Relativistically Thermal Plasma Generation by Magnetically Assisted Direct Laser Acceleration

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Motivation

- Relativistic electron motion significantly alters plasma dynamics, but experimental access is limited
  - non-perturbatively bulk-relativistic plasma is needed for verification of basic predictions and study of astrophysically relevant processes
  - examples
    - relativistic bioengineering
    - parametric and beam-pointing instabilities
    - astrophysical shock acceleration
    - Weibel instability
    - co-occurring ultra-high-intensity laser pulses obscure these phenomena

Entering the non-perturbatively bulk-relativistic plasma regime requires a new type of laser-plasma heating

- Requirements
  - non-perturbative bulk relativistic ($y > 1$ for most electrons)
  - persistent after all driving laser pulses have passed
  - large volume
  - optically diagnosable density

Plasma-heating mechanism

<table>
<thead>
<tr>
<th>Plasma-heating mechanism</th>
<th>Owing majority of electrons to interaction volume?</th>
<th>Scalable in large volume?</th>
<th>Last after laser pulse?</th>
<th>Optimally diagnosable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client laser acceleration (DLA) in vacuum</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe (reversible)</td>
<td>NA</td>
</tr>
<tr>
<td>Near-critical plasma</td>
<td>Yes</td>
<td>No (propagation unstable)</td>
<td>Maybe (surrounded by cold dense plasma)</td>
<td>Maybe (requires high-frequency probe)</td>
</tr>
<tr>
<td>Structured target</td>
<td>Yes</td>
<td>Yes</td>
<td>No (surrounded by cold dense plasma)</td>
<td>No (structure blocks diagnostic access)</td>
</tr>
<tr>
<td>Laser wakefield acceleration (LWFA)</td>
<td>No (not tied)</td>
<td>Maybe</td>
<td>No (propagation unstable)</td>
<td>Maybe (electrons escape)</td>
</tr>
<tr>
<td>Structured DLA (e.g., 500-1000 kW, 10 ps)</td>
<td>Maybe (requires large spot and long pulse)</td>
<td>Maybe (long pulse unstable)</td>
<td>Maybe (electrons escape)</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnetically assisted DLA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Multi-MeV plasma is predicted for a range of conditions

- Single-particle picture of heating
- Step 1: Multi-cycle acceleration by short pulse
- Step 2: energy kick by single cycle in long pulse
- The short pulse is needed to catalyze long-pulse heating

Multi-MeV plasma is predicted for a range of conditions

- Particle-in-cell simulation
  - Normal 3-D case ($y = 1$, $\delta = 300$ T, $\delta = 1.2$)
  - Hydrogen: $\alpha = 10^{-7}$, $\Delta = 100$ nm
  - Long pulse: $\delta = 10^{-7}, \, \alpha = 0.8$ ps
  - Short pulse: $\alpha = 10^{-7}, \, \Delta = 90$ fs
  - Both: 100 mm FWHM
  - Multi-MeV plasma is predicted for a range of conditions

- Theoretical scaling
  - Single kick by long pulse (max):
    - $\Delta \alpha = 2 \Delta^{-1/2} \Delta W^{1/2}$
  - Threshold for heating by long pulse:
    - $\Delta \alpha = 0.5 \Delta^{-1/2} \Delta W^{1/2}$

- Average energy of all electrons in $y > 3 \mu m$

Experimental verification is feasible with state-of-the-art technology

- Capacitor cell magnetic field (95) E-beamlines-like design
- Pulsed-power magnetic field (99) EP-ORAL-like design

Transverse magnetic fields break the usual DLA invariants, enabling energy retention, even in vacuum

$$B = 0$$

Regime for energy retention, $\alpha_{DLA} < 10^{-1}$

- momentum rotation is small compared to laser cycle, but not pulse duration
- momentum rotation affects electron interaction with a single laser cycle

$x$-propagating, $y$-polarized laser pulse with applied $B_y$, $A_{DLA} = 0$.
Motivation

- Relativistic electron motion significantly alters plasma dynamics, but experimental access is limited
  - non-perturbatively bulk-relativistic plasma is needed for verification of basic predictions and study of astrophysically relevant processes
  - examples
    - relativistic birefringence
    - parametric and beam-pointing instabilities
    - astrophysical shock acceleration
    - Weibel instability
  - co-occurring ultrahigh-intensity laser pulses obscure these phenomena

Relativistic birefringence \([1]\)

Hosing instability \([2]\)

Weibel instability \([3]\)
Entering the non-perturbatively bulk-relativistic plasma regime requires a new type of laser-plasma heating

