NUMERICAL AND EXPERIMENTAL STUDY OF H⁻ BEAM DYNAMICS IN J-PARC LEBT

T. Shibata[†], K. Ikegami, Y. Liu, A. Miura, F. Naito, K. Nanmo, H. Oguri, K. Ohkoshi, M. Otani,
K. Shinto, A. Takagi
J-PARC Center, Tokai, Japan

Abstract

Transport process of negative hydrogen ion (H⁻) in LEBT (Low Energy Beam Transport) is investigated by comparison of experimental and numerical results. A three dimensional Particle-In-Cell (PIC) particle transport model has been developed in order to take into account (i) axial magnetic field by two solenoids in J-PARC LEBT and (ii) radial electric field by space charge (SC) effect. Ratio of H⁻ beam particles inside the RFQ (Radio Frequency Quadrupole) acceptance to the total particles at the RFQ entrance is calculated for different current conditions in LEBT solenoid 1 and 2. The results are compared with RFQ transmission rate measured in the J-PARC linac commissioning. The double peak of RFQ transmission rate to the solenoid applied current seen in the measurement is explained by the calculation results. The results indicate that presence of the LEBT orifice for differential pumping plays a role as a collimator to reduce emittance at RFQ entrance.

LEBT TUNING IN J-PARC LINAC COMMISSIONING

A schematic drawing of J-PARC ion source (IS) and LEBT is shown in Fig.1. In J-PARC Linac commissioning, negative hydrogen ion beam extracted from the IS is focused by two solenoids in LEBT. The focused beam is injected toward the RFQ. The resent commissioning parameter for IS and LEBT are shown in Table 1. In the IS, AMFC (Axial Magnetic Field Correction) coil current, extraction voltage, acceleration voltage and applied currents for horizontal/vertical steering electromagnets (STM) are the adjustment parameters in the commissioning.

Table 1: Parameters for LEBT Tuning in J-PARC Linac Commissioning

Commissioning parameters	LI 30mA (2015)	LI 40 mA (2017)
AMFC coil (V)	0.0	2.0
Ext. voltage (kV)	9.9	9.8
Acc. Voltage (kV)	42.0	42.5
Hori. STM (A)	-1.0	-5.0
Vert. STM (A)	-5.5	-4.0
LEBT SOL1 (A)	495	500
LEBT SOL2 (A)	600	620

The AMFC and the extraction/acceleration voltages decide the initial divergence angle and beam energy of the H⁻ beam extracted from the IS. The beam energy is designed for 50 keV. Therefore, total value of extraction and acceleration voltages is 50 kV. However, recent results show that optimization of RFQ transmission rate is obtained for the total applied voltage up to around 51 – 52 keV while the beam intensity at LEBT increases monotonically with the applied voltage. The steering magnets are located in order to correct H⁻ beam bent by electron suppression magnets for reduction of co-extracted electron current.

In the LEBT, currents in two solenoid magnets are adjusted to obtain low emittance and Twiss parameter matching at the RFQ entrance. In the commissioning, current applied in the SOL 1 and 2 are set in ranges of 0 – 800 A to produce maximum 1.1 T at the solenoid center on beam axis. Optimization of the SOL currents are also shown in Table 1. At the center of the LEBT chamber, a 15 mm diameter orifice is located for differential pumping to prevent H_2 gas flow from the IS to the RFQ.

Figure 1: A schematic drawing of J-PARC IS and LEBT.
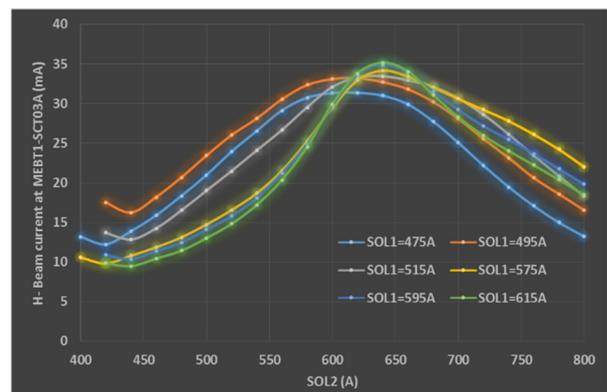
Figure 2: Dependence of H⁻ beam current measured at MEBT-SCT (just after RFQ exit) to the SOL1 and SOL2 currents in J-PARC Linac 30 mA operation.

† email address:takanori.shibata@kek.jp

The current flow in the LEBT is measured by a current transformer (SCT) located just after the orifice. The beam current transmitted through the RFQ is measured by MEBT-SCT which is located just after RFQ exit. The IS/LEBT parameters in the commissioning are tuned to optimize this MEBT-SCT current or the RFQ transmission rate which is obtained by dividing MEBT-SCT current with LEBT-SCT current.

