Kinetic magnetization by fast electrons in laser-produced plasmas at sub-relativistic intensities


Published in:
Physics of Plasmas

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
Copyright 2017 the authors.
This is an open access article published under a Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the author and source are cited.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.
Kinetic magnetization by fast electrons in laser-produced plasmas at sub-relativistic intensities


Citation: Physics of Plasmas 24, 102711 (2017);
View online: https://doi.org/10.1063/1.4995044
View Table of Contents: http://aip.scitation.org/toc/php/24/10
Published by the American Institute of Physics

Articles you may be interested in

Ultrafast multi-MeV gamma-ray beam produced by laser-accelerated electrons
Physics of Plasmas 24, 093104 (2017); 10.1063/1.4996020

Astrophysical particle acceleration mechanisms in colliding magnetized laser-produced plasmas
Physics of Plasmas 24, 092901 (2017); 10.1063/1.4993204

Evidence of nuclear fusion neutrons in an extremely small plasma focus device operating at 0.1 Joules
Physics of Plasmas 24, 082703 (2017); 10.1063/1.4989845

Terahertz radiation generation in magnetized plasma under relativistic effect
Physics of Plasmas 24, 083108 (2017); 10.1063/1.4997476

Controlling femtosecond-laser-driven shock-waves in hot, dense plasma
Physics of Plasmas 24, 072702 (2017); 10.1063/1.4990059

Laser pulse sharpening with electromagnetically induced transparency in plasma
Physics of Plasmas 24, 073108 (2017); 10.1063/1.4990440
Kinetic magnetization by fast electrons in laser-produced plasmas at sub-relativistic intensities

Tadeusz Pisarczyk,1,a) Sergey Yu. Gus’kov2,3 Tomasz Chodukowski,1 Roman Dudzak,4,5 Philipp Korneev,2,3 Nicolai N. Demchenko,2 Zofia Kalinowska,1 Jan Dostal,4,5 Agnieszka Żarás-Szydłowska,1 Stefan Borodziuk,1 Libor Juha,4,5 Jakub Cikhardt,5,6 Josef Krasa,4 Daniel Klír,5,6 Balzimaha Cikhardtova,6 Pavel Kubés,6 Eduard Krousky,5 Miroslav Krus,1,a) Jiri Ullschmied,5 Karel Jungwirth,5 Jan Hrebícek,4,5 Tomas Medrik,4,5 Jiri Golasowski,4,5 Miroslav Pfeifer,4,5 Oldrich Renner,4,5 Sushil Singh,4 Satyabrata Kar,7 Hamad Ahmed,7 Jiri Skala,9 and Paweł Pisarczyk1

1Institute of Plasma Physics and Laser Microfusion, 04-97 Warsaw, Poland
2P. N. Lebedev Physical Institute of RAS, 119991 Moscow, Russian Federation
3National Research Nuclear University MEPhI, 115409 Moscow, Russian Federation
4Institute of Physics, Czech Academy of Sciences, 182 21 Prague, Czech Republic
5Institute of Plasma Physics, Czech Academy of Sciences, 182 00 Prague, Czech Republic
6Faculty of Electrical Engineering, Czech Technical University, 166 27 Prague, Czech Republic
7Queen’s University of Belfast, BT7 1NN Belfast, United Kingdom
8Warsaw University of Technology, ICS, 00-661 Warsaw, Poland

(Received 10 July 2017; accepted 2 October 2017; published online 24 October 2017)

The problem of spontaneous magnetic field generation with nanosecond laser pulses raises a series of fundamental questions, including the intrinsic magnetization mechanisms in laser-driven plasmas and the understanding of charge-discharge processes in the irradiated target. These two issues are tightly bound as the charge-discharge processes are defined by the currents, which have in turn a feedback by magnetic fields in the plasma. Using direct polaro-interferometric measurements and theoretical analysis, we show that at parameters related to the PALS laser system (1.315 μm, 350 ps, and 1016 W/cm²), fast electrons play a decisive role in the generation of magnetic fields in the laser-driven plasma. Spatial distributions of electric currents were calculated from the measured magnetic field and plasma density distributions. The obtained results revealed the characteristics of strong currents observed in capacitor-coil magnetic generation schemes and open a new approach to fundamental studies related to magnetized plasmas. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). doi:10.1063/1.4995044

I. INTRODUCTION

Studies of physical processes accompanying the interaction of sub-relativistic nanosecond laser pulses with dense targets started a long time ago (see, for example, books1-3). Nowadays, plenty of analytical models and numerical schemes are used routinely for the prediction and explanation of experimental data dealing with fast electron generation, spontaneous plasma magnetization, dense matter heating, and many other phenomena. However, a variety of the studied physical effects is very rich and some of those which emerged recently may contribute substantially to our general understanding of laser-matter interactions.

