MULTIPLE CHARGE STATE ION BEAM ACCELERATION WITH AN RFQ LINAC

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Abstract

We are investigating space charge dominated beam dynamics in a Radio Frequency Quadrupole (RFQ) linac. In some accelerator systems, desired ions with different charge state ions are simultaneously injected into an RFQ linac. To describe the evolution of the multi charge beam inside the RFQ, we did particle simulation by using Particle-Mesh (PM) method. Here the high-intensity carbon beam made up of C^{4+}, C^{5+} and C^{6+} was applied to the simulation (C^{5+} was set to the designed ion). The space charge contributions to the transverse emittance growth and to the transverse and longitudinal particle motions are presented.

INTRODUCTION

The beam current from recent heavy ion sources are high enough that the self fields cannot be neglected in comparison to the applied fields. Some of the heavy ion sources are being developed to generate highly ionized particles. In these kinds of sources, desired ions with different charge state and contaminating particles are generated and extracted. In some heavy-ion accelerator systems, such as Electron Beam Ion Source (EBIS) Project at Brookhaven National Laboratory (BNL) [1] and Direct Plasma Injection Scheme (DPIS) [2], ions, which have close charge to mass ratio, are simultaneously injected into an RFQ linac with desired species.

In the EBIS-based pre-injector for Relativistic Heavy Ion Collider (RHIC) at BNL, which consists of EBIS, RFQ and Inter-digital H mode Drift Tube Linac (IH-DTL), the designed ion is Au^{32+}. However Au ions with different charge state are generated and extracted in the EBIS and transported through the Low Energy Beam Transport (LEBT) and injected into the RFQ linac.

The DPIS is the new method combining a Laser Ion Source (LIS) and an RFQ linac without an LEBT. In the DPIS, multiple charge state ions are extracted from the laser-produced plasma at the entrance of the RFQ. Therefore simultaneous injection of different charge state ions is unavoidable.

It is necessary to consider how the other charge state ions affect the condition of the desired ions especially in high-current accelerator systems. To evaluate the multi-charge effect, here we focus on the RFQ acceleration with numerical simulation using Particle-Mesh (PM) method [3] [4].

SIMULATION METHOD

Particles are forced by an external RF field of RFQ and internal space charge field. In this simulation, the external field was defined as two-term potential function [5] and the space charge field was obtained by solving three-dimensional Poisson equation inside the calculation box. This enables us to directly calculate the space charge field caused by the distribution of multiple charge ions. At each step in time, the simulation solves for the fields generated by the particles, and then produces particle motion.

RFQ Electric Field

The electric field is obtained from the gradient of the two-term potential function. The potential function is decided by the RFQ electrode parameters of intervene voltage, cell length, minimum radial aperture and modulation factor. Here, the parameters of our RFQ linac were used for the simulation. The RFQ linac (100MHz, 4-rod type, 118cell) was designed to accelerate high-intensity C^{4+} beam from an input energy of 20 keV/u to 100 keV/u (Fig. 1 and Fig. 2).

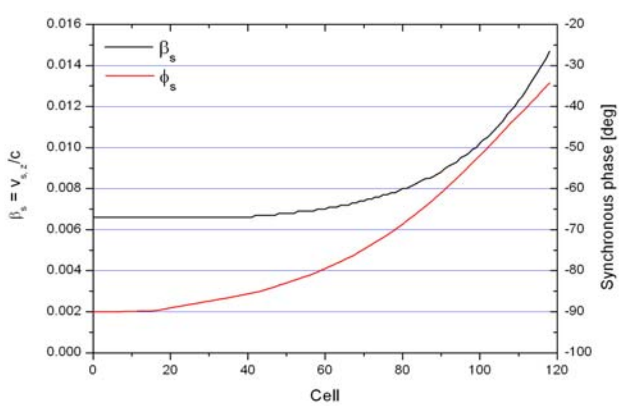

Figure 1: Normalized velocity of the synchronous particle and the synchronous phase at each cell of the RFQ. The cell length is equal to $\beta_s\lambda/2$ (λ is the wavelength of the RF).

