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EXPERIMENTAL STUDIES OF LASER GUIDING IN PLASMA CHANNELS.

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Abstract

We present results of experimental investigations of laser guiding in plasma channels. A new technique for plasma channel creation, the Ignitor – Heater scheme is proposed and experimentally tested in hydrogen and nitrogen. It makes use of two laser pulses. The Ignitor, an ultrashort (<100 fs) laser pulse, is brought to a line focus using a cylindrical lens to ionize the gas. The Heater pulse (160ps long) is used subsequently to heat the existing spark via inverse Bremsstrahlung. The hydrodynamic shock expansion creates a partially evacuated plasma channel with a density minimum on axis. Such a channel has properties of an optical waveguide. This technique allows, creation of plasma channels in low atomic number gases, such as hydrogen, which is of importance for guiding of highly intense laser pulses. The channel density was diagnosed with time resolved longitudinal interferometry. From these measurements the plasma temperature was inferred. The guiding properties of the channels were tested by injecting a >5x10^{17} W/cm^2, 75fs laser pulse.

1 INTRODUCTION

Several applications of intense laser beams, including laser acceleration [1], high harmonic generation [2], and recombination far UV and X-ray lasers [3], would greatly benefit if the laser beam was kept tightly focused over many diffraction distances of the laser (the Rayleigh range). Laser guiding in plasma channels has been proposed [4] as a means to extend the distance over which the laser remains intense. The index of refraction in a plasma of density n can be approximated by $\eta_R \approx 1-\omega_p^2/2\omega^2$. As in an optical fiber, a plasma channel can provide optical guiding if the index of refraction peaks on axis. This requires a plasma density profile that has a local minimum on axis.

Experimentally, low power laser pulses have been guided in plasma channels [5]. In these experiments one laser pulse (~100 ps, ~100 mJ) was brought to a line focus in a mixture of high atomic number (Z) gases with an axicon lens to produce a few cm long plasma, and subsequently heat it via inverse Bremsstrahlung. The resulting hydrodynamic expansion led to a time-dependent density profile with a minimum on-axis. Pulse propagation over distances of up to 70 Rayleigh lengths (about 2.2 cm) of moderately intense laser pulses (<5x10^{14} W/cm^2), with pulse lengths much larger than the plasma period, was demonstrated in these experiments. The intensity of the channel creation laser pulse, achieved in these experiments was not sufficient for ionization of low Z gases, but required instead the use of high Z gases. Unfortunately, in channels produced with high Z gases, an ultra-intense pulse would further ionize the gas on the channel axis, thereby negating the guiding. While the 100ps long laser pulse was energetic enough to cause significant plasma heating, ionization of low Z atoms requires an order of magnitude higher laser intensity. The intensity of the laser pulse, needed for channel creation in hydrogen, for instance, has to be ~1.5×10^{14} W/cm^2 [6]. It is important to note that once partial ionization has occurred, and plasma heating through inverse Bremsstrahlung takes place, collisional ionization plays a significant role as an additional mechanism for plasma creation. For low laser intensities the inverse Bremsstrahlung rate is independent of the laser intensity [7]. When the electron quiver velocity due to the laser field exceeds the thermal velocity, the heating crossection drops precipitously [8]. The optimum intensity for plasma heating is on the order of 1-2×10^{13} W/cm^2 [7]. Ionizing the gas and subsequently heating it with one pulse is inefficient.

To allow the use of low Z atoms and to demonstrate the feasibility of guiding of the highly intense laser pulses over many Rayleigh ranges we have developed a novel method for channel production: the Ignitor - Heater technique. Rather than utilizing a single laser pulse for ionization and heating, this scheme makes use of two laser pulses. A femtosecond "Ignitor" pulse is used to create the initial spark. A longer, ~160 ps, perfectly time synchronized "Heater" pulse is then introduced to heat the plasma. Results of Ignitor – Heater channel production experiments and measurements of the channel transverse plasma density profile with femtosecond Mach-Zehnder interferometry will be presented in Section 2. Results of guiding studies are reported in Section 3.

