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BEAM – 2D-CODE PACKAGE FOR SIMULATION OF HIGH PERVEANCE BEAM DYNAMICS IN LONG SYSTEMS

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Beam – 2D-code package for simulation of high perveance beam dynamics in long systems

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Abstract

A special code package BEAM developed for simulation of dynamics of non-laminar cylindrical beams with high perveance in long electron-optic systems is described. For this package the beam start conditions may be defined by the user as well as imported from the output files of two code packages SAM [1, 2] and SuperSAM [3] which are developed and used in BINP for gun simulation. The thermal spread of initial velocity of the beam particles induced by the cathode heating can also be taken into account. The non-laminar model of pipes of current is developed to describe space charge effects. This model allows to calculate the transverse sagging of potential induced by the beam space charge in cylindrical drift tube as well as in short accelerating gap between two tubes with high accuracy. Paraxial approximation of a high order is used for external electric and magnetic fields calculation. Axial distribution of external fields may be defined by the user or calculated with high accuracy by SAM code. The package runs on IBM PC with using interactive dialogue and graphics. Examples of real electron-optics systems simulation are presented.

1 Introduction

Developers of electron-optics systems (EOS) often face the problem of high accuracy simulation of high perveance ($P_\mu \sim 1$) beams in electro- and(or) magnetostatic systems, whose length L is many times longer than the beam radius a ($L \gg a$). Examples of such systems are the magnetic accompanying system of a high-power RF source, accelerating tube for a high-power beam forming, drift tubes section of EBIS etc. The high accuracy simulation of the beam dynamics in such systems using standard FDM and FEM computer codes is always a problem because of two reasons:

1. Both longitudinal and radial fields produced by a beam space charge are calculated with a noise because of numerical differentiation of a potential in FDM and FEM programs. This noise is collected in a long system.

2. The number of radial cells at the beam radius should be many times larger than 1 to describe the beam transverse dynamics with enough good accuracy. At the same time for standard FDM and FEM programs sizes of radial and longitudinal subdivisions either are exactly the same (FDM) or are values of the same order (FEM). Thus, because of the system length ($L \gg a$), either the total number of subdivisions reaches a limiting value or the calculation time becomes unacceptably long.

3. Attempts to avoid these problems by consecutive calculation of individual shorter parts of the system lead to a necessity of additional non-physical border conditions introduction at interfaces between segments and causes the calculation accuracy decreasing.

The presented paper describes the BEAM computer code, in which new line of attack on the problem of high perveance beam dynamics simulation for long systems is used. PIC method is used for describing beam transverse electric and magnetic fields. Therewith a careful smoothing initial transverse distributions of beam velocities and current density is performed. These distributions can be defined by the user or imported from SAM [1, 2] or SuperSAM [3] computer codes which have been developed and now are successfully used in BINP for electron and ion gun simulation. A heat spread of beam particles velocities can also be taken into account for initial transverse beam particles velocities distribution. This spread is determined by the size and temperature of a cathode and by a beam radius. Such an action is often associated with simulation of EOS with exacting requirements on a beam transverse emittance, especially if high beam area compression is used. Longitudinal beam electric field is considered by simulation of sagging of beam transverse potential in a drift tube. External electric and magnetic fields are calculated in paraxial expansion of a high order using a cubic spline for simulation of axial field distributions as well as their derivatives. Values of fields and derivatives are calculated by SAM code with an accuracy of $\sim 10^{-5}$. Charged particle trajectories in PIC method are calculated by Runge-Kutta method of the fourth order with an especially developed algorithm of automatic step selection.

All the methods and algorithms listed above which allow to increase the accuracy and decrease the time of a high perveance beam dynamics calculation for a long system are described in detail in section 2. Examples of real EOS simulation by the use of BEAM code package are presented in section 3 as well as measurement results for comparison purposes.

2 Methods and algorithms used in beam code package

2.1 Beam Initial Parameters Defining And Smoothing

Algorithms of beam initial parameters defining and smoothing essentially depend on that if these parameters are defined by the user or imported from SAM or SuperSAM programs, but in any case the beam voltage U_0 and the total beam current I_0 should be defined.

In the former case the user should also define the following initial beam parameters:

- beam radius a_0 and current density distribution $j_0(r)$;
- maximal incline angle α_0 of the beam outer trajectory in the case of absence of a cubic aberration;

- relative correction of the incline angle of the beam outer trajectory c_3 through the cubic aberration.

Defined beam current density distribution j_0 is smoothed by the method of least squares by a function, which can be displayed as a series:

$$\tilde{j}(x) = \sum_{i=0}^{N_j} \tilde{j}_i \cdot x^{2i} , \tag{1}$$

where $x = r/a_0$, N_j is the number of series terms defined by the user, $\tilde{j}_i$ are series coefficients. At the same time function $\tilde{j}(x)$ satisfies the normalization

$$2\pi a_0^2 \int_0^1 \tilde{j}(x) x \, dx = I_0 , \tag{2}$$

where I_0 is the total beam current.

