High Current Source of Relativistic Ribbon Electron Beam with Small Angle Divergence[1]

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Abstract –The design of revised and optimized ribbon diode of the accelerator U-2 (800 kV, 30 kA) intended for heating plasma by intense E-beam in the GOL-3 facility is described. Based on the results of the electron beam simulations made with 2½-D CAD POISSON-2, this optimization has permitted to increase the intensity of the beam. A 3D structure of electric and magnetic fields included self-consistent beam fields were calculated and analyzed in this diode. Results of simulation for a process of the beam transport and transformation of its cross section shape in the curvilinear guiding magnetic field are presented.

1. Introduction

The processes of beam-plasma interaction and hot dense plasma confinement in a long open magnetic trap are investigated on the GOL-3 facility [1] (BINP, Novosibirsk). The facility is a multimirror trap filled with dense deuterium plasma which is heated by high-current relativistic electron beam (REB) generated by the U2 accelerator [2]. To increase the energy content of the beam in order to enhance the plasma temperature an optimization of the beam source configuration has been done [3] with the CAD POISSON-2 [4].

The general scheme of the GOL-3 facility and magnetic field distribution on axis are shown in the Fig.1. Parameters of experiment and of optimized diode were presented in the paper [3]. We remind their main features below.

The E-beam generator U-2 consists of a capacitive energy storage, high-voltage switch, and the diode with a ribbon cathode (cross section is 5×75 cm^2) and a slit foilless anode. The cathode with negative potential of 0.8 MV is placed in the smoothly rising from 0.12 to 0.16 T magnetic field. The electron beam generated in the diode by an explosive emission cathode passes through the anode slit and then is transported in a slit vacuum channel with homogeneous magnetic field 0.27 T to a special unit called transformer. In this unit, the shape of the electron beam in the curvilinear magnetic field is converted from the ribbon to a square one. After transformation the beam is compressed by guiding magnetic field rising from 0.3 to ~ 6 T at the entrance to the multimirror trap. The beam cross section in the transport channel is 3.5×75 cm in the transformer it becomes 16×16 cm and finally after limiter in the plasma the beam has the diameter 5 cm.

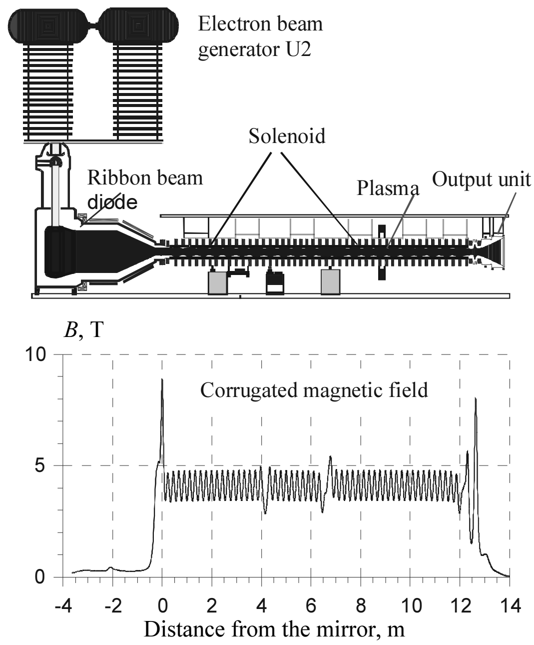

Fig. 1. GOL-3 layout

As the result of optimization of both the diode geometry and the magnetic field configuration the following parameters of electron beam have been obtained in the previous simulations [3]. A linear total current of the electron beam is about 28 kA/m. A maximal density of emitted current on the cathode is $j_0 \sim 80$ A/cm^2. Parameters of the electron beam in the transport channel are:

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

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

Average angle spread $\overline{\theta} \sim 0.037$.

