Laboratory measurements of 0.7 GG magnetic fields generated during high-intensity laser interactions with dense plasmas

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We report measurements of ultrahigh magnetic fields produced during intense ($\sim 10^{20}$ Wcm^{-2} μm^2) laser interaction experiments with solids. We show that polarization measurements of high-order vuv laser harmonics generated during the interaction (up to the 15th order) suggest the existence of magnetic field strengths of 0.7 ± 0.1 GG in the overdense plasma. Measurements using higher order harmonics indicate that denser regions of the plasma can be probed. This technique may be useful for measurements of multi-GG level magnetic fields which are predicted to occur at even higher intensities.

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I. INTRODUCTION

Continuing advances in laser technology have enabled experiments using laser pulses focused to extreme intensities (greater than 10^{20} W/cm^2) [1] thus making possible the exploration of new regimes in plasma physics [2]. An important characteristic of these interactions is the production of multi-MG strength magnetic fields [3–9]. These fields are predicted to exist in localized regions near the critical density surface (i.e., the region where most of the laser absorption takes place). Such spontaneous magnetic fields can be generated by several mechanisms including: nonparallel temperature and density gradients in the ablated plasma [8], by the ponderomotive force associated with the laser radiation itself [7] and by the current of fast electrons generated during the interaction [4,5]. The magnitude of magnetic fields generated by each of these sources can become hundreds of MG at high laser intensities. All of these fields are predicted to be in the azimuthal direction around the laser interaction region although the direction of the field due to plasma gradients should be opposite to that produced by the other mechanisms. Clearly, this is a little known regime of plasma physics which is difficult to access experimentally or even through the use of computer simulations.

Until recently, diagnostic techniques for magnetic fields used external optical probing techniques which were inadequate for measurements of ultrastrong magnetic fields where the plasma density is very high (e.g., at the critical density, $n_e \sim 10^{21}$ cm^{-3}) because the steep plasma density gradients in these regions cause unacceptable refraction of the probe beam. Using such techniques, only the magnetic field in the outer low-density plasma ($n_e \sim 10^{19}$–10^{20} cm^{-3}) can be measured (less than 10 MG) [3,9] which is far lower than that predicted to exist near the critical surface.

However, recently Tatarakis *et al.* [10,11] have introduced a technique for measuring these fields through measuring the polarization properties of self-generated harmonics of the laser frequency. It is well known that when an electromagnetic wave propagates in a strongly magnetized plasma with its **k**-vector perpendicular to the field, the X-wave, i.e., the component of the wave with its electric field perpendicular to the magnetic field, can experience cutoffs and resonances. A cutoff occurs when the index of refraction is equal to zero and a resonance occurs when the index of refraction approaches infinity. The X-wave is reflected when it encounters a cutoff and is absorbed at resonance (at the upper hybrid frequency). The ordinary wave (O-wave with electric field vector parallel to the magnetic field) is unaffected. Such cutoffs of low order self-generated harmonics of the laser frequency [12] have been observed during high intensity laser plasma interactions and magnetic fields as high as 400 ± 50 MG have been inferred from them [10,11]. However, these cutoff measurements have only been possible at the very highest laser intensities ($\sim 8 \times 10^{19}$ W/cm^2). At lower intensities, measurements of the Stokes vectors of the optical harmonics have been used to estimate the magnitude of the magnetic field from the Cotton-Mouton effect (an induced ellipticity) [11,13].

In this paper we present the first measurements of the polarization properties of the higher-order 8th–25th harmonics of the laser frequency (131–42 nm) generated under high intensity conditions. We show that a distinct increase in the ratio of s/p polarization components of the eleventh and higher-order harmonics can be observed at high intensity. A significant change in the magnetic field strength can consequently be inferred from these measurements since the observed polarization changes can be attributed to the Cotton-Mouton effect because of the observed wavelength scaling. Our measurements suggest that the field strength inferred

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from the lower order (below the tenth order) harmonics originates from the magnetic field in the surface layers of the laser-produced plasma, whereas the induced ellipticity of the eleventh harmonic onwards likely has a significant contribution from larger magnetic fields in deeper (higher density) regions of plasma which are created during the hole-boring phase of the interaction. These measurements demonstrate the λ^3 scaling of the induced ellipticity in the harmonic polarization due to the Cotton-Mouton effect and show the existence of 700 MG magnetic fields at 10^{20} Wcm^{-2} μm^2, in agreement with fields predicted by 2D particle-in-cell simulations.

