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DIRECT CONVERSION OF THE ENERGY OF LASER AND FUSION PLASMA CLOUDS TO ELECTRICAL ENERGY DURING EXPANSION IN A MAGNETIC FIELD

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The paper deals with the physical and electrotechnical principles of the promising method of direct conversion of the kinetic energy of an expanding plasma cloud to electrical energy by inductive generation of currents in short-circuited load coils that enclose the plasma and are oriented across the external magnetic field. An analysis of plasma deceleration by a magnetic field and transfer of plasma energy to an inductive load gave a solution of the problem in general form and the dimensionless parameters of the problem that determine the deceleration radius, the coil current, and the theoretical conversion efficiency. The role of the basic physical effects, including parasitic ones (plasma instabilities and Joule heating), influencing the real efficiency is assessed. A comparison of the results with data of experiments with laser-produced plasma clouds on a KI-1 *facility and with available numerical results shows that in the optimized version of the method for conversion of inertial confinement fusion energy, a* 30% *efficiency can be achieved.*

Introduction. Progress in designing Megajoule lasers such as NIF (U.S.A.), LMJ (France), and KONGOH (Japan) for inertial confinement fusion (ICF) has motivated recent interest in pulsed methods of direct conversion of fusion energy in magnetic-field systems [1–4]. The method considered here is based on the general idea proposed by Artsimovich [1], and, as applied to ICF, by Haught et al. [2]. This idea is to use coils that enclose an expanding diamagnetic plasma. When the external magnetic field is excluded by diamagnetic plasma and an inductive electromotive force (e.m.f.) is thus induced, currents J should be generated in the coils in the presence of a load. Raizer [5] obtained a limiting conversion efficiency of up to 80% of the initial kinetic energy E_0 of a plasma sphere (treated as a superconductor) whose expansion is stopped at radius $R_b \approx (3E_0/B_0^2)^{1/3}$ by a homogeneous magnetic field B_0 without coils. This value was determined from the change in total magnetic-field energy due to the formation of a diamagnetic plasma cavity of limiting radius $R_c = R_b$, inside which the field is $B = 0$ (outside the magnetic perturbation has a dipole structure). The first estimates of the efficiency of plasma energy conversion to electrical energy (about 50%) in the presence of short-circuited coils were obtained in the development of a rocket thrust using fusion microexplosions [3]. The efficiency of such conversion was first studied quantitatively by the method of particles in cells (PIC) in two-dimensional numerical calculations of an ICF reactor with D–^{3}He fuel using an idealized hybrid plasma model [6] (ignoring plasma instabilities and heating). In calculations for the regime of ohmic loading of coils, the maximum efficiency is approximately 20%, and for short-circuited coils, it reaches 80% (for a system of five coils). However, because this model cannot describe all essential processes of plasma energy conversion to field energy and because the approach used in [6] to determine the accumulated ("useful") inductive energy of short-circuited coils is not justified, there is need for further analysis of these processes and experimental verification of the numerical results of [6].

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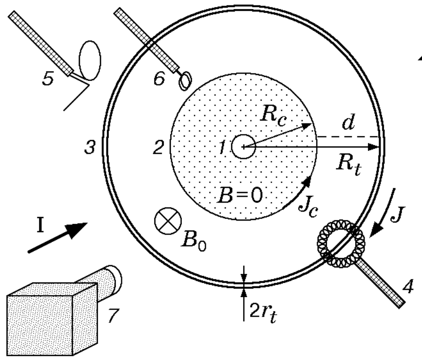

Fig. 1. Layout of the "Generator" experiment: 1) spherical laser target; 2) laser-paroduced plasma cloud; 3) short-circuited load coil; 4) Rogowski loop; 5) Langmuir double probe; 6) shielded magnetic probe; 7) gated optical imager (or a MDR-12 monochromator with a photomultiplier); I and II are beams of a CO_2 laser with a total energy of 100 J in a pulse with a duration of 100 nsec.

"Common" laser-produced plasmas (not fusion plasmas) are largely similar to ICF-produced plasmas. Laser-produced plasma clouds with a large number of particles (up to $N_i \sim 10^{19}$) and an energy of up to $E_0 \approx 300$ J [4, 7] and with nearly spherically symmetric geometry of expansion (with ions of charge z and small mass m, characterized by a ratio of $\langle m/z \rangle \approx$ 2–3 amu and a moderate velocity of the front $V_0 \approx$ 100–200 km/sec) can be used not only to explore the fundamental processes of plasma interaction with a magnetic field [7–11] but also to directly simulate [4, 10–12] the ICF energy conversion method considered. Although a large number of experiments have been performed with a laser-produced plasma in a magnetic field, only a few of them were performed with laser plasma clouds necessary for simulations. Problems related to inductive conversion of energy have not been studied (except for [2, 10], where some data on e.m.f. generation are given). The efficiency of the other conversion methods studied (primarily due to the use of the thermoelectromotive effect) does not exceed 1–2%.

Investigation of the inductive method of ICF energy conversion requires both a general analysis of the physical process of exclusion of a magnetic field by a plasma and the associated conversions of plasma energy and model experiments. The latter is especially important because many of the indicated processes cannot be described by the ordinary MHD equations (or adequately reproduced in purely collision-free calculations by the PIC method) provided that the ion Larmor radius is finite ($R_h \leqslant R_b$). This relation for values of the "directed" ion Larmor radius $R_h = mcV_0/(ezB_0)$ is typical of the parameters of the designed ICF reactors with a magnetic fields [6] and can lead to anomalously fast development of flute instability of the cloud boundary [11], enhanced penetration of the field into the cloud with turbulent collision frequency ν_{ef} of electrons (with mass m_e): $\nu_{ef} \approx 0.3eB_0/(m_e c) = 0.3\omega_{ce}$ [7, 10], and electron heating [7, 8, 11, 13]. The influence of these and other effects on the direct inductive conversion of the cloud energy and the real conversion efficiency η were first examined during the "Generator" experiment [12] on a KI-1 laser facility (Fig. 1).

