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B.B. Pollock, D.H. Froula, G.R. Tynan, L. Divol, D. Price, R. Costa, F. Yepiz, S. Fulkerson, F. Mangini, S.H. Glenzer

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B. B. Pollock,* D. H. Froula, G. R. Tynan,* L. Divol, D. Price,
R. Costa, F. Yepiz, S. Fulkerson, F. Mangini,† and S. H. Glenzer
Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94551

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We present a platform for producing long plasma channels suitable for guiding lasers over several centimeters by applying magnetic fields to limit the radial heat flux from a pre-forming laser beam. The resulting density gradient will be used as an optical plasma waveguide. The plasma conditions have been chosen to be consistent with the requirements for Laser Wakefield Acceleration where multi-GeV electrons are predicted. A detailed description of the system used to produce the high (5 T) magnetic fields and initial results that show a 5 cm long plasma column are discussed.

PACS numbers:

I. INTRODUCTION

Laser Wakefield Acceleration (LWFA) is a technique which employs a high-intensity laser pulse to drive large-amplitude plasma waves (the wake) in underdense plasma[1]. Electrons become trapped by the wake and gain energy from it over an acceleration length equal to the distance they travel with the wake. In order to reach electron beam energies >10 GeV an optical plasma waveguide is required to maintain the laser intensity over long acceleration lengths.

Recently a 1 GeV monoenergetic electron beam was demonstrated[2] by using a waveguide to maintain the intensity of a short-pulse laser over ∼1 cm. The acceleration lengths in previous studies were limited to a few millimeters[3–5]. We propose a novel scheme for producing an optical plasma waveguide that is inherently suited for multi-GeV LWFA, promising to extend acceleration lengths to several centimeters.

To produce this waveguide a heating laser pulse is fired into a gas target in the presence of a coaxial magnetic field. When an external magnetic field is applied parallel to a laser in a plasma, thermal transport transverse to the beam is inhibited[6]. This drives high electron temperatures along the laser axis, and the resulting pressure expels electrons away from the center of the laser. The choice of applied field strength determines the radial electron density profile in the plasma[7], which allows for the tuning of an optimal waveguide structure for LWFA.

This paper presents an approach for guiding a laser over many centimeters that employs an external magnetic field to produce an optical waveguide. In order to achieve long waveguides, axially uniform magnetic fields are necessary. We have developed a 20 cm long solenoid capable of delivering uniform fields over 12 cm. This allows for guiding over much greater distances than have previously been demonstrated, enabling longer acceleration lengths and greater energy gains for LWFA systems.

II. SOLENOID DESIGN

We have designed an electromagnetic solenoid as part of a low-inductance circuit to provide long, uniform magnetic fields for optical waveguide production. Beginning with a solid block of phosphorus bronze, the solenoid shown in Figure 1 was machined to be 20 cm long and have 8 turns with a bore diameter of 5.1 cm. This geometry yields a pitch angle of 9.5 degrees. The turn cross-section is square with 1.3 cm sides. A 10 cm diameter base plate was left attached during the machining process, shown on the left in Figure 1b, which makes electrical contact with a stainless steel flange. On the right a hole is drilled in the last turn to attach high voltage leads to the solenoid. This portion of the circuit is completed by an aluminum shell which electrically connects the base plate to the return of the high voltage leads, as shown in Figure 1a, while the coaxial design reduces the inductance of the circuit.

The current that generates the magnetic field is supplied by a pulsed power system[8] capable of storing 28.8 kJ when fully charged to 20 kV. The overall system is modeled as an underdamped LRC circuit described by

$$I(t) = \frac{V_0 e^{-t/\tau}}{\omega L} \sin(\omega t) \tag{1}$$

where $\omega = \sqrt{\frac{1}{LC} - (\frac{R}{2L})^2}$, $\tau = \frac{2L}{R}$, V_0 is the initial charge voltage, and the electrical parameters are C=144 μF of capacitance, L=3.5 μH of inductance, and R=100 mΩ of resistance. The inductance is dominated by cabling in this system, with less than 1 μH coming from the solenoid.

