COMPUTER CODE LIBRARY FOR SIMULATION AND OPTIMIZATION OF ELECTRON AND ION BEAM PARTICLE DYNAMICS

V. Alexandrov, V. Shevtsov, G. Shirkov, JINR, Dubna, Russia
Yu. Batygin, RIKEN, Saitama, Japan

Abstract

An interactive computer code library for the simulation of charged particle beam transport is presented. It allows to calculate the transport of multicomponent beam through a set of quadrupoles, solenoids, bends, accelerating sections.

1 INTRODUCTION

The program library for numerical simulation of the charged particle beam transport lines realized on IBM PC in Visual Basic code is presented. A number of computer codes has been developed earlier taking into account non-linear space charge fields in numerical simulations of charged particle beams [1-7]. The presented program library is purposed for the numerical calculation and optimization of the beam dynamics in the transport lines including various magnetic and electrostatic elements with the influence of self space charge on transverse beam dynamics. It is based on two different methods of mathematical simulation: the method of the distribution function moments [8,9] and the particle-particle method (PP-method).

This paper presents analysis and study of charged particle beams for sources of multiple-charged ions and the averaged beam characteristics, such as the mean velocity and root-mean-square dimensions. The main advantage of the moment method is to describe beam dynamics faster in comparison with methods of multiparticle description.

The PP-method is successfully used in investigation of detailed beam characteristics, distribution function of particles, ion transition from one charge state to another. This method is also helpful to consider nonlinearity of eigenfields of electrons and ions. It could be used to describe the motion of a dense medium, electrodynamics of the dense media and beams of charged particles.

2 MOMENT METHOD

Let us define a second order moments matrix M of the distribution function according to Ref [9] while considering the eigenfield nonlinearity:

$$M^{II} = \begin{pmatrix} M_{xx} & M_{xv} \\ M^{*}_{xv} & M_{vv} \end{pmatrix}$$

$$M^{i,j}_{xx} = \int f x_i x_j \vec{d x} \vec{d v}, \qquad M^{i,j}_{xv} = \int f x_i v_j \vec{d x} \vec{d v}$$

$$M^{i,j}_{vv} = \int f v_i v_j \vec{d x} \vec{d v}, \quad i,j=1,2,$$

here f is the beam distribution function, and x_i, v_i are particle coordinates and velocities. The evolution of the matrix M under beam transport through linear electromagnetic fields is defined by equations [10]:

$$\frac{d M_{xx}}{dz} = M_{xv} + M^{*}_{xv},$$

$$\frac{d M_{xv}}{dz} = M_{vv} + M_{xx} B^{*} + M^{*}_{xv} A^{*},$$

$$\frac{d M_{vv}}{dz} = B M_{xv} + M^{*}_{xv} B^{*} + A M_{xv} + M_{xv} A^{*}$$

where $z = v_z t$ and $v_z = \beta c$ are longitudinal coordinates and velocity, the matrix B includes external and space charge forces, matrix A includes external forces only (magnetic field defined by particle transverse motion is neglected), M^{*}, A^{*}, B^{*} are transposed matrices M, A, B. Space charge forces are considered to be linear [10, 11].

The solution of set could be used to define averaged values of the beam (transverse beam sizes and velocities, cross term). The main advantage is a shorter calculation time for the main beam characteristics due to the particleless approach.

The approach of linear forces is correct for long beams with the constant transverse density of charged particles. Real particle distributions usually have nonlinear eigenfields that could be described with high order moments and, according to this, a high order set of equations. 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.

3 EQUATIONS OF PARTICLE MOTION

The set of equations of the particle motion in various external fields has the following form:

$$\frac{d^2 x_i}{d s^2} = F^{p}_{xi} + \frac{Q}{\gamma^2 n} \sum_{i=1}^{n} \frac{x_i - x_j}{r^2_{ij}} Z_j$$

$$\frac{d^2 y_i}{d s^2} = F^{p}_{yi} + \frac{Q}{\gamma^2 n} \sum_{i=1}^{n} \frac{y_i - y_j}{r^2_{ij}} Z_j,$$

where x_i, y_i are transverse coordinates for i's particle, $Q = 2I / \beta^3 \gamma I_{cr}$, I is the linear current density of the beam, $\beta = v_z / c$ is the relative longitudinal velocity of any particle, c is the velocity of light, $\gamma = (1 - \beta^2)^{-1/2}$, $I_{cr} = m_p c^3 / e$ for ions and $I_{cr} = m_e c^3 / e$ for electrons. The distance r_{ij} between particles i and j is: $r^2_{ij} = (x_i - x_j)^2 + (y_i - y_j)^2$ if $r_{ij} \geq 2 a_0$ and $r_{ij} = 2a_0$ if $r_{ij} < 2a_0$, where a_0 is the radius of the particle, n is the particle number. The forces F^{p}_{xi} and F^{p}_{yi} determine the particle interaction with external electromagnetic fields.

