Investigation of spontaneous magnetic fields generated under different regimes of laser-produced plasma creation

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Shock ignition (SI) approach [1] currently becomes one of the most promising scenarios of target ignition in the inertial confinement fusion (ICF). One of the main research aims related to the SI is the understanding of ablation pressure generation mechanisms at different irradiation conditions. The corresponding investigations were carried out on PALS facility with different diagnostics [2-6]. From the SI point of view, particularly interesting is the initial phase of the expansion, related to the interaction of the laser pulse with the generated plasma. In this phase different processes of anomalous absorption, responsible for the generation of fast electrons, appear and the electric and magnetic fields are created. These fields can significantly modify plasma parameters and transport of fast electrons to the ablation surface affecting the formation of the shock wave ablation pressure.

For the experimental studies of these processes, the interferometry and polarimetry are highly demanded at the early phase of the laser plasma expansion, provided a sufficiently short diagnostic pulse would become available. This requirement was fulfilled by a two-channel polaro-interferometer, sketched in Fig. 1, irradiated by 40 fs Ti:Sa laser working at the wavelength of 808 nm.

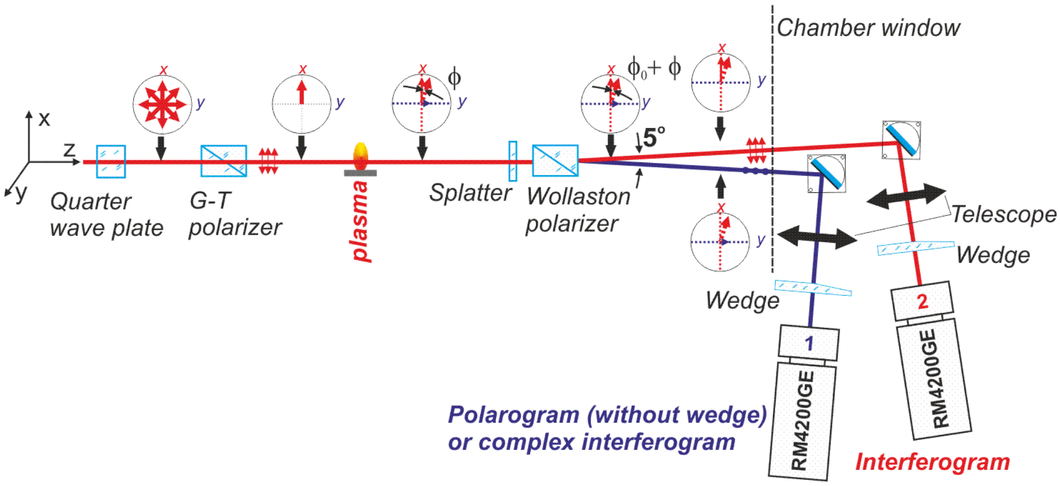

Fig. 1 Optical scheme of the two-channel polaro-interferometer.

Two-channel polaro-interferometer consists of two channels which provide a possibility to measure the magnetic fields in two ways depending on the optical configuration of the polarimetric channel. In the first case, a polarogram and an interferogram are recorded in each channel and magnetic field distribution in plasma are calculated on the basis of the Faraday rotation angle and the electron density distributions. In an alternate case, instead of the polarogram, a complex interferogram can be registered via an initial rotation of the polarization plane with a wedge added in the polarimetric channel (see Fig. 1). Information about magnetic field distribution can be obtained directly on the basis of the amplitude-phase analysis of the interferogram [7].

In the presented preliminary studies planar targets made of materials with different atomic numbers (plastic and Cu) were illuminated by the 1ω laser beam with energy range of 250-500 J, focused to the minimum possible focal spot radius - R_L=50 μm. A methodology presented in [8-10] was used for polaro-interferometric measurements. To ensure the optimal registration conditions in the polarimentric channel, the measurements at the initial angle of rotation of the polarizer of $\boldsymbol{\varphi_0 = 2°}$ were carried. The polarograms with corresponding interferograms illustrate the interaction of the 1ω laser beam at the energy about 250 J with the plastic targets are shown in Fig. 2a, while in the case of the Cu targets and the same experimental conditions are presented Fig. 2b.

