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The radiative magnetohydrodynamics of miniature laser plasma system

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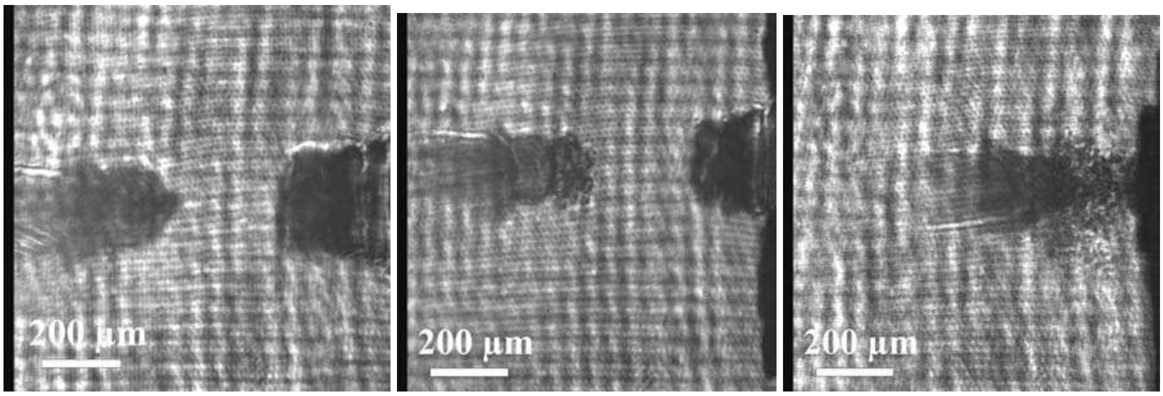
In this paper an interferometric observations and a polarametric measurements of the dynamics of laser bullets – accelerated thick plasma blocks, generated in air during the interaction of a picosecond laser pulse with an Al-target at irradiances of 10^{14} W/cm^2 are presented. The results of numerical simulations are also presented.

Megagauss Magnetic Fields Frozen in "Plasma Bullets"

An experimental setup for interferometric measurements and for detecting of the rotation of polarization is given in [1]. All experiments were carried out in air. A significant feature of our experimental set-up is the amplified spontaneous emission (ASE) arising in long pre-pulse (ns-range). The value of the contrast of laser radiation in the main peak to the pedestal radiation is 150 only, so the intensity in the pre-pulse was about 5 x10^{11} W/cm^2, which is well above the generally accepted long pulse threshold intensity for plasma generation in air. By focusing the heating laser beam to the spot size of 30 μm in front of the target, it was possible to form a low density plasma before the main pulse with I = 8x10^{13} W/cm^2 reached this region. The laser pulse energy equals to 100 mJ, pulse duration t = 100 ps and wave-length λ = 1064 nm. The shadowgramms show a shock wave fronts with a steep density gradient, which is formed at t ~ 2 ns before the pulse center of main laser beam reaches this point. A strong absorption of laser radiation in this thin plasma layer is witnessed by a characteristic plasma emission at the second harmonic of laser frequency. The $2\omega_0$ emission in the form of a concave disk with the diameter of 50 μm was found. In this the incident laser frequency ω_0 equals to the plasma frequency ω_p and the conditions for resonant absorption are fulfilled. For s-polarized laser heating pulse $\omega_p = \omega_0 \cos\theta$, where θ is an angle of incidence of plane laser wave on a stratified plasma. By taking $\cos\theta = 0.3$ we obtain $N_e = 1.2\text{x}10^{20}$ cm^{-3}, which is in good agreement with the interferometric plasma density measurements. When the leading part of the heating pulse penetrates into the plasma with such density gradient, a narrow filament (about of 5 μm in diameter and 200 – 300 μm long accompanied with strong shock waves) appears.

