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LASER PROPAGATION EFFECTS DURING PHOTOIONIZATION OF METER SCALE RUBIDIUM VAPOR SOURCE

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Abstract

The baseline AWAKE experiment requires a 10 meter long plasma source with a density of 10^{15} cm^{-3} and a density uniformity of 0.2%. To produce this plasma, a temperature stabilized rubidium vapor source is photoionized by a terawatt peak power laser pulse. In this paper we describe the laser pulse evolution within the plasma source including the dispersive, diffractive, and photoionization effects on the laser pulse. These calculations will be experimentally investigated in a meter long heat pipe oven using scaled laser parameters.

INTRODUCTION

The AWAKE project is a proof of principle proton driven plasma wakefield electron accelerator experiment [1,2], that scheduled to begin initial experiments at CERN in 2016. The experiment employs a 400 GeV proton beam from the Super Proton Synchrotron (SPS) that propagates through a 10 meter plasma to produce GeV/m wakefields via the mechanism of the self modulation instability [3–5]. The second phase of the AWAKE experiment, scheduled to begin in 2017, relies on SMI to accelerate a 15 MeV electron beam from a photoinjector and single RF booster. The electrons are injected on the axis of the proton beam 100 plasma periods behind the laser pulse that ionizes the rubidium and creates the plasma. For controlled injection of the electron beam to occur, the plasma wakefields must have a stable, well defined phase up to the longitudinal injection position, placing a requirement of 0.2% density uniformity on the plasma source.

The plasma is produced from a 10^{15}cm^{-3} rubidium vapor source. A 10 meter heat exchanger cell is being developed and built by Grant Instruments Ltd. [6]. The density of the rubidium vapor in the cell is well defined by the temperature of the device. A detailed description of the device, including density vs. temperature curves is given by E. Öz and P. Muggli [7]. The requirement of < 0.2% density stability over the device in the baseline design of the experiment is met by achieving the same level of temperature stability over the 10 meter device. Lastly, to create the plasma, the rubidium is photoionized by a 4 TW peak power laser pulse via field ionization described by Keldysh [8]. Because we are operating in a low Keldysh parameter regime in which the intensity is high and frequency low, the ionization time is much less than the laser pulse length and occurs at a laser threshold intensity of 2 TW/cm^2.

Rubidium was chosen over other Alkali metals due to it's low ionization energy of 4.2 eV and the relative technical simplicity of its use including producing the baseline vapor density at 200 degrees C and it being a solid at room temperature. The laser used to ionize the rubidium vapor was purchased from Amplitude Technologies [9]. This laser is uses and Erbium doped fiber oscillator with a central wavelength of 780 nm with a bandwidth of approximately 10 nm. The laser system is a chirped pulse amplification system that stretches the ~100 fs pulse to ~ 100 ps, amplifies it to a maximum value of 600 mJ, then recompresses the laser pulse so that it has a peak power of 4 TW at a maximum energy of 450 mJ per pulse.

To understand the laser pulse propagation we are conducting rubidium ionization experiments on a 1 m heat pipe oven and the laser to be used for the CERN experiment at Max Planck Institute for Physics (MPP). A comparative table of parameters for both the AWAKE experiment and the MPP scaled investigation are shown in Table 1.

Table 1: AWAKE and MPP Phase B Parameters

Parameter	AWAKE	MPP Phase B
Laser Pulse Energy	450 mJ	100 mJ
Rayleigh Range	5 m	35 cm
Rubidium Vapor Length	10 m	1 m

This paper describes the laser pulse propagation studies currently ongoing at MPP investigating the evolution of the pulse as it ionizes meter length scale Rubidium vapor.

DESCRIPTION OF MPP EXPERIMENT

The experiment at MPP is broken into two phases. Phase A is the study of the quasi-linear effects of the laser passing through cm scale rubidium at the baseline density of 10^{15}cm^{-3}. This length scale was chosen because the variation in the index of refraction across the bandwidth of the laser due to anomalous dispersion, $\delta n/n$ is on the order of 10^{-4}. With a wave number on the order of 10^6 m^{-1}, we expect order unit phase change across the bandwidth of the laser pulse at cm scales.