4 BEAM INITIAL DATA

The initial data for the method of distribution function moments and PP-method are related to each other. The beam initial data are determined by the values of Twiss

parameters α_x, α_y, β_x, β_y and emittances of the beam ε_x, ε_y in transverse phase planes xv_x, yv_y respectively. To unify the initial data, the RMS-dimensions and RMS-velocities of the beam are connected with the above parameters as follows:

$$\overline{a_x^2} = \varepsilon_x \beta_x \,, \overline{a_y^2} = \varepsilon_y \beta_y \,, \overline{xv_x} = -\varepsilon_x \alpha_x \,, \overline{yv_y} = -\varepsilon_y \alpha_y \,,$$

$$\overline{v_x^2} = \left(\left(\overline{xv_x} \right)^2 + \left(\overline{yv_y} \right)^2 \right) / \overline{a_x^2} \,, \overline{v_y^2} = \left(\left(\overline{xv_x} \right)^2 + \left(\overline{yv_y} \right)^2 \right) / \overline{a_y^2}$$

The beam parameters:
- total current (μA);
- 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 4-dimensional phase space; it is Kapchinsky-Vladimirsky distribution in case if the method of distribution function moments is used.

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 distributions. It is possible to select one of them according to the best approximation of the conditions to solve this problem. The initial distribution of the particles in four-dimensional phase space, i. e. it's coordinates and velocities are calculated by special programs using the random number generators. All of the above beam parameters are determined when the item "Initial Data" + "Beam's Parameters + Initial Data" is chosen in the main menu.

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 total current is distributed between different species, and the sum of their partial currents is always equal to the total current in this case. This distribution is plotted in the monitor screen and one can choose a number of charge states and the lowest and highest states from the complete charge states distribution according to the required accuracy of simulation. 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.

5 USER INTERFACE FOR SETTING UP PARAMETERS

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

The first of them allows one to set up the total length of the transport line, the total number of its elements, the diameter of the inner tube, the Z-coordinate and radius of the diaphragm.

User can determine the parameters of the line elements with 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:

horizontal dipole magnets, solenoids, vertical dipole magnets, quadrupoles, acceleration cavities, free spaces.

When User clicks the button "Enter" then the form appears in the screen of the monitor and offers to User to set on a free space 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).

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.

There are two possibilities for setting the external magnetic field of the solenoid in the program. The components of the magnetic field are executed analytically when calculation of beam dynamics is fulfilled in paraxial approximation, so it is necessary to set only the amplitude of the longitudinal magnetic field. The components of the field can be set up while reading the file when the components of the magnetic field are represented by the table of values experimentally measured or calculated along the solenoid axis on different radii.

The picture of the channel geometry appears in the screen of the monitor when procedures of setting up parameters of the transport line and initial beam data are finished. The main initial beam parameters are shown in special windows. 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.

The library has been used to simulate and optimize the tantalum ion beam transport and focusing from the laser ion source through the transport line to the ionic RFQ at CERN. An example of this simulation is shown in Fig 1:
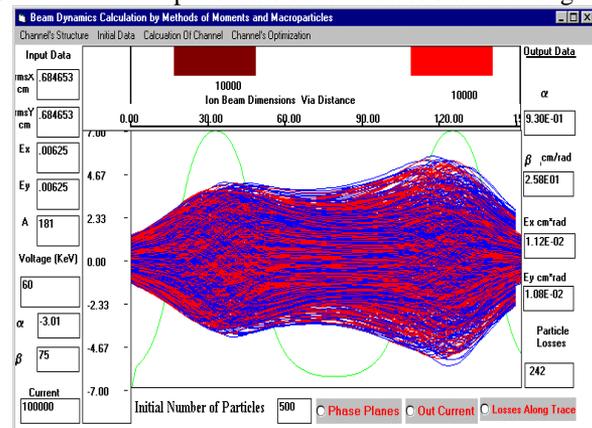

Figure 1: Panel visualizing the beam dynamics calculation

6 USER INTERFACE FOR CALCULATIONS

User interface for the transport line calculation with the method of moments of the distribution function is

described in this paragraph. The transport line could be calculated in two regimes:

• the transport beam line is calculated for all it's elements without any stops up to the last element,

• the transport beam line is calculated element by element with the stop after each element.