Radial trajectory incline angles distribution is described by the following function:

$$\tilde{\alpha}(x) = \alpha_0 \cdot (x + c_3 \cdot x^3) \tag{3}$$

Formulae (1–3) describe completely smoothed beam initital conditions when they are defined by the user.

Initial azimuthal velocities are calculated by the following formula:

$$v_\theta = v_{\theta B} \cdot (1 - C_s) , \tag{4}$$

where $v_{\theta B}$ is an azimuthal velocity calculated from the Bush theorem (for a start from the completely shielded cathode) and C_s is a cathode shielding coefficient defined by the user.

However, such an approach does not allow to describe a beam started from a cathode with a shielding coefficient depending on a radius. It is also impossible by this expedient to describe a non-laminar beam with intersection of trajectories.

These problems vanish in the case when initial parameters are imported from SAM or SuperSAM programs. Therewith a calculated current density distribution at a gun emitter is used, which are smoothed by the method of least squares by the formula (1). However, l/l_{max} ratio is used in this case as x variable, where l is the current value of a coordinate along the emitter generating line, l_{max} is a limiting value for this coordinate. For example, for a spherical cathode $x = \theta/\theta_{\max}$, where $\theta_{\max}$ is a cathode apex angle. Therewith normalizing $\tilde{j}(x)$ function is performed in the following form:

$$\int_0^1 \tilde{j}(x) J(x)\, dx = I_0 \ , \qquad (5)$$

where J(x) is a Jacobean describing an emitter area element.

Moreover, the following set of parameters calculated at a user defined start plane at a gun exit, are imported from SAM or SuperSAM:

- slope radius of trajectories $r(x_i)$;
- trajectory slope angle $\alpha(x_i)$;
- trajectory azimuthal speeds $v_\theta(x_i)$, where $x_i = l_i/l_{max}$, l_i is a coordinate along the emitter for trajectory number i.

All calculated distributions listed above are smoothed by the method of least squares with functions which are written as following series:

$$\tilde{r}(x) = \sum_{n=1}^{N_r} \tilde{r}_n \cdot x^{2n-1} \ ,$$

$$\tilde{\alpha}(x) = \sum_{n=1}^{N_\alpha} \tilde{\alpha}_n \cdot x^{2n-1} \ , \qquad (6)$$

$$\tilde{v}_\theta(x) = \sum_{n=1}^{N_\theta} \tilde{v}_{\theta n} \cdot x^{2n-1} \ ,$$

where N_r, N_α, N_θ are limiting numbers for series terms defined by the user, $\tilde{r}_n$, $\tilde{\alpha}_n$, $\tilde{v}_{\theta n}$ are series coefficients.

Note that functions (6) are unambiguous even for strongly non-laminar beam with intersection of trajectories, for which $\alpha(r)$ and(or) $v_\theta(r)$ functions may be ambiguous and cannot be smoothed by standard methods.

2.2 Simulation Of Transverse Velocities Heat Spread

The heat spread of transverse velocities for beam particles ensemble is simulated as the following random addition Δv_T to the transverse velocity for each particle:

$$\Delta v_{Ti} = \sqrt{\frac{2T_c}{m} \cdot \frac{r_c}{a_0}} \cdot f(p_{3i-2}) \cdot \sin^2\left(\frac{\pi}{2} \cdot p_{3i-1}\right) \ , \qquad (7)$$

where m is the particle mass, T_c, r_c are cathode temperature and radius, a_0 is the beam radius in the start point, i is the particle number, $0 \le p_k \le 1$ are numbers obtained from a random number generator, $f(p)$ is Maxwell distribution function normalized so that $< \Delta v_T^2 >= \sqrt{\frac{2T_c}{m}\frac{r_c}{a_0}}$. Projections of heat additions to the particle transverse velocity on x and y axes of the laboratory reference system, z axis of which is directed along the beam axis, are calculated by formulae:

$$\Delta v_{Txi} = \Delta v_{Ti} \cdot \cos(2\pi \cdot p_{3i})$$

$$\Delta v_{Tyi} = \Delta v_{Ti} \cdot \sin(2\pi \cdot p_{3i}) \qquad (8)$$

2.3 Simulation Of Space Charge Effects

PIC method for simulation of space charge effects is used in BEAM code. Therewith the user defines the total number N_c of radial cells and the number of particles in a cell N_{pc}. Each particle in this model carries an uniform current equal to:

$$I_p = \frac{I_0}{N_p} \ , \qquad (9)$$

where I_0 is the total beam current, $N_p = N_c \times N_{pc}$ is the total number of particles.