Current Generation in a Coil and Associated Additional Deceleration of Plasma. For analysis of plasma energy conversion to electrical energy, we consider an ideal system consisting of a superconducting, centered sphere of radius R_c and a superconducting, centered, closed round coil of radius R_t in an external magnetic field perpendicular to the plane of the coil, in which the initial current is $J = 0$ at $R_c = 0$ (before the onset of expansion of the diamagnetic plasma sphere). Using the simplest (zero) approximation and ignoring the back action of the coil current field B_t on the plasma and the decrease in the coil inductance L_0, it is easy to estimate the generated current (in the CGS system of units) as $J_0 = c\Delta\Phi/L_0$ [11] from the condition of conservation of the total initial field flux $\Phi_0 = \pi R_t^2 B_0$ inside the coil and taking into account the exclusion of part $\Delta\Phi$ of the flux by the plasma. Assuming that the current induced in the coil should compensate for the decrease of flux in the coil $\Delta\Phi = \Phi_0(R_c/R_t)^3$ only due to complete exclusion of the initial field B_0 from the plasma volume (ignoring the additional field B_t) and that the plasma diamagnetic cavity can expand to $R_c = R_t$, one finds that the current in a coil with intrinsic inductance

$L_0 \approx 4\pi R_t \ln G \approx 10\pi R_t$ (for coil thickness $2r_t$ and geometrical parameter $G = R_t/r_t$) can reach the limiting value $J_{0,\max} = c\Phi_0/L_0 \approx 0.1cR_c^3 B_0/R_t^2 \approx 0.1cR_t B_0$. Therefore, if the coil size is optimal for the zero approximation $R_t \approx R_b$, the highest possible inductive energy of one coil $[W_{0,\max} = L_0 J_{0,\max}^2/(2c^2) \sim R_c^6/L_0]$ can account for 50% of the value of E_0.

The above estimates support the high efficiency of the present system of plasma energy conversion. However, the same estimates show that even for the model of superconductors, the real efficiency can be well below the ideal efficiency $\eta_0 = W_{0,\max}/E_0 \approx 50\%$, primarily because the current depends strongly on the radius of the cavity (which cannot reach R_b owing to the additional deceleration of the plasma by the coil field) and because the coil inductance decreases in the presence of the sphere. Let us analyze the opposite effects of these factors on the current generated in a short-circuited coil by a spherical plasma cloud which expands without change of shape in a magnetic field.

Real Inductance and Current of the Coil and "Useful" Energy . In the presence of a superconducting sphere, the coil inductance decreases to the quantity $L = L_0 - \Delta L \equiv L_0 - R_t F$ due to the effect of their mutual inductance M [14–16]. This expression can be written as $L = L_0(1 - \Delta L/L_0) \approx L_0(1 - KX^3)$ with allowance for the approximation $\Delta L/L_0 \approx KX^3$ (for $K \approx 3.6/\ln G$ and $0.5 \leqslant X \leqslant 0.9$) for $X = R_c/R_t$ and the function $F(k)$ tabulated in [14], where $k = 2X/(1+X^2)$. Using the "image" method [15] with replacement of the system "coil–sphere" by an equivalent (from the viewpoint of the magnetic field outside the sphere) system "coil–imaginary coil" (with the reverse current of the image $J_- = JR_t/R_c$ on radius R_c^2/R_t inside the sphere), we can also determine the generated current of the coil using the condition of conservation of the total flux inside the coil and analyzing the balance of flux variations. Such a balance includes the decrease of the flux due to the exclusion of the field by the plasma $\Delta\Phi = \Phi_0 X^3$ and the contribution to the flux $M_- J_-/c$ from the mutual inductance $M_- = R_c F$ of the coil current and its image. This total effect of the flux decrease should be compensated for by its increase due to the coil current $L_0 J/c$. Then, the general balance condition $\Delta\Phi + M_- J_-/c = L_0 J/c$ leads to the desired relation $\Delta\Phi = (L_0 - R_t F)J/c \equiv LJ/c$ for determining the current $J(X) = J_{0,\max} X^3/(1 - KX^3)$. The corresponding real inductive energy of the coil with the maximum current $J_{\max}$ is equal to $W_{\max} = LJ_{\max}^2/(2c^2)$.

To determine the "useful" fraction of $W_{\max}$ that can be transferred to the load, we analyzed a cylindrical problem where the values of L and M are known and the work of the plasma on excluding the field and changing its energy can be determined exactly [6]. Theoretical and numerical analyses of the problem showed that the process of charging of capacitive load C (switched, according to [6], at the moment the plasma stops and the current reaches the maximum $J_{\max}$) and the accumulation of energy $W_C = CU^2/2$ at time $(\pi/2)\sqrt{LC}/c \ll R_b/V_0$ can be described by the equation $L(d^2J/dt^2) + c^2 J/C = 0$ with the constant value of L corresponding to the maximum of $X = R_c/R_t$. In this approximation of a stationary plasma (during charging of the capacitor), the value of $W_C = W_{\max}$ is reached, which accounts for 40% of the value of E_0. After termination of the charging and breaking of the load circuit [6], the remaining plasma energy (in the form of the inductive energy of its diamagnetic current) is converted to plasma heating due to penetration of the field into the plasma at a late stage. Calculations show that in this cylindrical problem, plasma expansion that occur with the capacitor in charge (as the current $J \to 0$) leads to an increase in the ratio W_C/E_0 by not more than to 60% for maximum plasma radius $R_c < R_t$. Because in an idealized cylindrical case, a value of $\eta \approx 50\%$ is reached within time much larger than the characteristic time of plasma deceleration $t_* \approx 1.3R_b/V_0$, it follows that under real conditions of possible development of anomalous flute instabilities (which are faster than MHD instabilities) or decrease in plasma pressure due to its expansion along the field, this efficiency can be considered close to the maximum value.

We note that a qualitatively similar result was obtained earlier in calculations for a cylindrical induction MHD generator [17], which showed that not more than 50% of the work of the plasma on overcoming the field pressure is transferred to the load. Hence, the above expression for the converted "useful" energy $W_{\max} = LJ_{\max}^2/(2c^2)$ for a capacitive load (or a low-resistance load with the same efficiency which should be connected to a circuit with predominantly inductive impedance) can be a lower bound of the real efficiency of the present method of direct conversion of expanding-plasma energy.