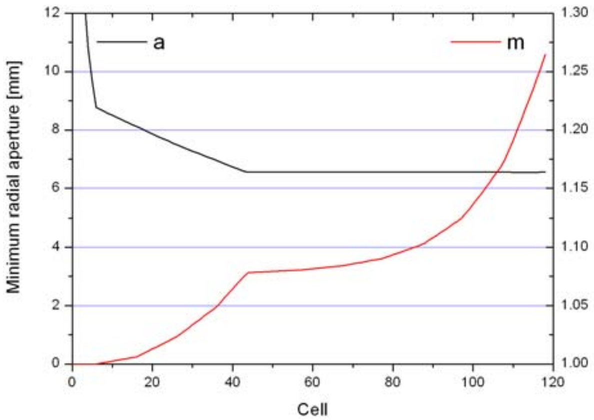

Figure 2: Minimum radial aperture and modulation factor at each cell of the RFQ.

Space Charge Electric Field

The space charge field is calculated inside the three-dimensional calculation box. The size of the box is transversely fixed to 20mm · 20mm and longitudinally set to βλ. This was decided by averaging β of the surviving, desired ions. This box was partitioned to 40 · 40 volumes transversely and 80 volumes longitudinally.

To calculate the charge density on the discrete grid points from the continuous particle positions, the electric charges of the macro-particles were assigned to the grid points by first-order weighting. The space charge potential on the grid points was obtained by solving Poisson equations using successive overrelaxation method. The boundary conditions of the calculation box is Dirichlet (u = 0) in the transverse direction and periodic in the longitudinal direction. The potential at the grid points inside the RFQ electrodes were set to zero (u = 0). The iteration was stopped when the maximum absolute value of the change rate became smaller than 0.001 ($(u_{new} - u_{old})/u_{new} \leq 0.001$) with the overrelaxation parameter of 1.8. The space charge field at the grid points was calculated by the central difference of the potential. The space charge field at the particle positions were obtained by linearly interpolating the space charge field at the nearest grid point as in the charge assignment.

Integration of the Equation of the Motion

The macro-particles are moved by both external RFQ field and space charge field described above. The equation of motion was integrated by using the leapfrog method. Then Δt was set to one RF cycle divided by 16 (10/16 ns). This means that 994 computational steps in time are needed for 118 cells of the RFQ electrode.

Conditions for Particle Simulation

In this simulation, multiple charge state carbon beam made up of C^{4+}, C^{5+} and C^{6+} was injected into the RFQ linac with same normalized emittance of 0.5 π mm-mrad. The C^{5+} beam have the designed input energy of 20 keV/u while C^{4+} and C^{6+} beam have the energy of 16 keV/u and 24 keV/u due to the same extraction voltage. The particles were randomly distributed inside the four-dimensional ellipsoid defined by the Twiss parameters. 1 macro-particle represents about 2500 particles.

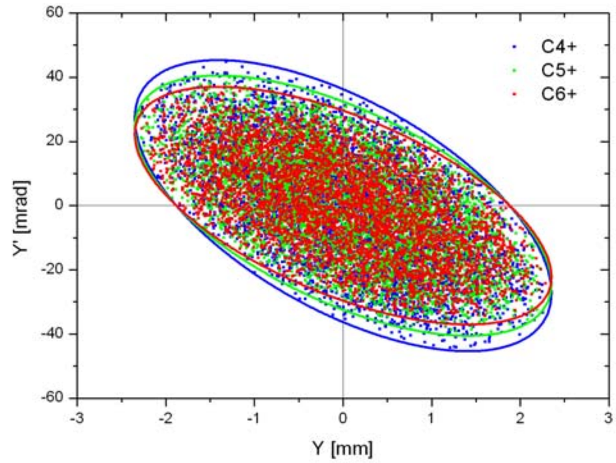

Figure 3: Initial distribution of the particles on the vertical phase space.

Table 1: Twiss Parameters for Initial Ellipse

	α	β (mm/mrad)	ε (mm-mrad)
C^{4+}	0.750	0.0648	85.310
C^{5+}	0.750	0.0725	76.301
C^{6+}	0.750	0.0794	69.658

The applied intervane voltage is 96 kV, which is the designed voltage to accelerate C^{5+} with input energy of 20keV/u to the designed output energy of 100 keV/u.

