Journal of Applied Mechanics and Technical Physics, Vol. 50, No. 3, pp. 380–388, 2009

OPTIMIZATION OF A RIBBON DIODE WITH MAGNETIC INSULATION FOR INCREASING THE CURRENT DENSITY IN A HIGH-CURRENT RELATIVISTIC ELECTRON BEAM

V. T. Astrelin, A. V. Arzhannikov, A. V. Burdakov,
S. L. Sinitskii, and V. D. Stepanov

UDC 53.072; 537.533

The geometry of the ribbon diode of the U-2 accelerator is optimized to increase both the current density and the total current of the relativistic electron beam for its subsequent injection into the plasma of a multimirror GOL-3 *trap. Beam simulation in the diode was performed using the* POISSON-2 *applied software modified on the basis of the results obtained using the theory of a planar diode in an inclined magnetic field. As a result of the optimization, the diode geometry and the magnetic field configuration were found that should provide a factor of* 1.5–2 *increase in the current density in experiments with a small angular divergence of electron velocities.*

Key words: *numerical simulation, electron-optical system, high-beam current, diode optimization, beam luminosity.*

Introduction. Studies of dense plasma heating by a high-current relativistic electron beam [2] and plasma confinement in a multimirror magnetic trap have been performed on the GOL-3 facility of the Institute of Nuclear Physics of the Siberian Division of the Russian Academy of Sciences [1]. During injection of a beam with a current density $j \approx 1.5$ kA/cm^2 into a plasma of density $n_p \approx 10^{21}$ m^{-3}, the plasma electron temperature in the experiments reached values $T_e \approx 2$–3 keV and the ion temperature values $T_i \approx 1$–2 keV. The plasma energy lifetime in the trap was 0.5–1.0 msec. The obtained plasma parameters are among the best results achieved for the class of open traps and are even comparable to the parameters of medium size tokamaks. This implies that the multimirror confinement of a plasma heated by an electron beam is a promising concept for use in thermonuclear reactors.

To further increase the plasma parameters, it is necessary to improve the beam characteristics, namely, to increase its density with retention of a small angular divergence of electron velocities and to increase the beam pulse duration. For this purpose, the diode geometry and magnetic field configuration were optimized by numerical calculations using the POISSON-2 applied software package [3]. To calculate the beam characteristics with the required accuracy, we modified the algorithms of the package taking into account the results of a previous theoretical analysis of the operation of a planar diode in an inclined magnetic field [4, 5].

1. Parameters of GOL-3 Experiments. The layout of the GOL-3 facility and the magnetic field distribution on the trap axes are shown in Figs. 1 and 2. The magnetic system of the facility consists of $N = 55$ magnetic mirrors (the length of each mirror $l = 22$ cm, mirror ratio $B_{\max}/B_{\min} = 4.8$ T/3.2 T) connected in series between the strong end magnetic mirrors with a field $B_{\text{entr}} \approx 6$ T at the beam entrance point and $B_{\text{exit}} \approx 9$ T at the exit point. A deuterium plasma of density $n_p \approx 10^{20}$–10^{22} m^{-3} is produced in a cylindrical conducting chamber located in the solenoid of the GOL-3 facility.

Institute of Nuclear Physics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Novosibirsk State University, Novosibirsk 630090; V.T.Astrelin@inp.nsk.su. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 50, No. 3, pp. 25–35, May–June, 2009. Original article submitted January 22, 2008; revision submitted April 3, 2008.

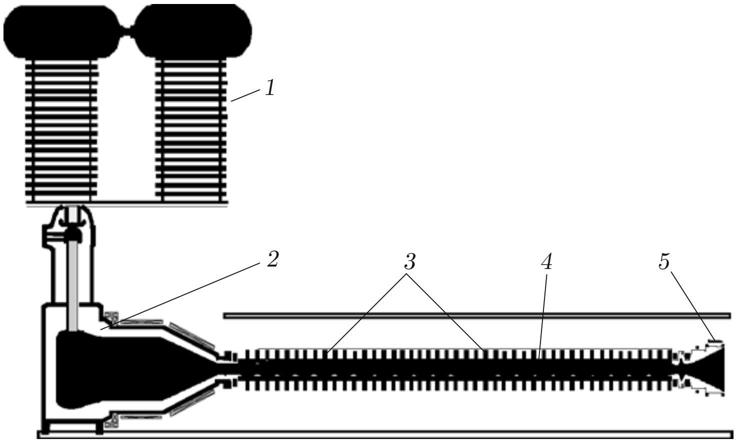

Fig. 1. Layout of the GOL-3 facility: 1) U-2 electron beam generator; 2) ribbon diode; 3) solenoid; 4) plasma; 5) exit unit.

