LATTICE AND ERROR STUDIES FOR J-PARC LINAC UPGRADE TO 50 MA / 400 MeV

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Abstract

Equi-partitioning (EP) settings are applied as the base-line designs both for present 15mA/181MeV operation and coming upgrade to 50mA/400MeV. On the other hand, the J-PARC Linac offers considerable flexibility to search for the overall optimum. A preliminary trial was made to mitigate the intra-beam stripping (IBSt) with a lattice with constant-envelop and off-EP setting (Tx/Tz~0.3) at the 3-fold frequency jump from SDTL to ACS. With simulations without error, no significant emittance growth and halo formation were found for the off-EP setting. But when the errors at generic level are added in the simulation, emittance growth becomes by far not acceptable. It is found that being off-EP could make the lattice less robust against errors and EP condition seems more important in a world with imperfections.

INTRODUCTION

Equi-partitioning (EP) [1] settings are applied as the base-line designs for the J-PARC Linac with H- beam both for present 15mA/181MeV operation [2] and coming upgrade to 50mA/400MeV [3]. On the other hand, the J-PARC Linac has considerable flexibility, which offers possibilities not only for investigating the basic principles but also for further optimizations capable to include more options. According to the hardware capability, it is possible to set the 50-MeV DTL (Drift Tube Linac), the 181-MeV SDTL (Separate-type DTL) and the future ACS (Annular-ring Coupled Structures) sections at given range of Tx/Tz, as shown in Fig.1. Tx/Tz is the ratio of oscillation energies in x (horizontal) and z (longitudinal), which can be written as,

$$\frac{T_x}{T_z} = \frac{r_x^2 k_x^2}{r_z^2 k_z^2} = \frac{\epsilon_x k_x}{\epsilon_z k_z},$$

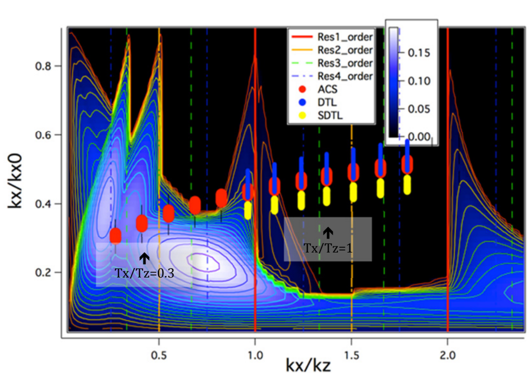


Figure 1: Tune-settings for J-PARC Linac in Hofmann stability chart, at 50mA, with $\varepsilon_x / \varepsilon_z = 0.7$, Tx/Tz range of 0.2-2.0.

Here r stands for the beam rms envelop, ε the rms emittance, focusing is represented by the wave number k (with current) and k_0 (0-current). Please do not be misled by the expressions of "Tx" over "Tz", and "kx" over "kz" in this paper. For settings to the left in Fig. 1 means less transverse focusing or more longitudinal focusing.

In high power H- LINAC, stripping of H- is one of the most important sources of uncontrolled beam loss [4][5]. Gas stripping and intra-beam stripping are the two dominating stripping effects in the J-PARC Linac.

Gas-stripping effect can be eased with better vacuum conditions. The measured vacuum pressure for the new ACS tanks is 2×10^{-6} Pa [6], in between two pumps and with RF on, which can suppress the beam loss by gas-stripping to ~0.01W/m level in the J-PARC ACS section. IBSt is harder to deal with, which is almost only dependent on lattice. Bigger envelope and/or smaller divergence can help, but it is usually not free to manage.

From SDTL to ACS, the RF frequency jumps from 324MHz to 972MHz. The longitudinal focusing will increase at the frequency jump, in case of same or higher acceleration gradient and similar synchronous phase. To keep EP condition, the transverse quadrupole gradient should also increase, which implies shrink of transverse envelope. This shrink increases particle density and convergence so that it will aggravate beam collective effects, including IBSt.

This is the motivation for off-EP settings with less transverse focusing. With longitudinal settings un-changed, decreasing transverse focusing is corresponding to move tunes to the left-hand-side following the footprints in Fig. 1. To set Tx/Tz=0.3 for ACS is simply to reduce quadrupole gradient to about 70% of nominal at ACS section, and it results in a constant-envelop transition from SDTL to ACS. This setting is off-EP, with tunes more depressed and close to the resonances kz=3kx and kz=2kx, so that emittance exchange from longitudinal to transverse planes is predicted.