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Expected values in the input mirror are:

$\theta_{in} < 0.42$ (< 0.28 for $0.9I_b$), $j_{b,in} \sim 2.4$ kA/cm^2;

Average angle spread is $\overline{\theta} \sim 0.17$.

On the base of calculated results, a technical drawing of the modified diode has been worked out. Due to chosen technical solutions it somewhat differs from that has been supposed during modeling. On this reason, it was decided to perform a check numerical simulation including the final real configuration of diode.

2. Design of the ribbon diode

A fragment of assembly drawing of the diode is shown at a view from above in Figs. 2 and 3.

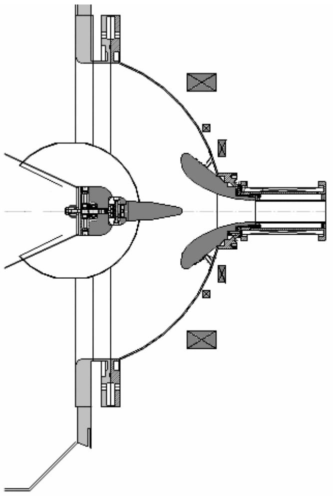

Fig. 2. Design drawing of the diode

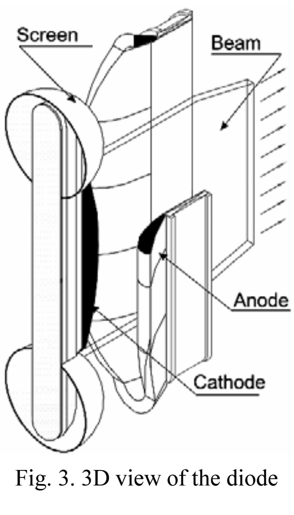

Fig. 3. 3D view of the diode

Here a cathode electrode (in center) is fixed on a special support. A circle in the center of Fig. 2 is a projection of one from two guard sphere metallic screens placed on the edges of the cathode. Their destination is to prevent too high emission of electrons on the edges and to decrease a surface electric field down to safety value for to provide acceptable assurance factor there. Cathode and anode electrodes are made of different graphite materials: fibrous and of compacted powder ones, correspondingly. They are shown as dark grey on the Fig. 2. A width of transport channel is 6 cm. A height of the cathode is 75 cm. The design drawing was elaborated taking into account both results of numerical simulation and restrictions of technological requirements.

3. A numerical simulation of the beam generation in the ribbon diode

Note, that in previous modeling we have taken into account an electron emission from the central part of the cathode only. It was founded on distribution of electric field along cathode electrodes surface (Fig. 4).

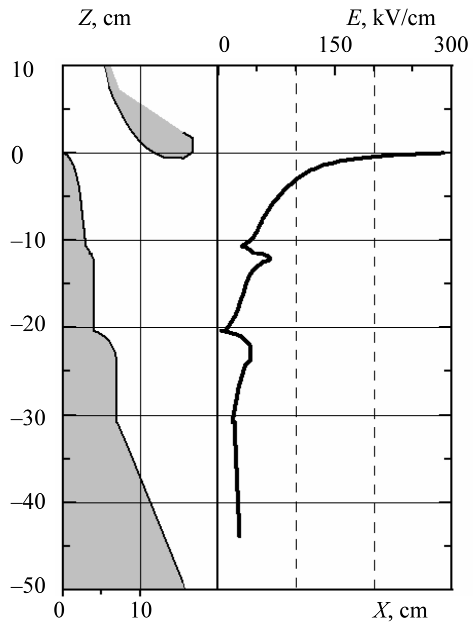

Fig. 4. Distribution of electric field on the cathode without the beam emission (2D calculations)

