Transmission of Dense Electron Beam through the Input Mirror of the Linear Magnetic System

V.T. Astrelin[1,2,a)], I.V. Kandaurov[1], V.V. Kurkuchekov[1,2], and Yu.A. Trunev[1]

[1] *Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia*
[2] *Novosibirsk State University, Novosibirsk, Russia*

[a)]Corresponding author: V.T.Astrelin@inp.nsk.su

Abstract. The results of experiments and numerical simulation of compression of an intense electron beam in increasing field of magnetic mirror and its transmission through a linear magnetic system are presented. This system is used as a test module for a section of the GOL-3 magnetic trap. The study was carried out for the beam with a spread in initial electron pitch angles and a non-uniform radial current distribution. An analytical estimate of the vacuum beam-current limit was obtained taking into account the initial pitch angles of electrons and the beam compression in the magnetic field. The simulation results are compared with the results of experiments; in both cases similar phenomena of beam reflection and diode breakdown are observed.

INTRODUCTION

Early experiments in the Budker Institute of Nuclear Physics SB RAS [1] were continued on the test module of the open magnetic trap GOL-3 using electron beam generation in the multi-aperture diode with plasma emitter [2, 3]. This module is intended for testing of materials under impact of powerful electron beam. The formed beam was injected into the trap along increasing magnetic field to a target. The experiments showed that the beam duration was limited due to electrical breakdown of the diode. One of the possible causes of this limitation may be the return of electrons reflected from the input magnetic mirror, and, as a result, appearance of the dense plasma on the external side of the anode, which then penetrates into the diode. To check this hypothesis, conditions of electron reflection from the magnetic mirror are described in this paper analytically and numerically. The magnetic field structure and the volume charge of the beam are taken into account, and the results are compared with the experiment.

EXPERIMENT

Layout of the test module is shown in Fig.1. The electron beam was generated by a source of diode type with cathode on the base of the plasma emitter in an almost-uniform magnetic field $B_0 \sim 10^{-2}$ T. The diode consisted of the plane cathode with 499 apertures of 3 mm in diameter, and the plane anode with oppositely placed apertures of 4.4 mm in diameter. Apertures were placed inside circles of 84 mm in diameter, while the distance of the anode plate from the cathode was 10 mm. The electron beam generated in the diode passed through the liner (diameter 90 mm, length 50 mm), through the growing magnetic field of the solenoid, and then was absorbed by the collector (Faraday cup) measuring the current I_{cF}. The emitted current of the diode, I_e, was measured in the high voltage circuit as the current to the cathode.

In the absence of the external magnetic field the diode generated currents up to 280 A at energy eU_d~ 90 keV with beam duration exceeding $\tau_b \sim 200$ μs. In this case the beam duration was limited by the power supply.

In the external magnetic field with mirror ratio $K = B_{max}/B_0 = 5 – 60$ the beam transmission through the mirror was studied for currents 30 – 100 A and energies 70 – 100 keV. At moderate parameters of the system about 10% of the

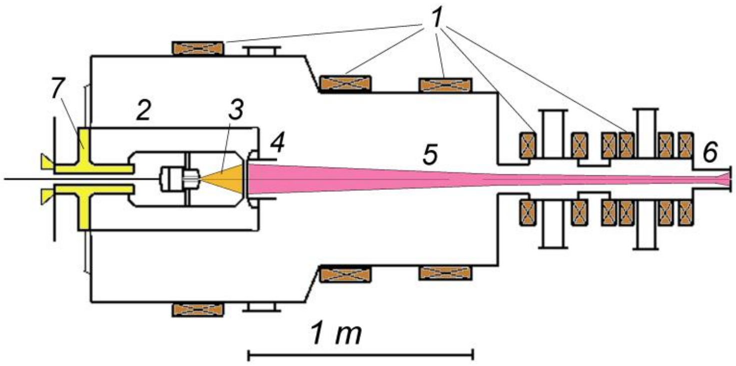

FIGURE 1. Layout of the experimental device. 1 – magnetic field coils, 2 – the beam source, 3 – plasma flow inside electron emitter, 4 – grounded liner, 5 – electron beam, 6 –collector of electrons (Faraday cup), 7 – high voltage insulator.

electrons, emitted from the cathode plasma, were lost in the diode. The rest of the beam electrons with current $I_b \sim 0.9\ I_e$ passed to the collector without reflection, so that $I_{cF} = I_b$. Here the beam duration was limited by the power supply too. The beam duration decreased with increasing of the beam current or the mirror ratio that was accompanied by the rise of the current of reflected electrons. An example of the beam transmission in the magnetic field with mirror ratio $K \approx 60$ is shown in Fig.2.

