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Generation of strong pulsed magnetic fields using a compact, short pulse generator

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The generation of strong magnetic fields (~50 T) using single- or multi-turn coils immersed in water was studied. A pulse generator with stored energy of ~3.6 kJ, discharge current amplitude of ~220 kA, and rise time of ~1.5 μs was used in these experiments. Using the advantage of water that it has a large Verdet constant, the magnetic field was measured using the non-disturbing method of Faraday rotation of a polarized collimated laser beam. This approach does not require the use of magnetic probes, which are sensitive to electromagnetic noise and damaged in each shot. It also avoids the possible formation of plasma by either a flashover along the conductor or gas breakdown inside the coil caused by an induced electric field. In addition, it was shown that this approach can be used successfully to investigate the interesting phenomenon of magnetic field enhanced diffusion into a conductor. *© 2016 AIP Publishing LLC*.
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I. INTRODUCTION

The generation of strong magnetic fields is of continuous wide interest because of its importance to the basic research of material properties and to several important applications, including magnetic resonance imaging,[1] magnetic phase transitions,[2] and the magnetization of different materials.[3] Recently, non-linear diffusion of a strong magnetic field (>20 T) became the subject of intense research, both theoretical and experimental.[4,5] High stored energy (>100 kJ) pulse generators are required to generate such strong pulsed magnetic fields. Magnetic fields obtained using non-destructive methods with amplitudes of up to ~100 T were reported,[6] while the record amplitude of a constant magnetic field is more than two times smaller.[7] To measure the pulsed magnetic fields, mainly B-dot loops, current transformers, Hall probes, and the effect of the Faraday rotation of a polarized laser beam are applied. A review of the physics and methods of generating strong magnetic fields can be found in a recently published text book by Shneerson *et al.*[8]

In this paper, the results of the measurement of pulsed magnetic fields of up to 50 T, generated by single–turn and three-turn coils supplied by a microsecond timescale current from a pulse generator with stored energy of ~3.6 kJ, are presented. The coils were only slightly deformed and therefore the process of magnetic field generation is essentially non-destructive. The experiments were performed in water to avoid the electrical breakdown along the coil due to the induced voltage and to allow non-perturbing measurements of the magnetic field using Faraday rotation. In addition, it was shown that this approach can be effectively applied to study enhanced magnetic field diffusion.

Although the volume inside a single-turn coil used in our experiments, where the maximal magnetic field was generated, is rather small for inserting some specimen for investigation, the volume around the axis of a three-turn coil becomes applicable for these kinds of applications. However, the single-turn coil can be used for the investigation of enhanced magnetic field diffusion into a conductor.

II. EXPERIMENTAL SETUP

A high-current generator[9] with stored energy of ~3.6 kJ generating a current pulse through a short-circuit inductive load with an amplitude of ~300 kA and rise time of ~1 μs at an inductive load of 15 nH was used in these experiments. The current pulse was delivered to single-turn coils made of either stainless steel or copper. The coils were wrapped in a shrink tube, and a Kapton insulator (0.4 mm thick) was put between the coil's input and output terminals. These measures allowed to avoid possible electrical breakdowns between those terminals and to minimize current losses through water. The cross section of the stainless steel coil was a square with sides 2 mm in length. The copper coils' cross section was a circle with a diameter of 2 mm. Two- and three-turn copper coils were also tested in these experiments. One end of the coils was connected to a high voltage electrode inside a chamber filled with distilled water (see Fig. 1(a)) having resistivity of $\geq 2\,\Omega$cm and the other end was connected with a thin copper wire to the grounded chamber wall. The latter was applied in order to avoid a periodical discharge of the pulse generator which can lead to shortening of the life time of the capacitor bank. The discharge current was measured using a self-integrated Rogowski coil.

The Faraday effect was applied to measure the magnetic field using linearly polarized collimated (2 mm in diameter) continuous wave lasers of two different wavelengths, 532 nm and 633 nm. The lasers were placed inside a Faraday cage. Using mirrors, the polarized laser beam was directed through the chamber's optical windows along the coil's axis to a polarizer, the polarization plane which was at a 90° angle with respect to the laser's polarization. The intensity of the laser