Simulations were made using the 3D particle-in-cell code IMPACT [7], starting with the new J-PARC RFQIII output with 95322 particles.

SIMULATION WITH NO ERROR

Simulations with no-error cases are presented in this section. The main results are shown in Fig. 2 and 3.

Figure 2 shows the simulated rms emittance for nominal EP setting compared with the constant-envelop setting, i.e. the case for $Tx/Tz|_{ACS}$=0.3. Clear emittance exchange is shown for $Tx/Tz|_{ACS}$=0.3, with no significant emittance growth found except for emittance exchange.

Figure 3 shows the simulated ratio between 99.5% horizontal emittance and rms one, for $Tx/Tz|_{ACS}$ =1, 0.3, and 0.7. The 99.5%-to-rms-emittance ratios for the 3 cases are almost identical and close to about 6.5, as implies no significant halo formation.

The simulated transverse 99.5% emittance for $Tx/Tz|_{ACS}$=0.3 at RCS septum is less than 6 π mm · mrad (unnormalized at 400MeV). Thus the constant-envelop setting seemed not bad.

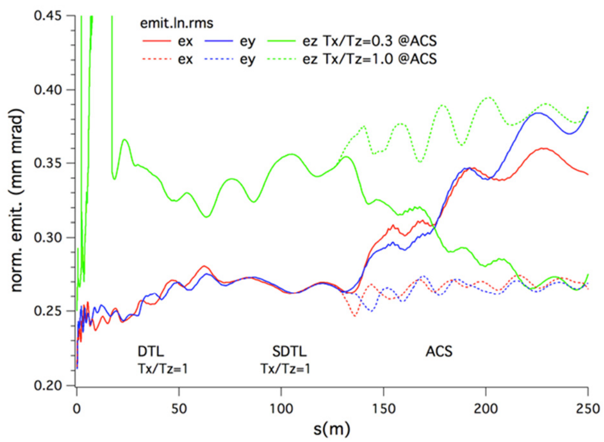


Figure 2: Emittance evolution comparison of lattices setting ACS at Tx/Tz=1.0 and Tx/Tz=0.3, simulated by IMPACT.

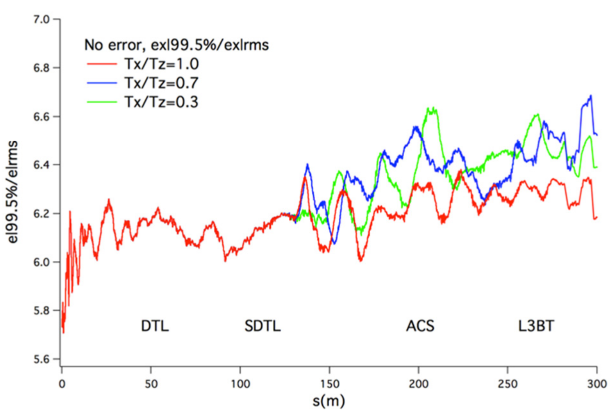


Figure 3: Simulated ratio of horizontal 99.5% emittance over rms emittance of lattices setting ACS at Tx/Tz=1.0, 0.3 and 0.7.

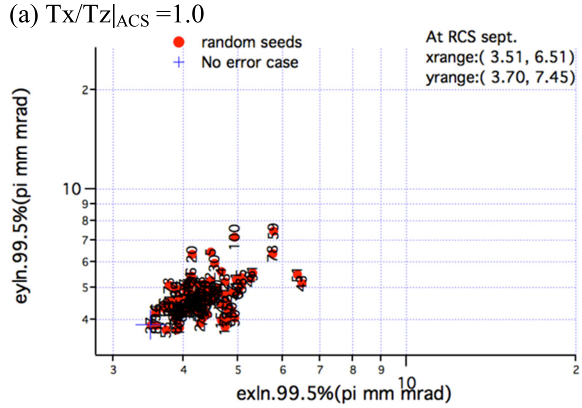
Based on above simulations, the IBSt loss can be calculated with the design beam duty cycle 0.7%, according to beam pulse of 500μs, repetition of 25Hz and chopper ratio of 56%.

