

STABILITY STUDIES FOR J-PARC LINAC UPGRADE TO 50mA/400MeV

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Abstract

J-PARC linac applies the Equi-partitioning (EP) setting as the base-line design. And it is the first machine to adopt this approach at the design stage. EP condition is a natural solution for avoiding emittance exchange between transverse and longitudinal planes. At J-PARC linac it is also possible to explore off-EP settings. One of the motivations could be a lattice with relaxed envelope for mitigating the intra-beam stripping (IBSt) effects in high current H- beam. During and after the energy upgrade in Jan., 2014 and beam current upgrade in Oct., 2014, experiments were carried out to study the stability and emittance evolution for the EP and off-EP settings with high current H- beam at J-PARC linac for better choices of lattice and better understanding.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high-intensity proton accelerator facility, which consists of a linac, a 3 GeV rapid cycling synchrotron (RCS), and a main ring synchrotron (MR).

The J-PARC linac consists of a 3 MeV RFQ, 50 MeV DTL (Drift Tube Linac), 181/190 MeV SDTL (Separate-type DTL) and 400 MeV ACS (Annular-ring Coupled Structure), as shown in Fig.1.

In Jan. 2014 the J-PARC linac energy was upgraded from 181 MeV to 400 MeV while the peak beam current was increased to 50 mA in Oct. 2014. These upgrades allowed the RCS to provide 1 MW equivalent beam powers, a major milestone in the development of J-PARC.

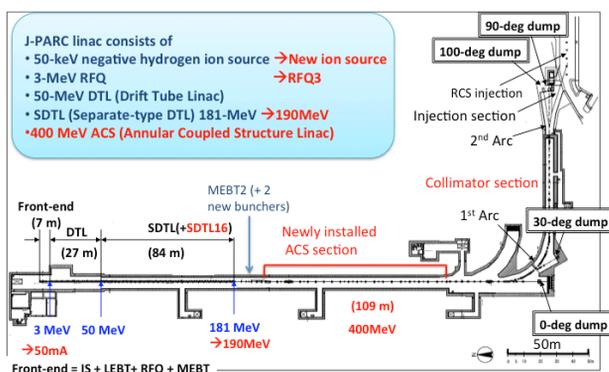


Figure 1: Layout of J-PARC linac.

During the design stage of J-PARC, there was sufficient evidence that an equi-partitioned (EP) lattice offers a natural solution for emittance conservation in high-intensity hadron accelerators, owing to pioneering

work by R. A. Jameson, M. Reiser, I. Hofmann [1], and et al. J-PARC linac RF tank were arranged with consideration of a baseline design satisfying EP condition. It also has the flexibility for a wide range of off-EP operating points, offering the opportunities not only for investigating the basic physics principles but also for further optimizations of the machine operation.

As shown in Fig. 2, within the hardware capability, it is possible to set the DTL, the SDTL and the ACS in a wide range of T_x/T_z . Normally $T_x=T_y$ is kept. T_x, T_y, T_z stand for the horizontal, vertical and longitudinal “temperature”.

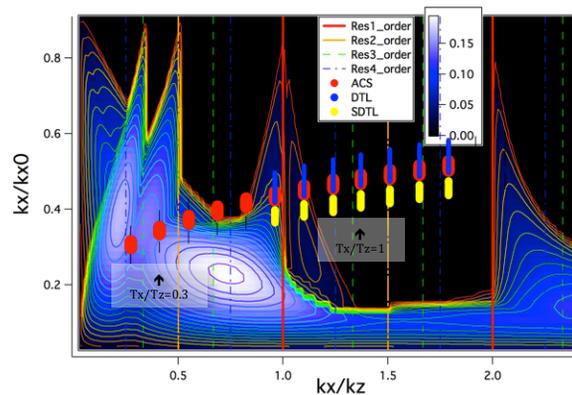


Figure 2: Tune-settings for J-PARC linac in Hofmann stability chart, at 50mA, with $\epsilon_x/\epsilon_z = 0.7$.