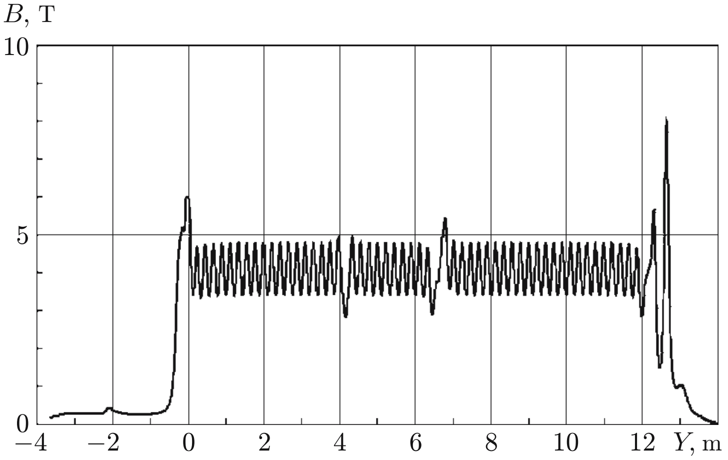

Fig. 2. Magnetic field distribution on the axis of the magnetic trap.

The vacuum diode of the U-2 accelerator contains a ribbon cathode of cross section 5 × 75 cm made of Carbotextim (graphite fiber material), a foilless slotted anode, and a slotted transport channel of planar geometry. High current density is produced by generating an electron beam in the diode under moderate magnetic field conditions with the electron cyclotron radius comparable to the gap between the anode and cathode calculated from the total energy. The diode magnetic field increases smoothly from $B_{\text{cat}} = 0.14$–0.17 T at the cathode to $B_{\text{ch}} = 0.28$ T in the transport channel. After the passage through the transport channel 1 m long, the beam enters the transformer, in which, under the influence of the quadrupole magnetic field component, its cross section smoothly (on a length of 1.5 m) takes a square shape. During the further compression of the beam by the leading magnetic field, its cross section near the input mirror of the solenoid decreases by a factor of approximately 20. In the same region, there is a pulsed valve for producing a krypton gas cloud of density about 10^{22} m^{-3}, which provides neutralization over the space charge and transportation of the high current density beam. After passage through the compression region, the beam is injected into a plasma column of the total length 12 m, in which it performs intense generation of plasma waves. At the exit from the plasma, the section of the beam moving in the decreasing magnetic field increases smoothly. At a distance of 1 m behind the output mirror, the beam is incident onto the collector located in a magnetic field of $B \approx 0.3$ T.

The maximum parameters of the beam obtained earlier in test experiments (electron energy $eU_b \approx 1$ MeV, total current $I_b \approx 50$ kA, beam duration $\tau_b \approx 8$ μsec) were slightly reduced to ensure constant beam parameters in series of experiments on plasma heating. Therefore, the experiments considered here were performed for electron energy $eU_b \approx 0.8$ MeV, beam current $I_b \approx 20$ kA, and beam energy content $W_b \leqslant 120$ kJ. The average pitch angles of electron velocities measured in [2] and extrapolated to a field $B_{\text{entr}} \approx 6$ T and their values obtained by numerical simulation did not exceed 0.3 rad. As regards the electron beam current density, due to the electron magnetization, it was proportional to the local magnetic field in the trap and varied in the range 1.0–1.5 kA/cm^2.

As noted above, the basic mechanism of electron beam energy transfer to the plasma electrons is the generation of intense plasma waves by the beam. For high generation efficiency, it is necessary to provide high electron density in the phase volume. For the beams, the density is characterized by the luminosity proportional to the ratio of the beam current density to the average square of the angular divergence of electron velocities. Indeed, the increment of the beam-plasma instability is given by the expression

$$\Gamma \approx \frac{\omega_p}{\langle \theta^2 \rangle} \frac{n_b}{\gamma n_p},$$

where γ is the relativistic factor, $\langle \theta^2 \rangle$ is the mean-square divergence of the pitch angles of electron velocities, and ω_p is the plasma frequency. Obviously, the increment is proportional to the beam luminosity. An increase in this parameter due the current density is the main objective of the optimization of the diode geometry and the magnetic field configuration performed in the present work.

