

# BEAM DYNAMICS

## BEAMDULAC-BL CODE FOR 3D SIMULATION OF ELECTRON BEAM DYNAMICS TAKING INTO ACCOUNT BEAM LOADING AND COULOMB FIELD

*T.V. Bondarenko, E.S. Masunov, S.M. Polozov*

*National Research Nuclear University "Moscow Engineering Physics Institute", Moscow, Russia*

*E-mail: smpolozov@mephi.ru*

BEAMDULAC-BL 3D code is designed last years to study the beam dynamics in linac taking into account both Coulomb and RF self field. The code versions for traveling and standing wave linacs are ready for operation. The especially designed numerical methods and algorithms used for the code design are discussed. Specific computing problems, abilities of the code and future design plans are presented.

PACS: 29.17.w, 29.27.Bd

### INTRODUCTION

One of the most serious problems of beam dynamics simulation is to correctly treat the beam own space charge influence. Coulomb field, beam radiation and beam loading effect are the main factors of the own space charge. Typically, only the Coulomb field are taken into account for low energy LINACs and radiation for higher energies. But both factors should be treated in modern low and high energy high intensity LINACs and both effects can sufficiently influence the beam dynamics in bunchers. The mathematical model taking into account both Coulomb field and beam loading influence in stationary case and transient mode should be developed for self-consistent beam dynamics study. That is why three-dimensional self-consistent computer simulation of high current beam is very urgent.

Codes to study the beam dynamics taking into account beam loading effect are been designed at the MEPhI Department of Electrophysical facilities for many years. First was the 2D axial-symmetrical DINUS code [1] designed by V.I. Rashchikov. The 3D BEAMDULAC-BL codes are been under development last few years [2 - 5]. The theory of beam dynamics influence developed by E.S. Masunov [6] is used in such code. Known Cloud-in-Cell (CIC) technique is used to Coulomb field treatment.

Let us describe the beam loading effect briefly. The beam dynamics in an accelerator should be studied self-consistently taking into account both external field and beam own space charge field. The RF field induced by the beam in the accelerating structure depends on the beam velocity as well as the current pulse shape and duration. The influence of the beam loading can reduce the external field amplitude and induce the irradiation in the wide eigen frequency modes. Therefore we should solve the motion equations simultaneously with Maxwell's equations for accurate simulation of beam dynamics.

The method of kinetic equation and the method of large particles are most useful methods for self-consistent problem solving.

The beam dynamics can be calculated for only one beam part that has the phase length equal to one period of the external RF field in the stationary case. It is necessary to calculate the dynamics for all beam particles for the transient case. We have to take into account all particles of short current pulse which are inside of the accelerating structure in the moment of time. In this

case the analyzed beam can be represented in 2D or 3D phase space as a number of the large particles. These large particles would have the torus form (a ring with finite-size) with a rectangular cross-section for 2D simulation due to the axial symmetry of the task. The parallelepiped large particles forms are conveniently used in 3D case.

Let us consider the algorithm of beam dynamics simulations taking into account the beam loading effect in accelerators working on a traveling wave in the transient mode.

### 1. THEORETICAL BASIS OF THE BEAM LOADING TREATMENT

The charge of any large particle is:

$$Q = J_{\text{pulse}} \cdot \tau_{\text{pulse}} / N, \quad (1)$$

where  $J_{\text{pulse}}$  – the pulse beam current,  $\tau_{\text{pulse}}$  – the duration of the current pulse,  $N$  – the number of large particles.

The dynamics of every large particle should be simulated in the external field and in the own space charge field self-consistently.

