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Magnetic field generation due to anisotropic laser heating

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Generation of magnetic fields around the laser speckles due to an anisotropic plasma heating is shown to be an important effect under the conditions previewed for the inertial confinement fusion. The structure of magnetic field around the laser beam is studied along with the effects of plasma dynamics, speckle intensity profile, and the electron heat transport.

Magnetic fields play an important role in the laser plasma interactions. They were found to be important for laser propagation, absorption, and energy transport in a plasma. Within the hydrodynamic model of plasma the magnetic field generation is associated with asymmetry of plasma flow where the gradients of the pressure and the density are non-parallel. This mechanism dominates in the high density regions, where there is no laser radiation. In the present paper we consider the generation of magnetic field in an underdense plasma around a laser hot spot due to anisotropic heating [1,2]. Since the laser intensity varies in the perpendicular plane more strongly than in the direction of propagation, we restrict ourselves to the two-dimensional geometry of plasma flow and consider a given spatial distribution of the laser intensity. We describe ions in the hydrodynamic approximation and neglect the magnetic pressure which is small compared to the thermal pressure. The electrons are described within the 10-moments approximation. The closure for the electron heat flux is taken in a form similar to that of Spitzer-Härm and Braginskii with a flux limiter. We account also for magnetization of the electron pressure and heat flux that are most important for the magnetic field saturation.

The derivation of basic equations and their discussion are presented in Ref. [3]. These are single fluid, quasineutral plasma equations which include the continuity and Euler equations for the plasma density $\rho = m_i n_e/Z$ and two components of the plasma velocity V_x and V_y in the plane perpendicular to the laser axis z. The Euler equation accounts for the forces related to the ponderomotive potential $\overleftrightarrow{W}$ and the electron pressure $n_e\overleftrightarrow{T}$ which are tensors. For the linearly polarized laser light along the axis x, the ponderomotive tensor has only one component $W_{xx} = W = I/2n_c c$ where I is the laser intensity and n_c is the critical electron density, while the electron temperature has four components, T_{xx},

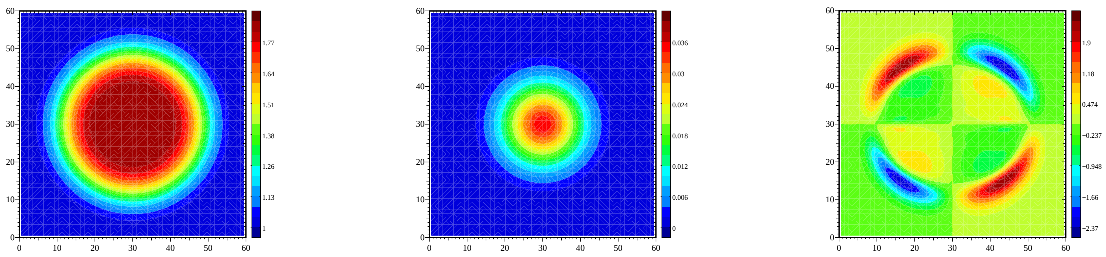
T_{yy}, T_{xy}, and T_{zz}. The system is completed by the Faraday equation for the magnetic field B_z which accounts for the source term, $\nabla \times \left((en_e)^{-1} \mathrm{div}\,(n_e \overleftrightarrow{U}) \right)$, where $\overleftrightarrow{U} = \overleftrightarrow{T} - \overleftrightarrow{W}$, the magnetic diffusion and convection, including the Hall and Nernst terms.