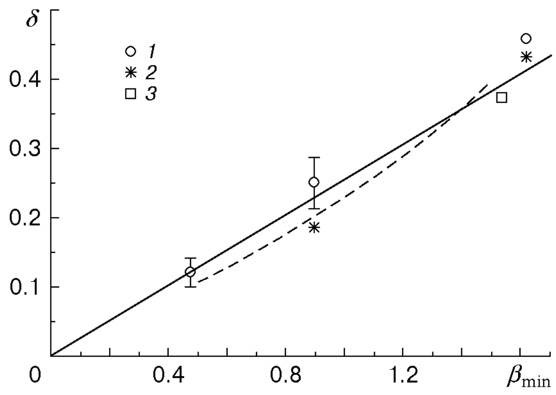

Fig. 2. Minimum dimensionless gap size δ versus the similarity criterion of the problem $\beta_{\min}$: the solid curve is a curve of $\delta \approx \beta_{\min}/4$, the dashed curve shows the solutions of Eqs. (1) and (2) based on the pressure and energy balances, respectively; points 1 and 2 are measurements by the magnetic probe and the gated optical imager, respectively, and point 3 is the result of the two-dimensional calculations of [6].

Stopping of Sphere Expansion by the Magnetic Field Inside the Coil. The maximum radius R_c of expansion of a diamagnetic (superconducting) sphere in the coil plane with allowance for the coil field B_t can be determined by two methods. The first uses the condition that the dynamic pressure P_c of a plasma at the moment it stops is equal to the pressure of the total field on the plasma surface, which in the coil plane can be written as $B_* = 1.5B_0 + 2B_t$ (with allowance for the "dipole-like" exclusion of the field by the sphere B_0 [5] and the field of the coil current "image" inside the sphere [15]). To simplify the further analysis, we can replace the total field B_* by the averaged quantity $\langle B_* \rangle = B_0/(1 - X^2)$ (with an error of about 30%), which follows from the law of conservation of the total field flux Φ_0 in a gap of width $d = R_t - R_c$. Following [5] and assuming that the pressure P_c is determined by the plasma flow with "undisturbed" ion concentration $n_{i0} = 3N_i/(4\pi R_c^3)$ decelerated to velocity $V \approx V_0/2$ (and reflected from the boundary), from the pressure balance condition $\langle B_* \rangle^2/(8\pi) = n_{i0}\langle m \rangle V_0^2/2$, we obtain the following equation for determining the maximum radius $R_c \equiv XR_t$ for the pressure model:

$$0.7\beta X \approx (1 - X^2)^{2/3}. \tag{1}$$

Here $\beta = R_t/R_b$ is the main similarity criterion of the problem. For $\beta \gg 1$, Eq. (1) leads to the obvious solution $R_c \approx R_b$ for the case with no coil.

The second method for determining R_c using the energy model of interaction of the sphere with the coil current is based on determination of the potential energy $J^2(X)\Delta L/c^2$ of this interaction [16]. Assuming that at the moment the sphere ceases to expand, the interaction energy is equal to some fraction of the cloud energy E_0/γ, we obtain the equation

$$0.7\beta X^2 \approx [(1 - KX^3)/\gamma]^{1/3} \tag{2}$$

with limited range of applicability for $\beta \leqslant 2.5$ (this simplified approximation ignores the potential energy of interaction of the sphere with the field B_0). An analysis of the numerical solutions of Eqs. (1) and (2) shows that for values from $\gamma = 8$ (for $\ln G \approx 3.5$) to $\gamma = 3$ (for $\ln G \approx 1.6$) and $0.2 \leqslant \beta \leqslant 2$, these equations give dependences $X(\beta)$ that differ only slightly from the linear function $\delta = \beta/4$ ($\delta = d/R_t \equiv 1 - X$ is the dimensionless gap between the sphere and the coil), which adequatety describes both the available data of calculations for an ICF reactor using the two-dimensional PIC model [6] and the data of the "Generator" experiment. This follows from Fig. 2, which gives the dependence of the minimum dimensionless gap size $\delta = d/R_t^{\min}$ [between the plasma or its cavity and a coil of the third type (see Table 1)] across the laser beams on the modified similarity criterion of the problem $\beta_{\min} = R_t^{\min}/R_b^{\min}$, which accounts for the equally oriented elliptic configurations of the coil (with semiaxis $R_t^{\min}$) and the cavity of minimum radius $R_b^{\min}$ in the same direction.

TABLE 1

Type of coil	Configurations	$R_t^{\min}$, cm	$R_t^{\max}$, cm	ln G^*	L_0, cm	E_0, J	B_0, Gs	$J_{\max}$, kA	η_{0t}, %	η_t, %	β_*
1	Circle	7.5	7.5	3.2	310	8	500–620	1.8	20	9	1
						8	220	2	—	7.5	0.5
2	Ellipse	4.5	10.5	3.1	340	8	500–620	1.8	20	9.5	1.1
						1	500–620	0.5	—	7	1.9
3	Ellipse	6.5	12.5	3.9	450	8	500–620	1.3	23	8	1.2
						1	500–620	0.5	30	10 ± 3	2.2

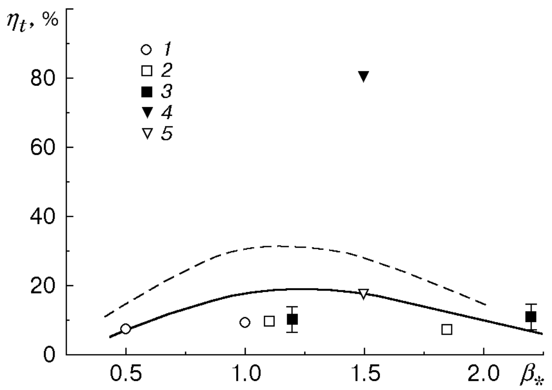

Fig. 3. Efficiency of direct conversion of exploding-plasma energy to electrical energy versus the criterion β_*: the solid curve shows theoretical values of η_t (4) for $K^* \approx 0.55K = 2/\ln G$ and $\ln G \approx 3.2$, the dashed curve is the same for $\ln G + 0.33 \approx 2.2$; points 1–3 are experimental values of the efficiency for the corresponding types of coils for $\ln G^* = 3.2$–3.9; point 4 shows the result of calculations using the two-dimensional model [6] of the "potential" efficiency η_{0t} for $\ln G \approx 3.2$; point 5 is the same for real values of η_t.