The RF field distribution in the periodic structures is independent of the time when the beam time-of-flight is much smaller than the pulse duration. Only RF field amplitude is varied in this case and we can intend that such amplitude is varied slowly this time. The beam excited RF field can be represented a series of the harmonics (eigen modes) for all resonant structure frequencies:

$$\mathbf{E}(\mathbf{r}, t) \approx \text{Re} \sum_{\nu} \mathbf{E}_{\nu}(\mathbf{r}, t) e^{-i\nu\omega t}. \quad (2)$$

We can intend that the coefficients in the sum (2) are slow functions versus the time in case when the frequency  $\nu\omega$  is close to the own frequency of resonant structure  $\omega_r$  and

$$\mathbf{E}(\mathbf{r}, t) \approx C_r^{(\nu)}(t) \mathbf{E}_r(\mathbf{r}), \quad (3)$$

where  $\mathbf{E}_r(\mathbf{r})$  is the own resonator function of  $r$  mode,  $C_r^{(\nu)}(t)$  can be defined in the frequency domain. The Eq. (2) can be rewritten this case as

$$\mathbf{E} = \sum_r C_r(\omega) \mathbf{E}_r(\mathbf{r}), \quad (4)$$

and

$$C_r(\omega) = -i \frac{\omega}{\omega^2 - \omega_r^2} \frac{1}{N_r} \int \mathbf{j} \mathbf{E}_r dV, \quad (5)$$

where  $N_r$  – normalizing coefficient,  $V$  – volume of resonant structure,  $\omega_r$  is the eigen frequency of  $r$  mode,  $\tilde{\omega}_r = \omega_r - i\omega_r'' = \omega_r' \left( -i/2Q_L \right)$  is the complex frequency,  $Q_L = \omega_r' / 2\omega_r''$  is loaded Q-factor. Loaded Q-factor for high quality structures  $Q_L \gg 1$  and  $N_r = 2W_r / |C_r|^2$ , here  $W_r$  is the storage energy of  $r$  mode.

Function  $C_r(\omega)$  should satisfy an equation

$$-\frac{dC_r^{(v)}}{dt} + i(\omega - \omega_r') \tilde{C}_r^{(v)} = \frac{1}{2N_r} \int j(\mathbf{r}, t, \mathbf{v}) \tilde{\mathbf{E}}_r dV \quad (6)$$

and can be defined easily with this equation. The current harmonic  $j(\mathbf{r}, t, \mathbf{v})$  will be expanded to the Fourier series

$$j(\mathbf{r}, t, \mathbf{v}) = \frac{1}{\pi} \int_{-\pi}^{\pi} j(\mathbf{r}, t) e^{i\nu\omega t} d\omega \quad (7)$$

when it is slow function of the time.

The RF field in the resonator can be presented as a sum of direct and backward waves (the backward wave is absent for travelling wave case) and the field components are  $E_{r,z} = 2E_{r,z}^{(l)} \cos(k_{r,l} z)$ ,  $h_{r,l} = \pi n / N + 2\pi l / D$ ,  $n = 0, 1, \dots, N-1$  and here is intended that the  $L$  resonator length consist of  $N$  periods,  $D=L/N$ .

Let we introduce the nonlinear phase  $\varphi(\mathbf{r}, t, t_0) = h_r z(t) - \omega t + \omega_0 t_0$ , where  $t_0$  is the time of particle input into the resonator. Because of total beam charge if the constant  $j dt = j_0 \int_0^{t_0} dt$  we can define the  $\nu$ -th beam current harmonic as

$$\tilde{I}_\nu(z) = \frac{1}{\pi} \int_{-\pi}^{\pi} \Pi(\varphi_0) e^{i\nu(\varphi_0 - \varphi)} d\varphi, \quad (8)$$

where  $\Pi(\varphi_0) = \omega_0 t_0$  is the initial beam phase distribution. Now the Eq. (5) can be solved:

$$\begin{aligned} \tilde{E} &= C_r \langle E_r \rangle, \\ -\frac{d\tilde{E}_r}{dt} + i(\omega - \omega_r') \tilde{E}_r &= \omega_r' \frac{J_0 R_{sh}}{2QL} \tilde{I}_\nu^{r,r'}, \quad (9) \\ \tilde{I}_\nu^{r,r'} &= \frac{1}{L} \int_0^L I_\nu(z, t) e^{i(\varphi_r - h_r z)} dz. \end{aligned}$$

Here  $R_{sh}$  is the shunt impedance. Such equation is the non-stationary excitation equation. It is written without any assumptions and can be used to simulate the self-consistent beam dynamics in resonator or waveguide accelerating structure taking into account beam loading effect.

