Simulation Study of Error Effects for the J-PARC Linac Energy Upgrade

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Abstract

The J-PARC linac will have an upgrade in recent years. As usual, effects of realistic errors on beam loss and beam-quality deterioration have been studied. All the beam dynamics with error and end-to-end systematic simulation was performed by using code IMPACT.

1. INTRODUCTION

After the successful progress of beam commissioning for the J-PARC linac stage one, an upgrade will be performed in recent years. The upgrade mainly includes energy upgrade from 181 MeV to 400 MeV by installing an ACS accelerator section, and peak current increase from 30 mA to 50 mA.

Same as current linac [1], beam partical losses and beam-quality deterioration are mainly caused by various errors, such as misalignment, RF setpoint errors, etc, it is important to perform particle simulations with as realistic errors as possible to estimate their effects.

2. UPGRADE J-PARC LINAC AND ASSUMED ERROR

The layout of J-PARC upgrade linac can be seen in Figure 1. After SDTL, 972 MHz ACS cavities will be installed to accelerate current 181 MeV H^- ions beam to 400 MeV. Meanwhile, to achieve the final beam power of 1 MW from RCS, beam current will be increased from nowadays 30 mA to 50 mA with new ion source and RFQ [2]. Beam envelope of designed upgrade linac can also be seen in figure 1. Transverse beam size in ACS section is about half of that in SDTL section. Quadrupole magnets in DTL, SDTL and ACS sections are set to satisfy the equipartition condition.

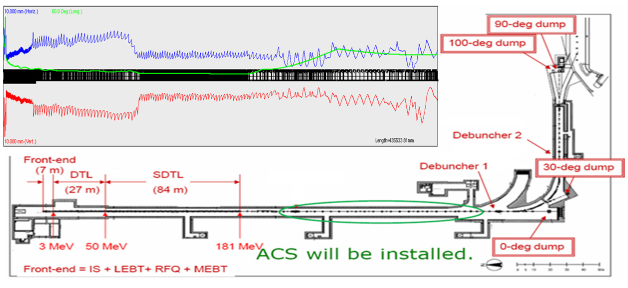

Figure 1: Layout of the J-PARC upgrade linac and beam envelopes

Based on these layout and envelope, error analyses were moved on by given assumed error to quandrupoles and RF systems shown in table 1. These errors are mainly considered static error. Both static error and the other kind of error "dynamic error" are described below.

- **static errors**: these errors can be detected and corrected. It contains displacement, alignment rotation error and effective length influece of quadrupoles. Meanwhile error from RF gap field, klystron field and phase are also included.
- **dynamic errors**: these errors can't be corrected. They are induced by the vibrations of the RF field or mechanical vibrations from the environment, power jitter and ripple of quadrupoles. The effect of those errors is designed to be at least one order of magnitude lower than the static errors [3].

Table 1: Assumed errors of J-PARC upgrade linac

Error	Range
Quad transverse displacement (δ_x, δ_y)	±0.1 mm
Quad x-y rotation error ($\phi_{x\text{-}y}$)	±0.05 mrad
Quad x-s/y-s rotation error ($\phi_{x\text{-}s}$, $\phi_{y\text{-}s}$)	±0.1 mrad
Quad gradient error ($\Delta G/G$)	±0.5 %
RF amplitude error (Δamp/amp)	±1 %
RF phase error ($\Delta\phi_{RF}/\ \phi_{RF}$)	±1 degree

3. BEAM LOSS DUE TO ERROR EFFECT

27 runs were done with random error considering error range in table 1. Beam loss in all cases is less than 0.3 %. Typical loss can be seen in figure 2. And all the loss is located in DTL section with 90% in DTL1 section. Because beam energy in DTL1 section is less than 20 MeV, beam loss can be accepted for normal operation.

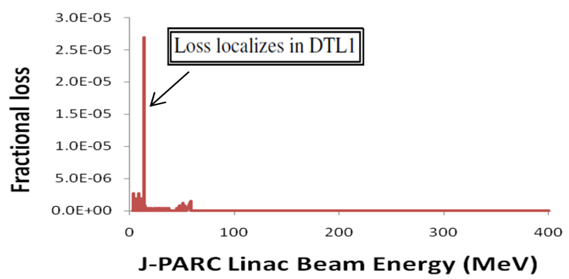

Figure 2: Beam loss caused by assumed error

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4. ERROR INFLUENCE TO TRANSVERSE EMITTANCE

This error study is performed in two stages. First, the sensitivity of separate error is determined in order to evaluate the individual contribution. Then, all errors are combined simultaneously to verify the set of tolerances determined previously and estimate the overall degradation of the beam properties.

