Numerical Simulation of Diodes with Plasma Electrodes

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Abstract – A problem of generation of high brightness long pulse power electron beams in a strong magnetic field is of general interest. Especially it is important for thermonuclear applications. To raise plasma parameters in the multi mirror trap GOL-3 it was proposed earlier to inject into the plasma an additional electron beam of sub millisecond duration with high power. This was a reason why an elaboration of source for generation of the beam on the base of plasma emitter with independently generated plasma has begun. A CAD POISSON-2 was used for modeling of the source; therefore, new algorithms were included in it for calculation of plasma surface shape. A numerical simulation of diodes with high density of emission current is made. Results of modeling are compared with those obtained by the code PBGUNS and with results of experiments carried out in BINP. Calculated characteristics for kiloampere range beam suitable for thermonuclear applications are obtained for designed source.

1. Introduction

In the Budker Institute of Nuclear Physics investigations on plasma heating and confinement in a multi mirror magnetic trap are carried out on the GOL-3 facility [1]. The facility (Fig. 1) consists of trap with gopher magnetic field \( B_{\text{max}}/B_{\text{min}} = 4.8 \, \text{T}/3.2 \, \text{T} \) placed between entrance mirror of 6 T and output mirror of 9 T, filled by dense deuterium plasma \( n_p \sim 10^{20} - 10^{22} \, \text{m}^{-3} \) and generator of high-current relativistic electron beam [2] used for plasma heating. In the experiments, the plasma was heated up to temperature of 1–4 keV. The energy confinement time for ions reached ~ 0.5–1 ms and it was limited in particular by binary collisions with electrons.

Experimental scaling and absolute values of the plasma parameters indicated a possibility of use a multi mirror trap as a thermonuclear reactor. To check this we would increase the main plasma parameters.

The electron beam pulse up to 8 \( \mu \)s, energy ~ 0.8 MeV and current ~ 20 kA provides a high electron temperature of plasma only for pulse time thanks to effect of electron thermal conductivity suppression, occurred during turbulent beam-plasma interaction [3] excited by a beam with current density 1–2 kA/cm\(^2\) and pitch-angles of electrons in magnetic field \( B \sim 5 \, \text{T} \).

The beam duration time is limited by explosive character of electron emission on a cathode. That is why it was suggested to use a second electron beam of less power but much longer than existing one, for to increase essentially the energy confinement time.

Now we are developing a generator that can produce a second electron beam of 100-\( \mu \)s duration and more. A source of the beam will be placed in special expander vessel behind output mirror with the magnetic field decreasing down to 0.1–0.2 T on a 2 m length. A low magnetic field is necessary to decrease a density of energy flow from GOL-3 of magnetized plasma and beam to value, safety for metal surfaces of the diode. Special experiments have shown that this occurs at \( B \leq 0.1 \, \text{T} \).

These requirements determine a complexity of a problem consisted in generating of a long pulse (100 \( \mu \)s and more) small pitch angles (< 0.03 rad) and high current density (20–40 A/cm\(^2\)) electron beam in...
low magnetic field ~ 0.1 T that must be compressed by driving magnetic field at 50 times. It was decided to generate 150 keV electron beam to minimize its total energy. To avoid uncontrolled explosive cathode plasma, we use an electron emission from a surface of cathode plasma generated by independent arc source.

The above formulated problem requires careful modeling. A numerical simulation was carried out by CAD POISSON-2 [4] after its upgrading by new algorithms for calculation of plasma boundary shape. This modification was necessary because all known codes accessible to us, are unable to solve tasks with more than one plasma emission boundaries. It is important because in our case anode plasma should be presented: it may be plasma flow leaked from GOL-3 or plasma appeared at ionization of residual gas by long pulse beam. New algorithms of POISSON-2 were checked by comparison with code PBGUNS [5] and further were used for modeling of existing diode and diode designed for long pulse beam generation.

Below we describe briefly the CAD POISSON-2 and used method of plasma boundaries simulation.

2. POISSON-2 and some its algorithms

POISSON-2 [4] is a code intended for solution of stationary 2½-D problems on forming charged particle beams in external and self-consistent electric and magnetic fields in vacuum and gas filled systems. It uses a method of integral equations with evaluation of potential \( \varphi (r) \) via the surface \( \sigma \) and the volumetric \( \rho \) charge density:

\[
\varphi (r) = \int_{\sigma} \frac{\sigma(R)}{|R-r|} d^2R + \int_{\rho} \frac{\rho(R)}{|R-r|} d^3R
\]

with set of boundary conditions described conductors, dielectrics, symmetries, periodicity, etc.