Peak Current and Energy of the Coil. The expression for the value of the gap size $\delta \approx \beta/4$ between a circular coil and the sphere at the moment the sphere stops obtained by solution of Eqs. (1) and (2) is the basis for calculation of the coil current, which becomes maximal at this time:

$$J_{\max}(\beta) = J_{0,\max} X^3/(1 - KX^3) \equiv J_{0,\max}\psi(X), \tag{3}$$

depends on the function $\psi(X) = X^3/(1-KX^3)$, the parameter $K \approx 3.6/\ln G$, and the value of $X(\beta) = 1-\delta \approx 1-\beta/4$, which is determined by the initial conditions of the problem via the criterion $\beta = R_t/R_b$. Similarly, it is easy to show that the expression for the maximum "useful" energy of the coil current $W_{\max} = LJ_{\max}^2/(2c^2)$ obtained by analysis of the cylindrical problem for the complete scheme of conversion with energy stored in capacitors [6] is determined by the same quantities K and β. For this, we consider a system of three independent coils that corresponds to the conditions of calculations [6] of the energy conversion efficiency. In particular, these calculations showed that two lateral coils together give about the same amount of energy as that produced by one central coil (if it is located in the plane of the ICF target and the lateral coils having radii equal to the radius of the central coil are shifted at distance $Z = \pm R_t/2$ along the field); two more distant lateral coils make little contribution to the efficiency. The relative efficiency of the lateral coils can be estimated using the general expression for the decrease of the field flux inside the coil due to field exclusion by the plasma $\Delta\Phi = \Phi_0 X^3/(1+\alpha^2)^{3/2}$ for arbitrary (in Z) arrangement of the coils, characterized by the parameter $\alpha = Z/R_t$. Then, for this system of three coils, the theoretical total conversion efficiency is $\eta_t \approx 2W_{\max}/E_0$ and, with allowance for (3), it is given by the function

$$\eta_t \approx 0.037[\beta(4-\beta)]^3\psi(\beta)/\ln G, \tag{4}$$

whose plot is presented in Fig. 3 [$\beta_* = R_t^*/R_b^{\min}$ is a generalized criterion and $R_t^* = (R_t^{\min} + R_t^{\max})/2$ is the average radius of the coil that accounts for its ellipticity in experiments]. Analysis of the theoretical curve of $\eta_t(\beta_*)$ in Fig. 3 for $\ln G \approx 3.2$ and $K^* \approx 0.55K = 2/\ln G$ (the value of the parameter K is corrected on the basis of experimental data) shows that the curve has the maximum $\eta_{t,\max} \approx 19\%$for $\beta \approx 1.2$. The "potential" efficiency calculated in [6] from the formula $\eta_{0t} \approx 2W_0/E_0 \approx 80\%$ for $W_0 = J_{\max}\Phi_0/(2c)$ and the same value of $\ln G$ is in good agreement with the efficiency calculated from formula (4) if one takes into account the relation between η_{0t} and $\eta_t \sim W_{\max} = LJ^2_{\max}/(2c^2) \equiv J_{\max}\Delta\Phi/(2c)$. From this relation it follows that for the same current strength $J_{\max}$, one obtains $\eta_t = \eta_{0t}\Delta\Phi/\Phi_0 = \eta_{0t}X^3 \approx 0.24\eta_{0t} \approx 20\%$ for $X \approx 0.63$, which corresponds to the calculated value of $\beta \approx 1.5$. We note that even the highest theoretical efficiency $\eta_{t,\max} \approx 32\%$ [achievable, according to Fig. 3, for $\beta \approx 1.1$–1.2 and the minimum allowable value of $\ln G \approx 2.2$ for which formula (4) is valid] in the model problem of deceleration of the sphere is consistent with the law of conservation of total energy in the system. In this case, because of a decrease in the cavity radius R_c (compared to its radius R_b without coils), the main energy of the surface current J_c (which excludes the field B_0 and produces the cavity) is estimated to be $(R_c/R_b)^3E_0$, which accounts for about 30% of the value of E_0, and is converted to plasma heating. The experimental values of the efficiency shown in Fig. 3 (see also Table 1) are determined from the formula $\eta_t = 2W_{\max}/E_0 = LJ^2_{\max}/(c^2E_0)$ for a three-coil system. In addition, for a three-coil system, the "potential" efficiency η_{0t} is determined with allowance for the total cross-sectional area of the coil [6] to find Φ_0: $\eta_{0t} = J_{\max}\Phi_0/(cE_0)$. The experimental data for η_t are obtained for $\beta_* \approx 1$ in the basic mode of experiments, for $\beta_* \approx 0.5$ in a decreased field $B_0 \approx 220$ Gs, and for $\beta_* \approx 2$, with decrease in the plasma energy E_0 to a value of about 1 J.

Simulation of ICF Energy Conversion in the "Generator" Experiment. The main dimensionless physical parameter that determines the interaction efficiency of plasma clouds expanding after explosion with a magnetic field in vacuum is the ion magnetization parameter $\varepsilon_b = R_h/R_b$, obtained in the experiments of [7, 9] on a KI-1 facility. As shown by experiments, grounded theoretically, and confirmed (according to the π theorem) by a dimensional analysis [18], for $N_i \gg 1$, $V_0/c \ll 1$, and $zm_e/m \ll 1$, the parameter ε_b is the main similarity parameter of the problem with the critical value of $\varepsilon_b^* \approx 1.3$–$1.7$. Only for values $\varepsilon_b \leqslant \varepsilon_b^*$ (for which the velocity of diffusion of a field with $\nu_{ef} \approx 0.3\omega_{ce}$ is lower than V_0), can the plasma cloud be decelerated by the field to the velocity $V \approx V_0/2$ at the radius R_b and produce a diamagnetic cavity of the same size necessary for effective transfer of the plasma energy to the field (or to the load in the presence of coils). For the ICF reactor being designed [6] based on the D–^{3}He reaction with a plasma energy a $E_0 = 140$ MJ ($V_0 \approx 30{,}000$ km/sec and $\langle m/z\rangle \approx 1.7$ a.m.u.) in a field of $B_0 = 4.4$ kGs, the condition of effective supply of plasma energy to the field ($\varepsilon_b \leqslant 0.2 < \varepsilon_b^*$) is obviously satisfied with $\beta = R_t/R_b \approx 1.5$ and $\ln G \approx 3.2$. To produce ICF conditions in experiment, one needs to "instantaneously" (in time $t \ll R_b/V_0$) generate a plasma cloud with nearly spherically symmetric geometry of expansion, necessary for effective deceleration of the plasma by the field, and without electrical drift of the plasma blob as a whole [2, 7, 13].