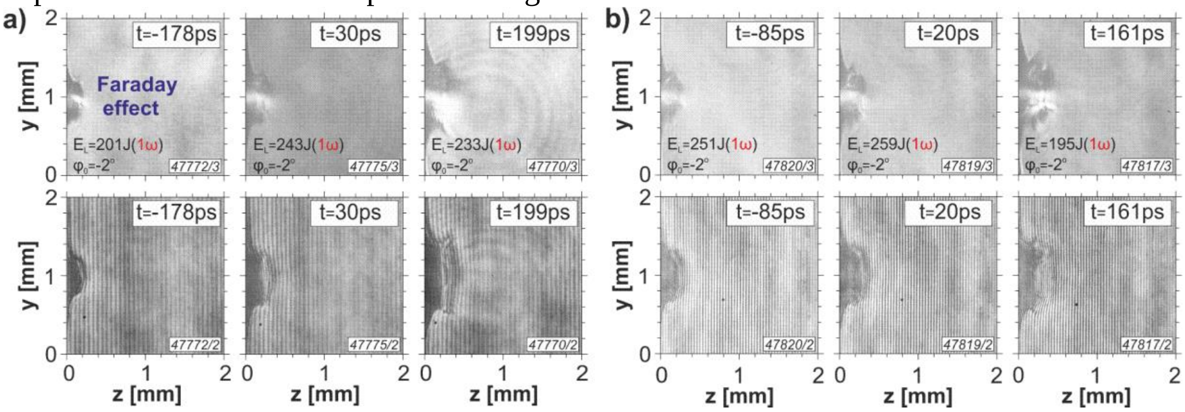

Fig. 2 Sequence of polarograms with corresponding interferograms registered for the 1ω laser beam interaction with the planar massive targets made of: a) plastic and b) Cu.

The Faraday effect, clearly visible in both polarograms, demonstrates a proper functioning of the polaro-interferometer. The effect is visible only in the bottom half polarograms, which proves that the spontaneous magnetic fields (SPM) have azimuthal symmetry.

One of the goals of such research was to prove the influence of the character of the ablative plasma expansion on the SPM structure, namely: (i) the spherical expansion of the fast component in the case of the light target material (plastic) and (ii) planar (axial) expansion which is enforced by a heavy Cu plasma [11]. To obtain the distribution of the magnetic field, the methods of analysis described in papers [6] have been applied. In the case of the axial plasma symmetry, the equations describing the relations between the Faraday rotation angle (φ), the distribution of phases ($\boldsymbol{\delta}$) and the plasma parameters are applied, namely:

$$\varphi(y) = 5.24 \cdot 10^{-17} \cdot \lambda^2 \int_y^R \frac{B_\varphi(r) n_e(r) y dr}{\sqrt{r^2 - y^2}} \qquad (1)$$

$$\delta(y) = 8.92 \cdot 10^{-14} \cdot \lambda \int_y^R \frac{n_e(r) dr}{\sqrt{r^2 - y^2}} \qquad (2)$$

where: $B_\varphi(r)$ - the azimuthal magnetic field distribution, $n_e(r)$-electron density distribution, λ – the wavelength of a probe beam.

Expressions (1) and (2) reduce simply to an integral Abel equation [10]:

$$S(y) = 2 \int_y^1 \frac{f(r) dr}{\sqrt{r^2 - y^2}} \qquad (3)$$

For the case (1) the transformation is given by:

$$f_B(r) = 2.62 \cdot 10^{-17} \cdot \lambda^2 R \left[\frac{B_\varphi(r) n_e(r)}{r}\right] \quad \text{and} \quad S_B(y) = \frac{\varphi(y)}{y} \qquad (4)$$

and for (2) it is:

$$f_n(r) = 4.46 \cdot 10^{-14} \cdot \lambda R n_e(r) \qquad \text{and} \qquad S_n(y) = \delta(y) \qquad (5)$$

Substitution of $n_e(r)$ from (4) to (5) gives for $B_\varphi(r)$:

$$B_\varphi(r) = \frac{1.7\cdot 10^3}{\lambda} \cdot \left[\frac{r f_B(r)}{f_n(r)}\right] \qquad (6)$$

To solve this equation and find the magnetic field distribution $B_\varphi(r)$, the FFT Abel inversion method was used. The SPM distributions for the different expansion time moments, as a result of the 1ω laser beam interaction with the planar massive plastic target are presented in Fig. 3a, while Fig. 3b shows distributions which correspond to Cu target for the same laser pulse parameters.