The current is measured with a Rogowski dI/dt probe on the return cable to the capacitor bank. This diagnostic is calibrated against a Pearson probe, and the peak current measured at maximum charge is 90 kA. The desired charge voltage is set on a Glassman FX20P15

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*University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093

†Saint Mary's College of California, 1928 Saint Mary's Road, Moraga, CA 94556

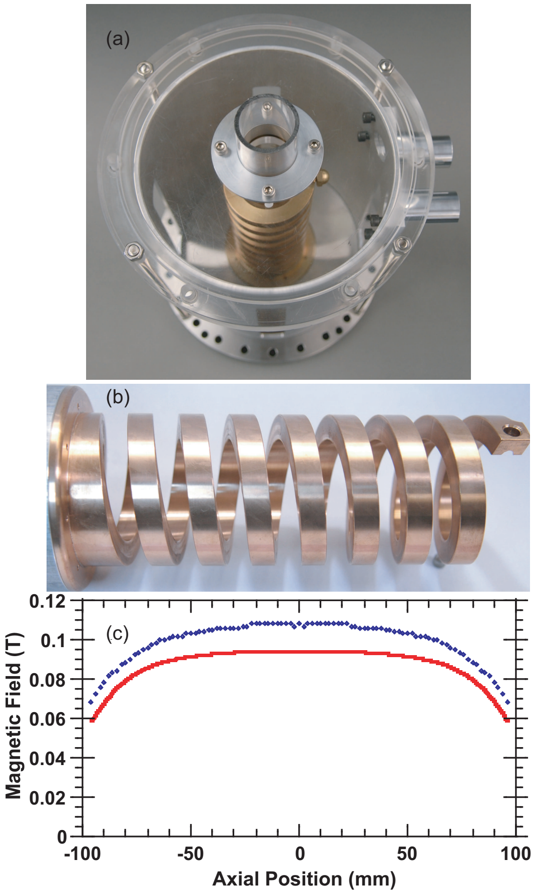

FIG. 1: (a) The solenoid is bolted to a stainless steel flange, while an aluminum shell returns the current to the high voltage coaxial cables. (b) The 20 cm-long solenoid was machined out of a solid block of phosphorus bronze. (c) The measured axial magnetic field profile of the solenoid (blue) agrees well with the profile calculated from Equation 2 (red). The measurement demonstrates that the field is uniform over 12 cm.

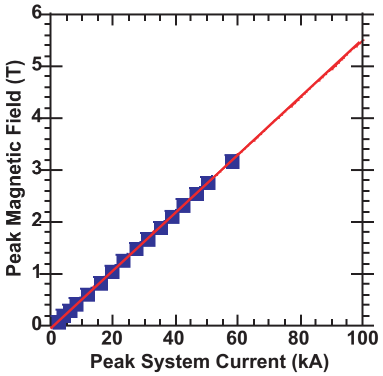

FIG. 2: The peak magnetic field measured at the center of the solenoid scales linearly with the peak system current at 55 mT/kA.

High Voltage Power System capable of supplying up to 20kV. A Ross High Voltage Dump Relay (k1) prevents the capacitors from charging or retaining charge when the dumps are engaged. The switching mechanism that allows current to flow between the bank and the solenoid is an NL8900 ignitron. To protect the capacitors from experiencing large current reversals, ABB Semiconductor diode stacks were installed in line with the return current path.

III. MAGNETIC FIELD CHARACTERIZATION

The magnetic field along the axis of a solenoid can be written as the product of a time-dependent current and a spatially dependent geometry factor[8]

$$B(t,z) = \frac{I(t)\mu_0 N}{2l}\left(\frac{z+\frac{l}{2}}{\sqrt{r^2+(z+\frac{l}{2})^2}} - \frac{z-\frac{l}{2}}{\sqrt{r^2+(z-\frac{l}{2})^2}}\right) \quad (2)$$

where I is the system current, N is the number of turns, l is the length of the solenoid, r is the inner radius, and z=0 corresponds to the center of the solenoid. Note that the outer turn radius does not affect the field as the current is carried in a shallow skin depth (<2 mm) at the inner surface of the solenoid.

