Beam Dynamics and Commissioning of the J-PARC Linac

Y. Kondo*, M. Ikegami†, T. Kobayashi*, T. Ohkawa,* and A. Ueno*

*JAERI, Tokai, Ibaraki, 319-1195, Japan
†KEK, Tsukuba, Ibaraki, 305-0801, Japan

Abstract. At the first stage of J-PARC (Japan Proton Accelerator Research Complex), the linac will accelerate a H\textsuperscript{−} beam to 181 MeV with a peak current of 30mA. A normalized transverse emittance of less than 4 πmm·mrad and a momentum spread of less than ±0.1% are required at the injection point of the rapid cycling synchrotron (RCS) following the linac. In order to find out operating points satisfying the above requirements and develop commissioning strategies, intense simulation studies of the linac have been performed. The beam commissioning of the drift-tube linac tank-1 (DTL1) has been performed at KEK. Transverse emittances at the DTL1 exit, phase scan property of the DTL1, and so on have been measured to confirm the validity of the simulations and commissioning strategies.

Keywords: J-PARC linac, beam dynamics, simulation, DTL, commissioning

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INTRODUCTION

The J-PARC linac consists of a 50keV H\textsuperscript{−} ion source (IS), a 3MeV RFQ (Radio-Frequency-Quadrupole linac), a 50MeV DTL (Drift-Tube Linac), a 190MeV SDTL (Separate-type DTL), a 400MeV ACS (Annular-Coupled-Structure linac) and a 600MeV SCL (Super- Conducting Linac). Operation frequencies are 324MHz for the RFQ, DTL and SDTL and 972MHz for the ACS and SCL. At the first stage of the J-PARC, the linac will be operated with an energy of 181MeV[1] and a peak current of 30mA. The maximum pulse width is 500µsec and the maximum repetition rate is 25Hz. At this stage, the ACS linac is replaced by a beam transport. Required beam characteristics of the linac are as follows: a normalized transverse emittance is less than 4 πmm·mrad and a momentum spread is less than ±0.1% at the injection point of RCS. The H\textsuperscript{−} particles outside this transverse acceptance will be scraped by charge exchanged into H\textsuperscript{+} with scraper foils and are transported to the 2kW H\textsuperscript{+} beam dump in a L3BT (Linac to 3GeV RCS Beam Transport) [2]. In this paper, we discuss the design and the simulation of the J-PARC linac and present the recent result of the beam commissioning of the DTL1 at KEK.

DESIGN AND SIMULATION

Beam dynamics design

The reference design of the J-PARC linac is an equipartitioned design, in which the ratio of the transverse and longitudinal temperatures is unity (\(T_t/T_l = 1\)), in order to avoid a transverse and longitudinal coupling resonance driven by space charge forces. Here, the temperature \(T\) is defined as emittance \(\varepsilon\) times tune \(k\) [3]. In case of 181MeV operation, the emittance ratio \(\varepsilon_t/\varepsilon_l\) = 1.09, the tune ratio \(k_t/k_l = 0.92\) and the transverse tune depression \(k_t/k_{t0} = 0.35 \sim 0.53\). Since all the quadrupole magnets, including those installed in the drift tubes of the DTL[4][5], there is a flexibility to optimize the tune of the transverse motion. In trying unequipartitioned setting, we are planning to start with “equipartition-like” setting, in which the temperature ratio is kept constant. In this setting, the coupling-resonance crossing is avoided and the smoothness of lattice parameters is automatically satisfied to some extent. For example, if we increase the focusing strength and the temperature ratio set to be the maximum value of 3.5, this is limited by the condition that the maximum zero-current transverse phase advance \(k_{t0}\) should be less than 90°, \(k_t/k_l\) and \(k_t/k_{t0}\) will be 0.26 and 0.59 ~ 0.70.

RFQ simulation

In precise calculations of the beam dynamics from the IS to the RFQ entrance, there are difficulties listed below.

- The beam in the low energy beam transport (LEBT) between the IS and RFQ is a continuous (unbunched) beam, and has large divergence to match the RFQ acceptance. This make a self consistent calculation of the field quite complicated.
- In the J-PARC LEBT, space charge neutralization is used to relax the space charge force. A rather high neutralization efficiency of 90% was measured in...
the same type of LEBT[6]. The precise efficiency function along the beam axis is needed for an accurate calculation.

