NUMERICAL METHODS TO THE SPACE CHARGE COMPENSATION (SCC) EFFECT OF THE LEBT BEAM *

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Abstract

Numerical simulation as well as experimental researches on space charge compensation for high intensity, low energy ion beam has been done at Peking University (PKU). In this paper we will describe the simulation model proposed at PKU and use it on the PKU ECR single-charged ion source. It consists of a new concept of equivalent density and more consideration of physical process. A series of arithmetical equations is gained through theoretical derivation. Although no numerical solutions have been carried out from our computation, it is foreseeable that the final result will be achieved soon.

INTRODUCTION

In the low energy part of an accelerator, a beam with high intensity would undergo serious space charge (SC) force, which results from the interaction among the beam particles with the same electric charge. Because the force would repel particles from each other, it is obvious that it's defocusing and bringing more negative results than the great increase of emittance. One effective way to diminish the effect is to ionize the residual gas and reduce the radial electronic field of the beam. That procedure is called as space charge compensation (SCC). It has so long been proved to be the most effective way to deal with the negative results brought by the SC force.

Earlier study [1] has put forward a completed theoretical model. In this model, the density distributions of various particles are derived from continuity equation, and modified by applying Fokker-Planck equation in the energy transfer. It mostly focuses on the steady compensation state. The model has successfully predicted the electric potential's response to the change of pressure and beam energy. However, the model has done little simplifying calculation and the result is too complicated to be applied in numerical computation.

In another study [2], a more accurate model was developed on the basic assumption of a evenly distributed beam, and the CARTAGO code was also put forward in the same article. The model analyzes from the aspect of the dynamics of particles and considers the electrons to oscillate in ellipse. However, it neglects the heat motion of electrons and other nonlinear factors. Furthermore, the assumption of evenly distributed beam does not coincide with realistic beam distribution, which is more likely to be a Gaussian-distribution.

Thus, we have developed a new model to study the SCC regime while the system is in a steady state, which means parameters of the system are time-independent. In our model, a new concept of equivalent particle density is introduced and applied into computation, and the distribution of residual gas is also taken into consideration.

THEORETICAL BASIS

Fundamental Assumptions

First of all, a classification of different particles interacting with each other is needed. There exist the beam and the residual gas, so the particles include ions of the beam, molecules (or atoms) of the residual gas, electrons ionized from the gas and low-energy ions also ionized from the gas. We label them one after another as subscripts 'b', 'g', 'e' and 'i'.

In order to simplify the process of compensation, a series of assumptions and approximations are listed as below:

- All structures and distribution of all parameters are circular symmetrical, with the same axis right in the middle of the transporting tunnel.
- The divergence angle of the beam is so small that $\cos\theta \approx 1$;
- Ions are all single-charged and ionized from a single atom;
- Ions' interaction with electrons will not change their transporting velocity, ions' interaction with nuclei will not ionize the atom, which means ionization and impingement are separated;
- Neglect the longitudinal electric field, and neglect the longitudinal motion of low energy (less than 1keV) particles;
- Neglect the magnetic field generated by charged particles in the system.

Such approximations are applicable for the PKU ECR single-charged ion source and transportation instruments attached to it. When applying in other conditions, one or two of the approximations have to be adjusted.

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The Equivalent Particle Density

Although reasonable assumptions have been seen to simplify the process of compensation, we still have to face a series of integral equations, which is hard for computer to solve, if no further simplification is done.

Thus, we introduce a new variant, the Equivalent Particle Density (EPD) [3] to replace the density of particles. EPD is defined as the mean of the density within a certain volume, given by the equation below:

$$\rho(r) = \frac{1}{\pi r^2 \cdot dz}\int_0^r n(x)2\pi x dx \cdot dz = \frac{2}{r^2}\int_0^r n(x)x dx \quad .(1)$$

By applying the EPD concept to our model, we can avoid solving integral equations with a minor deviance from the reality. Thus, our model is well simplified.