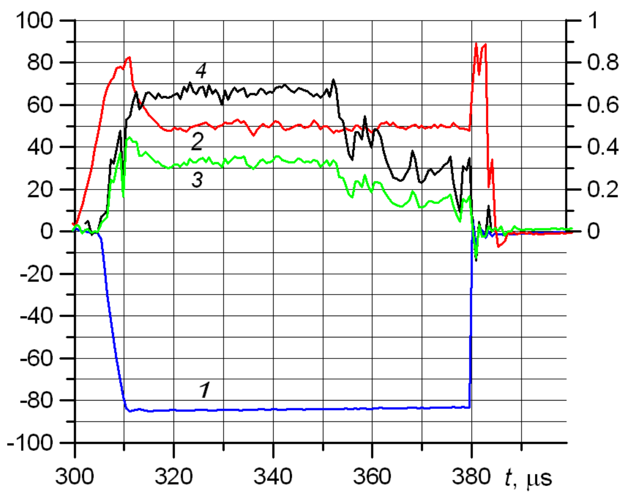

FIGURE 2. Waveforms of the beam parameters:
1 – cathode potential U_d [kV]; 2 – cathode current I_e[A]; *3* –Faraday cup current I_{cF} [A]; *4* – ratio I_{cF}/I_e (right scale)

In this example only ~ 65% of emitted electrons reached the collector in the time interval 315 – 350 μs. This means that in addition to ~ 10% of electrons that were lost in the diode, about 25% of emitted electrons were reflected by the magnetic field. About 72% of the beam electrons passed, $I_{cF}/I_b \sim (65/0.9) \approx 72\%$. As one can see in Fig.2, at the beginning of the beam pulse some stabilization process occurred in the diode for ~ 20 μs (t ~ 300 – 320 μs). After this the passing ratio of the beam I_{cF}/I_e did not change till ~350 μs. Then, in spite of the stable diode current, the collector current decreased with strong fluctuations till the breakdown at 380 μs. We suppose that this decrease corresponds to reflection of the beam electrons from the magnetic mirror. Below we present some estimates and numerical simulations for better understanding of the transmission processes.

ANALYTICAL ESTIMATES

Beam generation in the magnetic field is accompanied by appearance of the angular divergence of its electrons due to various causes: the imperfection of its optics (θ_S), the azimuthal magnetic field (θ_B) and the radial electric field of the beam (θ_E), can result in transverse velocity of electrons. For the beam with the radius R_{b0} ~ 4.2 cm, the energy eU_0 ~ 85 keV, and the current I_b ~ 50 A, in the magnetic field of 5.6 10^{-3} T near the diode, the angles may be estimated as $\theta_S \leq 0.05$ [4], $\theta_B \leq 0.04$ and $\theta_E \leq 0.15$ rad. The angular spread can limit the beam current due to the effect of reflection from the magnetic mirror and the space charge.

To estimate limitation of the beam current we used the formula from paper [5] derived for a beam with radially-uniform current density and equal initial electron velocities transverse to the magnetic field. It was taken that the electron gyroradius is much less than the diameter of the beam, the external magnetic field is uniform and is much stronger than the field of the beam. As a result, the beam-current limit was found as

$$I_{\max} = mc^3 \left(\gamma_0^{2/3} - \gamma_{0\perp}^{2/3}\right)^{3/2} / \left[e\left(1 + 2\ln\left(R_c / R_b\right)\right)\right] \quad (1)$$

where $\gamma_{0\perp} = (1 - v^2_{0\perp}/c^2)^{-1/2}$ is the relativistic factor for electrons in the initial transverse velocity $v_{0\perp}$ on the cathode, where their longitudinal velocity is zero, $\gamma_0 = \gamma_{0\perp} + eU_0/mc^2$, $U_0 > 0$ is the cathode potential, $v_{\|} = 0$, R_c is the radius of the transmission channel.

Following the method of Ref. [5], we can derive an expression similar to (1) for the case of a convergent magnetic field. Assuming conservation of the adiabatic invariant $\mu = p^2_\perp/2B$, we can replace $\gamma_{0\perp}$ by its value that takes into account the change of the magnetic field in the transmission channel, $\gamma_{0\perp} \to \gamma_{0\perp}\sqrt{1/\gamma_{0\perp}^2 + \left(B/B_0\right)\left(1 - 1/\gamma_{0\perp}^2\right)}$. The final expression for the beam-current limit is

$$I_{\max} = mc^3 \left(\gamma_0^{2/3} - \left(1 + \frac{B}{B_0}\left(\gamma_{0\perp}^2 - 1\right)\right)^{1/3}\right)^{3/2} \ / \ \left[e\left(1 + 2\ln\left(R_c / R_b\right)\right)\right]. \quad (2)$$

