

PROGRESS OF J-PARC LINAC COMMISSIONING

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Abstract

After energy and intensity upgrade to 400MeV and 50mA respectively, J-PARC linac were ready for 1 MW beam power from RCS. J-PARC is now successfully operated at 50mA/400MeV for 500kW at neutron target, and on the way to 1MW. The next milestones 1.2 and 1.5MW from RCS are relying on feasibility and property of increase of peak current to 60 mA and the pulse width to 600us in linac. Beam studies were carried out at linac to study the initial beam parameters from ion source/RFQ, to find the optimized lattice and matching, to clarify beam loss source and to mitigate the loss/residue dose for the power upgrade.

INTRODUCTION

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

The J-PARC Linac [1] 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).

The roadmap of J-PARC linac intensity upgrade is as follows.

- Energy upgrade from 181MeV to 400MeV in Jan., 2014, with commissioning of ACS.
- Intensity upgrade from 30mA to 50mA in Oct. 2014, operation peak current from 15mA to 30mA.
- The former upgrades paved the way for 1MW output from RCS, and equivalent 1MW beam from RCS was demonstrated in Dec.2014, which is the design objective of J-PARC.
- Linac peak current of 40mA were started in user operation from Jan., 2016.
- Next steps will be 1.2/1.5MW from RCS, with either or both of linac peak current upgrade from 50 to 60mA and linac beam pulse width extension from 500 to 600 μ s.
- First trial of 60mA beam study in Jul., 2017, with 68mA and 62mA achieved from ion source and MEBT1, respectively.
- Second trial of 60mA beam study in Dec., 2017, with 60mA after DTL without acceleration (3 MeV) and 57mA/400MeV achieved.
- Third trial of 60mA study in Jul., 2018, 62mA full energy beam was achieved in linac.
- 50mA in user operation from Oct. 2018.

- 50mA, 600us injection to RCS was achieved in Oct., 2018, which is corresponding to 1.2MW at RCS full energy.
- Fourth trial of 60mA study and injection (500 μ s) to RCS in Dec., 2018, also corresponding to 1.2MW.
- Planned study in Jul., 2019, 60mA/600us trial injection to RCS (\sim 1.5MW@RCS)

J-PARC will celebrate its 10th anniversary in Sep., 2019. J-PARC linac is now successfully operated at 50mA/400MeV for 500kW at neutron target, and promisingly on the way to 1MW. Beam loss at linac became one of the most crucial issues and the main challenge on the way of power upgrade.

The main sources of beam loss in J-PARC linac consists of H⁺ generated from neutralization in low energy beam transport from ion source to RFQ, longitudinal halo from RFQ, emittance growth and halo formation in MEBT1 due to space charge, aperture reduction due to deformation by earthquake, gas stripping of H⁻ to H⁰ in SDTL, halo due to mismatch in the 7 matching sections, intra-beam stripping (IBSt) [2] effect of H⁻.

IBSt is the dominant at J-PARC especially in the 200~400MeV section. Simulation and experiment studies were carried out since 2013. Recently an IBSt-mitigation lattice was applied in user operation.

60mA STUDY

For the feasibility of 60mA study, the newest measured beam distribution from J-PARC H⁻ rf ion source [3], as shown in Fig.1, was used as input of simulation study. The key points above all are, emittance from RFQ and aperture of DTL[4].

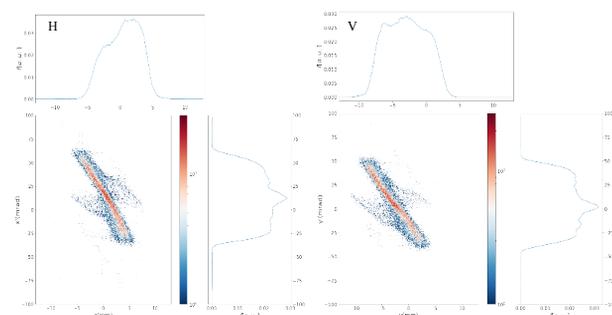


Figure 1: A typical distribution for 66 mA from ion source.