Initial parameters of i-th particle are defined so that:

$$\int_0^{x_i} \tilde{j}(x) J(x)\, dx = i \cdot I_p \ ,$$

$$r_i = \tilde{r}(x_i) \ , \quad \alpha_i = \tilde{\alpha}(x_i) \ , \quad v_{\theta i} = \tilde{v}_\theta(x_i) \ , \qquad (10)$$

where $\tilde{j}(x)$ function is described by the formula (1) and $\tilde{r}(x) = a_0 \cdot x$, $\tilde{v}_\theta(x)$, $\tilde{\alpha}(x)$ are either described by formulae (3– 4) in the case of user defining the beam parameters or described by formulae (6) if the initial beam parameters are imported from SAM or SuperSAM programs.

Calculation of a particle ensemble dynamics is performed simultaneously so that the longitudinal coordinate z will be the same for all the particles. Therewith at each step of integration for fixed value of z coordinate the particle ensemble is renumbered by k index so that there will be $r_{k+1} > r_k$, $k = 1, \ldots, N_p$. Boundary radii of N_c cells for space charge effects describing are built-up from 0 to the beam radius $a(z)$ and coincide with radial coordinates of particles under the numbers $k = N_{pc} \cdot m$, where $m = 1, \ldots, N_c$ is the cell number. Such an approach leads to crowding the cells at the radius increasing and equalizing possible error for all the cells.

Values of beam radial electric field component and azimuthal magnetic field component are determined at the cell boundaries by the formulae:

$$E_{rm} = \frac{Z_0 \cdot I_p}{2\pi r_m} \cdot \sum_{k=1}^{m \cdot N_{pc}} \frac{1}{\beta_k}\,, \qquad m = 1, \ldots, N_c \tag{11}$$

$$B_{\theta m} = \frac{\mu_0 \cdot I_p \cdot m \cdot N_{pc}}{2\pi r_m}\,,$$

where $Z_0 = 120\pi(\Omega)$ is the vacuum characteristic impedance, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the vacuum magnetic permeability, r_m is the outer radius of m-th cell, $\beta_k = \frac{v_{zk}}{c}$ is the longitudinal speed of k-th particle related to the speed of light, I_p is the single particle current determined by the formula (9), N_{pc} is the number of particles in a cell. Radial distributions of beam electric and magnetic fields are calculated by linear interpolation from node values determined by the formula (11).

To describe transverse potential sagging effects at the cost of the beam space charge one has introduced a concept of a drift tube contour on which a potential relative to the emitter is defined. This contour is defined by the user as a finite set of node points $(R_{Dl},\ Z_{Dl})$, $l = 1, \ldots N_D$. Therewith in each point $(R_{Dl},\ Z_{Dl})$ a voltage between the emitter and the drift tube should be defined. The drift tube contour is represented in this case as a set of straight line segments connecting defined node points consecutively. If voltages at segment ends coincide, the segment corresponds to a drift tube with constant potential. If the voltages differ, this contour element is considered as accelerating or decelerating gap. A potential distribution along a contour of such an element can be either linear (accelerating tube model) or determined by a formula:

$$\varphi_{CH}(x) = (1-x)\varphi_1 + x \cdot \varphi_2 - \frac{\varphi_2 - \varphi_1}{2\pi} \cdot \sin(2\pi x)\,, \tag{12}$$

where φ_1 and φ_2 are potentials in node points at the edges of the element, $x = l/L$ is a relative coordinate, l is a distance from the segment's edge with

potential φ_1, L is the total element length. Formula (12) describes with a good accuracy a potential distribution on the axis of the short gap of the length h many times shorter than the radius b of drift tubes adjacent to the gap if the beam radius in the gap is $a \ll b$ (a model of a gap between drift tubes EBIS).

A drift tube contour should be specified within the whole EOS area in which the beam dynamics calculation is to be performed. In this case for any coordinate z the following parameters can be determined: drift tube radius b, voltage U_{CH} between a drift chamber and the emitter. Also beam radius a and beam inherent electric field radial distribution $E_r(r)$ (see formula 11) are known. That allows to determine the voltage between the beam center and beam edge:

$$\Delta U_1 = -\int_0^a E_r(r)\,dr = \frac{Z_0 I_p}{4\pi} \sum_{k=1}^{N_p} \frac{1}{\beta_k}\,, \tag{13}$$

as well as between a beam edge and a drift chamber.

$$\Delta U_2 = -\int_a^b E_r(r)\,dr = \frac{Z_0 I_p}{2\pi} \ln\frac{b}{a} \sum_{k=1}^{N_p} \frac{1}{\beta_k} \tag{14}$$

As a result a voltage between the emitter and beam center can be found for a given z coordinate:

$$\Delta U_0 = U_{CH} - \frac{Z_0 I_p}{4\pi}\left(1 + 2\ln\frac{b}{a}\right) \sum_{k=1}^{N_p} \frac{1}{\beta_k}\,. \tag{15}$$

A voltage between the emitter and a point on m-th radial cell boundary can also be deduced:

$$\Delta U_m = \Delta U_0 - \int_0^{r_m} E_r(r)\,dr = \Delta U_0 - \sum_{i=1}^{m} \frac{E_{ri} + E_{ri-1}}{2}(r_i - r_{i-1})\,. \tag{16}$$

A voltage between the emitter and an arbitrary point inside a beam is computed by the formula:

$$\Delta U(r) = \Delta U_{m-1} - \left(E_{rm-1} + \frac{(E_{rm} - E_{rm-1})}{2} \frac{(r - r_{m-1})}{(r_m - r_{m-1})}\right) \cdot (r - r_{m-1})\,, \tag{17}$$

where $r_{k-1} \leq r \leq r_k$, ΔU_k, E_{rk} are calculated by formulae (16) and (11).

