Study of nanosecond pulsed magnetic fields using temporally resolved Faraday rotation through a magneto-optical waveguide

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We have measured magnetic fields up to 17.7 T with a rise time of 75 ns using temporally resolved Faraday rotation of a single longitudinal mode laser beam through a magneto-optically active bulk waveguide. We believe this to be the first time that such large, rapidly varying magnetic fields have been measured with this class of materials (multicomponent terbium borate glass). As there was no measurable lag between the magnetic field inferred from the angle of rotation of the laser beam and the electromagnetically measured field, our sample of terbium borate glass has a spin-lattice relaxation time of a few tens of nanoseconds at most at approximately room temperature (300 K). The highest peak magnetic fields were measured in wire-array Z-pinch experiments on a 0.5 MA pulsed power machine. © 2009 Optical Society of America

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We have used temporally resolved Faraday rotation of a single longitudinal mode (SLM) laser beam through a magneto-optically active waveguide to measure rapidly varying pulsed magnetic fields. In the present experiments, we have used bulk waveguides made of multicomponent terbium borate glass rods to measure magnetic fields (B fields) up to 17.7 T produced in wire-array Z-pinch experiments by the 0.5 MA, 50–75 ns rise time current pulse from the XP pulsed-power generator [1] and fields up to 10.2 T by the 1 MA, 100 ns rise time current pulse from the COBRA pulsed-power generator [2], at Cornell University. To the best of our knowledge, this is the first time that such rapidly varying and large B fields have been measured by this class of materials. The spatial resolution was limited by the physical sensor sizes, and the time-resolution was ~10 ns or better. The Z-pinch experiments' harsh environment determined the measurement validity time during the ~250 ns long COBRA current pulse and the ~150 ns long XP current pulse. With the waveguide placed just outside the Z-pinch plasma, a valid signal was obtained for >200 ns on COBRA (>75 ns on XP), but it was a few tens of nanoseconds with the waveguide inside the plasma.

Understanding the B-field evolution in wire-array Z-pinch plasmas is of critical importance to stockpile stewardship and inertial confinement fusion [3]. The standard method is to use a small magnetic (electromagnetic induction) probe [4]. Faraday rotation of a linearly polarized laser beam passing through a wire-array Z-pinch plasma has also been used to estimate B fields within the plasma [5], but this method is "spoiled" by the highly nonuniform nature of wire-array Z-pinches [6]. The equation that quantifies the Faraday rotation angle, Θ, is [7]

$$\Theta = \frac{e^3}{8\pi^2 c^3 \varepsilon_0 m_e^2}\lambda_0^2 \int n_e \vec{B}\cdot \mathrm{d}\vec{l}, \qquad (1)$$

where n_e (m^{-3}) is the electron density, λ_0 (m) is the laser wavelength, and the line integral is along the laser path through the plasma. Determining the B field accurately requires independent knowledge of the electron density (an average value obtained from interferometry) and is highly nonuniform over the laser path length. Therefore, either a very simple geometry (e.g., just four wires) or an unrealistic assumption about cylindrical symmetry must be made to infer the B field as a function of position (the measurement location is ill-defined as it entails the total laser path length). We were motivated by the desire to make a local B-field measurement without placing a conducting probe in the plasma.

Multicomponent terbium borate glasses have a high Verdet constant, which determines the amount of rotation of the plane of polarization of the SLM laser beam versus B-field strength per unit length of glass [8]. If the B field is parallel to the direction of propagation when polarized light enters a magnetoactive glass, then it rotates the plane of polarization by an angle, Φ, given by [8]

$$\Phi = V\int \vec{B}\cdot \mathrm{d}\vec{l}, \qquad (2)$$

where V is the Verdet constant (wavelength dependent), in radians (or degrees) per Tesla-centimeter, of the material, and $\int\vec{B}\cdot\mathrm{d}\vec{l}$ is the line integral of the field along the length of glass.

We measure the Faraday rotation angle, Φ, by balanced detection splitting a polarized 532 nm SLM laser beam traversing the magnetoactive glass sensor into three components (see Fig. 1): the p component (horizontal polarization), s component (vertical polarization), and r component (has a 45° phase delay with respect to the p and s components). The components are detected by ~2 ns rise time amplified photodetectors (PDA10A from Thorlabs). The input laser beam is initialized at 45° using a half-wave plate to maxi-