2. Consequences of the Theory of a Planar Diode in a Magnetic Field. We first consider some results obtained using the theory of a planar diode in an inclined magnetic field and implemented in the POISSON-2 software. As is known, analytical theory considering electron beam generation in diodes of various configurations provides exact solutions of problems in which the electrode geometry is described by simple expressions in any orthogonal curvilinear coordinate system (for example, planar, cylindrical or spherical geometries). Only in these cases, as a rule, using the nonrelativistic approximation ignoring the self-magnetic field of the beam, is it possible to calculate the beam characteristics in implicit form.

Real diodes forming high-current relativistic beams use electrodes of complex geometrical shapes. Most problems of calculation of such diodes are only solved using numerical methods. Furthermore, in the practically important case of beam current limitation in the diode by the space charge in the presence of a magnetic field inclined to the cathode, most simulation codes do not provide the required accuracy of the calculation of electron beam parameters due to imperfections of the methods used to solve the equation for electron trajectories in the initial stage of motion. The cause of this is the occurrence of a singularity of the space charge density function near the cathode surface due to the infinite emission capability of the cathode. A possible method for correctly taking into account this singularity is the use of an analytical solution of the equations of electron motion in the initial part of the trajectory (in a thin start layer) in the approximation of planar diode geometry. Next, the coordinates and velocities of the particles obtained from this solution on the layer surface are used as the starting (initial) conditions to calculate the remaining part of the trajectory by numerical solution of the equations of motion.

Usually, the cathode current density j_0 and the initial electron velocity V are calculated using the approximate model of a planar layer in the absence of a magnetic field. It is obvious that, in calculations using this model, the thickness of the starting layer d in a real diode should be small compared not only to the surface curvature radius but also to the distance from the cathode surface ζ_0 on which the forces exerted on the electron by the electric E and magnetic B fields become close in value ($eE \approx eVB/c$) and electron magnetization occurs [4, 5]:

$$\zeta_0 = j_0/(\varepsilon_0 B \omega_B^2)$$

or (in the CGS system)

$$\zeta_0 = 4\pi c j_0/(B \omega_B^2).$$

Here $\omega_B = eB/m$ is the electron cyclotron frequency and ε_0 is the complex dielectric constant of vacuum. For the diode of the U-2 accelerator ($j_0 \approx 20$–30 A/cm^2, $B \approx 0.15$ T), the distance $\zeta_0 \approx (2$–$3) \cdot 10^{-2}$ cm, which differs significantly in scale from the characteristic dimensions of the diode units of about 10 cm. The situation with the scale difference is complicated by the fact that, for diodes with a strong magnetic field, the use of this model requires a small grid step near the cathode ($d \ll \zeta_0$) to satisfy the condition $h \ll d$. Therefore, the solution of the problem using the model of a starting layer without a magnetic field can require considerable computing resources (operative, disk storage and computing time) to calculate the angular characteristics of the electrons beam with the required accuracy. To overcome these difficulties, special algorithms have been developed (see, for example, [6, 7]) in which analytical expansions take into account factors such as the external magnetic field, surface curvature, and

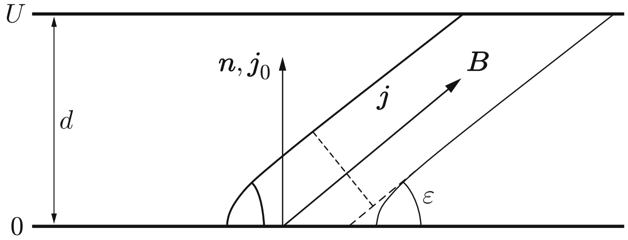

Fig. 3. Diagram of a planar diode in an inclined magnetic field.

emission nonuniformity on the cathode surface. As a rule, these algorithms are designed for particular classes of problems and are not universal.

To achieve sufficient accuracy to solve the problem in question and, at the same time, to preserve the universality of the numerical algorithms, we propose in the present paper to take into account the magnetic field in the starting layer by employing the exact solution obtained using the previously developed theory of a planar diode [4, 5] in a magnetic field inclined to the cathode (Fig. 3). Obviously, this will allow a significant extension of the range of magnetic field values during simulation of high-current diodes. The consequences of the theory which are of the greatest importance for computing applications are considered below [4, 5].