The large magnetic fields associated with resonant absorption in the plasma near the surface of critical density have been studied with the Faraday–rotation diagnostic system for the probe beam timing t = - 60 ps, 0 ps, + 60 ps, + 120 ps, + 200 ps. The Faraday rotation of the probing light appeares at t = 60 ps, reached its maximum near + 60 ps, and then decreases (it could be seen as late as + 200 ps). The well-localized thin bright stripes above and below the center of the plasma bullets are evident. The reversal of the analyzer orientation produces always a corresponding reversal in the position of the bright stripes. In opposite to the thermally generated magnetic fields the orientation of azimuthal magnetic field in plasma blocks is found to be consistent with the direction of the current flow driven by a ponderomotive force along the resonance absorption surface.



(a) + 60 ps (-25°) (b) + 60 ps (-42°) (c) + 60 ps (+45°)

Fig. 1. The shadowgrams of the "plasma bullets" with the time "frozen" magnetic field.

The azimuthal direction remained unchanged during the time interval (- 60 ps to + 200 ps) and the magnetic field lines were “frozen” in the moving massive plasma blocks (see Fig.1). Fig. 2 represents the ratio of the transmitted intensity in thin stripes to the background intensity versus the rotation angle of the polarizing sheet crossed position. Positive angles correspond to the rotation from the left to the right, when looking into the probing beam.

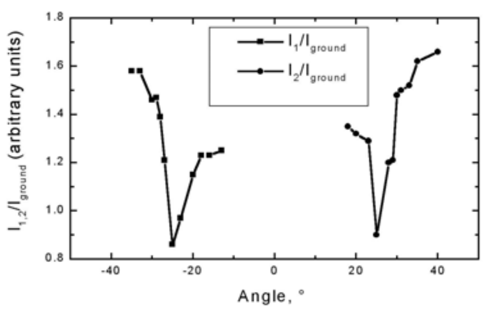


Fig. 2. Ratio of the transmitted intensity within the thin stripes to background intensity versus rotation angle of the analyzer for probe-pulse timing t = + 60 ps. I_1/I_{ground} – for lower and I_2/I_{ground} – for upper stripes.

A typical rotation approximately equals 0.4 – 0.6 rad. We can calculate the value of magnetic field required for this Faraday rotation angle by using an electron density distribution determined by Abel inversion of interferograms and assuming that magnetic field varies inversely as the radial position in plasma blocks,. The average values of magnetic field inductance B = 4 – 7 MGauss.

Computer simulation

Computer simulation of the magnetohydrodinamical processes in miniature plasma system (“plasma bullet” [2]) were carried out (in r-z geometry) by using mathematical model "ZEVS-2D". The electrophysical, thermophysical and optical properties [3] of the real matters were taken in to account. In this simulation the dependence of the boundary condition on the magnetic field from the laser beam parameters was produced in accordance with [4].

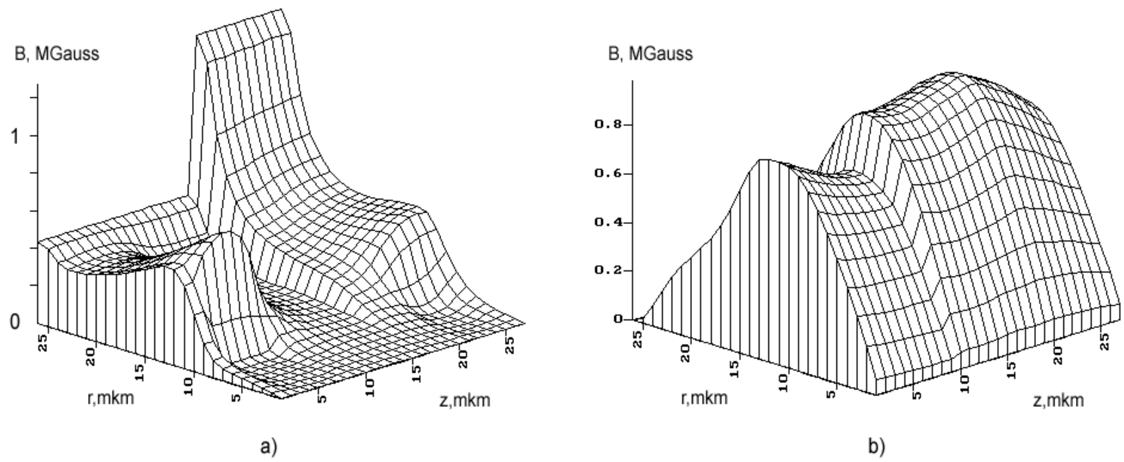


Fig. 3 Magnetic field in r-z geometry for: a) t = 2 ps, b) t = 120 ps.

