LEBT COMMISSIONING OF THE J-PARC LINAC

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Abstract

After J-PARC Linac update for increase of beam energy and current update in 2013 and 2014, sequences of beam commissioning has been made for optimization of RFQ transmission rate. The beam commissioning has been made by iteration of scanning 6 adjustable parameters scan. In the commissioning on January 2016, the highest current ratio between LEBT and MEBT (up- and down-stream of RFQ) up to 92.7 ± 3.3 % has been observed in the 40 mA beam current operation. In addition, numerical analysis has been made for H- beam transport in ion source and low energy beam transport to clarify beam t characteristics.

INTRODUCTION

In J-PARC Linac, a series of upgrades has been done in 2013 and 2014 to increase negative hydrogen ion (H^-) beam energy and current. In the beam energy upgrade, ACS (Annular-ring Coupled Structure Linac) is installed to the Linac which increased the beam energy from 181 MeV to 400 MeV [1]. The peak current upgrade in 2014 is made by exchanging ion source (IS) from arc driven source with LaB_6 (lanthanum hexaboride) filament to Radio Frequency (RF) source which results in increase in the beam current extracted from IS up to 45 mA in user operation (40 mA H- current from Linac) [2]. Also, structure of RFQ (Radio Frequency Quadrupole Linac) system is changed from Bolt type to Brazed type with new beam design for higher beam energy [3].

A sequences of beam commissioning in IS and LEBT (Low Energy Beam Transport) parameters has been made after J-PARC upgrade to keep high RFQ transmission rate. In this proceedings, the commissioning in 40 mA operation on Jan. 2016 is reported.

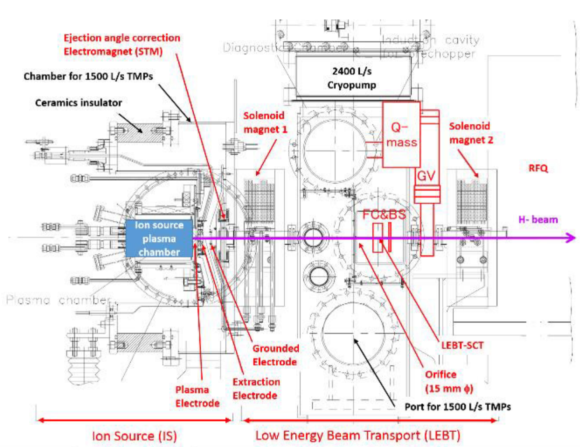

Figure 1: Schematic drawing of J-PARC ion source and LEBT.

LEBT CONSTRUCTION

Figure 1 shows the schematic drawings of IS and LEBT in the Front-End of J-PARC. In LEBT, two solenoid coils are located around beam ducts in up- and down-streams of LEBT chamber. The solenoid coils (SOL 1 and 2) has double pancake 90 turns conducting wire with maximum current 820 A to flow in application of 17 V from power supply which produces B_{max} = 1.1 T in axial direction inside. At the exit of IS, steering electromagnets (STM) are located for adjustment of ejecting angle from IS in vertical and horizontal directions. The LEBT chamber is divided into two region by orifice with aperture 15 mm ϕ in order to decrease conductance of H_2 gas flowing from IS to RFQ. The upstream part of LEBT chamber is pumped by a pair of TMP of 1500 L/s, while the downstream part is connected to Cryopump with pumping speed up to 2400 L/s. Installation of the orifice produces variation of H_2 gas pressure between up- and down-streams in an amplitude of order (~ 10^{-4} Pa and 10^{-5} Pa at up- and down-streams, respectively).

BEAM COMMISIONING IN FRONT-END

In the beam commissioning, 6 adjustable parameters in the followings are optimized for improvement of beam transmission in RFQ;

- Extraction voltage : 9.5 – 10.2 kV
- Acceleration voltage : 41.5 – 45.5 kV
- STM vertical & horizontal current : -10 – 10 A
- SOL 1 & 2 current : 490 – 820 A.

