

Optimization of Magnetically Insulated Ribbon Diode for Achievement of Small Angular Spread for High-Current REB

V.T. Astrelin, A.V. Arzhannikov, V.B. Bobylev,
A.V. Burdakov, S.L. Sinitsky, and V.D. Stepanov

*Budker Institute of Nuclear Physics SB RAS, Lavrentiev av.11, Novosibirsk, 630090, Russia,
Phone: +7(383)339-49-24, Fax: +7(383)330-71-63, Astrelin@inp.nsk.su*

Abstract - An optimization of diode geometry of accelerator U-2 was done for increasing of electron beam current and density together with decreasing of its emittance. On the base of theory of planar diode with inclined magnetic field the CAD POISSON-2 was modified and used for the beam simulation in the diode. The paper contains main analytic results, and results of optimization. It was shown that the current of diode may be increased almost twice at practically the same angle spread of electrons.

1. Introduction

An investigation of plasma heating and confinement in a long open magnetic trap is carried out at the GOL-3 facility [1] in Budker Institute of Nuclear Physics. The facility consists of multimirror trap with dense deuterium plasma and generator of high-current relativistic electron beam (REB) U-2 used for plasma heating [2]. In earlier experiments with uniform (non-corrugated) magnetic field in the plasma the temperature of plasma electrons was increased to $T_e \sim 1-2$ keV due to collective processes at the beam relaxation. An ion temperature did not exceed $T_i \sim 50$ eV during and after the electron beam pulse.

A situation has changed strongly in the experiments with multimirror regime of plasma heating and confinement. The temperature of electrons remains practically the same ($T_e \sim 2-3$ keV in the case of beam with higher current density and the plasma density of $n \sim 10^{21} \text{ m}^{-3}$). As for ion energy, in these experiments it increased up to few keV just after the beam pulse and then after maxwellization the measured ion temperature reaches the level of $T_i \sim 1-2$ keV. An energy life time is also increased up to $0.5 - 1$ ms due to multimirror regime of confinement. This result is one of the best in the class of open traps and it may be compared with parameters of middle size tokamacs. It seems that multimirror confinement of beam-heated plasma may be prospective as a concept for a thermonuclear reactor.

Further increase of plasma parameters demands to improve the beam characteristics by increasing of its density, pulse duration and simultaneous decreasing of velocity angle spread of the electrons. The optimization

of the diode geometry and magnetic field configuration to achieve the required REB parameters was made by consequent numerical simulations with CAD POISSON-2 [3]. Algorithms of CAD are modified on a base of earlier theoretical analysis of planar diode operating in inclined magnetic field [4, 5] for the calculation of the beam characteristics with the best precision.

2. Parameters of the GOL-3 experiment

The scheme of the GOL-3 facility and magnetic field distribution on axis are shown in Fig. 1.

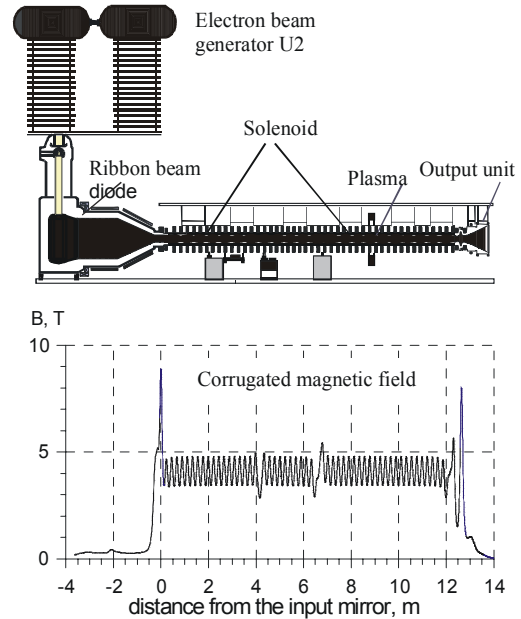


Fig. 1. GOL-3 layout

A solenoid consists of $N = 55$ magnetic cells of a length $l = 22$ cm with magnetic field on the axis $B_{max}/B_{min} = 4.8/3.2$ T placed between end mirrors of $B_{end} \sim 9$ T (now it is decreased to $B_{end} \sim 6$ T). A linear gas discharge along the metallic tube placed in the magnetic field of described configuration and filled with deuterium produces preliminary plasma with density of $n_p \sim 10^{20} - 10^{22} \text{ m}^{-3}$. The initial gas density formed with puff valves is almost constant in the interval $1 \div 11$ m and falls down in an order of magni-

