STUDIES OF BUFFER GAS COOLING OF ION BEAMS IN AN RFQ COOLER AND THEIR TRANSPORT TO THE EBIS CHARGE BREEDER*

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Abstract

In rare isotope accelerator facilities, an RFQ cooler is often used to manipulate ions. The RFQ cooler is a device to effectively cool and confine ions in gaseous environment. The RFQ cooler provides a radial electric force to the beam by applying RF voltages to the quadrupole electrode structures, and axial force by applying different DC voltages to the segmented electrodes. The ions are trapped inside the potential well of the RFQ cooler formed by the DC fields, so that they have more collisions with the buffer gas. Several important parameters such as transverse emittance can be improved when ion beams are extracted from the RFQ cooler. In order to design an efficient RFQ cooler, which can properly match the ion beams into the EBIS charge breeder, it is essential to analyze evolutions of the transverse emittance and transmission efficiency through the RFQ cooler. Moreover, to minimize emittance growth and maximize transmission efficiency, the beam transport line to the EBIS charge breeder needs to be optimized. In this work, we study the methods to apply the mechanism of buffer gas cooling in RFQ cooler to G4beamline and the beam transport line to EBIS charge breeder to TRACK.

INTRODUCTION

The ion motion in the Radio Frequency Quadrupole (RFQ) has been known through researches of Paul trap, Penning trap, and so forth. Based on these researches, the RFQ is used in many ways as a linear accelerator, a mass spectrometer, a cooler and buncher, and so on. And the RFQ cooler, which uses the buffer gas, is useful for the manipulation of ion beams. So, the RFQ cooler is used in some institutes.

The ions are confined by the radial force by the RF field and collide with the buffer gas. By the collisions with the gas, they lose their energy and temperature. And the axial DC field, which makes the potential well, helps them make more collisions effectively.

In this study, the motion of the ions in the RFQ is simulated by G4beamline, and the collision models used in it are compared other simulation tools. And the characteristics of the injected and extracted ion beams are measured by simulation.

BASIC THEORY

RF Field in RFQ

Simple RFQ cooler is composed of 4 electrodes, which make the RF electric field on transverse direction. The RF field induces transverse motions to ion beam. The potential function [1, 2] is

$$\Phi = \frac{V_{pp}}{2r_0^2}\cos(\omega_{RF}t)\cdot(x^2-y^2). \tag{1}$$

V_{pp} is a peak to peak amplitude of the RF voltage, $2r_0$ is the distance between opposite electrodes, and ω_{RF} is the RF frequency. And the electric field induced by the RF voltage [1] is

$$\begin{aligned}\boldsymbol{E} &= -\nabla\Phi \\ &= -\frac{V_{pp}}{r_0^2}\cos(\omega_{RF}t)\cdot(x\boldsymbol{i}-y\boldsymbol{j}).\end{aligned} \tag{2}$$

This oscillating field makes the motions of the ion beams composed of two components; micromotion and macromotion [3]. The micromotion results from the high-frequency field oscillation, and the macromotion is an oscillation in the pseudopotential with the macro-oscillation frequency depending on the amplitude of the electric field. And the equation of motion to interpret these motions on x-direction [2] is

$$\ddot{x} = -\frac{eV_{pp}}{mr_0^2}\cos(\omega_{RF}t)\cdot x. \tag{3}$$

This equation is the Mathieu equation, and solving this, these motions can be explained. And, using the Mathieu parameter, the stability of the motion of ion beams, which is how well they are confined, can be expected and the macro-oscillation frequency can be calculated. The parameter [1, 2] is

$$q = 2\frac{eV_{pp}}{m_i r_0^2\omega_{RF}^2}, \tag{4}$$

where m_i and e are respectively the mass and charge of ion. Generally, applying the only RF voltage, the motion of ion beams is stable at $q < 0.908$ [4].

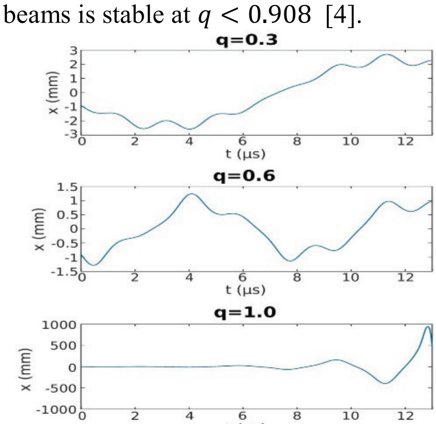

Figure 1: Graphs of the motion of an ion in the RFQ with various q obtained by G4beamline.

And the micromotion has a frequency ω_{RF}, and the macromotion has the macro-oscillation frequency ω_M, which can be approximated by

$$\omega_M \cong \frac{q}{2\sqrt{2}}\omega_{RF}, \tag{5}$$

for $q < 0.6$ [4].

