Comprehensive investigation of laser energy transport to a massive planar targets with femtosecond polaro-interferometry

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The paper is a continuation of the space-time resolved spontaneous magnetic fields (SMF) measurements performed on PALS (Prague Asterix Laser System) [1]. To measure SMF distributions with high temporal resolution, two-channel polaro-interferometer irradiated by the Ti:Sa laser pulse, with the wavelength of 808 nm and the pulse duration of 40 fs was used. The experiments were performed by using the 1ω single laser beam (1.315 μm) with the linear and the circular polarization, focused to the focal spot radius R_L=50 μm and interacted with the Cu planar massive target. The primary goal was to understand the interrelation between spontaneous magnetic field (SMF) creation and fast electron generation in laser plasma produced from Cu planar massive targets.

Obtained space-time distributions of SMF was used to calculate current density distributions and the energy deposited in the magnetic field of the ablative plasma and to estimate the electron energy for different expansion times during the laser-target interaction. Additionally, measurements of the total current through the target were carried out with current probes. The calculated from SMF distribution electron spectra in the expanding plasma were also compared to the electron spectra obtained by the magnetic electron spectrometer.

Results of the SMF measurements are presented in Fig. 1. Fig. 1a and 1b show the SMF distributions during interaction of the laser pulse with the target, which correspond to a several expansion time moments, namely: before the maximum laser pulse (t=-85 ps), close to the maximum (t= 20 ps), after the maximum (t=161 ps) and the end (t=257 ps). The spatial SMF energy distribution was calculated using the relation

$$E_B(z) = 2\pi \int_0^R \frac{B^2(r,z)}{2\mu_0} r dr\,, \quad [\mathrm{J/m^{-1}}] \qquad (1)$$

where $\mu_0=4\pi\cdot10^{-7}$- is vacuum permeability [$\mathrm{Hm^{-1}}$], B(*r, z*) is magnetic field distribution [T], *r* is distance from the symmetry axis [m]. The diagrams presented in Fig. 1c demonstrates the calculated distribution of the SMF energy per unit length of the plasma stream. These distributions provides the total SMF energy ($E_{BT} = \int E_B(z)\,dz$) in the plasma for the given expansion moment. From Fig. 1c, it is seen that the maximal deposited energy corresponds to the time moment t= 161 ps and contains approximately 2% of the total laser pulse energy. Both the magnetic field distributions (Fig. 1a) and the space profiles (Fig. 1b) show that the SMF is located mainly at the front of the plasma, and increases with the distance from the target. As Fig. 1a and Fig. 1b show for t=161 ps, the maximum value of about 28 MGs is achieved on the front of the ablative plasma at the time that corresponds to the end of the laser pulse. Considering the azimuthal geometry of the SMF, which is supported by the measurements of the Faraday effect at the initial rotation angle of the polarizer [1], such SMF distributions correspond to the axial flow of electrons. To demonstrate this, the current density $\vec{j}(r,z)$ distributions were calculated as

$$\vec{j}(r,z) = j_z(r,z)\overrightarrow{\boldsymbol{e_z}} + j_r(r,z)\,\overrightarrow{\boldsymbol{e_r}} = \frac{1}{\mu_0}\left[\frac{\partial B_\varphi(r,z)}{\partial r} + \frac{B_\varphi(r,z)}{r}\right]\overrightarrow{\boldsymbol{e_z}} + \frac{1}{\mu_0}\left[\frac{\partial B_\varphi(r,z)}{\partial z}\right]\overrightarrow{\boldsymbol{e_r}}, \qquad [\mathrm{A/m^2}] \qquad (2)$$

where $B_\varphi(r,z) \equiv \mathrm{B}(r,z)$, if we suppose magnetic field to be azimuthal $\vec{B}(0, B_\varphi, 0)$, and we disregard displacement currents. The results of the calculation are presented in Fig. 2. As follows from the $j_z(r,z)$ distributions, Fig. 2a, almost all the positive part of the current in the measured area flows is confined in a cylinder (located on the axis) with a diameter of about 100 μm. The total current $I_z(z) = 2\pi\int_0^R j_z(r,z) r dr$ along z-axis in different time moments are shown in Fig. 2b. These distributions demonstrate the increase of the total $I_z(z)$ current both as a function of the distance "z" from the target and as a function of the expansion time. The maximum calculated value of $I_z(z)$, related to the maximum spatial derivatives of

$B_\varphi(r,z)$ is about of 36 kA is seen on the front of the ablative plasma at the time moment that corresponds to the end of the laser pulse (see diagram in Fig. 2b for t=161 ps).