Among these, investigation of the spontaneous magnetic fields (SMFs) generated in the laser-produced plasma is a modern trend relating to a set of fundamental applications in high energy density physics. One can mention the capacitor-coil laser-driven schemes as interesting, e.g., in the fast ignition concept of the inertial confinement fusion (ICF) approach4-7 laser-production of magnetized plasmas in shaped targets8,9 considered also for neutronless ICF schemes10, SMF-related phenomena in the dense or compressed plasma and their influence on transport and relaxation properties, see, e.g., Ref. 11; astrophysical laboratory studies, see, e.g., Ref. 12, including well known problems of reconnection of magnetic lines and jet generation. An important question is a role of different sources of SMF generation under particular conditions of laser-matter interaction. Several of them are of paramount importance: the thermo-electric mechanism,13-15 ponderomotive currents,16 and laser accelerated fast electrons.17,18 In this paper, the SMF generation is studied in a plasma produced by interaction of the beam of the iodine laser PALS with a solid target, operating in the first harmonic. In many experiments carried out with terawatt nanosecond laser pulses in the absence of the efficient fast electron generation, magnetic fields in a range of several MGs were recorded (see, e.g., review19). Under these conditions, the thermo-electric current corresponding to the vector product of pressure and density gradients in a plasma torch was considered as a source of SMF.

In this work, we selected the experimental conditions which permit the action of two SMF-generation mechanisms associated with both thermo-electric and fast-electron currents. We unravel the origin of the SMF via the two mentioned sources of the magnetic field by analyzing the observed SMF and density distribution at different time...
periods of the laser-matter interaction. Although experimental measurements of the currents in the interaction region represent a quite difficult problem, the magnetic fields help us to define the integral electron currents and to compare them with previous data of fast electrons.

To switch on the fast-electron source of the SMF, the experiments were carried out with the laser beam tightly focused into a spot with a radius of 50 μm, which provided the radiation intensity on the target of about $I \approx 10^{16}$ W/cm². Sharp focusing and a relatively short pulse duration provided large pressure and density gradients during the irradiation of the target. A high laser intensity and a high coupling parameter $Ix^2 \approx 2 \times 10^{16}$ W μm²/cm² in a combination with the relatively short size of the plasma torch correspond to absorption of a large fraction of the laser energy by the resonant mechanism and its further transformation into the energy of fast electrons. Previous experiments performed under these conditions determined the fraction of the resonantly absorbed energy up to 5% of the total laser energy, while the fast electron energy was about 100 keV.

For the SMF measurements, we used the optical diagnostics based on the Faraday effect (rotation of the polarization plane) in combination with the measurement of the electron density distribution implemented earlier on the PALS system. Among many methods used for the magnetic field measurement in the laser-driven plasma, such as proton deflectometry, direct B-dot, and optical techniques, this one allows one to obtain probably the most complete information about the magnetic field, in particular, its spatial and temporal distribution, though only in the transparent area of the investigated plasma. However, due to a set of technical difficulties, e.g., time gating, synchronization of the plasma producing and probing beams, plasma self-emission, etc., hitherto this method has limitedly been applied in studies of the magnetized plasmas. Recent progress achieved in synchronization of the sub-ns plasma producing beam and the probe femtosecond beam provided a possibility to measure the SMF distribution in the ablative plasma with an extremely high spatial and temporal resolution. Due to collection of these high quality data characterizing the SMF evolution, the understanding of its nature and origin becomes possible.

II. EXPERIMENTAL SETUP AND RESULTS

The experiments were performed on the PALS facility. The 1ω, linearly polarized single laser beam (1.315 μm) delivered with a normal incidence an energy of $\approx 250$ J in 350 ps at a planar copper massive target, focused to a minimal focal spot radius (FWHM) $R_f = 50$ μm, which corresponds to the intensity of about $10^{16}$ W/cm². At the PALS Research Infrastructure, the Hartmann’s techniques are used to determine the minimal focal spot radius.