A magnetic field is calculated as a sum of external one and a constituent produced by beam current

\[
B(r) = B_0(r) + \frac{1}{c} \int \frac{Jx(R-r)}{|R-r|^3} d^3R
\]

that corresponds to condition \( B = 0 \) in infinity.

Flows of charged particles emitted from surfaces are simulated by current tubes of variable width with central trajectory. A shape of trajectories in electromagnetic field is calculated using relativistic Boris scheme. Volumetric charge density is calculated using continuity equation \( div \varphi = 0 \) or with account of non elastic collision processes in a gas. Self-consistent solution is obtained by iteration method with upper relaxation of space charge or trajectories current.

A combined algorithm based on “3/2 law” is used for calculation of emitted current. It takes into account a space charge of external beams [6]. Additional correction of local current density \( j_0 \) for arbitrary shape of emitters or for not uniform emission to comply the condition \( E_0 = 0 \) on an emitter surface is made by algorithm \( \Delta j_0 = \pm f j_0 (E U)^2 \), where \( E \) is a field on the surface and \( U \) is a potential at a distance \( d \) from it, if a current \( j_0 \) is not self consistent yet [7].

A calculation of plasma boundary shape is based on the step-by-step method. It uses a criterion function \( j_{a,3/2}(r_k) = j_{0a} \). This means that plasma boundary has settled when outgoing flow of particles is equal to coming one. In a model considered below \( j_{a,3/2}(r_k) \) is a density of total current in axial direction on an emitting surface \( \Gamma_a \) that is limited by a space charge and \( j_{0a}(r_k) \) is a distribution of desire current density that is caused by plasma source. This model possesses us to compare results of calculations with some other codes such as PBGUNS. In this paper we used a condition \( j_{0a}(r_k) = j_{0a} = \text{const.} \)

A plasma surface \( \alpha \) is described as a set of points with uniformly distributed transversal coordinates \( r_{0a} \) and changeable longitudinal co-ordinates \( z_{0a} \). A shape of boundary is reconstructed by the cubic spline method. A change of \( z_{0a} \) co-ordinates at each step is made by the following way. At first, we solve a self-consistent task with fixed boundaries in which we calculate a density of current \( j_{a,3/2}(r_k) \) for each trajectory. Then we find a value of partial shifts resulted from trajectories

\[
\Delta z_{0a}(r_k) = -a_{0d} \left[j_{a,3/2}(r_k) - j_{0a} \right] \Delta j_{0a}^a
\]

where \( d \) is the cathode-anode gap, \( |a_{0d}| \ll 1 \) are the coefficients that control a value of shifts and have sign determined by position of emitters in respect to diode gap. The shifts are used for change of co-ordinates \( z_{2a} \) and \( z_{2+1,a} \) adjacent to start point \( r_0 \) of trajectories exclude edge points. The values of change are proportional to shifts \( \Delta z_{0a}(r_k) \) and to reverse distances from \( r_0 \) to points \( z_{0a} \) and \( z_{2+1,a} \).

The last operation is smoothing small-scale inhomogeneities of plasma boundary shape that is necessary to suppress numerical instabilities

\[
z_{2+1,a} = (1-2\beta)z_{2+1,a} + \beta(z_{2+1,a} + z_{2+1,a})
\]

where \( \beta \ll 1 \) controls a level of smoothing.

3. A comparison of POISSON-2 and PBGUNS

A comparison of codes was done for cases of ion and electron emission. First is a source of proton beam that was calculated by two codes. Parameters of accelerator, geometry and trajectories of protons are shown in the Figs. 2 and 3. Plots of emittance are presented in the Figs. 4 and 5 in identical scales. Note that a model in PBGUNS considers ion particles with initial angle distribution that is absent yet in POISSON-2. Nevertheless, a good agreement in the results takes place.
Oral Session

Fig. 2. Code POISSON-2. Left grey area is plasma.

Fig. 3. Code PBGUNS.

Fig. 4. Code POISSON-2.

Fig. 5. Code PBGUNS.

Fig. 6. Code POISSON-2. Trajectories and $R-R'$ plot.

Fig. 7. Code PBGUNS. Scales are the same as in Fig. 6.

Fig. 8. Geometry of diode with plasma emitter. All sizes are in mm.

