played by the laser pre-pulse.
- Effects of external B-fields on fast electron, generation, transport and energy deposition.
- Studies of very intense electron beams interaction with compressed targets.
- Calibration of PIC and hybrid codes for FI conditions.
- All these points are important to advance towards a point design for e-driven FI.