II. EXPERIMENT

The results presented here were obtained using the high intensity VULCAN laser system at the Rutherford Appleton Laboratory. This laser produces pulses at a wavelength of 1.053 μm, with an energy up to 100 J having a duration of 0.7–1.2 ps. The beam was *p*-polarized and was focused to a 10 μm diameter spot at a 45 degree angle to the target normal producing a maximum intensity of about $I=9\times10^{19}$ Wcm^{-2}. The parameters of the laser pulse were measured simultaneously for every laser shot. In these experiments, 1 mm thick polished glass targets were used. The contrast ratio for the laser pulse was measured previously to be $\sim10^{-6}$ and, because of this, during our experiments the main interaction will occur with relatively long density scale length preplasma. However, because of the 1 ps long pulse duration in these experiments, ponderomotive steepening [4,5] of the critical surface can occur, which consequently allows efficient generation of high order harmonics [10].

In order to determine the self-generated magnetic field during the interaction, the Stokes parameters of the fifth, fourth, third, and second harmonics were measured with polarimeters using high dynamic range CCD arrays as detectors, as previously described [12]. Figure 1 shows the magnetic field strength inferred from these measurements for the second to the fifth harmonics. It is not possible to measure field strengths above the X-wave cutoff for each particular harmonic order using the Cotton-Mouton effect since such measurements obviously require that both polarizations be able to propagate. Consequently, to measure magnetic field strengths of the order of a GGauss or larger, measurements of the higher-order harmonics (with corresponding X-wave cutoffs at higher fields and electron densities) are required. Cutoffs for the various harmonics are typically separated by about $\Delta B=\omega_L m_e c/e$ (in this case $\Delta B\sim100$ MG) [11].

Harmonics above the fifth order occur in the vacuum ultraviolet (vuv) spectral region which is difficult to access experimentally, and where no wave plates presently exist. Hence, it is not possible to characterize completely the polarization state of short-wavelength harmonics via measurements of the Stokes vectors. But since the frequency of these higher harmonics is large compared with the cyclotron frequency in the magnetized plasma, the ratio between the minor (b) and major (a) axes of the polarization ellipse is sufficient to estimate the magnetic field strength from the ellipticity caused by the Cotton-Mouton effect to the initially

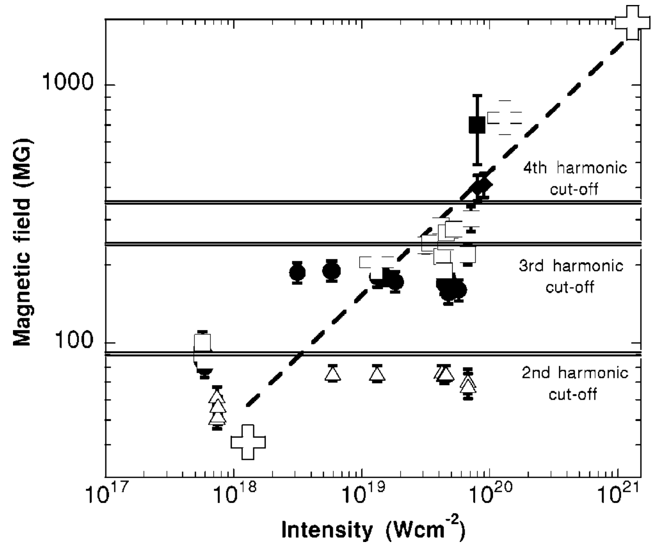

FIG. 1. Measured magnetic field incident laser intensity as determined from harmonic polarimetry. (△): second harmonic; (●): third harmonic; (□): fourth harmonic; (♦): fifth harmonic; (■): eleventh–thirteenth harmonics, open cross: peak magnetic field from PIC simulations (OSIRIS); dashed line: ponderomotive scaling "fit" to simulation results.

plane polarized electromagnetic wave [14] using the following formula:

$$\frac{b}{a}=2.49\times10^{-21}\lambda_{\mu\mathrm{m}}^3\int nB_{\mathrm{MG}}^2 dl,$$

where n is the plasma electron density (cm^{-3}), dl is the path length (μm), λ is the wavelength of the harmonic radiation (μm), and B is the magnetic field strength (MG).