Let us consider a diode placed in a magnetic field $\boldsymbol{B} = \boldsymbol{h}B$ directed at an angle $\varepsilon = \arcsin(\boldsymbol{nh})$ to the emitter surface with normal $\boldsymbol{n}$ in which the emission current is limited by space charge. In immediate proximity to the emitter, where the planar geometry approximation is applicable, the theory predicts the law of motion of nonrelativistic particles, which can be written in dimensionless vector form

$$(\boldsymbol{r} - \boldsymbol{r}_0)/\zeta_0 = \boldsymbol{n}(\tau - \sin\tau) + \boldsymbol{h}(\boldsymbol{n}\cdot\boldsymbol{h})(\tau^3/6 - \tau + \sin\tau) - [\boldsymbol{h}\times\boldsymbol{n}](\tau^2/2 - 1 + \cos\tau) \tag{1}$$

($\tau = t\omega_B = teB/m$ is dimensionless time and $\boldsymbol{r}_0$ is the vector of the initial particle coordinates on the emitter surface). The current density component j_0 normal to the surface can be found from the system of equations

$$\begin{gathered} d = (\boldsymbol{r}(\tau^*, j_0) - \boldsymbol{r}_0, \boldsymbol{n}), \\ U = \varphi(\tau^*, j_0) = \varphi_0[\cos^2\varepsilon((\tau^*)^2/2 - \tau^*\sin\tau^* + 1 - \cos\tau^*) + ((\tau^*)^4/8)\sin^2\varepsilon], \end{gathered} \tag{2}$$

which can be solved numerically for the variables τ^* and j_0. In (2), φ_0 is the characteristic potential at distance ζ_0 from the cathode:

$$\varphi_0 = j_0^2/(\varepsilon_0^2\omega_B^3 B)$$

or (in the CGS system)

$$\varphi_0 = (c/(\omega_B B))(4\pi j_0/\omega_B)^2,$$

τ^* is the time of particle motion from the point $\boldsymbol{r}_0$ on the emitter with zero potential to the plane with potential U at distance d (on the normal line) from the emitter.

Determining the quantities j_0 and τ^* from (2) and substituting them into the law of motion (1), we obtain the particle coordinate $\boldsymbol{r}$ and velocity, which are then used as the initial data to calculate the further particle motion on the trajectory. This method allows one to find the starting parameters of trajectories in arbitrary magnetic fields without considerable limitations on the starting layer thickness. Under the conditions considered, this method significantly increases the accuracy of numerical calculations of trajectory parameters, in particular, the pitch angles characterizing the angular divergence of beams.

The pitch angle of a particle that passed through a planar diode is determined from the formula [4]

$$\sin\theta = j_0\cos\varepsilon/(\varepsilon_0 c(\gamma^2 - 1)^{1/2}\omega_B B)$$

or (in the CGS system)

$$\sin\theta = 4\pi j_0\cos\varepsilon/((\gamma^2 - 1)^{1/2}\omega_B B). \tag{3}$$

From this, it is possible to obtain a lower-bound estimate for the pitch angles of the beam electrons that reached the anode (which has a potential of 800 kV) in the U-2 accelerator diode at a current density $j_0 \approx 20$–30 A/cm^2 in a magnetic field $B = 0.15$ T:

$$\theta > \theta_{\min} \approx 10^{-2} \text{ rad}.$$

Here it is assumed that the only factor responsible for the occurrence of pitch angles is the noncollinearity of the electric and magnetic fields at the cathode.

In the simulation, the angles for any point of the trajectory can be determined from the difference of the total particle velocity $\boldsymbol{V}$ and its drift velocity:

$$\tan\theta = [(\boldsymbol{V} - [\boldsymbol{E} \times \boldsymbol{B}]/B^2) \times \boldsymbol{B}]/(\boldsymbol{V} \cdot \boldsymbol{B}).$$

Theory [4, 5] for $\tau^* \gg \cot\varepsilon$ and $d \gg \zeta_0$ provides two estimates. First, Eq. (2) leads to the expression for j_0

$$j_0 \approx j_{\text{CL}} \sin\varepsilon, \tag{4}$$

where the quantity j_{CL} is equal to the current density of a planar diode with a magnetic field normal to the emitter and is described by the Child–Langmuir law. Second, from (3) and (4) it follows that

$$\sin\theta \sim j_{\text{CL}} \sin 2\varepsilon.$$

This implies that the electron pitch angles in the diode with the external magnetic field are small not only in the region $\boldsymbol{n} \parallel \boldsymbol{h}$, in which this is natural since the magnetic field is parallel to the electric field ($\varepsilon = 90°$) in this region, but also in the region $\boldsymbol{n} \perp \boldsymbol{h}$, in which the magnetic field is almost parallel to the cathode surface ($\varepsilon \approx 0°$). From formula (4), it follows that, if $\boldsymbol{n} \perp \boldsymbol{h}$, the pitch angles decrease due to a decrease in the current density component normal to the cathode surface (see also [5]). In addition, from the geometry of the electron beam at the exit from this diode (see Fig. 3), it follows that the current density along the magnetic field direction is equal to $j \approx j_0/\sin\varepsilon \approx j_{\text{CL}}$, i.e., it coincides with the value of j_{CL} and does not depend on the angle ε. Thus, with a change in the angle of inclination of the emitting surface to the magnetic field direction, the current density along the field remains almost unchanged, and the angular divergence of the electrons decreases to zero for $\varepsilon \approx 0°$ and $\varepsilon \approx 90°$.