By these means for an arbitrary radius the value of the kinetic energy gained by a particle is $W(r) = e\Delta U(r)$. Note that the process of finding the radial distribution of the beam particle energy is non-linear because beam velocities in formulae (11) and (13–15) depend on energy of particles. It is especially difficult at particles' start, when longitudinal velocities of all the particles are defined to be identical and determined from the total particle energy given by the user. However, as is often the case, several iterations are enough to obtain the actual initial distribution of transverse velocities in the beam with regard to the potential sagging effect due to space charge. Decreasing relative particle energy variation between iterations down to a value less than 10^{-5} is a convergence criteria. Hereafter beam particle energy recalculation is performed at every intermediate step of the Runge-Kutta method used for trajectory calculation (see section 2.5).

Note, that formulae given in this section for calculation of potential sagging and an electrical field produced by the beam space charge are valid in the case when the average radial velocity of beam particles is small as compared with the average longitudinal velocity only $< v_r > \ll \ < v_z >$. This condition is usually satisfied for long EOS, exclusive for areas of the gun and the collector.

2.4 Calculation Of External Fields

External electric and magnetic fields acting on a beam are calculated in BEAM program as a paraxial expansion by the following formulae:

$$E_r(r,z) = -\frac{r}{2}E'(z) + \frac{r^3}{16}E'''(z) - \frac{r^5}{384}E^{(5)}(z)\ ,$$

$$E_z(r,z) = E(z) - \frac{r^2}{4}E''(z) + \frac{r^4}{64}E^{(4)}(z)\ , \qquad (18)$$

where $E(r)$ is an axial field distribution, $E^{(n)} = \dfrac{d^n}{dz^n}E(z)$.

Values of axial fields and their first five derivations are calculated for finite set of node points by SAM program. A cubic spline interpolation is used for calculation of these values in an arbitrary z coordinate. The required calculation accuracy is provided by the high accuracy ($\sim 10^{-5}$) calculation of fields and their derivatives by SAM program in which the boundary element method is used.

2.5 Simulation Of A Beam Dynamics

The four-step Runge-Kutta method is used in BEAM program for a trajectory analysis. Therewith all the beam particle trajectories are calculated simultaneously with the same step along z axis, given in the process beginning. This step can be decreased simultaneously for all the particles in the following cases:

a) if the beam radius is less than Brillouin equilibrium radius r_B for a high perveance beam in magnetic field B:

$$a < r_B = 2r_{L\ \max}\sqrt{J}\ , \qquad (19)$$

where $r_{L\ \max} = \dfrac{m\gamma v}{eB}$ is the maximum Larmor radius of a particle trajectory, $J = \dfrac{Z_0 I_0}{2\pi(\gamma^2-1)^{3/2}mc^2}$ is a space charge factor, I_0 is the total beam current. Steps are divided by 2^n, where n is chosen so that the restriction $\frac{r_B}{2^n} < r < \frac{r_B}{2^{n-1}}$ is satisfied. This algorithm allows to simulate a dynamics of strongly pulsating beams in magnetic field, starting from fully or partly shielded cathode, with good enough accuracy.

b) if the step exceeds some fixed part of the maximal Larmor circle for the given value of magnetic field:

$$s > s_{\max} = \frac{2\pi r_{L\ \max}}{N}\ , \qquad (20)$$

where $2\pi r_{L\ \max}$ is the maximal length of the Larmor circle, $r_{L\ \max}$ has been introduced above, and N is an integer number, value of which are chosen empirically according to the accuracy of a trajectory integrating method. The step is also divided by 2^n so that the following restriction is satisfied:

$$\frac{s_{max}}{2^n} \leq s \leq \frac{s_{max}}{2^{n-1}}\ . \qquad (21)$$

The given algorithm allows to simulate dynamics in magnetic field for beams which started from the fully magnetized cathode with a high accuracy.

2.6 Data Input And Displaying Simulation Results

Data input for BEAM program can be proceeded either from a console in interactive mode or by reading data from a file.

Results of a calculation are displayed in interactive mode, at the same time a graphical representation of the results are displayed in a special graphic window. Therewith there is a possibility to get axial distributions of fields and potentials as well as beam envelopes containing the desired fractions of the total current. It is also possible to display transverse distributions of beam current and a beam phase portrait at the given number of integration steps.