When a particle hits the electrode or goes transversely out of the calculation box, the particle is eliminated from the calculation. When a particle goes longitudinally out of the box, the particle comes back to the box from opposite side keeping the same x, v_x, y, v_y, v_z. Particles which have energy difference of more than 250k eV are excluded from the velocity and rms averaging.

RESULTS

For the beam dynamics simulation, a multi-charge state ion beam (shown in Table 1) was injected into RFQ linac.

Table 2: Beam Current of each Charge State injected into RFQ

Total (mA)	C4+ (mA)	C5+ (mA)	C6+ (mA)
3.0	0.8	1.0	1.2
12.0	3.2	4.0	4.8
21.0	5.6	7.0	8.4
30.0	8.0	10.0	12.0

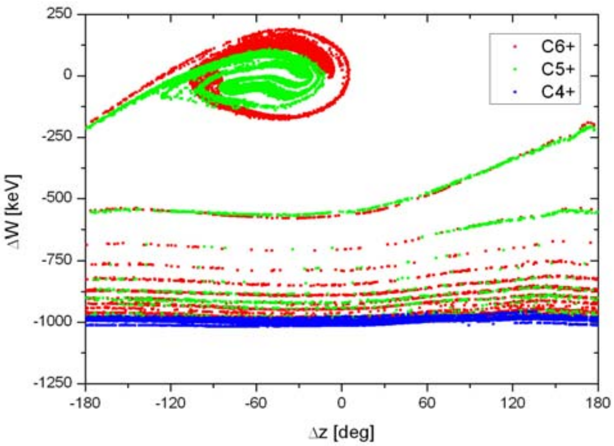

Figure 4: Longitudinal phase space at the last cell. The beam currents of each charge state are 3.2 mA, 4.0 mA and 4.8 mA for C^{4+}, C^{5+} and C^{6+}.

Transmission Efficiency

Fig. 4 shows the multi charge beam with the total current of 12.0 mA on the longitudinal phase space at the last cell. In this case, about 90% of C^{5+} ions can be accelerated, while all the C^{4+} ions are not accelerated and maintain the initial velocity due to the insufficient injection energy and intervane voltage. Due to the high injection energy, about half of the C^{6+} ions are not accelerated and accelerated C^{6+} ions are not distributed at the center of the longitudinal bucket.

Table 3 shows the transmission efficiency (both transversely and longitudinally survived) of each charge state. The transmissions of C^{5+} and C^{6+} decrease with increasing beam current.

Table 3: Transmission Efficiencies of each Charge State

Total (mA)	C^{4+}	C^{5+}	C^{6+}
0.0	0%	96%	70%
3.0	0%	94%	52%
12.0	0%	91%	53%
21.0	0%	90%	50%
30.0	0%	83%	47%

Transverse Emittance Growth

Fig. 5 shows the transverse rms-emittance growth of C^{5+}. The C^{5+} emittance growth of single charge beam (C^{5+}) was plotted in black and red (horizontal and vertical). The C^{5+} emittance growth of multi charge beams (C^{4+}, C^{5+}, C^{6+}) was plotted in green and blue (horizontal and vertical). The ellipse parameters of injected beam are matched in beam current of 0 mA case. Therefore this figure includes a space charge effect not only from the particle distribution but from radial mismatching.

If the total current is same, single charge beam has larger emittance growth than multi charge beam. One reason can be considered that each charge state beam has its own oscillations both transversely and longitudinally. The period of these oscillations depend on the charge to mass ratio. This results in a smaller space charge effect to the desired particles than in a single charge beam.