2 CHANNEL PRODUCTION

To implement the Ignitor-Heater channel creation scheme, the two laser pulses were combined in a line-focus by means of cylindrical optics onto a gas jet, Figure 1. The gas jet was used to avoid ionization induced refraction [9] in a statically filled experimental chamber. The femtosecond intense (~5 10^{14} W/cm^2) Ignitor pulse was focused to a line by reflecting off a cylindrical reflector. The cylindrical reflector is a plano-concave (R=38 mm) cylindrical lens, coated with a dielectric high reflection coating for 45° angle of incidence 800 nm radiation. By using a reflective optic we have avoided beam filamentation, self-focusing, and other undesirable nonlinear effects that would prevent from obtaining a well focused, near diffraction limited beam spot. The Heater pulse was focused with an F/5 refractive cylindrical lens (focal length fl=50mm) at the exact location of the ignitor focus. In addition to the fact that the channel forming beams propagate perpendicularly to the guided pulse, the use of two independent cylindrical optics provides precise independent adjustment of both the positions, angles of incidence, and sizes of the line foci.

A Mach-Zehnder type interferometer with a measured spatial resolution of 4 μm was built to measure line integrated plasma density. This interferometer measures the relative spatial phase shift between two blue (400 nm) 50 fs pulses, one propagating through plasma and one through air. These pulses are produced by frequency doubling and are perfectly synchronized with the high power beams used in plasma production. The evolution of the 2-D transverse plasma density profile can be measured with a temporal resolution determined by the duration of the blue pulse (~50 fs).

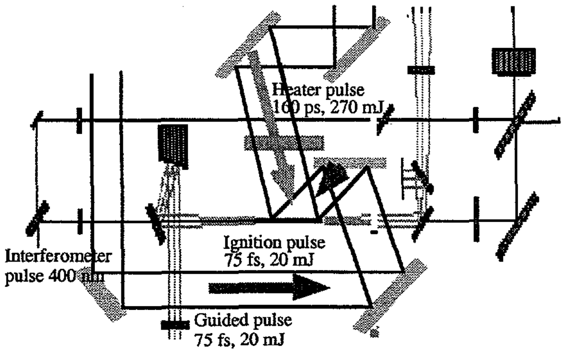

Figure 1: Experimental Setup

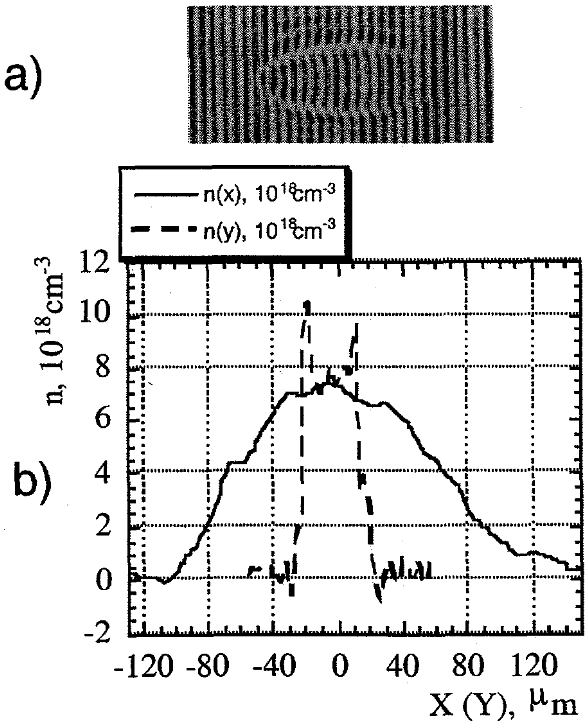

Figure 2: a) Channel interferogram at 1ns after the heater pulse; b) Inferred plasma density lineouts.