The Column Cell

In order to carry out our numerical simulation, we therefore introduce the column cell.

According to approximation 1, we can divide the beam into many columns that have the same height of *dz*, and divide every column into a series of columns with one common axis and different radius. Each of the small columns is a column cell.

Next, we will number the column cells with two variables (*j*, *k*). *j* represents the axial position of the column cell, meaning that the distance between that column cell and the starting point is *jdz*. *k* represents the radius of the column cell. All column cells with a common *k* value should contain the exact amount of beam particles, if we ignore the loss of beam during transporting.

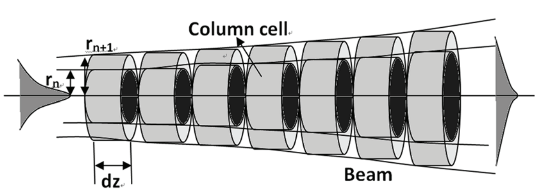

Figure 1: The column cell.

Physical Processes of Compensation

In this subsection, major physical progresses that occur during the drift section are discussed about, and other minor interactions are neglected. According to our assumption of steady state, the density (or the EPD) of particles, including free electrons, low-energy ions and residual gas molecules, are time-independent within any of the column cells. Therefore, three equilibriums are presented as below:

- The equilibrium of free electrons.
  There are two ways to increase the number of electrons in a column cell and two other ways to reduce it.
  Within a time period *dt*, the ionization of residual gas caused by the beam ions generates *dGe* electrons; the mobility of electrons that undergoes radial electric field causes $dM_{ie} = u_e(r)\cdot n_e(r)2\pi r\cdot dz\cdot dt$ electrons to go inside the column cell (in this case, $u_e(r)$ means the mobility velocity of free electrons); the combination of beam ions and free electrons consumes *dHe* electrons; and diffusion of electrons causes $dM_{oe} = D_e \cdot \frac{dn_e(r)}{dr} \cdot 2\pi r\cdot dz\cdot dt$ electrons to move out of the column cell.
  Thus, the equilibrium of free electrons demands:

$$dG_e + dM_{ie} = dH_e + dM_{oe} \quad . \qquad (2)$$

- The equilibrium of low-energy ions.
  There is one way increase the number of electrons in a column cell and another way to reduce it.
  Compared to free electrons, low-energy ions are generated at the same rate by the ionization of residual gas, but consumed by the combination with electrons at a much slower rate which can be neglected. Also, the diffusion coefficient of low-energy ions is much smaller than the one of electrons, so it can be neglected too. The only one that contrasts with the case of free electrons is the mobility effect, which causes positive ions to move out of the column cell in a number of $dM_{oi} = u_i(r)\cdot n_i(r)2\pi r\cdot dz\cdot dt$ within a time period of *dt*.
  Thus, the equilibrium of low-energy ions demands:

$$dG_i = dM_{oe} \quad . \qquad (3)$$

- The equilibrium of residual gas molecules.
  There is one way increase the number of electrons in a column cell and another way to reduce it.
  Within a time period of *dt*, *dHg* residual gas molecules are ionized; the loss molecules can be replenished by the diffusion of outer residual gas, and the amount of neutral gas molecules that move into the column cell is $dM_{ig} = D_g \cdot \frac{dn_g(r)}{dr} \cdot 2\pi r\cdot dz\cdot dt$.
  Thus, the equilibrium of residual gas molecules demands:

$$dH_g = dM_{ig} \quad . \qquad (4)$$

According to basic static electric field theory, the field strength is given by the Gaussian law, which can be simplified in our model as:

$$E = \frac{e}{2\varepsilon_0} r[\rho_b(r) + \rho_i(r) - \rho_e(r)] \quad . \qquad (5)$$