T_x/T_z is the ratio of oscillation energies in transverse and longitudinal plane, which is defined as,

$$\frac{T_x}{T_z} \equiv \frac{r_x^2 k_x^2}{r_z^2 k_z^2} = \frac{\epsilon_x k_x}{\epsilon_z k_z} \quad (1)$$

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). For instance settings to the left in Fig. 2 indicate less transverse focusing or more longitudinal focusing and vice versa. The EP condition generates largest stable area.

COMPLETION OF UPGRADES AND REMAINING QUESTIONS

Both energy [2] and beam current [3] upgrades were accomplished within the planned schedules with satisfying levels of beam loss and extinction rate. From 2015, J-PARC started ramping up of the RCS operation output power from 300 kW, in steps of 100 kW, towards the goal of 1MW in early 2016.

However, questions and difficulties remain. For example, the longitudinal measurement at MEBT2 was missing during the energy upgrade due to bunch shape monitor (BSM) vacuum problems. This measurement is

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necessary for matching to the ACS section, which has 3-fold frequency-jump from SDTL. In order to help the intensity upgrade, one of the BSMs was installed in the MEBT2 during the summer shut down of 2014, although three BSMs are planned periodically in the ACS cells.

Another example is the beam parameters at the output of the new frontend (a new RF ion source and the new RFQ3), which is the initial condition for MEBT1. Due to the limited precisions in the RFQ simulation and measurements before installation, we found “slight” differences, as shown in Fig.3, between the expected (mainly based on RFQ simulation) and on-line measured initial beam parameters, which proved to be critical for the matching with MEBT1 to the DTL. The transmission with the lattice prepared with the expected initial condition is so low that the MPS (machine protection system) fired and commissioning could not continue, as shown in the “Before” curves in Fig.4. An on-line quadrupole scan measurement finally helped to get the “right” initial transverse beam parameters.

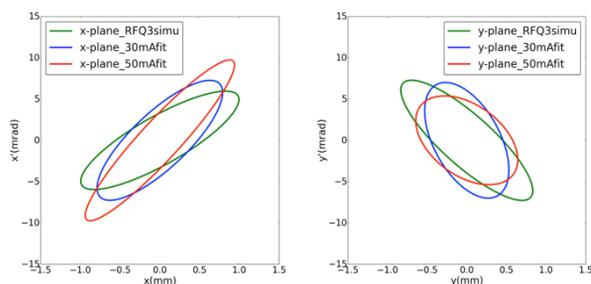


Figure 3: Comparison of the expected and on-line measured initial beam parameters of J-PARC new frontend.

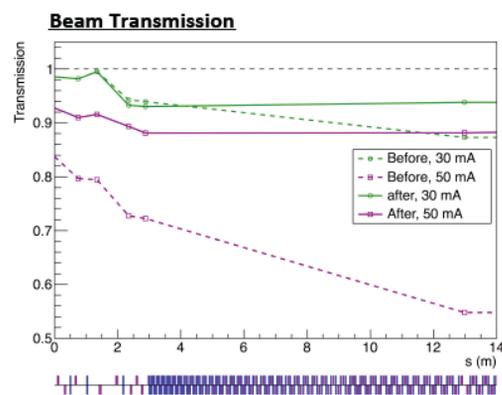


Figure 4: Comparison of the transmission for settings based on the expected and on-line measured initial beam parameters.

It is clear that there are always non-ideal situations such as alignment, field errors and ambiguities. The major impact of errors/mistakes could be reduced by accumulated measurements and commissioning/beam studies. On the other hand, the machine should be as tolerable as possible, i.e. with good stability.

Previous studies [4] have shown that the J-PARC baseline design with EP condition has better stability than other settings.