It is easy to generalize this equation taking into account the field attenuation in the structure and the structure dispersion [5]. It should be remembered that for the fixed time  $t$  and for the length  $\Delta z$  the field value is additionally reduced by the small amount of  $-\left( \alpha - \frac{1}{2R_{sh}} \frac{\Delta R_{sh}}{\Delta z} \right) \tilde{E}^+$ . Here  $\alpha$  is the RF power attenuation. As the result we will finally have the equation of beam motion in the point of bunch placement taken into account the beam loading effect [6]:

$$\begin{aligned} \left( -\frac{1}{v} \pm \frac{1}{v_{gr}} \right) \frac{\partial \tilde{E}^+}{\partial t} + \frac{\partial \tilde{E}^+}{\partial z} + \left( \alpha - \frac{1}{2R_{sh}} \frac{dR_{sh}}{dz} \right) \tilde{E}^+ \pm \\ \pm R_{sh} \tilde{I}_1(\mathbf{r}, t) = 0. \end{aligned} \quad (10)$$

For system having positive dispersion sign “+” should be used and “-” for structure with negative one.

There are no limitations on the value of the group velocity in the derivation of non-stationary equations of excitation (9), (10). So they will be used just like for highly dispersed systems and for the weak dispersion of waveguide systems. The transient mode field excited by the beam with  $\tau_{pulse} < T_f$  can be calculated using Eq. (9) and (10). Indeed the transient mode beam loading problem can be solved for the resonant system for different matching conditions at the waveguide section ends and without any limitations to the beam current values and the group velocities  $v_{gr}$ .

The time dependence in Eq. (10) disappears for the long pulse duration  $\tau_{pulse} > T_f$  and we can acquire the equation:

$$\frac{d\tilde{E}^+}{dz} + \left( \alpha - \frac{1}{2R_{sh}} \frac{dR_{sh}}{dz} \right) \tilde{E}^+ = \mp R_{sh} I_1. \quad (11)$$

The stationary field distribution and the current harmonics magnitudes along of the longitudinal coordinate  $z$  could be calculated using this equation.

## 2. THE EQUATION OF MOTION IN SELF CONSISTENT FIELD FOR THE TRAVELLING WAVE

The motion equation can be written in 3D Cauchy form and in addition equation defines the RF field amplitude variation during the beam loading. The Coulomb field and the external focusing solenoid magnetic field should be taken into account. We will consider the stationary case and only base RF field and beam current harmonic for simplicity. Finally the motion equations are:

$$\begin{aligned} \frac{d\gamma}{d\tau} &= \beta_z \hat{e}_0 \xi S_0 + \hat{b}_{0,\perp} \beta_z S_1 \eta \beta_x - \rho \beta_y + \hat{e}_z^c, \\ \frac{d\beta_x}{d\tau} &= \hat{e}_0 \xi S_1 \rho / \gamma + \hat{b}_{0,z} \xi \beta_y S_0 - \hat{b}_{0,\perp} \xi \beta_z S_1 \eta / \gamma - \\ &-\hat{e}_0 \xi \beta_x \beta_z S_0 + S_1 (\rho \beta_x + \eta \beta_y) / \gamma - \\ &-2B(\xi) \Sigma_s \sin \varphi / \gamma - \hat{b}_{sol} \rho / \gamma + \hat{e}_x^c / \gamma, \\ \frac{d\beta_y}{d\tau} &= \hat{e}_0 \xi S_1 \eta / \gamma + \hat{b}_{0,\perp} \xi \beta_z S_1 \rho - \hat{b}_{0,z} \xi \beta_x S_0 / \gamma - \\ &-\hat{e}_0 \xi \beta_y \beta_z S_0 + S_1 (\rho \beta_x + \eta \beta_y) / \gamma - \\ &-2B(\xi) \Sigma_s \sin \varphi / \gamma - \hat{b}_{sol} \eta / \gamma + \hat{e}_y^c / \gamma, \\ \frac{d\rho}{d\tau} &= \beta_x, \quad \frac{d\eta}{d\tau} = \beta_y, \quad \frac{d\xi}{d\tau} = \beta_z, \end{aligned} \quad (12)$$