The average loss due to IBSt at ACS section is 0.060W/m for $Tx/Tz|_{ACS}$ =1.0, 0.027W/m for $Tx/Tz|_{ACS}$ =0.3 and 0.047W/m at $Tx/Tz|_{ACS}$. They are all below the threshold of 0.1W/m.

SIMULATION WITH ERROR

Error study is done for all above lattices giving 100 uniform random seeds for quadrupole transverse alignment error of ±0.1mm, RF amplitude error of ±1% and RF phase error of ±1 degree, with no cell-to-cell field/phase error assumed in each RF tank.

(a) $Tx/Tz|_{ACS}$ =1.0



(b) $Tx/Tz|_{ACS}$ =0.3

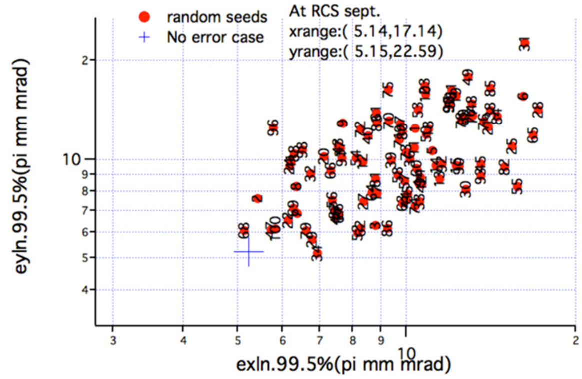


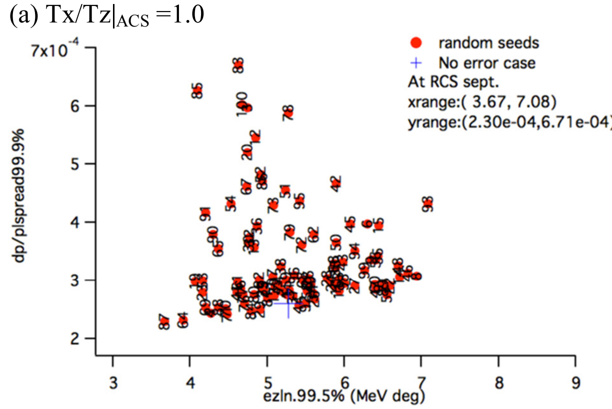
Figure 4: Error study for 99.5% transverse emittance at RCS septum for (a) $Tx/Tz|_{ACS}$=1.0 and (b) 0.3.

Simulated 99.5% transverse emittance at the septum of the Rapid Cycling Synchrotron (RCS), for seeds of uniform random errors with ACS setting at (a) Tx/Tz=1.0 and (b) 0.3 are shown in Fig. 4. Results differ significantly, so that logarithmic scaling has to be used.

The maximum final 99.5% emittance found in the error studies is 2 times of no-error case for $Tx/Tz|_{ACS}$ =1.0. But it is more than 4 times for $Tx/Tz|_{ACS}$ =0.3, thereafter resulting in an uncontrollable situation with normalized 99.5% transverse emittance ranged up to ~20 π mm · mrad (20 π mm · mrad unnormalized at 400MeV).

Figure. 5 shows the seed-distribution of longitudinal 99.5% emittance and 99.9% momentum spread at RCS septum. No obvious difference was found.

(a) $Tx/Tz|_{ACS}$ =1.0



(b) $Tx/Tz|_{ACS}$ =0.3

ISBN 978-3-95450-122-9

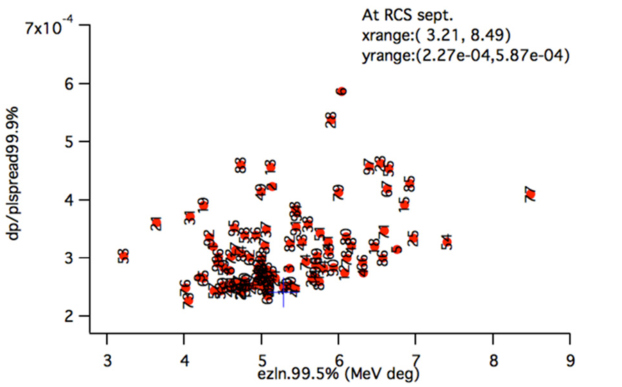


Figure 5: Error study for longitudinal plane, at septum of RCS for (a) $Tx/Tz|_{ACS}$=1.0 and (b) 0.3.

