

# CHARGE STATE SELECTIVE ION BEAM ACCELERATION WITH RFQ LINAC

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## Abstract

DPIS (Direct Plasma Injection Scheme) is one of the effective methods for high-intensity heavy ion beam acceleration. In the DPIS, multiple charge state ions are simultaneously injected into an RFQ. And then, ions whose charge states are comparable with that of ions desired for an RFQ acceleration are captured by the RF bucket. To prevent the unneeded ions from being accelerated, we investigated the motion of multiple charge state ions in an RFQ. We found that the discontinuous transition of a synchronous phase inhibits the unneeded ion's acceleration without a significant loss of desired ions. The particle tracking simulation for  $C^{5+}$  acceleration shows that 89% of  $C^{5+}$  and 9% of  $C^{6+}$  are accelerated with the discontinuous transition of the synchronous phase, whereas 96% of  $C^{5+}$  and 73% of  $C^{6+}$  are accelerated with the smooth transition. To validate the designed cell parameters, we manufactured new 4-rod RFQ electrodes and planed to perform beam acceleration test using the new RFQ electrodes.

## BACKGROUND

We have been investigating high-intensity carbon beam acceleration using DPIS (Direct Plasma Injection Scheme). In this scheme, high-intensity carbon plasma generated by irradiating a graphite target with a pulsed laser is directly injected into an RFQ [1, 2]. And then, ions are extracted at the entrance of the RFQ. Because the DPIS doesn't have an LEBT (Low Energy Beam Transport), multiple charge state ions are simultaneously injected into the RFQ. The simultaneous injection of multiple charge state ions is unavoidable. And also, the beam is not matched for the RFQ injection [3].

Ions whose charge states are comparable with that of ions desired for the RFQ acceleration are captured by RF bucket and accelerated with the desired ions [4]. Therefore, we have investigated an RFQ which doesn't accelerate unneeded ions (different charge state ions) [5]. And then, we manufactured new RFQ electrodes based on the result of particle tracking simulation. In this paper, the designed RFQ cell parameters and the tracking simulation result are shown.

## MANUFACTURED RFQ ELECTRODES

The new RFQ was designed to accelerate  $C^{5+}$  and not to accelerate different charge state carbon ions such as  $C^{6+}$  and  $C^{4+}$ . The differences of  $A/Q$  gives the smallest value for carbon ion under this condition. Ions which charge state is higher than that of ions desired for an RFQ acceleration

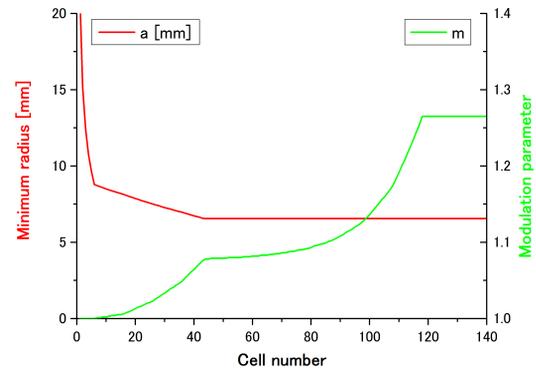


Figure 1: The minimum aperture and modulation factor.

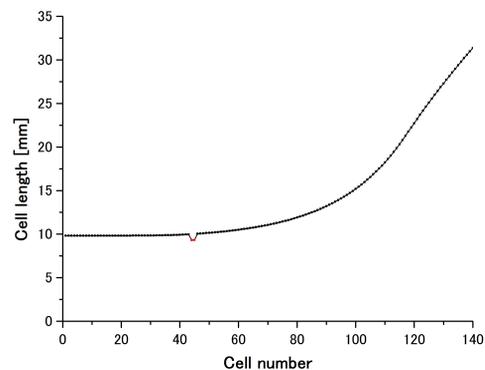


Figure 2: The cell length.

are captured by the longitudinal RF bucket more than lower charge state ions. Therefore, the requirement for the new RFQ is to prevent  $C^{6+}$  from being accelerated and not to decrease the rate of the accelerated  $C^{5+}$ .