- A focusing system with two solenoid magnets are used for the LEBT. A system consists of solenoid magnet can be calculated axi-symmetrically. However, the configuration of the magnet at the IS extraction part is not axi-symmetric, this is essential to produce the $H^-$ beam and reduce the electron current[7]. Therefore, the tree-dimensional field calculation is required.

- The electric field at the radial matching section of the RFQ is time dependent. We need to treat a time dependent self-consistent field.

To avoid these difficulties, we adopt an assumed distribution at the entrance of the RFQ, which is derived from the experimental emittance measured in the LEBT and would reproduce the emittance measured at the exit of the medium energy beam transport (MEBT) between the RFQ and DTL. With this initial distribution, RFQ and MEBT simulations have been performed and obtained distributions were compared with experimental data[8]. The emittance at the MEBT exit was measured in the commissioning before the installation of the DTL1[9].

The DTL of the J-PARC linac is consist of 3 tanks (50MeV) and the commissioning up to the first tank (DTL1:19.7MeV) was finished at KEK in October 2004. The DTL1 contains 76 acceleration cells and 77 Q-magnets[15]. FIGURE 1 shows the experimental setup of the commissioning.

**Simulation Studies of the Linac**

By using the particle distribution at the exit of the RFQ obtained above, simulation studies of J-PARC linac (from the MEBT entrance to the injection point of the RCS) have been performed with PARMILA in the 181MeV operation case. As discussed in [13], following errors are assumed as sources of “static” errors: As for the quadrupole magnet, transverse displacement is $\pm 0.1\text{mm}$, skew is $\pm 5\text{mrad}$ and gradient error is $\pm 0.25\%$. RF set-point errors are $\pm 1\%$ and $\pm 1^\circ$ for amplitude and phase, respectively. RF tuning schemes to achieve these set-point accuracy are described in [14]. We are planning to utilize a phase-amplitude scan method to obtain the RF operation point. With these errors, the load for the halo collimator system is estimated to be 1-3%, this is acceptable for the system. In addition, $\pm 1\%$ and $\pm 1^\circ$ dynamic fluctuations of RF are took into account. Even in this case, the simulation showed that the energy spread is within the requirement (less than $\pm 0.033\text{MeV}$ for 181MeV operation). Our goal for the RF dynamic error is $\pm 0.5\%$ and $\pm 0.5^\circ$.

**DTL1 COMMISSIONING RESULTS**

**Experimental apparatus**

The DTL of the J-PARC linac is consist of 3 tanks (50MeV) and the commissioning up to the first tank (DTL1:19.7MeV) was finished at KEK in October 2004. The DTL1 contains 76 acceleration cells and 77 Q-magnets[15]. FIGURE 1 shows the experimental setup of the commissioning.

A temporal beam line was located downstream of...
the DTL1 and was equipped with diagnostic devices, as shown in FIGURE 2. The beam current was measured with a SCT (Slow Current Transformer) and a FC (Faraday cup). The beam energy was measured by the time of flight (TOF) method with a FCT (Fast CT) and a BPM (Beam position Monitor). The position and angle of the beam were measured with two BPM's. Double-slit type emittance scanners were used to measure the emittance of the DTL1. They were located about 3m down-stream from the DTL1 exit. The gap of the slit was set to be 0.1mm. Typical wave forms of 25mA beam are shown in FIGURE 3. In this case, the pulse width was 50µsec and repetition rate was 5Hz. The transmission efficiency through the DTL was 100% within errors of current measurements of several %.

![FIGURE 3. Wave form of the beam at peak current 25mA. Top figure is at the exit of the RFQ, middle one is in the MEBT and the bottom one represents the beam current at the DTL1 exit.](image)

**RF tuning of the DTL1**

We use phase-amplitude scan method to adjust the phase and amplitude of RF cavities including the DTL1 cavity as mentioned above. FIGURE 4 represents the experimental result of the phase-amplitude scan.

The left figure is plots of beam phases as functions of the tank phase for different tank amplitudes. The beam phases (degrees) were measured with the FCT located just after the DTL1. The vertical axis of the right figure represents the beam energy of the DTL1 (MeV). Each curve in the figure shows the phase scan result with different tank amplitude. FIGURE 5 shows simulated phase-scan curves obtained with PARMILA corresponding to the experiment. The experimental results show good agreement with the simulation. These results demonstrate that the 1%, 1° set-point accuracy is achievable with the phase-amplitude scan method, at least for the DTL1.