Fig. 9. Output current $I_{beam}$ and electron current to anode $I_e$ in the diode.

Fig. 10. Modeling of diode with cathode and anode plasma.

Fig. 11. Coaxial multi-slit plasma emitter diode in field $B = 0.1$ T.
Another sample for comparison of codes is an electron gun with plasma cathode, experimentally investigated in the BINP [8]. Gun geometry and phase plot of the beam are shown in Figs. 6 and 7. One can see that there is a good compliance of results obtained by two different codes.

4. Experiment on diode with plasma electrodes

Geometry of diode is presented in Fig. 8. The anode of arc plasma source (B) and the cathode of diode (C) are connected electrically. An arc discharge is switched on in hydrogen puff cloud with discharge current up to 600 A and ~ 250 μs duration. It creates plasma flow directed to the cathode aperture. A pulse of accelerating potential up to ~30 kV is applied for t ≤ 300 μs to the cathode. The anode (A) is grounded. Anode plasma is appeared behind the anode as a result of ionization of residual gas, P ≤ 10^{-2} Torr.

At the absence of external magnetic field an electron beam with small angular divergence is formed in the diode. A typical current-voltage characteristic of the diode for fixed parameters of the arc source, provided emission current ≈ 3 A, is shown in Fig. 9. The solid curve on the figure I_{m}c (U_{c}) is a calculated maximum electron current, which can pass through anode aperture from the diode with plasma cathode without anode plasma (an analogue of Child–Langmuir law).

For U > 20 kV the beam current does not depend on a diode potential and the current on the anode electrode is small. The beam pulse duration is equal to the high-voltage modulator pulse (~ 250 μs). With decreasing of the potential, the output current and the pulse duration slightly decrease too. At U ~ 10 kV the anode current rises sharply and the beam pulse became shorter, less than 50 μs. Here the value of the beam current becomes I_{beam} ~ 2I_{m}c that proves the influence of the anode plasma and corresponds to bipolar regime of the planar diode.

To estimate an ion current density and explain shorting of diode gap, a numerical simulation of the electron and the ion flows in the diode has been done including calculation of the plasma boundaries shape. The electron emission of the cathode plasma was taken equal to j_{oe} = 43 A/cm² to make the beam current close to 3 A. An ion emission j_{ia} from anode plasma was chosen so that calculated electron current to anode electrode should be equal to experimental value for every diode potential U < 18 kV.

A typical picture of trajectories in a bipolar plasma diode is shown in Fig. 10 for diode potential U = 12 kV. One can see that experimentally observed value of electron current to anode corresponds to fall of small part of periphery beam electrons onto inner edge of anode aperture. The main results of these modeling are the following.

First, the ion emission from anode plasma is near 0.7 A/cm² and rises slightly with decreasing of diode potential from 15 to 10 kV. In experiments, the electron current on the anode does not depend on residual gas in a wide interval of pressure. Second, the ion beam imprint on the cathode plasma surface (equal to 1.3 mm in Fig. 10) enlarges from 0.3 to 1.5 mm and covers cathode aperture at U ~ 10 kV.

This means, at first, that anode plasma is generated mainly on the anode surface, additionally to plasma appeared due to ionization of residual gas. A density of anode plasma, needed for the ion emission for the case of Fig. 10, may be estimated as n ~ 10^{12} cm⁻³. Second, a shorting of diode occurs, when ions from anode plasma fall onto cathode surface. In addition, an electron current to the anode rises and may exceed value, critical for diode breakdown.

5. Modeling of the high power diode with plasma emitters

A numerical simulation of 1.5-kA, 150-kV diode has been done. The diode is intended for generation of millisecond electron beam in external magnetic field 0.1 T. A result of modeling is shown in Fig. 11.

Geometry of cathode-anode coaxial slits was chosen to provide a minimal angle divergence of electron velocities. The emitting surface is formed by four circular slits of 6 mm in width and central hole of 6 mm in diameter, separated by focusing electrodes of 4 mm width. The anode is formed by a set of coaxial ring electrodes with small diameter 3 mm and large diameter 6, 16, 26, … mm so that inner edges of anode slits are shifted by 1 mm to the axis relatively to cathode slits. This is necessary to provide a transparency of anode for arbitrary azimuthal magnetic field that is changed with beam current. The electron and ion emission from plasma boundaries was put equal to j_{oe} = 40 A/cm² and j_{ia} = 0.6 A/cm². A distribution of pitch angles is shown in Fig. 12.
References