Relativistically Transparent Magnetic Filaments: a short-pulse path to megaTesla fields and efficient gamma radiation

Hans Rinderknecht
University of Rochester
Laboratory for Laser Energetics

Anomalous Absorption Conference
11:00 AM, Tuesday June 7th 2022

Schematic of a magnetic filament

Relativistically Transparent Magnetic Filaments: a short-pulse path to megaTesla fields and efficient gamma radiation

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Schematic of a magnetic filament

Predicted radiation ($I = 5 \times 10^{22} \text{ W/cm}^2$)

Photon energy

Efficiency


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Summary

Magnetic filaments promise a repeatable and efficient laser-driven source of MT fields, relativistic electrons, and MeV photons

- Intense lasers in relativistically-transparent plasmas generate ultra-strong magnetic filaments
  - Electrons are trapped and accelerated, efficiently radiating MeV-scale photons

- Scaling laws were derived for magnetic filament radiation, and validated with 3-D PIC simulations
  - Efficiency of >10% is predicted for intensity above $6 \times 10^{21} \text{ W/cm}^2$

- Experiments have been performed on Texas Petawatt and OMEGA-EP to test these predictions
  - The predicted electron and photon signatures were observed in a subset of experiments
Collaborators

LLE/UR:
• Hans Rinderknecht
• Gerrit Bruhaug
• Kathleen Weichman
• Matthew Van Dusen-Gross
• John Palastro
• Mingsheng Wei

UCSD:
• Alexey Arefiev
• Tao Wang

HZDR:
• Toma Toncian
• Alejandro Laso Garcia

Texas Pettawatt (TPW)/UT Austin:
• Hernan J. Quevedo
• Todd Ditmire

General Atomics (GA):
• Jarrod Williams
• Alex Haid

ELI-NP:
• Domenico Doria
• Klaus Spohr

Johns Hopkins University:
• Dan Stutman
Relativistic transparency allows an intense laser to interact with a plasma above the classical critical density ($n_{cr}$)

3-D PIC simulations ($a_0 = 50 \sim 3\times10^{21}$ W/cm$^2$)$^1$:

$$a_0 \equiv \frac{|e|E_0}{m_e \omega c} \propto \sqrt{\text{Intensity}}$$

$\geq 1 \rightarrow$ relativistic electrons

$$n_{cr} = \frac{\epsilon_0 m_e}{e^2} \omega_L^2$$

= critical plasma density limit for a laser of frequency $\omega_L$

$a_0 > 1 \rightarrow$ Relativistic Transparency:

$$n_e \leq n_{cr} \langle \gamma \rangle \approx n_{cr} a_0$$

The ponderomotive force drives a relativistic current, producing a strong azimuthal magnetic field: a magnetic filament

3-D PIC simulations \((a_0 = 50)^1\):

Magnetic field of current normalized to laser field:

\[
\frac{B_j}{B_0} = \left( \frac{\mu_0 j r}{2} \right) \left( \frac{2 \pi a_0 mc}{e \lambda} \right)
\]

\[
= \pi \left( \frac{r}{\lambda} \right) \left( \frac{n_e \beta}{n_{cr} a_0} \right)
\]

\[
= \pi r^2 S_a
\]

Quasi-static magnetic fields of the order of the oscillating laser field are produced.

---

Electrons oscillate within the filament: those in phase with the laser are rapidly accelerated.

Electron orbits & acceleration \((a_0 = 50)^1\)

\[ y_{MB} = 1.6\mu m \]

\[ y \ [\mu m] \]
\[ x \ [\mu m] \]

\[ 1200 \]
\[ 600 \]
\[ 0 \]

Y

\^1Z. Gong, et al., Phys. Rev. E 102, 013206 (2020);
Electrons oscillate within the filament: those in phase with the laser are rapidly accelerated, and radiate in the strong magnetic field.

