# USING BEAMDULAC CODE FOR MULTI-BEAM DYNAMICS INVESTIGATION IN ION LINAC

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The BEAMDULAC code was developed for beam dynamics investigation in RF linacs and transport channels. The beam dynamics can be studied with the accurate treatment of space charge effects by means of this code. In this paper the space charge neutralization of positive and negative charged ions is investigated using the BEAMDULAC code. The progress in code development is discussed.
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## 1. INTRODUCTION

The investigation of a self-consistent beam dynamics in linear RF accelerators and beam transport channels is one of traditional goals. The influence of the beam Coulomb field is the main problem for low-energy high intensity ion accelerators. The accurate calculation of this field can be made by numerical simulation.

The BEAMDULAC code is developing in Moscow Engineering Physics Institute by E.S. Masunov, N.E. Vinogradov and S.M. Polozov since 1999. By means of this code was early computed the self-consistent beam dynamics study in the axisymmetric radio frequency focusing (ARF), the ribbon radio frequency focusing (RRF) accelerators and the undulator accelerators (UNDULAC). 2D and 3D versions were developed for axisymmetric structures and for ribbon beams respectively. The main features of BEAMDULAC code were briefly observed bellow.

The linear undulator accelerator (UNDULAC) was proposed by E.S. Masunov [1, 2] as a possible method of beam intensity enlarging. This method of acceleration in fields without a synchronous wave has been suggested and studied in [1-3]. It was shown that the high intensity ion beam can be accelerated in UNDULAC [3-4]. The especial peculiarity of UNDULAC is the possibility of negative and positive charged ions acceleration in the same bunch. This peculiarity can provides to the limit beam current enlarging by the space charge neutralization.

The possibility of the space charge neutralization in UNDULAC was studied analytically and verified by numerical simulation [5]. The simulation was provided using the especially developed code BEAMDULAC-2B for multi-ion beam dynamics study in linacs.

## 2. BEAMDULAC CODE

The BEAMDULAC code is developing for self-consistent beam dynamics investigation in RF linacs and transport channels as it is noted above [4, 6]. The dynamics of axi-symmetrical and ribbon ion beams can be studied by means of this 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 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. 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. Time is used as an independent variable and 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 representing as a polynomial coefficient series) and in “real field” which is defined on 2D or 3D grid by electrodynamics simulation codes or experimental measurement [6]. BEAMDULAC code can be used for the numerical simulation of ion dynamics with different charge to mass ratio in low energy transport system, RF buncher and linac. The several of new code versions are discussed bellow in this paper.

## 3. LINEAR UNDULATOR ACCELERATOR

The linear undulator accelerator was proposed as the new structure provides to enlarge the intensity of ion beam. UNDULAC can be realized in periodical IH structure where a field has no spatial harmonics in synchronism with the beam. The physical acceleration mechanism is similar to an inverse free electron laser. In UNDULAC the accelerating force is driven by a combination of two non-synchronous waves (two undulators) in a periodical RF structure. The phase velocity of undulator wave must differ significantly from the beam velocity. There are three different types of undulator that can be used to design the required configuration of nonsynchronous fields: magnetic,


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electrostatic and RF undulator. It has been shown that one of the undulator must be only RF type and the second can be a magnetic, electrostatic (UNDULAC-E) or radio frequency (UNDULAC-RF) type.

The main factor limiting beam intensity in ion accelerator is a space charge force. There exist, at least, two ways to increase ion beam intensity: (i) to enlarge beam cross section and (ii) to use space charge neutralization. One of the possible methods of the beam cross-section enlarging is the ribbon beam using. It was shown that the high intensity ribbon ion beams could be accelerated in UNDULAC-RF and UNDULAC-E. [2-4]. These methods will be studied analytically and verified by numerical simulation for UNDULAC.

In a conventional RF linac (RFQ, DTL) the opportunity substantially to increase beam intensity is absent. Actually, in this structure an accelerating force is proportional to the charge sign of the particles, and oppositely charged ions are bunched in different phases of the accelerating wave. Two bunches with positive and negative charges become separated and don't overlap each other, excluding the initial bunching subsection. In this case the beam intensity can be doubled. In undulator linear accelerator the accelerating force value is proportional to squared particle charge and oppositely charged ions with the identical charge-to-mass ratio can be accelerated simultaneously within the same bunch [5]. The space charge compensation can be realized in UNDULAC along.

## 4. BEAMDULAC-2B AND SPACE CHARGE NEUTRALIZATION IN UNDULAC-RF

The positive and negative charged ions can be accelerated in the same bunch in UNDULAC as it is shown above. But beam dynamics study can not be provided correctly by means of analytical methods only. The space charge effects can be considered by means of numerical simulation. The correct treatment of space charge for dual beam is not easily. The especial code version BAMDULAC-2B was developed for this investigation.