During beam transportation in the leading magnetic field and the subsequent magnetic compression of the beam, the adiabatic invariant of the electrons and the magnetic flux in each current tube are conserved. The following relations hold:

$$\frac{j}{j_0} = \frac{B}{B_0}, \qquad \frac{\theta}{\theta_0} \approx \sqrt{\frac{B}{B_0}}, \qquad 2\pi\Phi = \frac{j_0}{\theta_0^2} \approx \frac{j}{\theta^2} \approx \text{const}. \tag{5}$$

Here the quantities denoted by the subscript 0 are the quantities in the diode, and those without the subscript are the quantities in the transport channel and the input mirror of the trap; Φ is the beam luminosity. Expressions (4) and (5) were used to determine diode optimization methods.

3. POISSON-2 Software Package for Numerical Simulation of Diodes. The POISSON-2 package is designed to solve two-dimensional stationary problems of the formation and transportation charged-particle beams in external and intrinsic electric and magnetic fields in vacuum and gas-filled systems [3]. This package uses the method of integral equations with the potential at a point calculated through the surface and space charge densities with surface boundary conditions describing dielectrics and symmetry and periodicity conditions for the planar and axisymmetric cases.

The magnetic field in the system is calculated as the sum of the external field and the fields produced by the beam current. The fluxes of charged particles from the cathode are simulated by current tubes with a central trajectory. The shape of the trajectories in the electromagnetic field is determined by solving the relativistic equations of motion. The space charge density inside the current tubes is calculated from the continuity equation. A self-consistent (by the space charge and magnetic field of the beam) solution is found by an iterative method.

The POISSON-2 package includes algorithms for specifying the initial velocities and coordinates of current tubes and the emission current density, which are found from Eqs. (1) and (2). In addition, a correction is made of the local current density j_0 [8], which provides more exact satisfaction of the condition $E_0 = 0$ imposed on the electric field on the emitter in the case of nonuniform emission from surfaces of arbitrary shape for emission limited by space charge. This correction is performed by the formula $\Delta j_0 = \pm j_0 (Ed/U)^2$, where E is the field at a certain point on the emitter surface under conditions of incomplete self-matching of the emission current and U is the potential at a small distance d from this point on the normal.

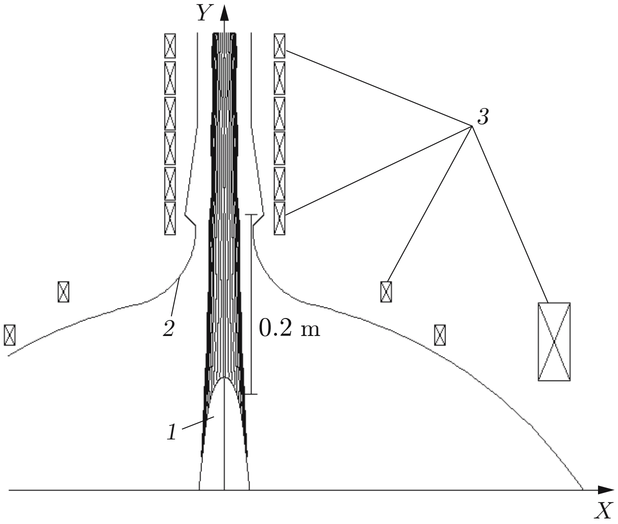

Fig. 4. Beam trajectories in the diode of the U-2 accelerator: 1) cathode with a potential of −800 kV; 2) anode; 3) magnetic field coils.

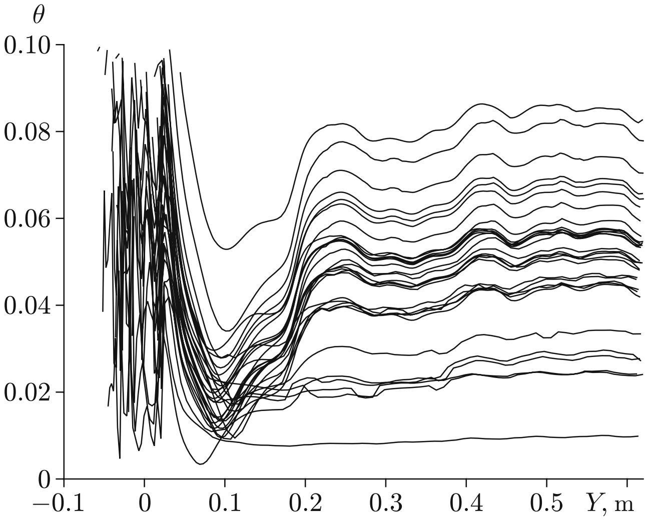

Fig. 5. Pitch-angle distribution in the diode of the U-2 accelerator (cathode coordinate $Y = 0.02$ m).