The maximum magnetic field seen by electrons depends on the laser focal radius and the initial transverse momentum.

\[ \hbar \omega_{rad} \propto \gamma^2 B, \quad P_{rad} \propto \gamma^2 B^2 \]

\[ Y_{MB} = 1.6 \mu m \]

\[ \text{channel edge} \]

\[ \text{Photon radiation (} a_0 = 190 \text{)}^2 \]

\[ \text{Electron orbits & acceleration (} a_0 = 50 \text{)}^1 \]

\[ \text{Emissions (a.u.)} \]

\[ \text{Radiation events:} \]

\[ \bullet > 2 \text{ MeV} \]

\[ \bullet > 30 \text{ MeV (a.u.)} \]

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\[ ^1 \text{Z. Gong, et al., Phys. Rev. E 102, 013206 (2020);} \]

Analytical scaling laws and 3-D PIC simulations of magnetic filaments predict > 10% radiation efficiency of MeV photons from sufficiently intense lasers.

Photon energy and radiation efficiency \( \propto a_0^3 \propto I^{3/2} \)

**Parameters:**
- \( a_0 = 190 \) (5×10^{22} W/cm^2)
- \( S_\alpha = 0.105 \) \((n_e = 20n_{cr})\)
- \( R_\lambda = [0.65, 2.1] \)
- \( \tau_\nu = 10.5 \) (35 fs)

**For more details, please see:**
doi:10.1088/1367-2630/ac22e7
Initial experiments to study relativistically transparent magnetic filaments were performed at the Texas Petawatt Laser (TPW)\textsuperscript{1}

- Wavelength: 1057 nm
- Energy: 98.8 ± 6.0 Joules
- Duration: 140 fs
- Power: 694 ± 38 TW

- Intensity: [1.09 ± 0.07]×10\textsuperscript{21} W/cm\textsuperscript{2} (a\textsubscript{0} = 29.9 ± 1.0)
- Radius: 2.6 ± 0.12 μm (at 50% peak intensity)
- Pointing: 8-μrad rms → 5-μm rms on target

- Primary diagnostics: EPPS electron spectrometer\textsuperscript{2}
  Gamma calorimeter

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\textsuperscript{1}See http://texaspetawatt.ph.utexas.edu/
\textsuperscript{2}H. Chen et al., RSI 79, 10E533 (2008)
Microchannel targets filled with low-density foam \( (n_e = 5 \text{ or } 10 \text{ n}_c) \) were developed for this campaign.

Given the pointing stability (5-\( \mu \text{m rms})\), we did not expect channel interactions on every shot.

11 shots were performed with good laser-target alignment:

- \([\times 5]\) 6-\( \mu \text{m channels}, 5\text{-n}_c \text{ fill}\)
- \([\times 3]\) 6-\( \mu \text{m channels}, 10\text{-n}_c \text{ fill}\)
- \([\times 1]\) 6-\( \mu \text{m channels}, \text{unfilled}\)
- \([\times 2]\) Planar foam, 10-\( \text{n}_c\)

Channels filled with low-density CH foam:

\(15 \text{ or } 30 \text{ mg/cm}^3\)
The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots consistent with the predicted magnetic filament behavior.

**Electron temperatures**

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Electron temperature (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
</tr>
</tbody>
</table>

6-μm ID
15 mg/cm³
30 mg/cm³

**Example electron spectra**

- 3D PIC (channel)
- 3D PIC (solid)

(b) 6-μm ID, 15-mg/cm³ fill

The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior.

Electron temperatures

3-D PIC simulations:
- 15 mg/cm$^3$ channel fill
- 30 mg/cm$^3$ channel fill
- “solid” (~0.6 g/cm$^3$)
The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior.

Given the pointing stability and channel size, the probability of observing N interactions is:

<table>
<thead>
<tr>
<th>N</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.21</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>0.03</td>
</tr>
<tr>
<td>5+</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

We conclude that the predicted electron acceleration was observed in a subset of these experiments.
A follow-on campaign on OMEGA-EP (Dec 2022) used a new target engineering technique to improve laser-target coupling: 3-D printing inside foam.

![Image of foam-filled channel targets]

This technique increases the density of channel openings and guarantees the foam fully fills the channel.