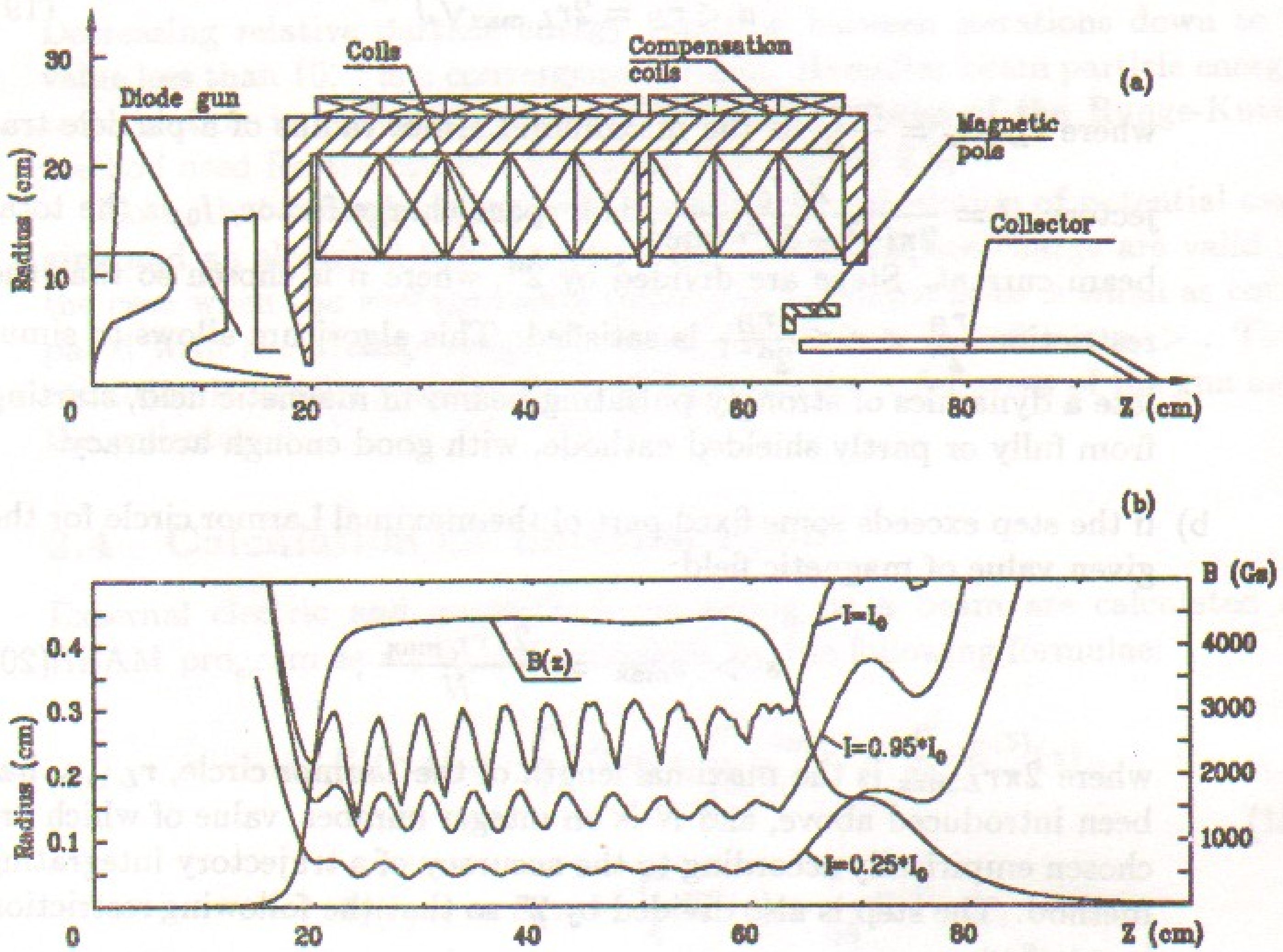

Figure 1: Simulation results for 100 MW beam (430 kV, 230 A) dynamics in the magnetic accompanying system of 7 GHz magnicon: a) general view of system; b) axial distribution of magnetic field and beam envelopes for different fractions of total beam current $I/I_o = 0.25, 0.95, 1$.

3 Examples of actual system simulations performed by beam profram

Simulation results for 100 MW beam (430 kV, 230 A) dynamics in a magnetic accompanying system of 7 GHz magnicon amplifier [4] have been cited as the first example. A general view of this system is shown in Fig.1a. A beam radius in the center of the solenoid with length ~500 mm for an accompanying magnetic field of about 4500 Gs is close to the Brillouin one (start from a shielded cathode) and makes up ~1 mm. Figure 1b shows simulation results for beam envelopes with the following fractions of the total beam current: $I/I_0 = 0.25, 0.95, 1$. A magnetic field axial distribution imported from SAM program and interpolated by cubic spline is also presented on this figure. A heat spread of beam particle transverse velocities has been taken into account. The beam has been formed in the gun with the cathode of 120 mm in diameter, a beam area compression is 1:3000. Transverse distributions of the current density and the beam phase portrait at minimum (a) and maximum (b) of beam envelope pulsating in the center of the solenoid are shown in Fig.2. Results of a beam envelope simulation presented in Fig.1 are in great agreement with measurement results published in [4].