tude at the end mirrors. A vacuum diode of accelerator consists of a ribbon cathode (cross section is $5 \times 75 \text{ cm}^2$) made of a fiber carbon material and a slit foilless anode. The relativistic electron beam is generated in the diode in the magnetic field $\sim 0.14 - 0.18 \text{ T}$ on the cathode, passes through a transport channel in a field gradually increasing to $B \sim 0.3 \text{ T}$. Then it is transformed to a square shape and compressed by a guiding magnetic field before injection into plasma. Then the beam passes the plasma column and dumps to a collector placed at 1 m distance behind the exit mirror. An additional puff valve for krypton is used to neutralize the beam space charge and current in the trap entrance. Peak parameters of the beam are: the electron energy $eU_b \sim 1 \text{ MeV}$, the beam current $I_b \sim 25 \text{ kA}$ and the pulse duration is $\tau_b \sim 8 \text{ } \mu\text{s}$. A total energy content of the electron beam is $W_b \sim 120 \text{ kJ}$. Pitch-angles of electron velocities in the field 6 T were measured [2] and calculated as $\leq 0.3 \text{ rad}$. So as electrons of the beam are magnetized in their motion, a density of the beam electrons is proportional to magnetic field and changes along the trap in the range $n_b \sim (2 - 3) \cdot 10^{17} \text{ m}^{-3}$.

Efficiency of plasma electron heating depends on increment of beam-plasma instability Γ

$$\Gamma \sim \frac{\omega_p}{\theta^2} \frac{n_b}{\gamma \cdot n_p} \quad (1)$$

Here γ is a relativistic factor, $\overline{\theta^2}$ is a mean square spread of beam electron pitch-angles. The instability develops if the increment exceeds a frequency of electron-ion collisions, $\Gamma > \nu_{ei}$. Evidently, the best conditions of plasma heating are expected for high-dense beams with small angle spread. In order to improve beam characteristics and such a way, to increase plasma parameters, we analyse two diode configurations by numerical methods. The first one will be an existing diode and the second is optimized. Further, we consider some consequences from theory of planar diode in inclined magnetic field and its implementation in modelling code POISSON-2.

3. Code POISSON-2 for numerical simulation of diodes

CAD POISSON-2 [3] is intended for solving 2-dimension stationary problems of forming charged particle beams in external and self-consistent electric and magnetic fields in vacuum and gas-filled systems. It uses the method of integral equations with calculation of potential φ in point \vec{r} through surface σ and space ρ density of charges

$$\varphi(\vec{r}) = \int_S \frac{\sigma \cdot d^2 \vec{R}}{|\vec{R} - \vec{r}|} + \int_V \frac{\rho \cdot d^3 \vec{R}}{|\vec{R} - \vec{r}|},$$

with rich set of boundary conditions on surfaces Γ_i , describing dielectrics, symmetries and periodicities

$$\begin{aligned} (\varphi + a\varphi_n')|_{\Gamma} &= b(\Gamma), & \varepsilon_1 \varphi_n'|_{\Gamma_1} &= \varepsilon_2 \varphi_n'|_{\Gamma_2}, \\ \varphi(x+L_x, y+L_y)|_{\Gamma_3} &= \varphi(x, y), \\ \varphi(-x, -y) &= M_x M_y \varphi(x, y), & M_x, M_y &= \pm 1. \end{aligned}$$

A magnetic field in system is calculated as a sum of external field and a constituent one produced by the current density of beam \vec{j}

$$B(\vec{r}) = \vec{B}_0(\vec{r}) + \frac{1}{c} \int_V \frac{[\vec{j} \times (\vec{R} - \vec{r})] d^3 \vec{R}}{|\vec{R} - \vec{r}|^3},$$

that corresponds to field in space with boundary condition in infinity $\vec{B} = 0$.

Flows of charged particles from the cathode are simulated by current tubes of variable width with central trajectory. A shape of trajectories in electromagnetic field is calculated using Boris scheme. A space charge density is calculated using equation of continuity $\text{div } \rho \vec{v} = 0$.