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Beam</th>
<th>Peak I x10^{20}</th>
<th>a_0 max</th>
<th>Target ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>35891</td>
<td>BL</td>
<td>3.49</td>
<td>16.8</td>
<td>Empty channels</td>
</tr>
<tr>
<td>35892</td>
<td>SL</td>
<td>1.42</td>
<td>10.7</td>
<td>Empty channels</td>
</tr>
<tr>
<td>35893</td>
<td>BL</td>
<td>10.1</td>
<td>28.6</td>
<td>3 mg/cc (1 n_{cr})</td>
</tr>
<tr>
<td>35894</td>
<td>SL</td>
<td>3.84</td>
<td>17.6</td>
<td>3 mg/cc (1 n_{cr})</td>
</tr>
<tr>
<td>35895</td>
<td>BL</td>
<td>7.69</td>
<td>25.0</td>
<td>3 mg/cc (1 n_{cr})</td>
</tr>
<tr>
<td>35896</td>
<td>SL</td>
<td>3.01</td>
<td>15.6</td>
<td>3 mg/cc (1 n_{cr})</td>
</tr>
<tr>
<td>35897</td>
<td>BL</td>
<td>9.64</td>
<td>28.0</td>
<td>5 mg/cc (1.6 n_{cr})</td>
</tr>
<tr>
<td>35898</td>
<td>SL</td>
<td>3.08</td>
<td>15.8</td>
<td>3 mg/cc (1 n_{cr})</td>
</tr>
<tr>
<td>35899</td>
<td>BL</td>
<td>6.76</td>
<td>23.4</td>
<td>5 mg/cc (1.6 n_{cr})</td>
</tr>
<tr>
<td>35900</td>
<td>SL</td>
<td>2.74</td>
<td>14.9</td>
<td>5 mg/cc (1.6 n_{cr})</td>
</tr>
<tr>
<td>35901</td>
<td>BL</td>
<td>6.56</td>
<td>23.1</td>
<td>5 mg/cc (1.6 n_{cr})</td>
</tr>
<tr>
<td>35902</td>
<td>SL</td>
<td>4.49</td>
<td>19.1</td>
<td>5 mg/cc (1.6 n_{cr})</td>
</tr>
<tr>
<td>35903</td>
<td>BL</td>
<td>6.80</td>
<td>23.5</td>
<td>Empty channels</td>
</tr>
<tr>
<td>35904</td>
<td>SL</td>
<td>1.55</td>
<td>11.2</td>
<td>5 mg/cc (1.6 n_{cr})</td>
</tr>
</tbody>
</table>
The first OMEGA-EP experiments show electron acceleration on all target types: No significant difference was observed between target types.

EPPS data:

Shot 35893: BL, 3 mg/cc

Shot 35901: BL, 5 mg/cc

Shot 35903: BL, empty

**possible exception
Shot 35897: BL, 5 mg/cc
Subsequent 3-D PIC simulations predict that, for 0.7 ps pulses, the magnetic field amplitude and electron and x-ray spectra are independent of fill density. All cases essentially behave the same as the empty channel.

Slide courtesy of: Kathleen Weichman
For future EP experiments, we will continue to test out advanced targets for improved laser-channel coupling and “long-pulse” coupling physics.

### Improved target arrays
(June 15, 2022)

Contentrator targets
(Matt Van-Dusen Gross (GS), FY23)

Channels extend slightly (10 μm or less) beyond foam.

Channels have tapered entrances:
- resolution limit = 0.5 μm for walls
- At entrance, channels are 7.5 μm diam, tapering to 6 μm diam over >10 μm
- $\tan(\text{Angle}) < (1.5) / (10) \rightarrow \phi < 9^\circ$
With 10-PW lasers now becoming available, magnetic filaments promise exciting opportunities for high-flux gamma-ray sources.

<table>
<thead>
<tr>
<th>Laser</th>
<th>ELI-NP†</th>
<th>ELI-Beamlines L4‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ</td>
<td>0.8 μm</td>
<td>1.057 μm</td>
</tr>
<tr>
<td>τ</td>
<td>23 fs</td>
<td>150 fs</td>
</tr>
<tr>
<td>Peak power</td>
<td>10 PW</td>
<td>10 PW</td>
</tr>
<tr>
<td>Intensity (a₀)</td>
<td>5×10²² W/cm² (153)</td>
<td>5×10²² W/cm² (202)</td>
</tr>
<tr>
<td>Design choice: Sα</td>
<td>0.01</td>
<td>Sα = 0.05</td>
</tr>
<tr>
<td>Photon energy &lt;ε&gt;</td>
<td>68 MeV</td>
<td>9.2 MeV</td>
</tr>
<tr>
<td>Total energy Eγ,tot</td>
<td>111 J</td>
<td>51 J</td>
</tr>
<tr>
<td># photons Nγ</td>
<td>1.0×10¹³</td>
<td>3.5×10¹³</td>
</tr>
<tr>
<td>Efficiency η</td>
<td>48%*</td>
<td>22%*</td>
</tr>
</tbody>
</table>

By varying the channel design, the photon spectrum and flux may be optimized.