The designed RFQ have a discontinuous transition of the synchronous phase in the bunching section. The cell parameters for the RFQ are shown in Fig. 1 and Fig. 2. The cell length is shorten at the 43th and 44th cell as shown in Fig. 2, whereas the cell length is smoothly increased in an usual RFQ acceleration. This shortening of the cell length shifts the synchronous phase smaller (to negative direction) and leads to the discontinuous transition of the synchronous phase. In the smooth transition of the synchronous phase, the synchronous phase is gradually increased from -90 degree to positive direction.

The new 4-rod RFQ electrodes were manufactured in Hiroshima and delivered to J-PARC in Tokai site of Japan

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Figure 3: The manufactured RFQ electrodes.

Atomic Energy Agency. Parts of the manufactured electrodes are shown in Fig. 3. We are planning to ship these electrodes to Brookhaven National Laboratory and perform beam acceleration test by applying these electrodes to the DPIS.

### LONGITUDINAL MOTION

Using the cell parameters shown in Fig. 1 and Fig. 2, particle tracking simulation was conducted. In this simulation, motions of  $C^{4+}$ ,  $C^{5+}$ ,  $C^{6+}$  were tracked without a space charge effect. The resonant frequency of the RFQ is 100 MHz and the inter-vane voltage was set to 96 kV for  $C^{5+}$  acceleration. This RFQ accelerates ions from 20 keV/u to 200 keV/u with 2 m long of electrodes. The injection energy of each charge state is shown in Table. 1. These values were derived from 48 kV of extraction voltage for  $C^{5+}$  acceleration. The initial longitudinal distribution is shown in Fig. 4.  $C^{4+}$ ,  $C^{5+}$  and  $C^{6+}$  are shown by green, red and blue dots, respectively.  $\Delta W$  in each charge state was set to zero because the energy spread of the laser-produced plasma is incomparably small compared with the extraction voltage. The transverse emittance was set to  $1 \pi$  mm-mrad of normalized emittance for both horizontal and vertical direction. And also, the ellipse parameters (shown in Fig. 5) were set to match the RFQ injection to eliminate the transverse loss. In this simulation, we focused only on longitudinal motion to discuss how the acceleration of the unneeded ion is avoided.

The result of the particle tracking simulation shows that 89% of  $C^{5+}$  and 9% of  $C^{6+}$  are accelerated with the discontinuous transition of a synchronous phase, whereas 96% of

Table 1: Injection Energy of Each Charge State

| Ion      | Energy [keV] | Energy [keV/u] |
|----------|--------------|----------------|
| $C^{4+}$ | 192          | 16             |
| $C^{5+}$ | 240          | 20             |
| $C^{6+}$ | 288          | 24             |

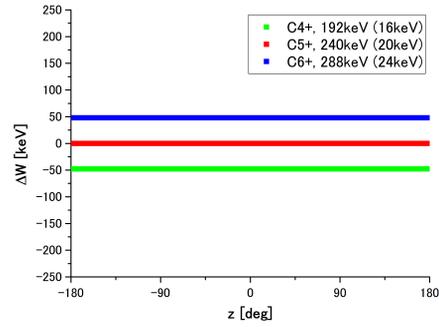


Figure 4: Initial distribution for z-z' plane.

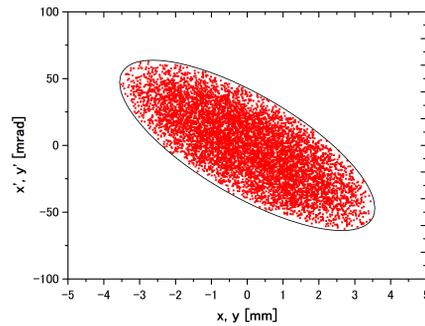


Figure 5: Initial distribution for x-x' and y-y' plane.

$C^{5+}$  and 73% of  $C^{6+}$  are accelerated with the smooth transition. Figure. 6 shows the rates of unaccelerated ions in each charge state. Particles that have more than 250 keV of  $\Delta W$  are identified as longitudinally lost particles.  $C^{4+}$  cannot be accelerated due to the lack of injection energy with both smooth and discontinuous transition of a synchronous phase. No particles are lost in the transverse direction (All the particles goes through the RFQ even under unaccelerated condition).