For this experiment we used a small rubidium cell with a length of 3.5 cm. This cell was heated to 200 degrees C and the density was measured using the "hook method" technique [10, 11], which employs a white light Mach-Zehnder interferometer and high resolution spectrometer. The separation of the first large distortions of the interference fringes near the D2 resonance line for rubidium acts as a diagnostic for the vapor density. An image of the cell can be seen on the left in Fig. 1.

Upon verification of the rubidium vapor density for a given temperature, 400 μJ laser pulses were propagated through

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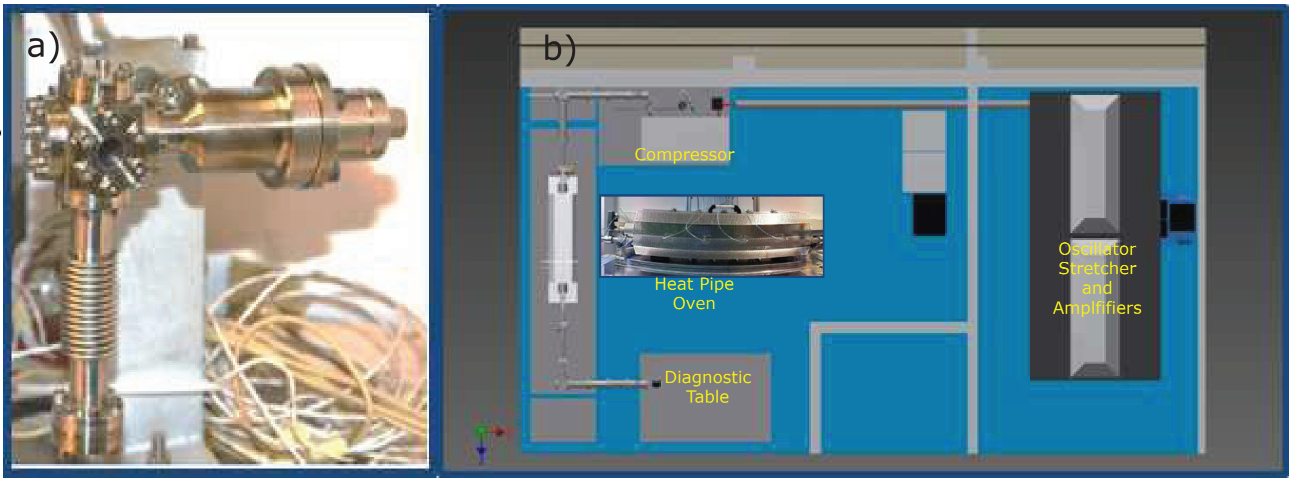

Figure 1: Layout of scaled laser pulse propagation study. a) Photograph of the 3.5 cm rubidium cell used for the quasilinear pulse elongation study. b) CAD layout of the MPP laser / plasma room for phase B of the laser pulse propagation investigation.

the cell. The length of the laser pulses is determined with a second harmonic generation (SHG) intensity autocorrelator purchased from Amplitude Technologies. As a background, the pulse length is measured through the cell at room temperature and it is found to have negligible pulse stretching through the cold cell.

Autocorrelation data from the phase A experiment is shown in Fig. 2. Over the 3.5 cm cell the pulse stretches dramatically, with the pedestal's increasing by over a factor of 2.

This anomalous dispersion has the potential to stretch the pulse over the 10 meters in the CERN experiment and lower the peak intensity of the laser pulse as it propagates through. Fortunately, the dispersion changes significantly once ionization occurs. At the operational vapor density the laser frequency components are significantly higher than the plasma frequency, with the index of refraction having the form of n = $(1 - \omega_{pe}^2/\omega_l^2)^{1/2}$. The resulting in changes in index over the bandwidth are reduced to be on the order of 10^{-7}.