*model limited by radiation depletion

† D. Ursescu, et al., Romanian Reports in Physics 68, S11 (2016)
Summary

Magnetic filaments promise a repeatable and efficient laser-driven source for MT fields, relativistic electrons and MeV photons

- Intense lasers in relativistically-transparent plasmas generate ultra-strong magnetic filaments
  - Electrons are trapped and accelerated, efficiently radiating MeV-scale photons

- Scaling laws were derived for magnetic filament radiation and validated with 3-D PIC simulations
  - Efficiency of >10% is predicted for intensity above $\sim 10^{22}$ W/cm$^2$

- Experiments have been performed on Texas Petawatt and OMEGA-EP to test these predictions
  - The predicted electron and photon signatures were observed in a subset of experiments
Electrons orbit within a magnetic boundary. Those in phase with the laser are accelerated, and radiate by deflecting in the strong magnetic field.

Magnetic boundary:\(^1\):  
\[
\frac{r_{mb}}{\lambda} \approx \frac{1}{\pi} \sqrt{\frac{\gamma_i n_e}{n_c}} \approx \frac{1}{\pi} \sqrt{\frac{f_i}{S_{i\alpha}}} 
\]

\[
\left( f_i = \frac{\gamma_i}{a_0} \right)
\]

The maximum magnetic field seen by electrons is limited by the smaller of focal radius and magnetic boundary.

\(^1\)Z. Gong, et al., Phys. Rev. E 102, 013206 (2020);

Using simple assumptions for the electron acceleration and orbits, we derive scaling laws for the radiation from magnetic filaments.

0: Electrons are thermal

\[ f_e(\dot{\mathcal{U}}, t) = \frac{N_e}{T_e} \exp \left[ -\frac{\mathcal{U}}{T_e} \right], \quad \text{where} \quad N_e = n_e \left( \pi R^2 \right)(ct) \]

1: Electron acceleration is linear in time

\[ T_e(t) = C_T d_0 \left( \frac{ct}{\lambda} \right) mc^2 \equiv C_T d_0 t, mc^2 \]

2: Radiation is synchrotron-like

\[ \frac{dP}{d\mathcal{U}} = f_r \frac{4}{9} \alpha_{jsc} \frac{mc^2}{\hbar} \left( \frac{B}{B_{cr}} \right) F \left[ \frac{\mathcal{U}}{\mathcal{U}_c} \right], \quad \text{where} \quad \mathcal{U}_c = \frac{3}{2} \gamma mc^2, \quad F[x] \equiv \frac{9\sqrt{3}}{8\pi} \int_{0}^{\infty} K_{5/3}(z) dz \left[ \int_{0}^{\infty} F(y) dy = 1 \right] \]

3: The laser depletes by heating electrons

\[ \frac{E_e}{E_{Laser}} \leq 1 \quad \rightarrow \quad \tau_{v,max} \leq \frac{\sqrt{\pi}}{4 (\ln 2)^{3/2}} \frac{1}{C_T S_\alpha}. \quad \text{We define:} \quad \tau_{v,cut} \equiv f_t \tau_{v,max} \approx 0.768 \frac{f_i}{C_T S_\alpha} \]

These assumptions have four constants: \( f_i, f_t, f_r, C_T \) and four design parameters: \( a_0, S_\alpha, R/\lambda, ct/\lambda \)

Using simple assumptions for the electron acceleration and orbits, we derived scaling laws for the radiation from magnetic filaments.

