A SIMULATION STUDY ON ERROR EFFECTS IN J-PARC LINAC

Masanori Ikegami, KEK, Tsukuba, Ibaraki 305-0801, Japan
Tomohiro Ohkawa, Yasuhiro Kondo, Akira Ueno, JAERI, Tokai, Ibaraki 319-1195, Japan

Abstract

In this paper, effects of realistic errors on beam loss and beam-quality deterioration in J-PARC linac are examined with systematic simulations with PARMILA. Necessity of transverse collimation is also discussed.

INTRODUCTION

Requirements on the momentum spread and transverse emittance are severe for J-PARC linac [1, 2] to realize effective injection to the succeeding RCS (Rapid Cycling Synchrotron). The requirement for the momentum spread at the RCS injection is less than $\pm 0.1\%$ including beam centroid momentum jitter, and that for the normalized transverse emittance is less than 4πmm·mrad. To achieve the requirement for the transverse emittance, we have transverse halo collimators in the beam transport line between linac and RCS [2]. To meet the requirement for the momentum spread, we have two debuncher cavities in the beam transport line to the RCS, with which the bunch is rotated to minimize momentum spread [2, 3].

As losses and beam-quality deterioration are mainly caused by various errors, such as misalignment, RF setpoint errors, etc, it is essentially important to perform particle simulations for J-PARC linac with as realistic errors as possible to estimate their effects. In this paper, effects of realistic errors on beam loss and beam-quality deterioration in J-PARC linac are examined with systematic 2D and 3D simulations with PARMILA [4].

SIMULATION CONDITIONS

As discussed in a separate paper [1], we plan to start beam operation with the lower linac energy of 181-MeV. In this paper, simulations are performed with PARMILA from the exit of RFQ to the injection point to RCS for the 181-MeV case. In the simulations, we assume the peak current of 30 mA, which is the design value for 181-MeV operation. The initial distribution at the exit of RFQ is obtained with PARMTEQM [5]. The number of simulation particles is 95,322 and the number of meshes is set to 20x20x40 for 3D cases and 20x40 for 2D cases.

The quadrupole magnets in DTL and SDTL sections are set to satisfy the equipartition condition. No halo collimation has been assumed in the simulation.

EFFECTS OF STATIC ERRORS

In error analyses, dynamic errors and static errors should be treated separately. For example, beam orbit distortion is mainly caused by the alignment errors of quadrupole magnets, which are static by nature. Another obvious example is the beam centroid momentum jitter, which is solely determined by the dynamic component of the RF errors. We here refer drift or sway of RF phase and amplitude as “dynamic” regardless of their time-scale, and tuning errors of RF setpoints as “static”.

Table 1: Assumed static errors

Errors	Range
Quad alignment error (transverse displacement)	± 0.1 mm
Quad alignment error (roll error)	± 5 mrad
Quad gradient error	$\pm 0.25\%$
RF amplitude error	$\pm 1\%$
RF phase error	± 1 deg

At first, we consider the static errors listed in Table 1. The errors are uniform-randomly distributed in the range. 20 cases with different random seeds have been considered. Simplified beam-orbit correction has been assumed only in the cases where the beam loss is significant, while we have an elaborated beam steering system in the actual linac. At the end of MEBT (in Run #8, 11, 14, and 17), we give a tilt to the beam to minimize the beam loss in DTL1. At the entrance of SDTL (in Run #8), we simply shift the beam center to the origin to avoid the loss in SDTL. Similarly, we shift the beam center to the origin at the exit of SDTL (in Run #5, 9, 11, 16, and 19) to avoid the loss in the beam transport line to RCS.

Figure 1 shows the obtained normalized emittance at the injection to RCS. The result for the case without errors is also shown. As seen in Fig. 1, the emittance exceeds 4πmm·mrad in most cases, and the particles outside 4π ellipse should be eliminated with halo collimators. Then, we estimate the collimator load by counting the number of particles locating outside the 4π boundary. We find that the collimator load ranges from 1 to 3 % and it is typically around 1.5 %, which is tolerable with the current radiation shielding of the halo collimator.

In the 20 cases, we have the beam loss of up to 2 % (typically less than 0.2 %), but they are mostly localized in the first DTL tank as shown in Fig. 2. While small amount of loss (up to 0.2 %) is observed at the DTL-SDTL transition, we have confirmed that it can be reduced to less than 0.01 % (2 W) level with beam steering at MEBT.

