Review of Laser Guiding Experiments

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Outline

• Why do we need waveguides?
• Hollow capillary waveguides
• Plasma waveguides
• Relativistic and ponderomotive guiding
Limitations to the laser-plasma interaction length

Diffraction

Spot size: Refraction

1/e² radius in intensity

Diffraction limits the interaction length to the order of the *Rayleigh range*:

$$Z_R = \frac{\pi W_0^2}{\lambda}$$

Example: $W_0 = 10 \ \mu m; \ \lambda = 1 \ \mu m$

$\Rightarrow Z_R = 0.3 \ \text{mm}$

For partially ionized plasmas, refraction further limits the interaction length

$$\eta = \sqrt{1 - \frac{N_e e^2}{\gamma m_e \varepsilon_0 \omega^2}}$$
Hollow capillaries: Multimode guiding

Issues

- Complex transverse intensity profile
- Higher losses
- Modal dispersion (temporal distortion)
- Low group velocity

- Capillaries 100 µm diameter, 30 mm long
- Guiding of 1 J, 1 ps pulses at input intensity of $\sim 2 \times 10^{17}$ W cm$^{-2}$ ($\sim 20$ µm input spot)
- $T = 16\%$
Hollow capillaries: Single-mode guiding


- In order to excite only the lowest-order (EH$_{11}$) mode, the spot size of the input beam must be adjusted to give maximum overlap with that mode.
- Can couple 98% of Gaussian into EH$_{11}$ if $W_0 = 0.645 \, a$

radius = 30 µm, $L = 54$ mm
Hollow capillaries: Single-mode guiding


**Laser:**
- pulse duration 120 fs
- peak intensity $5 \times 10^{16}$ W cm$^{-2}$

**Issues:**
- Addition of gas increases both coupling and propagation losses.
  - e.g. factor of 6 reduction in transmission for 20 mbar He.
- Unwanted structure on laser can damage capillaries in only a few shots
Gradient refractive index guiding - Plasma waveguides

For non-relativistic intensities the refractive index of a plasma may be written:

\[ \eta = \sqrt{1 - \frac{N_e e^2}{m_e \varepsilon_0 \omega^2}} \approx 1 - \frac{1}{2} \frac{N_e e^2}{m_e \varepsilon_0 \omega^2} \]

Hence a \textit{parabolic electron density profile}:

\[ N_e(r) = N_e(0) + \Delta N_e \left( \frac{r}{r_{ch}} \right)^2 \]

supports matched guiding of Gaussian beams with a constant spot size:

\[ W_M = \left( \frac{r_{ch}^2}{\pi r_e \Delta N_e} \right)^{1/4} \]
An *axicon* lens is used to produce an extended longitudinal focus in a gas (Ar, N$_2$ etc).

Focused pulse has intensity of $\sim 10^{14}$ W cm$^{-2}$ and duration of $\sim 100$ ps so as to ionize and heat the gas.

Hydrodynamic expansion of resulting cylindrical plasma column produces guiding channel.
high intensity mode structure

end coupling

axicon

OptLett97

injection

$50 \, \text{mJ}, 70 \, \text{fs}$

$800 \, \text{nm}$

$100 \, \mu \text{m}$

$1.5 \, \text{cm}$

$I_{\text{inside}} \sim 10^{17} \, \text{W/cm}^2$

gas jet

Gas jet: APL98
Gas jet guiding: PRE99
Bessel beam coupling: PRL00
Plasma waveguides: Hydrodynamic expansion

Issues

• Plasma channel only partially ionized (Ar$^{8+}$)
• Difficult to achieve avalanche breakdown in gases such as H or He

Improvements

• Ignitor-heater method: Use intense fs laser pulse to produce seed electrons by optical field ionization
• Use a discharge to provide seed electrons
Plasma waveguides: Hydrodynamic expansion

- Guiding of $10^{17}$ W cm$^{-2}$ over 15 mm with $T= 50\%$ in fully ionized He channels
- Axial plasma density $4 \times 10^{18}$ cm$^{-3}$

Issues
- Low density possible?
- Require one or more auxiliary laser systems to form plasma channel
- Energy of auxiliary laser scales with length of channel
Plasma waveguides: Hydrodynamic contraction
B. M. Luther *et al.* 8th International Conference on X-Ray Lasers (2002)

Fast-rising current pulse in capillary discharge causes collapse of plasma by z-pinch.

- Capillary ~ 4 mm diameter
- Peak current ~ 5 - 20 kA
- Rise-time 10 - 50 ns
Plasma waveguides: Hydrodynamic contraction

B. M. Luther et al. 8th International Conference on X-Ray Lasers (2002)

- Capillary 3.2 mm dia., 110 mm long
- Discharge 15 - 20 kA, rise-time ~ 60 ns
Plasma waveguides: Hydrodynamic contraction
B. M. Luther et al. 8th International Conference on X-Ray Lasers

- Guiding of $\sim 10^{15}$ W cm$^{-2}$ over 110 mm long channels
- Plasma density on axis $\sim 2 \times 10^{17}$ cm$^{-3}$

Issues
- Plasma fully ionized?
- Rapid collapse of plasma column requires very low timing jitter $< 1$ ns
- Relatively complex driving circuit
Plasma waveguides: Discharge-ablated capillary waveguides


Discharge through *evacuated* capillary forms plasma

- Peak current 100 – 200 A
- Rise-time ~ 100 ns

Plasma channel formed by radial thermal conduction

Guiding of $10^{17}$ W cm$^{-2}$ over 20 mm with $T = 75\%$.

**Issues**

- Ablation of capillary wall leads to short lifetime
- Plasma channel is only partially ionized
Plasma waveguides: Gas-filled capillary discharge waveguide

- 300 µm diameter alumina capillary
- Gas injection points comprise 4, 600 x 75 µm slots
- Gas flowed continuously or pulsed for ~ 2 s
- Peak current 100 - 500 A
- Rise-time ~ 50 – 100 ns
Plasma waveguides: Gas-filled capillary discharge waveguide


Plasma profile mainly determined by thermal conduction to (cold) capillary wall:

\[
\frac{1}{r} \frac{d}{dr} \left( r \kappa_{e\perp} \frac{dT}{dr} \right) + \sigma_{\perp} E^2 = 0
\]
Plasma waveguides: Gas-filled capillary discharge waveguide


30 mm long, 400 µm diameter waveguide
Input intensity $1 \times 10^{17}$ W cm$^{-2}$

Issues
- Scalable to lower electron density?
Relativistic guiding

Hence the refractive index is of the form:

\[ \eta = \eta_0 + \eta_2 l \]

This leads to self-focusing for beams above a critical power given by:

\[ P_c = 17.4 \left( \frac{\omega}{\omega_p} \right)^2 \text{ GW} \]

Example

\[ N_e = 10^{18} \text{ cm}^{-3}, \lambda = 800 \text{ nm} \]

\[ P_c = 8 \text{ TW} \]
Ponderomotive channelling

The ponderomotive force expels electrons from the axial region forming a plasma channel.

- laser power 4.3 TW
- focused to ~ 10 µm spot (vac)
- $N_e \sim 4 \times 10^{19}$ cm$^{-3}$
<table>
<thead>
<tr>
<th>Technique</th>
<th>Density (cm(^{-3}))</th>
<th>Length (mm)</th>
<th>Intensity (W cm(^{-2}))</th>
<th>Issues</th>
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<td>Monomode capillary</td>
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<td>10(^{17})</td>
<td>Short capillary lifetime</td>
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<td>10(^{17})</td>
<td>Auxiliary laser required</td>
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