The code algorithms were tested by comparing the simulation results for a planar diode with an inclined magnetic field and theoretical values obtained by formulas of [4, 5] for this diode; the thickness of the layer on whose surface the initial data for the trajectories were calculated was 0.1 of the size of the diode gap. The calculations showed that the pitch angles calculated by simulation in the test problem differed from the theoretical values by not more than 5%.

4. Analysis of the Geometry of the U-2 Ribbon Diode. The beam characteristics of the foilless diode of the U-2 accelerator were determined by numerical simulation. The diode geometry and calculated trajectories are shown in Fig. 4.

An analysis of the pitch-angle distribution over the entire beam path made it possible to determine the regions of the cathode in which these angles are maximal even at the stage of emission and the regions of the system in which they vary with the acceleration and transportation of the electrons (Fig. 5). The pitch angles are maximal in the peripheral regions of the cathode, in which the emission current density is not low and the magnetic field is directed at a small angle to the cathode [see (3)]. In the acceleration region ($Y < 0.1$ m) along the length of

TABLE 1

Beam Parameters in Various Regions of the Facility

Diode	Cathode			Transport channel			Input magnetic mirror			
	$\bar{j}_{\text{cat}}$, A/cm^2	J_{cat}, A/cm	$j_{\max}$, A/cm^2	$\bar{j}_{\text{ch}}$, A/cm^2	$\theta_{\text{ch}}^{\max}$, rad	$\bar{\theta}_{\text{ch}}$, rad	$\bar{j}_{\text{in}}$, kA/cm^2	$\theta_{\text{in}}^{\max}$, rad	$\bar{\theta}_{\text{in}}$, rad	I_b, kA
U-2	25	170	50	70	0.08 (0.05)	0.03	1.4	0.37 (0.23)	**0.15**	**13**
Optimized diode	40	280	60	100–110	0.09 (0.06)	0.033	2.2	0.46 (0.28)	**0.16**	**21**

Note. The maximum angles for most of the beam with a current equal to $0.9I_b$ are given in parentheses.

the system, the angles first decrease and then increase at the entrance to the anode slit ($Y \approx 0.15$ m) and on the coordinate $Y \approx 0.2$ m corresponding to the local shape change of the anode slit at the site of its junction to the transportation channel.

In the stationary case, the main factor responsible for an increase in the pitch angles is the nonconservation of the adiabatic invariant $p_\perp^2/B$ at the sites of the trajectory at which the curvature radii of the lines of force of the electric field or magnetic field ($\tilde{R}$) decrease to values comparable in the total energy ρ_e to the electron cyclotron radius. In the diode considered, this occurs at the entry of the electrons into the anode slit and at the exit from it. In these regions, the curvature radii of the electric field lines $\tilde{R} \approx 2$–3 cm are close to the electron cyclotron radius $\rho_e \approx 1.4$–1.8 cm.

Table 1 gives calculated beam characteristics at the cathode (for magnetic flux density $B_{\text{cat}} \approx 0.14$–0.17 T), in the transportation channel ($B_{\text{ch}} \approx 0.28$ T; $Y \approx 0.5$ m), and in the input mirror of the trap ($B_{\text{entr}} \approx 6$ T) of the U-2 accelerator diode. Here $\bar{j}_{\text{cat}}$ is the emission current density averaged over the cathode surface, J_{cat} is the current density (per unit length of the cathode), $j_{\max}$ is the maximum current density on the cathode axis, $\bar{j}_{\text{ch}}$ is the average current density in the channel, $\theta_{\text{ch}}^{\max}$ are the maximum pitch angles in the channel, $\bar{\theta}_{\text{ch}} = \sum \theta_i I_i \Big/ \sum I_i$ is the pitch angle in the channel averaged over the trajectories, $\bar{j}_{\text{in}} = \bar{j}_{\text{ch}}(B_{\text{entr}}/B_{\text{ch}})$ is the average current density in the input mirror of the trap, $\theta_{\text{in}}^{\max} = \theta_{\text{ch}}^{\max}\sqrt{B_{\text{entr}}/B_{\text{ch}}}$ are the maximum pitch angles in the mirror, $\bar{\theta}_{\text{in}} = \bar{\theta}_{\text{ch}}\sqrt{B_{\text{entr}}/B_{\text{ch}}}$ is the average pitch angle in the mirror, and I_b is the total beam current.