![FIGURE 4. Phase-amplitude scan of the DTL1. The left figure represents the beam phase measured with the FCT (deg.) at the exit of the DTL1. The right side figure shows the beam energy measured by the TOF method (MeV). The horizontal axes of both figures represent the tank phase of the DTL1 (deg.).](image)

![FIGURE 5. Simulated phase-amplitude scan curves of the DTL1 with PARMILA. The labels such as 0.98 mean applied tank amplitudes normalized to the nominal one.](image)

![FIGURE 6. RF stabilities of the DTL1. The pulse-to-pulse stabilities are less than 0.5% and 0.5°.](image)

FIGURE 6 shows in-pulse and pulse-to-pulse stabilities of the amplitude and phase applied to the DTL1 measured with pick-up monitors of the cavity. For the J-PARC linac, a digital feedback system will be applied to stabilize the RF, however, in the commissioning at KEK, an analog feedback system was used because the digital feedback system was not ready. The sag in the pulse will be improved by adding a feedback loop to stabilize the klystron output. This was also omitted in the commissioning at KEK due to lack of circuits. These results show that the requirement of 0.5° and 0.5% “dynamic” stability is reasonable, but to achieve this for all RF mod-
Transverse matching

As discussed in reference [16], due to the large bore diameter of the Q-magnets, we need to take the fringing field into account to reproduce the measured Twiss parameters at the MEBT exit. In order to treat fringing field in the TRACE3D[17] calculation, all Q-magnets were divided into 20 segments and each of them had different field-gradient parameter to reproduce the calculated distribution of the field-gradient with MAFIA[18]. However, with this manner, it is difficult to calculate matching solutions with TRACE3D because matching elements are too many. Therefore, we adopt an alternative method, that is, instead of the Q-magnet element, we used the permanent quadrupole magnet (PMQ) element to simulate the fringing field. For example, in FIGURE 7, cases of MEBT Q2 and DTL Q6 (DTQ6) are shown. Both the field-gradient calculated with MAFIA and generated by the PMQ element are plotted in the figure. The PMQ elements were used for all the Q-magnet of the MEBT and DTL1. Matching was done at the entrance of the DTL1 and points where the quadrupole thickness are changed in the DTL1. Four Q-magnets were used for matching at each place. FIGURES 8 and 9 represent matched beam envelope for the MEBT and DTL1 obtained with TRACE3D, respectively.

![Figure 8](image1.png)

**FIGURE 8.** Beam envelope in the MEBT calculated with TRACE3D using PMQ elements.

![Figure 9](image2.png)

**FIGURE 9.** Beam envelope in the DTL1 calculated with TRACE3D using PMQ elements.

Transverse emittance of the DTL1

FIGUREs 10 and 11 show the transverse emittance measured with the emittance scanners located at downstream of the DTL1. The measured normalized rms emittances at 25mA beam current were $0.3\pi mm \cdot mrad$ in both planes. Simulated value of the emittance at the DTL1 exit are $0.25$ and $0.26\pi mm \cdot mrad$ in horizontal and vertical planes, respectively.
FIGURE 10. Horizontal emittance measured at the exit of the DTL1. Normalized rms emittance was 0.30πmm·mrad.

FIGURE 11. Vertical emittance measured at the exit of the DTL1. Normalized rms emittance was 0.29πmm·mrad.

CONCLUSION

The design and simulation studies for the J-PARC linac have been performed. The initial distribution used for the simulation is a realistic one based on the experimental data. The simulation show that the requirements of the transverse emittance (4πmm·mrad) and the momentum spread (less than ±0.1%) at the RCS injection point are satisfied even with realistic static and dynamic errors.

Up to the first tank of three DTL tanks have been commissioned at KEK. The RF operation point was tuned by using the phase-amplitude scan method. Transverse matching was done with TRACE3D and the PMQ element of the TRACE3D was used to simulate the fringing field effect of the Q-magnets. The emittance was measured at the exit of the DTL1. The measured normalized rms emittances at 25mA beam current were 0.3πmm·mrad in both horizontal and vertical planes, which are consistent with the reference values.

The J-PARC linac will be installed in JAERI-Tokai site from July 2005. And the commissioning will be started in fall 2006.

REFERENCES