$$\frac{d\phi}{d\tau} = \left( \frac{\beta_z}{\beta_{ph}} - 1 \right) \pm \frac{B \Sigma_s}{\hat{e}_0(\xi)},$$

$$\frac{d\hat{e}_0}{d\xi} = \left( \frac{d \ln B}{2d\xi} - w \right) \hat{e}_0(\xi) \mp 2B \Sigma_c + \frac{d\hat{e}_{0,m}}{d\xi},$$

here  $\tau = \omega t$  is the normalized time;  $\hat{e}_0 \xi = eE_0 z \lambda / 2\pi W_0$  is the amplitude of RF field taking into account it's modification during initial distribution, beam loading and attenuation;  $\hat{b}_{0,z} \xi = eB_{0,z} z \lambda c / 2\pi W_0$  and  $\hat{b}_{0,\perp} \xi = eB_{0,\perp} z \lambda c / 2\pi W_0$  are normalized amplitudes of magnetic components of

RF field;  $\beta_z = v_z/c$ ,  $\beta_x = v_x/c$ ,  $\beta_y = v_y/c$  and  $\beta_{ph} = v_{ph}/c$  is the phase velocity of the wave;  $\gamma = 1/\sqrt{1-\beta_z^2}$ ;  $\xi = 2\pi z/\lambda$ ,  $\rho = 2\pi x/\lambda$ ,  $\eta = 2\pi y/\lambda$  are normalized coordinates;  $\hat{b}_{sol} = eB_{sol}\lambda c/2\pi W_0$  is normalized amplitude of solenoid magnetic field;

$$S_0 = I_0 \left( \frac{\sqrt{\rho^2 + \eta^2}}{\beta_{ph}\gamma} \right) \cos\varphi,$$

$$S_1 = -\frac{1}{\sqrt{\rho^2 + \eta^2}} I_1 \left( \frac{\sqrt{\rho^2 + \eta^2}}{\beta_{ph}\gamma} \right) \sin\varphi, \quad I_0 \text{ and } I_1 \text{ are}$$

modified Bessel functions;  $\hat{e}_{x,y,z}^c = eE_{x,y,z}^c \lambda/2\pi W_0$  are normalized components of Coulomb field;  $\varphi = \int \frac{d\xi}{\beta_{ph}} - \tau$  is the particle phase;  $w = \alpha\lambda/2\pi$  is the

normalized attenuation;  $B(z) = eJ_1(z,t)\lambda^2 R_{sh}(z)/4\pi W_0$  is the beam-wave coupling coefficient,  $J_1(z,t)$  is the first harmonic of the beam current;

$$\Sigma_c = \frac{1}{N} \sum_n I_0 \left( \frac{\sqrt{\rho_n^2 + \eta_n^2}}{\beta_{ph}\gamma} \right) \cos\varphi_n,$$

$$\Sigma_s = \frac{1}{N} \sum_n I_0 \left( \frac{\sqrt{\rho_n^2 + \eta_n^2}}{\beta_{ph}\gamma} \right) \sin\varphi_n, \quad N \text{ is the number of}$$

large particles representing the bunch; part  $d\hat{e}_{0,m}/d\xi$  in the last equation defines the dependence of RF field amplitude in cold system;  $\omega$  and  $\lambda$  are frequency and wave length of the main RF field harmonics;  $W_0 = mc^2$ . For system having positive dispersion sign “+” should be used for Eq. for phase and “-” for Eq. for amplitude and opposite signs should be used for structure having negative dispersion.

