Effects of Kilotesla-Level Magnetic Fields on Relativistic Laser–Plasma Interaction

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Pronouns: they/them
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Kilotesla-level applied magnetic fields introduce new possibilities for relativistic laser–plasma interaction

- Currently available magnetic fields appear “weak” by bulk metrics, yet are sufficiently strong to influence laser-plasma dynamics
- Laser plasmas with embedded magnetic fields do not always behave diamagnetically
- Applied magnetic fields can dramatically change plasma expansion
- Kilotesla or subkilotesla fields can enable new forms of direct laser acceleration-based heating
- Applied magnetic fields open the door to many additional phenomena

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How strong are experimentally available magnetic fields?

- “Obvious” effects require strong magnetic fields
  - $B_0 > B_{\text{laser}}$
  - cyclotron resonance ($\omega_{ce} \gtrsim \omega_{\text{laser}}$)
  - direct magnetization ($\beta_e = \frac{8\pi n_e T_e}{B_0^2} < 1$)


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- State-of-the-art magnetic fields reach 100 T to 1 kT

- Compare to fs- to ps-duration pulses with $a_0 = \frac{|e| E_{\text{laser}}}{m_e c \omega_{\text{laser}}} \sim 1 - 3$:
  - $B_0/B_{\text{laser}} \lesssim 1/10$
  - $\omega_{ce}/\omega_{\text{laser}} \lesssim 1/10$
  - $\beta_e \gtrsim 20$

A kilotesla magnetic field is “weak” by bulk metrics, yet can still have a strong impact.

RCF: radiochromic film
A relativistic laser produced plasma is not always diamagnetic and can generate magnetic fields

\[ B_{20} = 100 \, \text{T to} \, 1 \, \text{kT} \]

**Opaque target**

- 2-\(\mu\)m thick CH < \(\rho_L\)
- 0.1-\(\mu\)m preplasma scale length

**Laser**

- \(1 \times 10^{19} \, \text{W/cm}^2\)
- 100 fs FWHM
- \(\lambda = 0.8 \, \mu\)m
- y polarized

**Simulations**

- 1-D and 2-D
- \(EPOCH\) PIC code

- (Hypothetical) diamagnetic picture
  - laser generates hot plasma
  - current in hot plasma reduces the applied magnetic field

\[ B_z = 0.8 \, \mu\text{m} \]

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PIC: particle in cell
Surface field generation is an overshoot of the diamagnetic effect

- Cyclotron rotation of hot electrons originating at the laser–plasma interface leads to a net transverse current
- Hot electron current is screened by cold population within the target, allowing it to overshoot the usual diamagnetic limit
- The magnetic-field estimate based on cyclotron rotation agrees well with observed fields (for $\Delta x < \rho_L$)

Surface magnetic field generation is a kinetic effect.
Surface magnetic-field generation can have surprising consequences

- Microtube implosions generate and amplify magnetic fields
  - Microtube target
    - 3-µm thick CH shell
    - 3-µm radius central void
    - four lasers
  - Lasers
    - $1 \times 10^{21}$ W/cm²
    - 15 µm FWHM
    - 25 fs FWHM
    - $\lambda = 0.8$ µm
    - y polarized

Any magnetic field present can be amplified by the implosion.

The sign of the amplified field can be reversed due to surface magnetic-field generation.

Seed magnetic fields enable strong magnetic-field generation.

\[ B_{z0} = 3 \text{ kT} \]

Plasma expansion and sheaths
Target-normal applied magnetic fields can enhance sheath-based ion acceleration

Opaque target:
- 5-μm thick CH
- 1.5-μm-preplasma scale length
- 3-D simulation

Laser:
- $2 \times 10^{19}$ W/cm$^2$
- 3 μm FWHM
- 150 fs FWHM
- $\lambda = 1$ μm
- $y$ polarized

Target-normal applied magnetic fields can enhance sheath-based ion acceleration

Opaque target
5-μm thick CH
1.5-μm preplasma scale length
3-D simulation

Laser
2 × 10^{19} W/cm^2
3 μm FWHM
150 fs FWHM
λ = 1 μm
y polarized

Target thickness ~ Larmor radius substantially increases ion energy and number

\[ \theta = 1 \mu m \]

\[ \text{y polarized} \]