In addition, interferometric information about the electron density distribution and current density distributions gives a rough estimate for the kinetic energy $E(r,z) \approx \frac{m_e \cdot v_z(r,z)^2}{2}$ of the electrons, responsible for the current, where $v_z(r,z) = j_z(r,z)/(en_e(r,z))$, and $n_e(r,z)$ is the measured electron density distribution. The results of this estimation, presented in Fig. 2c show, that the energy of the electrons, at different expansion times, has values in the range up to hundreds of keV, though not very much number of them (note the log scale in Fig. 2c). These energies are correlated also with the results of measurements of the electron energy performed at PALS with an electron spectrometer (see proc. P2-102), shown in Fig.3.

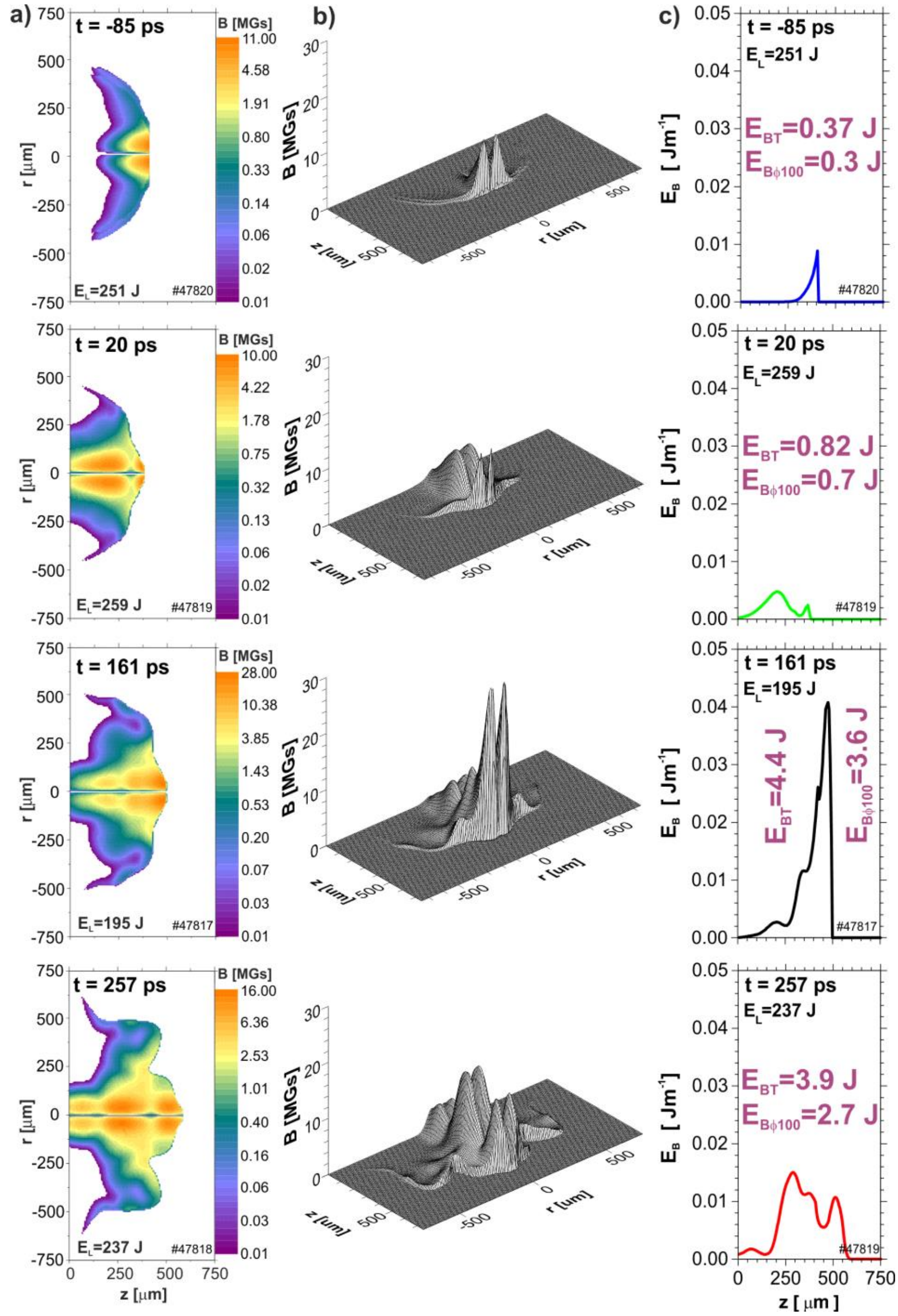

Fig. 1 The SMF distributions: a) colour-plots and b) space profiles as well as distributions of the deposited energy of SMF during the laser pulse interaction with Cu massive planar target.

It is worth to note that the maximum in the calculated electron spectra corresponds to the energy of about 100 keV, in agreement with the numerical modeling presented in [2]. Another issue, following from Figure 4 is that only 3.5-8% of the total population of electrons participates in the flow of current through the thin cylinder, and that almost all the energy of the SMF is deposited in area of this cylinder.