Each simulation consists more than 20 runs. emittance growth are statistically averaged. The relative emittance increase $\Delta\varepsilon$ in each run is expressed with respect to the nominal case, *ie* the case where beam is transported through the ideal linac without errors:

$$\Delta\varepsilon = \frac{\varepsilon_{error} - \varepsilon_{design}}{\varepsilon_{design}} \tag{1}$$

Where, ε_{error} and ε_{design} are the emittances of the beam through the structure with and without errors.

The sensitivities of emittance due to assumed error can be seen in table 2. Those emittance data are simulation data at the end of linac, which is also the injection point of J-PARC/RCS. Any separate error gives less than 6% increase of transverse rms emittance. The error from displacement and gradient of quadrupoles support main part, while rotation error gives very small influence.

Table 2: Sensitivities of emittance due to assumed error

Error	$<\Delta\varepsilon_x>$±SD	$<\Delta\varepsilon_y>$±SD	$<\Delta\varepsilon_z>$±SD
	[Unit: %; rms: rms. emittance;	995: 99.5% emittance]	
δ_x, δ_y	rms:5.3±2.1 995:-1.6±2.1	rms:4.0±2.0 995:-0.9±1.0	rms:5.7±1.5 995:-6.5±3.5
$\phi_{x\text{-}y}$	rms:-0.2±0.3 995:0.3±0.9	rms:0.0±0.2 995:-0.3±0.8	rms:0.0±0.4 995:-1.0±1.5
$\phi_{x\text{-}s}$, $\phi_{y\text{-}s}$	rms:0.3±0.4 995:-0.8±0.8	rms:0.2±0.4 995:-0.7±1.1	rms:0.5±0.8 995:-2.0±1.7
$\Delta G/G$	rms:5.5±5.9 995:1.0±9.4	rms:3.8±4.4 995:5.5±5.7	rms:1.8±2.0 995:-1.5±4.8
Δ_{amp}/amp	rms:2.6±2.0 995:0.2±3.8	rms:3.0±2.3 995:1.4±2.2	rms:12.0±6.1 995:1.3±4.8
$\Delta\phi_{RF}$/ ϕ_{RF}	rms:3.2±2.7 995:-0.1±3.9	rms:2.8±2.4 995:1.6±1.8	rms:15.5±17.7 995:4.7±18.4
With all	rms:12.0±6.5 995:-3.2±9.9	rms:12.6±5.5 995:6.7±5.0	rms:23.6±16.9 995:4.5±18.2

Totally, with all error, the growth ratios of horizontal and vertical rms emittance are 12.0±6.5 and 12.6±5.5. For 99.5 % emittance, the growth ratios shows uncertain around the emittance value in design. Both those information can be seen in figure 3 obviously. The blue point is transverse emittance for design while the other red points stand for the cases with error. Those influences can be acceptable for linac operation and RCS injection with suitable transverse collimation setting.

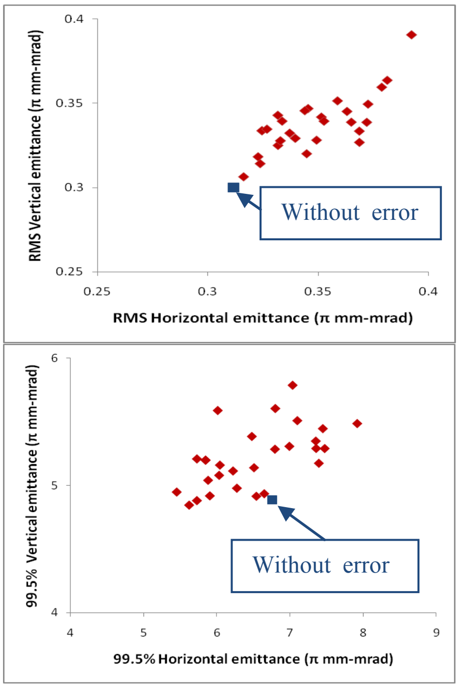

Figure 3: Horizontal and vertical emittance growth by assumed error at the end of linac (emittance: normalized; up: rms emittance; down: 99.5 % emittance)

The growth ratios of horizontal rms emittance along linac from the end of RFQ to the RCS injection have been studied also. From figure 4, increase ratios of 4 seeds are drawn in different colour lines. Considering linac layout, rough experience can be got as that: horizontal rms emittance is increased rapidly in DTL section, initial 20 meters of SDTL section and ACS section.