**Radiation property:**

- **...if focal radius \( R < r_{mb} \):**
  - **Photon energy**
    \[ \langle \hat{\mathcal{U}} \rangle_{\text{tot}} \approx 1.38 \times 10^{-6} f_i^2 a_0^3 S_a^{-1} R_{\lambda}^3 \lambda_{\mu n}^{-1} m_e c^2 \]
  - **Radiated energy**
    \[ E_{\gamma,\text{tot}} \approx 7.74 \times 10^2 f_i f_i^3 C_T^{-1} a_0^5 R_{\lambda}^4 \tau_y m_e c^2 \]
  - **# photons**
    \[ N_{\gamma,\text{tot}} = 5.59 \times 10^8 f_i f_i^3 C_T^{-1} a_0^2 S_a R_{\lambda}^3 \lambda_{\mu n} \]
  - **Radiation efficiency**
    \[ \eta_{\gamma} = 2.88 \times 10^{-7} f_i f_i^3 C_T^{-1} a_0^3 R_{\lambda}^2 \lambda_{\mu n}^{-1} \]

- **...if focal radius \( R > r_{mb} \):**
  - **Photon energy**
    \[ \langle \hat{\mathcal{U}} \rangle_{\text{tot}} \approx 4.40 \times 10^{-7} \sqrt{f_i f_i^3 a_0^3 S_a^{-3/2} \lambda_{\mu n}^{-1}} m_e c^2 \]
  - **Radiated energy**
    \[ E_{\gamma,\text{tot}} \approx 7.84 \times 10^1 f_i f_i^3 C_T^{-1} a_0^5 R_{\lambda}^2 \tau_y m_e c^2 \]
  - **# photons**
    \[ N_{\gamma,\text{tot}} = 1.78 \times 10^8 \sqrt{f_i f_i^3 C_T^{-1} a_0^2 S_a^{1/2} R_{\lambda}^2 \tau_y \lambda_{\mu n} \}
  - **Radiation efficiency**
    \[ \eta_{\gamma} = 2.92 \times 10^{-8} f_i f_i^3 f_i C_T^{-1} a_0^3 S_a^{-1} \lambda_{\mu n}^{-1} \]

→ **4 Parameters:** 
  - Intensity \((a_0)\), Relativistic transparency \((S_a = n_e/n_0 a_0)\), Focal radius \((R_f)\), Pulse duration \((\tau_y)\)

→ **3 Constants:** 
  - Initial e- momentum scalar \((f_i \sim 1)\), cutoff scalar \((f_t < 1)\), radiation duty cycle \((f_r < 1)\)

**For more details, please see:**
doi:10.1088/1367-2630/ac22e7
The scaling laws show good agreement with 3-D PIC simulations that varied the focal radius, with reasonable constants.

**Photon energy**

**Total radiated energy**

**# photons**

**Efficiency**

<table>
<thead>
<tr>
<th>Parameters:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0 = 190$ (5×10$^{22}$ W/cm$^2$)</td>
<td></td>
</tr>
<tr>
<td>$S_\alpha = 0.105$ ($n_e = 20n_{cr}$)</td>
<td></td>
</tr>
<tr>
<td>$R_\lambda = [0.65, 2.1]$</td>
<td></td>
</tr>
<tr>
<td>$\tau_v = 10.5$ (35 fs)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constants:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_i = 1.533$, initial electron momentum scalar,</td>
<td></td>
</tr>
<tr>
<td>$f_t = 0.311$, cutoff time scalar,</td>
<td></td>
</tr>
<tr>
<td>$f_r = 0.189$, radiation duty cycle,</td>
<td></td>
</tr>
</tbody>
</table>

doi:10.1088/1367-2630/ac22e7
Primary diagnostics were an electron spectrometer (EPPS) and a gamma calorimeter (GCAL) in the expected radiation direction.

A factor of 5 difference in photon brightness is predicted between microchannel and ‘solid’ targets.
The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior.

Electron temperatures

Example electron spectra

The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior.
The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior.

Given the pointing stability and channel size, the probability of observing N interactions is:

<table>
<thead>
<tr>
<th>N</th>
<th>Probability</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0.21</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>0.27</td>
</tr>
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<td>3</td>
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<td>0.03</td>
</tr>
<tr>
<td>5+</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

We conclude that the predicted electron acceleration was observed in a subset of these experiments.

The ‘hot’ electron temperature was elevated on 2 of 8 microchannel shots, consistent with the predicted magnetic filament behavior.

The number of photons > 10 keV also scaled with hot electron temperature as expected.