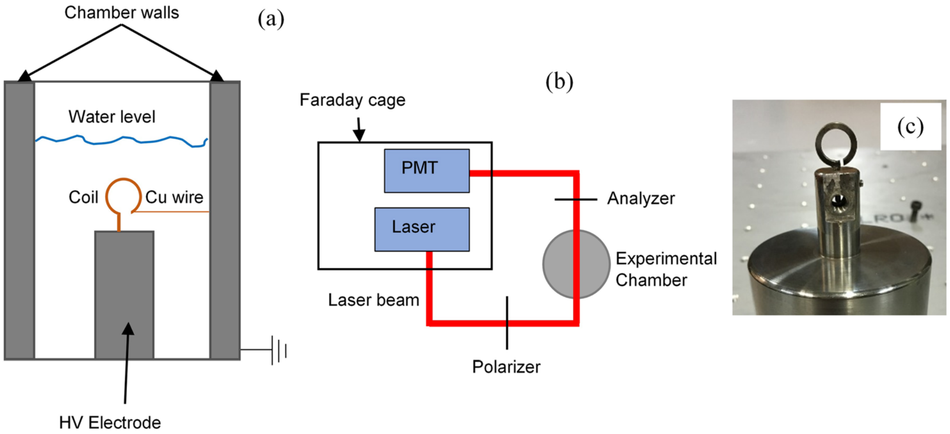

FIG. 1. (a) Single-turn coil inside the experimental chamber connected at one end to the high voltage electrode and at the other to the grounded chamber wall. (b) Laser beam path from the laser to the PMT. (c) External view of a single-turn coil.

was measured by a photomultiplier tube (Hamamatsu R6095) (PMT) placed also inside the Faraday cage (see Fig. 2(b)).

III. EXPERIMENTAL RESULTS AND ANALYSIS

Typical waveforms of the discharge current and PMT are shown in Fig. 2. The electrical and optical signals do not necessarily have the same time origin. The time delay of the optical signal was estimated to be ~60 ns. One can see that the start of the discharge current leads to the appearance of the laser intensity registered by the PMT being zero prior to the beginning of the current because of the polarizers being placed initially perpendicular to each other.

An increase in the discharge current is followed by an increase in the laser's intensity because of the rotation of the laser's polarization plane in the presence of an axial component of the generated magnetic field. Further, a decrease in the discharge current, and consequently, a decrease in the magnetic field, as expected, leads to a decrease in the laser beam's intensity. In addition, one can see that the decrease in the laser beam intensity begins before the current's peak, which can be explained by the laser's polarization plane rotation by more than 90°. In general, the intensity of the laser beam should be symmetric with respect to the current. However, one can see that the intensity of the laser beam is slightly weaker after the peak in the discharge current than during its rise time. The reason for this asymmetry will be discussed later. To ensure that the registered laser light intensity is due to the Faraday rotation and not due to other unrelated processes, experiments without a coil and with the coil placed at the side of the laser beam's path were performed. In these experiments, the laser beam's intensity recorded by the PMT was almost zero.

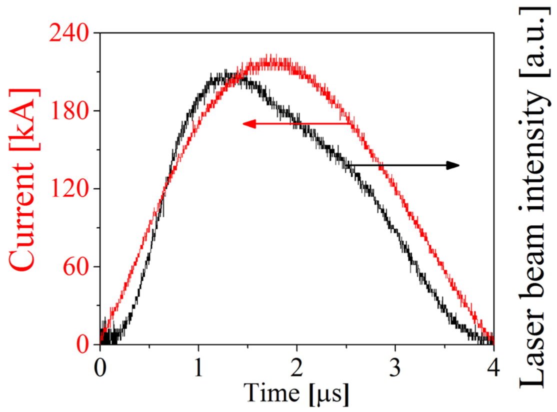

FIG. 2. Typical waveforms of the discharge current and laser beam intensity registered by the PMT.

To calculate the value of the magnetic field in the center of the coil, the following analysis was performed. The rotation of the laser beam's polarization plane due to the component of the magnetic field parallel to the propagation of an electromagnetic wave is given by $\theta = \nu \int B_z(l)dl$, where ν is the Verdet constant, $B_z(l)$ is the axial magnetic field, and the integral is along the path of the laser beam. The axial magnetic field distribution of a single-turn coil along the axis of symmetry can be written as $B(l) = B_0 f(l)$, where B_0 is the magnetic field in the center of the coil, $f(l) = (\mu_0/2)R^2/(z^2 + R^2)^{3/2}$ is the distribution of the axial magnetic field, and $R = 5 \times 10^{-3}$ m is the internal radius of the coil. Thus, the rotation angle can be written as $\theta = \nu B_0 \int f(l)dl$. The relationship between the magnetic field and current through the loop is linear, and therefore $\theta \propto I \int f(l)dl$. During the present experiment, the value of $\int f(l)dl$ was not changed, and therefore $\theta \propto I$. The recorded intensity of the laser beam by the PMT is related to the degree of rotation as $A \sin^2(\theta)$, where A is the laser beam intensity when $\theta = 90°$. Because the value of $\theta \propto I$, one can write the dependence of the laser beam intensity P versus the amplitude of the discharge current as $P = A \sin^2(\phi I)$, where ϕ is the proportionality constant between θ and I. The dependence of the laser's intensity versus the angle of the analyzer's polarization plane was obtained prior to the experiments with the pulse generator and it was verified that $P = A \sin^2(\theta)$. By fitting the obtained intensity waveform to $P(\phi I)$, one obtains the value of ϕ. This allows one to determine the rotation angle θ versus the amplitude of the discharge current through the loop $\theta(I) = \phi I$, and, consequently the value of $B_0 = \theta[\nu \int f(l)dl]^{-1}$. Typical results of the time evolution of the magnetic field for a single– and three-turn coil are shown in Fig. 3. One can see that in the case of a three-turn coil, the magnetic field reaches ~50 T as compared with ~33 T in the case of single-turn coil.