The effects of anisotropy appear in the electron energy balance equation

$$n_e \left[d_t \overleftrightarrow{U} + (\overleftrightarrow{U} : \nabla \otimes \mathbf{V}_e)^S \right] = -\mathrm{div}\, \overleftrightarrow{\mathbf{Q}} + 2 n_e \nu_e \chi(I) \overleftrightarrow{W} - 1.2 n_e \nu_e (\overleftrightarrow{T} - \overleftrightarrow{1}\bar{T}) - \frac{n_e e}{m_e} (\overleftrightarrow{U} \times \mathbf{B})^S$$

where the terms in the right hand side account for the heat transport, inverse Bremsstrahlung (IB) heating (including the Langdon correction χ), the temperature isotropization, and the rotation of the energy tensor in the self-consistent magnetic field. The IB term creates the anisotropic components $\Delta T = \frac{1}{2}(T_{xx} - T_{yy})$ and T_{xy} which are responsable for the magnetic field generation. Although for typical parameters the anisotropy $T_a = (\Delta T^2 + T_{xy}^2)^{1/2}$ is of the order of 10% or less, compared to the average temperature $\bar{T} = \frac{1}{3}(T_{xx} + T_{yy} + T_{zz})$, it is sufficient for the magnetic field generation with the rate of more than 1 T/ps and for the electron magnetization.

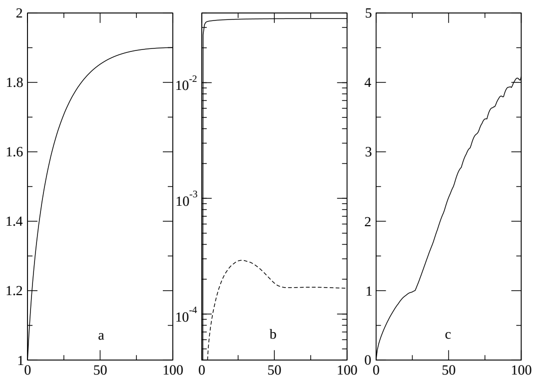
Figure 1 shows a typical snapshot of principal plasma characteristics for the laser intensity of 3×10^{15} W/cm^2. The laser beam has a round Gaussian shape of the radius 5 μm, the laser wavelength $\lambda = 0.35\,\mu$m, the plasma density $n_e = 10^{21}$ cm^{-3}, and the electron initial temperature $T_0 = 1$ keV. The average ion charge $Z = 5$ and the mass $m_i = 6.5\, m_p$ correspond to the fully ionized CH plasma. The profile of plasma average



a b c

Figure 1: Snapshots for the principal plasma characteristics in the x, y-plane (in μm) 50 ps after turn on the laser: (a) the average plasma temperature, $\bar{T}/T_0$; (b) the temperature anisotropy T_a/T_0; (c) the magnetic field B (in T).

temperature (a) is defined by a competition of the inverse Bremsstrahlung absorption and the electron heat transport. The plasma anisotropy is elongated in the direction of the laser field polarization (the axis x). Its relative amplitude, $T_a/\bar{T}$ is of the order of the ponderomotive potential, $W/\bar{T} \sim 3\%$. The calculated structure of magnetic field has a double quadruple shape - the inner one at the distance of one beam radius, while the external peak almost twice farther from the laser axis. This is a manifestation of the Langdon effect in the magnetic field generation.



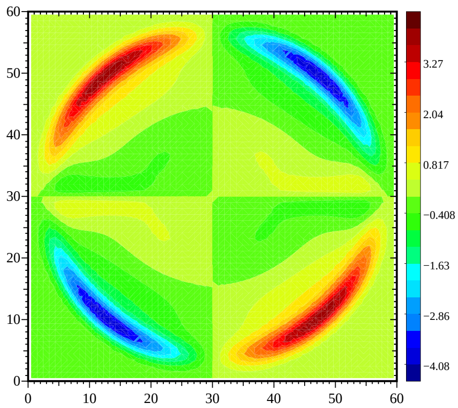


Figure 2: Temporal evolution of the principal plasma characteristics (in ps): (a) the maximum average plasma temperature (normalized by the initial temperature T_0), (b) the maximum temperature anisotropy (normalized by the initial temperature T_0), (c) the maximum of the axial component of the magnetic field (in T). The parameters of plasma and laser are same as in Fig. 1.

