COMPARATIVE STUDY OF BEAM DYNAMICS IN THE RFQ FOR J-PARC LINAC

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Abstract

A new linac front-end had been installed for intensity upgrade of J-PARC in 2014, July-September. It consists of a 50 keV Ion Source (IS), a two-magnetic solenoid based Low Energy Beam Transport (LEBT) and 324 MHz RFQ accelerating 50 mA H^- beam to 3 MeV. In the linac, there are three beam transport sections were implemented to match the beam between the different accelerator elements. This paper presents the simulation study of high intensity beam dynamics in the RFQ and the study of transverse dynamics of secondary particles in RF field generated by residual gas ionization of H^- beam. Comparison of studies of a uniformly generated particle distribution and a more realistic beam, the distribution re-constructed from Test Stand emittance measurement has been made. Emittance and twiss parameters at the exit of RFQ are determined and can be used for beam matching optimization in the Medium Energy Beam Transport (MEBT1) section.

INTRODUCTION

The J-PARC [1] Linac accelerating scheme is shown as block diagram in Fig. 1 which begins with a negative ion source for producing a H^- beam. A two-solenoid based 50-keV LEBT is installed between the ion source and the 324-MHz RFQ. 3-MeV output beam from RFQ will be matched through MEBT1 into 324-MHz Drift-Tube Linac(DTL) and Separated DTL(SDTL). There is a third matching section MEBT2 before the Annular-ring Coupled Structure (ACS). For high intensity beams in LEBT region of accelerator the space charge effects has to be considered for optimum beam matching. Such beams are usually transported in a space charge compensation regime in order to reduce the defocusing space charge forces. High intensity negative ion beams can be space charge neutralized/compensated by positive secondary ions produced by the residual gas ionization. Positive ions will be trapped by the beam potential leading to a decrease of the local charge density and therefore the electric field inside the beam. The process will continue until a steady state is reached. If no lost mechanism is assumed, the neutralizing positive ions accumulate up to the space charge becomes negligible. The characteristic time required to reach the steady state is inversely proportional to vacuum pressure. LEBT configuration of the J-PARC Linac has two different residual gas(vacuum) pressure at upstream and downstream parts separated by 15-mm aperture. Measured vacuum pressure is 3×10^{-3} Pa and 2×10^{-5} Pa, relatively. The vacuum pressure inside the RFQ is approximately 1.1×10^{-5} Pa. The space charge depends on beam energy and therefore has to be investigated up to 50 MeV at least. We propose to study space charge compensation regime in the presence of RF field. The study assumes no longitudinal modulation of electrodes are present in order to simplify the study and to only illustrate the transverse behavior of the secondary particles.

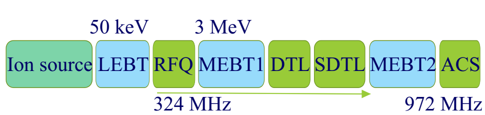

Figure 1: Block diagram of J-PARC Linac.

TRANSVERSE DYNAMICS OF THE RESIDUAL GAS IONS IN RF FIELD

The transverse dynamics of the residual gas positive ions in the RFQ field is studied assuming there is no longitudinal modulation of electrodes present. Residual gas composition in the RFQ beampipe are mainly molecular nitrogen and molecular hydrogen is also possible. Particles are lost on the vacuum chamber if their transverse trajectory amplitudes are larger than the dimension of the vacuum chamber. When RF field is off and beam is absent, positive ions will collide to chamber due to their thermal energies.

Equation of motion

The equation of motion of the ionized particle in horizontal degree of freedom is given:

$$m\ddot{x}(t) = Q \cdot E_f \cdot cos(\omega \cdot t) \tag{1}$$

with $E_f = a \cdot x(t)$, $a = 2 \cdot U_{vane}/r^2$. Where r is the distance between vane-electrode and the RFQ beam axis, U_{vane} is the vane voltage. The solution of this second order differential equation is the Mathieu function [2, 3]. The Mathieu functions appear in physical problems involving elliptical shapes or periodic potentials, and were first introduced by Mathieu (1868) when analyzing the motion of elliptical membranes. There are two initial conditions in solving the equation of motion; secondary positive ions produced by residual gas ionization of 50-mA H^- beam has only thermal energy, it is negligible compared to the H^- ion velocity. The transverse coordinates of positive ions are close to the beam axis that can interact with H^- beam field and will be captured. Beam pipe diameter within the RFQ is 6-mm if the geometrical structure of vane-electrode modulations are neglected. Process of dynamics in the vertical degree of freedom is identical to the horizontal case with only opposite sign. Relevant parameters to this calculation is summarized in Table 1.