The properties of laser plasma clouds (LPC) produced by bilateral irradiation of small-size targets in the form of particles [2, 8, 18] or filaments [7, 13, 18] meet the general requirements of simulations of explosive phenomena, and the parameters of a KI-1 facility [18] makes it possible to perform experiments with LPC [7, 9, 10] for values of $\varepsilon_b \approx 0.2$–$0.3$, which correspond to the ICF conditions [6]. The basic model experiments were performed for a plasma energy of $E_0 \approx 8$ J and a minimum value of $\varepsilon_b \approx 0.7$ in a field of $B_0 = 620$ Gs. For these conditions, by comparing the results of studies of the three-dimensional structure and dynamics of the LPC (and its cavity) produced in the "Cavity" experiments without coils [8–11] and the results obtained in these experiments with a coil, it is possible to determine the effect of the coil. In the "Generator" experiment (see Fig. 1), a caprolon ($C_6H_{11}ON$) spherical laser target of diameter $D \approx 3$–4 mm was irradiated on two sides in a direction transverse to the field by identical laser beams with cross-sectional diameter of about $2D$ (in the region of the target) and with a total energy of $Q_0 \approx 100$ J in a CO_2 laser pulse with a duration of 100 nsec and a wavelength of 10.6 μm. In the basic mode of experiments (field $B_0 = 500$–620 Gs), the initial parameters of a quasistatic LPC with a total energy of $E_0 \approx 8$ J are characterized by a velocity of $V_{0\parallel} \approx 200$ km/sec along the beams and a velocity of $V_{0\perp} \approx 170$ km/sec across them and the corresponding energies per unit solid angle: 1.2 J/sr (for a characteristic value $\Delta\Omega \approx 5$ sr) and 0.45 J/sr. These energies can also be expressed in the form of effective energies in these directions $E_\parallel = 4\pi(dE_0/d\Omega)_\parallel \approx 15$ J and $E_\perp \approx 5.5$ J, which, according to the data of the "Cavity" experiment, can be used to estimate the corresponding maximum radii $R_b^{\max} \approx 11$ cm and $R_b^{\min} \approx 7.5$ cm of a diamagnetic cavity in these directions (with no coils). For such cavity dimensions and the parameter of $\langle m/z \rangle \approx 2.5$ a.m.u. for the basic mode (for H^+ and C^{+4} plasma ions [18]), the characteristic value of $\varepsilon_b \approx 0.7$ was small enough, but with decrease in the laser energy to $Q_0/3$ (and formation of LPC with an energy E_0 of about 1 J and $E_\perp \approx 0.5$ J for $\langle m/z \rangle \approx 3$–4 a.m.u.), it could exceed the critical value ε_b^*. Under these conditions. we explored current generation in three types of short-circuited copper coils having dimensions close to R_b and basically elliptic configurations, in which the asymmetry of plasma expansion was accounted for by orientation of the minor semiaxis of the coil $R_t^{\min}$ along the radius $R_b^{\min}$. The effects of plasma deceleration and formation of its cavity were studied in experiments with a third coil.

The coil current J was measured by a shielded broad-band Rogowski loop of 2 cm diameter with a transfer coefficient of $1.8 \cdot 10^{-8}$ V $\cdot$ sec/A and a resolution of 10 nsec in the mode of recording dJ/dt and subsequent integration through a RC circuit (60 μsec) at the S8-14 oscillograph input. The initial parameters and deceleration of the LPC outside the radius and plane of the coils were measured by Langmuir double probes, and the dynamics of the plasma and its cavity inside the coil were examined using a gated optical imager (GOI) and miniature shielded magnetic probes (isolated from the plasma by a 6-mm glass tube). All indicated systems of plasma diagnostics [19] had a resolution of not less than 20–30 nsec, and plasma expansion transverse to the field was recorded by the GOI operating in the plasma charge-exchange emission regime due to the admission of H_2 into a chamber up to a pressure of 0.015 Pa (initial chamber pressure 0.0003 Pa). This ensured visualization of the distribution of the concentration n_i of C^{+4} ions [19]. To obtain experimental estimates of the increase in the electron temperature T_e in the plasma skin layer, we employed the method of [20] for local recording (by an MDR-12 monochromator and FÉU-84 photomultiplier) of the relative intensity of emission from neutral helium (He I) at 389 and 502 nm excited by the electrons. Helium was let in up to a pressure of $P_{\mathrm{He}} \approx 0.015$ Pa and did not influence the examined processes.

Results of Model Experiments and Conclusions. Measurements using magnetic probes located at a distance of 3 mm from the plane of a coil of the third type showed that as a result of action of the coil current, the radius of the cavity, i.e., the dimension of the region in which the field $B < B_0$ decreases to $R_c^{\min} \approx 4.5$–5.3 cm in a direction transverse to the laser beams (in contrast to $R_c^{\min} \approx 7.5$ cm recorded in the "Cavity" experiment with no coils in the basic mode of experiments). GOI photographs show that for a time $t \approx 0.7$ μsec, the plasma undergoes considerable deceleration at the same radius, and later, flute instability typical of plasma expansion in a homogeneous magnetic field with no coils develops on the plasma boundary [7, 11]. The experimental values for the minimum dimensionless gap of the cavity $\delta = (R_t^{\min} - R_c^{\min})/R_t^{\min}$ (and the plasma boundary as a function of the corresponding parameter $\beta_{\min} = R_t^{\min}/R_b^{\min}$) given in Fig. 2 are well described by the theoretical dependence $\delta \approx \beta/4$. This maximum size of the cavity (with a skin layer of width $a \approx 1$ cm on the boundary) is preserved for about 1.1 μsec (Fig. 4), and its total "lifetime" is about 2–3 μsec, as in the absence of a coil. During this period of time, the coil current reaching a maximum value of $J_{\max} \approx 1.3$ kA is recorded. The magnetic measurement data given in Fig. 4b are obtained by two probes located inside the diamagnetic cavity on a line parallel to the laser beams (see Fig. 1) and separated from them by 4 cm. The probes are 6 cm apart and are symmetric about the target. Recording of the ion flow dynamics by Langmuir probes outside the coil (the probes are located at a distance 5–10 cm from the coil plane and at a distance of 15 cm or more from the target) shows that most of the plasma expands across the field, as in the "Cavity" experiment with decreased velocity (to $V \approx V_0/2$) and has an irregular jet nature (due to development of flute instability).

