RECENT PROGRESS IN THE BEAM COMMISSIONING OF J-PARC LINAC

M. Ikegami *, KEK/J-PARC, Tokai, Japan,
H. Sako, A. Miura, G. Wei, JAEA/J-PARC, Tokai, Japan

Abstract

The user operation of J-PARC linac was started in December 2008 with the limited beam power of 270 W from the linac. Since then, we have experienced some operational issues including those caused by uncontrolled beam losses. Mechanisms and cures for some of them have been identified in the beam studies, and we have succeeded in mitigating them. Presently, we are operating with the linac beam power of 7.2 kW. In this paper, we present recent progress in the beam commissioning of J-PARC linac with emphasis on the effort to mitigate the beam losses.

INTRODUCTION

J-PARC (Japan Proton Accelerator Research Complex) is a high-intensity proton accelerator facility which consists of an injector linac, 3-GeV RCS (Rapid Cycling Synchrotron), and 50-GeV MR (Main Ring) [1, 2]. The injector linac consists of a 50-keV negative hydrogen ion source, a 3-MeV RFQ (Radio Frequency Quadrupole linac), a 50-MeV DTL (Drift Tube Linac), and a 181-MeV SDTL (Separate-type DTL). While the output beam energy of J-PARC linac is currently 181 MeV, we have planned an upgrade to 400 MeV by adding ACS (Annular Coupled Structure linac) section after existing SDTL (Separate-type Drift Tube Linac) section [3]. We aim to realize 1 MW beam power from RCS with the energy upgrade and an peak current upgrade of the injector linac.

The user operation for the neutron target has been started since December 2008 with 4.5 kW beam power from RCS (270 W from linac). The beam power has been gradually increased since then, and we are now operating with 120 kW from RCS (7.2 kW from linac) [2]. Accompanying the high-duty-factor operation for users, we had the following three issues in the J-PARC linac.

- Beam loss localized at the first bending magnet of the first arc section after the linac
- Beam loss widely distributed in the future ACS section (the straight section after SDTL)
- Significant emittance growth in the DTL section followed by the halo development in the SDTL section

We have been focused to these issues in the recent beam study for J-PARC linac, and the relevant progresses will be reviewed in this paper.

* masanori.ikegami@kek.jp

BEAM LOSS AT THE FIRST BENDING MAGNET

After the commencement of the user operation, the beam loss at the first bending magnet after the linac became obvious. The residual radiation level at the bending magnet reached 210 μSv/h outside the yoke and 550 μSv/h inside after a three-day beam operation with 4.5 kW beam power from RCS. The radiation level we show in this paper is all measured with contact after several hour after beam shutdown. While we cannot access to the hottest point inside the yoke, it is expected to exceed 1 mSv/h at the surface of the vacuum chamber. This activation level is considerable considering the low beam power delivered from linac.

From the detailed distribution of the residual radiation around the bending magnet, we suppose that protons accelerated to nearly the design energy of 181 MeV are the main cause of the observed loss. The residual radiation shows that the loss is concentrated on the opposite side from the negative hydrogen ion deflection. A possible mechanism of the proton acceleration is protons generated in the beam transport line between the ion source and RFQ. If a proton is generated at the region with a double-stripping scattering with the residual gas, it can be captured by the RFQ around the opposite RF phase to the main negative hydrogen ion component. Then, it can be accelerated up to the design energy and ends up by causing a beam loss at the first bending magnet.

This supposition has been confirmed with a proton removal experiment [4], where the proton component is eliminated by setting up a chicane orbit in the beam transport line between RFQ and DTL with steering magnets. In this setting, protons accelerated with RFQ are stopped with a beam absorber originally installed for beam chopping. After adopting the proton removal, the residual radiation level around the bending magnet has been significantly reduced to the negligible level with 120 kW beam power from RCS. We are regularly using the proton removal in the beam operation to mitigate the beam loss at the first bending magnet.