The SMF distributions were measured by means of the two-channel polaro-interferometric diagnostic system driven by the Ti:Sa laser pulse with the wavelength of 808 nm and the pulse duration of 40 fs; see Ref. 23 for more details.

The quantitative analysis of the SMF and plasma density distributions was based on polarograms and interferograms registered at different times during the expansion of the ablative plasma from the laser-irradiated target surface. The corresponding raw images are shown in Fig. 1.

Reconstruction of the SMF distributions was performed by the standard methodology described, e.g., in Ref. 23. The results of the reconstructed SMF and the plasma density distributions are shown in Figs. 2 and 3, respectively. The data corresponds to the four time moments during the plasma expansion, which are related to the maximum laser pulse intensity ($t = 0$), namely, before the maximum of the laser pulse ($t = -85$ ps), near the maximum of the laser pulse ($t = 20$ ps), after the maximum of the laser pulse ($t = 161$ ps), and at the end of the laser pulse ($t = 257$ ps).

The magnetic field distributions (Fig. 2) show that the SMF in general grows up to the front edge of the plasma. As follows from Fig. 2 for $t = 161$ ps, the maximum value (about 28 MGs) is observed on the front of the ablative plasma at the end of the laser pulse ($t = 161$ ps).

Using the measured space-time SMF distributions, we calculated the current density distributions and the SMF energy for the selected times. The additional data obtained in previous PALS experiments were attracted for the analysis, namely, the total electric currents in the target support measured in Ref. 26 and the electron spectra in the range from few hundred keV up to 3 MeV measured in Ref. 27. The latter was obtained using the spectrometer with the opening diameter of 1 mm placed at a distance of 28 cm from the target at the angle of 30° from the laser beam axis; see Ref. 27 for details.

A. Current density distributions

Based on the spatial distribution of the magnetic field, we calculated the relevant current density. Considering only the azimuthal component of the SMF $\vec{B} = (0, B_\phi, 0)$, which is supported by the observed geometry of the interaction and antisymmetry of the raw data in Fig. 1, the current density distributions $j_r(r, z)$ read by the Ampere’s law:

![FIG. 1. Femtosecond raw interferograms (left) and polarograms (right) registered at different expansion times during the laser beam interaction with the Cu planar massive target.](image-url)
\[ \vec{j}(r, z) = j_z(r, z) \hat{e}_z + j_r(r, z) \hat{e}_r, \]
\[ = \frac{1}{\mu_0} \left[ \frac{\partial B_\phi(r, z)}{\partial r} + \frac{B_\phi(r, z)}{r} \right] \hat{e}_z \]
\[ + \frac{1}{\mu_0} \left[ \frac{\partial B_\phi(r, z)}{\partial z} \right] \hat{e}_r, \]

where \( \mu_0 = 4\pi \cdot 10^{-7} \) H/m is the vacuum permeability and \( B_\phi(r, z) \) is the magnetic field distribution.

We use the cylindrical coordinate system where \( r \) is the distance from the symmetry axis. In Eq. (1), we disregard displacement currents, because the time evolution is quite slow. The calculated results are presented in Fig. 4 where we artificially separated the currents to direct with \( j_z > 0 \) (electrons are moving predominantly from the target) and return with \( j_z < 0 \) (electrons are moving predominantly toward the target). For both cases, the absolute value of the current \( j = ||\vec{j}|| \) is shown. As follows from the direct \( j(r, z) \) distributions [Fig. 4(a)], almost the whole direct current in the area available for polaro-interferometry is confined within an axial cylinder of about 130 \( \mu \)m in diameter. In contrary, the return current has a wide spatial spread outside this cylinder, and thus the return current density is much smaller than that of the direct current; see the color scales in Fig. 4. The evaluation of the spatial distribution of both the direct and return current densities shows a much complex structure than it was observed with the use of a wire-probe technique employed by Drouet et al.\textsuperscript{28,29}
Nevertheless, there the return current distribution had a similar configuration.

To demonstrate clearly the structure of these distributions, the radial magnetic field and current density profiles in the cross-section at $z = 250 \mu m$ are shown in Fig. 5.