The peak current $J_{\max}$ for all types of coils and in all modes was reached at $t \approx 0.6$–0.8 μsec from the moment when a laser pulse is supplied. The largest values of the current are given in Table 1 and are comparable in order of magnitude with the ultimate possible value of $J_{0,\max} = c\Phi_0/L_0$. The curve of $J_{\max}(B_0)$ presented in Fig. 5 for a coil of the third type in the range 10 Gs $< B_0 <$ 620 Gs is adequately described by the theoretical function (3). For this, in (3) one should use the parameter $K^* \approx 0.55K \approx 2/\ln G^*$ (with the effective quantity $G^* = R_t^*/r_t$) and the average radius of the coil R_t^*, and in determining the parameter $X = R_c/R_t = 1 - \beta/4$, the quantity β should be taken in the form $\beta_* = R_t^*/R_b^{\min}$. An analysis of the theoretical dependence (solid curve) shows that the peak current $J_{\max}$ must be reached for $\beta_* \approx 1.2$ and the corresponding field $B_0 \approx 600$ Gs, for which only current saturation was observed in experiments. For smaller

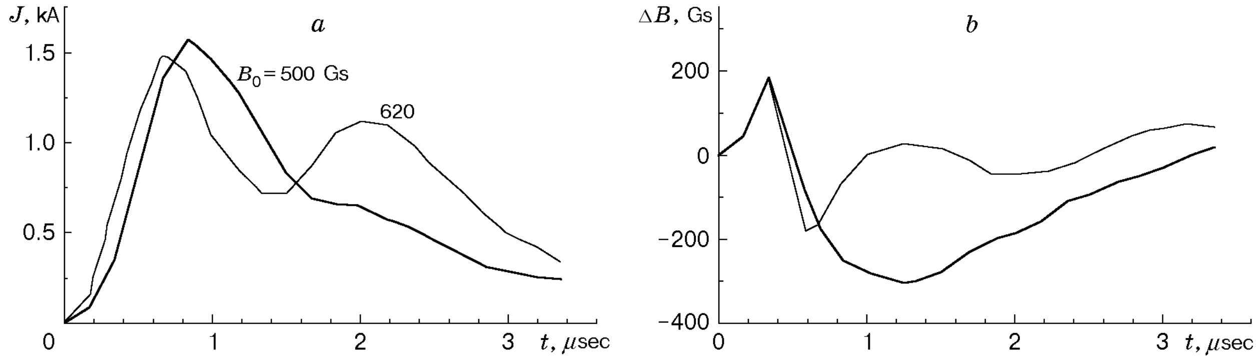

Fig. 4. Dynamics of the current (a) of a coil of the third type in the field B_0 and field exclusion (b) inside the coil from data obtained using two probes in the basic mode of experiments.

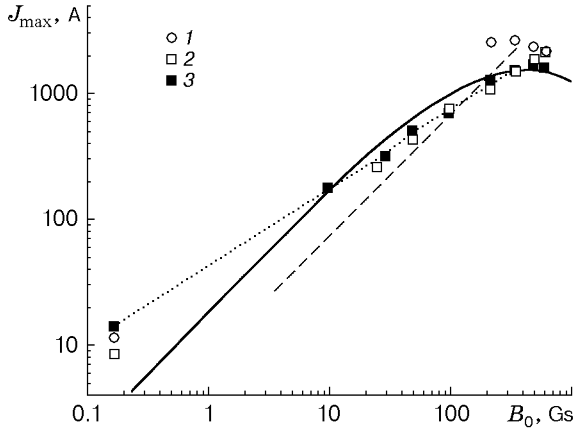

Fig. 5. Peak coil current versus magnetic field for the plasma energy in the basic mode of experiments: the solid curve is the theoretical dependence (3) for a coil of the third type ($R_t^* = 9.5$ cm and $K^* = 2/\ln G^*$), the dotted curve is extrapolation of the experimental data in the form $J_{\max} \sim B_0^{0.6-0.7}$ and the dashed curve is the ultimate possible current strength $J_{0,\max} = c\Phi_0/L_0 \sim B_0$ at constant inductance; points 1–3 are experimental values for the corresponding coils.

fields, as high as $B_0 \approx 10$ Gs (when the gap size $d \approx 2$ mm becomes equal to the finite radius r_t of the coil conductor, which is ignored in theory), the experimental dependence is described more accurately by the function $J_{\max} \propto B_0^{0.6-0.7}$ (dotted curve).

Thus, experimental data on the minimum gap size and peak coil current and on the form of their dependences on field (which are in good agreement with theoretical dependences) confirm the validity of models (1)–(3) for plasma deceleration by the field and coil-current generation with allowance for the decrease in its inductance due to the effect of the plasma [14–16]. Hence, the above dependences for d and measured values of $J_{\max}$ can be used to calculate the real inductance of the coil L and estimate the experimental value of the efficiency of direct conversion of the total plasma energy ($E_0 \approx 8$ J) to the inductive energy of the coil [$W_{\max} = LJ_{\max}^2/(2c^2)$]. With this purpose, in the expression for the real inductance, the correction term was written as $\Delta L/L_0 \approx K^*X^3$ for $X = 1-\beta_*/4$ and the corresponding quantity β_* was used for comparison with a theoretical function $\eta_t(\beta)$ of the form (4). Finally, the experimental efficiency η_t (see Table 1) was defined as $2W_{\max}/E_0$ (as earlier for a system of three coils considered separately). From Fig. 3 it follows that the experimental data on the energy conversion efficiency obtained in the range $\beta_* \approx 0.5$–2.2 for $\ln G^* \approx 3.2$–3.9 are consistent with the corresponding theoretical dependence (solid curve) of the total efficiency on β_* (for comparison, the data for a coil of the third type in Fig. 3 are increased by factor of 1.2, because for this coil, $\ln G^* > 3.2$). The fact that for a coil of the third type, the experimental value of η_t obtained for $\beta_* > 2$ is much larger than the theoretical value can be due to the effect of later change of current direction (the reason

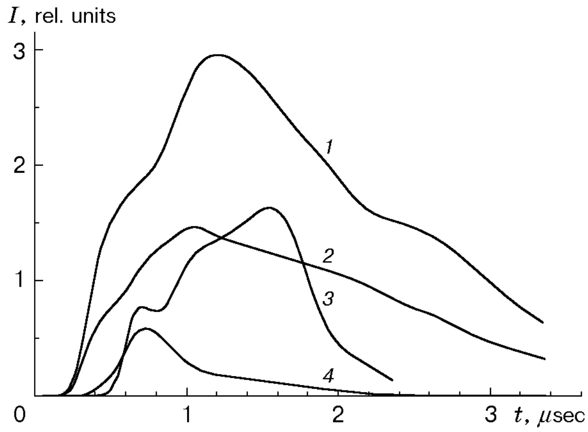

Fig. 6. Dynamics of the emission lines of helium and charge-exchange emission of the plasma: curve 1 refers to $\lambda_1 = 502$ nm (He I), curve 2 to $\lambda_2 = 389$ nm (He I), curve 3 to $\lambda_3 = 469$ nm (He II), and curve 4 to $\lambda_4 = 580$ nm (C^{+4}).

for the occurrence of this effect is not clear yet), which was observed only for this coil in the mode considered (for E_0 of about 1 J and $B_0 = 500$–620 Gs). For a reverse current of about $0.3J_{\max}$ (at the time $t \approx 1.5$ μsec), this effect was also recorded by magnetic probes located near the coil in such a manner that only the coil current field could be measured.