Figure 3 shows the energy spread and the longitudinal emittance at RCS injection. While substantial momentum spread increase have be observed, we have confirmed that dynamic RF errors plays a more dominant role in determining the final momentum spread as discussed later. As seen

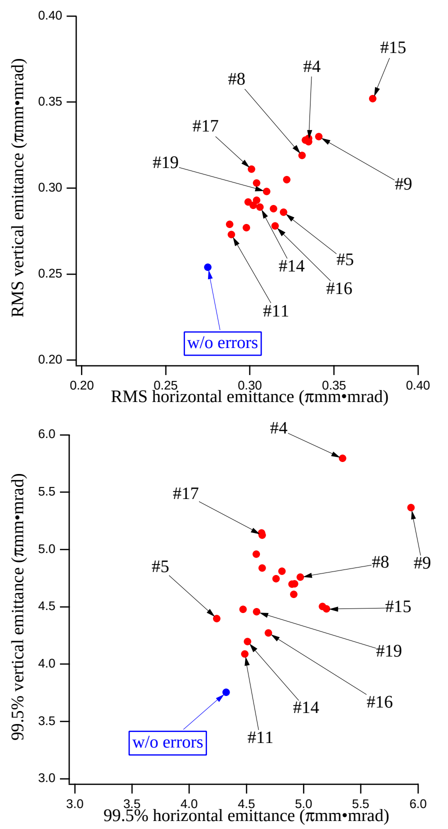

Figure 1: The normalized rms (top) and 99.5% (bottom) transverse emittances. Run numbers are labeled for the cases with characteristic results and those with beam orbit corrections.

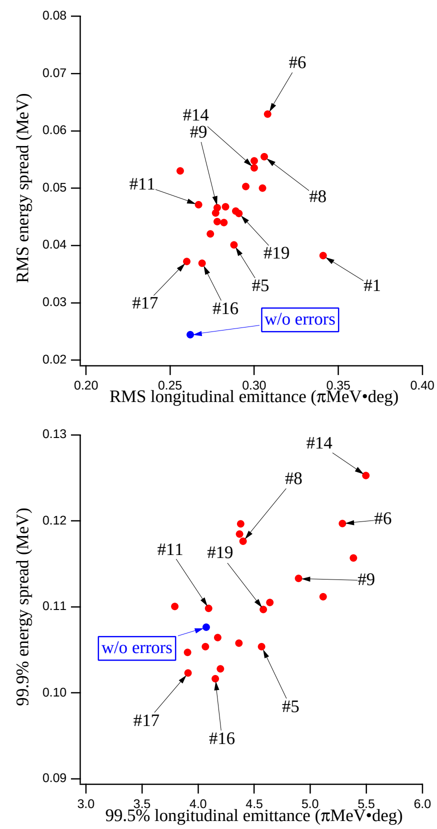

Figure 3: The rms energy spread vs the longitudinal rms emittance (top), and the 99.9% energy spread vs the 99.5% longitudinal emittance (bottom).

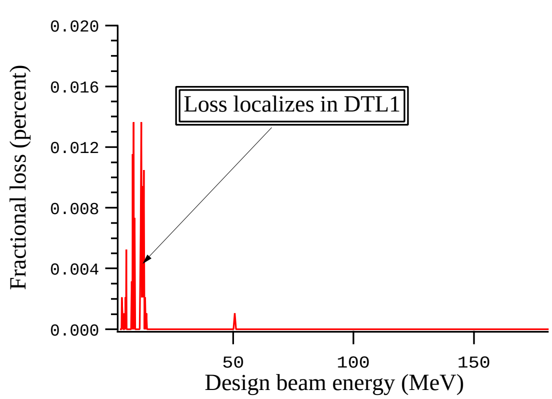

Figure 2: Typical beam loss profile (Run #1).

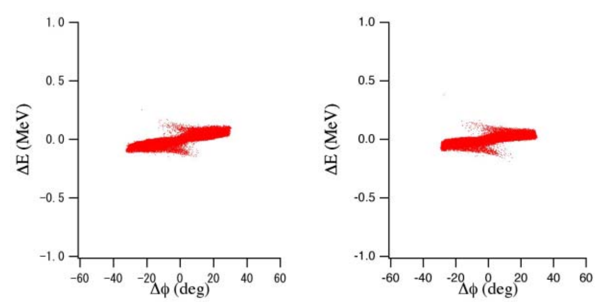

Figure 4: Longitudinal phase-space distribution for the cases with the largest energy spread (static RF errors). Run #6 (left) and Run #14 (right).

in Fig. 4, the phase-space distribution looks similar to the the case without errors [6].