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Equations

Combining all four subsections above, applying the EPD to all equations and replacing the density n with it, substituting the mobility speed and the diffusion coefficient with their specific expressions [4], then we have equations below:

$$c_1 + c_2\sqrt{b(i,j)-e(i,j)+i(i,j)}\cdot[e(i,j)+\frac{r}{2}\dot{e}(i,j)] = c_3\cdot e(i,j)+\frac{3}{2}c_4\frac{\dot{e}(i,j)}{\sqrt{b(i,j)-e(i,j)+i(i,j)}}. \quad (6)$$

$$c_5 = c_6[b(i,j)-e(i,j)+i(i,j)]\cdot[i(i,j)+\frac{r}{2}\dot{i}(i,j)]. \quad (7)$$

$$c_7\cdot b(i,j)g(i,j)r(i,j) = c_8\cdot\dot{g}(i,j). \quad (8)$$

$$v(i,j) = c_9[b(i,j)-e(i,j)+i(i,j)]\cdot r(i,j). \quad (9)$$

$$r(i+1,j) = r(i,j)+v(i,j)\cdot\frac{dz}{v_b}. \quad (10)$$

$$b(i+1,j) = (1-S_{dz})\cdot b(i,j)[\frac{r(i,j)}{r(i+1,j)}]^2. \quad (11)$$

where $c_1 \sim c_9$ are all constants depending on certain background conditions.

And for all the derivatives in equations (13) – (18), we have:

$$\dot{\rho}(i,j) = \frac{\rho(i,j)-\rho(i-1,j)}{r(i,j)-r(i-1,j)}. \quad (12)$$

INTRODUCTION

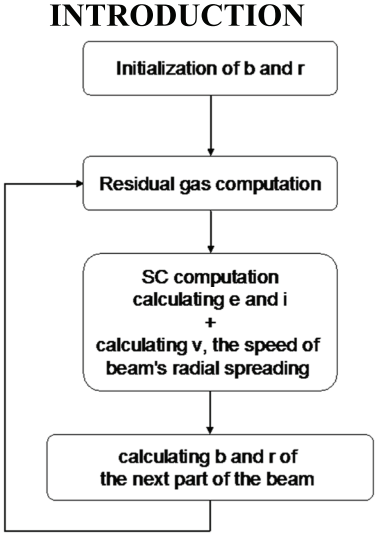

Figure 2: Algorithm of the model.

First of all, this section is focused on the application of our model on the case that the He+ beam current is 10 mA and Gaussian-distributed, with its energy 50 keV and its mean beam radius 30 mm, that the length of the drifting section is 300mm, and that the residual air is argon with its pressure to be 1.0×10-3 Pa. Assume that the temperature of the system remains 300 K.

The algorithm of our model is shown as Fig. 2. With some other experimental data, such as the cross section of ionization and combination [5], [6], we are able to compute the result of the model.

Up till now, we have only got the result of our model in the case of no compensation at all. As we can see from Fig. 3, the distribution of the beam changes from the initial Gaussian-distribution quickly to a uniform one. This proves that our model is reasonable and feasible.

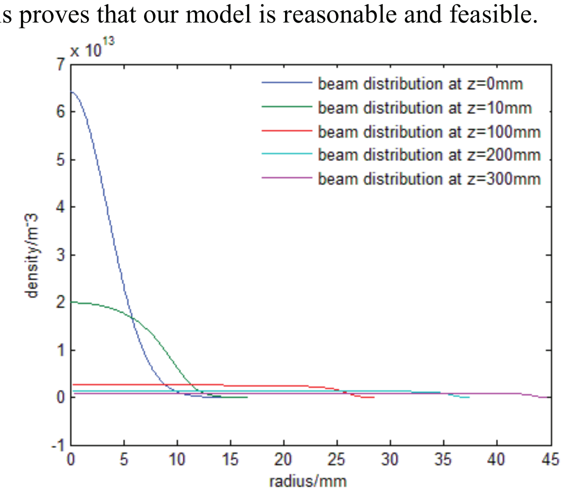

Figure 3: The beam distribution, simulation result for the distribution of the beam, with no compensation at all.

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