*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-1.120 (2008)*

RELATIVISTIC MAGNETO-ACTIVE LASER PLASMAS

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Principal results of investigations of relativistic laser plasmas are presented here. We found parameters of magnetic fields generated in laser plasma – the amplitude of the magnetic field, its lifetime, and the increment, the spatial structure. Mechanisms of acceleration of charged particles have been investigated which are related with considered magnetic fields.

Main peculiarities that determine properties of relativistic laser plasmas are:

1. <u>Electrons interacting with a field of electromagnetic wave can be considered as free particles.</u>
2. <u>Free electrons in relativistic laser plasmas interact only with an electromagnetic wave.</u>
3. <u>The conservation laws and motion integrals are valid also in the range of relativistic laser intensities.</u>

Equations describing quasi-stationary magnetic fields which are generated in laser plasmas can be derived from the conservation law for generalized momentum:

$$\overline{\mathbf{P}} = m\overline{\mathbf{v}}\gamma - \frac{e}{c}\overline{\mathbf{A}} \tag{1}$$

Here $\overline{\mathbf{A}}$ is the vector-potential of an electromagnetic wave. The relativistic equation of motion is of the form

$$\frac{d}{dt}m\overline{\mathbf{v}}\gamma = e\overline{\mathbf{E}} + \frac{e}{c}\left[\overline{\mathbf{V}} \times \overline{\mathbf{B}}\right] \tag{2}$$

Deleting the intermediate derivations, we present final equations for vortex electron structures producing magnetic field in laser plasmas:

$$\overline{\boldsymbol{\varpi}} = rot\overline{\mathbf{v}} \tag{I}$$

$$div\overline{\mathbf{V}} = 0 \tag{II}$$

$$\frac{d\overline{\boldsymbol{\varpi}}}{dt} + rot\left[\overline{\boldsymbol{\varpi}} \times \overline{\mathbf{V}}\right] = 0 \tag{III}$$

Here $\overline{\boldsymbol{\varpi}} = \dfrac{e\overline{\mathbf{B}}}{mc\gamma}$ is a cyclotron frequency for electron rotation in the magnetic field $\overline{\mathbf{B}}$, and $\gamma = 1\Big/\sqrt{1 - v^2/c^2}$ is the relativistic factor.

These equations mean conservation laws for vortex electron structure: Eq. (I) is the conservation law for a generalized momentum (1); Eq. (II) is the conservation law for a number of particles, and Eq. (III) is the conservation law for a magnetic flow, or for an angular momentum.

It should be noted that these equations allow undamped solutions. In general case solution of these equations taking into account losses is a difficult mathematical problem knowing as a problem of magnetic field generation. In particular, explanation of Earth magnetism is a part of this problem.

Equations (I) – (III) coincide with equations for real potential vortexes in mechanics of continuum matter which correspond to three Helmholtz theorems [1].

The potential vortex presents good description of the observed vortex. Uniform rotation is unfit for description of the observed vortex. The velocity inside the observed vortex is high and outside of it is small, while the inverse statement is valid for the case of the uniform rotation.

Coincidence of equations for a magnetic field in laser plasmas and for a potential vortex results in identity of their spatial structures (see Fig. 1).