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As shown in Fig. 1, the motion of the ion beams are stable in the RFQ for $q < 0.908$ and unstable for $q > 0.908$ with the micromotion and macromotion. So, appropriate q should be chose to confine the ions radially.

DC Field along Longitudinal Direction

Whereas the RF field focuses the ion beams radially, the axial DC field by the segmented electrodes, which are like Fig. 2, makes the potential well [5] to trap them. In order to effectively cool and confine the ions, buffer gas is used in RFQ.

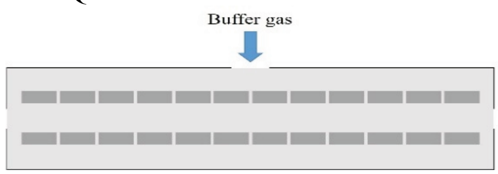

Figure 2: Geometrical view of the segmented electrodes in RFQ.

So, while moving back and forth along blue dash line in Fig. 3 by the potential well, they continuously collide with the gas. After the energy of the ion beams decrease due to the collisions with buffer gas, they are extracted.

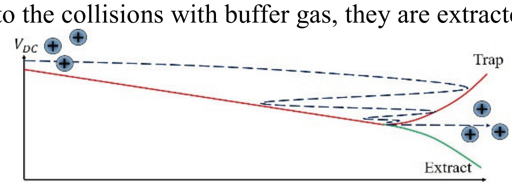

Figure 3: Potential well by the segmented electrodes and movement of ion along axial direction.

This potential well make the ions collide with the gas effectively. The energy spread and the emittance of the ion beams can be reduced by trapping them.

Collision Models

Two collision models are mainly used. One is viscous drag model using ion mobility, and the other one is hard-sphere model generally using the Monte-Carlo methods [6].

The viscous drag model considers the collisions between the ions and gas molecules as forming a viscous drag. In this model, the motion of them is calculated by the equation of motion adding the ion mobility term [3], which is

$$\ddot{x} = -\frac{eV_{pp}}{mr_0^2}\cos(\omega_{RF}t)\cdot x - \frac{e}{mK}\dot{x}, \qquad (6)$$

where K is the ion mobility. Although this model cannot show stochastic effect, it can calculate an average collisional cooling effect for each ion like decay of the energy and velocity of the ion beams, the stability of them, and the overall tendency of the motion of them.

In other hand, the hard-sphere model calculates the energy transfer and scattering angle for the individual collisions between the ions and gas molecules [6]. The motion of the ion beams is calculated using a collision frequency and a cross-section between them and the gas, the scattering angle, and the energy transfer. In addition, this model can show the stochastic effect because it considers each collision as a unique event. So, when using the G4beamline, it needs to be checked which collision model can be used in it.

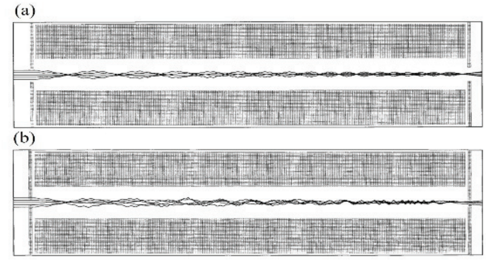

Figure 4: Comparison the ion motion of (a) the viscous drag model and (b) the hard-sphere model simulated by SIMION, from [6].

SIMULATION USING G4BEAMLINE

G4beamline is a particle tracking simulation program based on Geant4 [7], which is a platform for the simulation of the passage of particles through matter using the Monte-Carlo methods.

Only RF Field

First, the setup of the simulation is following; the distance between opposite rods is $2r_0 = 20$ mm, the buffer gas is N_2, the pressure of the gas is 0.13 Pa, the ion is Cs ion, the energy of it is ~ 100 eV, the RF frequency is $\omega_{RF} = 700$ kHz, and the macro-oscillation is $\omega_M = 60$ kHz. But, in the G4beamline, applying the RF voltage to the rods is impossible. So, in order to make the RF field, it calculated by Eq. (2) is put in it.

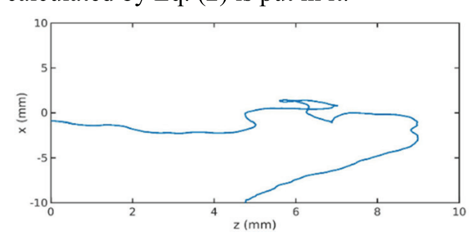

Figure 5: The motion of an ion simulated by G4beamline, turning on the multiple coulomb scattering process.