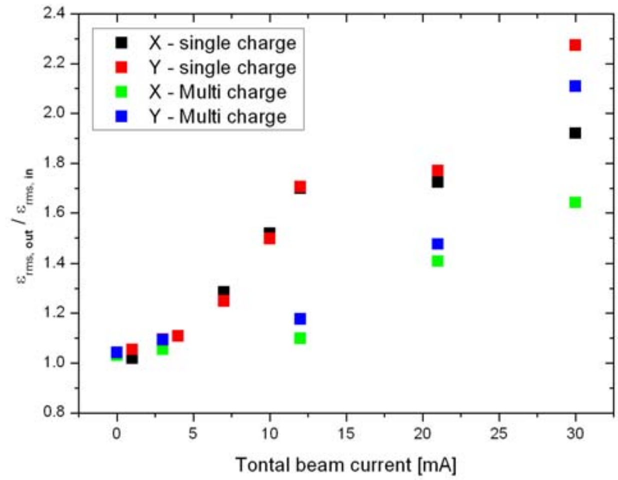

Figure 5: Transverse rms-emittance growth of C^{5+} beam.

We can see the longitudinal example in Fig. 6 and Fig. 7. These are the longitudinal phase space at the 18th cell. Both have the same total current of 12 mA. At the 18th cell, synchronous phase is to -89.4 deg for C^{5+} acceleration. The width of the separatrix is almost 360 deg. Particles inside the separatrix are successively accelerated by longitudinal restoring forces. This forces produce phase and energy oscillations about the synchronous particle. Due to the different initial energy and the different bucket shape, each charge state ion moves differently on the longitudinal plane. From these figures, we can see that space charge density in multi charge beam is less localized than in single charge beam because C^{4+} and C^{6+} ions are distributed in the longitudinal direction with uniformity. In Fig. 6, C^{5+} ions can rotate around the synchronous particle (center of the phase space), while in Fig. 7, C^{5+} ions bounce at the center by the strong space charge repulsion force.

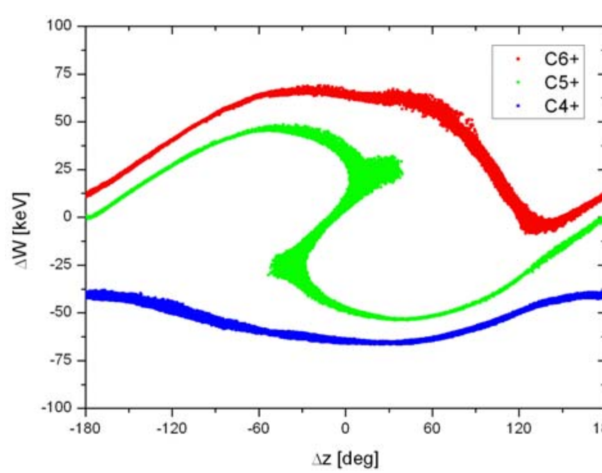

Figure 6: Longitudinal phase space of multi charge beam with total beam current of 12 mA at 18th cell.

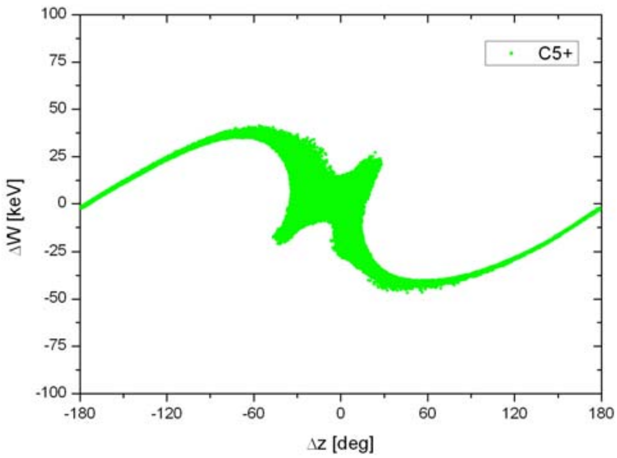

Figure 7: Longitudinal phase space of single charge beam with beam current of 12 mA at 18th cell.

CONCLUSION

To describe the evolution of the beam inside the RFQ, we simulated the multiple charge state ion beam acceleration. Due to the different charge to mass ratio, each charge state beam oscillates differently in both transverse direction and longitudinal direction, influencing each other. As an example, we saw the difference in how the beam is bunched even under the same total beam current. This can affect the transverse motion of particles. In high current RFQ acceleration like DPIS, to estimate the effect to the desired ions from the other ions will be more important. We need to continue this study by considering the charge distribution, particle distribution and beam matching of the injected beam.

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