As one can see, the electric field strength on salient parts of cathode is close to 50 kV/cm and is locally amplified. This may increase the electron emission in presence of ultraviolet irradiation due to appearance of explosive plasma on the central part of cathode. On this reason, it was decided to include a possibility of emission from the surfaces neighbor to the central part of the cathode into the numerical model. Here we supposed that electron emission is limited by the space charge only. The result of simulation is shown in Fig. 5. An electron stream propagating practically along the magnetic field lines doesn't touch walls of anode slit and the transport channel. The amplitude of Larmour oscillations in the stream is noticeable only near the cathode and practically negligible near side of the anode. A distribution of current density and pitch angles across the beam in the transport channel in magnetic field 0.27 T is shown in Fig. 6. A total current of the electron beam is 27.8 kA/m including current from central part of cathode (23.8 kA/m,

$X < 1.34$ cm) and current from its side parts (4 kA/m). A maximal density of emitted current on the cathode is $j_0 \sim 60$ A/cm^2. Parameters of the electron beam in the transport channel are:

An average density of current $j_{b,ch} \sim 100$ A/cm^2;

Pitch-angles $\theta_{ch} \le 0.08$ (≤ 0.06 for $0.9I_b$);

Average angle spread $\bar{\theta} = \sum \theta_i I_i / \sum I_i \sim 0.04$.

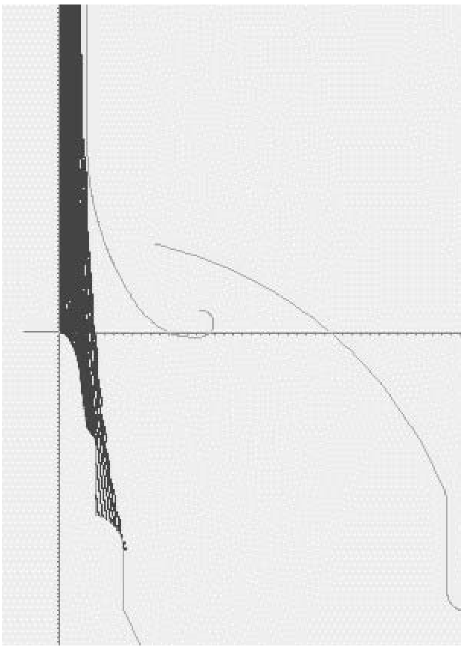

Fig. 5. Shape of trajectories in the diode

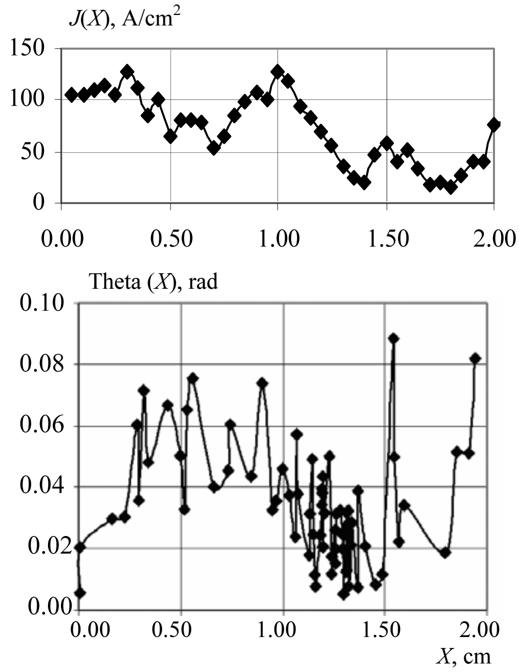

Fig. 6. Distribution of current (up) and pitch angles (down) across the beam in the transport channel

The most part of the resulting angle spread is obtained in the vicinity of the cathode region. It may be explained by drastic spatial variation of both the average electric field and the current density on the cathode. An increasing of angles in the near cathode region is ~ (0.01–0.015) rad.

In the input mirror calculated values are:

$\theta_{in} < 0.38$ (< 0.28 for $0.9I_b$), $j_{b,in} \sim 2.2$ kA/cm^2

Average angle spread $\bar{\theta} \sim 0.18$.

