PROGRESS IN THE BEAM COMMISSIONING OF J-PARC LINAC AND ITS UPGRADE PATH

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Abstract

The beam commissioning of J-PARC linac was started in November 2006, and its initial stage was completed in October 2007. Since then, we start to provide the linac beam for the beam commissioning of downstream facilities. During this period, we have performed occasional high-power demonstrations, where we have recently achieved the linac beam power of 12.7 kW (210 kW from RCS) for a limited period of time. We have also confirmed that the short-term beam stability and beam availability of the linac have already reached a sufficient level. The final goal of 1 MW from RCS is to be pursued though a staged upgrades.

INTRODUCTION

J-PARC (Japan Proton Accelerator Research Complex) is a multi-purpose high-intensity proton accelerator facility jointly constructed by KEK (High Energy Accelerator Research Organization) and JAEA (Japan Atomic Energy Agency). J-PARC accelerator consists of a 400-MeV linac, 3-GeV RCS (Rapid Cycling Synchrotron), and 50-GeV MR (Main Ring). Figure 1 shows the schematic layout of J-PARC facilities.

J-PARC linac serves as an injector for the entire J-PARC facility. The output beam from linac is injected into RCS, and that from RCS is delivered to both MR and a neutron production target. We also have a muon production target through which a proton beam penetrates before reaching the neutron target. Meanwhile, MR is accommodated with two beam extraction systems. One is a slow extraction system, and the other is a fast extraction system. The beam extracted with the slow extraction system is utilized for studies on hadron physics, and the fast-extracted beam is delivered to a neutrino production target for a long-baseline neutrino oscillation experiment. The final goal of the project is to deliver a 1-MW beam from RCS and 0.75-MW beam from MR.

To achieve the final goal, a phased approach is taken in the J-PARC project as discussed in a later section. We are currently in the first phase of the project, where the output energy from linac and MR are 181 MeV and 30 GeV, respectively. In this phase, the linac consists of a 50-keV negative hydrogen ion source, 3-MeV RFQ (Radio Frequency Quadrupole linac), 50-MeV DTL (Drift Tube Linac), and 181-MeV SDTL (Separate-type DTL). The schematic layout of the linac is shown in Fig. 2. The operation frequency of these accelerating cavities is 324 MHz, and the RF power is fed by 3-MW klystrons. Aside from these accelerating cavities, we also have two buncher cavities and two chopper cavities in MEBT (Medium Energy Beam Transport) between RFQ and DTL. In addition, two debuncher cavities are installed in the beam transport line between the SDTL exit to RCS, to which we refer as L3BT (Linac-to-3-GeV RCS Beam Transport). In 181-MeV operation, two SDTL tanks are temporarily utilized as debunchers.

At this point, the initial commissioning of RCS is approaching its completion [2]. The first neutron and muon beams were respectively produced in May and September 2008. Then, neutron production runs are to be started in December 2008. The initial commissioning of MR has recently been started with a beam storage mode, and the acceleration up to 30 GeV will be tried in December 2008 [3]. We plan to deliver the beam to the hadron experimental facility by February 2009, and to the neutrino production target by June 2009.

In this paper, we summarize the achieved performance in J-PARC linac after briefly reviewing its commissioning history. We also show the recent situations with emphasis on the stability of the beam operation and the machine activation experienced to date. Finally, we will present an upgrade path planned for J-PARC linac.

COMMISSIONING HISTORY AND PRESENT SITUATION

The beam commissioning of J-PARC linac was started in November 2006, and its initial stage was completed in October 2007 [4, 5, 6]. During the beam commissioning, the design beam energy of 181 MeV was achieved in January 2007. Then, the output beam power of 1.2 kW (3.3 % of the design value) was demonstrated in June 2007. From February to May 2007, fundamental tunings have been conducted including the phase scan tuning for the RF set-points [7, 8, 9], orbit correction, and transverse match-

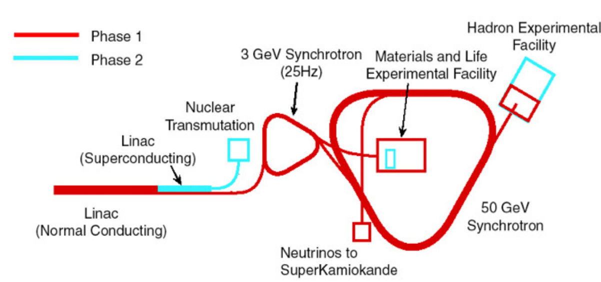

Figure 1: Schematic layout of J-PARC facility.

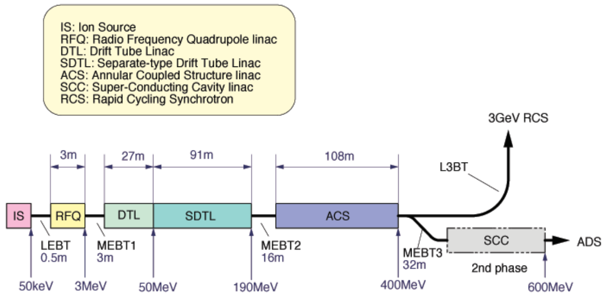

Figure 2: Schematic layout of J-PARC linac.

ing [10]. Subsequently, the output beam from the linac was delivered to RCS in October 2007.