Therefore, a two-channel VUV-polarimeter (Fig. 2) was constructed to enable measurements of these very high magnetic fields [15]. Two VUV-polarizers were setup orthogonally, one for *s*-polarized light and one for *p*-polarized light. Each consists of a triple-mirror-configuration, which is partially polarizing due to Fresnel reflections of the three gold-coated mirror surfaces. The incident angle of the harmonic radiation was 25° with respect to the surface of the mirror. The two polarized beams were then focused onto the slit of an Acton 502 VUV spectrometer. A large area open microchannel-plate (MCP) coupled to a charge coupled device (CCD) by a fiber-optic bundle was used as the detector and was aligned to intercept the focal plane of the spectrometer—allowing the simultaneous measurement of both polarizations of the 8th–25th harmonic orders for each shot.

The polarization properties of the Fresnel mirrors were determined using two independent measurements of the optical constants [16]. The calculated extinction ratio for both channels also included the polarization properties of the 1200 lines/mm diffraction grating. In addition, the vuv polarimeter was calibrated using the well-defined source of atomic harmonic emission developed at the ultraviolet laser facility at the Foundation of Research and Technology Hellas (FORTH) in Greece. In this calibration, all of the compo-

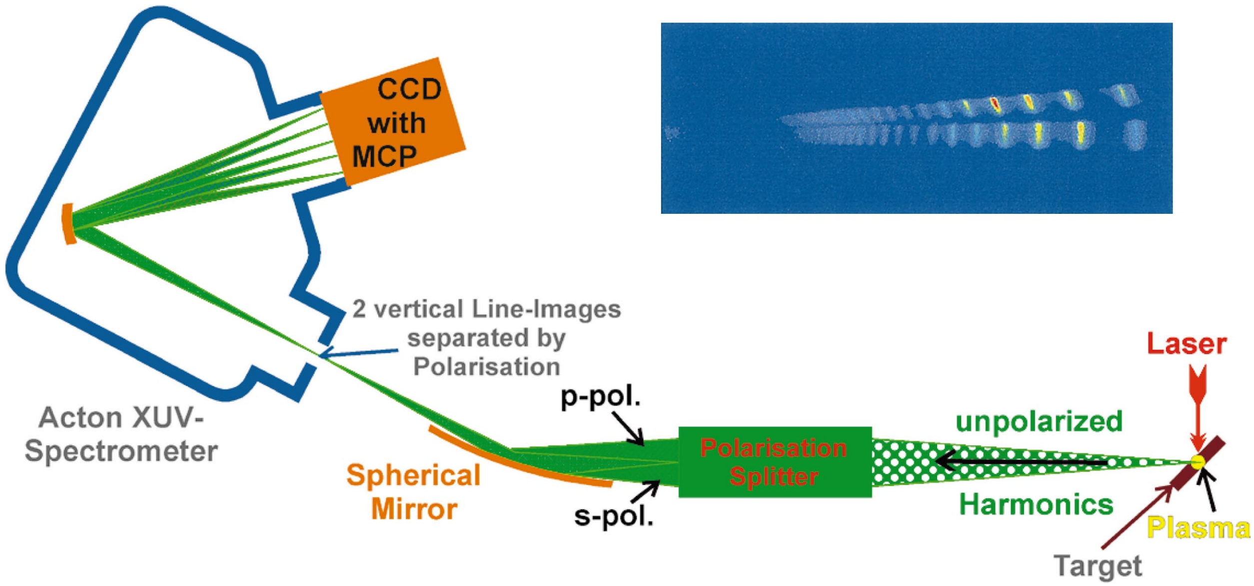

FIG. 2. (Color) Setup for VUV polarimetry. Inset is shown as an example of raw data with eighth–25th harmonic (wavelength increases left to right) separated into *s* and *p* polarization components (up/down).

nents of the polarimeter were considered as one optical element and the Muller matrix [14] was measured. The experimentally defined Muller matrix was in good agreement with the matrix found from the calculated reflectivities of *p*- and *s*-polarized vuv radiation on gold mirrors.

III. RESULTS

A typical set of data acquired during the experiment is shown in the inset of Fig. 2. From this one can estimate the magnetic field strength assuming that the ratio of $s/p = \text{const} \times b/a$ (i.e., initially assume that the Faraday effect is small). Then the magnetic field strength (B) is given by $B = \text{const} \times [(s/p)\lambda^3]^{1/2}$ a.u. Figure 3 shows that the harmonics from the seventh to the tenth follow a λ^3 scaling consistent with having an induced ellipticity due to the Cotton-Mouton effect (this scaling is shown as the solid lines in the figure). This is also consistent with our initial assumption that the Faraday effect, which scales like λ^2 (as indicated by the dashed line in Fig. 3), is negligible. However, a notable feature in these data is the jump in apparent field strength at the eleventh harmonic which then subsequently follows a λ^3 scaling until the thirteenth harmonic. Harmonics of higher order than the thirteenth were not used in this analysis due to large uncertainties resulting from lower image resolution and the increased level of background at shorter wavelengths.