The efficiency can reach a maximum value of $\eta_{t,\max} \approx 32\%$ in a hypothetical system of three coils of optimum radius $[R_t \approx (1.1\text{–}1.2)R_b]$ and very large thickness ($r_t \approx 0.15R_t$). In this case, the total value of the logarithmic factor in the expression for inductance [14] is $\ln G + 0.33 \approx 2.2$. These values correspond to the geometry of a real facility for irradiating a ICF target. It should be noted that by employing additional methods to use plasma energy more completely (placing additional coils along the field and using the e.m.f. generated at the final stage of the cycle during collapse of the cavity), it is possible to increase the theoretical efficiency to 40–45%. Within the framework of an ideal plasma model, this value is nearly limiting because, e.g., in a solid angle enclosing the main system of coils, almost half the plasma (and energy E_0) expands in directions nearly transverse to the field. In this case, a particular fraction of energy should remain in the plasma, at least, to maintain the balance between plasma pressure and field pressure [5] when the plasma boundary is stopped by the magnetic field at distance R_c.

In practice, the remaining energy of plasma motion largely consists of the energy of flutes which drift almost freely across the field (not less than 10% of E_0) [11], the energy of accelerated plasma flows along the fields (not less than 20% of E_0) [11, 13], and, finally, the thermal energy E_t of the plasma [13] in its Joule heating due to field penetration into the skin layer of finite width a for an anomalously large field-diffusion coefficient [7]. Such "rethermalization" of the plasma can result in an increase in the electron temperature T_e to values comparable to their initial temperature [7, 11, 13, 21]. Previous indirect estimation using magnetic measurement data from the "Cavity" experiment [8] gave the value of $E_t/E_0 \sim a/R_b \approx 0.2$. In the present work, the quantity T_e, which strongly affects the efficiency, was determined from the emission lines of He I by a direct spectroscopic method [20]. The influence of Joule heating of the plasma on the current generated by the plasma is due to the fact that the formation of a real skin layer of width a leads to an apparent decrease of the flux $\Delta\Phi$ excluded by the plasma and, in addition, cannot occur without simultaneous plasma heating. Taking this effect into account in calculations of the current from formula (3), one finds that the real value of $\Delta\Phi$ (proportional to $J_{\max}$) is smaller than the ideal value $\Delta\Phi = \Phi_0 X^3$ by a factor of about $1 + 1.5(a/R_c)$. Therefore, even a rather narrow measured skin layer (with a relative width of $a/R_c \approx 0.15$) can decrease the coil current by about 30% compared to the calculated value (3) and decrease its energy, proportional to $(\Delta\Phi)^2$, by about a factor of 1.5. This explains the significant discrepancy between the experimental and theoretical (4) values of the efficiency for $\beta_* \approx 1$ (see Fig. 3).

To estimate the electron heating in the skin layer, we recorded the emission lines of neutral helium ($\lambda_1 = 502$ nm and $\lambda_2 = 389$ nm) excited by plasma electrons and measured the emission from ionized helium at $\lambda_3 = 469$ nm, which indicates the presence of a large number of electrons with energy higher than 75 eV. Data of such measurements of emission from a 1×1 cm region located at a distance 5.5 cm from the target on the cavity boundary in the direction of location of magnetic probes (see Fig. 1) are given in the same relative units in Fig. 6. The figure also gives the dynamics of emission at 580 nm from C^{+4} ions (excited after single charge exchange with neutral hydrogen), which characterizes, according to [19], the behavior of the concentration n_i of these ions in the plasma flow decelerated by the field with about the same amount of protons moving at the leading edge of the plasma. These data show that in this region, dynamics of arrival of the plasma and field exclusion by the plasma (see Fig. 4b) correlates well with the beginning of electron heating (see Fig. 6, curves 1–3). The degree of heating was determined from both the relative intensity of emission at λ_1 and λ_2 and the absolute intensity of emission at λ_2. Both methods (taking into account the large values of $P_{\rm He}$ for trapping of the emission at λ_1 [20] and ignoring the effect of additional excitation at λ_2, which is difficult to determine for a high concentration of $n_i \sim 10^{13}$ cm^{-3}), give close values of $T_e \approx 50$–70 eV in the range 0.6 μsec $< t < 3$ μsec. These values are confirmed by recording intense emission at λ_3 and are approximately equal to the initial plasma temperature T_0. Values of 50–70 eV for the temperature T_0 might be expected for a laser radiation flux level at the target of $(2–4) \cdot 10^9$ W/cm^2 [18]. A close value of T_0 can be obtained for a known initial velocity of plasma expansion using the formula $T_0 \approx E_i/5(1 + \langle z \rangle) \approx 50$ eV with an ion energy of $E_i = \langle m \rangle V_0^2/2 \approx 1$ keV and a mass of $\langle m \rangle \approx 6$ amu. It is established that in an early stage of Joule heating of electrons (at the time $t_* \approx 1$ μsec, when the current reaches a maximum), predominantly the periphery of the plasma cloud is heated. Therefore, assuming that of every 2.5 electrons (which fall on 1 ion on the average), only half acquires energy $(3/2)T_e$ up to 100 eV, the cloud energy losses in heating E_t can be estimated by $E_t/E_0 \approx 3\langle z \rangle T_e/(4E_i)$. Hence it follows that the initial losses of E_t accounts for 10–15% of the value of E_0. This energy loss, which is comparable to Joule losses of plasma in a field without a coil [7, 8] for time $t \approx t_*$ and smaller than the loss (by more than 30%) at a late stage $t \geqslant 2t_*$ [13] may be responsible for the difference (less than 10% of the energy E_0) between the measured and calculated values of the energy conversion efficiency in the optimal mode for $\beta_* \approx 1$ (see Fig. 3). Thermal energy E_t appears to constitute the major portion of the cloud energy losses due to expansion transverse to the field because at this stage ($t \approx t_*$) of peak current generation in the coils, the flute instability at $\varepsilon_b \leqslant 0.5$ is still insignificant [10].