It is found that in the typical distribution for 66 mA beam in J-PARC about 5% of beam could be identified as “halo”. And for the 95% “core” of the beam rms emittance is about 30% larger than that of 40mA beam in operation. In other word, 60 mA beam is a “new beam”

compared with the nominal (almost) halo-free 40 or 50 mA beam.

The results of RFQ simulation with the realistic distribution were shown in Table 1. It is found that instead of emittance increase at the RFQ exit, the halo is scraped at the cost of RFQ transmission. Therefore, one should worry more about the RFQ transmission rather than the downstream aperture.

Table 1: RFQ Simulation Results Inputting of Measure Distribution at 66mA as Shown in Fig. 1

I(mA)	η	Norm. rms (mm*mrad)			Trace3d definition (mm*mrad/deg*keV)			Envelope (mm)	
		ϵ_x	ϵ_y	ϵ_z	ϵ_x	ϵ_y	ϵ_z	rx	ry
(For ref.) 30	0.95	0.26	0.26	0.32	20.68	20.92	583.35	2.16	1.23
(For ref.) 40	0.94	0.24	0.24	0.33	19.07	19.04	600.90	2.15	1.21
(For ref.) 50	0.93	0.22	0.23	0.34	17.81	18.02	624.95	2.12	1.20
60	0.91	0.22	0.22	0.34	17.41	17.41	624.50	2.14	1.19
70	0.90	0.22	0.21	0.34	17.25	17.08	630.30	2.15	1.20

Five sets of lattices (A to E) were prepared for the study. Transverse envelope with 5 times of rms. emittance (upper) and drift-tube-quadrupole (DTQ) setting (lower) were shown in Fig. 2.

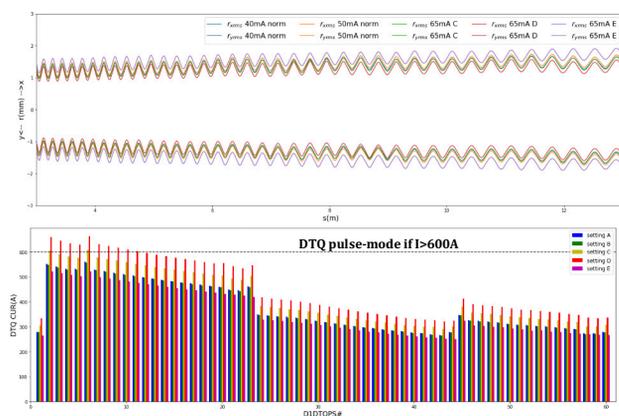


Figure 2: DTL lattice preparation, beam envelope (5*rms) and operational DTQ current.

- (A) 40mA lattice for operation (as reference)
- (B) 50mA lattice for beam study (as reference)
- (C) 40mA lattice scaled for 65 mA, to keep the same envelop and same phase advance. About 5% increase of DTQ strength.
- (D) 40mA lattice scaled for 65 mA according to large emittance, with About 5% increase of DTQ strength.
- (E) Equipartitioning setting for 65 mA.

The lattices C and D are with stronger quadrupole gradient, prepared in case of larger emittance than expectation. Several DTQ for lattices C and D are too high to run in DC mode, which will cause operation complexity.

In first 60mA study the 5 lattices were tested and lattice E proved to be good enough as the base-line setting. Based on the Twiss measurement at MEBT1 in the first trial, 3 MeV 60 mA beam was obtained at DTL

end, in second trial experiment in Dec. 2017, and 56 mA for the full-accelerated beam, as shown in Fig. 3. The two main bottle necks are at RFQ and MEBT1 scraper. The ultimate solution is ion source improvement for less-halo distribution. But for the time being, it is necessary to use practical ways such as tradeoff with RFQ tank level, as shown in Fig. 4, and scraper setting adjustment (with guaranteeing the chopping extinction), as shown in Fig. 5.

