BEAM DYNAMICS OF MULTI CHARGE STATE IONS IN RFQ LINAC

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Abstract

Laser ion source with DPIS (Direct Plasma Injection Scheme) is a promising candidate for a pre-injector of a high-brightness accelerator. In DPIS, high current ion beam is extracted from laser plasma at the entrance of an RFQ linac. Therefore, without LEBT (Low Energy Beam Transport) where the space charge effect is severe, ions are injected directly into the RFQ linac and high brightness ion beam can be accelerated. However, the injected beam consists of ions with various charge states. The unneeded ions cause space charge force and consume energy of RF field, emittance growth and excess beam loading occurs. In this research, we study the beam dynamics of ions with various charge states in an RFQ. Using the result of computer simulations, a set of 100 MHz 4-rod RFQ vanes, which accelerates Al 12+ ion among various charge states of aluminium ions from 8.9 keV/u to 180 keV/u, is newly designed and fabricated for beam acceleration test with beams from laser ion source.

LASER ION SOURCE WITH DPIS

Laser ion source is one of the promising candidates for a front end of future high power heavy ion accelerators [1]. The acceleration of relatively light ion nucleus (such as carbon, aluminum, iron) from laser ion source with DPIS is successfully demonstrated [2,3,4].

Although laser ion source with DPIS can provide high brightness ion beams, ions in laser plasma are provided in thermal process and their charge state distribution is broad. For example, to produce Al^{12+} ions in laser ion source, almost same number of Al^{11+} and Al^{13+}, and relatively small number of other ions with lower charge states are provided. Therefore, extracted beam into RFQ have various charge states ions, and ions other than those who have designed charge state would be accelerated. These unneeded ions consume RF power and strengthen space charge effect. These phenomena would be critical issue in operation of RFQ with space charge dominant region. Furthermore, if these unneeded ions are accelerated by RFQ and subsequent front-end accelerators, they must be aborted by some analyzer magnets in beam transport line after MEBT. However, in high power beam operation, such abort section provides excess radiation. Therefore, an RFQ that accelerates only designed charge state ions has advantages for future high power accelerator front-ends.

CHARGE STATE SELECTIVE ION BEAM ACCELERATION

The ions injected into RFQ have different kinetic energies depending on their own charge states, because they are extracted from same electric field. Therefore, ions whose charge state is enough lower than designed charge-to-mass ratio would not captured and just drift to the exit of RFQ tank, because the electric force is too small for an ion to be captured in an RF bucket, which might be absent entirely. However, ions whose charge states are higher or comparable with the designed charge to mass ratio would be captured by RF bucket and accelerated in RFQ.

To design an RFQ linac that accelerate only ions with a designed charge state, beam behavior of ions with various charge states are simulated with various cell parameters. We choose Al^{12+} ion as the design particle. To demonstrate beam acceleration with a 100 MHz 4-rod RFQ tank in Brookhaven National Laboratory, simulation conditions are set as shown in Table 1. In our simulation, Al^{11+}, Al^{12+}, and Al^{13+} are tracked. In order to study various vane parameters, we simplify the beam simulation condition; beams are tracked only in the longitudinal direction, space charge effect is ignored, and electric field in all cells is described by two-term potential function.

As first simulation, we apply the conventional RFQ design with adiabatic bunching section [5]. However, RFQs with such designs would accelerate Al^{13+} and capture rate of Al^{13+} is almost same number as that of Al^{12+}. It is because RFQ linacs with the adiabatic bunching section has large longitudinal acceptance.

Second, we don't apply the adiabatic bunching section, and introduce pre-buncher section and drift section in RFQ linac. In this case, pre-bunch section consisting of a few number of cells with modulation are located at the beginning part of RFQ to rotate longitudinal phase. In subsequent cells, modulations of vane suddenly vanish, and beams are bunched due to their velocity differences. Selecting the length of this drift section, ions with different charge states can be bunched in different phases, because their initial energies depend on their charge states and their phase slip factors are different. At the region where this phase difference to be 180 degree, the modulation of vane is gradually increased and Al^{12+} would be captured. However, our simulation shows that, with this pre-buncher scheme, capture rate of Al^{12+} is less

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ISBN 978-3-95450-142-7

Table 1: Simulation Condition

Structure	4 rod
Frequency	100 MHz
Designed charge to mass ratio	12/27 (Al^{12+})
Length	2 m
Input Energy	8.89 keV/u
Output Energy	180 keV/u
Designed Vane Voltage	50 kV
r_0	4.5 mm
Maximum m Value	1.2