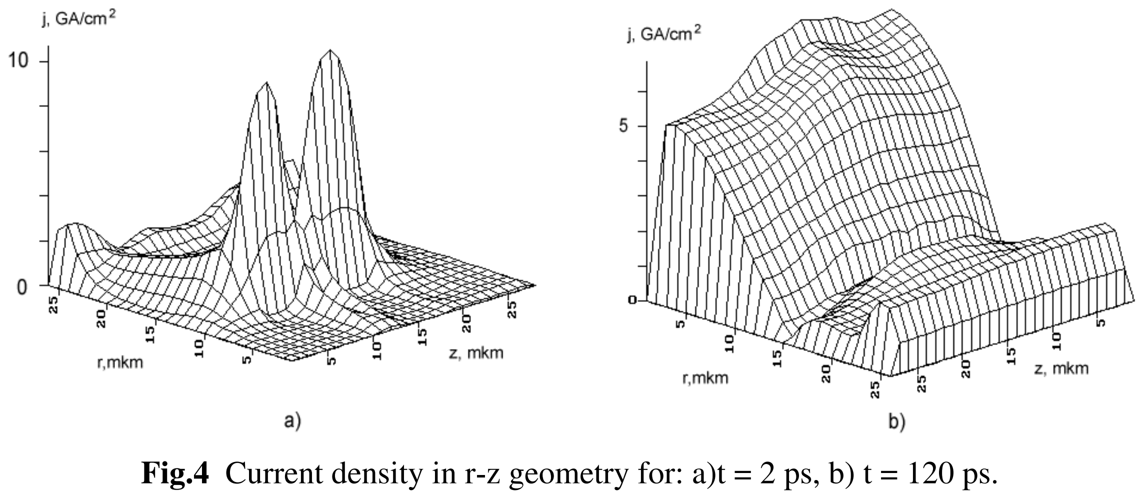


Fig.4 Current density in r-z geometry for: a)t = 2 ps, b) t = 120 ps.

The results of the numerical calculations are presented in Fig. 3 – 4. It is evident that an inductance of the magnetic field reaches a value B ≈ 1 MGauss, that is in few times less than in experiments. Thes calculation shows, that there is an ultrahigh frequency oscillation of a current densities with a values up to 10 GA/cm^2. An experimental values of self-induced magnetic fields in plasma were essentially greater then the calculated one. It may be connected with an incomlitence of a theoretical model used for computer simulations. More improved model is considereted in [5] which reveals more consistent agreement with an experiments.

Conclusions

A generation of thin plasma channels and extremely stable accelerated plasma blocks in a preformed plasma near critical density has been observed experimentally. The velocity of "plasma bullets" reaches values of order of 4.5x10 ^{8} cm/s and they are stable during the acceleration and propagation in air. The magnetic field is generated by dc currents driven by the ponderomotive force of the laser pulse within the skin layer where resonance absorption of laser light occurs. It follows from high values of magnetic fields (4 – 7 MGauss) observed in our experiments, as well as from the structure of measured magnetic fields, which arise within the plasma layer and are oppositely directed to the thermo-electric fields. Computer simulation shows that a strong magnetic fields (B ≈ 1 MGauss) and ultrahigh frequency oscillation of current densities take place in "plasma bullets". The observed difference of inductance between calculated and experimental results in determination of B demonstrated that it is needed to use another approach in computer simulation (e.g., as in [5]).

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