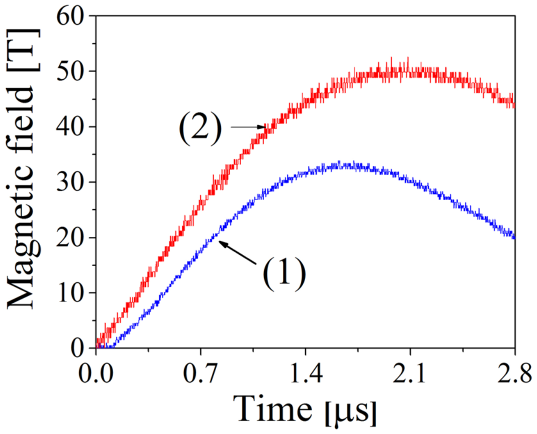

FIG. 3. Calculated magnetic fields at the center of a single-turn coil (1) and three-turn coil (2).

To validate the integrity of the results obtained with the 633 nm laser, additional experiments were performed with a single-turn coil and a 532 nm laser. The rotation angle θ was expected to be different because of the difference in the Verdet constant for these two wavelengths, which is ~280°/(T m) and ~190°/(T m) for the 532 nm and 633 nm laser wavelengths, respectively.[10] Indeed, a larger value of θ for the 532 nm wavelength laser was obtained.

The error in the presented analysis of the magnetic field is composed of errors related to the fitting procedure, inexact alignment of the laser beam at the center of the coil, error in the radius of the coil, and the accuracy of the measurements of the discharge current by the Rogowski coil. Thus, the total error in the determination of the magnetic field was calculated to be $\leq 15\%$.

IV. DISCUSSION

The experiments showed that the application of a three-turn coil magnetic field leads to an increase in the magnetic field only ~1.5 times more than that of a single-turn coil. This can be explained by the small aspect ratio between the length and diameter of the three-turn coil. In addition, the increase in the inductance of the coil, which is $\propto n^2$ (here, n is the number of turns per unit length), leads to a decrease in the magnetic field $B \propto (L_g + L_c)^{-0.5}$ and an increase in the period of the magnetic field $T \propto (L_g + L_c)^{0.5}$, where L_g and L_c are the inductance of the pulse generator and coil, respectively.

In the experiments, the intensity of the laser beam registered by the PMT was not symmetrical with respect to the maximum of the discharge current, namely, it was slightly weaker after the peak in the discharge current than during its rise time. This asymmetry can be explained by an increased diffusion rate of the magnetic field into the coil. The skin-layer of the discharge current in the copper single-turn coil can be estimated as $\delta_{sl} = 503.3\sqrt{\rho/f} \approx 0.14$ mm, where $\rho = 0.017\ \Omega\,\text{mm}^2/\text{m}$ is the copper specific resistivity and $f \approx 2 \times 10^5\ \text{s}^{-1}$ is the frequency of the discharge current. However, this skin-layer estimate is not correct in the case of fast Joule heating of the conductor by the discharge current. The current density in our experiments reached $4.5 \times 10^6\ \text{A/cm}^2$. This should lead to the fast heating of the conductor, and consequently, to an increase in its resistivity and in the magnetic field diffusion rate. Following the analysis presented in Refs. 4, 5, the characteristic magnetic field at which the resistivity of the copper doubles as a result of Joule heating should be >25 T, which is satisfied in our experiments. In addition, the results of magnetohydrodynamic (MHD) simulations[11] coupled with the Equations of State for copper[12] and a conductivity model[13] performed for a 220 kA amplitude of the current pulse with a rise time of 1.4 μs through a 2 mm diameter copper wire show that starting at ~0.5 μs with respect to the beginning of the current pulse, the maximum of the current density radial distribution is moved toward the axis with a typical velocity of 3×10^4 cm/s. In the experiments with the coil, the current density is not azimuthally uniform, being larger at its inner radius. This should lead to an increase in the velocity of the current diffusion into the conductor toward the larger radii with respect to the axis, and consequently, to a decrease in the magnetic field in the center of the coil. Thus, the application of non-disturbing measurement diagnostics of the magnetic field based on Faraday rotation coupled with MHD simulations can be used for studies related to non-linear magnetic field diffusion in different conductors.

To conclude, this experimental research showed that using single- or multi-turn coils immersed in water, one can generate strong magnetic fields with amplitudes exceeding 50 T using a pulse generator with relatively small stored energy and measure these fields by the non-disturbing method of Faraday rotation of the polarized laser beam. This approach does not require the use of magnetic probes that are sensitive to electromagnetic noise and which are damaged in each shot and avoids the possible formation of plasma by either a flashover along the conductor or a gas breakdown inside the coil caused by an induced electric field. In addition, it was shown that this approach can be used successfully to investigate the interesting phenomenon of magnetic field-enhanced diffusion into a conductor.

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