The magnetic field increases in a cylinder of $\approx 130 \mu m$ in diameter, where the current density is positive, and decreases outside the cylinder, where the current density is negative. The electron flux corresponding to a direct current $j \approx 0.5-1 \times 10^{14}$ A/m$^2$ is $n_e v = j/e \approx 3-6 \times 10^{28}$ cm$^{-2}$ s$^{-1}$. This value considerably exceeds that for the flow of thermal electrons. Indeed, in the low-density region of the plasma torch, practically all the energy is contained in the kinetic energy of the plasma particles. Then, knowing that the inverse-bremsstrahlung absorption of laser radiation occurs near the critical plasma density, at a laser intensity of $10^{16}$ W/cm$^2$, the estimate for the thermal electron velocity is about $7 \times 10^7$ cm/s. Then for the densities in the range of measured values $n_e = 10^{18}-4 \times 10^{19}$ cm$^{-3}$, the thermal electron flux varies in the range from $3 \times 10^{25}$ to $7 \times 10^{25}$ cm$^{-2}$ s$^{-1}$. Thus, the current corresponding to the generation of a measured magnetic field with an amplitude exceeding 10 MG is formed by electrons whose flux is 2–3 orders of magnitude higher than the flux of thermal electrons of an expanding plasma. This is an important experimental indication that this current is formed by the fast electrons. It is supported by the results of previous experiments at PALS performed under similar conditions and by the data of numerical simulation related to these experiments. The fast-electron spectra measured in Ref. 27 had a characteristic energy of about 100 keV. Studies of shock wave generation in experiments using first and third harmonic radiation showed that at an intensity of the first harmonic radiation of $0.5-1 \times 10^{16}$ W/cm$^2$, up to 6% of the laser energy is transformed into fast-electron energy with an average particle energy of 50–100 keV. For the energy of fast electrons of 70 keV and the degree of transformation of laser energy into the fast electron energy of 5%, we obtain for the fast electron flux the value of $4.5 \times 10^{28}$ cm$^{-2}$ s$^{-1}$, the density of electrons in this flux is about $3 \times 10^{18}$ cm$^{-3}$. In Sec. III, the detailed analysis is presented particularly for the conditions of the considered experiment.

B. Integral direct and return currents

The total direct and return current along the $z$-axis are defined as

$$I_z(z) = 2\pi \int_0^\infty j_z(r,z)rdr,$$

![FIG. 4. The current density calculations: distributions of (a) the direct current density and (b) the return current density for the selected time moments corresponding to Fig. 2.](image)

![FIG. 5. An example of the radial magnetic field and the current density profiles at $t = 257$ ps (see Fig. 4).](image)
where \( I_z(r,z) \) corresponds to either the direct or return current. The results of these calculations, shown in Fig. 6, demonstrate that the integrated direct current is almost the same as the integrated return current, which is obvious for the compact magnetic field distribution. The difference may indicate the input of fast electrons, escaping from the plasma torch, but the reduced plasma density does not allow measuring the magnetic field there. In these peripheral areas, the sensitivity of the polar-interferometer is too small to record both the shift of the interferometric fringes in the interferometric channel and the distributions of the Faraday rotation angle in the polarimetric channel. Note that the errors bars for the differences appear to be much larger than differences themselves, which allows only the qualitative estimation for the fast electron current flux. However, as Figs. 6 and 4 show, the main part of the electron current returns on the plasma periphery. Figure 6 confirms that the total direct current flows within the thin cylinder (with a diameter of about 130 \( \mu \)m) along the plasma torch axis. Figure 6 also shows that both direct and return integral currents \( I_z(z) \) have an increasing trend with the distance from the target and with the expansion time. This probably should be attributed to the return currents in the plasma in the considered cylindrical region, which cannot be separated from the direct currents in Eq. (1). The maximum absolute value obtained for the direct and return \( I_z \) about 700 kA, is located at the front of the ablative plasma close to the end of the laser pulse (see the diagram in Fig. 6 for \( t = 161 \) ps). Since the pipe-type collimation is observed up to the end of the laser pulse, we may conclude that the SMF self-consistently directs the laser-accelerated electrons.

C. Energy of the SMF

The spatial SMF energy distribution was calculated using the relation

\[
E_B(z) = 2\pi \int_0^\infty \frac{B^2(r,z)}{2\mu_0} r dr \frac{1}{m}. \tag{3}
\]

Figure 7 shows the calculated SMF energy per unit length in the plasma torch.