### 3. THE EQUATION OF MOTION IN SELF CONSISTENT FIELD FOR THE STANDING WAVE

The motion equations for standing wave operating structure the motion equation are the similar to the traveling wave ones:

$$\begin{aligned} \frac{d\gamma}{d\tau} &= \beta_z \hat{e}_0 \xi S_0 + \hat{b}_{0,\perp} \beta_z S_1 \eta \beta_x - \rho \beta_y + \hat{e}_z^c, \\ \frac{d\beta_x}{d\tau} &= \hat{e}_0 \xi S_1 \rho / \gamma + \hat{b}_{0,z} \xi \beta_y S_0 - \hat{b}_{0,\perp} \xi \beta_z S_1 \eta / \gamma - \\ &- \hat{e}_0 \xi \beta_x \beta_z S_0 + S_1 (\rho \beta_x + \eta \beta_y) / \gamma - \\ &- B(\xi) \Sigma_s \sin\varphi / \gamma - \hat{b}_{sol} \rho / \gamma + \hat{e}_x^c / \gamma, \\ \frac{d\beta_y}{d\tau} &= \hat{e}_0 \xi S_1 \eta / \gamma + \hat{b}_{0,\perp} \xi \beta_z S_1 \rho - \hat{b}_{0,z} \xi \beta_x S_0 / \gamma - \\ &- \hat{e}_0 \xi \beta_y \beta_z S_0 + S_1 (\rho \beta_x + \eta \beta_y) / \gamma - \\ &- B(\xi) \Sigma_s \sin\varphi / \gamma - \hat{b}_{sol} \eta / \gamma + \hat{e}_y^c / \gamma, \\ \frac{d\rho}{d\tau} &= \beta_x, \quad \frac{d\eta}{d\tau} = \beta_y, \quad \frac{d\xi}{d\tau} = \beta_z, \end{aligned} \quad (13)$$

$$\frac{d\varphi}{d\tau} = \frac{\beta_z}{\beta_{ph}} \pm \frac{B\Sigma_s}{\hat{e}_0(\xi)},$$

$$\frac{d\hat{e}_0}{d\xi} = \left( \frac{d \ln B}{d\xi} - w \right) \hat{e}_0(\xi) \mp B\Sigma_c + \frac{d\hat{e}_{0,m}}{d\xi},$$

$$\text{where } S_0 = I_0 \left( \frac{\sqrt{\rho^2 + \eta^2}}{\beta_{ph}\gamma} \right) \cos \left( \int \frac{d\xi}{\beta_{ph}} \right) \cos\tau,$$

$$S_1 = -\frac{1}{\sqrt{\rho^2 + \eta^2}} I_1 \left( \frac{\sqrt{\rho^2 + \eta^2}}{\beta_{ph}\gamma} \right) \sin \left( \int \frac{d\xi}{\beta_{ph}} \right) \cos\tau \text{ and}$$

other variables are the same as for traveling wave.

The algorithm of simulation for the transient mode is mainly similar to the algorithm developed for the stationary case [1 - 2]. The method of Coulomb field treatment used for BAMDULAC-BL and BEAMDULAC-BLNS code was discussed in [3].

### 4. ALGORITHMS OF SIMULATION

The BEAMDULAC code is developed for self-consistent beam dynamics investigation in RF LINACs and transport channels as it is noted above [4, 7, 8]. The 2D (axial-symmetrical) and 3D (Cartesian) dynamics beams can be studied by means of this code.

The BEAMDULAC code utilizes the cloud-in-cell (CIC) method to accurate treat the quasi-statically space charge effects (Coulomb field) that are especially important in the case of a high-intensity beam. The motion equation for each particle is solved in the external fields and the inter-particle Coulomb field simultaneously. The charge density is deposited on the grid points using the CIC technique. To determine the potential of the Coulomb field, the Poisson equation is solved on the grid with periodic boundary conditions at both ends of the domain in the longitudinal direction. The aperture of the channel is represented as an ideally conducting surface of rectangular or circular cross-section. Therefore the Dirichlet boundary conditions are applied at transverse boundaries of the simulation domain. In such an approach, the interaction of the bunch space charge with the accelerating channel boundaries is taken into account. This allows consideration of the shielding effect, which is sufficiently important for transverse focusing in the narrow channel. The fast Fourier transform (FFT) algorithm is used to solve the Poisson equation on a 3D grid. The Fourier series for the space charge potential obtained can be analytically differentiated, and thus each component of the Coulomb electrical field can be found as a series with known coefficients and the RF field distribution on the grid can be calculated having the same accuracy as the potential.