MOTIVATIONS FOR OFF-EP AND SIMULATIONS

Stripping [5][6] is one of the main sources of uncontrolled beam loss in H- linacs. Gas stripping is dominant at J-PARC SDTL according to the bad vacuum level. In the ACS tanks 2×10^{-6} Pa is achieved in between pumps, and therefore gas stripping is supposed not serious. The intra-beam stripping (IBSt) is predicted in the ACS section. IBSt is only dependent on lattice for a given beam and vacuum. From SDTL to ACS, the RF frequency jumps from 324 MHz to 972 MHz. The longitudinal 0-current focusing increases proportionally to the frequency. Transverse focusing should be increased correspondingly to keep the EP condition according to eq. (1), resulting in shrunk envelope and increased divergence, as shown in Fig. 5a. A constant-envelope lattice could be obtained by setting with $T_x/T_z=0.3$ or 70% quadrupole gradient, as shown in Fig. 5b. Data in Fig.5 were obtained with Trace3d calculation. With this setting, IBSt can be reduced to 1/3 with designed beam parameters at 50mA. But simulation studies show that this setting is more sensitive to errors [4].

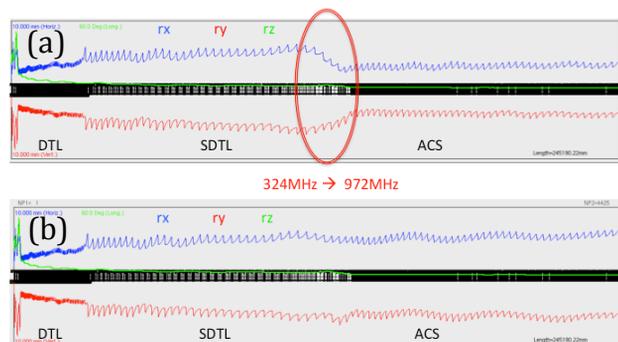


Figure 5: Comparison between EP and equi-envelope lattices obtained with Trace3D.

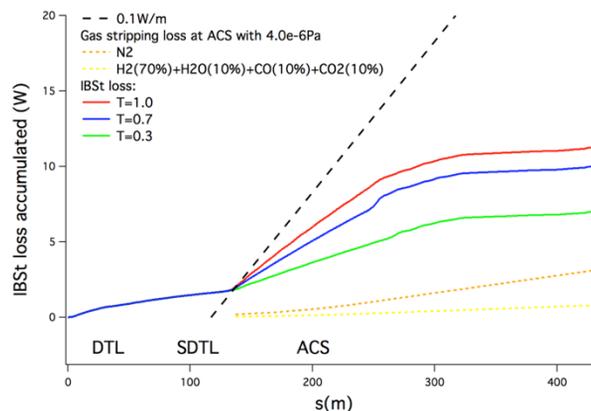


Figure 6: IBSt beam loss power for lattice with $T_x/T_z|_{ACS}=0.3, 0.7$ and 1.0, compared with gas stripping at ACS, with designed beam parameters at 50 mA.

A comparison of IBSt effects for lattice with different T-ratios, together with gas stripping loss (at ACS only) with pessimistic (N_2) and expected (H_2+H_2O+COs) components, is shown in Fig.6. Beam loss power is based on particle-in-cell (PIC) simulation with IMPACT, given a peak current of 50mA, operation duty cycle at 25Hz and 53% chopping rate.

The highest residue radiation measured at ACS is ~ 2 mSv/h at beam duct surface ~ 5 h after beam stop for previous 300kW (RCS) operation. It increased by about 1.5 times after the beam power was ramped up to present (Arlil 2015) 500kW level. Fig. 7 shows the beam loss monitor (BLM) signal at 400 and 500 kW operation scaled with 300 kW data, where the increase is qualitatively proportional. The residue radiation is expected to increase at least linearly toward 1MW operation.

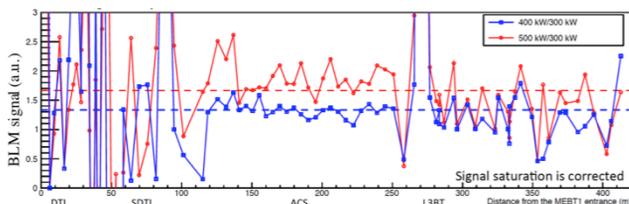


Figure 7: Measured BLM signal at 400 and 500 kW operation scaled with 300 kW data.

Beam studies for lattices with different T-ratio were planned. The first motivation is to verify the IBSt effects and look for mitigating solutions.