Thus, in the mode providing for maximum efficiency in a system of three coils ($R_t \approx R_b$ and $r_t \approx 0.15R_t$), at best, as much as 45% of the initial energy E_0 of the cloud could be converted to electrical energy. However, because at the time $t \approx t_*$, as much as 15% of the energy E_0 is converted to plasma heating, the real efficiency of this method of direct conversion of ICF energy could reach about 30% when using optimized loads (capacitors switched to the coil circuits at the moment of peak current) [6]. For comparison, in systems of explosive-driven MHD generators, whose operation is based on the same physical processes of field compression (by a hollow metal conductor rather than by a plasma), even for a more effective cylindrical geometry, the experimental energy conversion efficiency for the external explosion (which compresses the conductor) is only 10%.

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REFERENCES

1. L. A. Artsimovich, *Controlled Thermonuclear Reactions* [in Russian], Fizmatgiz, Moscow (1963).
2. A. F. Haught, D. H. Polk, and W. J. Fader, "Magnetic field confinement of laser irradiated solid particle plasmas," *Phys. Fluids*, **13**, 2842–2857 (1970).
3. R. Hyde, L. Wood, and J. Nuckolls, "Prospects for rocket propulsion with laser-induced fusion microexplosions," AIAA Paper No. 72-1063, New York (1972).

4. Yu. P. Zakharov, A. M. Orishich, and A. G. Ponomarenko,"KI-1 facility," in: *News of Thermonuclear Research in the USSR* [in Russian], No. 1 (1987), pp. 10–11.
5. Yu. P. Raizer, "On the retardation and energy transformations for plasma expanding in vacuum in the presence of a magnetic field," *Prikl. Mekh. Tekh. Fiz.*, No. 6, 19–28 (1963).
6. H. Shoyama, H. Nakashima, and Y. Kanda, "Plasma energy recovery from a D–3He inertial confinement fusion reactor," *J. Plasma Fusion Res.*, **69**, 1250–1259 (1993).
7. Yu. P. Zakharov, A. M. Orishich, A. G. Ponomarenko, and V. G. Posukh, "Effectiveness of slowing of expanding clouds of diamagnetic plasma by magnetic field (experimental)," *Fiz. Plazmy*, **12**, No. 10, 1170–1176 (1986).
8. Yu. P. Zakharov, A. V. Melekhov, S. A. Nikitin, et al., "Diamagnetizm of exploding plasma and study of its energy changes on magnetic disturbances in vacuum," in: *Proc. of the Int. Conf. on Plasma Physics* (Nagoya, September 9–13, 1996), Vol. 2, Jpn. Soc. Plasma Sci. and Nucl. Fusion Res., Nagoya (1996), pp. 1670–1673.
9. Yu. P. Zakharov, A. V. Melekhov, A. M. Orishich, et al., "Diamagnetic cavity of plasma clouds expanding in magnetized media," *J. Plasma Fusion Res.* (Series), **2**, 398–401 (1999).
10. Yu. P. Zakharov, A. G. Ponomarenko, H. Nakashima, et al., "Direct energy conversion of inertial confinement fusion and experiments with laser-produced plasma in magnetic fields," in: *Proc. of the 9th Int. Conf. on Emerging Nuclear Energy Systems* (Herzlia, June 28–July 2, 1998), Vol. 1, Dan Knassim Ltd., Ramat-Gan (1998), pp. 384–391.
11. Yu. P. Zakharov, A. G. Ponomarenko, A. V. Melekhov, et al., "Plasma confinement and direct energy conversion of ICF-microexplosion in open magnetic system," *Trans. Fusion Technol.*, **35**, 283–287 (1999).
12. Yu. P. Zakharov, V. M. Antonov, A. V. Melekhov, et al., "Laser-produced plasma simulation of the direct conversion of ICF-energy in magnetic field," in: *Proc. of the 1st Int. Conf. on Inertial Fusion Sci. and Application* (Bordeaux, Sept. 12–17, 1999), Elsevier, Paris (2000), pp. 827–830.
13. S. Sudo, K. N. Sato, and T. Sekiguchi, "Re-thermalization and flow of laser-produced plasmas in a uniform magnetic field," *J. Phys. D*, **11**, 389–407 (1978).
14. P. L. Kalantarov and L. A. Tseitlin, *Calculation of Inductances* [in Russian], Énergoatomizdat, Leningrad (1986).
15. M. L. Levin, "Solution of one problem of quasistationary electrodynamics by the image method," *Zh. Tekh. Fiz.*, **34**, No. 3, 395–398 (1964).
16. V. N. Belozerov, "Confinement of a superconducting sphere by a system of circular currents," *Zh. Tekh. Fiz.*, **36**, No. 5, 852–859 (1966).
17. V. I. Yakovlev, "Inductive interaction of an expanding plasma cord with an external circuit," *Prikl. Mekh. Tekh. Fiz.*, No. 2, 31–38 (1963).
18. Yu. P. Zakharov, A. M. Orishich, and A. G. Ponomarenko, *Laser-Produced Plasma and Laboratory Simulation of Nonstationary Space Processes* [in Russian], Inst. of Theor. and Appl. Mech., Sib. Div., Russian Acad. of Sci., Novosibirsk (1988).
19. I. F. Shaikhislamov, V. M. Antonov, Yu. P. Zakharov, et al., "Application of a charge-exchange process to optical diagnostics of the interaction of a laser-degenerated plasma with a dipole magnetic field," *Prikl. Mekh. Tekh Fiz.*, **36**, No. 4, 8–15 (1995).
20. N. Brenning, "Electron temperature determination in low-density plasmas from the He I 3889 Å and 5016 Å line intensities," *J. Phys. D*, **13**, 1459–1475 (1980).
21. Yu. P. Zakharov, A. Kasperczuk, P. Kasperczuk, et al., "Interaction of laser-produced plasma streams with a strong transverse magnetic field," in: *Proc. of the 24th Int. Conf. on Phenomena in Ionized Gases* (Warsaw, July 11–16, 1999), Vol. 2, Space Res. Centre, Warsaw (1999), pp. 87–88.