Standard fourth-order Runge-Kutta method is applied for integration of the motion equation. The external fields in BEAMDULAC code can be represented three different methods: analytically, as a series of space harmonics (the field amplitude is represented as a polynomial coefficient series) and in “real field” which is defined on 2D or 3D grid by electrodynamics simulation codes or experimental measurement [8].

A number of initial particles distributions (uniformly, gauss and water bag) can be defined by user by

means of Twiss-parameters or phase ellipses sizes and initial emittances.

Two ways to define the structure parameters were utilized at BEAMDULAC-BL code. The first is to define the structure as a number of slow varying variables (versus longitudinal coordinate) as: RF field amplitude, phase velocity, aperture size, RF field attenuation, shunt (or series) impedance. Functions as shown at Fig. 1 are used and they are represented by the series as

$$f(\xi) = \sum_{n=0}^{n_{max}} a_n \xi^n$$

with user defined number of the series is used to simulate the solenoid field distribution.

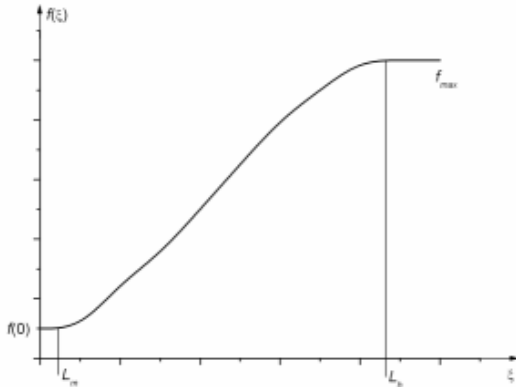


Fig. 1. General view of the function used to define structure parameters,  $f(0)$  and  $f_{max}$  are minimal and maximal function values,  $L_m$  and  $L_b$  are the matching and bunching parts of channel lengths respectively

The cell-to-cell parameters definition is the other way to describe the structure. The view of the “structure” file is shown in Fig. 2. Main geometrical and field parameters should be defined by user for all structure cells. Such way allows easy describing the structures operating in  $\pi$  or  $\pi/2$  modes.

N	beta_s	0_n	GAP_H	E_n	kV/cm	H_1	A/m	H_t	A/m	f_i	E	A	H	Bsol	T	ALFA_ATT	R_p	OHM/H
1	0.80	0.08	0.08	57.0	0.	0.	0.	0.	0.01	0.1	0.	50.E+6						
2	0.87	0.087	0.087	58.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
3	0.94	0.094	0.094	59.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
4	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
5	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
6	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
7	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
8	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
9	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							
10	1.00	0.1	0.1	60.0	0.	0.	0.	0.01	0.1	0.	50.E+6							

Fig. 2. General view of the “structure” file

But cell-to-cell structure definition way has one serious difficulty. The merging of piecewise defined parameters should be done accurately. The two steps merging algorithm is used in BEAMDULAC-BL. The user defines the part of cell in which the structure parameter is constant and after that the parabolic interpolation is used. An example of merging algorithm application is illustrated in Fig. 3. The RF field amplitude distribution in biperiodic ( $\pi/2$  mode) DLW structure with small drift tubes on diaphragms is shown.

Note that the time is used as the independent value to solve motion equations. But the equation of RF field amplitude variation taking into account beam loading, RF field attenuation and etc. is defined using the longitudinal coordinate. It was necessary to define the longitudinal grid to solve such equation and the RF ampli-

tude distribution is calculated every time step to correct treat its variation during the bunch motion.

A number of standard tests were used to verify the code: short bunch motion in external magnetic field (without acceleration and with it); beam transverse size enlargement along the Coulomb field influence (beam drift test) and etc.