The initial pitch-angle of electrons at the anode, where $B \approx B_0$, is as follows:

$$\sin\theta_0 = p_{0\perp} / p = \sqrt{\left(\gamma_{0\perp}^2 - 1\right)/\left(\gamma_0^2 - 1\right)} \ . \quad (3)$$

Dependence of the current limit I_{max} versus the initial pitch angle θ_0 for three compression ratios of the guiding magnetic field, $K = B/B_0$, is shown in Fig.3 for the beam energy $eU_0 = 80$ keV. Here the geometry factor $\ln(R_c/R_b)$ ~ 1.9 corresponds to the region of the magnetic mirror. As one can see the current decreases with increasing value of the initial pitch angle. For instance, in the case $K = 100$ and $\theta \to 0.1$ the current falls to zero that corresponds to reflection of all beam electrons. Note, that in any uniform magnetic field the beam begins to be limited by the potential minimum on the axis, while in the case of substantial compression in the magnetic field – by the magnetic mirror on the periphery of the beam.

NUMERICAL SIMULATION

Numerical simulation was made using the stationary two-dimensional code POISSON-2 [6]. In the code the Poisson equation for potential was solved by numerical method for Fredholm integral equations. Trajectories of current tubes were computed by relativistic scheme with second-order accuracy.

The following model was used. Electrons were injected along the axis through the flat anode of the diode. The

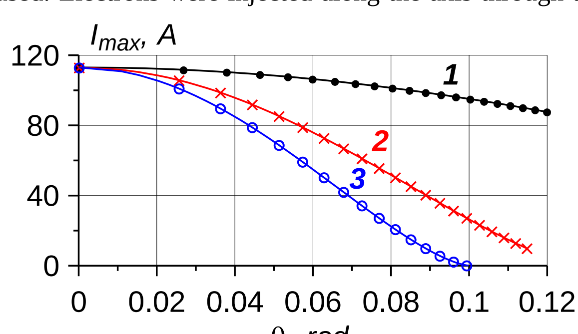

FIGURE 3. Dependence of the beam-current limit on the initial pitch angle of electrons; *1* – $K = 10$, *2* – $K = 60$, *3* – $K = 100$

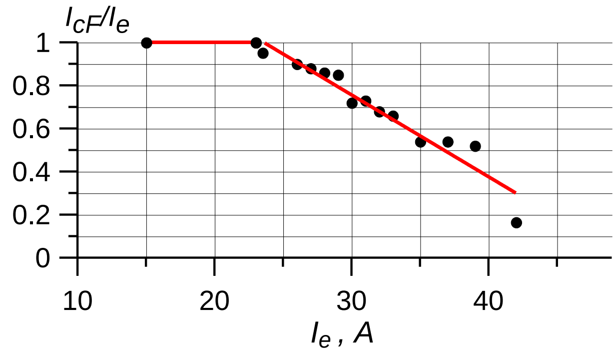

FIGURE 4. Dependence of the transmission coefficient of electron beam on the beam current

anode and walls of the transmission channel were grounded. Geometry used in the model was close to the real one (Fig. 1). An electron beam with initial energy of electrons 80 keV was emitted from the area with radius R_b = 4.2 cm at the input end of the computational domain. The radial distribution of the beam-current density was based on experimental measurements of bremsstrahlung of the beam electrons at the target [7] and was close to Gaussian,

$$j_e(r) = I_0 \exp\left(-r^2/r_b^2\right) / \left[\pi r_b^2 \left(1-\exp\left(-R_b^2/r_b^2\right)\right)\right] \text{ for } r < R_b, \qquad (4)$$

where $r_b \approx$ 21 mm is the standard width of the distribution of the beam current, $R_b \approx$ 42 mm is the beam radius; $j_e = 0$ for $r \geq R_b$.

In experiments the electron pitch angles in the transmission channel, θ_0, were measured by the new diagnostic similar to [7] as $\theta_0 \leq 0.1$ rad. In the modeling the initial angle distribution of emitted electrons was represented by five groups of trajectories with angles θ_S = 0, ±0.03, ±0.06 rad and equal current densities. The following series of model calculations was done with parameters of Fig.2 in order to determine conditions, in which the electrons of the beam are barely reflected on the way from the beam source to the Faraday cup. We simulated the beam transmission with full and separate influence of its electric and magnetic fields. The following cases were studied:

1a. Transmission of the beam in the converging magnetic field (mirror ratio $K \approx 60$) assuming that the volume charge is compensated ($\rho = 0$) and the angular spread is zero ($\theta_S = 0$), to test the influence of azimuthal magnetic field of the beam onto generation of pitch angles. The beam-current limit without reflected electrons is $I_{b,\max} \sim$ 410 A.