Results and discussion

Vacuum compositions in the RFQ, molecular nitrogen and molecular hydrogen are electrically neutral in a molec-

Table 1: Specifications

Ions		**RF field**
Mass (N_2^+)	28	U_{vane} $(48\ kV)$
Mass (H_2^+)	2	f_{RF} $(324\ MHz)$
T (N_2^+)	485 ns	T_{RF} $(3.086\ ns)$
T (H_2^+)	34 ns	r $(3\ mm)$

ular state. When H$^-$ ionize them the transverse dynamics of secondary positive ions are studied for N_2^+ and H_2^+ accordingly. The horizontal coordinates of N_2^+ ion as a function of time in the RF field is shown in Fig. 2 and in Fig. 3. Ions reveal high frequency oscillation where the period is the same as RF field as shown in Fig. 2 during 90 ns. Also low frequency oscillations of ion motion are present as shown in Fig. 3, which depend on many other parameters such as ion mass, RF frequency and vane voltage. It has been concluded that, the transverse motion of positive ions in the RF field is a stable motion. Two radial forces are present in the system, RF and space charge field which is only valid until the H$^-$ beam is fully charge neutralized. Electrons produced by residual gas ionization will immediately be removed from beam region due to the radial forces. Therefore electrons has no contribution in these dynamical processes. The results obtained for H_2^+ ions in horizontal plane are shown in Fig. 4 and in Fig. 5. The high frequency oscillations of the motion can be seen in Fig. 4, where the oscillation period is equal to the RF period. Fig. 5 shows that, low frequency oscillations have shorter period compared to N_2^+ ions.

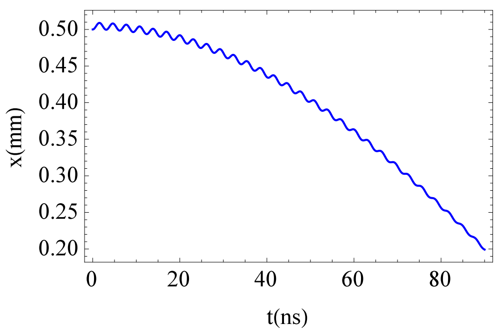

Figure 2: The horizontal coordinates of N_2^+ ion in the RF field is shown for the time duration of 90 ns. This time window clearly shows the high frequency oscillation of the ion motion. Initial position of ion is 0.5-mm where the particle is ionized.

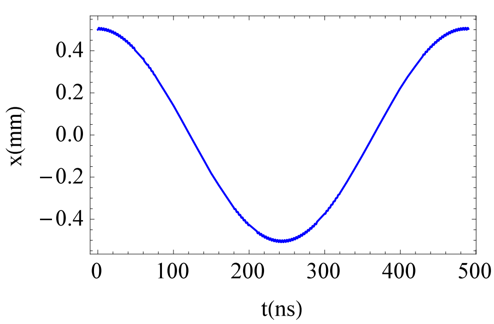

Figure 3: The horizontal coordinates of N_2^+ ion in the RF field is shown for the time duration of 500 ns. This time window is equal to one period of the low frequency oscillation.

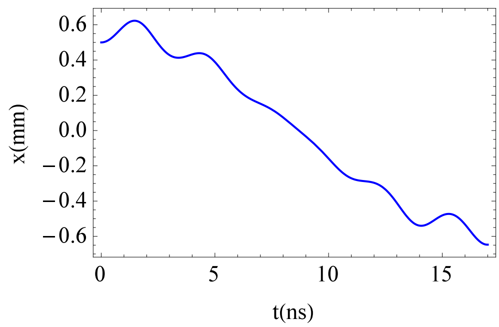

Figure 4: The horizontal coordinates of H_2^+ ion in the RF field is shown for the time duration of 17 ns, which clearly shows the high frequency oscillation of the ion motion. Initial position of ion is 0.5-mm where the particle is ionized.

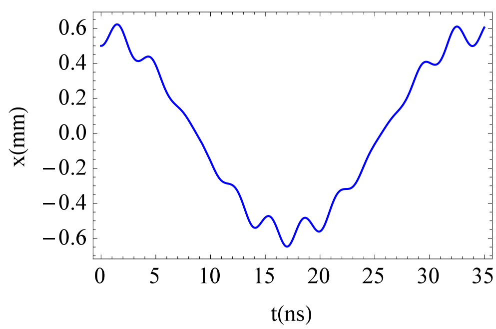

Figure 5: The horizontal coordinates of H_2^+ ion in the RF field is shown for the time duration of 35 ns.