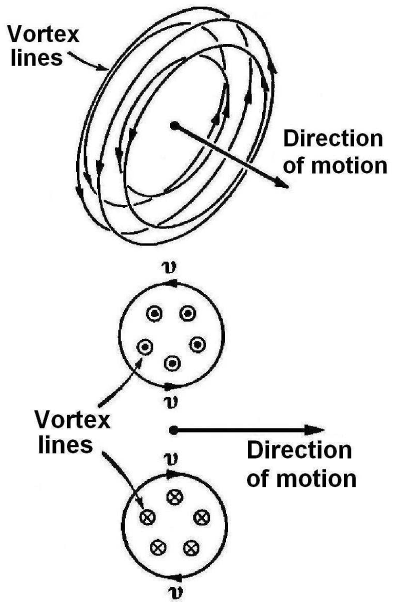

Fig. 1a. Vortex lines of moving potential vortex and its cross section

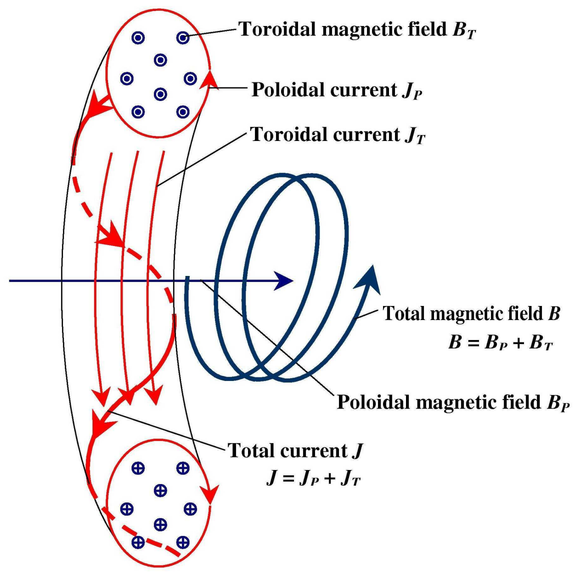

Fig. 1b. Structure of magnetic field produced in laser plasmas

An electron vortex producing a quasi-stationary magnetic field and their analogous classical potential vortex can exist only in motion. In general case the transformation of rotational energy into a translational motion is a relativistic effect. This fact follows from requirement of relativistic invariance for motion of charged particles; it takes place also at small non-relativistic velocities. The expression for the motion integral follows from the equation (2), taking into account also the Maxwell equations for an electron in the field of an electromagnetic wave which propagates along the direction $\bar{\mathbf{n}}$:

$$\frac{1-\bar{\mathbf{n}}\cdot\bar{\mathbf{v}}/c}{\sqrt{1-V^2/c^2}} = Const \qquad (3)$$

This expression is useful at the consideration of dynamics of relativistic particles in a field of an electromagnetic wave. For example, if a charged particle (for example, an electron) rotates with the velocity V in a circularly polarized field of an electromagnetic wave, then this particle acquires obligatory some velocity along the direction $\boldsymbol{n}$ of the wave propagation.

When $\overline{\mathbf{V}}/c = 0$, the expression (3) is equal to unity. This value does not change also for other velocities. Hence, one obtains the next expression for the particle velocity along the direction of propagation of electromagnetic wave:

$$\frac{V}{c} = \frac{\gamma - 1}{\gamma} = \frac{\sqrt{1+a^2} - 1}{\sqrt{1+a^2}} \quad . \tag{4}$$

Here the quantity a is determined by the electromagnetic wave intensity J: $a = 0{,}85\sqrt{\frac{J}{10^{18}}}$, J [W/cm^2].

Positively charged atomic ions prevent from motion of the considered electron vortex in a target because of the forces of the Coulomb attraction.

The requirement of quasi-neutrality results in motion of positively charged atomic ions. Omitting details of derivations and taking into account the Vlasov equations for a quasi-neutral two-component plasma and conservation law of the generalized momentum both for ions and for electrons, we present the final result:

Electrons and ions in relativistic laser plasmas form the one vortex structure – a potential vortex. This structure moves together with produced electromagnetic fields having the velocity of an electric drift (at **E** < **B**):

$$\overline{\mathbf{v}} = c\frac{\left[\overline{\mathbf{E}}\overline{\mathbf{B}}\right]}{\overline{\mathbf{B}}^2}. \tag{5}$$

Let us remark one peculiarity. The ion velocity and the ion free path are small in the process of ion motion. Ions are decelerated in a target; then new ions take their place, and finally the whole vortex structure occurs on the rear side of the target. If l_{i} is the depth for ion deceleration, the last ions propagate together with electrons producing quasi-neutral potential plasma vortex.

The drift motion does not produce the electric current and charge separation, since particles with positive and negative charge drift in the same direction with the same velocity. Thus, drift produces motion of neutral plasma.