The optical polarimetry measurements taken simultaneously and at a similar collection angle showed that there was an X-wave cutoff for the fourth harmonic but none for the fifth harmonic suggesting that the peak field strength measured by the low order harmonics was ~400 MG. The "jump" in the ratio of s/p for the eleventh harmonic orders onwards indicates that these higher frequency harmonics are affected by a much larger magnetic field in the plasma (i.e., 700 ± 100 MG). It is interesting to note that the critical density for the eleventh harmonic is $1.1 \times 10^{23} \text{cm}^{-3}$ suggesting that these harmonics can sample magnetic fields in higher density regions of the plasma which are only accessible because of laser hole boring into higher density plasma at extreme intensities [4]. It should be noted that this jump in the observed ellipticity is very likely to be mainly due to an increase in magnetic field through which the harmonics propagate since the difference in critical density between the tenth and eleventh harmonics is only 4% and the increased penetration distance (dl) should also be relatively small. This observed jump in the ratios of the two polarizations was consistently observed throughout these experiments although occasionally the jump in the polarization ratio of the XUV harmonic spectrum was observed to occur between the eleventh and twelfth harmonics.

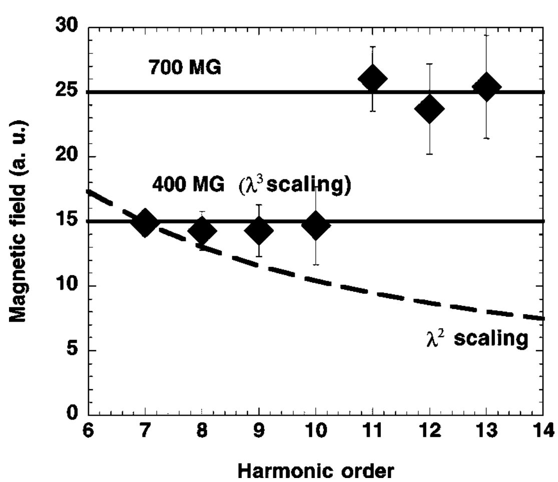

FIG. 3. Calculated magnetic field from experiment at $I = 9 \times 10^{19}$ W/cm^2: note that this displays the λ^3 scaling (solid line) which is characteristic of the Cotton-Mouton effect.

It is also likely that higher-order harmonics are produced in a smaller spatial region than lower orders. Consequently, higher order harmonics may on average sample higher mag-