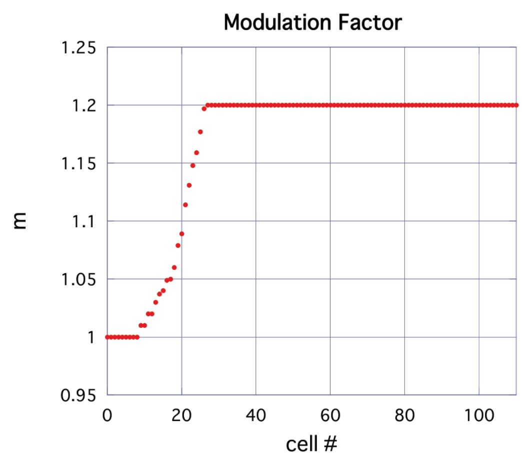

Figure 1: Applied modulation factor along cell number.

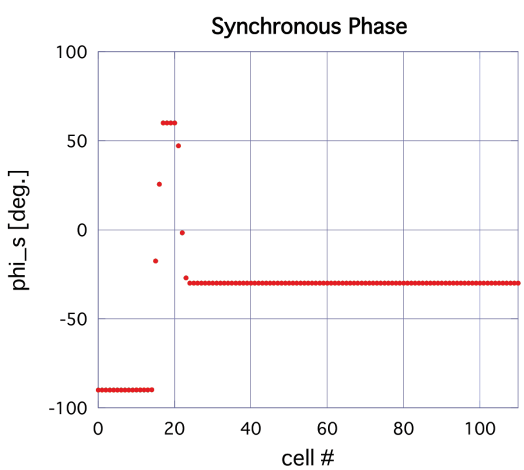

Figure 2: Applied synchronous phase along cell number.

than 50 %, and that of Al^{13+} is larger than 30 % for various vane parameters.

To overcome the limitation described above, we apply phase jump section. Applied cell parameter is shown in Figure 1 and 2. In this design, synchronous phase jumps to positive values before the modulation factor goes to the maximum value. Figure 3 shows the particle distribution in longitudinal phase space through the phase jump section. In these figures, vertical axis is energy difference from the designed reference particle and horizontal axis is phase difference from the reference particle. Blue, green, and red dot shows the distribution of Al^{13+}, Al^{12+}, and

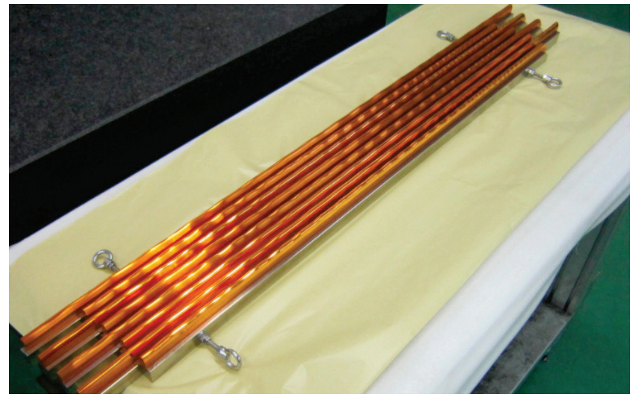

Figure 4: Fabricated RFQ rods.

Al^{11+}, respectively. Cyan and magenta curves are estimated separatrix for Al^{13+}, Al^{12+}, respectively. In initial condition, the kinetic energies of Al^{13+}, Al^{12+}, and Al^{11+} are different because they are extracted by same electric field and the energies of Al^{13+} (Al^{11+}) are 1/12 % higher (lower) than the energy of Al^{12+}, due to the difference of their charge. In phase jump section, as longitudinal oscillation experiences 45 degree in phase, the synchronous phase jumps from -89 degree to 60 degree. Due to the unstable characteristics at the saddle point, ions other than designed particle move away from the reference particle. However, the Al^{12+} ions remain the position near the reference particle. After that, synchronous phase change -30 degree and ions near oscillation center would be captured and accelerated. Although this cell parameter has somewhat drastic change in synchronous phase, the acceleration rates for Al^{13+}, Al^{12+}, and Al^{11+} are 8 %, 60 %, and 5 %, respectively.

In order to check the validity of the applied cell parameter via beam acceleration test, vanes for 100 MHz 4-rod RFQ is designed with the applied cell parameters and fabricated. Figure 4 is a picture of fabricated vanes. These vanes will be attached to 4-rod RFQ tank in laser ion source laboratory in BNL. Beam acceleration test is planed in next few months.

