# NEW VERSIONS OF THE BEAMDULAC CODE FOR HIGH INTENSITY ION BEAM DYNAMICS INVESTIGATION

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New versions of the BEAMDULAC code are described. Such code can be used for high intensity ion beam dynamics investigation in linear accelerators. New abilities of the code are presented and the code testing is observed. A code version for beam dynamics investigation in a beam transport channel is also discussed.

*PACS:* 29.17.+w, 29.27.Bd

## 1. INTRODUCTION

The correctly investigation of a self-consistent beam dynamics in linear RF accelerators and beam transport channels is one of traditional tasks. The influence of the beam Coulomb field is the main problem for low-energy high intensity ion accelerators. The accurate calculation of this field is a problem in beam dynamics. Several methods of Coulomb field treatment are well known: a uniformly charged ellipsoid, particle-to-particle methods and particle-in-cell methods.

A number of codes for beam dynamics study, such as DYNAMION, TRACE, PARMELA, COBRA and etcetera are well known. Each of these codes has own range of the application, own abilities and drawbacks, different methods for Poisson and motion equations solving are used.

The BEAMDULAC code was developed at Moscow Engineering Physics Institute by E.S. Masunov, N.E. Vinogradov, and S.M. Polozov in 1999. This code was early computed for self-consistent beam dynamics study in an axisymmetric radio frequency focusing (ARF, [1]), a ribbon radio frequency focusing (RRF, [2]) accelerators and undulator accelerators (UNDULAC, [3, 4]). 2D and 3D versions were developed for axisymmetric structures and ribbon beams, respectively.

Let us briefly observe the old versions of the BEAMDULAC code.

## 2. BEAMDULAC CODE

The BEAMDULAC code utilizes the cloud-in-cell (CIC) method for accurate treatment of the space charge effects 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. 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 of ribbon beams. 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. The Coulomb repulsion force is the main factor limiting the beam current in high-intensity linacs. In our code, the space charge field can be calculated with the same precision as the Coulomb potential without numerical differentiation.

The external fields in the BEAMDULAC code are represented as a series of space harmonics. The field amplitude is represented as a polynomial coefficient series. Time is used as an independent variable and standard fourth-order Runge-Kutta method is applied for integration of the motion equation.

The different version of BEAMDULAC code was used for beam dynamics investigation in RF accelerators noted above. The especial version was computed for dynamics study in UNDULAC-E linac in which the RF and electrostatic fields are used.

## 3. NEW CODE

The external fields in old version of the BEAMDULAC code are represented analytically as a series of space harmonics as it was noted above. This disadvantage does not permits to use such code for beam dynamics study in a “real field” which is defined on 2D or 3D grid by electrodynamics simulation codes or experimental measurement. The new code versions were designed for this case.

### 3.1. 2D GRID

The investigation of beam dynamics in external fields represented on grid is not an easily task. A correct multidimensional interpolation is the main problem. The traditional methods of interpolation as a polynomial or spline can not be used in this case because the field can be fast oscillating and have a great number of local extremums and zeros on a grid.

The code version for 2D grid (BEAMDULAC-G2D) utilizes the well known “area weighted interpolation” (Fig.1) method for this goal. Let us recall the main characteristics of this method. For clarity, we will consider this method with a constant grid step for both *r* and *z* directions, namely $h_z$ and $h_r$. Let us suppose a particle is located at a point μ and the field is known in four node points $E_{i,j}$, $E_{i+1,j}$, $E_{i,j+1}$ and $E_{i+1,j+1}$. The grid cell area is known $S= h_z{\cdot}h_r$. The desired point μ puts into rectangular cell center, which sides are $h_z$ and $h_r$. Let us have four cells with areas $S_{i,j}$, $S_{i+1,j}$, $S_{i,j+1}$ and $S_{i+1,j+1}$. Next, the field $E_\mu$ can be calculated by means of the area weighted method:

$$E_\mu = \frac{1}{S}\sum_{i}^{i+1}\sum_{j}^{j+1} E_{i,j}\cdot S_{i,j} \ . \qquad (1)$$

This method can be easily used with a varying grid step also.

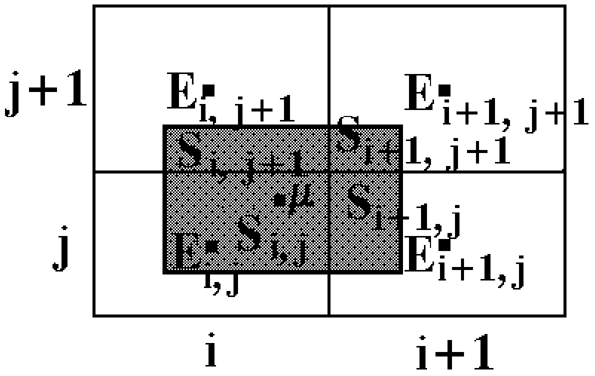


*Fig.1. Area weighted interpolation method*

The choosing of extrapolation methods is also important for the simulation. The traditional Fourier extrapolation technique was used in the BEAMDULAC-G2D code for calculations in a longitudinal direction. It is possible because the field in accelerators is periodical. The field is represented as a series of space harmonics for transverse interpolation. The harmonic amplitudes can be calculated in this case and the field is extrapolated by a series of Bessel functions.