The obtained calculated characteristics agree with experimental data (the beam current behind the voltage rise front in the diode is equal to 15–20 kA, and the angles in the trap are approximately equal to 0.2–0.3 rad).

5. Diode Optimization. Using the results obtained in Secs. 1–4, we analyze the effect of the geometrical parameters and diode field characteristics on the beam parameters for the purpose of increasing them. Since the magnetic field in the trap is specified, to increase the current density in the trap, it is necessary to reduce the diode magnetic field (the beam will then be compressed more highly) or to increase the cathode current density.

Since $\theta_0 \sim j_0 \cos\varepsilon / B_0^2$, for the case $\varepsilon = \text{const}$ we obtain

$$\Phi \sim j_0/\theta_0^2 \sim B_0^4/(j_0 \cos^2 \varepsilon).$$

Thus, as the diode magnetic field B_0 decreases, the beam luminosity Φ decreases as B_0^4, and an increase in the current densities during compression is accompanied by a considerable increase in the pitch angles. The same effect will be achieved by increasing the cathode current density j_0. This means that the problem of increasing the beam luminosity by increasing the current density, posed in Sec. 1, involves a contradiction. After a decrease in the cathode magnetic field, the increased velocity divergence in the beam can be reduced only by optimization of the diode geometry and the structures of the electric and magnetic fields aimed at improving the conservation of the adiabatic invariant of electrons.

A considerable increase in the cathode emission current density is undesirable since, under explosive emission conditions, this will lead to a reduction in the beam duration due to the short circuiting of the diode gap during expansion of the cathode explosive plasma. The effect of this factor can be reduced by providing a more uniform emission along the cathode surface. In this case, the heterogeneity the explosion emission plasma at the cathode and the change in the shape of the emitting surface in time should be minimum.

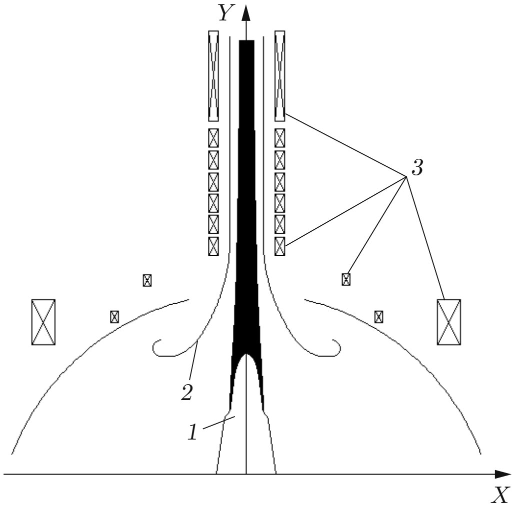

Fig. 6

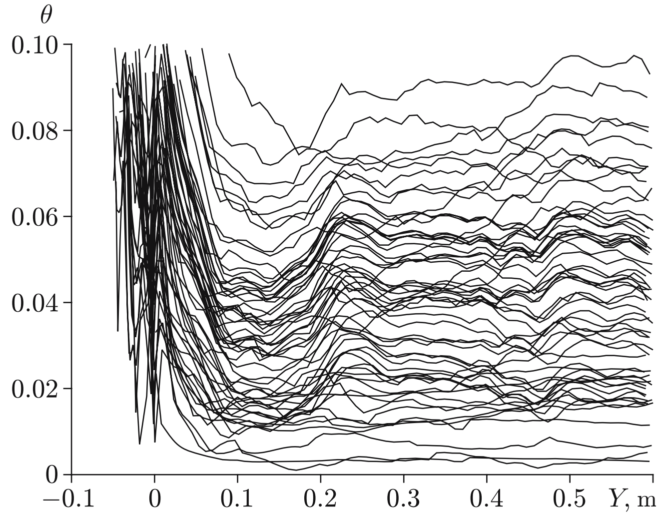

Fig. 7

Fig. 6. Beam trajectories in the optimized diode (notation the same as in Fig. 4).

Fig. 7. Pitch-angle distribution in the optimized diode (cathode coordinate $Y = 0$).

On the periphery of the cathode, the pitch angles are maximal; they can be decreased by reducing the angle of inclination of the magnetic field to the cathode surface [see formula (3)] and using Pierce type focusing electrodes, which level the emission along the surface preventing its local increase at the beam boundary.