COMMISSIONING RESULTS

Figure 2 shows dependence of current flow in MEBT-SCT for different SOL 1 and 2 values. The beam current is 33.9 mA in order to extract 30 mA from the Linac. In the figure, two peaks of the current are seen for the SOL current pairs up to (SOL1, SOL2) = (495 A, 600 A) and (615 A, 640 A). The first peak for the lower SOL1 and 2 currents show wider peak while the second peak shows higher and narrower peak. The wider peak means that the beam current supplied from linac is stable for the fluctuation of SOL current due to noise or surge currents. Therefore, we adopted the first peak for the LEBT tuning result. However, reason of these double peak is not clearly understood.

NUMERICAL ANALYSIS

In order to clarify the H⁻ beam particle transport in the LEBT, a three-dimensional (3D) Particle-In-Cell (PIC) model is developed [1]. Basic equation of H⁻ particle is 3D Boltzmann equation;

$$ m \frac{d\mathbf{v}}{dt} = q \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right). \tag{1} $$

The variables $\mathbf{v}$, $\mathbf{E}$ and $\mathbf{B}$ are velocity of H⁻, electric field due to SC effect and magnetic field by solenoids. The constants m and q are mass and charge of particles, respectively. For the different beam current and SC neutralization degree, spatial potential ϕ is calculated from Poisson equation;

$$ \nabla^2 \phi = -\frac{\rho}{\varepsilon_0} \tag{2} $$

where ρ and ε_0 are spatial charge distribution and permittivity in vacuum, respectively. In the present calculation, degrees of SC neutralization are given as parameter in each region. The SC neutralization degree given in different regions are (i) 100 % in the region before the orifice, (ii) 98 % in the region between the orifice and the SOL2 center, and (iii) 97 % between the SOL2 center and the RFQ entrance. In the region before the orifice, gas pressure is relatively high due to the incoming gas flux from the IS. The incoming flux is decreased by the 15 mm diameter orifice. In the actual J-PARC linac, gas pressure in the upper stream of the orifice is around 10^{-3} Pa, while the pressure is in the order of 10^{-4} Pa in LEBT chamber just after the orifice and 10^{-5} Pa near the RFQ entrance. Although it is well known
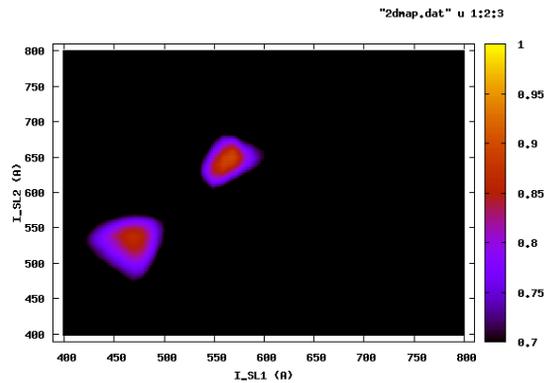
Figure 3: Dependence of RFQ transmission rate (color bar) to the SOL1 (horizontal) and SOL2 (vertical) current setting in the calculation.
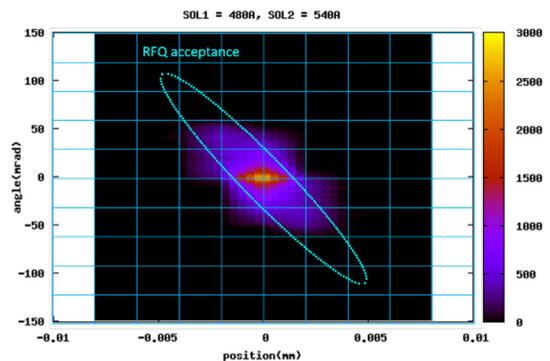
(a)
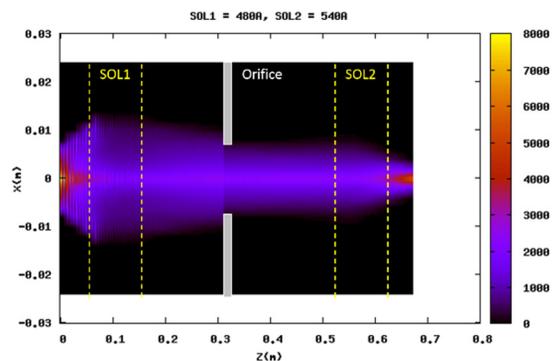
(b)

Figure 4: Calculated phase space (a) and beam profile in XZ plane (b) for condition SOL1 = 480 A and SOL2 = 540 A with RFQ transmission rate 86.8%.

that the SC neutralization degree is higher for higher gas pressure, the appropriate value of the SC neutralization degree is not studied well. In the present analysis, these values are scan preliminary and decided from the comparison with experimental results. From the SC neutralization degree, spatial charge distribution in a plane perpendicular to the axis is calculated as

$$\rho(r) = -j_{H^-} \times \delta(r_{beam} - r) \times (1 - n_{SC}) / v_{H^-} / S_{H^-}. \quad (3)$$

where j_{H^-} and v_{H^-} are H$^-$ beam current and H$^-$ velocity corresponding to the beam energy. The parameters r_{beam} and S_{H^-} are beam radius and area at certain position on beam axis, respectively. In the present model, charge density distribution in the beam area is given uniformly by step function $\delta(r)$. From the potential distribution solved by Successive-Over-Relaxation (SOR), the electric field in radial direction is given as $E_r = -\partial\phi/\partial r$.