The total SMF energy in the plasma, defined as \( E_{BT} = \int E_B(z) dz \), is depicted in Fig. 8 for selected times during the interaction process. Figure 8 also presents the laser energy \( E_L \), delivered to the target up to the given time. SMF
energy reaches the maximum at time $t = 161$ ps when containing approximately 2% of the total laser pulse energy.

### III. DISCUSSION

This section is devoted to the magnetization process of the ablative plasma, which is the key point of the current study. The analysis presented below shows that the observed SMF distributions in Fig. 2 are formed mainly due to the kinetics of the fast electrons, though in general it is a competition of the two main mechanisms of field generation, namely, the thermo-electric currents and the fast electron currents (including both the direct and the return currents, see Fig. 4).

Now, consider the theoretical predictions for the magnetic field generation, based on the numerical modeling of plasma hydrodynamical evolution in the conditions of the experiment. It was performed with the Lagrangian hydrodynamic code,\(^3\) which includes refraction of the laser radiation in the axially symmetrical plasma corona, bremsstrahlung, and resonant absorption mechanisms. The later plays a decisive role in the conditions of the experiment, and it is responsible for the generation of the fast electrons. The energy of the fast electrons in the code was defined as an oscillatory function of the laser radiation losses, the laser energy of the incident pulse was decreased in the axially symmetrical plasma corona, bremsstrahlung, and resonant absorption mechanisms. The later plays a decisive role in the conditions of the experiment, and it is responsible for the generation of the fast electrons. The energy of the fast electrons in the code was defined as an oscillatory function of the laser radiation losses, the laser energy of the incident pulse was decreased.

The mass density and the experimentally obtained electron temperatures (Fig. 3 and the calculated in Fig. 9) demonstrate a good correspondence in the experimentally achievable region. With this rescaling, the two distributions (the experimental and the calculated in Fig. 9) correspond to the real incident pulse.

Figure 9 shows the plasma density [Fig. 9(a)] and temperature [Fig. 9(b)] distributions in the plasma torch, obtained in the simulation at the time moments, corresponding to the experimental data. The density distribution $\rho$ is plotted in the mass density (g/cm\(^3\)) units, which are standard units for hydrodynamic equations, and, for convenience, the same values are presented in recalculated units of the electron density according to the average ion charge (in cm\(^{-3}\)). The mass density and the experimentally obtained electron density $n_e$, are related by $n_e = \rho / m_p Z A$, where $Z$ and $A$ are the average charge and atomic number of plasma ions, and $m_p Z A$ is the proton mass), which gives $Z = 27$ and $n_e = 2.6 \times 10^{24} \rho$. With this rescaling, the two distributions (the experimental in Fig. 3 and the calculated in Fig. 9) demonstrate a good general agreement in the experimentally achievable region. The calculated distributions, however, are performed for the whole space from the solid target to very small densities, while the experimental range is limited by undetectable plasma densities and resolution. So, experimental distributions (Fig. 3) cover only the range $4 \times 10^{15} - 10^{18}$ cm\(^{-3}\), which corresponds with the given ionization states $Z = 27$ to mass densities in the range $\sim 1.6 \times 10^{-4} - 4 \times 10^{-6}$ g/cm\(^3\).
compared to the values in Fig. 9(a). At the first time moment (−90 ps) in numerical data, the region corresponding to experimental data does not have a sufficient resolution. At the second time moment (30 ps), one can compare, i.e., the experimental density at a distance along the z-axis 380 μm, which is $2 \times 10^{18}$ cm$^{-3}$, with plasma density in simulations $8 \times 10^{-6}$ g/cm$^3$, which rescales to $n_e = 2.1 \times 10^{18}$ cm$^{-3}$. At the last time moment (270 ps), the similar comparison at a distance 700 μm the experimental electron density is $10^{18}$ cm$^{-3}$, while the plasma density in simulations is $4 \times 10^{-6}$ g/cm$^3$, which corresponds to $n_e = 1.05 \times 10^{18}$ cm$^{-3}$. Note, that in the density region $4 \times 10^{19}...10^{18}$ cm$^{-3}$ the experimental data shows a higher value of the density gradients, which at late times even acquires a concave shape in the central direction. These features are not reproduced in the numerical simulations, and are likely related to the effect of the plasma magnetization due to the fast electron currents.