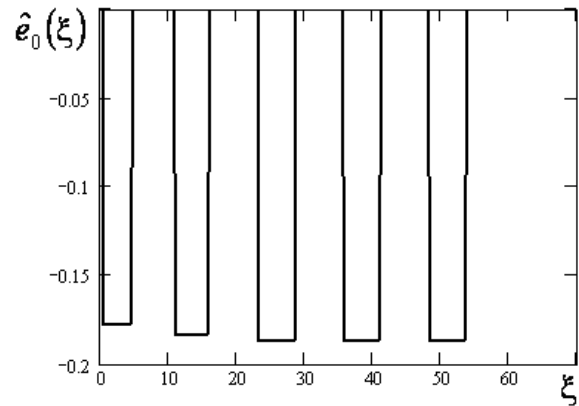


Fig. 3. An example of merging algorithm application for cell-to-cell structure definition

The verification of the beam loading algorithm is much more difficult procedure. Only power balance calculation gives the necessary information. Indeed the total beam power growth is calculated step-by-step and compared with storage RF power losses. The storage

power is defines as 3D integral of  $\int_V [E_z(\xi, \rho, \eta)]^2 dV$ .

The distribution simulated for standard disk loaded waveguide (DLW) was used to define the transverse dependence and the simulated  $E_z(\xi)$  distribution to define the longitudinal one. The comparison shows very good tolerance of the developed algorithm. The test in which the traveling wave has zero amplitude at the end of section (limit current test) was also used. Such test can be verified analytically.

## 5. EXAMPLES OF SIMULATION

Finally results of two beam dynamics simulations are presented. They are the simulation of short high-brightness bunch dynamics in regular traveling wave accelerating section with main parameters as: section length 85 cm, minimal and maximal RF field amplitude 57 and 60 kV/cm (for not loaded structure, attenuation is absent), phase velocity increases in range 0.8...1.0, channel aperture 1 cm, series impedance 50 MOhm/m,  $\lambda=10$  cm, initial transverse emittance 2.5 mm-mrad, solenoid field 0.1 T. The results of the simulation with beam current 7 A are shown in Fig. 4 and with 70 A in Fig. 5: the dependence of RF field amplitude (a), bunch averaged energy (b) and beam envelope (c) versus longitudinal coordinate, phase spaces in  $(\gamma, \varphi)$  (d) and  $(\beta_x, x)$  (e) phase spaces and beam cross-section (f). The initial beam parameters of Figs. 4, 5,d,e are shown by red color, output – by blue. Note that the RF field amplitude is equal to zero at the end of channel in second case because of the beam loading.

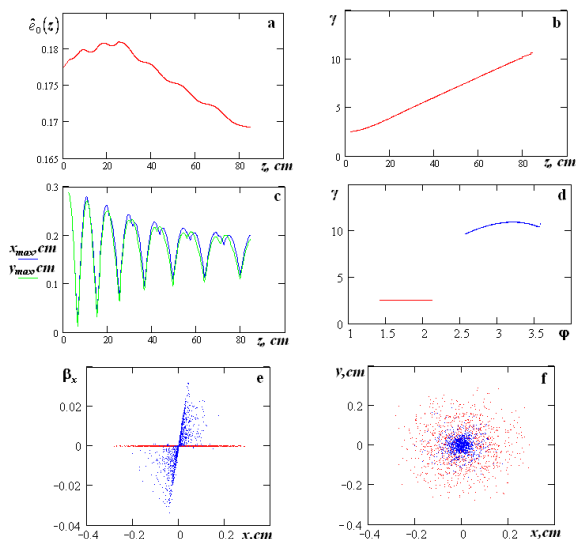


Fig. 4. Beam dynamics simulation results for beam current 7 A

### CONCLUSIONS

The code BEAMDULAC-BL for the beam dynamics simulation taking into account both beam loading and Coulomb field is discussed. The having four versions code is developed: for traveling and standing waves and for two ways of structure parameters definition (by function and cell-to-cell). The analytical suggestions which were used to develop the code are presented. Algorithms, difficulties, code testing methods and results of simulation are presented.