The H^- beam current is measured by SCT (split-core current transformers) (1) in LEBT chamber just after the orifice aperture and (2) in MEBT, at the exit of RFQ. In the commissioning, ratio between current measured in (1) and (2) are calculated. This ratio is not exactly the RFQ transmission rate, but strong relation takes place between these parameters. Error of this current ratio may take place at time averaging of the SCT currents. The current measurement is made at the very end part of beam pulse to obtain steady state value. On the other hand, beam current ramp-down (at the end of the beam pulse) takes place with temporal fluctuation in range of a few μsec. This leads to inclusion of decreased current into the time averaging. From careful investigation of the beam pulse waveforms, error bar of the current ratio I_{MEBT}/I_{LEBT} is estimated to be around ± 3.3 % in the present case.

As there are 6 adjustable parameters, it is difficult to make optimization in one scanning event. Instead, scanning of each parameters are made repeatedly for a few times in order to obtain iteration. Initially, scan for SOL 1

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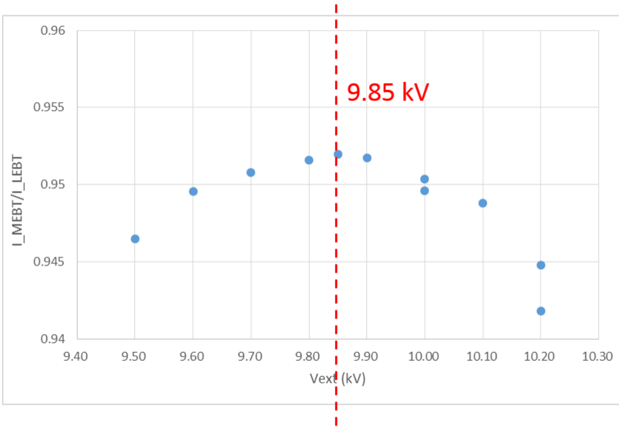


Figure 2: Dependence of the LEBT- and MEBT-SCT current ratio to the extraction voltage.

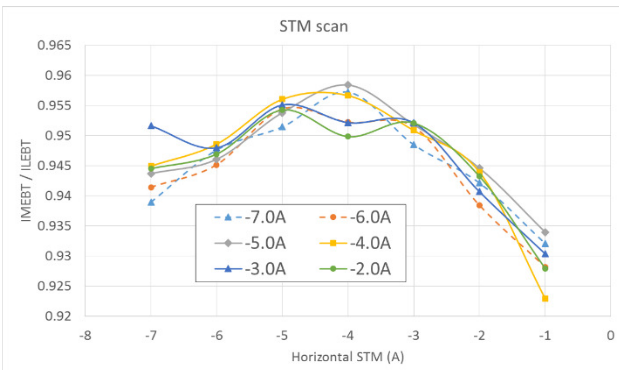


Figure 3: Dependence of the LEBT- and MEBT-SCT current ratio to horizontal STM current for different vertical STM current (in different line color).

& 2 currents has been done. In the first scan, most other variable parameters are given same as in the previous operation. By this scan, solenoid currents are roughly optimized. After the rough optimization of SOL current, the other parameters are optimized.

OPTIMIZATION OF EXT. AND ACC. VOLTAGES

The beam extracted from IS is accelerated by two steps of electrostatic voltages. As shown in Fig.1, three electrodes with aperture (plasma-, extraction- and grounded- electrode; PE, EE and GE, respectively) are located just after the IS plasma chamber. Extraction voltage V_{ext} is the voltage difference between PE and EE which leads to the initial acceleration. Then, acceleration voltage V_{acc} is applied between EE and GE to make second acceleration. Although the present design of RFQ in J-PARC is desired to accelerate beam energy by V_{ext} and V_{acc} up to 50 keV, the transmission rate of RFQ is optimized for the total electrostatic voltages up to 53.0 kV. In the commissioning, a sum of these voltages are fixed to this optimized value. Figure 2 shows current ratio between LEBT and MEBT (up- and down-stream of RFQ) for different extraction voltage. The optimization is obtained for $V_{\mathrm{ex}} = 9.85$ V and $V_{\mathrm{acc}} = 43.15$ V.

