Magnetic Guiding for Electron Fast Ignition

D. J. Strozzi
Lawrence Livermore National Laboratory

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Magnetic pipes can guide electrons to fast-ignition hot spot

• Fast electron source:
  – too energetic to stop in DT hot spot
  – large angular divergence

• Imposed axial magnetic field \( \sim 50 \) MG overcomes divergence
  – Magnetic mirroring: increasing field reflects electrons back to source
  – Magnetic pipe: hollow field inside beam radius – prevents mirroring

• Azimuthal pipe of right sign works better than axial pipe:
  – Agrees with expectation from orbits

• Sign of axial pipe matters!
  • Not based on orbits, or resistive Ohm’s law \( E = \eta J_{\text{return}} \)
  • non-resistive terms in Ohm’s law gives different field evolution

• Co-authors: M Tabak, D Larson, H Shay, L Divol, A Kemp, C Bellei, M Marinak, M Key

Fast ignition modeling at LLNL

**Explicit PIC** for short-pulse laser-plasma interaction: A. J. Kemp, L. Divol

**Rad-hydro:** fuel assembly in hohlraum, around cone: H. D. Shay, M. Tabak, D. Ho

**Transport modeling**

Zuma (hybrid-PIC): fast electrons, E/B fields coupled to Hydra: rad-hydro, burn, radiation

Subject of this talk
Zuma: D. J. Larson: Hybrid PIC code for fast electron transport in collisional plasmas

- RZ cylindrical (this talk) or 3D Cartesian geometries

- Reduced dynamics: no light, plasma waves: \( \omega \ll \omega_{pe}, \omega_{laser} \quad k \ll k_{laser}, \lambda^{-1}_{Debye} \)

- Electric field from Ohm's law = massless momentum eq. for background electrons:

\[
m_e \frac{d\vec{v}_{eb}}{dt} = -e\vec{E} + ... = 0 \quad \rightarrow \quad \vec{E} = \vec{E}_C + \vec{E}_{NC}
\]

\[
\vec{E}_C = \vec{\eta} \cdot \vec{J}_{\text{return}} - e^{-1}\vec{\beta} \cdot \nabla T_e \quad \vec{E}_{NC} = -\frac{\nabla p_e}{en_{eb}} - \vec{v}_{eb} \times \vec{B}
\]

Resistive Ohm's law: \( \vec{E}_C = \eta \vec{J}_{\text{return}} \)

\( \vec{\eta}, \vec{\beta} \) from Lee-More-Desjarlais and Epperlein-Haines

Relativistic fast electron advance: \( \vec{F} = -e(\vec{E} + \vec{v} \times \vec{B}) \)

- Fast e- energy loss and angular scattering [Solodov, Davies]

- \( \vec{J}_{\text{return}} = -\vec{J}_{\text{fast}} + \mu_0^{-1} \nabla \times \vec{B} \)

Ampere w/o displacement current

\( \vec{J}_{\text{return}} \cdot \vec{E}_C \) collisional heating

- \( \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \) Faraday

Full Ohm’s law results differ from \( E = \eta^* J_{\text{return}} \)

Nicolai et al., APS DPP 2010, Phys Rev E 84, 016402 (2011)

Strozzi et al., IFSA 2011 (submitted)
This talk:
- both codes in R-Z geometry, fixed Eulerian meshes
- 20 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)

Diagram:
- Coupling step
  - $t_0$: Plasma conditions to Zuma (densities, temperatures)
  - $t_1$: Hybrid transport (energy, momentum deposition rates)
  - $t_2$: Hydro steps

Flowchart:
- Zuma steps...
- Hydra steps...

Code coupling:
- Zuma steps
- Hydra steps
- Coupling step
Electron spectra from PSC full-PIC sims (A. J. Kemp, L. Divol)

**Energy spectrum**

\[
\frac{dN}{d\varepsilon} = 0.82 \exp[-\varepsilon/1.3] + \frac{1}{\varepsilon} \exp[-\varepsilon/0.19]
\]

“hot:” from pre-plasma  \( \varepsilon = \frac{E}{T_{\text{pond}}} \)  \( \langle \varepsilon \rangle = 1.02 \)

“cold:” from \( n_{\text{crit}} \)

\[
T_{\text{pond}} / m_e c^2 \equiv \left[ 1 + a_0^2 \right]^{1/2} - 1 \sim a_0
\]

**Angle spectrum**

\[
\frac{dN}{d\Omega} = \exp\left[-(\theta / \Delta\theta)^4\right] \quad \Omega = \text{solid angle}
\]

\[
\langle \theta \rangle \approx 0.69 \Delta\theta
\]

<table>
<thead>
<tr>
<th>( \Delta\theta )</th>
<th>( \langle \theta \rangle )</th>
<th>runs used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>6.9°</td>
<td>artificially collimated source</td>
</tr>
<tr>
<td>90°</td>
<td>52°</td>
<td>matches PSC; realistic source</td>
</tr>
</tbody>
</table>

\[ \Delta \theta \]

\[ \langle \theta \rangle \]

transport code

PSC

classical ejection angle:

\[ \tan \theta = \left[ \frac{2}{(\gamma - 1)} \right]^{1/2} \]
Idealized high-gain target: carbon cone, ideal ignition energy of 8.7 kJ

Ideal e-ignition energy [Atzeni et al., PoP 2007]:
• 2D rad-hydro, no cone, cylindrical beam heat source
  
  \[ E_{ig} = \frac{140 \text{ kJ}}{(\rho/100 \text{ g/cc})^{1.85}} \]
  
  \[ = 8.7 \text{ kJ} \]