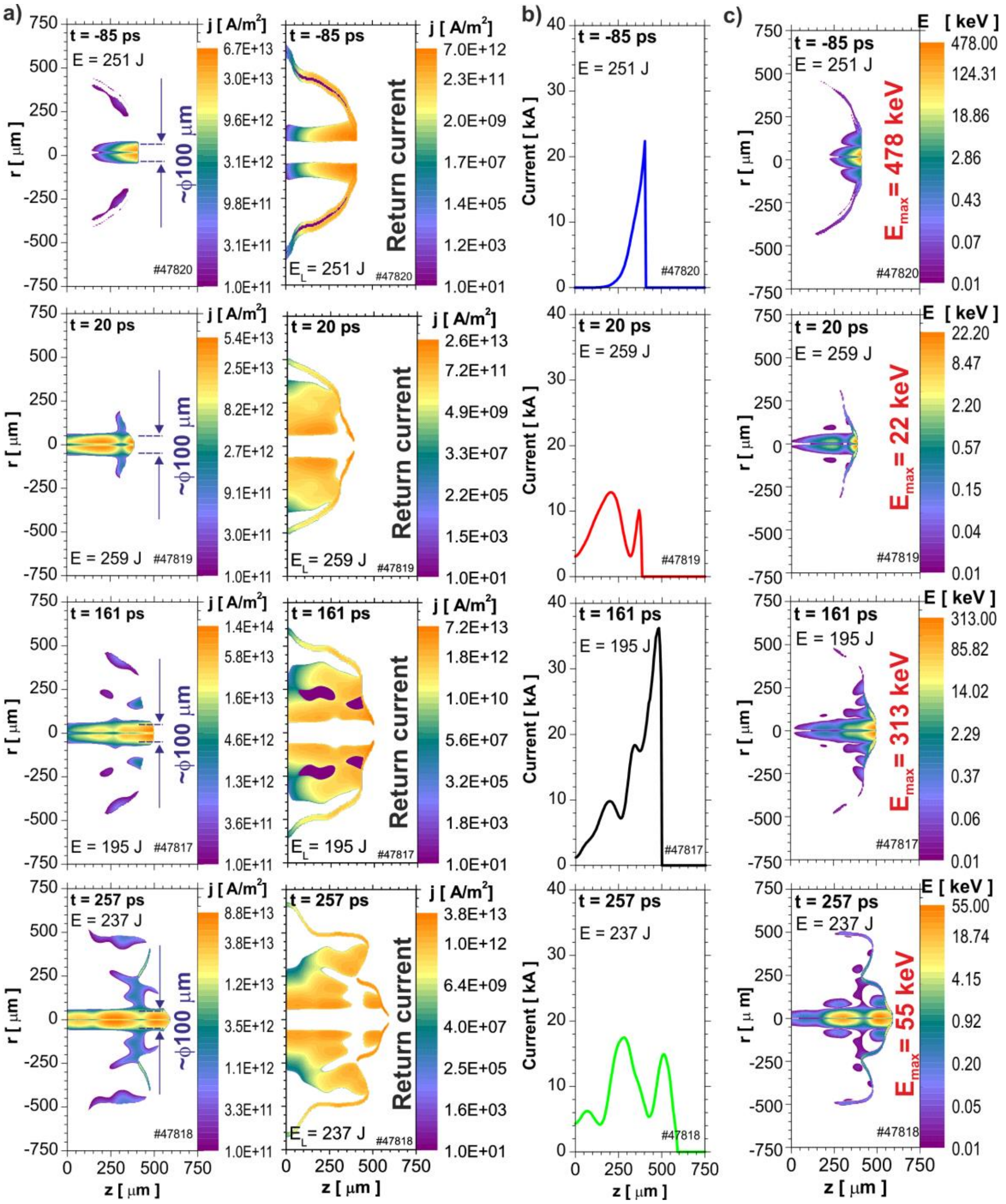

Fig. 2 Distributions of the calculated positive current density (a, left panel), negative current density (a, right panel), the total z-current (b), and distributions of electron kinetic energy (c) for the different expansion time moments during the laser beam interaction with the Cu massive planar target.

The calculated from polarimetric data electron currents surprisingly is in agreement with the measurements of the total current flowing through the target [3] using the current probe at z = 0, despite of the effect of the return currents in the ablated plasma. This integrated current on the surface was found approximately to be 1-2 kA for the laser energy of 250J, used in the experiments.

The complex SMF distribution, see Fig. 1, indicates a competitive character of the magnetic field generation in the expanding plasmas. To distinguish between the Biermann-battery mechanism, hot electron currents, magnetic field convection and diffusion, the electron current distribution, which possesses both direct and return electron flows (see Fig. 2) and