CONCLUSION

To demonstrate charge state selective ion beam acceleration with RFQ linac, beam dynamics in RFQ linac with various cell parameters are simulated. The result shows a cell parameter including drastic change in synchronous phase is one of the effective parameters. Applying this cell parameter, RFQ vane are fabricated and a beam acceleration test with the vane is planed.

ACKNOWLEDGMENT

This research was supported by the U.S. Department of Energy and RIKEN Junior Research Associate Program.

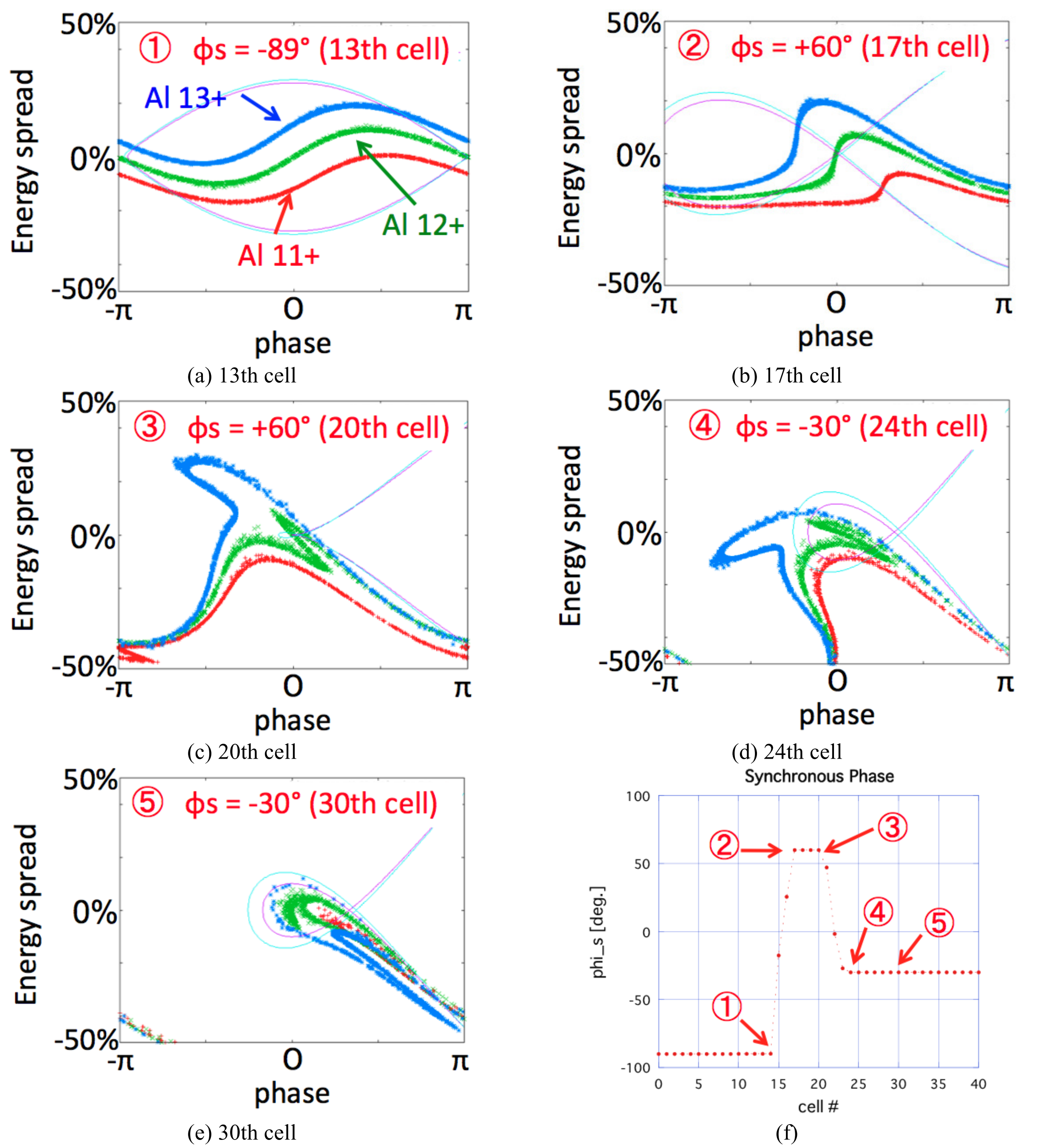

Figure 3: Results of particle tracking with applied cell parameter. (a)-(e) Particle distribution in longitudinal phase space. Blue, green, and red dots shows Al 13+, Al 12+, and Al 11+, respectively. (f) Applied synchronous phase.

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ISBN 978-3-95450-142-7