Thus, the main parameters of the electron beam in the analyzed diode geometry practically were not changed. Hence, the beam may be used for heating plasma in the GOL-3 experiments.

4. Modeling of beam transportation and cross section transformation

The simulation of the ribbon beam transport in the vacuum channel was realized as a solution of 2.5D self-consistent problem on the propagation of the beam with arbitrary shape of its cross section in a perfectly conducting liner. It was proved [5] that for the isospeed beam with initially homogeneous distributions of the beam charge and current densities, the profiles of these parameters remain flat at the beam transport in the strong external guiding magnetic field (self fields are small in comparison with external one). Basing on this statement we have calculated evolution of the beam cross-section border in time due to the $\mathbf{E} \times \mathbf{B}$ drift motion and the displacement by self magnetic field. To find self beam fields we solved 2D Poisson equation for the potentials A_z and φ by decomposition in Fourier series, then calculated $\mathbf{E}$ and $\mathbf{B}$ and moved border in respect with mentioned drift and magnetic displacement. This 2D model is adequate if the shape of the liner slightly changes along the axis on the length comparable with the minimal gap between the liner walls. Evolution of the cross section shape along the beam pass in the channel and transformer at different degrees of the space charge neutralization are shown in Fig. 7.

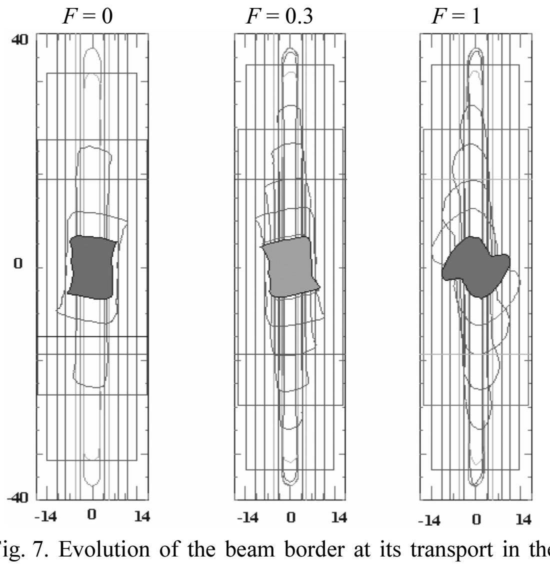

Fig. 7. Evolution of the beam border at its transport in the channel and transformer

We compared the calculated beam cross sections at the end of the transformer (filled with dark color) with the beam imprint registered on the graphite limiter in the experiment, see Fig. 8.

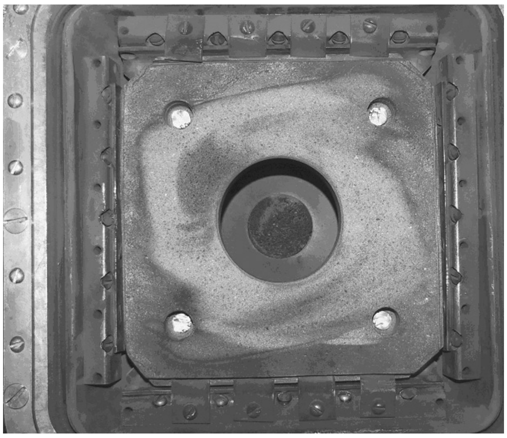

Fig. 8. The beam imprint at the exit of the transformer

As it follows from rotational displacement of the imprint, the estimate for typical value of neutralization degree is close to 0.3. Unfortunately this model becomes inadequate in the compression region for two reasons. Firstly the compression length is comparable with transverse size of the beam and the problem becomes 3-dimensional. Secondly, the high current density of the beam in this region provides the appearance of dense plasma which neutralizes both space charge and current density of the beam.

5. 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 U2 and to enlarge the ribbon electron beam current, the diode's geometry was optimized. This step 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.

The modeling of transport and transformation of electron beam and comparison with experiment has shown an influence of space charge neutralization.

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