An iteration method with relaxation of space charge and magnetic field (or current of trajectories) is used to find the self-consistent solution $\rho^k = \omega_k \hat{\rho}^k + (1 - \omega_k) \rho^{k-1}$, $\vec{B}^k = \omega_k \hat{\vec{B}}^k + (1 - \omega_k) \vec{B}^{k-1}$, k is a number of iteration, ω_k is a coefficient of relaxation, $\rho^0 = 0$, $\vec{B}^0 = 0$. Here $\hat{\rho}^k, \hat{\vec{B}}^k$ are density and field evaluated from calculation of current tubes characteristics.

Calculations of current density and pitch-angle distribution are the most important for our problem. They depend strongly on precision of simulation in near cathode zone. A possibility to rise a precision had appeared after evolution of theory and its implementation to simulation code.

We consider the case of electron emission limited by space charge. In presence of magnetic field $\vec{B} = \vec{h}B$ inclined to cathode surface with normal ort \vec{n} under angle $\varepsilon = \arcsin(\vec{n}\vec{h})$, the theory [4, 5] for near cathode zone in approximation of plane geometry predicts shape of trajectory as

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

where $\zeta_0 = 4\pi j_0 / B\omega_B^2$ is a distance at which the electrons become magnetized, $\tau = t\omega_B = teB/mc$ is a dimensionless time. The normal to surface component j_0 of current density may be found from the conditions

$$d = (\vec{r}(\tau_*, j_0) - \vec{r}_0) \cdot \vec{n},$$

$$U = \varphi(\tau_*, j_0) = (4\pi j_0 / \omega_B)^2 (c / \omega_B B) \cdot [\cos^2 \varepsilon (\tau_*^2 / 2 - \tau_* \sin \tau_* + 1 - \cos \tau_*) + \sin^2 \varepsilon \cdot \tau_*^4 / 8]$$

Here τ_* is a flight time of electron till point \vec{r} , removed normally at a distance d from the cathode, U is its potential.

As for curvilinear cathode these results may be approximately valid near the cathode, the value j_0 is corrected to fulfill the condition $E = 0$ on the cathode surface [6]. As for pitch-angles, an accuracy of their calculation raises essentially if to use written above results of theory [5]. Angles are calculated from the electron velocities excluding ExB drift as

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

The theory [4,5] derives some useful relations for planar diode with inclined magnetic field at the conservation of adiabatic invariant:

$$\sin \theta = 4\pi \cos \varepsilon \cdot mcj_0 / \left[(\gamma^2 - 1)^{1/2} eB^2 \right],$$

$$j_0 \sim \sin \varepsilon \cdot j_{CL} \quad \text{for } \tau_* \tan \varepsilon \gg 1,$$

where j_{CL} is described by Child-Langmuir law.

4. Simulation of existing diode

The geometry of existing diode is shown in Fig.2 together with trajectories. The current density emitted normally to cathode surface reaches its maximum ~ 60 A/cm² on the edge of the cathode. A distribution of pitch-angles of electrons started from different places of cathode ($B_{cat} \sim 0.14$ - 0.18 T) is shown in Fig.3.

Evidently, there are two main reasons of pitch-angles increase. The first one is a large angle between magnetic and electric fields near the cathode together with weakness of magnetic field on there. Another reason is a comparability of variation scale of magnetic and transversal electric field with Larmour radius of electrons during acceleration and transportation of the beam electrons. These reasons cause the poor conservation of adiabatic invariant p^2_{\perp}/B and the increase of pitch-angles.

As one can see, pitch-angles of electrons rise from ~ 0.03 to ≤ 0.07 in an interval 0.1 - 0.2 m that is strongly correlated with sharp change of electric field acting on particles (Fig.4). Calculated characteristics of electrons in a transport channel ($Y \sim 0.5$ m, $B_{ch} \sim 0.28$ T) are:

$$\text{Average current density } j_{b,ch} \sim 70 \text{ A/cm}^2.$$

$$\text{Pitch-angles } \theta_{ch} < 0.08 \text{ } (< 0.05 \text{ for } 0.9I_b)$$

$$\text{Average angle spread}$$

$$\bar{\theta} = \sum \theta_i I_i / \sum I_i \sim 0.033$$

In the input mirror $B_{in} \sim 6$ T expected values are:

$$j_{b,in} = j_{b,ch} \cdot B_{in} / B_{ch} \sim 1.5 \text{ kA/cm}^2$$

$$\theta_{in} = \theta_{ch} \cdot \sqrt{B_{in} / B_{ch}} < 0.37 \text{ } (< 0.23 \text{ for } 0.9I_b),$$

$$\text{Average angle spread is}$$

$$\bar{\theta} \sim 0.15$$

So, the task of optimization was to increase current density $j_{b,in}$ in the trap by varying of diode geometry and simultaneously to decrease pitch-angles (not to increase them, at least). Here we have some limitations for optimal choice. At first, in case of explosive emission a duration of beam pulse τ_b and surface cur-