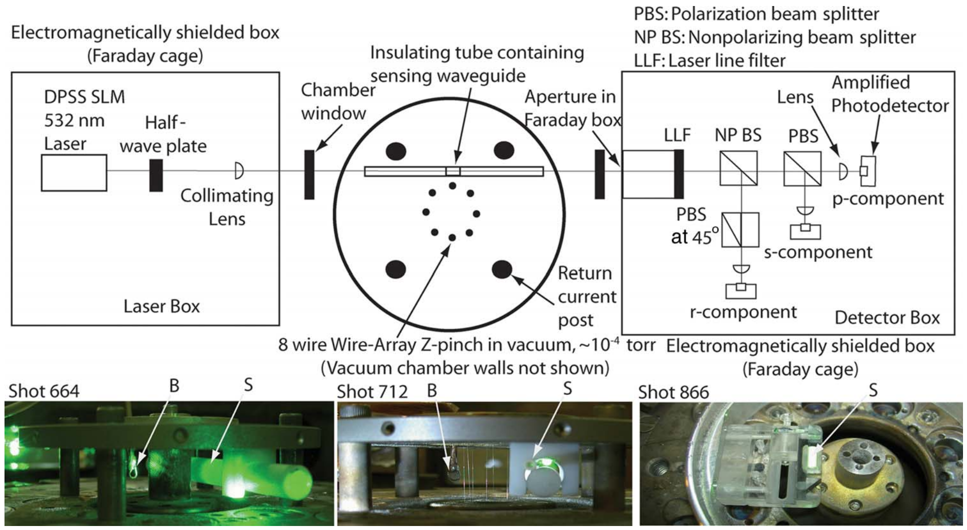

Fig. 1. (Color online) Diagram of the Faraday rotation optical system arrangement. The photographs show the experimental setup for the different tests. The arrows denoted with a "B" indicate the position of the magnetic probe. The arrows denoted with an "S" indicate the position of the waveguide sensor located inside its protective ceramic tube.

mize the measurement sensitivity. The r component resolves any ambiguities in the direction of the B-field change at a peak or valley in the p- or s-component signals (determines if the B field is increasing/decreasing or has changed direction). To analyze the signals (p, s, and r) we first apply a high-frequency noise filter followed by a normalization routine. We then use Malus' law [9] and Eq. (2) to calculate the total component rotation (measured by signal intensity changes) by examining the total number of maxima/minima, from which the $B(t)$ field is obtained. The signal bandwidth is limited by the amplified photodetectors to 150 MHz (~2 ns rise time).

The Z-pinch plasma configuration consists of a cylindrical array of (typically) eight wires (see middle photograph in Fig. 1) strung between anode and cathode electrodes as the COBRA generator load. A pulsed current of ~1 MA, rise time of 100 ns is then driven through the wires, causing them to explode and form a hot plasma. The current density (J) in the plasma around the exploding wires interacts with the magnetic field (B) from the total current to produce a $J \times B$ force that accelerates the current-carrying plasma portion toward the array symmetry axis. The resulting high inward velocity produces a high energy-density (~100 eV, $\geqslant 10^{20}/\text{cm}^3$ electron density) plasma on-axis (z axis). The large B fields of interest are just outside of and within the wire-array Z-pinch. A similar process occurs in XP pulsed-power generator load experiments (0.5 MA, 50–75 ns rise time).

The setup for the COBRA experiments is shown in Fig. 1. The wire-array configuration consisted of eight Al or W wires (each 12.5 or 25 μm in diameter, array radius of 0.8 cm, and height of 2.0 cm). Each return current post is 4.45 cm from the wire-array axis. Initially, the terbium borate glass in the middle of a ceramic tube is just outside the wire array (see Fig. 1). We used a SLM diode-pumped solid-state 532 nm 100 mW cw laser (Coherent Compass 315M-100). The ~10-cm-long alumina ceramic tube prevented the wire-array Z-pinch plasma from refracting the laser beam in free-space propagation and eliminated Z-pinch emission within the bandwidth of the 532 nm laser line filter at the detector box aperture. Electromagnetically shielded boxes (Faraday cages) were used to reduce the electrical noise from the ~10^{12} W COBRA pulsed-power generator.

We used three different terbium borate glasses for our experiments. First, there is M-18 from Kigre Inc., USA (~2-cm-long, 1 cm diameter rod; Verdet constant of 62.3°/T·cm). The second glass material is BTS-18 from Sumita Optical Glass, Japan (1-cm-long, 0.5 cm diameter rod; Verdet constant of 125°/T·cm). The third material is MR3-2 from Xi'an Aofa Optoelectronics Technology Inc., China (1-mm-long, 1.5 mm diameter rod; Verdet constant of 79.3°/T·cm). These Verdet constants (at 532 nm) were measured either by the manufacturers or by other users. Three different loads (see Fig. 1) were used: a short circuit load with return current posts, wire arrays, and a return current cylinder geometry.