H$^-$ BEAM ACCELERATION IN RFQ

Particle tracking and 3D field map methods are useful in accelerator modeling and beam dynamics simulations. Therefore, we employ 3D RFQ field map in beam acceleration simulation for J-PARC linac intensity upgrade. Beam dynamics simulation of 50-keV H$^-$ beam to be accelerated to 3-MeV by RFQ is performed to determine the acceleration efficiency and beam twiss parameters. Comparison of the studies of a uniformly generated particle distribution and a more realistic beam, the distribution re-constructed from Test Stand emittance measurement has been made. Fig. 6 and Fig. 7 shows the hyper-ellipsoid distribution generated in both transverse planes and uniform in longitudinal plane. The knowledge of beam phase space at the IS exit is essential for transverse matching of the beam into the RFQ. For this purpose, an algorithm to reconstruct the beam phase space distribution from emittance measurement is developed. The result of constructed beam initial phase space at the IS exit (23-mm above the first solenoid in LEBT) is shown in Fig. 8 and Fig. 9 in both transverse planes. Beam initial parameters will be used to find the optimized solenoid settings for transverse matching when we study the beam dynamics considering space charge effects from start-to-end simulation throughout the Linac. In particular, emittance and twiss parameters at the exit of RFQ are determined and will be used for beam matching optimization in the Medium Energy Beam Transport (MEBT1) section.

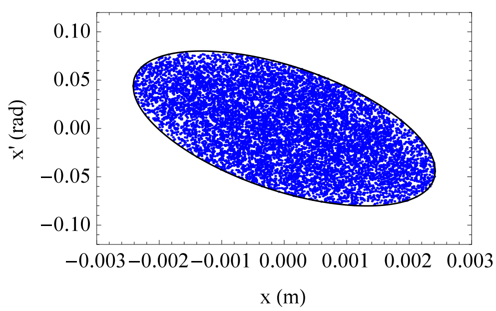

Figure 6: Hyper-ellipsoid beam distribution in the horizontal plane. The normalized rms emittance of 1.5 π mm·mrad.

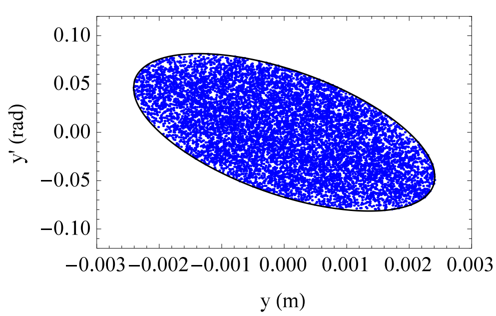

Figure 7: Hyper-ellipsoid beam distribution in the vertical plane. The normalized rms emittance of 1.5 π mm·mrad.

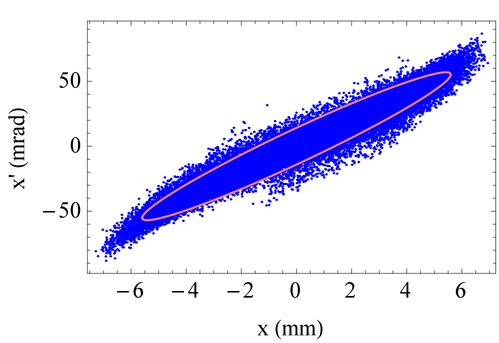

Figure 8: 66-mA H^- beam distribution at the exit of ion source. (Calculated phase space ellipse is equal to 4 times of the normalized rms emittance, 0.816 π mm·mrad, comprising of 87% of the total particles).

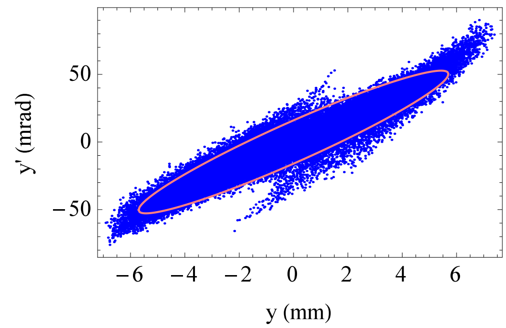

Figure 9: 66-mA H^- beam distribution at the exit of ion source. (Calculated phase space ellipse is equal to 4 times of the normalized rms emittance, 0.94 π mm·mrad, comprising of 87% of the total particles).

CONCLUSION AND OUTLOOK

Two different distributions of 50-mA H^- beam emittance in the RFQ beam acceleration simulation were studied. The hyper-ellipsoid (in transverse) and a uniform distribution in longitudinal plane is relatively more flexible beam losses than the gaussian beam. More realistic beam distribution which is reconstructed from beam emittance measurement shows that there are beam losses due to beam tails induced by the nonlinearities. We cut-off some intensity below than a certain threshold (10% of the measured total intensity) in order to keep the phase space elliptic. Then the raw data is back-tracked throughout the solenoid 3D field map and beam emittance at the IS exit, that is at the entrance of the first solenoid of LEBT is constructed. The result will be used as an initial distribution from the start-to-end beam dynamics simulation of Linac. Complete beam dynamics studies from recieving the 50-keV, 61-mA H^- beam from the ion source and transporting it through 2-sectioned LEBT having two different vacuum conditions where space charge effects is subject to the time is ongoing. We also propose to investigate space charge effects in the RFQ beam acceleration and in the drift up to 50-MeV.

REFERENCES

[1] J-PARC website: http://j-parc.jp/index-e.html

[2] http://reference.wolfram.com/language/ref/MathieuC.html

[3] http://dlmf.nist.gov/28.29