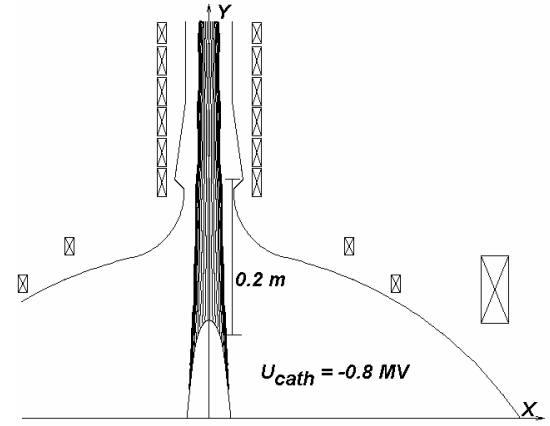


Fig.2. Layout of existing diode geometry and trajectories

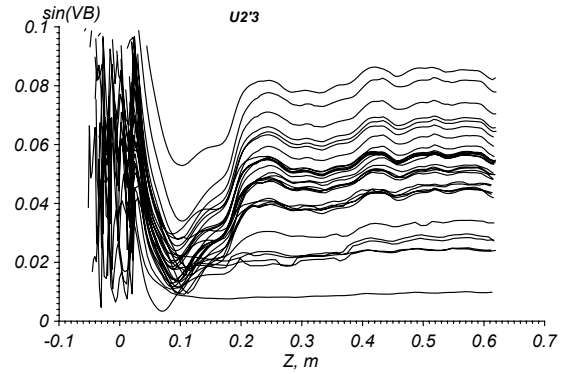


Fig. 3. Pitch-angles of electrons along axis of beam. End of cathode is positioned at $Y = 0.02$ m

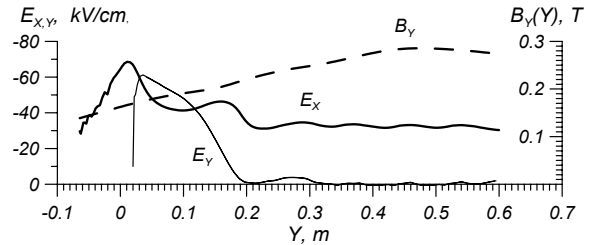


Fig. 4. Distribution of magnetic (dashed line) and electric (solid) fields along axis of beam

rent density j_0 are tied by experimentally found condition for fibrous graphite material $\tau_b j_0 < \sim 10^3$ $\mu\text{sA/cm}^2$. So, for 10- μs beam duration the normal density of emission current is limited as $j_0 < 10^2$ A/cm². To compress it up to $j_{b,in} \sim 2$ - 4 kA/cm² we must lower magnetic field at the cathode to $B_{cat} \sim 0.15$ - 0.3 T that is near the existing field. Then, if we increase the density of cathode current by increasing of cathode voltage or decreasing of cathode-anode gap, it follows to the increase of pitch-angles and may short beam pulse duration. Therefore, it has been decided to smooth anode and to move it toward cathode. Then, we have changed a shape of the cathode in order to compress electron flow in the diode by a strong incli-

nation of the cathode surface to magnetic field as for a magnetron. Moreover, we have optimized the geometry of the current-carrying bands induced magnetic field so that to smooth the guiding magnetic field lines. The chosen optimized geometry is described below.