The calculated temperature distributions have a natural maximum near the critical density. Time dependence of the maximum temperature follows the laser intensity. At the time moment near the maximum laser intensity (30 ps), temperature maximum is about 3.4 keV, and at time moments of increase and decrease of the laser pulse intensity (−90 and 150 ps), temperature maxima are about 2.5 keV. At the moment of 270 ps, which is 20 ps after the end of the laser pulse, the temperature value at maximum is only 1 keV. Simulation results evidently demonstrate isothermal plasma expansion with undercritical density; the spatial temperature distributions in the experimentally accessible region are almost homogeneous. At the time moments of 30, 150, and 270 ps, the plasma temperatures in this region are 2.8 keV, 2 keV, and 1 keV, respectively. The calculated energy of the thermal electrons with the density in the range $4 \times 10^{19}...10^{18}$ cm$^{-3}$, which corresponds to the experimental measurements, is 0.1 J for the time moment of 150 ps and 0.06 J for 270 ps.

The radial plasma size in the numerical simulations is less than that in the experimental data and approaches the later (reaching 500 μm) at the fourth time moment (270 ps). This is due to the laser pulse profile, which additionally heated the target out of the ideal (gaussian with the size of 50 μm) focal spot size, used in the simulations.

To distinguish between the different magnetic field sources, namely the thermocurrent and the fast electron currents, we first estimate the magnetic field values by the hydrodynamic approach without kinetic effects, and then refer to the electron currents (both the direct and the return, see Fig. 4).
To extract the SMF generation due to the thermo-current mechanism defined by a crossing gradients $\nabla n_e \times \nabla T_e$, an additional module was introduced in the hydrodynamic code. This module calculates the density and temperature gradients at each time step using the spatial distributions of the density $n_e(r,z)$ and the temperature $T_e(r,z)$, see Fig. 9.

Based on this data, the spatial distribution of the time derivative $\frac{dB}{dt} = -c^2 \frac{\nabla n_e}{\sigma} \times \nabla T_e$ is shown in Fig. 10(a). Integration of $\frac{dB}{dt}$ in time is performed in Lagrangian coordinates, so that the full time derivative reads $\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{\partial}{\partial r} \cdot \vec{v}$, which allows to take into account the field convection. Although the full set of magnetohydrodynamic equations is not resolved in this scheme, it nevertheless gives the correct estimate for the magnetic field, produced by the $\nabla n_e \times \nabla T_e$ mechanism. To substantiate this statement, we remind a single-liquid hydrodynamic Eq. (13) in Ref. 23. The estimations of different terms, presented in Ref. 23, showed, that the thermocurrent source plays a major role in the conditions of this experimental setup.

$$\frac{\partial \langle \vec{B} \rangle}{\partial t} + \frac{\nabla \times \langle \vec{B} \rangle}{c} = -\frac{\nabla \times \langle \vec{v} \rangle}{\sigma} - \frac{e}{c} \frac{\nabla p + R_T}{n_e} \nabla \nabla \approx 0,$$  \hspace{1cm} (4)

where $\langle \vec{B} \rangle$ is the average magnetic field, and $\vec{v} = \langle \vec{V} \rangle$ is the average plasma flow velocity. For the qualitative estimation for the magnetic field, it is enough to leave the source term [the fourth one in Eq. (4)], and to rewrite the convective term [the third one in Eq. (4)]

$$\nabla \times \langle \vec{v} \times \langle \vec{B} \rangle \rangle = -\langle \vec{v} \nabla \rangle \langle \vec{B} \rangle - \langle \vec{B} \rangle \langle \nabla \vec{v} \rangle + \langle \vec{B} \rangle \nabla \langle \vec{v} \rangle,$$

where $\langle \vec{B} \rangle \nabla \approx 0$ because of the geometrical orientation of the magnetic field (azimuthal symmetry). Using the continuity equation we see that $\langle \vec{B} \rangle \nabla \langle \vec{v} \rangle = \langle \vec{B} \rangle \frac{d \rho}{n_e dt}$ is a slowly varying function. Then qualitatively

$$\frac{\partial \langle \vec{B} \rangle}{\partial t} + \langle \nabla \rangle \langle \vec{B} \rangle = \frac{\partial \langle \vec{B} \rangle}{\partial t} \approx \frac{e}{c} \frac{\nabla \nabla \rho}{n_e},$$  \hspace{1cm} (5)

where $R_T$ occurring in Eq. (4) is omitted within the considered accuracy, taking into account that the temperature gradients are small in the highly magnetized region inside the plasma torch (see Fig. 2), as described above.