Figure 1c compares the peak magnetic field measured along the solenoid axis to the peak field predicted by Equation 2 when driven by a 2 kA peak current from our pulse-power system; the data agree to within 15% of the calculated fields. Figure 2 shows a linear scaling between the peak magnetic field measured at the center of the solenoid and the peak current. To measure the magnetic field along the solenoid axis a 10 turn, 2.83 mm diameter pickup probe was constructed. The probe was inserted into the solenoid and measurements were taken every 2 mm.

IV. EXPERIMENTAL SET-UP

Preliminary experiments using the 20 cm solenoid to produce long plasma columns have been performed at the Jupiter Laser Facility, Lawrence Livermore National Laboratory (LLNL)[6]. A 2 cm diameter tube is inserted coaxially inside the solenoid, and He gas is injected to fill pressures up to 4x10^{18} cm^{-3} neutral density. The plasma is formed by a long (1ns), 1ω (1054 nm) laser pulse which is focused through an f/50 optical system to the center of the solenoid at intensities up to 3x10^{14} W/cm^2. The spot size of this beam has been measured and is shown in Figure 3b to be less than 100 μm radius over 6 cm. This measurement is consistent with a three-times diffraction limited spot, w_0, in the standard definition of the Rayleigh length $Z_R = \pi w_0^2/\lambda$.

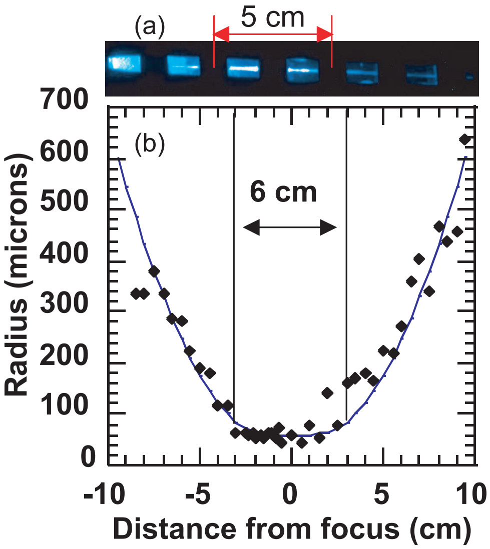

FIG. 3: (a) Plasma columns in excess of 5 cm are produced when a 100J laser is fired into a 1.5x10^{18} cm^{-3} neutral density He gas fill. Visible plasma emission (400 nm $< \lambda <$ 800 nm) is collected by a CCD camera. The spaces between the turns of the solenoid are 1.3 cm wide. (b) The spot size of the heating beam has been measured to be less than 100 μm radius over 6 cm in the propagation direction of our f/50 optical system.

Figure 3a shows that this system is capable of producing ∼5 cm long plasma columns. The image is recorded by a gated charge-coupled device (CCD) that time averages the visible plasma emission for 20 ns over the length of the solenoid. Future experiments will incorporate interferometry and Thomson scattering to measure the plasma density and temperature profiles. This experimental set-up will then serve as a platform for LWFA experiments with a 200TW short-pulse laser. Calculations have been performed which indicate that for plasma densities of $10^{18}\mathrm{cm}^{-3}$, a 200 TW system will produce a multi-GeV electron beam[9].

V. CONCLUSION

We have presented a platform for guiding a high-power, short-pulse laser beam for more than 5 cm using a magnetic field and a laser to form an optical plasma waveguide. By applying a uniform magnetic field parallel to the laser during plasma formation, thermal transport is inhibited, allowing control over the radial electron density profile. The laser beam intensity has been measured to be nearly uniform over 6 cm, while the magnetic field is uniform over twice that length. These parameters have been chosen to be consistent with requirements to produce monoenergetic GeV electron beams from LWFA.

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