The code modification was provided for the investigation of multi ion beam dynamics in RF accelerator. The Coulomb field calculation was updated mainly. The Poisson equation is solving in BEADULAC code by the conventional FFT algorithm: the particle distribution on 3D grid is calculating on first stage. The Fourier series coefficients for charge are defining at second and the algebraic equation connecting Fourier coefficients for charge and potential is solving on grid. The final stage is the Fourier synthesis for Coulomb potential and its differentiation for space charge field components defining. The modification of space charge distribution calculation and algebraic equation for Fourier coefficients was provided for multi ion beam self-consistent dynamics simulation in especial BEAMDULAC code version. It should be noted that such BEAMDULAC-2B version can be used not only for simultaneously positive and negative ion beam dynamics study. The simulation of beam dynamics is now possible in case when beam contains the ions with different charge or mass. Such case is observing in ion source, beam transport and in heavy ion accelerators also.

The numerical simulation was provided for ribbon beam of deuterium $D^-$ ions in UNDULAC-RF [3-4]. Let us consider briefly the results of simulation. The simulation was provided with next parameters: initial energy of deuterium ions $W_{in}$=100 keV ($\beta_{in}$=0.01), length of accelerator channel 2 m, accelerator channel cross-section size (0.8×12) cm$^2$, length of wave $\lambda$ =1.5 m. The limit zero harmonics amplitude of the RF field $E_0$ was chosen equal 230 kV/cm, coefficient $\chi=E_1/E_0$ =0.3. In this case the output beam energy is equal 1 MeV. The numerical simulation of beam dynamics when a space charge field is taken into account shows that current transmission coefficient, $K_t$, is not exceeding to 85…90% for beam size (5×0.3) cm$^2$. The optimal for maximal current transmission value of $\chi$ is equal to 0.3 and coincides with analytically founded value. In UNDULAC-RF the limit current $I_{max}$=0.2…0.25 A.

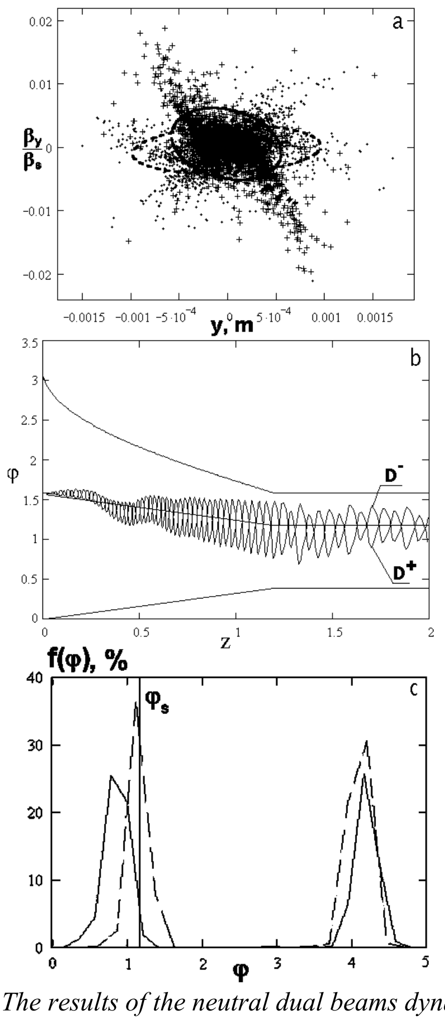


*Fig.1. The results of the neutral dual beams dynamics simulation*

Let us represent some results of dual beam dynamics simulation provided by means of BAMDULAC-2B. The output normalised transverse emittances in ($y$,$\beta_y$) phase plane are shown at Fig.1,a. The output parameters of dual beams are shown for $D^+$ by "×" and solid black line and for $D^-$ by points and dot line. The oscillations of phase mass centre are plotted at Fig.1,b for both particle



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types. Figure also shows the borders of combined wave separatrix and reference particle phase variation. The output phase spectra for $D^+$ and $D^-$ ions are shown at Fig.1,c. The beam bunching is illustrated in Fig.2, which shows the longitudinal beam emittance for different $z$ coordinates. As it was proposed $D^+$ and $D^-$ ions are accelerating in the same bunch in UNDULAC. The phase trajectories for positive and negative ions are oscillating in different directions.