The deceleration induced by the shortened cell at 43th and 44th cell contributes to the feature of non-accelerating

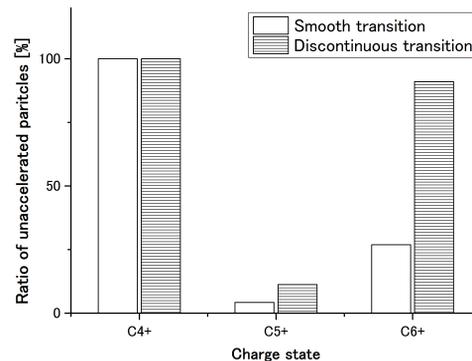


Figure 6: Rates of unaccelerated ions in each charge state.

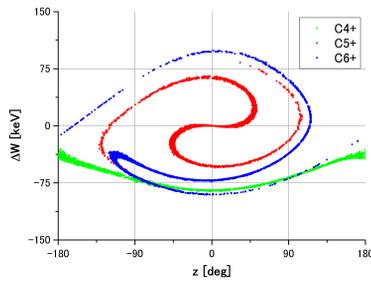


Figure 7: 50th cell (smooth).

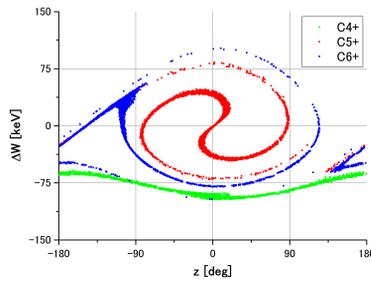


Figure 8: 58th cell (smooth).

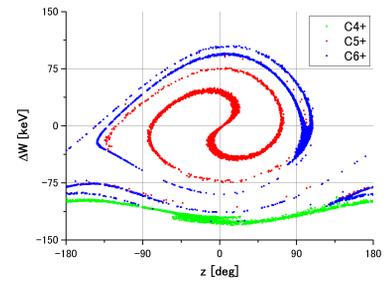


Figure 9: 70th cell (smooth).

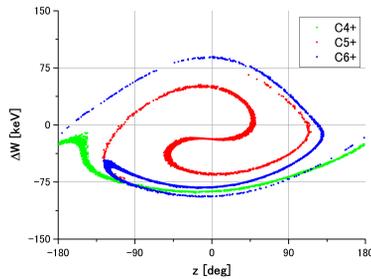


Figure 10: 50th cell (discontinuous).

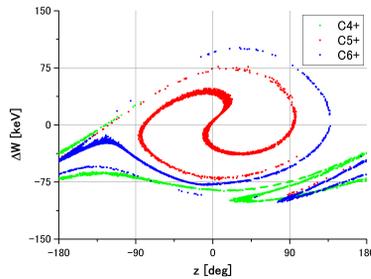


Figure 11: 58th cell (discontinuous).

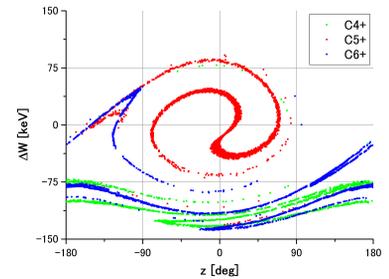


Figure 12: 70th cell (discontinuous).

$C^{6+}$ . The longitudinal motion with smooth transition of the synchronous phase are shown in Fig. 7, Fig. 8 and Fig. 9. In case of the discontinuous transition, ions move as in Fig. 10, Fig. 11 and Fig. 12. In the 43th and 44th cell, most of the  $C^{6+}$  ions are located in the bottom part of the separatrix (longitudinal acceptance for successive acceleration). By choosing the synchronous phase lower than  $-90$  degree, most of the ions are decelerated and shifted further to bottom side in the longitudinal phase space. When the synchronous phase returns to the original value, most of the shifted  $C^{6+}$  are located outside of (below) the separatrix.

## SUMMARY

To prevent unneeded ions from being accelerated, we performed particle tracking simulation for multiple charge state ions in the RFQ. According to the simulation result, the discontinuous transition of a synchronous phase inhibits the acceleration of the unneeded ions without significant loss of the desired ions. To validate the designed modulation parameters, we manufactured new RFQ electrodes based on the simulation result. We are planning to perform a beam acceleration test by applying the new electrodes to the DPIS.

## ACKNOWLEDGMENT

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