• 527 nm (2\(\omega\)) wavelength laser: lowers \(T_{\text{pond}} \sim \lambda\)

• Ideal burn-up fraction: \(\rho R/(\rho R+6) = 1/3\)

• Ideal fusion yield = 64 MJ
Ignition energy is 15x ideal value with collimated electron source

\[ E_f = \text{fast e− energy [kJ]} \]

<table>
<thead>
<tr>
<th>Energy spectrum</th>
<th>initial $\Delta \theta$</th>
<th>angular scattering</th>
<th>E/B fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 MeV</td>
<td>0</td>
<td>no</td>
<td>none</td>
</tr>
<tr>
<td>1.5 MeV</td>
<td>$10^\circ$</td>
<td>yes</td>
<td>none</td>
</tr>
<tr>
<td>PIC</td>
<td>$10^\circ$</td>
<td>yes</td>
<td>none</td>
</tr>
<tr>
<td>PIC</td>
<td>$10^\circ$</td>
<td>yes</td>
<td>$E = \eta J_{\text{return}}$</td>
</tr>
<tr>
<td>PIC</td>
<td>$10^\circ$</td>
<td>yes</td>
<td>full Ohm’s</td>
</tr>
</tbody>
</table>
Realistic divergence greatly increases ignition energy; axial magnetic field 30-50 MG mitigates divergence

- Omega implosion experiments: compressed 50 kG seed field to:
  30-40 MG (cylindrical\textsuperscript{1}), 20 MG (spherical\textsuperscript{2})

- Rad-hydro-MHD studies of B field compression have begun: H. D. Shay, M. Tabak

\textsuperscript{1}J. P. Knauer, Phys. Plasmas 17, 056318 (2010)
Axial magnetic field that increases in $z$ leads to mirror force, reflects fast electrons

$$\nabla \cdot \vec{B} = 0 \quad \rightarrow \quad B_r = -\frac{1}{r} \int_0^r dr' r' \frac{\partial B_z}{\partial z}$$

$$\vec{F} = q\vec{v} \times \vec{B} \quad \rightarrow \quad F_z = -qv_\phi B_r$$

mirroring: $F_z$ towards decreasing $B_z$

**Initial $B_z$ profiles**

**Fast e- energy reflected to left edge**

**Fusion yield**

- Fast e- energy [kJ]
- Energy fraction
- Fusion yield [MJ]
- z [µm]
- $B_z$ [MG]
- DT fuel

- Fast e-source
- Sharp rise near source

DJS: AA 2012   p. 10
Magnetic pipe: hollow inside spot radius, avoids mirroring

\[ B_{z0} = 50 \text{ MG pipe} \]
\[ B_{z0} = 50 \text{ MG uniform} \]
\[ B_{z0} = 50-75 \text{ MG} \]
\[ B_{z0} = 0-50 \text{ MG} \]

Fusion yield

Fast e- energy reflected to left edge

Initial \( B_z \) max = 50 MG

DT fuel

pipe

Fast e- energy [kJ]

energy fraction

fast e- energy [kJ]
Magnetic pipes: sign and direction (axial vs. azimuthal) matters

Thinner pipe: easier to assemble

- So far I’ve used $B_z > 0$, the wrong sign – sorry!


* Courtesy C. Bellei
Orbits of electrons in magnetic pipe fields

Orbit-based quality of pipe confinement:
B_φ < 0
B_z < 0 and B_z > 0 same
B_φ > 0

Orbits explain performance of B_φ signs, and B_φ vs B_z – but not role of sign(B_z)

Cartesian geometry: (r,φ,z) = (x,y,z)
Magnetic pipes in simplified, uniform plasma

Zuma runs, no Hydra, no cone or dense fuel

Next page: Power = rate energy exits at right, \( r < 20 \, \mu m \), at most 1.3 MeV per electron (~ stopping in hot spot)
Full Ohm’s law gives different confinement based on sign($B_z$):

- **$E = 0$, $B$ fixed**
  - $B_\phi < 0$ best
  - $B_z < 0$ and $> 0$ same
  - $B_\phi > 0$ worst
  - Coupling as expected from orbits

- **$E = \eta J_{\text{return}}$, $B$ evolves**
  - coupling drops:
    - plasma diamagnetic
  - ordering unchanged

- **$E$ = full Ohm’s law**
  - $B_z < 0$ better than $B_z > 0$!
Full Ohm’s law: magnetic fields evolve differently than with $E = \eta J_{\text{return}}$, and for each sign ($B_z$)

$B_{z0} > 0$
$+B_z$ plotted

$B_{z0} < 0$
$-B_z$ plotted

Initial $B_z$

Fields at $t = 20$ ps

$E = \eta J_{\text{return}}$

$E = \text{full Ohm’s law}$

plasma diamagnetic: reduces pipe, similar for both sign($B_z$)

More change in $B$ field, different for each sign($B_z$)!

$230$ MG peak!
Is fast ignition a pipe dream?

- Imposed, axial magnetic fields 30-50 MG recover ignition energy of artificially-collimated electron source

- Magnetic mirroring in increasing field reduces benefit

- Mirroring overcome with magnetic pipes – hollow out to e-source radius

- Pipe confinement best for one sign of $B_\phi$ – beats either $B_z$ sign
  - Orbits explain this
  - Fast e- can self-generate in radial resistivity gradient

- $B_z < 0$ pipe confines better than $B_z > 0$
  - Orbits don’t explain this!
  - Nor does resistive Ohm’s law $E = \eta J_{return}$
  - Full Ohm’s law does: $B$ fields evolve differently