The RFQ transmission rate is calculated by dividing number of particles which are included inside the RFQ acceptance in phase space with total number of particle which reaches to the RFQ entrance.
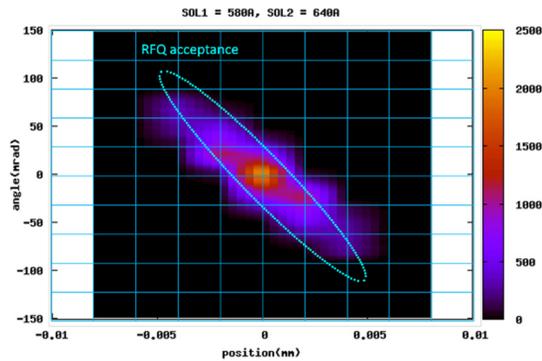
(a)
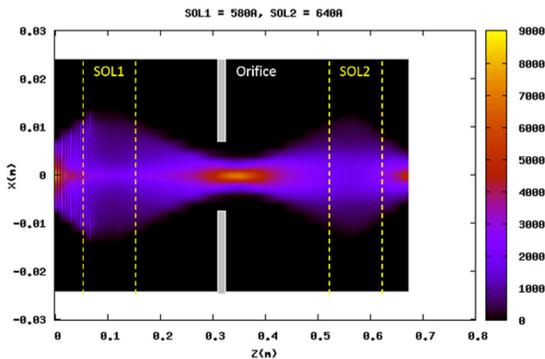
(b)

Figure 5: Calculated phase space (a) and beam profile in XZ plane (b) for condition SOL1 = 580 A and SOL2 = 640 A with RFQ transmission rate 90.2%.

NUMERICAL RESULTS AND DISCUSSION

Figure 3 shows dependence of RFQ transmission rate to the SOL1 and 2 currents for the beam current up to 30 mA. It is noticable that double peaks are seen in the RFQ transmission rate for relatively lower SOL current pair (SOL1, SOL2) = (480 A, 540 A) with the calculated rate up to 86.8 % (1st peak) and for higher SOL current pair (SOL1, SOL2) = (580 A, 640 A) with the rate up to 90.2 % (2nd peak). Fixing SOL1 current, the 1st peak shows wide range of high transmissin rate to SOL2 while the 2nd peak shows narrow and higher peak to the SOL2 variation.

A characteristic phase space at the RFQ entrance and beam profile in XZ plane for the 1st peak are shown in Fig.4. As in the figures, the H- beam extracted from the IS exit are focused by the SOL1. For lower magnetic field, the beam component which is not focused enough collides toward the orifice at the center of the LEBT chamber. Since the halo component is collimated at the orifice, focued beam after the SOL2 has low emittance. The low emittance beam at the RFQ entrance leads to high transmission rate.

Phase space and beam profile of the 2nd peak are shown in Fig.5. For the strong SOL1 magnetic field, the beam is well focused and pass through the orifice without injecting the orifice. The SC effect just after the orifice is relatively high which produces strong radial electric field. The expanding beam is focused by the strong SOL2 field. Although the beam emittance at the RFQ entrance is larger thanfor the 1st peak case, the similarity of the phase space to the RFQ acceptance is better in this case. As a result, higher RFQ transmission rate is obtained in the calculation.

CONCLUSION

The beam transport process in the J-PARC LEBT is investigated by comparison between the experimental results in J-PARC commissioning for 30 mA operation and the numerical results by PIC simulation which takes into account the SC effect and the spatial configuration of the beam duct. The both results show high transmission rate in the RFQ for two pairs of SOL1 and SOL2 current settings.

In the case of the 1st peak, low emittance is obtained at the RFQ entrance as the orifice takes a role as collimator of the beam which removes growing halo components. On the other hand, for the strong SOL1 and 2 settings, the beam pass through the orifice. This leads to the relatively larger emittance at the RFQ entrance while the similarity of the beam phase space to the RFQ acceptance is obtained.

The clarifiation of these characteristics observed in the actual commissioning leads to the high reproducability of the beam optics in each RUN. From these results, the transimssion rate is optimized in the Linac commissioning together with LEBT-SCT current which is measured at just after the orifice to avoid beam cut off at the orifice.

REFERENCES

[1] T. Shibata, et al., "LEBT Commissioning of the J-PARC LINAC", in Proc. LINAC'16, East Lansing, MI, USA, Sep. 2016, paper MOPLR052, pp. 251-253.

Beam dynamics, extreme beams, sources and beam related technologies

Beam Dynamics, beam simulations, beam transport