Due to the small size of the 3.5 cm rubidium cell, ionization intensities cannot be reached without damage of the sapphire windows. To perform the ionization experiments we must complete phase B.

Phase B of the MPP laser propagation study involves ionization of rubidium over a meter long heat pipe oven [12]. To avoid nonlinear effects in air at higher intensities as the laser focuses, as well as damage of nearby sapphire windows, we extended out the vacuum system and fill it with argon gas at a pressure that confines the rubidium vapor into the heat pipe oven. This allows us to propagate the full beam and remain above ionization threshold intensities throughout the rubidium while operating the laser with 100 mJ pulses. The layout of the Phase B experiment can be seen at right on Fig. 1

The hook method will be used once again to determine the line neutral integrated density within the oven. Additionally, an array of sensors along with four independent heating elements allow us to form a shorter rubidium vapor lengths of 25, 50 and 75, cm as well as study the effects of longitudinal density ramping by being able to apply temperature gradients across the oven.

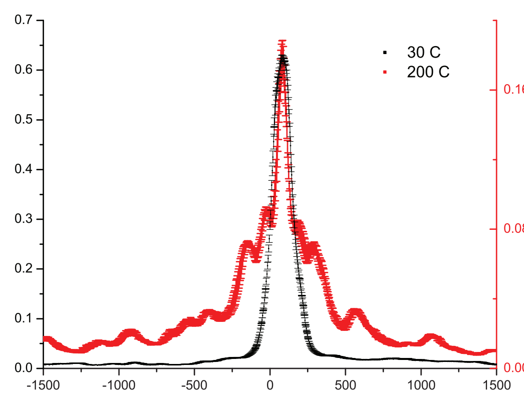

Figure 2: Phase A quasi linear pulse elongation.

MODELING OF LASER PULSE

To model phase B of the proposed MPP experiment we are working to modify an existing laser propagation code from the University of Geneva. This code is typically used to model ionizing laser propagation through the atmosphere [13]. The original code uses the Fourier transform split step method. This method transforms to the frequency and wavenumber domains to apply the linear dispersion and diffraction effects then it transforms back to the time domain to apply intensity dependent effects, such as Kerr and ionization effects.

The code solves the master paraxial propagation equation, displayed in Eq. 1 [14]

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$$\nabla^2 E - \frac{1}{c^2}\partial_t^2 E = \mu_0(\partial_t J + \partial_t^2 P) \quad (1)$$

Here E is the electric field profile, J is the current and P is the polarization, including those terms of polarization that are higher order in E. Typically this equation will be solved using the Fourier transform split step method, in which the equation is solved in the frequency and wavenumber domain and a unitary transformation, or phase shift transformation is applied with the resulting k_z. This transformation is responsible for diffractive and linear dispersion effects. The laser pulse is then transformed back into the time domain and the nonlinear polarization terms as well as ionization losses are applied in the time domain.

Because we are in a strongly ionizing regime, the dispersion changes along the pulse, making necessary construction of response functions from the bound state rubidium and plasma. These modifications are currently underway to the propagation code. The effect of limiting the aperture at the vapor entrance is also included int these calculations. The limited aperture is used to decrease the outflow of the Rb vapor, thereby decreasing the characteristic length of the resulting plasma ramp.

CONCLUSION

The investigation of ultrafast laser pulse in rubidium vapor for the AWAKE experiment is underway. The propagation is being studied both experimentally using a scaled experiment with a heat pipe oven and using simulations to model the propagation to ensure that the peak intensity does not decrease below the ionization threshold intensity before traversing the entirety of the 10 m source at AWAKE. Although significant pulse elongation occurs in the linear regime, once the rubidium is ionized, most of the laser pulse will travel through with very little pulse elongation. Because significant pulse elongation occurs over only a few centimeters, the laser profile can be used as an ionization diagnostic.

Phase B of the ionization experiment, assembly and construction will be finished by June 2015 and the experimental laser program will be complete by January 2016.

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