electron density distribution (not presented here), may be very useful. Further analysis would provide the nature of the generation mechanisms and explain of the non-monotonous features in the different parts of the interaction region.

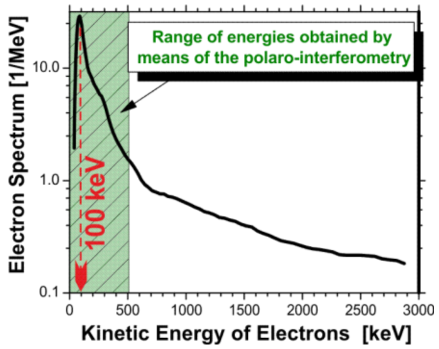

Fig. 3 The fast electrons spectrum registered on the PALS experiment by the electron magnetic spectrometer.

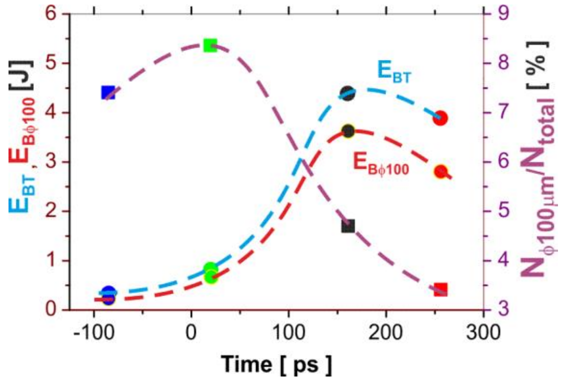

Fig. 4 The SMF energy in the thin cylinder of the current flow (100 μm diameter), the total SMF energy and the electron number in the cylinder of the current flow (100 μm diameter) as a relation to the approximated total electron number in the whole ablative plasma.

Conclusions: The femtosecond polaro-interferometry was proved to be a unique tool for the laser plasma research, in particular to study SMF and density distributions. On the basis of these measurements, laser-plasma interaction and the fast electron emission may be analyzed, which has a wide application range from studies of ICF to laboratory astrophysics.

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