Guideing Channels for Next-Generation LWFA:

Simulations of low-density and high rep. rate plasma channels

**Outline:**
- Axicons have been used for many years to form long plasma channels\(^1\), but these were limited by the heating mechanism to high densities
- Optical Field Ionization (OFI) can heat electrons on the femtosecond timescale, independent of target density
- We simulate the creation of hot plasma columns using OFI and their subsequent evolution into plasma channels, which are all-optical and could operate at kHz repetition rates
- Our results demonstrate the creation of long (10s of centimetres) and low density (10\(^13\) cm\(^{-3}\) and below) plasma channels, which would be suitable for > 10 GeV LWFA stages

**Scheme:**
1. Create a long and hot plasma column along an axicon focus, using Optical Field Ionization from a femtosecond pulse
2. The column expands outwards into the cold neutral gas, forming a shock front and leaving a cavity on axis
3. After some time, a second co-propagating pulse can be guided by the plasma channel within this cavity

**Key Physics:**
- Operate at 10\(^9\) - 10\(^10\) cm\(^3\) with \(T_e\approx 10\) eV. 10s \(\mu m\) scale channel.
- Shock propagates near sound speed \(c_s\approx 10\) km/s, expanding 10s of microns in nanoseconds
- Spitzer equilibration and isotropization collision times are \(\tau_{\text{coll}}\approx 1\) - 10 ps
- Debye length \(\lambda_D\approx 10\) - 100 nm and only 10 ppm of electrons have \(E_k > V\approx m_e c^2/\lambda_D^2\) and can escape channel
  \(\Rightarrow\) No charge separation and a thermal and isotropic velocity distribution means a fluid code can accurately describe channel expansion
- Repetition rate is limited by dissipation of the shock waves and plasma recombination, on much longer timescales

**Process** | **Timescale** | **Model with:**
--- | --- | ---
Optical Field Ionization | fs | EPOCH PIC Code
Thermalization & Isotropization | ps | Spitzer Collisions
Shock Propagation / Channel Expansion | ns | HELIOS Fluid Code
Laser Guiding | ns | In-House Propagation Code
Recombination / Quiescence | \(\mu s\) | -

**High Energy Gain LWFA stages:**
- Dephasing between electrons and laser limits stage length, \(L_d\approx 1\) GeV
- OFI heating can produce channels this length using very little energy
- \(E_k = \frac{2 \lambda D \nu_{\text{ion}}}{\pi} I_{\text{th}} < 100\) mJ/m for ionization at \(I_{\text{th}}\approx 4\times 10^{14}\) W/cm\(^2\)
- At the dephasing length energy gain is \(\Delta W\approx \frac{3 m_e c^2}{L_d}\approx \frac{3 m_e c^2}{\nu_{\text{ion}} L}\)

**Properties:**

<table>
<thead>
<tr>
<th>On-Axis Density</th>
<th>Dephasing Length</th>
<th>Estimated Energy Gain</th>
<th>Axion Parameters</th>
<th>Approx. OFI Energy Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^17) cm(^{-3})</td>
<td>90 cm</td>
<td>30 GeV</td>
<td>(\alpha = 2), (R = 3)°</td>
<td>&lt; 90 mJ</td>
</tr>
</tbody>
</table>

---

\(^{[1]}\) Axicon Channels - C. G. Durfee III et al, PRL 71, (1993)
\(^{[2]}\) Waveguide Modes - H. Sheng et al, PRE 72, (2005)
\(^{[3]}\) OFI Channels - Lemos et al, Phys. Plas. 20, (2013)

---

Christopher Arran, R. J. Shallow, J. Jonnerby, J. Holloway, L. Corner, H. M. Milchberg, R. Walczak, S. M. Hooker

Heating with Optical Field Ionization:
- Canonical momentum \(P(t) = p(t) + eA(t)\) is conserved, so electron momentum after a laser pulse has passed is \(P_f = p(t_0) + eA(t_0)\).
- If an electron is born at rest after ionization at \(t_0\), the final electron energy after only femtoseconds is therefore \(E_k = \frac{|p|}{2m_e} |A(t_0)|^2\)
- Electrons are ionized mainly when \(|A(t_0)|\approx A_{\text{th}}\).

\(E = -\frac{\partial A}{\partial t}\) so \(|A(t_0)|\) can be very high, for a circularly polarized laser \((E_k \approx 2I_0)\), or very low, for linear polarization \((E_k \approx 0)\)

\(\Rightarrow\) Simulate this in EPOCH for Hydrogen at different laser ellipticities
- Changing the target species increases \(E_{\text{th}}\) and hence \(|A(t_0)|\) and \(E_k\)

Channel Expansion:
- Simulate channel expansion with HELIOS fluid code, using initial conditions from simulating an axicon beam in Hydrogen
- Can compare to Sedov solution \(r(t) = (r + 1) \left(\frac{E_0}{M_{\text{ion}}}\right)^{1/2} \left|A_0(t_0)\right|^{1/2}\)
- Fit matched spot with in-house beam propagation code \(^1\) and find losses
- Calculated matched spot 20-40 \(\mu m\), with \(\%\) attenuation length 40-100 cm
- Suitable to guide LWFA drivers over channels of lengths of up to a meter, well suited to the axicon
- On axis density falls to 10\(^7\) cm\(^{-3}\)

See also: J. Jonnerby, Experimental design, poster 144
R. J. Shallow, Experimental results, WG5 Tuesday
Thanks to: STFC UK, grant no. ST/J002011/1
Helmholtz Association, grant no. VH-VI-503