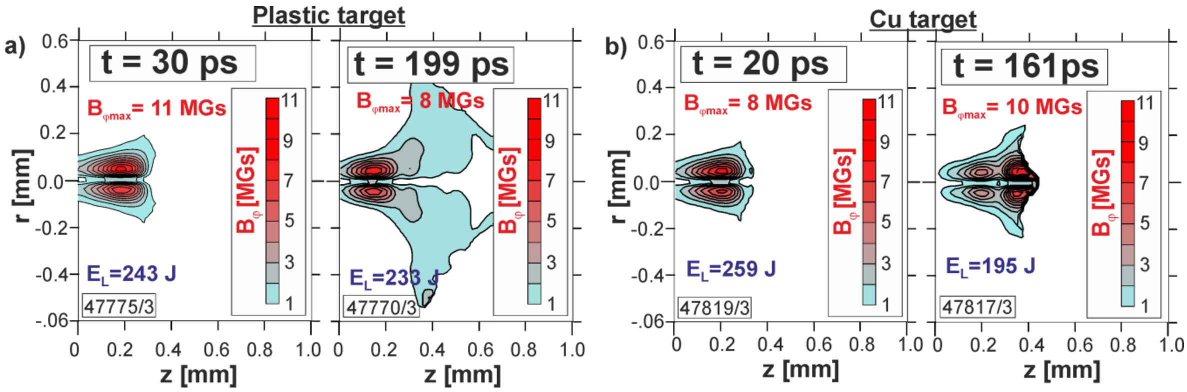

Fig. 3 2D distributions of the SPM in the ablative plasma during the 1ω laser beam interaction with: a) the plastic and b) Cu target for two different expansion times related to the maximum intensity of the laser pulse.

From the Fig. 3a maximum value of SPM about 10 MGs is seen in the vicinity of the target surface does not significantly change during the action of the laser pulse. However, the distribution of the SPM changes distinctly with the time, while the ablative plasma expands. The spherical expansion of the more fast light plasma from a plastic target causes that the distribution of SPM is becoming clearly divergent at the expansion time moment t=199 ps *(it resembles the effect of fountain stream*). The SPM distributions generated at different expansion times, as a result of the 1ω laser beam interaction with the planar Cu massive target, are shown in Fig. 3b. The influence of the planar plasma expansion is clearly seen in this case. In contrast with the plastic plasma, total current cross-section flows in a plasma column within diameter not exceeding 0.5 mm. Moreover, the distribution of the SPM in the plasma column clearly differs from the distribution for the case of light plastic plasma. These distributions prove that the axial expansion of the heavy plasma significantly reduces the divergence angle of the *fountain flow* of electrons from the front part of the plasma column. Due to this fact, the maximum amplitude of the SPM at the front of the plasma column is larger than the one in the vicinity of the target and reaches a value of about 10 MGs.

For a more consistent theoretical analysis of the expanding plasma parameters and the SMF, the general plasma transport relations may be useful. Following [12], the equation for the magnetic field balance with plasma parameters may be written as follows (the small items are omitted for simplicity):

$$\frac{\partial \vec{B}}{\partial t} + \frac{c^2}{4\pi} \nabla \times \frac{\nabla \times \vec{B}}{\sigma} - \nabla \times \left(\vec{v} \times \vec{B}\right) - \frac{c}{e} \nabla \times \frac{\nabla p + \vec{R_T}}{\partial t} = 0, \qquad (7)$$

where t is time, c is the light velocity, σ is the plasma conductivity, v is the plasma flow velocity, e is the electron charge absolute value, $p \approx neTe$ is the plasma pressure, $\vec{R}_T \sim n_e \nabla T_e$ is the so-called thermo-force, T_e is the electron temperature. From Fig.2 it follows that the characteristic distances are ~30 μm and times ~100 ps, measured in the experiment;

measured densities of plasma flow $n_e \approx 3 \times 10^{19}$ cm^{-3} (not shown in figures), and the plasma temperature for the considered laser parameters has the order of $T_e \sim U_p \sim 3$ keV, where U_p is the ponderomotive energy. Considering estimations for $\vec{R}_T$ and σ from [12], for the third and fourth items in eq. (7) we find the scaling $\sim 10^{16..17}$ Gauss/sec. Then, the first item $\frac{\partial \vec{B}}{\partial t} \sim \vec{B}/10^{10}\ sec^{-1}$ leads to the estmation value of magnetic field as several Megagauss. While the third item in (7) regulated the relation between the flow velocity and SPM, the main effect for the SPM generation comes from the last item in (7), which contains the gradient of the electron temperature T_e.

Conclusions: It should be emphasized that the realized investigations of the SPM on PALS experiment by means of the femtosecond polaro-interferometry are greatly innovative if we take into account that: (i) as far as we know the space-time SPM distributions during the laser pulse interaction with the target have been measured with the high resolution for the first time, and (ii) such detailed information about SPM distributions offer major cognitive possibilities, especially in the SI concept.

The hitherto studies on SI performed by the authors [3, 4, 6, 11] show that investigations of the expansion regimes play a central role in the knowledge of absorption processes and ablation mechanisms responsible for the ablation pressure formation, with the participation of fast electron. In addition, they showed that the character of the plasma expansion depends not only on the target material but also on the irradiation conditions of the target, namely: the focal spot radius and the wavelength of the laser beam. It is expected that wider range of a diagnostic possibilities for the measuring the SPM distributions can be particularly useful for further studies of the SI scenario.

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