The Ignitor-Heater scheme was implemented with 20-40mJ, 75 fs Ignitor pulse and ~270 mJ, 160 ps Heater pulse in nitrogen and hydrogen backed gas jet. Figure 2 a) shows an interferogram taken with the interferometer pulse delayed by 1 ns with respect to the Heater pulse. The X-size of the channels roughly corresponds to the Rayleigh range of the Ignitor pulse. From the inferred plasma density lineouts of Figure 2 b), it is seen that a plasma channel is created only in the vertical direction. These channels are expected to guide in Y-direction only.

From the interferograms of the plasma channels, the shock front diameter, D, is found by measuring the separation (in Y) between the points of commencement of the fringe shifts in the middle section of the channel. From the channel size and density dynamics, the initial temperature of the spark is inferred in two ways. By equating the shock speed to ion acoustic speed, the electron temperature can be found. From Sedov's solution of strong explosion in a homogeneous atmosphere [10], a theoretical calculation that relates the energy per unit length in the initial spark to the form of the expansion curve, the temperature can be calculated once again. From the shock speed, the initial temperatures (right after the Heater pulse) are calculated to be ~20 eV and ~120 eV in hydrogen and nitrogen respectively. This agrees well with the deposited energy calculation from Sedov' solution. From the inverse Bremsstrahlung theory [8], in hydrogen, with $n_I=2\times10^{18}$ cm^{-3}, laser $I=7\times10^{12}$ W/cm^2, and laser pulse duration w=150 ps, the temperature was calculated to be $T_e=19$ eV. In nitrogen, with $n_I=1.6\times10^{18}$ cm^{-3}, $\langle Z\rangle=3.5$, and the same laser parameters, the temperature was calculated to be $T_e=118$ eV.

3 GUIDING

This Section describes the results of experiments on guiding high intensity laser pulses in the plasma channel. The laser pulse (injection pulse) was focused near the entrance of the channel using an off-axis parabola. The time delay between the Ignitor pulse and the injection pulse was fixed to 600 ps. (This constraint arose from physical limitations in the available vacuum chamber.) To diagnose the guiding, the laser beam was imaged onto a CCD camera with a MgF_2 lens of 1 inch diameter and focal length of fl=68.3 mm at 800 nm. The CCD camera was mounted on an optical rail so that it could be moved over about 50 cm range, thus changing the position of the imaging plane. The resolution and magnification of the imaging system was calibrated for different CCD camera locations. By comparing the laser beam images with and without the gas flowing out of the gas jet (valve pulsing or not), it was possible to clearly observe the effect of guiding on the laser beam. Figure 3 shows images of the injection laser pulse a) propagating through vacuum (gas jet turned off), b) after undergoing ionization induced refraction in the gas jet plume without the Heater pulse being present, hence no channel formed, and c) guided by the channel, for a gas jet backed with nitrogen at 1000 psi. Vertical lineouts of images of Figure 3 clearly demonstrate the changes induced by the plasma channel on the guided laser pulse. The change in size of ~8 times is consistent with a laser beam of Z_R~0.1 mm propagating a distance of 0.8 mm (the width of the jet).

As seen in Figure 2, for the specific Ignitor and Heater pulse parameters, plasma channels were created in an elongated, elliptical shape. In turn, the guided beam images (Figure 3) had a similar elongated shape. We next demonstrate that through control of the Ignitor pulse intensity, channels with circular cross-sections, possessing guiding properties in X as well as in Y direction, can be created.