BEAM LOSS AT THE FUTURE ACS SECTION

The next most significant beam loss we observes is that widely distributed in the future ACS section. Two debunchers are currently installed in this section. As there is a narrow section just before the second debuncher, the residual radiation at that location marks the highest level of around

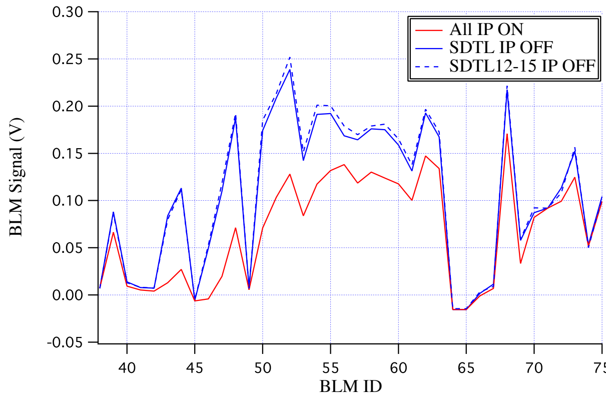

Figure 1: BLM raw signals with different IP settings. With all IP's on (red), IP's in the SDTL section off (blue solid), and IP's in the downstream quater of the SDTL section off (blue broken). BLM #40 corresponds to the one at the SDTL end, and BLM #44 to #65 correnspond to those in the future ACS section.

600 μSv/h after an operation with 120 kW beam power from RCS. Weaker radiation level of 100 to 300 μSv/h is widely distributed in the rest of the region. We have confirmed that the proton removal discussed above barely affects the beam loss in this region. It has also been confirmed that the loss is mostly insensitive to the beam steering and change in the quadrupole setting. Therefore, a simple transverse beam halo is not likely to explain the mechanism of the beam loss. Actually, the reduction of the transverse tail discussed in the next section barely affects the beam loss in this region.

The remarkable insensitivity of the beam loss suggests that the beam loss is caused by the H^0 component generated with the electron stripping in the residual gas scattering. This supposition is supported with the experiment where the dependence of the beam loss on the vacuum pressure is measured with turning off some of the IP's (Ion Pumps). The beam loss is clearly increased by turning off IP's in some part of the SDTL section and the future ACS section. Figure 1 shows a result in the experiment where the dependence of the BLM raw signals on the IP setting in the SDTL section is measured. Similar results are obtained for the IP setting in the future ACS section although they are not shown here. We are planning to add some vacuum pumps during the next summer shutdown to further study the cause of the beam loss.

EMITTANCE GROWTH & HALO DEVELOPMENT

With the design peak current of 30 mA, we observed a significant emittance growth in DTL. The measured emittance at the exit of DTL is 0.42 πmm·mrad in horizontal and 0.36 πmm·mrad in vertical. On the other hand, the measured emittance at the exit of RFQ is around 0.22 πmm·mrad. There is no significant emittance growth after the DTL exit. This tendency has not been seen with the lower peak current of 5 mA. The emittance values shown in this paper are all normalized rms.

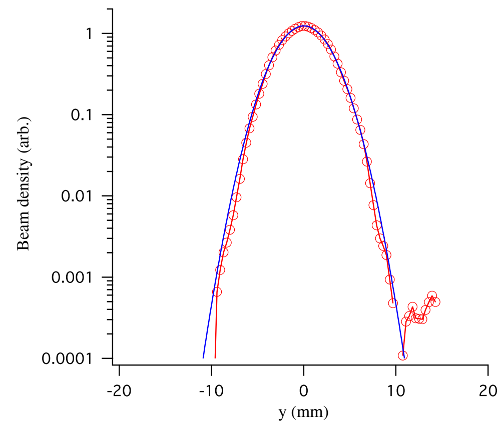

Figure 2: Typical beam profile measured at the DTL exit with 30 mA peak current. Red circle: measurement, blue line: Gaussian fit. The same notation is adopted in Figs. 3, and 4.

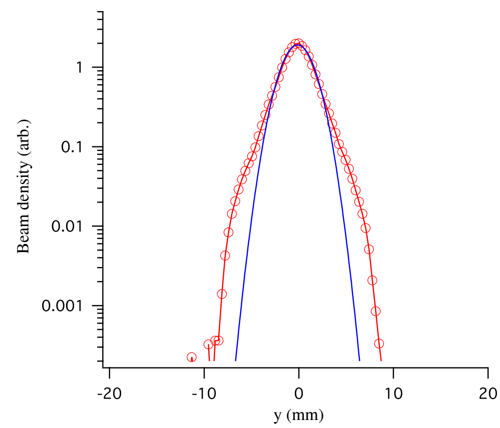

Figure 3: Typical beam profile measured at the SDTL exit with 30 mA peak current.

The measured beam profile also shows an interesting feature. Figure 2 shows a typical beam profile measured at the DTL exit. The beam profile is measured with four wire scanners in this section, and each wire scanner is 7 $\beta\lambda$ apart. As readily seen in this figure, the beam profile is virtually Gaussian in spite of the significant emittance growth in DTL. Contrary to our expectations, the measured beam profile at the DTL exit lacks obvious beam halo. As the phase advance between neighboring two wire scanners is about 60 deg in this region, the halo is supposed to be detected by some of these wire scanners if it has been generated. Meanwhile, the halo-like structure is clearly seen at the SDTL exit as shown in Fig. 3. It should be stressed here that the halo is developed in the SDTL section despite the absence of significant emittance growth in this region.