One more example is simulation of electron beam dynamics within a drift tubes area of Electron Beam Test Stand (EBTS), which is a quasi-stationary prototype of Electron Beam Ion Source (EBIS) for Relativistic High Ion Collider (BNL) [5]. Beam parameters are: voltage of 70 kV and current of 22.5 A. The feature of that system is a necessity for effective ion accumulation of maximal beam deceleration near the main solenoid center down to an energy close to a critical value for virtual cathode appearing. For this purpose there is a set of isolated drift tubes with a diameter of ~30 mm with ~ 6 − 10 mm gaps between them. The central superconductive solenoid forms a magnetic field with B ~50 kGs, the beam radius in the center of the solenoid is about 0.8 mm, the drift tubes area total length between the gun and collector is about 2400 mm (see Fig.3a).

Originally simulation of this system was carried out by SuperSAM [3] and EGUN [6] programs through dividing all the system into short sections. However, the accuracy of the simulation was not good enough, so attempts to decelerate the beam caused a virtual cathode appearing at an energy about two times higher than the critical value. This problem has been overcome by the use of the special edition of BEAM program, modified especially for EBIS simulation (a model of short accelerating or decelerating gaps has been added).

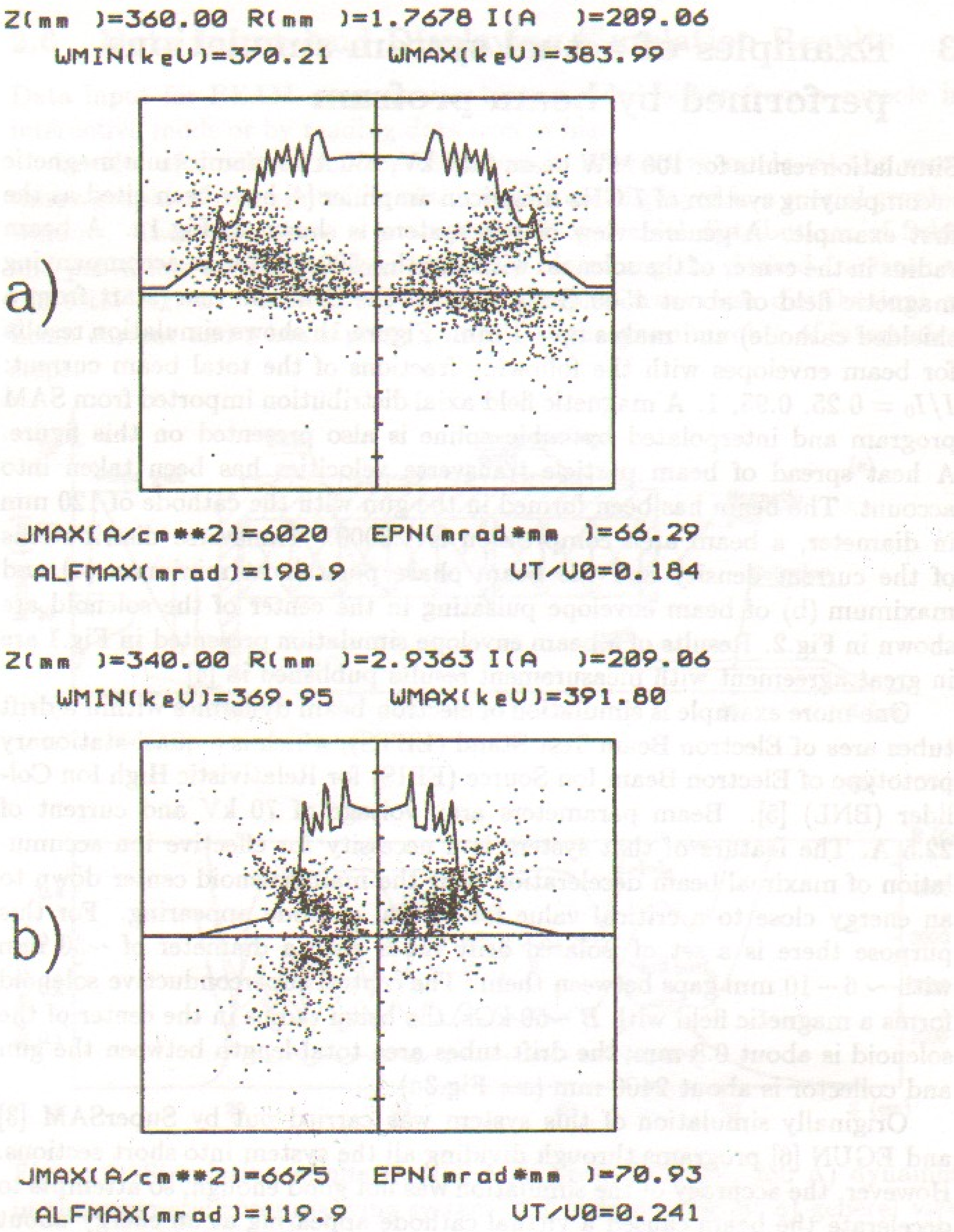

Figure 2: Current density distribution versus radius and beam phase portrait at minimum (a) and maximum (b) of beam envelope pulsating in the center of solenoid of magnetic accompanying system of 7 GHz magnicon.

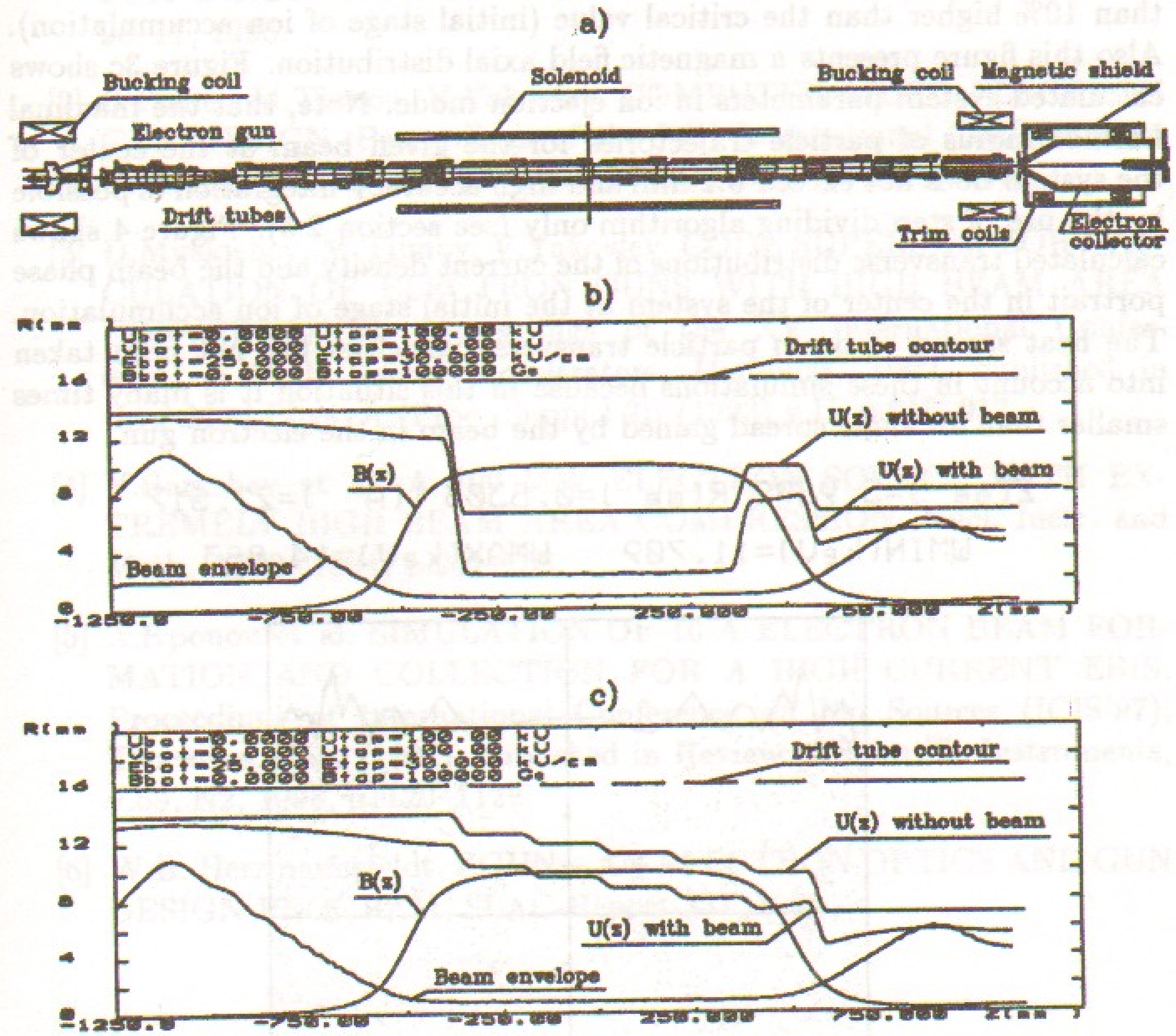

Figure 3: Results of simulation of the electron beam dynamics (70 kV, 22.5 A) within a drift tube area of EBIS prototype for RHIC (BNL): a) general view of system; b) axial distributions of magnetic field and potential with beam and without it and beam envelope at initial stage of ion accumulation; c) the same results in ion ejection mode.