SUMMARY ACCORDING TO TX/TZ

Now we try to summarize for each simulated Tx/Tz ranged from 0.3-1.2. The rms and 99.5% emittance at exit of ACS section for worst cases and the no-error cases are shown in Fig. 6 and 7, vs. Tx/Tz.

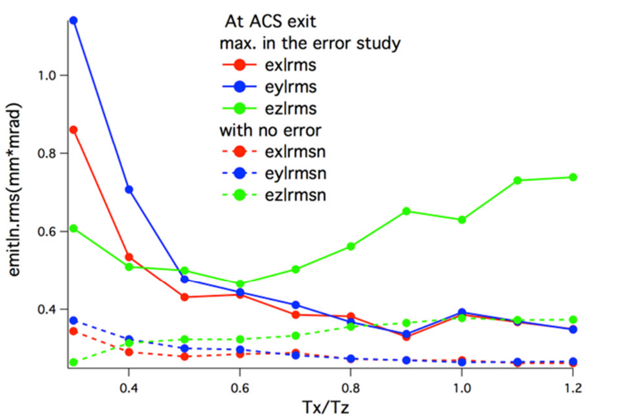


Figure 6: Simulated normalized rms emittance for ACS setting at Tx/Tz =0.3-1.2, with comparison of no-error cases and the seeds with maximum emittance growth.

Emittance exchange is clearly shown. No-error cases show monotonously emittance exchange from longitudinal to transverse planes, with $Tx/Tz|_{ACS}$ from 1.2 to 0.3.

For far-off-EP cases of $Tx/Tz|_{ACS}$ < 0.6, longitudinal emittance growth was present, together with sharp transverse emittance growth, for both rms and 99.5% emittance. Nevertheless longitudinal the 99.5% emittance for the worst case for $Tx/Tz|_{ACS}$ < 0.6 is even bigger than that of $Tx/Tz|_{ACS}$ =1!

The different behavior of rms and 99.5% longitudinal emittance shows the halo is formed.

It is interesting and motivating further studies.

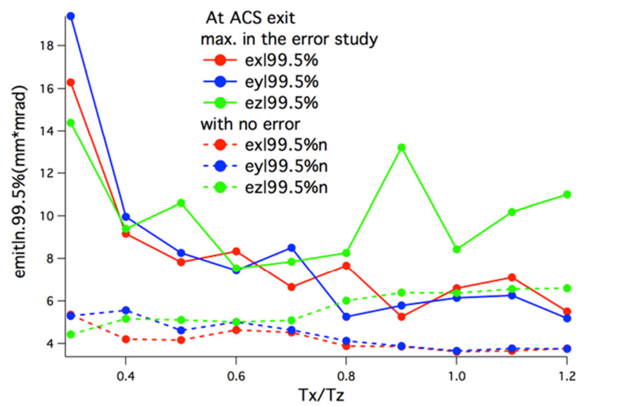


Figure 7: Simulated normalized 99.5% emittance for ACS setting at Tx/Tz=0.3-1.2, with comparison of no-error cases and the seeds with maximum emittance growth.

CONCLUSION AND DISCUSSIONS

For the frequency transition from SDTL to ACS in the J-PARC upgrade, a far-off-EP setting (Tx/Tz=0.3) of ACS had been considered helpful to mitigate beam loss due to IBSt. No significant emittance growth and halo formation were found in the simulations without error. But error studies show a completely different view. The transverse 99.5% emittance is as big as ~20 π mm · mrad unnormalized at 400MeV for the worst seed found in the simulation, which is 4 times of no-error case and by far not acceptable for RCS injection.

Therefore being off-EP could make the lattice less robust against errors and EP condition seems more important in a world with imperfections.

According to the example in this paper, it seems worth trying Tx/Tz=0.8 or even Tx/Tz =0.7. An overall optimization is dependent on where the critical points are, both for the transverse emittance at RCS injection and for the tolerable beam loss due to IBSt.

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