Numerical Simulation of Multicomponent Ion Beam from Ion Sources

V. Alexandrov[*], Yu. Batygin[#], N. Kazarinov[*], V. Shevtsov[*], G. Shirkov[*]

[*]*Joint Institute for Nuclear Research (JINR), 141980,Dubna, Russia*
[#]*Institute for Physical and Chemical Research (RIKEN), Saitama, 351-01, Japan*

Introduction

The program library for numerical simulation of the charged particle beam transport lines realized on the IBM PC with Windows user interface of Visual Basic is presented. A number of computer codes for the numerical simulation of charged particle beams with non-linear space charge field of the beam have been developed since 70-s[1-8].

The present program library is used for the numerical calculation and optimization of beam dynamics in the transport lines including various magnetic and electrostatic elements. Nonlinear transverse space charge is taken into account. The main advantage of the code is simultaneous simulation of a number of particle components with different masses and charge states. This peculiarity is very important, in particular, for the low energy stage transport of a high current ion beam from ion source to accelerator or beam analyzing system.

The library is based on three different methods of mathematical simulation: (i) the momentum method for particle distribution function[9,10], (ii) macroparticle method (PP-method) and (iii) the solution of Poisson equation in 2D Cartesian Coordinates using the fast Fourier transformation method[11].

Fast analysis and study of the averaged beam characteristics, such as mean velocity and root-mean-square (RMS) dimensions is attained by the momentum method. The main advantages of the momentum method for distribution function are a short calculation time for the main beam characteristics and applicability for optimization. Space charge forces in this approach are considered to be linear [10,15]. Approximation of self linear forces is correct for long beams with the constant transverse density of charged particles. Real particle distributions usually have nonlinear space charge fields that could be described with higher order moments. The approach of effective linearisation of transversal fields for a special kind of distribution function was introduced to solve the problem in the frames of second order moments[10].

The macroparticle method is successfully used for detailed investigation of beam distribution. This method is helpful to consider the nonlinearity of electron and ion space charge and external fields.

Earlier these methods were applied to calculate and optimize the high intensity beam injection line for the Meson Factory of the Institute for Nuclear Research (Troitsk)[12]. Those methods and codes were used as a background for the new generation code library. The first version of the present code library without using the fast Fourier transformation method for the solution of Poisson equation was presented earlier[13,14].

The library is installed on the modern PC hardware and software to extend a number of used finite particles and sells of field mesh in simulation as well as available transport line elements. An advanced Windows graphical interface makes it comfortable and friendly for the User in the interactive mode operation. The program may be used for numerical simulation of dynamics of multicomponent

Beam Initial Data for the Distribution Function in Moments and PP-Methods

Initial positions of particles in phase space are determined by the values of Twiss parameters $\alpha_{x,y}$, $\beta_{x,y}$ by the values of emittances of the beam $\varepsilon_{x,y}$ in transverse phase planes xv_x, yv_y and by type of distribution function.
The beam parameters are:

- total current ($\_\_$ A);
- type of beam: electron or ion; the beam in the first case has a charge, which is equal to the electron charge, in the other case, the beam is characterized by the ratio of the ion charge to the atomic number; and it is necessary to set the atomic number here.
- type of density distribution in the four-dimensional phase space: Kapchinsky-Vladimirsky distribution is used for the method of moments. For achieving the coincidence of the initial conditions in the averaged sense for the various random generation the linear transformation of the phase space variables (x , $x\_\_$, y , $y\_\_$) is used.

Figure 1. The form to select and insert the beam parameters

The initial data in PP-method are determined by the same values. There are four types of density distribution in the four-dimensional phase space: uniform, Gaussian, water bag and parabolic. The initial coordinates and velocities are calculated by special programs using the random number generators[17]. All of the above beam parameters are determined when the item "New Beam" + "Beam's Parameters + Initial Data" is chosen in the main menu. A special form appears in the screen of the monitor as a result of choosing this item (Fig. 1).

User can determine the beam data from the keyboard by focusing the mouse pointer to the text field or by clicking the key "Tab". The data will be loaded into the memory when User selects the button "Enter". This data may be written in a special file (see below).