Proton
Carbon

0 T
0°
10°

Test electron trajectories

(Eventual) magnetization of sheath induces ion focusing

Magnetization: \( \frac{E_{\text{sheath}}}{B_0} \sim \sqrt{\frac{4\pi n_e T_e}{B_0^2}} \sim \sqrt{\beta_e} \lesssim 1 \)

- Initially \( \beta_e > 1 \), but \( n_e \) (and \( \beta_e \)) drop during plasma expansion
- Change in \( E_\perp \) leads to ion focusing

A target-normal magnetic field produces a focusing ion source with enhanced energy and numbers.

Direct laser acceleration and plasma heating
Applied magnetic fields enable new regimes in direct laser acceleration

A transverse magnetic field \((B_z)\) with \(y\)-polarized laser enables electron energy retention

- **Partial cyclotron rotation**
  - initially cold plasma
  - pulse duration < cyclotron period
  - \(\gamma_{\text{final}} \lesssim a_0\)

- **Magnetically assisted kicks**
  - initially hot plasma
  - pulse duration \(\gg\) cyclotron period
  - \(\gamma_{\text{final}} \sim a_0^{3/2} (\omega_{\text{laser}}/\omega_{\text{ce}})^{1/2}\)

These acceleration strategies can be combined.

Magnetized direct laser acceleration can create a relativistic, underdense thermal plasma.

\[ B_{z0} = 100 \text{ to } 500 \text{T} \]

Magnetic fields enable relativistic plasma generation in an otherwise difficult-to-access regime.

**Femtosecond laser**
- \( a_0 = 5 \)
- 20 fs FWHM

**Picosecond laser**
- \( a_0 = 1 \)
- 0.8 ps FWHM

**Both lasers**
- \( 10^{-3} \text{ to } 10^{-2} n_c \)
- 100-\( \mu \text{m} \)-thick-H
- \( \lambda = 1 \mu\text{m} \)
- 100 \( \mu \text{m} \) FWHM

Relativistic energy retained in plasma

Magnetic fields enable relativistic plasma generation in an otherwise difficult-to-access regime.
Magnetized relativistic laser-plasma physics offers many additional phenomena

A few examples

Magnetic-field amplification in a solid by return current*

Electromagnetic wave generation during plasma expansion into neutral gas**

Multiple cycles of ponderomotive energy gain (e.g., by a flying focus pulse)

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Backup slides
Scale comparison for 1 kT

**Typical parameters for modestly relativistic laser-plasma**

<table>
<thead>
<tr>
<th>Laser parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser amplitude</td>
<td>$a_0 = \frac{</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>100 fs – 10 ps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot electron temperature</td>
<td>$T_e \sim \text{MeV}$</td>
</tr>
<tr>
<td>Plasma density (hot part)</td>
<td>$n_e \sim 10^{-4} - 1 \times n_{cr}$</td>
</tr>
<tr>
<td></td>
<td>$\sim 10^{17} - 10^{21} \text{ cm}^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser-plasma scales</th>
<th>Magnetic field scales</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser frequency</td>
<td>Cyclotron frequency</td>
<td>$\omega_{laser}/\omega_{ce} \gtrsim 10$</td>
</tr>
<tr>
<td>Laser field $B_{laser}$</td>
<td>Applied field $B_0$</td>
<td>$B_{laser}/B_0 \gtrsim 10$</td>
</tr>
<tr>
<td>Thermal pressure</td>
<td>Magnetic field pressure</td>
<td>$\beta_e = 8\pi n_e T_e/B_0^2 \sim 20 - 500$</td>
</tr>
<tr>
<td>Scale of electron motion</td>
<td>Larmor radius $\rho_L$</td>
<td>$\rho_L/l \sim 1 - 10$</td>
</tr>
</tbody>
</table>
Surface magnetic field generation

\[ B_{z0} = 1 \text{kT} \] generates \( > 10 \text{kT} \)

\[ \frac{B_z}{B_0} - 1 \] (1000 T)

Strong magnetic field generation is due to cyclotron rotation of hot electrons in target