The further code testing and comparison with operating LINACs are the following task. The problem of beam dynamics simulation in case when the RF pulse and beam pulse lengths are approximately similar should also be studied.

This work is supported in part by the Ministry of Science and Education of Russian Federation under contract № 14.516.11.0084.

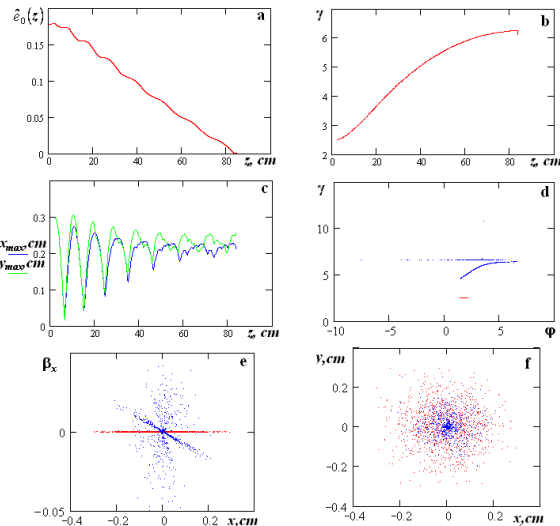


Fig. 5. Beam dynamics simulation results for beam current 70 A

### REFERENCES

1. E.S. Masunov, V.I. Rashchikov. *Accelerators*. Moscow: "Atomizdat". 1977, №17, p. 96.
2. E.S. Masunov et al. / *Proc. of IPAC'2010*. 2010, p. 1348.
3. E.S. Masunov et al. / *Proc. of HB 2010*. 2010, p. 123.
4. E.S. Masunov, S.M. Polozov // *Phys. Rev. ST AB*. 2008, v. 11, p. 074201.
5. E.S. Masunov // *Sov. Phys. – Tech. Phys.* 1977, v. 47, p. 146.
6. E.S. Masunov, S.M. Polozov, V.I. Rashchikov, A.V. Voronkov // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2012, v. 4(80), p. 96-99.
7. E.S. Masunov, S.M. Polozov // *NIM A*. 2006, v. 558, p. 184-187.
8. E.S. Masunov, S.M. Polozov // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2006, v. 3(47), p. 119-121.

Article received 03.09.2013

### ПАКЕТ ПРОГРАММ BEAMDULAC-BL ДЛЯ ТРЕХМЕРНОГО МОДЕЛИРОВАНИЯ ДИНАМИКИ ЭЛЕКТРОННЫХ ПУЧКОВ С УЧЕТОМ СОБСТВЕННОГО ЭЛЕКТРОСТАТИЧЕСКОГО ПОЛЯ И НАГРУЗКИ ТОКОМ

*Т.В. Бондаренко, Э.С. Масунов, С.М. Полозов*

Рассмотрены алгоритмы и численные методы, использованные в новой версии программы BEAMDULAC-BL для трехмерного численного моделирования динамики с учетом как квазистатического поля, так и нагрузки током. Обсуждаются специфические проблемы, возникшие при разработке, основные возможности программы и планы ее дальнейшего развития.

### ПАКЕТ ПРОГРАМ BEAMDULAC-BL ДЛЯ ТРИВИМІРНОГО МОДЕЛЮВАННЯ ДИНАМІКИ ЕЛЕКТРОННИХ ПУЧКІВ З УРАХУВАННЯМ ВЛАСНОГО ЕЛЕКТРОСТАТИЧНОГО ПОЛЯ І НАВАНТАЖЕННЯ СТРУМОМ

*Т.В. Бондаренко, Е.С. Масунов, С.М. Полозов*

Розглянуто алгоритми та чисельні методи, використані у новій версії програми BEAMDULAC-BL для тривимірному чисельного моделювання динаміки з урахуванням як квазістатичного поля, так і навантаження струмом. Обговорюються специфічні проблеми, що виникли при розробці, основні можливості програми та плани її подальшого розвитку.