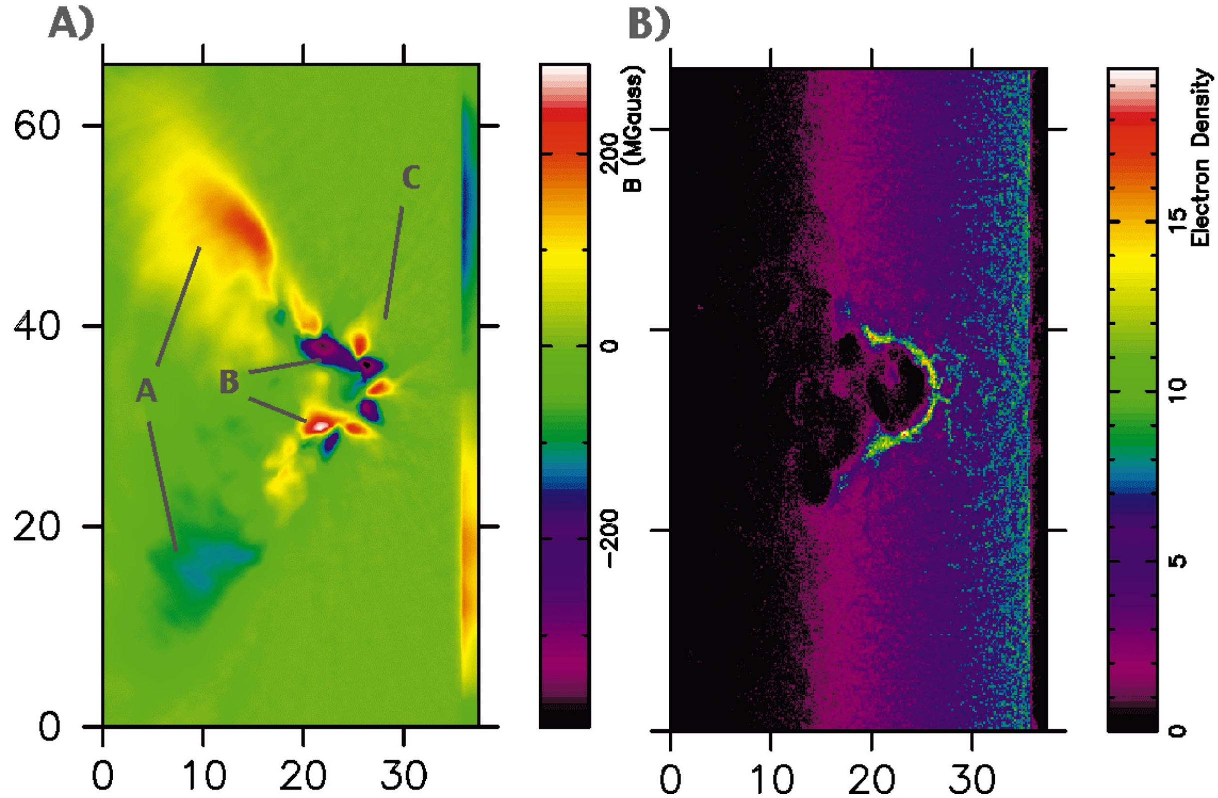

FIG. 4. (Color) Simulation of high intensity interaction using 2D particle in cell code, OSIRIS, showing hole-boring effects and regions of magnetic field. Region (A) nonparallel temperature and density gradients; region (B) ponderomotive source; region (C) magnetic fields due to Weibel-like instability from laser generated electron beams. Laser is normally incident onto a linearly increasing density ramp (maximum density 15 n_{cr}) and $I=10^{19}$ W/cm^2. Box size is 6.5 μm$\times$10 μm and grid is in units of the collisionless skin depth (c/ω_{pe}).

netic fields than lower order harmonics, simply because the source of these harmonics is more well-defined in the regions of highest intensity.

IV. DISCUSSION AND CONCLUSIONS

For comparison, 2D particle-in-cell simulations were undertaken using the code OSIRIS [17]. These indicated that the peak measured fields generated by these experiments were in general agreement with the values obtained by our measurements (see simulation points in Fig. 1). The maximum field in these simulations was also found to grow with an approximately "ponderomotive" scaling [i.e., $\sim(I\lambda^2)^{1/2}$]. This indicates that the primary magnetic field generation mechanism is likely that due to the ponderomotive source as discussed in Ref. [7]. Figure 4(A) displays the results from a 2D OSIRIS simulation (at $I=10^{19}$ W/cm^2) in which magnetic fields resulting from the three different mechanisms can be distinguished. In region (A) fields are produced via nonparallel temperature and density gradients in region (B) the fields are produced via a ponderomotive source; and in region (C) magnetic fields are likely due to Weibel-like instability in the laser generated electron beams. The laser beam is normally incident onto a linearly increasing density ramp (maximum density 15 n_{cr}) and $I=10^{19}$ W/cm^2. The electron density is also shown [Fig. 4(A)] which indicates the extent of the hole boring and which shows that the region of highest laser intensity is surrounded by plasma density up to 20 times critical density. This will affect which harmonics will be able to propagate out of the plasma, and also which harmonics will be able to sample the largest magnetic fields.

In the theoretical calculations from Ref. [7] the very large magnetic fields were predicted to extend into the plasma for only a collisionless skin depth, however, in simulations of these interactions these fields are observed to have a larger spatial extent [4,12]. In particular, in our simulations it was found that the high magnetic fields exist in a region having a spatial dimension which is several times the collisionless skin depth near the critical density surface. This relatively large depth to which the magnetic field extends is likely the reason why higher frequency harmonics suggest the existence of larger magnetic fields in our measurements.

