

MEASUREMENT AND SIMULATION IN J-PARC LINAC

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Abstract

The beam commissioning of J-PARC linac was started in November 2006, and its initial stage was completed in October 2007. During the initial beam commissioning, we have accumulated significant amount of experimental data. Simulation studies have been conducted to understand the underlying physics of the experimental results and realize finer tuning. Among the simulation studies, we focus on an analysis regarding the beam profile measurement after the DTL exit. In the measurement, significant emittance growth and halo generation have been observed. A simulation study has been conducted introducing various mismatch, and its results are compared with the experimental measurements.

INTRODUCTION

The initial beam commissioning of J-PARC linac has been completed in October 2007, and it has been operated, since then, to provide a stable beam for the commissioning of downstream facilities [1]. In parallel with the stable operation, numerical studies have been initiated to understand the experimental results obtained in the beam commissioning to date. It is of practical importance for finer tuning to realize higher beam power.

Among them, we here present a simulation study regarding the beam profile measurements after the DTL (Drift Tube Linac) exit. J-PARC linac consists of a 50-keV ion source, 3-MeV RFQ (Radio Frequency Quadrupole) linac, 50-MeV DTL, and 181-MeV SDTL (Separate-type DTL). The output beam from SDTL is delivered to 3-GeV RCS (Rapid Cycling Synchrotron) with a beam transport line named as L3BT (Linac-to-3-GeV RCS Beam Transport). The beam profile is measured at several locations after the DTL exit, and the measured results are compared with those from numerical simulations to understand the underlying physics.

In the simulations, we assume a certain mismatch artificially introduced in the beam transport line between RFQ and DTL. This beam transport line is named as MEBT (Medium Energy Beam Transport), and the proper matching in this section is supposed to be one of the most important tasks to achieve high beam quality. The beam matching in this section is supposed to be most difficult because of the non-periodical nature of the lattice, larger modulation of the transverse and longitudinal envelopes, and profound space-charge effects due to lower beam energy.

Beam Dynamics in High-Intensity Linacs

Table 1: Measured emittance with 5 mA peak current

| Location | Horizontal [π mm·mrad] | Vertical [π mm·mrad] |
|-----------|--------------------------------|------------------------------|
| DTL exit | 0.27 | 0.25 |
| SDTL exit | 0.23 | 0.27 |
| ACS exit | 0.25 | 0.27 |

Table 2: Measured emittance with 30 mA peak current

| Location | Horizontal [π mm·mrad] | Vertical [π mm·mrad] |
|-----------|--------------------------------|------------------------------|
| DTL exit | 0.42 | 0.36 |
| SDTL exit | 0.35 | 0.40 |
| ACS exit | 0.37 | 0.40 |
| Design | 0.3 | 0.3 |

BEAM PROFILE AND EMITTANCE MEASUREMENT

We have seven matching sections in the linac and L3BT as shown in Fig. 1 [2]. The beam profile is measured with wire scanners at these matching sections. Each matching section has more than four wire scanners so that we can find the transverse Twiss parameters and rms emittances from the measured beam profile. Tables 1 and 2 summarize the normalized rms emittance measured at some of these matching sections. We here determine the transverse Twiss parameters and rms emittances to bet fit the measured rms

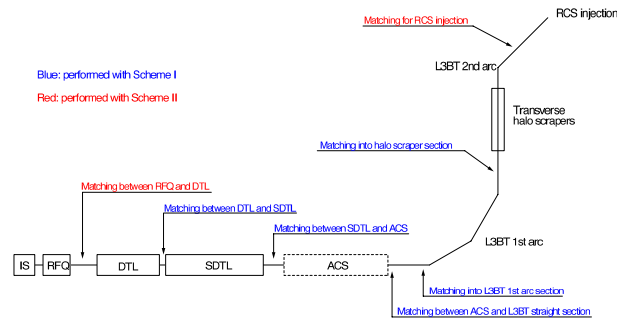


Figure 1: Schematic layout of J-PARC linac and transverse matching sections. An array of four or more wire scanners are located at each matching sections indicated in this figure. The wire scanners are placed periodically in a matching section in blue, but not in a matching section in red.