User has a possibility to exchange the position of the element along the line and the amplitude of the physical field of this element in the last case. This case will be realized if User chooses the item of the main menu "Channel's Run on Element". The beam envelopes appear on the panel to visualize the beam dynamics calculation in the both cases. The red line shows the envelope of the beam in horizontal direction, the blue - in the vertical one. The green line shows the amplitude of the longitudinal magnetic field via the distance.

The calculations go on until the right hand end of the first element is reached. Then the calculations are stopped and the box with the question "Will you continue? Choose the answer!" and two buttons "Yes!" and "No!" appear. The calculations will be continued up to the right hand side of the next element if User chooses "Yes". The background color of the top panel's part will be changed if User chooses "No". It means that the program is ready to get new data from User. User can click the mouse pointer on the box of the elements and the foreground color of this box will be red. If User clicks the button "Insert" on the keyboard, then the box with the number of this element, the old value of the field amplitude in this element will appear in the monitor screen. The empty string offers to User to set up a new value of the amplitude. The calculations will be continued from the right hand end of the previous element or from the beginning of the transport line when the first element parameters vary then User clicks the mouse pointer in the position of the element.

User is also able to alter the position of any element changing it's field amplitude. It is necessary to click the mouse pointer on the box of this element and click the buttons "->" or "<-" for moving the element to the right or to the left. The text box in the bottom of the monitor screen with the longitudinal coordinates of the left hand end of the element will appear in the last case.

7 OUTPUT DATA

As it was described above, the beam envelopes in horizontal and vertical directions are shown in the monitor screen in the tempo of the transport line calculation, if the method of the moments is selected. The real beam dimensions along the trace will be shown in the monitor screen if the PP-method is selected. 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 possibilities for User:

• the particle losses along the trace of the transport line,

• the phase portrait and dimensions in the horizontal and vertical dimensions,

• the output current distribution.

8 CONCLUSION

The program library to calculate transport lines of intense beam of charged particles is developed. There are two different methods for these calculations. The first of them, based on the method of moments for distribution function allows one to define the mean square root characteristics of the beam in interactive regime. Users can change the parameters of the transport lines and choose a quasioptimal variant of these parameters during calculations. User interface in this case gives visualized results in the screen monitor in the real rate of calculations. The detailed characteristics of the beam behavior along the line axes may be calculated with PP-method when this variant of the transport line is chosen. The program library may be used to calculate the electron and ion beams, the distribution of ion charge states and beam eigenfields could be taken into account.

Parameters of the transport line and the main beam characteristics can be written in special files and then read again, that allows one to calculate and optimize the transport line in a short period of time. The results of calculations can be printed and written in files from the program.

The main disadvantage of the presented PP-method codes is the way of eigenfield calculation as a particle-particle Coulomb interaction. These eigenfield calculation requires a very long calculation time and limits the number of the test particles in the beam simulation. To introduce the Poisson equation into the procedure means to improve the situation and develop the library.

REFERENCES

[1] I. Kapchnskij and V. Vladimirskij, in Proc. of Int. Conf. on High Energy Accelerators, CERN, Geneva, 1959, p. 274.

[2] B. Bru, GANIL Report A88-01.

[3] K. Mittag and D. Sanitz, in: Proc. Linear Accelerator Conf., Bishop's Lodge, Santa-Fe, New Mexico, 1981, R.A. Jameson and L.S. Taylor, Eds., LANL Report LA-9234-C, pp. 156-158, 1982.

[4] G. Boicourt and J. Merson, "PARMILA Users and Reference Manual", LANL Report LA-UR-90-127, 1990.

[5] W.John and C. Kost, TRIUMF design note TRI-DN-73-11, 1973.

[6] K. R. Crandall, LANL, Report LA-11054-MS, 1987.

[7] M.S. de Johg and E.A. Heighway, IEEE Transactions on Nuclear Science NS-30, 2666-2668, 1983.

[8] J. Farrell, in: Proc. of the Europhysics Conf., Berlin CmBH, W. Busse and R. Zelazny, Eds. (Springer-Verlag, Berlin, New-York, 1984), pp. 267-272.

[9] A. Dymnikov and E. Perelstein, NIM, v. 148, p. 567.

[10] N.Yu. Kazarinov, E.A. Perelstein, V.F. Shevtsov, Particle Accelerators, 1980, v. 10, p. 1.

[11] F.J. Sacherer, IEEE Transections of Nuclear Science, 1971, NS-18, 3, p.1105.

[12] M.Bourgeois at al., In: Proc. of the Linac96, XVIII Int. Linac Conf., Geneva, August, 1996.