The PP-method makes it possible to take into account a charge distribution and Coulomb interaction of all species. In this case the total current is distributed between different species if the beam has more than one ion species. The charge distribution is determined in a file with extension "*.txt" and could be corrected/created by any text editor. This distribution is plotted in the monitor screen and one can choose the region from the lowest to highest state. Simple mouse clicking is used for all interactive manipulations. The text field with a charge number changes the color when User clicks this field. The next mouse clicking makes the black color over all the region of selected charges. User interface for choosing the charge state is shown in Fig. 2.
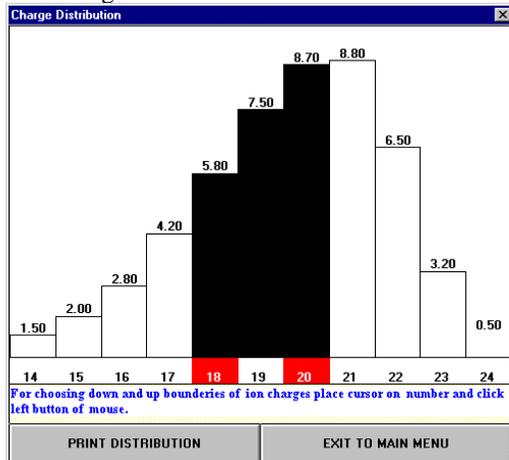

Figure 2. User interface for choosing the input charge state distribution

The beam parameters may be written in a special file with extension "*.ind" when User chooses the menu item "New Beam" + "Writing of Initial Data". User is able to indicate a path to this file and it's name in the Windows dialogue regime. User can read this file choosing the menu item "Reading and Simulation" + "Reading Initial Data File" for the next program runs.

User Interface for Setting Up Parameters of the TransporT Line

Parameters of the transport line are determined in the regime of a dialogue. There are two main forms for this aim.

The first of them allows to set up the total length of the transport line, the total number of its elements, the diameter of the vacuum pipe. This form is presented in Fig. 3.

User can determine the line by the second form. First of all, it is necessary to determine the type of elements. Both programs can work with the following types of elements: solenoids, vertical dipole magnets, horizontal dipole magnets, quadrupoles, acceleration cavities.

When User clicks the button "Enter", then the form (Fig.4) appears in the screen and offers to User to set on a drift length before this element, the length of the element, it's aperture and value of the physical parameter of this element (the amplitude of the longitudinal field for the solenoid, the value of gradient for the quadrupole and so on).
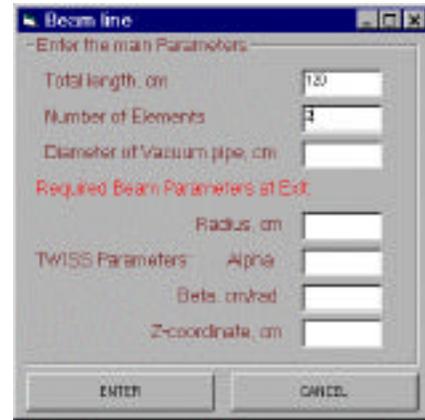

Figure 3. User interface for setting up the parameters of transport line

This dialogue continues until the number of the element is less than the total number of the elements. The program automatically returns to the main menu when the parameters of the last element of the transport line are determined. User can write these data in a special file with extension "*.str" choosing the item of the main menu "New structure" + " Writing Channel Data".

The transport line structure can be restored by choosing the item "Reading and Simulation" + " Reading Channel Parameters File".
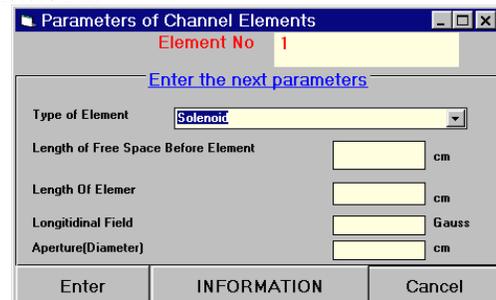

Figure 4. User interface to define the element parameters

There are two possibilities to determine the external magnetic field of a solenoid:
- the components of the magnetic field can be calculated analytically;
- the field can be set up from a file with a field table. Then the dialogue box will appear in the screen if User chooses the item "Reading field table file".

The procedure provides linear interpolation of the external magnetic field. The file with the field data is created and corrected by any text editor. All magnetic field values can be changed multiplied by the scaling factor defined in the start-up form (see Fig. 5).