Figure 3: Structure of the magnetic field after 100 ps evolution. The parameters of plasma and laser are same as in Fig. 1.

The temporal evolution of the plasma parameters, Fig. 2 shows four time scales. The plasma density (a) evolves in the time scale R/c_s where c_s is the ion acoustic velocity. The temperature evolution (b) proceeds in a faster time scale of a few ps defined by the heat conduction. The temperature anisotropy (c) is established even faster within the electron collision time. The magnetic field (d) grows linearly in time with the rate proportional to the laser intensity. Its saturation is due to the Nernst effect – the convection of the magnetic field with the electron heat flux – and due to the feedback effect of rotation of the temperature anisotropy in the self-induced magnetic field. An appropriate description of the electron heat transport is of prime importance for the long-term magnetic field evolution.

In our model the electron heat flux is a tensor of third rank. In the case of a weak anisotropy, $T_a \ll \bar{T}$, we presented it as a sum of two terms: $\overleftrightarrow{\mathbf{Q}}=\overleftrightarrow{\mathbf{Q}}_{iso}+\overleftrightarrow{\mathbf{Q}}_{ani}$. The first term depends on the average temperature $\bar{T}$ and its gradient, $\mathbf{n}_T = \nabla\bar{T}/|\nabla\bar{T}|$ [3]:

$$\overleftrightarrow{\mathbf{Q}}_{iso}=\frac{2}{3}\,Q\left(4\,\mathbf{n}_T\otimes\mathbf{n}_T\otimes\mathbf{n}_T-\frac{1}{5}(\overleftrightarrow{I}\otimes\mathbf{n}_T)^S\right)$$

where $Q = \min\{-\kappa_{SH}|\nabla\bar{T}|, -f_{lim}n_0\bar{T}v_{the}\}$ is the flux-limited heat flux of Spitzer and Härm. This form assures a correct diffusion of the mean temperature and all the components of the tensor. However it conserves the anisotropy and does not introduce the diffusion of anisotropic components, ΔT and T_{xy}. Such a form is sufficient for description of the forced generation of the magnetic field by the laser-induced anisotropy, but it is not sufficient for the correct description of the Weibel-type instabilities.

The perturbation analysis of the coupled equations for the field B_z and the temperature component T_{xy} demonstrates the instability in the direction perpendicular to the anisotropy axis. The growth rate γ is proportional to the the perturbation wave number, $\gamma = -\eta k^2 + Wk^2/m_e\nu_e$, where $\eta = \nu_e c^2/\omega_{pe}^2$ is the magnetic resistivity, and it is not stabilized at short wavelengths. This fact creates serious difficulties for the numerical solution and it is also in contradiction with the kinetic analysis of the Weibel instability in the semi-collisional regime by [4]. The second term $\overleftrightarrow{\mathbf{Q}}_{ani}$ corrects this problem. It depends on the temperature anisotropy and it is chosen in such a way that it introduces the diffusion in anisotropic components without affecting the isotropic part:

$$\overleftrightarrow{\mathbf{Q}}_{ani} = -\delta\ \kappa_{SH}\ \mathrm{div}(\overleftrightarrow{U} - \overleftrightarrow{1}\ \bar{U})$$

The dimensionless constant $\delta \approx 0.1$ was chosen in order to get the agreement with the kinetic theory [4] and to stabilize the spatial scales, which cannot be resolved numerically. Figure 3 shows an elliptic-shaped magnetic field obtained from a circular laser beam after a 100 ps evolution.

In conclusion, the plasma temperature anisotropy created due to the IB heating is an important mechanism of the magnetic field generation under the conditions of present and future laser-plasma interaction experiments. The magnetic fields are generated in a short time scale of tens of ps and they are strong enough to magnetize the heat transport around speckles and correspondingly produce more anisotropic plasma environment. The newly developed model of the anisotropic heat transport allows a long-term studies of the magnetic field evolution.

References

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