Ten Meter Laser Propagation with Resonance Enhanced Ionization of Rubidium for Plasma Generation at AWAKE

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AWAKE stands for Advanced WAKefield Experiment

- Proton driven wakefields over 10 meters of plasma
- Self modulation of proton beam driver
- Saturated wakefields are > 100MV/m

**See Patric Muggli’s plenary invited talk tomorrow at 9:50 for AWAKE overview and first experimental results***
AWAKE Plasma Source

- 10 meter rubidium vapor source
- Rubidium is controlled to within .2% neutral density, gradients can be controlled
- Vapor is photo-ionized by peak power 4.5 TW Ti:Sa laser

See Erdem Öz ‘s presentation in WG5 for details
Photoionization Requirements for AWAKE

Ionization laser must do three things:

- Provide a singly ionized plasma from the Rb vapor that has a density profile identical to that of the vapor for the entire length of the vapor source.
- The radial extent of the plasma must be greater than trajectory of plasma electrons.
- Seed self modulation by igniting on the plasma at a timescale at or shorter than the plasma period where the proton beam can drive the wakefields.
### Laser System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>Er:Fiber/OscillatorTi:Sapphire</td>
</tr>
<tr>
<td>Pulse wavelength, $\lambda_0$</td>
<td>780 nm</td>
</tr>
<tr>
<td>Pulse length, FWHM</td>
<td>120 fs</td>
</tr>
<tr>
<td>Pulse energy (after compressor)</td>
<td>450 mJ</td>
</tr>
<tr>
<td>Laser power</td>
<td>4.5 TW</td>
</tr>
<tr>
<td>Focused laser size, $\sigma_{x,y}$</td>
<td>1 mm</td>
</tr>
<tr>
<td>Rayleigh length, $Z_R$</td>
<td>~3.5 m</td>
</tr>
<tr>
<td>Energy stability, r.m.s.</td>
<td>$\pm1.5%$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

- Fiber laser chosen for stability on long runs
- Laser BW is only 15nm with peak spectrum at 780nm
- Several Rb lines within spectrum
Resonant Transitions

Primary state path to ionization:

- Resonant lines within laser bandwidth:
  - $5^2P_{3/2} \rightarrow 5^2D_{3/2}, 5^2D_{3/2}$
  - $5^2S_{1/2} \rightarrow 5^2P_{3/2}$
  - $5^2P_{1/2} \rightarrow 5^2D_{3/2}$
  - $5^2S_{1/2} \rightarrow 5^2P_{1/2}$
Pulse Propagation in the “Linear Regime”

\[ \chi_{\text{bound}} = \frac{N e^2}{m \epsilon_0} \left( \frac{f_1}{\omega_{01}^2 - \omega^2 - i \Gamma_1 \omega} + \frac{f_2}{\omega_{02}^2 - \omega^2 - i \Gamma_2 \omega} \right) \]

\[ k_{\text{bound}} = \frac{\omega}{c} \sqrt{1 + \chi(\omega)} \]

Two resonances would cause anomalous dispersion, pulse stretching, etc. If it is different across the beam then the beam can blow up, multifilament, etc. **We can expect some behavior like this in the wings**
High Intensity Laser pulse

\[ k_{\text{bound}} = \frac{\omega}{c} \sqrt{1 + \chi(\omega)} \]

\[ k_{\text{plasma}} = \frac{\omega}{c} \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \]

- Leading edge of the pulse ionizes or saturates the transition
- Most of the pulse travels through plasma, samples plasma dispersion, which has a differential index on the scale of $10^{-8}$

If beam does not deplete, it can make it through without stretching or destroying mode quality, creating a stable sized plasma channel
AWAKE Experimental Area

- Final Laser mirror
- Virtual Line
- Vapor Source
- Downstream Pickoff, LBDP3
Pickoff Setup

Avoid nonlinearity in sampling by:

• Wedge picked off .5% of laser (close to Brewster’s angle)

• Mirror splits beam to autocorrelator or power meter and bleedthrough goes to transverse measurement

• Telescope images downstream iris of the vapor source

Main limitations to setup:

• Power meter too insensitive below .5 mW (10 mJ energy hitting the wedge)

• Wedge will still burn if energy is increased above 250 mJ

• Offline measurement (no protons)
Virtual Line Images
Initial Conditions of Laser / Vacuum Behavior

Virtual Entrance
Virtual Center
Virtual Exit
Pick off imaged here

10 m
Preliminary Propagation Results

Vacuum
En = 40 mJ

Beam Blowup, multifilamentation

En = 55 mJ

En = 60 mJ

Beams Stable
En = 240 mJ

Rb n = 7e14 / cm³
Simulation Model

Maxwell for $E$:
\[ \nabla^2 E(r, t) - \frac{1}{c^2} \frac{\partial^2 E(r, t)}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2} \]

Schrödinger for atoms:
\[ |\Psi\rangle = \sum a_i |i\rangle, \quad \hat{H}_I = -\hat{d}E \]
phenom. loss terms

Material optical response:
\[ P(r, t) = N \langle \Psi | \hat{d} | \Psi \rangle + \text{ionization loss} \]

- Atomic models of varying complexity (4 / 18 / 10 levels)
- Ionization as loss (PPT rates)
- 1D propagation

Laser Pulse collapse
“Slow pulse”

Further extended to 2D

G. Demeter
Preliminary Simulation Results

\( I_0: 3 \text{ TW/cm}^2 \)

Subthreshold:
Ionization channel collapse,
Output laser pulse destroyed

\( I_0: 40 \text{ TW/cm}^2 \)

Super Threshold:
Stable ionization channel,
Stable laser output
Propagation Confirmed but Ionization?

Self modulation frequency vs neutral density demonstrates consistency with complete ionization within uncertainties.

AWAKE Typical run well above threshold energies: 200 mJ

Scaling!

Value!

See for details: F. Batsch, K. Rieger, M. Martyanov, F. Braunmueller

AWAKE Typical run well above threshold energies: 200 mJ
Conclusions and Outlook

Conclusions:
• Experimental demonstration of laser propagation above and below channel collapse limit
• Qualitative results of simulation match what is observed with experimental results
• Measured self modulation frequency versus neutral density consistent with full ionization
• A strength of resonance enhanced ionization is when laser depletion occurs ionization drops off sharply and a stable transverse laser mode fails to propagate out of plasma. This can serve as an diagnostic to ensure the plasma channel is the full length of the vapor source

Outlook:
• Experimental program for ionization experiments thus far limited by higher priority needs of AWAKE (SM experiments, electron beam development)
• A program with quantitative systematic study scheduled for early next year including:
  – Laser Spectrum
  – Time resolved plasma light spectrum (A-M Bachmann, M. Martyanov)
  – Energy depletion scaling
  – Precision neutral density dependencies
  – Input laser pulse length dependencies (chirped pulsing)
  – Input transverse mode quality dependencies
• Further numerical model development to compare new results