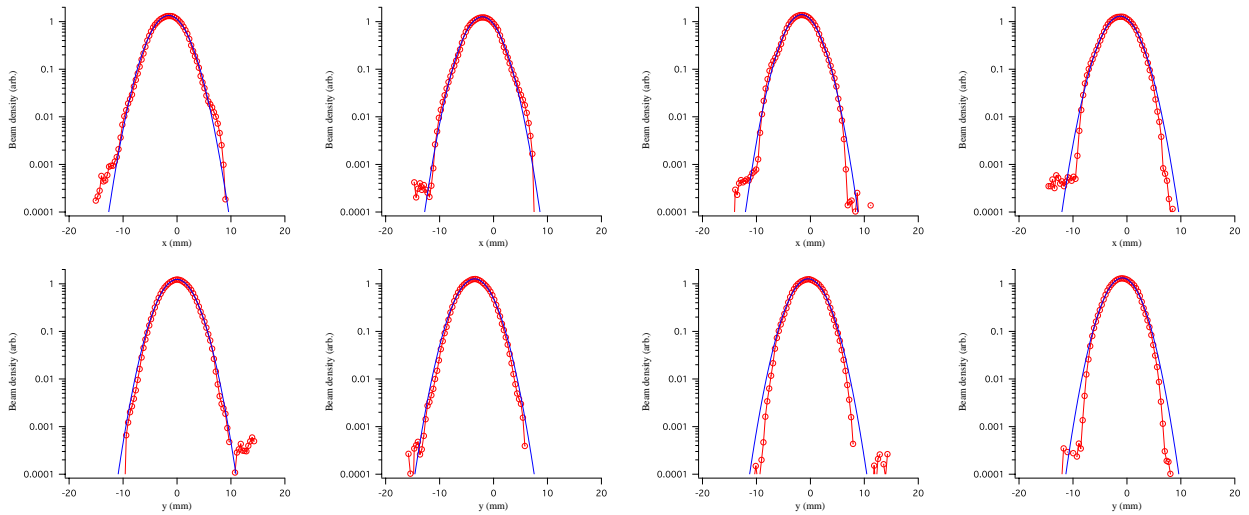


Figure 2: Typical beam profile measured at DTL exit with 30 mA peak current. Red circle: measurement, blue line: Gaussian fit. The beam profile measured with an array of four wire scanners are shown. The left two figures are the results with the first (the most upstream) wire scanner with the horizontal profile on the top and the vertical profile on the bottom. The mid-left, mid-right, and right figures are respectively results with the second, third, and fourth wire scanners. The same notation is adopted in Figs. 3, 6, and 7.

beam widths. In the fitting, we assume the design Twiss parameters and rms emittance for the longitudinal direction. Three wire scanners are sufficient to find these parameters in principle, and the redundant wire scanners are utilized to improve statistical accuracy. The location denoted as “ACS exit” in these tables corresponds to the exit of future ACS (Annular Coupled Structure) section located about 130 m downstream from the SDTL exit.

While it is not listed in these tables, the emittance at MEBT measured with a double-slit-type emittance monitor is typically $0.17 \pi \text{ mm-mrad}$ for 5-mA case and $0.22 \pi \text{ mm-mrad}$ for 30-mA case. It means that we have a significant emittance growth in DTL especially in the case of 30 mA. Besides, we don’t see significant emittance growth after the DTL exit in both 5-mA and 30-mA cases as seen in Table 1 and 2. This tendency has also been confirmed in more downstream sections, while the measured emittances are not listed here.

Another interesting feature of the measurement is the shape of beam profile. Figure 2 shows a typical beam profile measured at the DTL exit. The beam profile is measured with four wire scanners in this section, and each wire scanner is $7 \beta \lambda$ apart. Here, β and λ denote the beam velocity scaled by the speed of light and the RF wavelength, respectively. As readily seen in this figure, the beam profile is virtually Gaussian in spite of the significant emittance growth anticipated in DTL. Contrary to our expectations, the measured beam profile at the DTL exit lacks beam halo or “shoulder-like structure”. As the phase advance between wire scanners is about 60 deg in this region, the halo is supposed to be detected by some of these wire scanners if it has been generated. Meanwhile, the halo-like structure is clearly seen at the SDTL exit as shown in Fig. 3. It should

be stressed here that the halo is generated despite the absence of significant emittance growth in SDTL.