OPTIMIZATION OF STEERING ELECTROMAGNET CURRENT

Applied currents of the STM in horizontal and vertical directions are scanned between -10 to 10 A. The LEBT- and MEBT-SCT current ratio for the different STM currents is shown in Fig. 3. The horizontal axis of Fig.3 shows horizontal STM current. Variation of vertical STM current is shown in different line color and type. The optimized STM currents in horizontal and in vertical directions are -4.0 A and – 5.0 A, respectively.

OPTIMIZATION OF SOLENOID 1 & 2 CURRENT

After optimization of extraction voltage, acceleration voltage and STM currents, the current ratio dependence to SOL 1 & 2 currents is scanned again. Figure 4 shows the SCT current ratio for different SOL 1 & 2 currents. The highest value is up to 92.7 ± 3.3 % with error bar which is achieved for SOL 1 current around 500 – 510 A and SOL 2 current around 640 A.

The high ratio results in decrease of required H^- current extracted in LEBT, and hence power injection into the IS via 2 MHz RF antenna. Figure 5 shows trends of injected power injected into IS, LEBT- and MEBT-SCT currents at beam commissioning in Dec. 2015 (a) and in Jan. 2016 (b). The LEBT-SCT current is reduced from around 49 mA to 47 mA which results in reduction of RF power injection from 38.5 kW to 36 kW to keep 45 mA current after RFQ (namely, at MEBT-SCT).

NUMERICAL ANALYSIS OF BEAM TRANSPORT IN ION SOURCE AND LEBT

A three-dimensional Particle-In-Cell (PIC) code which takes into account wall loss, magnetic configuration $\boldsymbol{B}$ by solenoid 1 & 2 in LEBT and electric field $\boldsymbol{E}$ due to space charge effect. For beam transport, equation of motion is solved directly by Leap-Frog method;

$$m_{\mathrm{H-}} \frac{\Delta \boldsymbol{v}}{\Delta t} = -q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}), \qquad (1)$$

with Poisson equation;

$$\Delta\phi = -\frac{\rho}{\varepsilon_0}, \qquad (2)$$

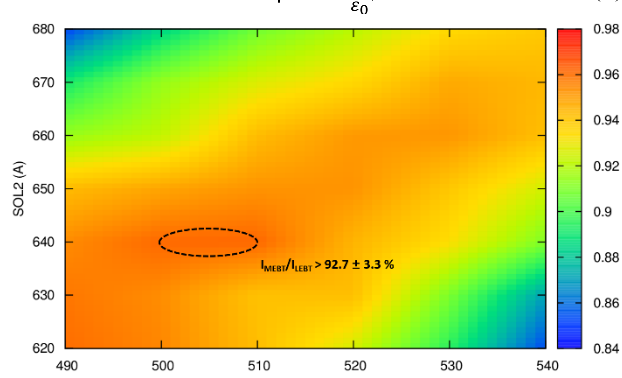
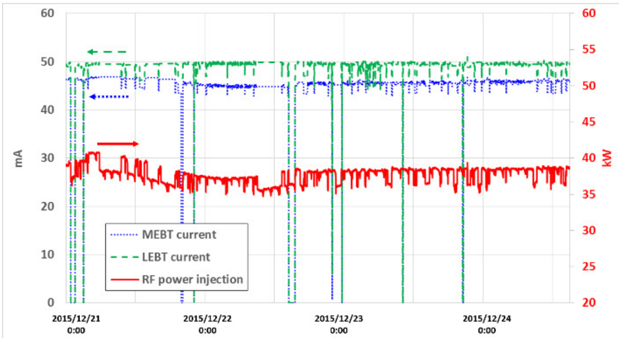
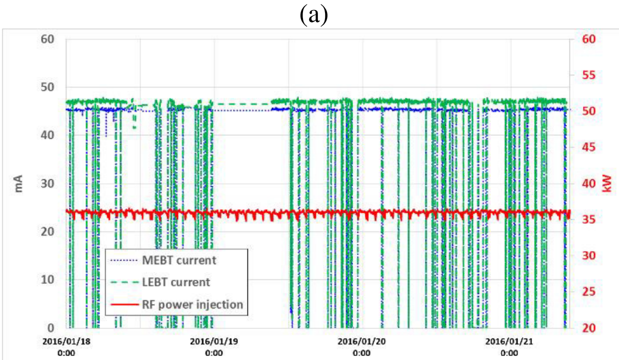


Figure 4: Dependence of the SCT current ratio on SOL 1 and 2 current. The color bar shows the current ratio. Relatively higher ratio is obtained for SOL 1 current 500 – 510 A and SOL 2 current around 640 A.