1b. The same as *1a* with initial angular spreads θ_S = 0, ±0.03, ±0.06 rad. The resulting current limit is $I_{b,\max} \sim$ 190 A.

These currents are much higher than the emitted current, $I_e \sim$ 50 A, and the current to the collector, $I_{cF} \sim$ 35 A (see Fig.2). This means that the beam charge affects the transmission, i.e., the charge compensation in experiment was not full and the contribution of azimuthal magnetic field in reflection of electrons was small and appeared only at high currents.

2a. Transmission of the beam with zero angular spread ($\theta_S = 0$) taking into account the volume charge and the current. The model showed $I_{max} < 41$ A for the beam transmission without reflection of electrons.

2b. The same as *2a* with angular spreads θ_S = 0, ±0.03, ±0.06 rad. Reflection of electrons began at $I_e \sim$ 25 A.

Since the last simulations (*2a*, *2b*) had shown currents that are sufficiently less than the experimentally emitted current ~ 50 A, we decided to investigate the dependence of transmission coefficient I_{cF}/I_e on the emitted current I_e. If we find the beam current for which the transmission coefficient is equal to experimental one (~72%), we may estimate the degree of charge neutralization in the experiment in Fig. 2. The result is shown in Fig. 4. As one can see, the desired current is ~ 30 A, which permits to estimate the degree of neutralization as the ratio of the 'desired current' to the measured one, i.e. 30/50 = 0.6.

As an example, graphical plot of numerical simulation for the case *2b* with emitted current 23.5 A is shown in Fig. 5. Here the trajectories reflected electrons are highlighted in black.

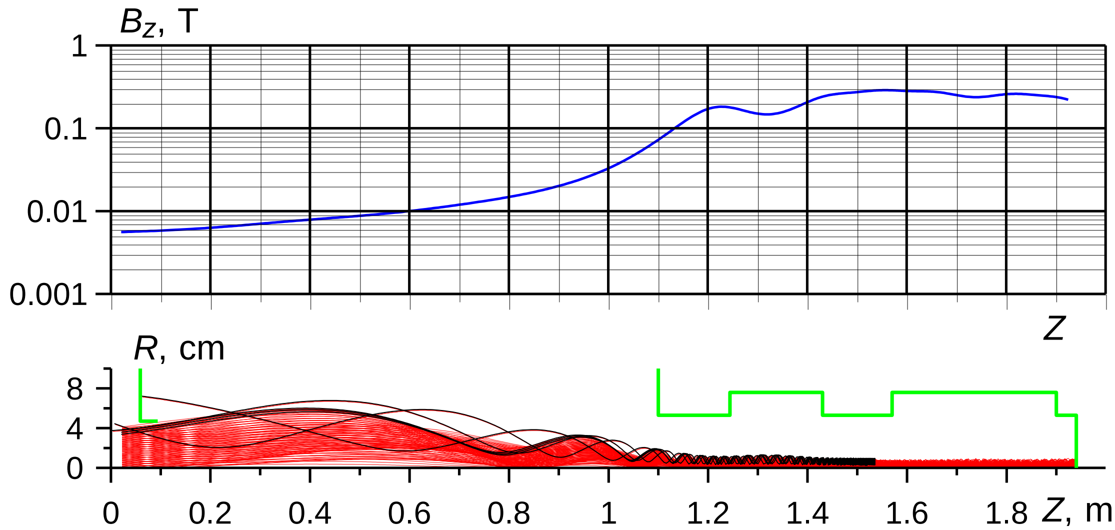

FIGURE 5. Distribution of the magnetic field and trajectories of electrons in the transmission channel.

CONCLUSIONS

Conclusions obtained from the investigation are as follows. The main factor forming the divergence is the electric field of the beam. It forms the angular divergence of electron velocities that limits the beam current by reflection of electrons in convergent magnetic field together with the beam space charge. The analytical estimates and results of numerical simulations are in satisfactory agreement between themselves and with the experiment: the limit of the beam current ~ 25 A without electron reflection is consistent with estimated (Fig. 3, curve 2) and measured angles ~ 0.1 rad.

As for the before-break-down regime (Fig. 2), direct measurement of the reflected current and its comparison with the results of the modeling (Fig. 4), permits us to find the neutralization factor for the beam charge (~ 0.6 for this regime). Moreover, the temporal dynamics of current transmission indicates plasma accumulation in the transmission channel and its influence on current transmission via current instability and further breakdown of the diode. But verification of this preliminary conclusion requires further detailed studies.

ACKNOWLEDGMENTS

The theoretical and simulation part of the work was supported by Russian Science Foundation (project N 14-50-00080), the experiments were supported by RFBR Grant N 16-08-00785-a. Authors are thankful to Dr. S. Sinitsky for useful discussions and Prof. A. Beklemishev for the help in translating text.

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