This interesting feature has motivated us to perform particle simulations. To reproduce the experimental result, IMPACT [3] simulations have been performed with various mismatch conditions in MEBT. Needless to say, it is of practical importance to understand the mechanism of the emittance growth and find the way to avoid it. Especially, reduction in the transverse emittance enables more flexible painting injection into RCS, and it is expected to contribute to the beam loss mitigation in RCS.

PARTICLE SIMULATION

Particle simulations have been performed from the RFQ exit to SDTL exit introducing various mismatch at MEBT. We have used IMPACT as the simulation code. The initial distribution is generated with PARMTEQM [4, 5], and 95,322 macro-particles are employed. As seen in Fig. 4, the assumed initial distribution at the RFQ exit is nearly Gaussian and it is reasonably consistent with the measurement results in MEBT. The number of mesh points are set to $32 \times 32 \times 64$, and the integration step width is set to around $\beta \lambda / 10$.

We have tried several kinds of mismatch at MEBT in both of the transverse and longitudinal directions. Especially, the effects of longitudinal mismatch are carefully examined because we don’t have a sufficient longitudinal diagnostics in MEBT. The lack of the longitudinal diagnostics is considered to be a potential cause of excess longitudinal mismatch. IMPACT simulations reveal that 30 to 40 % transverse mismatch at the upstream portion of DTL is anticipated to account for the observed emittance

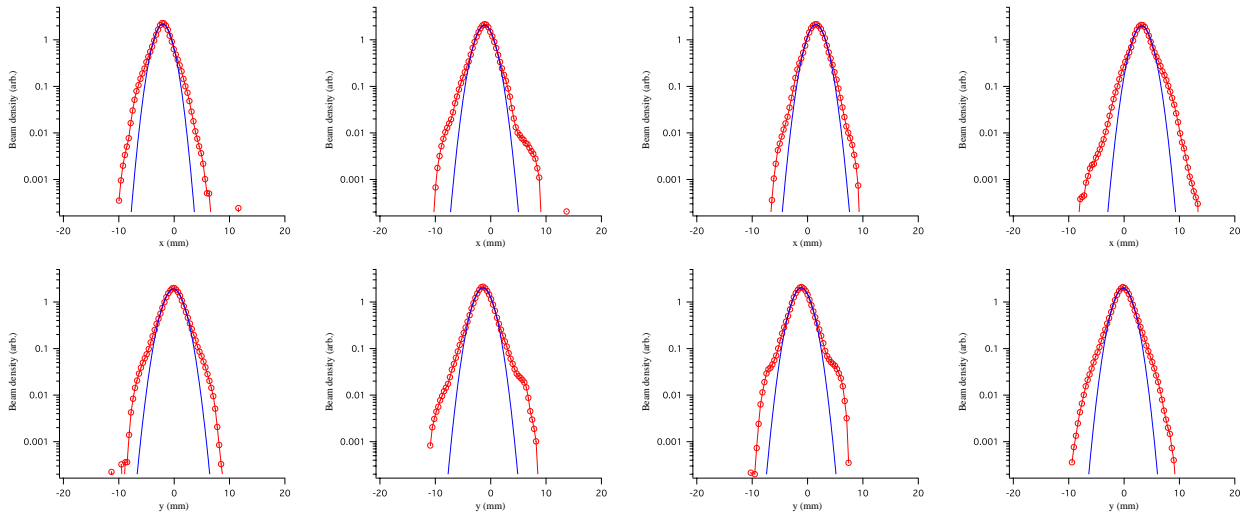


Figure 3: Typical beam profile measured at SDTL exit with 30 mA peak current.

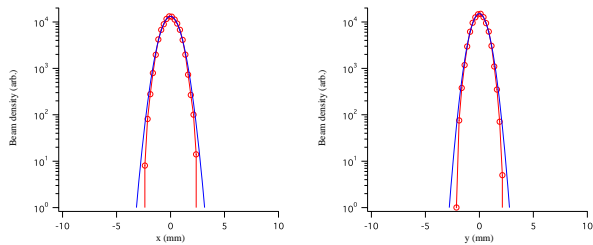


Figure 4: The initial beam profile at the RFQ exit assumed in particle simulations. Left: horizontal, right: vertical.

growth (See Fig. 5 for example). We here define the degree of mismatch as the mismatch oscillation amplitude in the rms beam width. Either of the transverse and longitudinal mismatch in MEBT can drive the transverse mismatch oscillation in DTL.