- non-perturbatively bulk relativistic ($\gamma \approx 1$ for most electrons)
- persistent after all driving laser pulses have passed
- large volume
- optically diagnosable density

### Plasma-heating mechanisms

<table>
<thead>
<tr>
<th>Plasmas heating mechanisms</th>
<th>Heats majority of electrons in interaction volume?</th>
<th>Scalable to large volume?</th>
<th>Lasts after laser pulse?</th>
<th>Optically diagnosable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct laser acceleration (DLA) in vacuum</td>
<td>Yes</td>
<td>Yes</td>
<td>No (reversible)</td>
<td>N/A</td>
</tr>
<tr>
<td>Near-critical plasma</td>
<td>Yes</td>
<td>No (propagation unstable)</td>
<td>Maybe (surrounded by cold dense plasma)</td>
<td>Maybe (requires higher-frequency probe)</td>
</tr>
<tr>
<td>Structured target</td>
<td>Yes</td>
<td>Yes</td>
<td>No (surrounded by cold dense plasma)</td>
<td>No (structure blocks diagnostic access)</td>
</tr>
<tr>
<td>Laser wakefield acceleration (LWFA)</td>
<td>No (hot tail)</td>
<td>Maybe</td>
<td>No (electrons escape)</td>
<td>Yes</td>
</tr>
<tr>
<td>Stochastic DLA (e.g., SM-LWFA)</td>
<td>Maybe (requires large spot and long pulse)</td>
<td>Maybe (long pulse unstable)</td>
<td>Maybe (electrons escape)</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnetically assisted DLA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
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SM-LWFA: self-modulated laser wakefield acceleration
Transverse magnetic fields break the usual DLA invariants, enabling energy retention, even in vacuum

\[ B = 0 \]
\[ \frac{d}{dt}(p_y - a) = 0 \]
\[ \frac{d}{dt}(y - p_x) = 0 \]

\[ B \neq 0 \]
\[ \frac{d}{d(\omega_0 t)}(p_y - a) = \frac{\omega_c}{\omega_0} p_x \]
\[ \frac{d}{d(\omega_0 t)}(y - p_x) = \frac{\omega_c}{\omega_0} p_y \]

- Regimes for energy retention, \( \omega_c \ll \omega_0 \)
- momentum rotation is slow compared to laser cycle, but not pulse duration [4]
- momentum rotation affects electron interaction with a single laser cycle [5]

\( x \)-propagating, \( y \)-polarized laser pulse with applied \( B_0 \hat{z} \); \( \omega_c = eB_0/mc \)
Utilizing two laser pulses couples regimes of magnetically assisted direct laser acceleration, generating relativistically thermal, underdense plasmas [6].

Single-particle picture of heating

Step 1: multi-cycle acceleration by short pulse

Step 2: energy kicks by single cycle in long pulse

The short pulse is needed to catalyze long-pulse heating

Particle-in-cell simulation [7]
Nominal 2-D case ($x-y$)
$B_0 = 500 \ T$ (in $z$)
Hydrogen; $n_e = 10^{-3} \ n_c$
$L = 100 \ \mu m$

Long pulse:
$a_\phi = 1$, $t_\phi = 0.8 \ ps$

Short pulse:
$a_\phi = 5$, $t_\phi = 20 \ fs$

Both: 100 $\mu m$ FWHM

Bulk-relativistic plasma is generated with 2-D isotropic momentum

Spectra for $|r| < 25 \ \mu m$

Hot plasma persists beyond laser pulse duration

Average energy of all electrons in $|r| < 25 \ \mu m$
Multi-MeV plasma is predicted for a range of conditions [6,8]

Theoretical scaling
Single kick by long pulse (max): \( \Delta y = 2^{3/2} \alpha_s^{3/2} \sqrt{\omega_0/\omega_{c0}} \)

Threshold for heating by long pulse: \( y_0 \geq 0.3 \sqrt{\omega_0/\omega_{c0}} \)

Average energy if fraction of electrons above \( y_0 \) after short pulse is \( f_{\text{hot}} \):
\[
\langle \gamma \rangle \approx 0.6 f_{\text{hot}} \frac{\tau_f}{\tau_{c0}}
\]

\( \tau_{c0} = 2 \Delta y/\omega_{c0} = \Delta y \tau_{c0} \)
\( \rho_L = c \tau_L / 2\pi \)

Heating can be improved from the 2-D case
Experimental verification is feasible with state-of-the-art technology.

References

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