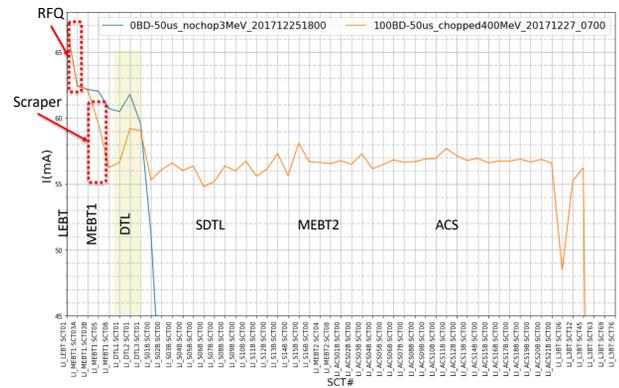


Figure 3: Transmission measured 60 mA trial in Dec. 2018.

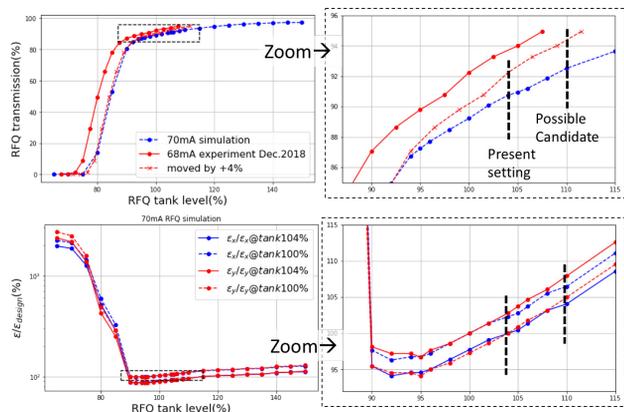


Figure 4: Tradeoff of transmission and output emittance with RFQ tank level.

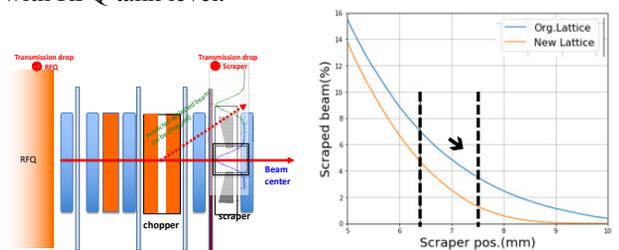


Figure 5: Layout of chopper-scraper system, and scraper adjustment.

By increase RFQ tank level by 6%, transmission was increased by 2% at the cost of emittance increase by 5%. Another 2% of transmission was obtained by widen scraper setting without affecting the extinction. Request of beam current from ion source was also increased from 68mA to 72mA. Based on these knobs, 62mA fully

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accelerated beam was achieved in linac in Jul. 2018, and successfully injected in Jul. 2019.

IBST AND MITIGATION

The loss rate by IBSt can be only affected by lattice.

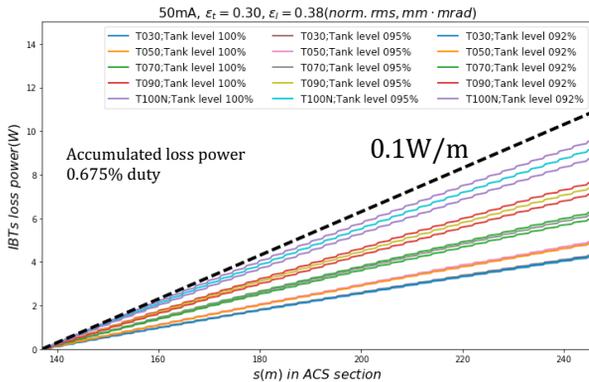


Figure 6: Beam loss power by IBSt in ACS.