This anomalous skin depth is likely due to the relativistic motion of the plasma electrons in the huge electric fields generated by the focused laser beam and can be easily estimated. The electron fluid equation of motion of plasma in the field of a laser beam propagating in the z direction is given by:

$$\gamma m_e \frac{\partial v_x}{\partial t} + \gamma m_e v_z \frac{\partial v_x}{\partial z} = -eE_x,$$

where the x component is dominated by the convective term, where v_z is given approximately by $(eE)/\gamma m\omega$ (i.e., the relativistic forward velocity in the "figure of 8" quiver motion) and where

$$\frac{\partial}{\partial z} \sim \frac{1}{L}.$$

For overdense plasma, Ampère's law can be written as $B_y/L = -n_e e \nu_x \mu_o$ and Faraday's law is $E_x/L = i\omega B_y$. This then gives

$$L \approx \left(\frac{\gamma c^2}{\omega_{pe}^2} \cdot \frac{\gamma}{2\pi} \right)^{1/3}$$

if $\nu_z \sim c$. Therefore, we estimate that in our experiments L can be many times larger than the collisionless skin depth (c/ω_{pe}) (since $\omega_{pe} > \omega_{\rm Laser}$, from ponderomotive steepening).

The maximum magnetic field is also found to extend to distances further into the plasma. This also implies that shorter wavelengths harmonics, which are able to penetrate further, will sample regions of plasma which have a higher magnetic field.

In conclusion, a multichannel VUV polarimeter has been constructed and deployed to measure magnetic fields in intense laser-produced plasmas. These measurements suggest that peak dc fields up to 0.7 ± 0.1 GG occur in the high density regions of plasma at incident laser intensities of $9 \times 10^{19}\ \mathrm{W/cm^2}$ in agreement with particle-in-cell simulations. These harmonics sample the largest magnetic fields which likely extend into the plasma for distances significantly larger than the collisionless skin depth, a situation which is likely due to the relativistic motion of the plasma electrons in these ultrahigh intensity interactions. Such measurements are significantly larger than any previous observations of laboratory magnetic fields.

VUV polarimetry is essential to diagnose the multi-GG dc magnetic fields, which are expected to be generated with the next generation of high power lasers. The magnetic fields which can be produced in these experiments are only an order of magnitude less than that of the oscillating magnetic field of the focused laser pulse itself and begin to approach those required to generate Landau quantization of electron motion in hydrogen [18]. As the intensity of laser systems is increased further, these magnetic fields may begin to affect fundamental parameters of the plasma such as the equation of state and the opacity. Consequently, laboratory tests of astrophysical models developed for extreme conditions (such as those in the atmosphere of neutron stars) may soon become possible.

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[1] M. D. Perry and G. Mourou, Science **264**, 917 (1994).
[2] E. L. Clark *et al.*, Phys. Rev. Lett. **84**, 670 (2000); M. H. Key *et al.*, Phys. Plasmas **5**, 1966 (1998); R. D. Edwards *et al.*, Appl. Phys. Lett. **80**, 2129 (2002).
[3] J. A. Stamper, Laser Part. Beams **9**, 841 (1991).
[4] S. C. Wilks *et al.*, Phys. Rev. Lett. **69**, 1383 (1992).
[5] A. Pukhov and J. Meyer-ter-Vehn, Phys. Rev. Lett. **76**, 3975 (1996).
[6] R. J. Mason and M. Tabak, Phys. Rev. Lett. **80**, 524 (1998).
[7] R. Sudan, Phys. Rev. Lett. **70**, 3075 (1993).
[8] J. A. Stamper *et al.*, Phys. Rev. Lett. **26**, 1012 (1971).
[9] M. Borghesi *et al.*, Phys. Rev. Lett. **80**, 5137 (1998).
[10] M. Tatarakis *et al.*, Nature (London) **398**, 489 (2002).
[11] M. Tatarakis *et al.*, Phys. Plasmas **9**, 3642 (2002).
[12] P. A. Norreys *et al.*, Phys. Rev. Lett. **76**, 1832 (1996); I. Watts *et al.*, *ibid.* **88**, 155001 (2002).
[13] A. S. Sandhu *et al.*, Phys. Rev. Lett. **89**, 225002 (2002).
[14] I. H. Hutchinson, *Principles of Plasma Diagnostics* (Cambridge University Press, Cambridge, UK, 1987); S. E. Segre, Plasma Phys. Controlled Fusion **41**, 1257 (1999).
[15] U. Wagner, Ph.D. dissertation, Friedrich Schiller University, 2002.
[16] J. R. Robinson, *Handbook of Spectroscopy* (CRC, Boca Raton, 1981); *Handbook of Optical Constants*, edited by E. D. Palik (Academic, New York, 1985), p. 286.
[17] R. Hemker, Ph.D. dissertation, UCLA, 2000.
[18] D. Lai, Rev. Mod. Phys. **73**, 629 (2001).