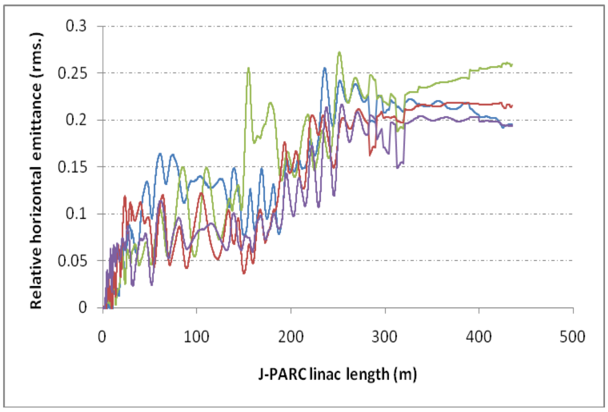

Figure 4: Horizontal emittance growth ratio along linac

5. ERROR INFLUENCE TO BEAM ENERGY AND LONGITUDINAL EMITTANCE

To get a good estimate of the beam center of energy and phase, 94,720 macroparticles per run are sufficient. Based on assumed error 1 % for all RF amplitude and one degree for all RF phase, offset and standard deviation of center energy at the end of linac would be 1.4 keV ± 89.0 keV, with phase of 0.15 ± 2.8 degree, which can also be seen in figure 5. In this figure, blue point stands for design result, while red points stand for the simulation result with error. The largest shift for beam energy is less than ± 0.2 MeV. On one hand, last two debunchers in linac could be used to diminish beam energy shift; on the other hand, these values are very small which can be ignored.

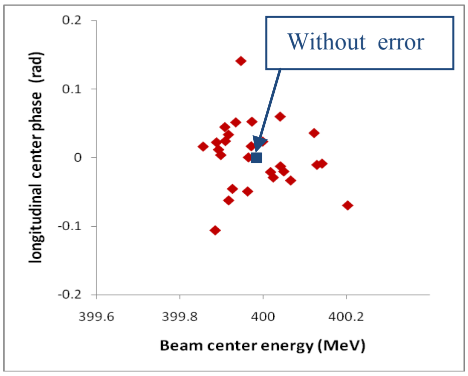

Figure 5: Offsets of beam centre energy and phase caused by assumed error

Not like small change on beam energy and absolute phase, longitudinal emittance and momentum spread has an obvious difference between design and cases with assumed error. This difference can be seen in table 2. RF amplitude error gives 12.0 %±6.1 % change for beam longitudinal rms emittance at the end of linac, while RF phase error gives 15.5 %±17.7 % influence. Any error from quadrupole doesn't give big influence. Totally the rms longitudinal emittance has 23.6 %±16.9 % growth for with error cases.

This growth can also be seen in figure 6. In figure 6, momentum spread (Δp/p) at RCS injection is also mentioned. While substantial momentum spread increase has been observed, all the values are less than 0.6 ‰. And the last 2 debunchers can be used to tune the momentum spread. For the growth ratio of 23.6 %±16.9 %, those are for rms emittance. For 99.5 % longitudinal emittance, which is also mentioned in table 2 and figure 6, not so large growth can be seen. Meanwhile for J-PARC/RCS injection, longitudinal painting is used. Large longitudinal acceptance can endure this growth.

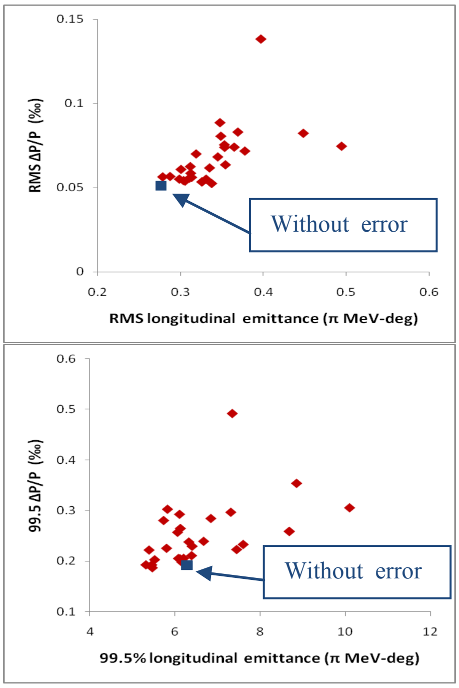

Figure 6: Momentum spread and longitudinal emittance growth caused by assumed error. (up: rms; down: 99.5%)

6. SUMMARY

Follow upgrade of J-PARC linac, effect of realistic errors have been performed. Assumed errors of quadrupole with displacement, alignment rotation error, gradient error, and RF system with amplitude error and phase error are considered in simulations by using code IMPACT. Beam losses are found, but all the losses are small fraction (maximum case <0.3 %) and located only in DTL section, 90% beam loss in DTL1. In DTL1, beam energy is less than 20 MeV, so influence of beam loss can be ignored. With error, offset and standard deviation of center energy at the end of linac, which is also injection point of ring, would be 1.4 keV ± 89.0 keV, with phase offset of 0.15 ± 2.8 degree. Those values are also very small. For error effect on beam emittance, influence weights by separate kinds of error have been studied. For transverse rms emittances, errors from displacement and gradient of quadrupole give large influence for emittance growth. Meanwhile for longitudinal rms emittance, RF errors have big weight. All the growths can be accepted by linac acceptance and RCS injection painting with suitable setting of transverse collimation.

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