Figure 5 shows the result of the simulation, but it is a little weird. The cause of this result is the multiple coulomb scattering process, one of the physical processes used in the G4beamline. The Geant4 manual [8] explains that this process may provide wrong results in low-density media. Thus, it is turned off, and the result of the simulation is shown in Fig. 6.

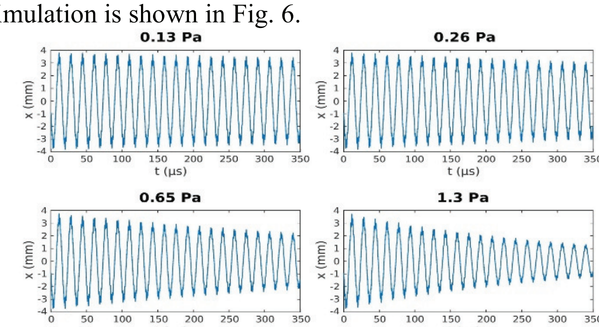

Figure 6: The motion of an ion simulated by G4beamline, varying the pressure of the buffer gas.

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Other conditions are same, but the pressure of the gas only varies from 0.13 to 1.3 Pa. Compared to Fig. 4, the result in Fig. 6 shows the sinusoidal shape of the ion motion, and it does not have the stochastic effect, so, the collision model in the G4beamline is not the hard-sphere model. The comparison of it with the viscous drag model [3] is shown in Fig. 7.

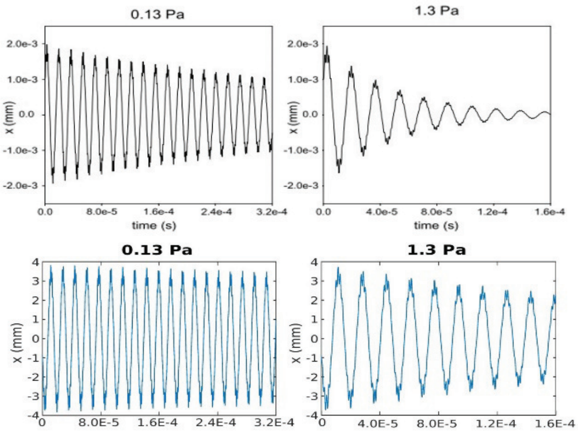

Figure 7: Simulation by G4beamline and the result of the equation of motion [3].

The motions of the ion beams in this figure are similar in the overall tendencies of them, but, the degree of the energy decay is different. This means that the collision processes of the G4beamline is different to it of other simulation tools.

Collision Processes in G4beamline

In order to check which processes affect the motion of the ions in the G4beamline, all processes in it is controlled one by one. As a result, the ionization process of the ion only affects it. Except this process, the other processes do not affect the motion of the ion beams.

The ionization process calculates the energy loss of them. This process is similar to the viscous drag model in the way that this provides the continuous energy loss, so, this does not show the stochastic effect. However, other processes are also needed to simulate correctly.

With DC Field

The simulation setup with DC field is matched up with it of RISP [9] for now. To compare them, the ion motion is simulated by the G4beamline.

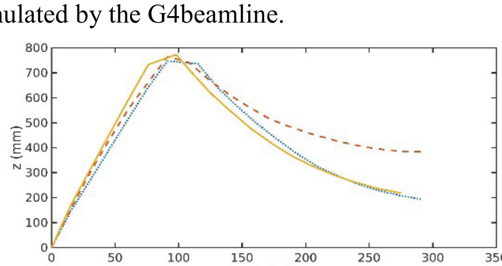

Figure 8: The motion of three ions.

As shown Fig. 8, the ions have turned back once, but, they stop at some point. When the simulation has been done in various conditions like the pressure, the amplitude of the DC potential, the ion energy, and so on, the points of the stop occur. After analysing those point, the simulation terminates when the energy of ion reaches about 1 eV. Thus, in order to use the G4beamline for trapping the ion beams, it should be modified so that it does not terminate below 1 eV of the ion.

CONCLUSION AND FUTURE WORK

The RFQ cooler should be designed considering the characteristics of the ion beams in it. And they have been researched using other simulation tools. Different from these researches, we have used G4beamline to study the RFQ cooler. As a result, the micromotion and macromotion of the ions by the RF field and the energy decay of them by the buffer gas are shown, but, the result using it is not matched up with other researches. The G4beamline is very useful simulation tool in high energy physics, but, it is not perfect to simulate heavy ions or low energy physics like the RFQ cooler. So, the codes of the G4beamline need to be modified to proper collision models. And the ions are not stopped at the end of the RFQ cooler, but they keep going next facilities like the EBIS charge breeder. Thus, the ion beams should be under the control to keep the best condition. As a future work, we will investigate the properties of the ions in RFQ cooler by modifying the codes of G4beamline and their transport to next facility, the EBIS charge breeder.

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