Rectangular boxes in the top of this picture represent the elements of the transport line. The numbers disposed over these boxes show the values of gradients, the amplitude of the magnetic field and so on. An example of this picture is shown below in the Fig. 6 with visualization of beam dynamics in the PP-method.

Output Data

As it was described above, the beam envelopes in horizontal and vertical directions are shown in the monitor
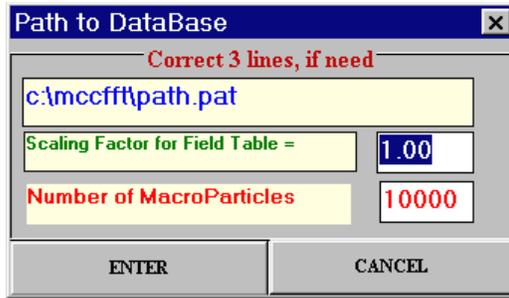
Figure 5. The start-up form.

screen in the tempo of the transport line calculation if the method of the moments is selected. The color traces of each finite particle are presented in the screen and form the image of real beam dimensions along the axes in the PP-method. In this case User can see the output Twiss parameters, the number of lost particles and emittances in the horizontal and vertical directions when the calculations are finished. There are three opportunity for User to have an additional information of the beam parameters: the particle losses along the trace of the transport line, the phase portrait and dimensions in the horizontal and vertical planes, the output

current distribution. User clicks the corresponding button to make a choice (see Fig. 6).

Figures 6-8 represent examples of beam dynamic simulation during the optimization of Low Energy Beam Transport (LEBT) line at CERN. The LEBT is aimed to transport the beam from Laser Ion Source (LIS) into the ionic RFQ and consists from two solenoids (two panels on the top of Fig. 6). The data for one of the LIS experimental beams of Tantalum ions were taken to demonstrate here the PP-method possibilities. These calculations used from 1000 to 20000 particles on the 32x32 mesh with the integration step of 0.5 cm. One variant of such kind calculations takes about 1 hour of computation time at Pentium II/300 IBM PC (for 5000 particles). The initial charge state distribution of Tantalum ions is shown in Fig. 3 with actual current of each charge state on the top of corresponded ion bar. The input beam parameters are presented in the left column of Fig. 6. This Fig shows the visualization of the beam dynamics. This color image is a superposition of 1000 traces of all particles. Each charge state is presented with different color. The right side column shows the output beam parameters.
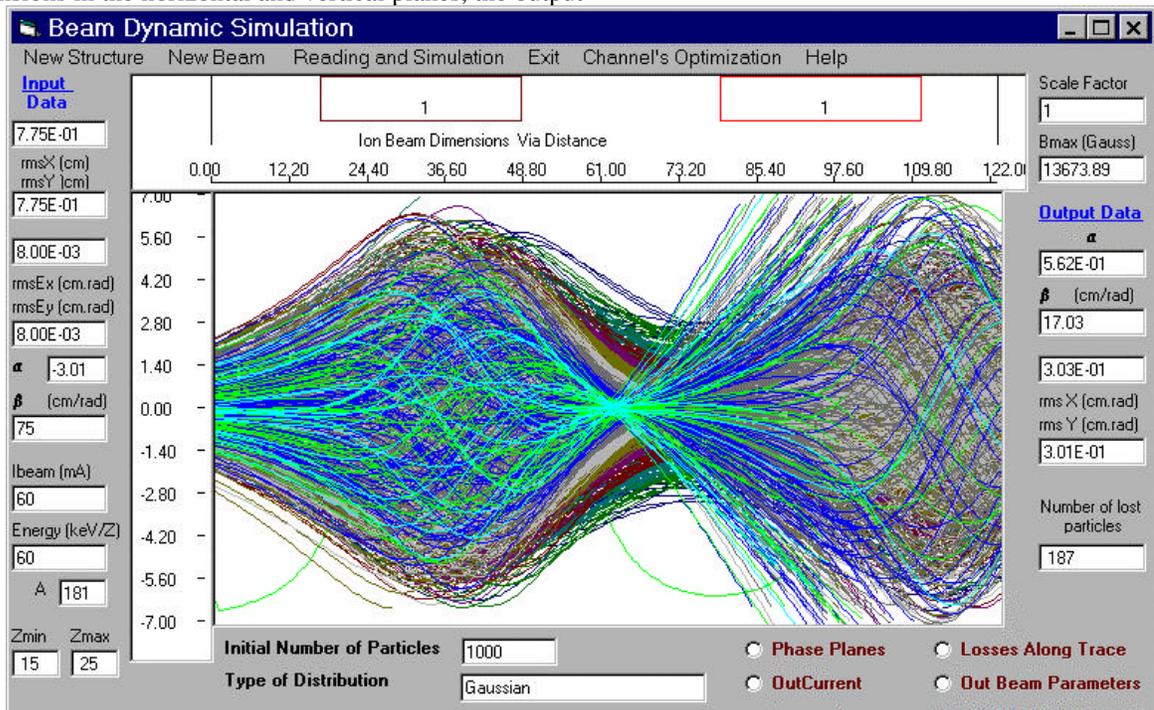
Figure 6. Visualization of the beam dynamics simulation