Figure 3b shows results of simulation performed by BEAM program for a beam envelope and axial potential distributions with a beam and without it at beam decelerating in the center of the solenoid down to an energy no more than 10% higher than the critical value (initial stage of ion accumulation). Also this figure presents a magnetic field axial distribution. Figure 3c shows calculated system parameters in ion ejection mode. Note, that the maximal Larmor radius of particle trajectories for the given beam at the center of the system does not exceed 0.2 mm and high accuracy integration is possible by the use of step dividing algorithm only (see section 2.5). Figure 4 shows calculated transverse distributions of the current density and the beam phase portrait in the center of the system at the initial stage of ion accumulation. The heat spread of beam particle transverse velocities has not been taken into account in these simulations because in this situation it is many times smaller than an angle spread gained by the beam in the electron gun.

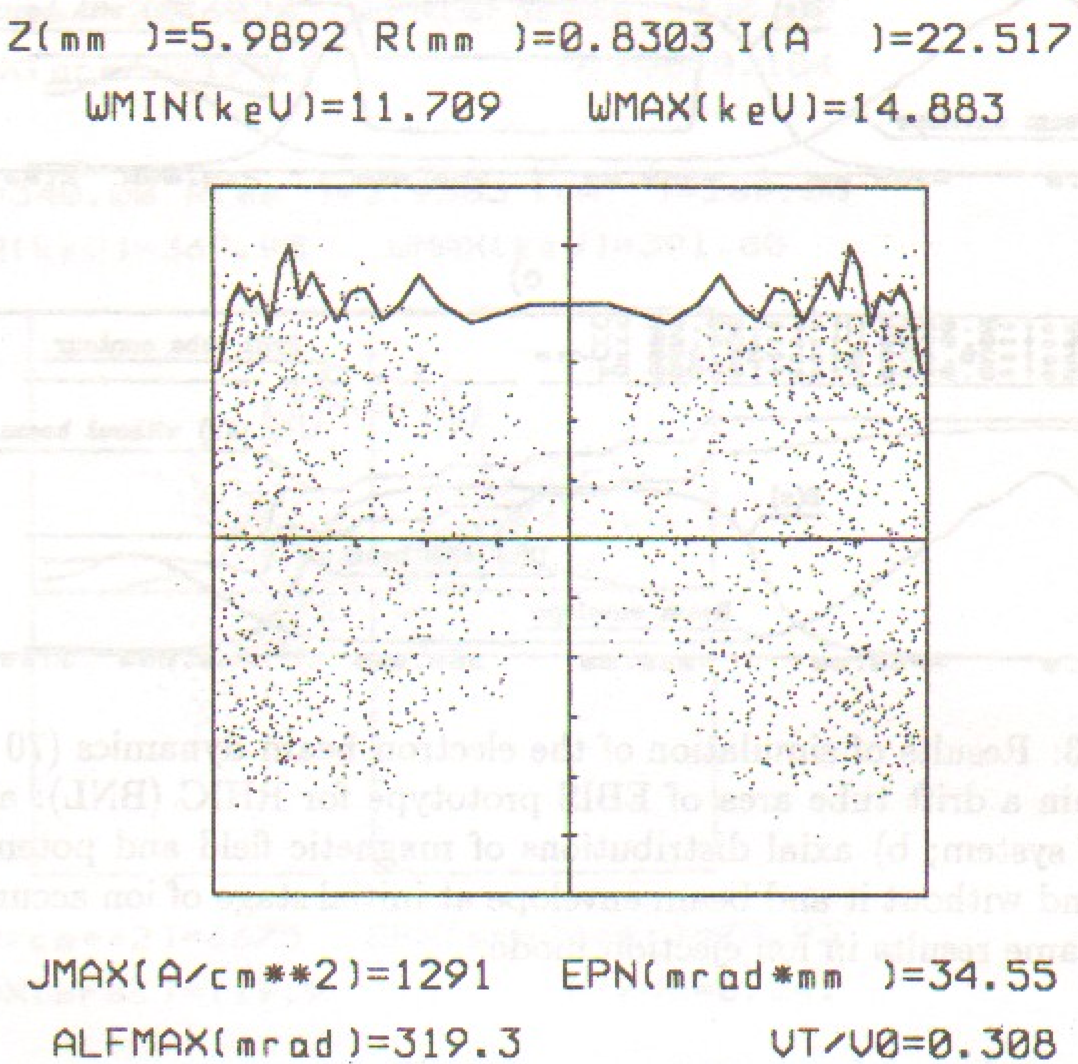

Figure 4: Results of current density versus radius and beam phase portrait calculation in the center of supercondactive solenoid of EBIS prototype for RHIC (BNL).

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BEAM – пакет двумерных программ
для расчета динамики высокопервеансных
пучков в длинных системах

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