EFFECTS OF DYNAMIC ERRORS

We have confirmed that the longitudinal filamentation in the debunching process is the primary source of the momentum spread at ring injection, and the dynamic RF errors play a dominant role in the filamentation [3]. In this section, we concentrate on the effect of dynamic RF errors, because satisfying the requirement for the momentum spread is one of toughest challenges in the J-PARC lianc commissioning.

The mechanism with which the filamentation occurs is simple. If the output beam energy from SDTL deviates, the energy deviation is translated into large phase deviation at debuncher location because of the long drift length between them. For example, energy deviation of 0.4 MeV at the

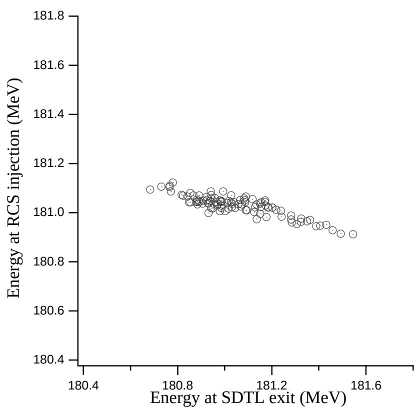

Figure 5: Beam centroid energy at RCS injection vs beam centroid energy at SDTL exit.

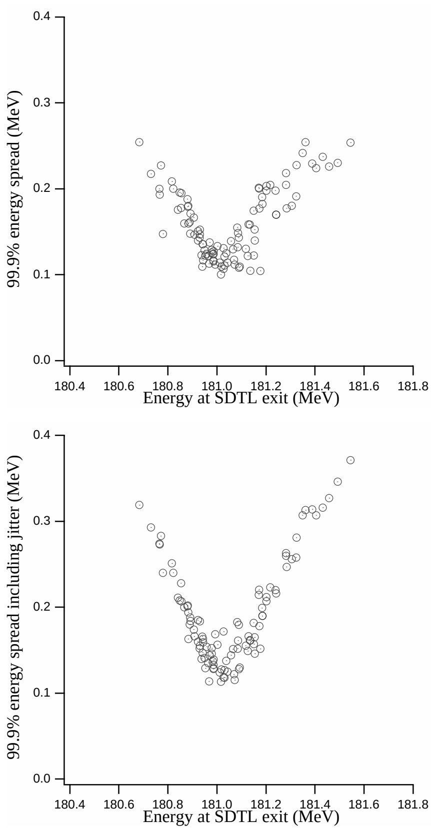

Figure 6: Energy spread at RCS injection. 99.9% energy spread (top) and that including beam centroid energy jitter (bottom).

exit of SDTL causes phase deviation of 32 deg at the first debuncher. To be noted here is that we don't have the large phase deviation for static RF errors, because the debuncher phase is adjusted to the shifted beam phase in a beam-based tuning procedure in that case.

To evaluate the effect of dynamic RF errors of debunchers, we have performed 100 2D runs with the dynamic RF errors of 1 deg and 1 % (Our goal for the dynamic RF error is 0.5 deg and 0.5 %). Figure 5 shows the beam energy jitter at RCS injection, which is reduced to around ± 0.1 MeV by debunchers. In Fig. 6, it is clearly seen that the beam with larger energy deviation at SDTL exit has larger energy spread at RCS injection. In spite of the severe filamentation as shown in Fig. 7, the energy spread meets the requirement (less than ± 0.333 MeV for 181-MeV operation) for RCS injection mostly, which is consistent with 3D simulation study [3] .

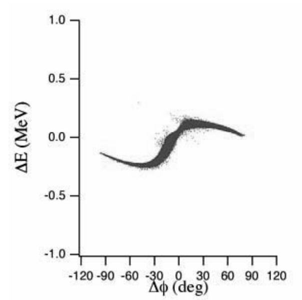

Figure 7: Longitudinal phase-space distribution for the case with the largest energy spread (dynamic RF errors).

SUMMARY

The effect of realistic errors are examined with 3D PARMILA for J-PARC linac. Transverse collimation is necessary to meet the requirement for the normalized transverse emittance at RCS injection. The fraction of 1.5 % should be eliminated at halo collimators in typical cases. While visible beam loss is observed in some cases, it is reasonably localized in the low-energy section of DTL. The energy spread meets the requirement for RCS injection mostly, although substantial increase of energy spread is anticipated due to dynamic RF errors. Because it is obvious that the linac output energy deviation is the primary source of the energy spread increase, feedback of the linac energy to the phase or amplitude of the last klystron is foreseen to eliminate the effects of slow drift of RF properties.

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