In most cases, however, the halo develops more rapidly than the experimental observation with the assumed level of initial mismatch. In these cases, a clear halo has already been generated at the DTL exit, and it should be detected with some of the wire scanners there.

An extensive simulation study reveals that the onset of halo generation has a certain sensitivity to the kind of mismatch assumed in the simulation. Actually, the onset is delayed in some cases, where a halo is barely developed in DTL. Figures 6 and 7 show an example of these cases, where a larger longitudinal emittance is assumed than the PARMTEQM prediction. As readily seen in these figures, the beam profile at the DTL exit is virtually Gaussian, while that at the SDTL exit has a clear halo. As seen in Fig. 5, the emittance growth in SDTL is modest in this case.

It is demonstrated in this case that the experimentally observed beam behavior can be qualitatively reproduced with a particle simulation assuming a certain type of mismatch. The similarity in Figs. 2, 3, 6, and 7 is significant,

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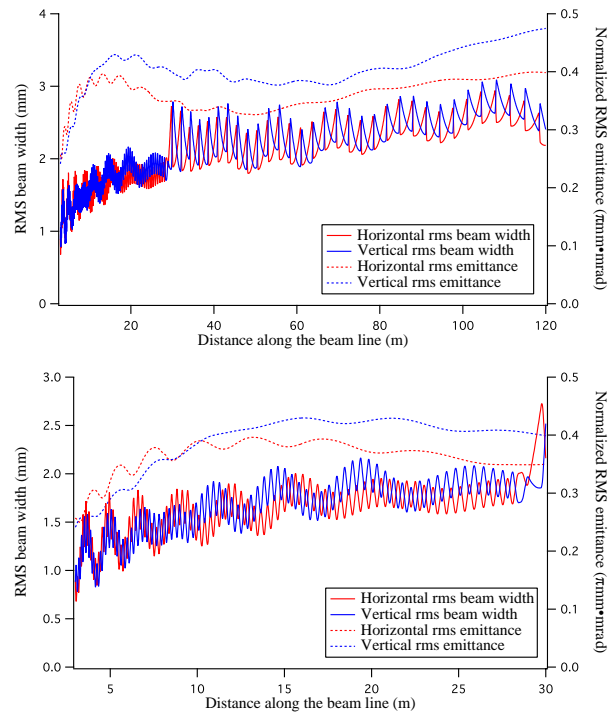


Figure 5: The simulated beam envelope and the rms emittance profile along DTL and SDTL with a certain type of mismatch at MEBT. Top: result for DTL and SDTL, bottom: a close-up view of the top figure. The range of the horizontal axis is from the DTL entrance to SDTL exit (top), and from the DTL entrance to DTL exit (bottom).

while the simulated halo at the SDTL exit is a little less pronounced than the measurement. This finding does not exclude the possibility that the actual cause of mismatch is different from that assumed in this case. However, it suggests that we can narrow down the possible source of