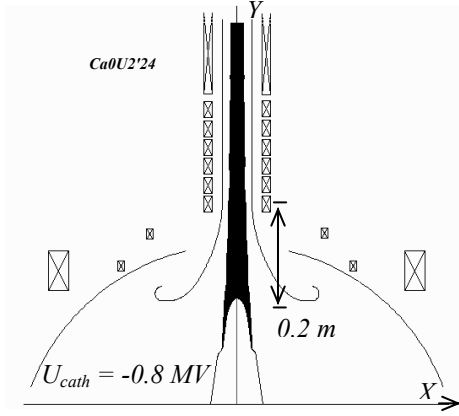


Fig. 5. Layout of optimized diode

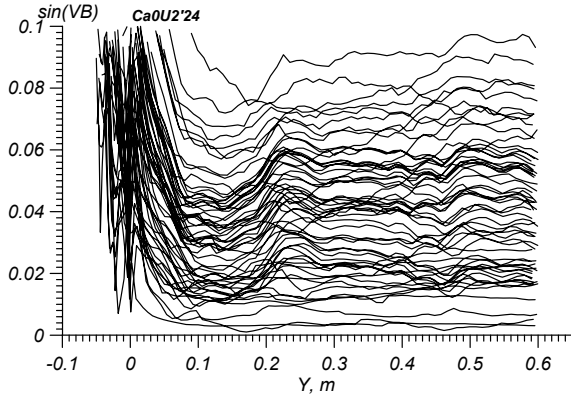


Fig. 6. Pitch-angles for the optimised diode. End of cathode is positioned at $Y = 0$

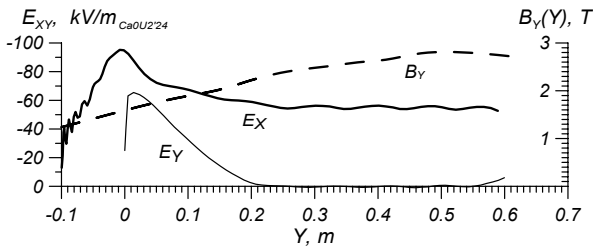


Fig. 7. Distribution of fields along axis of beam for the optimized diode

5. Simulation of optimised diode

The Fig.5 shows optimized geometry of diode. It differs from existing one by smooth shape of the anode electrodes which are placed closely to the cathode. Then, force lines of magnetic field and shape of the

cathode were smoothed just a bit too. As a result, a linear total current of the electron beam has been increased from 17 kA/m till 28 kA/m (at 1.7 times). A maximal density of emitted current on the cathode has increased up to $j_0 \sim 80 \text{ A/cm}^2$. Parameters of the electron beam in the transport channel are:

An average density of current $j_{b, ch} \sim 110 \text{ A/cm}^2$;

Pitch-angles $\theta_{ch} \leq 0.09$ (≤ 0.06 for $0.9I_b$),

Average angle spread

$$\bar{\theta} \sim 0.037$$

As one can see, the most part of the angle spread growth takes place in the near cathode region and here its value is more than for the existing diode. It may be explained by increasing of average electric field and density of current on the cathode. It is important, that increasing of angles in the cathode-anode gap is less than in previous case (0.01-0.015 instead 0.02-0.04).

In the input mirror expected values are:

$\theta_{in} < 0.46$ (< 0.28 for $0.9I_b$),

$j_{b, in} \sim 2.4 \text{ kA/cm}^2$

Average angle spread

$$\bar{\theta} \sim 0.17$$

6. Conclusions

The simulation of the beam in the ribbon diode for generation of relativistic high current REB has been done. To make better the performance of accelerator U-2 and to enlarge the ribbon electron beam current, the diode's geometry was optimized. This has permitted almost to double a beam current with the same angle spread of electrons. Predicted parameters of the electron beam are expected to provide more efficient heating of plasma in experiments.

References

- [1] V.S.Koidan, A.V.Arzhannikov, V.T.Astrelin et al., Transactions of fusion science and technology, **47**, No.1T, 35(2005).
- [2] A.V.Arzhannikov, V.B.Bobylev, V.S.Nikolaev, et al., in *Proc.10th Int. Conf. on High Power Particle Beams*, **1**, 1994, pp.136-139.
- [3] V.T.Astrelin, V.Ya.Ivanov, *Autometriya*, **3**, 92 (1980) (in Russian).
- [4] D.D.Ryutov, *About angle characteristics of electron beam obtained in foil less diode*, Preprint 83-146, Institute of Nuclear Physics, Novosibirsk, 1983 (in Russian).
- [5] V.T.Astrelin, I.A.Kotel'nikov, and S.L.Sinitskii, *Sov. Phys. Tech. Phys.* **34** (4) 46(1989).
- [6] V.T.Astrelin, V.Ya.Ivanov, *Iteration algorithm for calculation of density of current limited by space charge*, Preprint 87-133, Institute of Nuclear Physics, Novosibirsk, 1987 (in Russian).