The integrated magnetic field component is shown at the selected times in Fig. 10(b). The spatial distribution of the magnetic field differs from the experimental observation shown in Fig. 2. While in Fig. 2, the maximum magnetic field is close to the axis of the plasma torch, in Fig. 10(b) the magnetic field increases out from the axis, i.e., for large distances $r$, due to the magnetic source properties and convection. Besides, the maximal values of the magnetic field, generated by the thermocurrents, more than an order less, than those registered in the experiment. The difference between the density gradients and the front shape of the expanding plasma in the theoretical simulations and the experimental data, noted above, take place in the low-density region, where thermocurrents are not high enough to generate the magnetic field efficiently, see the regions in Fig. 10. In the important high-density plasma region, the gradients of the electron density and the temperature in simulation are only slightly greater than the experimental values due to smaller torch radius, as discussed above. So, the calculated magnetic field values, originated from thermocurrents, may be considered as upper values [Fig. 10(b)]. This proves, that the thermocurrents cannot explain the experimental values of the magnetic field of the 10–30 MG level.

The observed difference may be explained by the kinetic of the fast electrons, which do not explicitly act as a magnetic field source in the used numerical scheme. However, several important characteristics calculated within the hydrodynamic code provide a possibility to estimate the source kinetics and the corresponding magnetic field amplitude. In the calculation scheme, the maximum energy of the fast electrons is defined for an optimal incident angle, as described in Ref. 32. The average fast electron energy was approximated as a half of the maximum fast electron energy. Fast electrons are present in the simulations only during the laser pulse action, so the latest moment, $t = 270$ ps, is omitted in the estimation.

Table I shows the fraction of the laser energy corresponding to the resonance absorption ($\delta_{\omega_\alpha}$), average fast electron energy ($\langle \epsilon \rangle$), average fast electron velocity ($\langle v \rangle$), and

FIG. 10. Results of the 2D numerical modeling of the massive planar Cu target irradiated by the laser pulse of the same parameters, as in the experiment: (a) $\frac{dB}{dt} = -c^2 \frac{\nabla n_e}{\sigma} \times \nabla T_e$, and (b) the SMF distributions obtained by integration of the time derivative $\frac{dB}{dt}$. 


incident laser energy flux ($Q_{in}$), absorbed in fast electrons energy flux ($Q_{ar}$). Table II presents at different time moments the estimates for average fast electron density $n_h$ in the central channel with the radius, equal to the laser beam radius $r_0$, average density of the fast electron current $j_h$, and average value of the magnetic field $B_h$, generated by the fast electrons, as well as the current density and the magnetic field amplitudes, registered in the experiment. The estimates in the Table II were performed with the numbers from Table I by the following expressions:

\begin{align}
    n_h &= \frac{Q_{ar}}{\pi r_0^2 e^2 v_h}, \\
    j_h &= en_a e v_h, \\
    B &= \frac{2eQ_{ar}}{c e^2 v_h}.
\end{align}

Agreement between the theoretical and experimental numbers of Table II shows that the magnetic fields of the 10–30 MG scale, registered in the experiment at PALS, are produced by the current of the fast electrons, generated due to the resonant absorption mechanism. Note, that the fast electron current of 300–800 kA, corresponding to the current density of $3–10 \times 10^{13}$ A/m², see Table II, exceeds the Alfvén limit of 17 kA for the current of non-relativistic electrons. This fact may be explained by the presence of additional electrostatic tension in the plasma torch, which was not measured in the experiment.