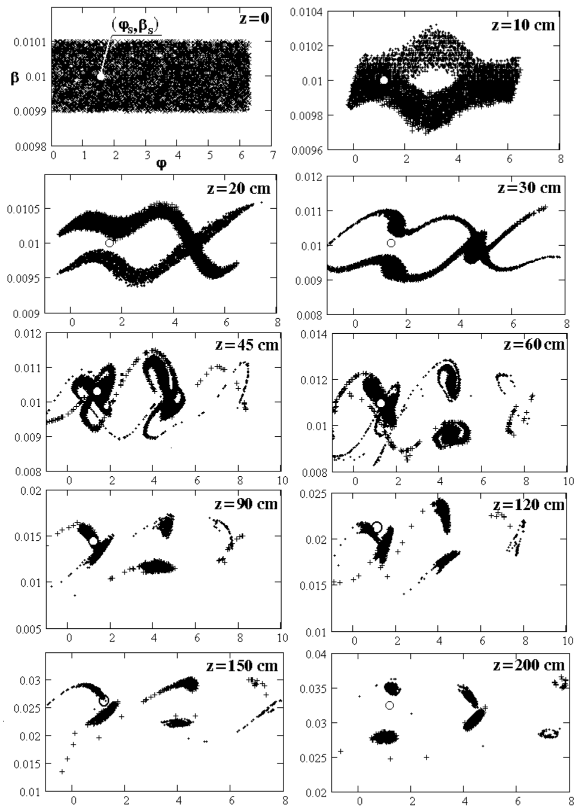


*Fig.2. The bunching of the neutral dual beams*

The numerical simulation shows that the output beam flux of neutral dual beams in UNDULAC-RF can be done very large (see Fig.3,a).

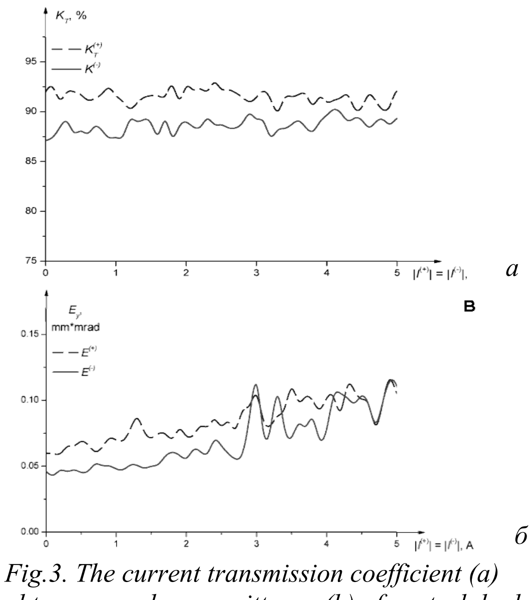


*Fig.3. The current transmission coefficient (a) and transverse beam emittance (b) of neutral dual beams versus the input beam current*

The current transmission coefficient is not reduced with enlarging current for every beam in case when intensities of ion beams $D^+$ and $D^-$ are equal: $|I^{(+)}| = |I^{(-)}|$. In this case total Coulomb field compensation is observed. The nonlinear Coulomb effects cause the decreasing of current transmission and beam emittance enlarging only when the current of every beam is larger than 4 A (see Fig.3,b).

It is interesting to study dynamics of quasi neutral dual beams when $|I^{(+)}| \neq |I^{(-)}|$. The transmission coefficient for $D^+$ ions, $K_t^{(+)}$, is larger in case when $|I^{(+)}| < |I^{(-)}|$. In dual beams the transmission coefficient for $D^-$, $K_t^{(-)}$, is equal approximately to transmission coefficient for a single ion beam $D^-$ with current $I=|I^{(-)}|-|I^{(+)}|$. The transmission coefficient increases for $D^+$ and decreases for $D^-$ with $|I^{(-)}| / |I^{(+)}|$ ratio enlarging and $K_t^{(+)}=K_t^{(-)}$ when $|I^{(+)}| \approx |I^{(-)}|$. This effect is observing when the both beam currents are not very large. It should be noted that beam with smaller current has the smaller output emittance.

## 5. NEW BEAMDULAC CODE VERSIONS

Let us observed the new versions of BEAMDULAC code developed last two years.

### 5.1. NEW BEAMDULAC CODE FOR RF LINACS

Early designed versions of BEAMDULAC code allows to investigate the beam dynamics in accelerators with different types of RF focusing (ARF, RRF) and undulator linear accelerators. The new versions were developed for beam dynamics study in conventional RFQ and DTL accelerators and structures with independently phased superconducting resonator and superconducting solenoids. Such structures are now developing for large heavy ion accelerator projects as RIA, FZJ etc. The codes for DTL not utilize the traditional matrix method for beam dynamics calculation. The motion equation is integrating step-by-step which provides to correctly treat the space charge influence to the beam dynamics. The structure parameters as period length, accelerating gap length and potentials between the drift tubes are used as parameters of simulation.

### 5.2. TRANSPORT CHANNELS

The BEAMDULAC includes codes for beam dynamic simulation in transport channels. As an example BEAMDULAC code is using for beam dynamics study in the plane electrostatical undulator, which proposed for ribbon ion beam transport in ITEP-MEPhI common project of ion implanter. The parameters of undulator were investigated for boron, phosphorus and other high intensity beams by using of BEAMDULAC-Tr.