Plasma magnetization results in small divergence of these flows. It is explained by a stability of vortex quasi-neutral structures as quasi-particles

Some recent publications report about experimental confirmation of generation of magnetized toroidal plasma structures. Ring-shaped proton flows with small divergence were observed [2, 3]. The magnetic field of about 100 MG has been measured by direct spectral method on large distance (several hundreds of microns) from the target surface [4].

Our experiments at the peak laser intensity of 3×10^{18} W/cm^2 allows us to observe on the rear side of thin (30 μm) titanium target clear ring-shaped structures by the proton detector CR-39 placed on a distance of 20 mm. Photo of ring-shaped proton structure is presented in Fig. 2a, and proton distributions with the energy of 2.5 MeV are presented in Fig. 2b. The divergence of the proton beam is $\varphi_{1/2} \approx 14°$. Protons with the energy higher than 2.5 MeV present narrow collimated beam with the divergence angle of $\varphi_{1/2} = 3°$. Inside this narrow collimated beam with the divergence angle $\varphi_{1/2}$ = 3° we observed well collimated proton beams with the divergence angle of $\varphi_{1/2}$ = 0.1°÷0.3°.

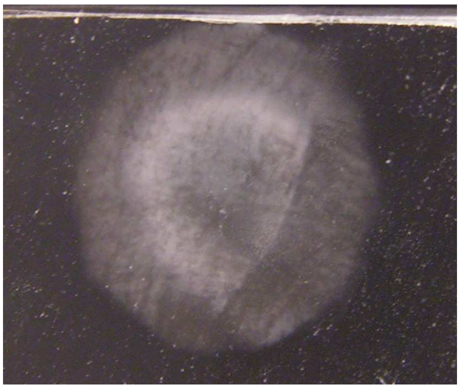

Fig. 2a. The photo of the track detector CR-39 covered by 11 mm Al filter. Detector CR-39 shows the tracks of protons with energies E_p > 0.8 MeV; $\varphi_{1/2}$ » 14° (cone half angle)

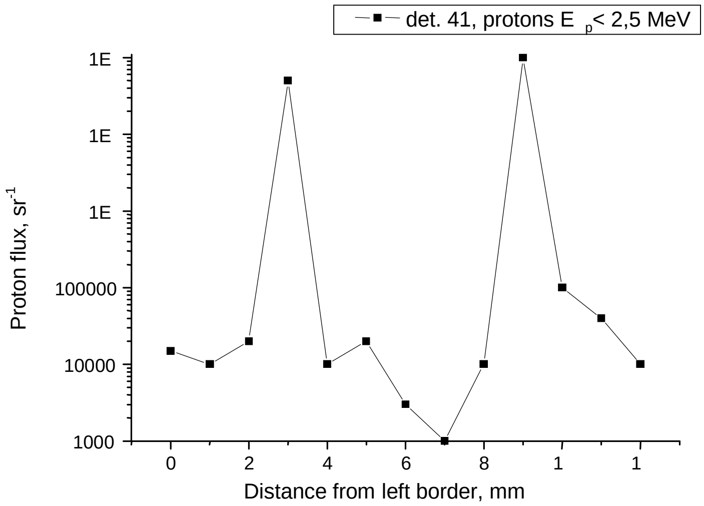

Fig. 2b. The proton distribution inside the spot for detector with 11 μm Al (E_p > 0.8 MeV). Target Cu 25 μm. Protons with energy E < 2,5 MeV

Note, that drift velocity can increase significantly under condition of development of pinch-effect up to relativistic values. Respectively, not only electron velocity, but also the velocity of heavy positively charged atomic ions can increase up to relativistic values [5].

Deleting the intermediate derivations, we present expressions for lifetime considered magnetic field:

$$T = 2\frac{\varepsilon}{\Delta\varepsilon}\Delta t \quad (6)$$

where ε - laser pulse energy, $\Delta\varepsilon$ - losses of an energy for electron vortex structure, $\Delta t = \lambda^2/D$, D – coefficient of Bohm's diffusion. This lifetime does not depend on duration of laser action and can exceed it on one-two order. For this reason the superstrong magnetic fields generated in laser plasma, term quasistationary.

Increment of the considered magnetic field is equal to the ionization rate ω_i, which is larger than the plasma frequency.

References.

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