Figs. 7 and represent the phase portraits in *XX'* and XY for final beam. The large ring of particles in the *XY* plane of Fig. 7 is the image of lost particles that had been excluded from the calculations after reach the radii of vacuum pipe. The brown ellipses in the left plane and circle in the right plane show the RFQ acceptance and aperture.

The table in Fig.8 includes the complete input-output information for every charge states used in consideration. In particular, the penultimate column gives the relative growth of every charge state emittances and the last one indicates the number of particles successfully met the input requirements of RFQ.

Figure 7. Initial phase planes of beam emittance and cross density

Conclusion

The program library to calculate transport lines of intense charged beams is developed. There are two different methods for these calculations. The first of them, based on the method of moments for distribution function allows to define the root mean square characteristics of the beam in interactive regime. Users can change the parameters of the transport lines and choose a first approximation. User interface gives visual results in the screen monitor in the real time of calculations. The detailed charac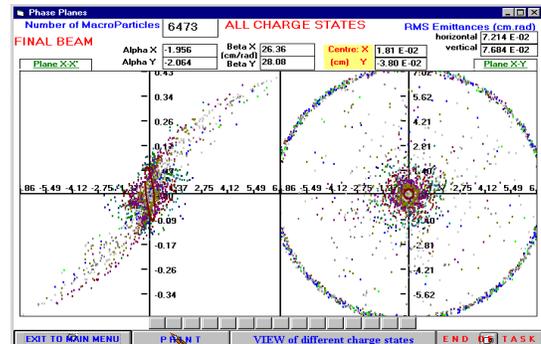teristics of the beam can be calculated with PP-method. The program library may be used to calculate the electron and ion beams, the distribution of ion charge states including space charge of the beam.

Parameters of the transport line and the main beam characteristics can be written in special files and then read again, that provides the convenient conditions for calculations and optimizations of the transport lines. The results of calculations can be printed and written in files from the program.
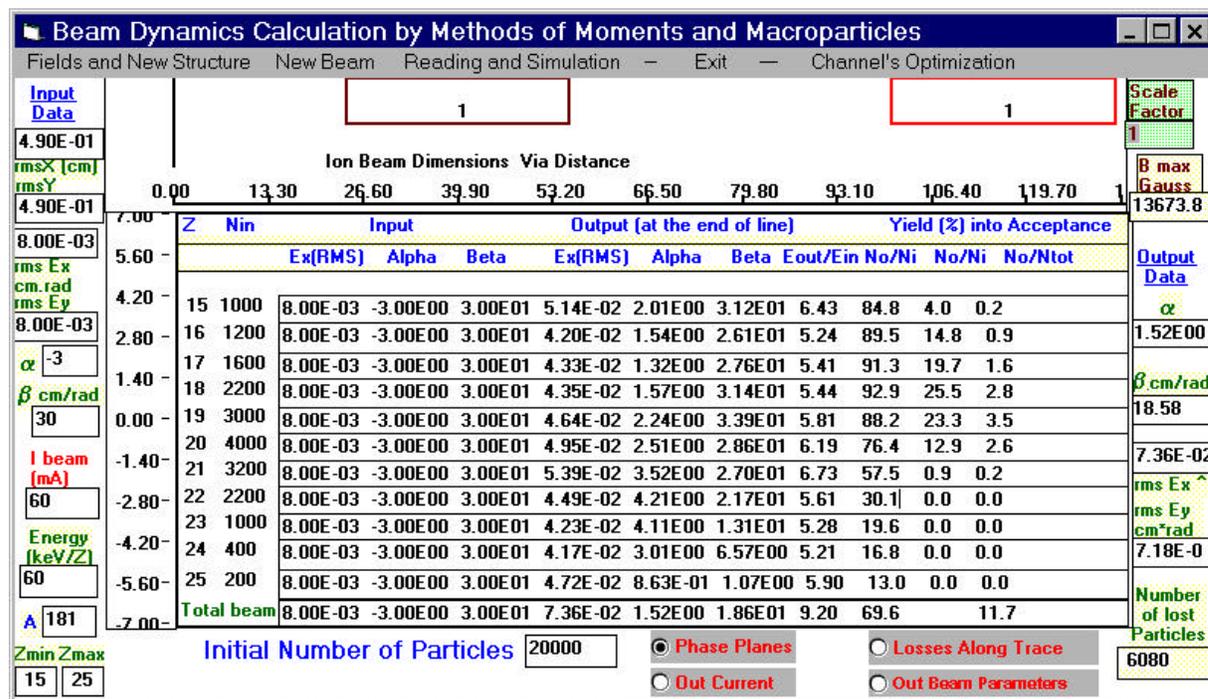
Beam Dynamics Calculation by Methods of Moments and Macroparticles