One of problem solved by means of this code is the study of multi ion beam dynamics in transport line. This problem arises because the ions with different charge-to-mass ratio are providing by Bernas ion source uses in implanter. The ions can be produced in channel also. The problem of multi ion beam dynamics study was solved using the BEAMDULAC-2B algorithm.

### 5.3. CONSTRUCTION ERRORS INFLUENCE

The accelerator channel construction errors can influence to the beam dynamics. The correct treatment of this influence is one of difficult problem in accelerator design. The exhaustive methods are commonly uses for error treatment. Very extensive statistics and very large number of calculations are necessary for this.

The different method was proposed for this goal. The method has two stages. At first, the field distribution in channel is calculating for all possible types construction errors. Five-ten calculations are necessary for each type. The field distributions defining on channel axis and in 2-4 different lines which are parallel to the axis. The field on lines distributes by coefficients of Fourier series. This distribution provides to find the high order harmonics amplitudes. In real structure all high order harmonics amplitudes varying for different construction errors values. But for not critical errors this variation is close to linear.

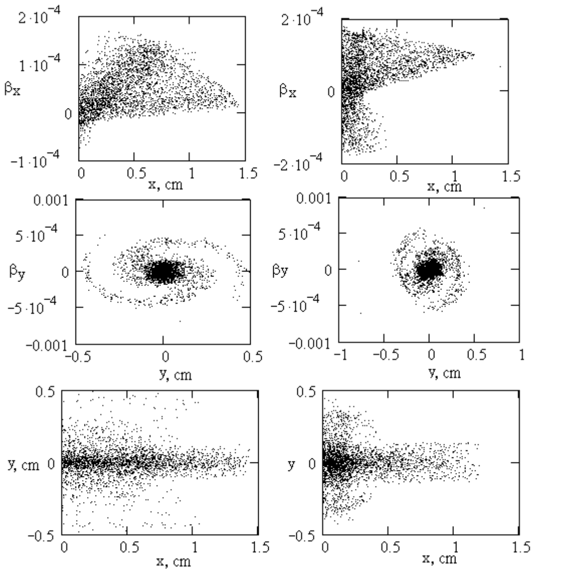


*Fig.4. The results of construction errors influence study*

The tables of Fourier coefficients are used for beam dynamics study in linac or transport channel. The errors can be taken into account as a statistical value, which is not larger, that in coefficients table. The influence of beam construction errors can be studied by means of this method and a several calculations are necessary.

An example illustrating this method is presented in Fig.4. The ribbon beam dynamics of boron ion was studied in transport channel with the next parameters: the beam current 1 mA, ion energy 10 keV, the channel has 25 periods. The output transverse emittance in ($\beta_y$, $y$) and ($\beta_x$, $x$) planes and beam cross-section are shown for "ideal" channel (no constriction errors, left figures) and with treatment of electrodes shift along longitudinal axis (right figures). The maximal shift of electrodes is equal 300 μ in this example. It is clear from figures that such error can be critical for ion beam transport.

## CONCLUSION

The new versions of BEAMDULAC code are observed. The dynamics of oppositely charged ion beams was studied in radio frequency undulator linac and the results of dual beams dynamics simulation are presented. Such results are studied by means of BEAMDULAC-2B code, which provides to simulate the multi ion beam dynamics. It was shown the flux intensity of neutralized dual beams in UNDULAC-RF can be very large. The several of new code versions were observed.

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### ИСПОЛЬЗОВАНИЕ ПРОГРАММЫ BEAMDULAC ДЛЯ ИССЛЕДОВАНИЯ ДИНАМИКИ МНОГОКОМПОНЕНТНЫХ ИОННЫХ ПУЧКОВ


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Программа BEAMDULAC разработана для исследования динамики пучков в линейных высокочастотных ускорителях и каналах транспортировки. Моделирование динамики пучка проводится с точным учетом влияния собственного поля пучка. В данной статье с помощью программы BEAMDULAC изучается возможность компенсации влияния пространственного заряда положительно и отрицательно заряженных ионов. Также рассматриваются новые возможности программы.


### ВИКОРИСТАННЯ ПРОГРАМИ BEAMDULAC ДЛЯ ДОСЛІДЖЕННЯ ДИНАМІКИ БАГАТОКОМПОНЕНТНИХ ІОННИХ ПУЧКІВ


***Е.С. Масунов, С.М. Полозов***



Програма BEAMDULAC розроблена для дослідження динаміки пучків у лінійних високочастотних прискорювачах і каналах транспортування. Моделювання динаміки пучку проводиться з точним обліком впливу власного поля пучку. У даній статті за допомогою програми BEAMDULAC вивчається можливість компенсації впливу просторового заряду позитивно і негативно заряджених іонів. Також розглядаються нові можливості програми.