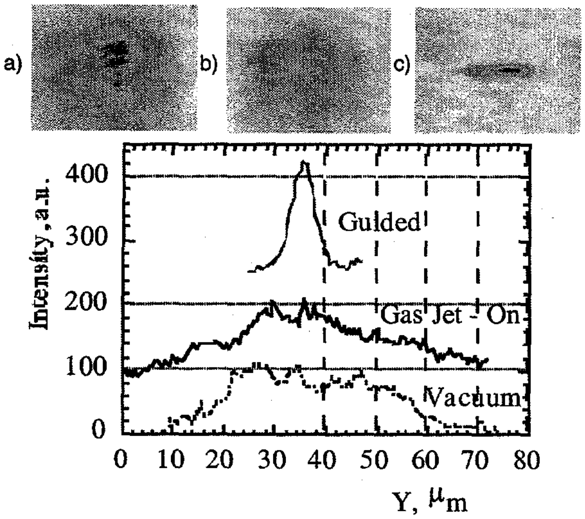

Figure 3: Laser beam images and vertical lineouts. pulse a) gas jet turned off, b) gas jet - on, without Heater pulse, and c) guided by the channel, for a gas jet backed with nitrogen at 1000 psi.

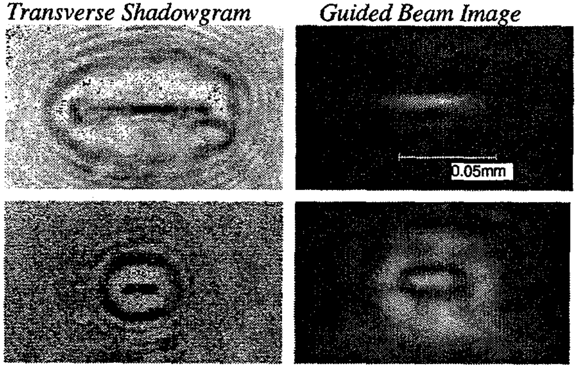
Transverse Shadowgram *Guided Beam Image*

Figure 4: Guided beam images next to the corresponding channel shadowgrams. Aspect ratio of the guided beams is improved by a factor of 2.

Since the initial volume of plasma is determined by the volume over which the intensity of the Ignitor pulse exceeds the ionization threshold intensity, the Ignitor pulse intensity can serve as means of control over the channel shape. By decreasing the Ignitor pulse intensity (via detuning the compressor, i.e. lengthening the pulse), plasmas were produced over smaller extent in x-direction, Figure 4, and hence, the energy deposition by the Heater pulse was localized to a much smaller area, leading to an aspect ratio of the resultant channel that was much closer to 1. Laser pulses guided in such channels developed similar round shape. In Figure 4 the guided beam images are shown next to the corresponding channel shadowgrams. A shadowgram is an interferometer image taken with only the probe arm incident on the CCD camera chip.

4 CONCLUSIONS

To overcome the laser diffraction length limit, a novel method of plasma channel production for laser guiding, the Ignitor - Heater technique, was proposed and tested experimentally. This scheme made it possible, for the first time, to create preformed guiding plasma channels in hydrogen and deeply ionized nitrogen without high atomic number additives, thereby allowing high intensity laser pulse guiding. To avoid the ionization induced refraction of the guided laser pulse, the plasma channels were formed in a plume of a pulsed gas jet. It should be also noted that the Ignitor – Heater scheme employs cylindrical optics that could be kept out of the path of the accelerator beam and, potentially, allow the recycling of the laser beams. The channel formation process was fully characterized with time resolved 2-D longitudinal interferometry diagnostic using a femtosecond probe pulse. From the measured dynamics of the radial shock expansion, the temperature and energy of the heated plasma were calculated. The ability to independently control the intensity of the Ignitor pulse allowed us to control the transverse extent of the initial ionization spark. The length of the initial spark affected the shape of the plasma channel. In this fashion channel transverse aspect ratio was controlled from ~ 3 to ~10. Future work will concentrate on further improving this aspect ratio.

Laser pulses at record high intensity (~5×10^{17} W/cm^2) were guided in these channels over ~ 10 Rayleigh lengths. Control over the channel shape allowed us to observe guiding in one transverse dimension, for channels with high aspect ratio, or guiding in both X and Y, if a round channel was formed.

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