Taking into account the possibilities and contradictions listed above, the optimization of the U-2 generator was performed without considerable changes in the parameters. The cathode was shifted from the anode by 2 cm relative to the initial position, so that at its end the magnetic field decreased from 0.17 to 0.16 T, and on the base, it decreased from 0.138 to 0.125 T. The section at the end of the cathode of the U-2 generator is an ellipse with semiaxes $a_X = 2.16$ cm and $a_Y = 8$ cm. The minor semiaxis length was increased to 2.48 cm, so that the curvature radius of the cathode on the increased from 0.58 to 0.77. This made it possible to decrease the local maximum of the current density on the axis, and then to increase the current density on the entire cathode surface.

The shape of the anode was changed the most significantly to provide a smooth increase in the electric field at the entrance to the anode slit (in the presence of the beam) according to the condition $\tilde{R} \gg \rho_e$. The curvature radius of the anode surface was increased to the maximum possible value (approximately 33 cm) at the beam entrance to the anode slit. The average distance between the anode and cathode was decreased by a factor of 1.2–1.3 to raise the average emission current density. Transportation channel wall roughness was eliminated at the site of junction of the graphite anode electrode and the steel walls of the channel. In addition, the coordinates of the current carrying bus bars forming the magnetic field were corrected, which provided a smooth rise of the field during motion from the diode gap to the transportation channel and satisfaction of the condition $\tilde{R} \gg \rho_e$ for the magnetic field at this site. The geometry of the optimized diode is shown in Fig. 6, and the pitch-angle distribution in Fig. 7.

The calculated beam characteristics of the optimized diode at the cathode, in the transport channel, and at the entrance to the GOL-3 are given in Table 1. A comparison of the beam characteristics for both diodes shows that the optimization resulted in a factor of 1.6 increase in the beam current density at the input mirror of the GOL-3 ($B = 6$ T) (to 2.2 kA/cm^2) with the nearly unchanged angular divergence of the electrons equal to 0.15–0.16 rad.

Conclusions. A model was proposed to calculate the cathode emission current parameters in simulations of the formation of high-current beams with the current limited by the space charge in arbitrary magnetic fields. The model is based on the use of the analytical solutions for a planar diode in a layer adjacent to the cathode with a magnetic field inclined to the cathode. The model was implemented in the algorithms of the applied POISSON-2 software package. Simulation of the high-current diode forming a relativistic ribbon electron beam was performed.

The diode was optimized to increase the beam luminosity. This provided a factor of almost two increase in the calculated beam current density in the trap with unchanged angular divergence of electron velocities. It is expected that the obtained electron beam parameters will provide more effective plasma heating in the GOL-3 multimirror trap.

This work was supported by the Russian Foundation for Basic Research (Grant No. 07-08-00682) and Innovative Education Project No. 456.

REFERENCES

1. V. S. Koidan, A. V. Arzhannikov, V. T. Astrelin, et al., "Progress in multimirror trap GOL-3," *Fusion Sci. Technol.*, **47**, No. 1, 35–38 (2005).
2. A. V. Arzhannikov, V. B. Bobylev, V. S. Nikolaev, et al., "New results of the total scale ribbon beam experiments on the U-2 device," in: *Proc. of the 10th Int. Conf. on High Power Particle Beams* (San Diego, June 20–24, 1994), Vol. 1, NTIS, Springfield (1994), pp. 136–140.
3. V. T. Astrelin and V. Ya. Ivanov, "Software package for calculating the characteristics of intense beams of relativistic charged particles," *Avtometriya*, **3**, 92–99 (1980).
4. D. D. Ryutov, "Angular characteristics of the electron beam produced in a foilless diode," Preprint No. 83-146, Inst. of Nucl. Phys., Novosibirsk (1983).
5. V. T. Astrelin, I. A. Kotel'nikov, and S. L. Sinitskii, "Negative differential resistance of an electron diode in a magnetic field," *Zh. Tekh. Fiz.*, **59**, No. 4, 46–50 (1989).
6. V. M. Sveshnikov, "Calculation of cathode area in electron-optical systems forming the intensive beams of charged particles," *J. Appl. Phys.*, No. 1, 50–54 (2004).
7. V. A. Syrovoy, "New results of geometrized theory of dense electron beams," *J. Appl. Phys.*, No. 3, 25–42 (2002).
8. V. T. Astrelin and V. Ya. Ivanov, "Iterative algorithm for determining the density of the current limited by space charge," Preprint No. 87–133, Institute of Nuclear Physics, Novosibirsk (1987).