Estimate based on momentum rotation in target \( (\Delta x < \rho_L) \)

\[ \frac{B_{\text{gen}}}{B_{\text{seed}}} \sim -2\pi \frac{\Delta x}{\lambda_{\text{laser}}} \]

\[ \Delta x \sim \rho_L \]

Surface magnetic field generation can have surprising consequences

Microtube implosions generate and amplify magnetic fields

Microtube target
- 3 μm thick CH shell
- 3 μm radius central void
- 4 lasers

Lasers
- 1x10^{21} W/cm²
- 15 μm FWHM
- 25 fs FWHM
- λ = 0.8 μm
- y-polarized

Initially unmagnetized \((B_{z0} = 0)\) case
- Asymmetry provides seed magnetic field
- \(B\) is amplified by electron current after ions reach center \((E \times B)\)

Early (electron) \(t < t_c\)
Later (ion) \(t \approx t_c\)

Any magnetic field present can be amplified by the implosion

Polarity of amplified field is sensitive to parameters

Amplification of surface field

Circular case

- **Initial** $t = 15$ fs
- **Implosion** $t = t_c$
- **Explosion phase** $t = t_c + 15$ fs, $t = t_c + 50$ fs

When surface magnetic field is unstable, it can be amplified in lieu of the seed

- **Unstable**
  - Circular $w_0 = 15$ µm
- **Stable**
  - Square $w_0 = 15$ µm

Transverse magnetic fields can also affect target expansion

\[ B_{z0} \gtrsim 1 \, kT \]

**Opaque target**
- 2 \( \mu m \) thick CH target \( \gtrsim \rho_L \)
- 0.1 \( \mu m \) preplasma scale length
- 2D simulation

**Laser**
- 1x10^{19} \text{ W/cm}^2
- 100 fs FWHM
- \( \lambda = 0.8 \, \mu m \)
- \( y \)-polarized

**Unusual:** acceleration from the front surface can exceed the rear surface

**Deflection from laser axis**

Magnetized direct laser acceleration can create relativistic, underdense thermal plasma

\[ B_{z0} = 100 - 500 \, T \]

Long pulse

\[ a_0 = 5 \]

20 fs FWHM

fs laser

\[ \lambda = 1 \, \mu m \]

Both lasers

\[ 100 \, \mu m \text{ FWHM} \]

\[ a_0 = 1 \]

0.8 ps FWHM

ps laser

\[ \lambda = 1 \, \mu m \]

Plasma

\[ 10^{-3} - 10^{-2} n_{cr} \]

100+ \( \mu m \) thick H

\[ 100+ \, \mu m \text{ thick H} \]

Both lasers

\[ \lambda = 1 \, \mu m \]

2D simulation

Magnetic fields enable relativistic plasma generation in an otherwise difficult-to-access regime
Heating mechanism is robust to electron motion in the third direction

With $p_z \neq 0$

$$p_x = |p| \cos \theta$$

$$\frac{d\theta}{ds} = \sqrt{1 - \frac{p_z^2}{p_y^2 + p_z^2}} \cdot \frac{\omega_c}{\omega_0} + \frac{1}{\gamma (1 - \beta \cos \theta)} \frac{da}{ds}$$

$$\frac{dy}{ds} = \sqrt{1 - \frac{p_z^2}{p_y^2 + p_z^2}} \cdot \frac{\beta \sin \theta}{1 - \beta \cos \theta} \frac{da}{ds}$$

Final average energy: 0.9 MeV

Motion in third direction preserves $\theta$ during acceleration, but reduces energy gain
Heating is robust over $10^{-3} - 10^{-2} n_{cr}$, but breaks down for higher density

- Lasers substantially modify density profile for $10^{-3} n_{cr}$, but this does not appear to affect spectrum.
- At lower density (e.g. $10^{-4} n_{cr}$), have $\omega_p < \omega_c$, which changes dynamics (based on 1D simulations).
- At higher density, charge separation $E$ visibly interrupts cyclotron rotation.
1D simulations predict even higher energy can be achieved in mm plasma, including with lower fields.

\[ B_0 = 500 \text{T} \]

\[ B_0 = 200 \text{T} \] (longer pulse duration)

Magnetically assisted DLA may be experimentally realizable using easily accessible plasma conditions.