Fields and New Structure New Beam Reading and Simulation — Exit — Channel's Optimization

Input Data: rmsX [cm] 4.90E-01, rmsY 4.90E-01, rms Ex cm.rad 8.00E-03, rms Ey 8.00E-03, α -3, β cm/rad 30, I beam (mA) 60, Energy (keV/Z) 60, A 181, Zmin Zmax 15 25

Scale Factor 1, B max Gauss 13673.8, Output Data α 1.52E00, β cm/rad 18.58, 7.36E-02, rms Ex 7.18E-0, Number of lost Particles 6080

Ion Beam Dimensions Via Distance: 0.00 13.30 26.60 39.90 53.20 66.50 79.80 93.10 106.40 119.70

Z	Nin	Input Ex(RMS)	Alpha	Beta	Output (at the end of line) Ex(RMS)	Alpha	Beta	Eout/Ein	Yield (%) into Acceptance No/Ni	No/Ni	No/Ntot
15	1000	8.00E-03	-3.00E00	3.00E01	5.14E-02	2.01E00	3.12E01	6.43	84.8	4.0	0.2
16	1200	8.00E-03	-3.00E00	3.00E01	4.20E-02	1.54E00	2.61E01	5.24	89.5	14.8	0.9
17	1600	8.00E-03	-3.00E00	3.00E01	4.33E-02	1.32E00	2.76E01	5.41	91.3	19.7	1.6
18	2200	8.00E-03	-3.00E00	3.00E01	4.35E-02	1.57E00	3.14E01	5.44	92.9	25.5	2.8
19	3000	8.00E-03	-3.00E00	3.00E01	4.64E-02	2.24E00	3.39E01	5.81	88.2	23.3	3.5
20	4000	8.00E-03	-3.00E00	3.00E01	4.95E-02	2.51E00	2.86E01	6.19	76.4	12.9	2.6
21	3200	8.00E-03	-3.00E00	3.00E01	5.39E-02	3.52E00	2.70E01	6.73	57.5	0.9	0.2
22	2200	8.00E-03	-3.00E00	3.00E01	4.49E-02	4.21E00	2.17E01	5.61	30.1	0.0	0.0
23	1000	8.00E-03	-3.00E00	3.00E01	4.23E-02	4.11E00	1.31E01	5.28	19.6	0.0	0.0
24	400	8.00E-03	-3.00E00	3.00E01	4.17E-02	3.01E00	6.57E00	5.21	16.8	0.0	0.0
25	200	8.00E-03	-3.00E00	3.00E01	4.72E-02	8.63E-01	1.07E00	5.90	13.0	0.0	0.0
Total beam		8.00E-03	-3.00E00	3.00E01	7.36E-02	1.52E00	1.86E01	9.20	69.6		11.7

Initial Number of Particles 20000
● Phase Planes   ○ Losses Along Trace
○ Out Current   ○ Out Beam Parameters

Figure 8. Table of the input and output data for all charge states

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