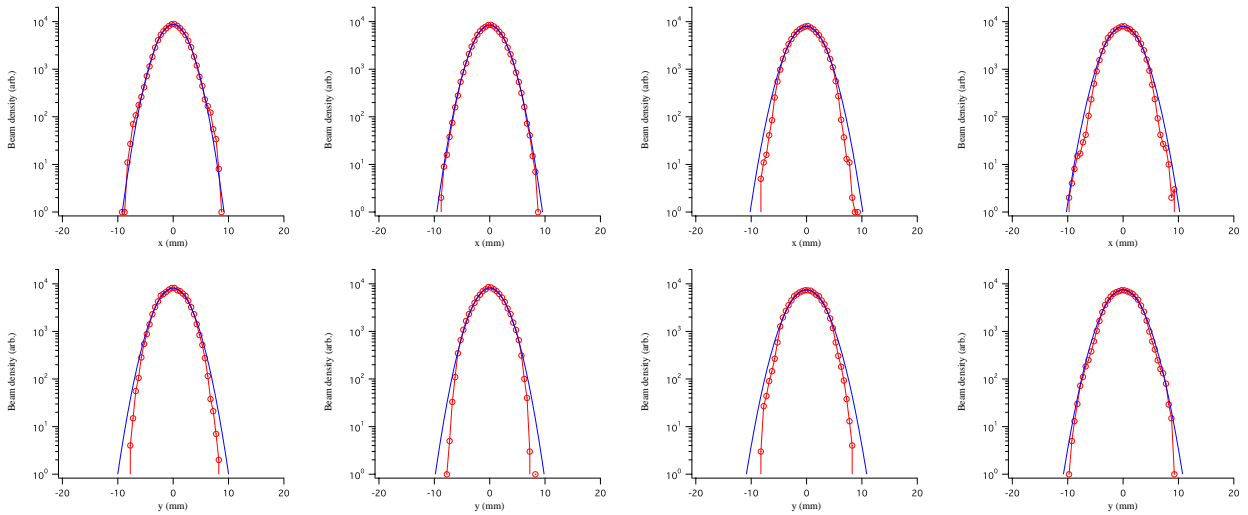


Figure 6: Simulated beam profile at DTL exit with 30 mA peak current assuming a larger longitudinal emittance than the PARMTEQ prediction.

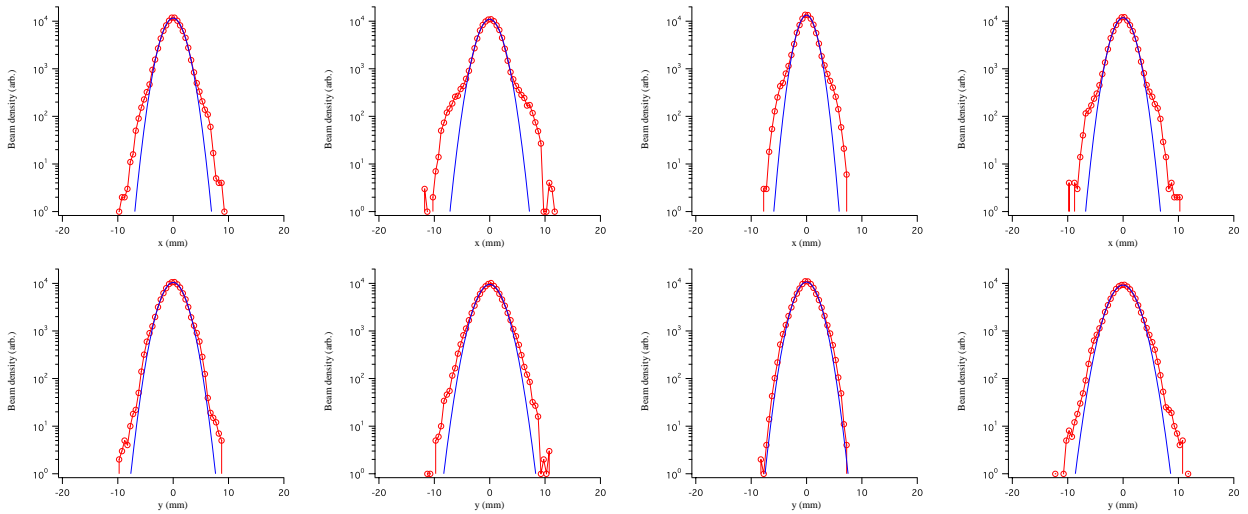


Figure 7: Simulated beam profile at SDTL exit with the same conditions as Fig. 6.

mismatch by surveying the parameter space with more extensive and comprehensive simulations. Then, it can contribute to identifying the actual cause of the mismatch.

DISCUSSIONS

In the beam experiment, we have observed a significant emittance growth in DTL without halo generation with the peak current of 30 mA. Then, it is followed by clear halo generation in SDTL without a significant emittance growth. Particle simulations have been conducted to reproduce this peculiar experimental result obtained with wire scanners. The comparison between the experimental and numerical studies indicates that it is highly likely to have a significant mismatch in MEBT in the case of 30 mA. It seems reasonable to assume that the mismatch is more likely longitudinal than transverse due to the lack of longitudinal di-

agnostics in MEBT. Actually, the qualitative behavior can be reproduced by assuming a certain type of longitudinal mismatch. While more extensive simulation studies may be able to narrow down the possible cause of mismatch, it is desirable to introduce a bunch shape monitor [6] or some other longitudinal diagnostics in MEBT to avoid the ambiguity in a more direct way.

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