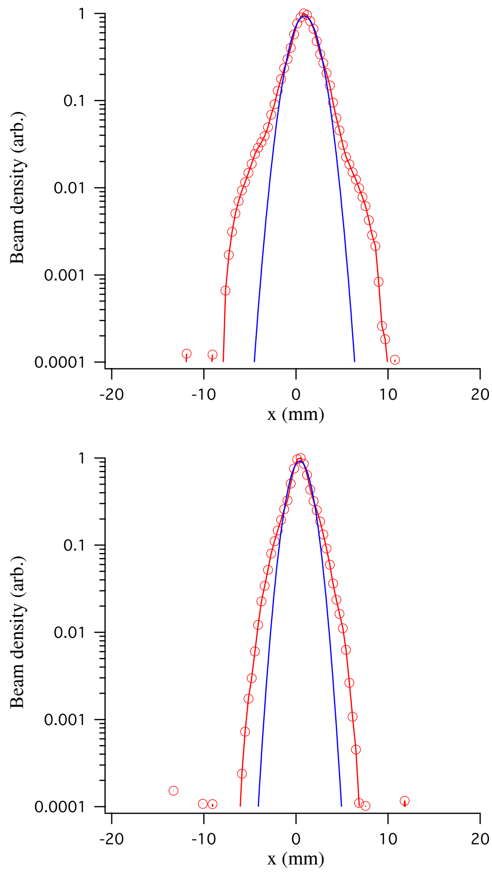

Figure 4: Typical beam profile measured at the SDTL exit with 15 mA peak current. Before (top) and after (bottom) the longitudinal matching at the DTL entrance.

As reported in a workshop [5], an extensive simulation study reveals that the onset of halo generation has a certain sensitivity to the kind of mismatch assumed in the simulation. Actually, the onset is delayed in some cases with certain types of longitudinal mismatch. Assuming a certain longitudinal mismatch at the DTL entrance, the measured behavior can be qualitatively reproduced in the simulation.

Based on this finding, we have performed a longitudinal matching at the DTL entrance varying the buncher amplitudes with a trial-and-error method. The tuning has been performed with the peak current of 15 mA, which is the present nominal peak current for the user operation. In the tuning, the amplitudes of two bunchers are changed by 10 to 20 %. After the tuning, the horizontal emittance at the DTL exit has been reduced from 0.266 πmm·mrad to 0.232 πmm·mrad. The vertical emittance has also been reduced from 0.231 πmm·mrad to 0.207 πmm·mrad. At the same time, the halo development in the SDTL section has been mitigated as shown in Fig. 4.

SUMMARY & DISCUSSIONS

At the commencement of high-duty-factor operation for users in December 2008, we recognized the following three issues for the J-PARC linac beam commissioning, namely, considerable residual radiation localized at the first bending magnet after the linac, weaker but more widely distributed residual radiation in the future ACS section, and the significant emittance growth in DTL followed by the halo development in the SDTL section.

The cause of the beam loss at the first bending magnet has been identified to be protons captured at RFQ, and the beam loss has been successfully mitigated by introducing a chicane orbit at the beam transport line between RFQ and DTL.

As for the beam loss at the future ACS section, experiments indicate that the beam loss is caused by H^0 component generated with the electron stripping of negative hydrogen ions due to residual gas scattering. We are planning to increase vacuum pumps in the SDTL section and the future ACS section in the next summer shutdown to further study the cause of the beam loss. It is important to fully understand the mechanism for this beam loss in order to seek higher beam power.

The cause of the emittance growth in DTL and the following halo development has been identified to be longitudinal mismatch at the DTL entrance with an extensive particle simulations. Then, both the emittance growth and the halo development has been successfully mitigated with a trial-and-error tuning of the buncher amplitudes. This indicates that the particle simulations are capable of helping to indenify the cause for the experimental results and serving as a practical tool to find the direction of the beam tuning for a high-intensity hadron linac. This measurement also indicates that there existed a significant error in the initial longitudinal matching at the DTL entrance. The initial matching was performed with a phase and amplitude scan method with time-of-flight measurement with two phase monitors. In the measurement, the amplitudes of two bunchers are determined assuming a simulated longitudinal emittace with PARMTEQM. It is important to pursue the reason why we had the significant tuning error for the future improvement of the tuning procedure.

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