(a)



(b)

Figure 5: Trends of Radio Frequency (RF) power injection to IS (solid line), LEBT-SCT current (dashed line) and MEBT-SCT current (dotted line) at beam commissioning in Dec. 2015 (a) and in Jan. 2016 (b).

where ϕ and ρ are electric potential and charge density. At the end part of LEBT (corresponds to RFQ vane), ratio of H^- particle inside RFQ acceptance envelope to total incoming H^- particle to RFQ vane is calculated.

Figure 6 and 7 shows numerical result of beam projection in *XZ* plane (position *X* indicates horizontal direction which is parallel to magnetic filter and electron suppression fields in IS and position *Z* shows the axial direction along beam line) and emittance diagram at RFQ vane for similar adjustable parameters in the measurement. As shown in Fig.6, diverging beam from IS is converged

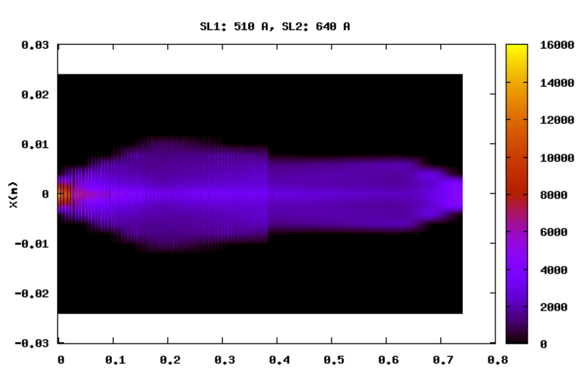


Figure 6: Numerical result of beam projection in XZ plane where X and Z are positions in horizontal and in axial directions. Color bar shows sample particle number.

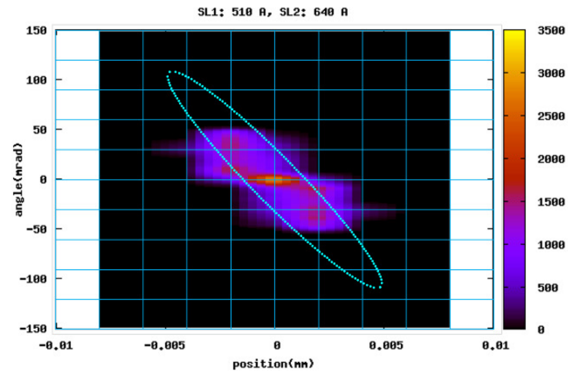


Figure 7: Emittance diagram of H^- beam at RFQ vane in simulation. Color bar shows sample particle number. Light blue line is envelope of RFQ acceptance.

by SOL 1 at Z = 200 mm in the simulation. A part of the beam is cut by orifice at Z = 405 mm and converged again by SOL 2 at Z = 650 mm. This beam transport results in emittance diagram in Fig. 7. The H^- sample particle ratio defined above is over 90 % for SOL 1 current up to 500 – 550 A and SOL 2 current up to around 640 A.

SUMMARY

In the beam commissioning in Jan. 2016, the high ratio between LEBT and MEBT current up to 92.7 ± 3.3 % was observed in the 40 mA beam operation. The scanning of extraction voltage in IS and the iteration of SOL 1 & 2 current scan is effective compared to the previous beam commissioning. LEBT current and injection power in IS is reduced for same current at RFQ exit. The commissioning leads to not only preventing heat loadings to RFQ but also possibility to obtain higher beam current in same IS injection power.

Numerical simulation by PIC code shows that (i) beam conversion by SOL 1 & 2 currents around 510 A and 640 A and (ii) beam cut by orifice is effective for achievement of higher transmission rate.

Although we observed high beam current ratio in up- and down-stream of RFQ, experimental error is still not negligible. For accurate measurement, sensitivity of SCT current values to averaging duration will be investigated in the near future using similar H^- beam.

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