### 3.2. 3D GRID

The "volume weighted interpolation" is used in the BEAMDULAC-G3D. This method is similar to previously observed for the 2D case. The external field must be defined in eight grid points and a grid sell volume $V$ must be known. The field in a desired point μ is equal now to:

$$E_\mu = \frac{1}{V}\sum_{i}^{i+1}\sum_{j}^{j+1}\sum_{k}^{k+1} E_{i,j,k}\cdot V_{i,j,k} \ . \qquad (2)$$

The similar extrapolation techniques are used for the 2D and 3D simulation. Fourier extrapolation is used in the longitudinal direction and the series of space harmonics and hyperbolic sine and cosine for the transverse one.

## 4. ERRORS OF SIMULATION AND BEAMDULAC-GRID TESTING

A high accuracy of simulation was achieved by means of the area and volume weighting interpolation methods. An interpolation error in the field calculation is no more than 0.5% for the 2D case and 2% for the 3D case. An extrapolation error in the longitudinal direction is 0.5…2%. In the transverse directions it is 1…3% for 2D dynamics and 1…5% for 3D.

The results of beam dynamics simulation in the RF field defined on a grid was compared with the results obtained for the analytically defined field. The comparison was provided for the ARF, RRF and UNDULAC linacs. Some results of ion beam dynamics simulation with the analytically defined and "real field" are shown in Fig.2,3. The longitudinal and transverse emittances are plotted for the ARF structure (2D beam dynamics) in Fig.2. The output longitudinal and input ("×"-s) and output ("points") transverse emittances were calculated for an ion with a charge-to-mass ratio A/Z=1/60 in the analytically defined field (Fig.2,a and 2,c respectively) and in the "real field" (Fig.2,b and 2,d). It is clear from the figure that the simulation results are similar and simulation on a grid was performed with the high accuracy.

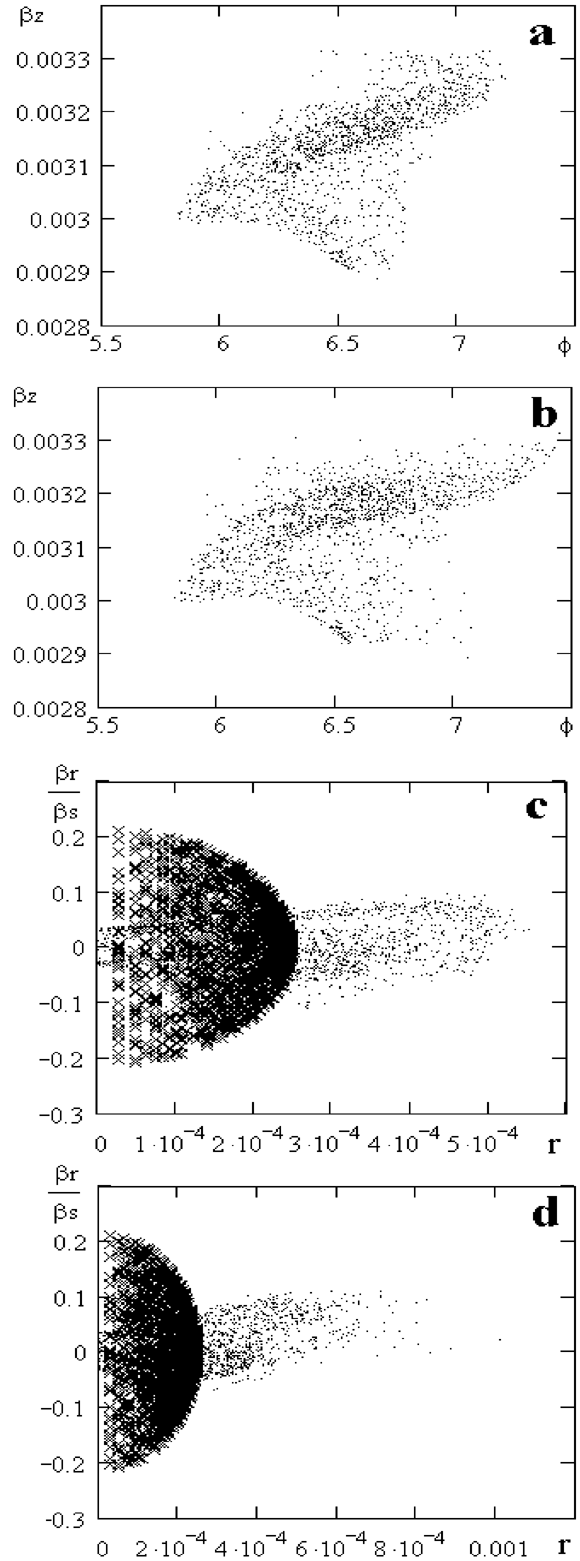


*Fig.2. 2D beam dynamics simulation results*

The input and output transverse emittances of a deuterium ion beam are shown in Fig.3. The beam dynamics was calculated for the UNDULAC-RF accelerator