To understand the response of the bulk waveguide material, short circuit load tests were conducted. A 1.5 cm diameter cylindrical brass rod (short circuit) replaced the wire-array load. Results from one such test (COBRA pulse 664) using BTS-18 as the waveguide inside a ceramic tube positioned about 1.5 cm from the rod center are shown in Fig. 2(a). The calculated B field tracks the optically measured B field very well. This result was reproduced in all short circuit load tests, demonstrating that the Faraday rotation measurements accurately track B-field changes. The short circuit load tests also show there is no noticeable time lag between the B field determined from Faraday rotation and the calculated B field (obtained from the machine current measured using a Rogowski coil). We therefore conclude that for this sample of BTS-18 glass, at a temperature of about 300 K, the spin-lattice relaxation time is a few tens of nanoseconds at most. Previous work [10], with Hoya FR-5 glass, a terbium-ion-doped borosilicate glass,

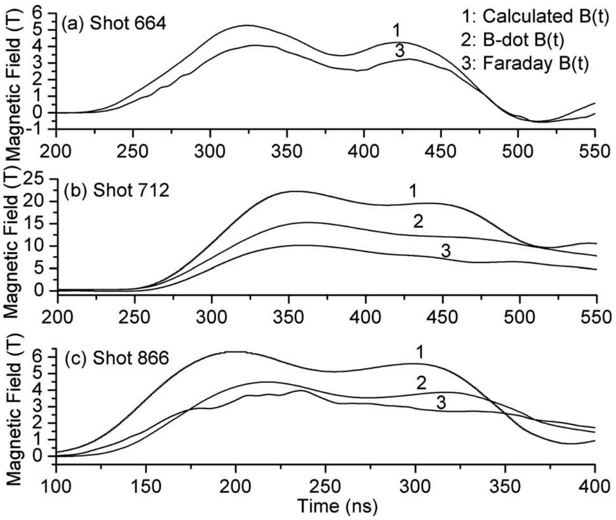

Fig. 2. Magnetic field profiles from a short circuit load test, a wire-array Z-pinch (eight-wire, 12.5 μm W test), and a return current can geometry test.

experimentally determined the spin-lattice relaxation time for such materials to have an upper limit of ~150 ns at a temperature of 30 K. We believe this is the first time that the spin-lattice relaxation time for multicomponent terbium borate glass has been experimentally determined to be less than 100 ns at room temperature (300 K). This also confirms the previously reported hysteresis effect in magneto-optical glasses [10] is an experimental artifact and not a real physical effect.

For wire-array test 712 (on COBRA with W wires), a MR3-2 glass rod in the center of a 10-cm-long ceramic tube was positioned with its center 1.1 cm from the wire-array axis (oriented tangentially to a circle centered on-axis). A magnetic probe was also positioned at a symmetrically opposite position to the waveguide (see Fig. 1). Using Faraday rotation, we measured a peak field of 10.2 T [see Fig. 2(b)], and the measurement lasted the entire current pulse, as did the magnetic probe signal since both were placed outside the plasma. The calculated $B(t)$ at the sensor assumed the load current (measured by the Rogowski coil) flowed through an infinitely long central conductor on the array axis, and the return current from the anode was split equally among the four return current posts (see Fig. 1). Thus, no azimuthal asymmetries due to wire-array plasma dynamics were considered. Using the short circuit load results, the differences in the Faraday and magnetic probe profiles are likely due to imperfect symmetry of the plasma (which can be substantial with only eight wires in an 8 mm radius array [6]), the possibility of unstable plasma motion and uncertainty in the probe placement at the ±0.5 mm level.

We also positioned a MR3-2 waveguide (in a short ceramic tube) 2–4 mm from the wire-array center inside an eight-wire 12.5 μm Al wire array. Laser shadowgraphy showed plasma engulfing the glass rod shortly after the start of current. Evidently the free-space laser coupling to the waveguide was broken by a shock wave refracting the beam. Mostly no useful measurement was made, but in COBRA pulse 627, we measured a field for about 40 ns (peak of just over 1.9 T).

Subsequent tests used a polarization-maintaining (PM) fiber (HB450 from Thorlabs) to deliver the light to a MR3-2 glass sensor (inside an optical assembly) where the output light propagated in free space. The return current geometry is similar to that used in studies on the Z Machine [11]. We used a short circuit load and a thin-walled cylindrical 11 cm diameter Al return current conductor. The results were reproducible, and Fig. 2(c) shows one such measurement (COBRA pulse 866), where the MR3-2 is at 2.7 cm from the 1.5 cm diameter brass rod center.

Recently, we tested an integrated optical fiber sensor (fiber-sensor-fiber assembly) in 0.5 MA, 50–75 ns experiments on XP. The integrated assembly consists of an input PM fiber that delivers light to a MR3-2 glass sensor inside a ceramic tube. The output light is coupled into an output PM fiber whose "eyes" are aligned at 45° with respect to the input fiber. Preliminary results have yielded the B field (peak of 17.4 T) for ~125 ns from the start of current for a 0.95 cm diameter short circuit load test with the sensor at 0.76 cm from the load center. With the sensor positioned 7.62 mm from the wire-array axis center (2.12 mm from the nearest wire) for a 10 mm diameter four-wire 25 μm W array, we measured the B field (peak of 17.7 T) for about 75 ns from the start of current.

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