An important conclusion could be obtained from the comparison between the energy of the magnetic field and the energy of the fast electrons which form the electric current. We note that for a coil-type electron current in a stationary regime, the magnetic field energy may be scaled as $E_{BT} \sim \frac{L^2}{I^2}$, where $L$ is an inductance and $I$ is the total current for the given magnetic field. For our fountain-like geometry $L \sim \mu \mu_0 r^2/4$, where $\mu$ is the magnetic permeability, $r \sim 500 \mu$m is the characteristic radius of the SMF distribution, $I \sim \pi r_0^2 \times e n_a v_h$, and $r_0 \sim 50 \mu$m is the characteristic radius of the current distribution (pipe radius in Fig. 4). Energy of the electrons which form the electric current (hot, or fast electrons) scales as $E_{hc} \sim \frac{z_0 m_e^2 \pi r_0^2}{2}$, where $z_0 \sim 500 \mu$m is a characteristic length of the SMF and electric current distributions. Then,

$$E_{BT} \sim \mu \pi E_{hc}, \quad \mu \equiv \mu_0 \frac{m_e e^2 \pi r_0^2}{4 z_0 m_e} \sim 280.$$
return currents. As a result of this, the maximum values of the SMF are in a good agreement between the experimental data and the calculated numerical results only at the front of the plasma torch, where these return currents are small. To the left of the region of the peak direct current in Fig. 6, the shown curve indicates actually an integrated current which increases to the left (in average) part of the directed return current in the central region. The magnetic field in the torch volume, therefore, is weaker, and the magnetic field energy is less so there would be no appearance of return currents. Note that this is a simple estimation, which does not take into account any time-dependence, plasma structure, other magnetization mechanisms, experimental errors, and other factors. It just explicates how the magnetization of the plasma torch may be related to the fast electron current.

IV. CONCLUSIONS

Our combined analysis of the highly resolved experimental data reveals the nature of the magnetic field generation in the situation, when the intense sub-relativistic laser pulse irradiates a massive target. It is shown that the fast electrons are of crucial importance for the formation of the magnetic fields, whose distribution was directly observed in the experiment. This key feature is consistent with the analysis of currents and energies of the fast electrons derived from the experimental data. However, most of the fast electrons are not fast enough to escape from the plasma plume. Only a fraction of the fast electrons responsible for the magnetic field distribution observed in the central part of the plasma plume can overcome the charge-separation potential created by slow ions. This condition of quasi-neutrality is normally satisfied for the time scales of a few tenths of picoseconds or even less in the laser-driven plasmas.

The highly-resolved SMF distributions were measured using femtosecond polaro-interferometry. A successful application of the novel technique proves the usefulness of this unique tool for laser plasma research. We have also demonstrated that the SMF distributions may be used for measurements of the current distribution in the plasma corona. Based on this approach, we found that the plasma magnetization in the sub-relativistic regime results from the kinetic processes related to the fast electrons in the plasma corona. The kinetic magnetization is quite effective in the considered region of parameters and gives the magnetic field values of about an order higher than the $\nabla n_e \times \nabla T_e$ mechanism. The understanding of the physics of the SMF generation is very important for many problems related to the astrophysical magnetized plasma, ablative plasma behaviour, fast electron generation, etc. The generated fast electron currents may effectively magnetize ablative plasma, which in turn collimate the fast electron flow. The detailed understanding of these effects may help to produce jets of magnetized plasma with the desired characteristics, optimize capacitor-coil targets, generate tailored fluxes of fast electrons or contribute to the development of particle laser-based acceleration schemes.

ACKNOWLEDGMENTS

This paper was supported by the Access to the PALS RI under the EU LASERLAB IV project (Grant Agreement No. 654148), by the Ministry of Science and Higher Education, Republic of Poland (Decision no. 3554/H2020/2016/2), by the Ministry of Education, Youth and Sports of the Czech Republic, Grant No.: LM2015083 (PALS RI) and the ELI: Extreme Light Infrastructure Project No. CZ.02.1.01/0.0/0.0/15008/0000162, and by the Czech Science Foundation, Project No. P205/11/P712. The work of S. Gus’k and N. Demchenko was supported by the Russian Foundation for Basic Research Project Nos. 17-02-00059- and 17-02-00021- and the work of Ph. Korneev was supported by RFBR 16-52-50019-JF. This work was also supported by the Program of Increase in the Competitiveness of the National Research Nuclear University MEPhI (Contract No. 02.a03.21.0005, 27.08.2013). This work has also been carried out within the framework of the EUFusion Consortium and received the funding from the Euratom research and training programme 2014-2018 under Grant Agreement No 633053 (Project No. AWP15-ENR-01/CEA-02). The views and opinions expressed herein do not necessarily reflect those of the European Commission. We are thankful to V. Tikhonchuk for productive discussions.