A second motivation is also interesting. To set for various T-ratios successfully and to distinguish the more delicate IBSt effects, the matching should be precise enough. In other words, we need consistency between the initial conditions used in the matching procedure and for the real beam. It offers chances for checking and improving the consistency.

MEASUREMENT

The beam studies were done on nights of April 2, and April 22 with a peak current of 30 mA. We kept the beam condition unchanged up to SDTL, and set the ACS section for $T_x/T_z = 0.3, 0.7, 1.3,$ and $T_x/T_z=1.0$ the nominal. We prepared matched lattice setting for each T-ratio, using MEBT2 quadrupoles and bunchers, and with initial MEBT2 beam parameters obtained from transverse and longitudinal profile measurements. Starting from the prepared lattices, for each T-ratio it took 3 transverse matching iterations to get the final matching.

Reference IBSt losses (30 mA, 25 Hz, 53% chop rate) obtained with IMPACT simulation is shown in Fig. 8.

The measured BLM signals are shown in Fig.9. It shows almost the same tendency as the simulation, except for the abnormal regions for $T_x/T_z=0.3$ marked by red circles. This result shows the signature of IBSt.

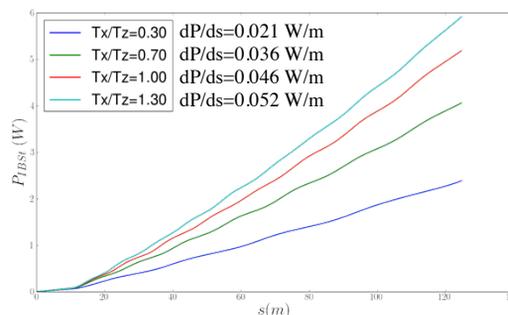


Figure 8: Simulated IBSt for the lattices tested (30 mA).

In the simulation, emittance exchange from longitudinal to transverse planes was found for $T_x/T_z=0.3$ and 0.7, and not in $T_x/T_z=1.0$ and 1.3. And for all cases total emittance growth was not found and neither the beam loss.

The circled “abnormal” sudden increase of beam loss near ACS#7 and ACS#19/20 in the measured $T_x/T_z = 0.3$ BLM signal looks different from the simulated beam loss mainly from IBSt shown in Fig. 8. This can be understood looking at ref. [4], which pointed out that for no error case, a far off-EP setting like the $T_x/T_z=0.3$ could be ok, but it is more sensitive to machine errors, i.e. less stable. For some of error seeds the emittance could be blow up and beam loss could happen in and after ACS. Nevertheless obvious transverse emittance growth was found for the $T_x/T_z = 0.3$ lattice with wire scanner monitor measurements. Emittance changes for $T_x/T_z = 0.7, 1.0$ and 1.3 are not clearly found because for these cases the transverse profiles after ACS are too narrow.

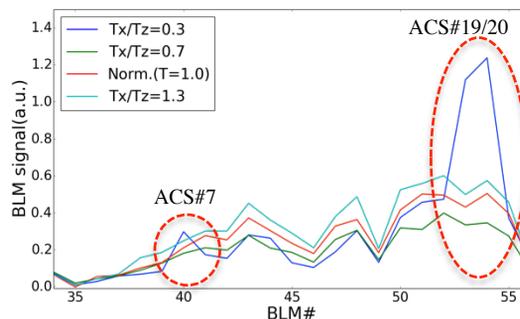


Figure 9: Measured BLM signal at ACS for lattices tested.

CONCLUSION

Off-EP lattice settings were tested in the J-PARC linac ACS section. Lattice-dependent beam loss was found and it might imply that IBSt effects play a role in the ACS section. Preliminary studies suggest that a lattice with T_x/T_z around 0.7 could be feasible for mitigating IBSt loss.

“Abnormal” beam loss spots for the far off-EP setting with $T_x/T_z=0.3$ were also found. This is consistent with previous predictions that off-EP settings (especially those with bigger tune depression) may encounter stability problems due to higher sensitive to the errors.

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