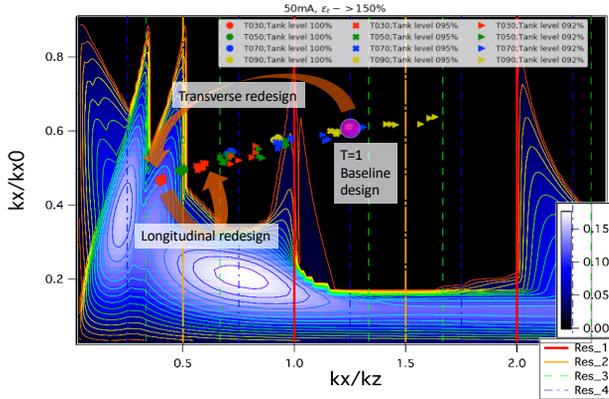


Figure 7: Stability Diagram (Hofmann chart).

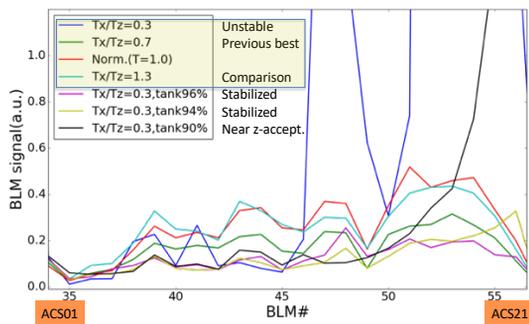


Figure 8: Measured beam loss for the lattice settings.

Weaker focusing is preferred to mitigate the IBSt, as shown in Fig. 6, but one should be careful of the stability of the setting at the same time, as shown in Fig. 7. The transverse/longitudinal temperature ratio ramps from base-line equipartitioning setting with $T \equiv T_{x,y}/T_z=1$, to 0.9, 0.7, 0.5, 0.3 by ramping down of all quadrupoles in the ACS section.

For $T=0.3$ and 0.5 the tunes are already in resonance, and longitudinal adjustment is needed to be resonance-

free. The simulation results were verified in the experiment, as shown in Fig. 8.

Lattice with $T=0.7$ is good candidate because it can mitigate IBSt by 40% and is stable without changing longitudinal parameters. The operation parameter with $T=0.7$ at ACS was ready since Oct., 2019, and is applied in user operation since Apr., 2019. The measured residue radiation dose verified the 40% mitigation with same operation condition 50mA/500kW, as shown in Fig. 9.

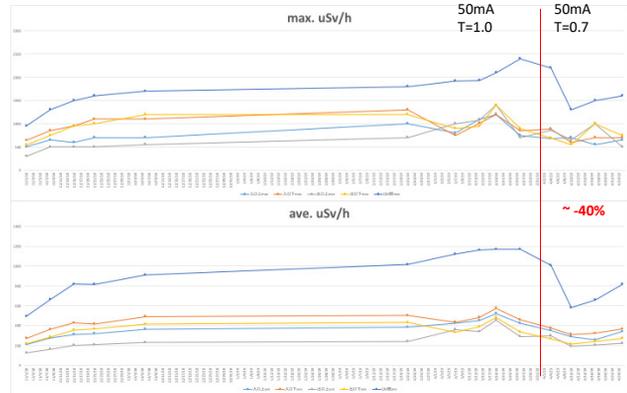


Figure 9: Measured residue radiation (on surface) in ACS.

CONCLUSION AND OUTLOOK

J-PARC started to prepare for equivalent 1.2/1.5 MW beam from RCS. As a key of next power upgrade, 60 mA linac beam studies were conducted. And 62mA was obtained with practical tradeoffs in linac and successfully injected RCS. Ongoing ion source development is needed for intense halo-free beam and the targeted power upgrade.

IBSt is the dominant source of residue radiation in J-PARC linac. Simulation and experiment studies were carried out for years to explore stable IBSt-mitigation lattice. Lattice with $T=0.7$ is applied in operation since this April and the mitigation is consistently verified by the residue radiation measurement. For the present 500kW (at neutron target) operation, the maximum dose on surface decrease from 2.5mSv/h to the level of ~ 1.5 mSv/h, which is very helpful for the future ≥ 1 MW operation.

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