(3D dynamics). The beam has a small halo if the beam dynamics was calculated in the “real field” (see Fig.3,b). It is come through the extrapolation error.

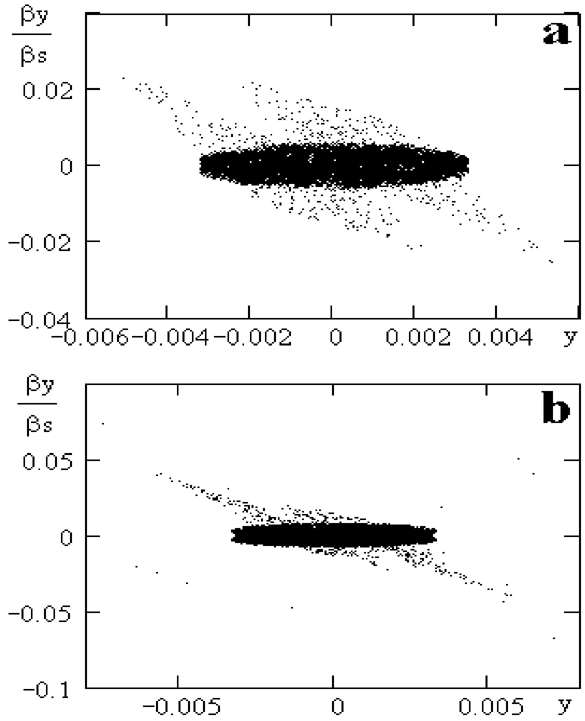


*Fig.3. 3D beam dynamics simulation results*

## 5. BEAMDULAC-T FOR BEAM TRANSPORT CHANNELS

The transport of low energy ion beams from a source to an accelerator or target is very difficult. The choice of an effective beam transport system design depends on the main beam parameters, such as initial transverse emittance, ion energy, charge to mass ratio, beam current. The transport design of high intensity low energy ($W$=0.1...1 keV/u) ion beams for A/Z=1/10...1/120 is very complicated. Generally, systems of magnetic or electrostatic lenses are used for the axisymmetrical beam focusing. For transport of intensive ribbon ion beams a special beam line is needed. The periodic system of electrostatical lenses (electrostatic undulator) was suggested for this goal [5]. The version of the BEAMDULAC code was developed for beam dynamics study in electrostatic transport channels.

It was shown using the BEAMDULAC-T code that the heavy ion low energy beams could be transported at a distance of several meters by the electrostatic undulator. The beam quality does not degrade.

## 6. CONCLUSION

The new BEADULAC code versions are observed. The codes are computed for beam dynamics investigation in RF field defined on 2D and 3D grid. It was shown that these new code versions are effective for ion beam dynamics study in RF linacs and transport channels. The simulation methods allow having the high accuracy of calculation. In future, a code will be developed for beam dynamics study in crossed electric and magnetic field. Versions for the RFQ and multi-ion beams are in future plans as well.

The work was supported by RFBR: Grant 04-02-16667.

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## НОВЫЕ ВАРИАНТЫ ПРОГРАММЫ BEAMDULAC ДЛЯ ИЗУЧЕНИЯ ДИНАМИКИ ИНТЕНСИВНЫХ ИОННЫХ ПУЧКОВ

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Рассматриваются новые варианты программы BEAMDULAC. Эта программа предназначена для изучения динамики сильноточных ионных пуков в линейных ускорителях. Рассматриваются новые возможности программы и результаты тестирования. Также обсуждается вариант программы, предназначенный для исследования динамики пучков в каналах транспортировки.

## НОВІ ВАРІАНТИ ПРОГРАМИ BEAMDULAC ДЛЯ ВИВЧЕННЯ ДИНАМІКИ ІНТЕНСИВНИХ ІОННИХ ПУЧКІВ

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Розглядаються нові варіанти програми BEAMDULAC. Ця програма призначена для вивчення динаміки потужнострумових іонних пуків у лінійних прискорювачах. Розглядаються нові можливості програми і результати тестування. Також обговорюється варіант програми, призначений для дослідження динаміки пучків у каналах транспортування.