The beam power of 1.2 kW (which corresponds to 20 kW from RCS) is the commissioning goal set for the year 2008, and it is assumed for the initial neutron production run planned in December 2008. Then, we marked the completion of the initial beam commissioning for the linac with achieving 1.2 kW beam power and the beam delivery to RCS without notable beam losses. After completing the initial commissioning for the linac, the beam commissioning of RCS and then MR has been started subsequently [2, 3]. Consequently, the emphasis has been put on the stable beam supply in the linac operation with the minimum beam study for the linac tuning.

As we have focused on the operational stability in this period, some emphasis will be put on this topic in the next section. Needless to say, good stability of the linac is a key to the success in the beam commissioning of the downstream facilities.

ACHIEVED BEAM PARAMETERS AND THEIR STABILITIES

Currently, the beam power is kept very low for most commissioning runs to avoid excess machine activation at downstream facilities. Then, the high-power operation is performed as a demonstration for limited period of time. The main beam parameters achieved to date are summarized in Table 1. The chopping ratio in this table is defined to be the chopper beam-on ratio during a macro-pulse. Then, parameters with an asterisk is those obtained in a high-power demonstration sustained for only 70 seconds due to a limitation from the beam dump capacity.

The design peak current of 30 mA has already been achieved at the exit of RFQ with the pulse width of 0.25 ms. However, the peak current delivered to RCS is currently limited to around 27 mA. The transmission efficiency is mostly determined by the small aperture of the chopper system in MEBT. Besides, the transmission efficiency of RFQ in this operation was 90 %.

We have performed a high-power demonstration with the reduced peak current of 15 mA. In the demonstration, the macro-pulse width is widened to the design value of 0.5 ms. The repetition rate is also increased to the design value of 25 Hz. Accordingly, the duty factor is the design value of 1.25 %. This operation is sustained for only 70 seconds due to dump capacity limit. The highest beam power from the linac has also been marked in this operation, where the beam power of 12.7 kW is delivered to RCS and 210 kW from RCS with tolerable beam loss rate. The beam intensity of 2.93×10^{13} protons per pulse (corresponding to 352 kW with 25 Hz repetition) has also been achieved in a single-shot operation. The stable operation for the neutron target is currently performed with a few kW beam power. The RF source has been operated with the design duty factor since a very early stage of the beam commissioning.

Table 1: Beam parameters achieved to date

Parameter	Design	Achieved	Remark
Beam energy [MeV]	181	181	
Peak current [mA]	30	30	at RFQ ext.
		27	at RCS inj.
Beam power [kW]	36	3.1	27 mA
		3.4	15 mA
		12.7*	15 mA
Pulse len. / repetition / chop. ratio [ms/Hz/%]	0.5/25/53	0.1/2.5/100	27 mA
		0.5/2.5/100	15 mA
		0.5/25/40*	15 mA
RF width/ repetition [ms/Hz]	≥0.5/25	≥0.5/25	

The normalized rms emittance at the SDTL exit is around 0.4 πmm·mrad with the peak current of 27 mA. The observed emittance is larger than the design value of 0.3 πmm·mrad due to emittance growth in DTL [11].

As for the stability of beam parameters, we have measured the jitter of the beam centroid energy and the beam centroid position. Figure 3 shows a typical histogram of the measured beam centroid energy, where the energy jitter is monitored for nine hours with TOF (Time Of Flight) measurement utilizing FCT's (Fast Current Transformers). The rms jitters are respectively 39 keV, 15 keV, and 16 keV at the exit of SDTL, the first debuncher, and the second debuncher. The 100 % jitter is sufficiently smaller than the design goal of 333 keV or 0.1 % in momentum.

A typical histogram of the measured beam position is also shown in Fig. 4, where the position jitter is monitored for 30 minutes with two BPM's (Beam Position Monitors). These two BPM's are located at the end of L3BT. The two BPM's are 4.1 m apart with one quadrupole magnet in-between. The rms jitter is found to be around 60 μm for both BPM's, which is sufficiently small.

It is also noteworthy that the beam availability of J-PARC linac has already exceeds 90 % in recent beam commissioning runs [6, 12].

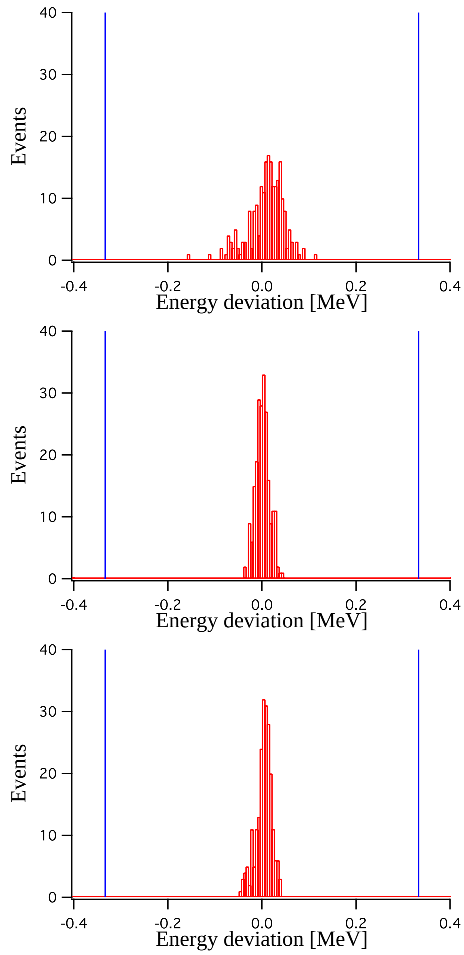

Figure 3: Energy jitter at the SDTL exit (top), the fist debuncher exit (middle), and the second debuncher exit (bottom). The blue vertical lines show the specification of ± 0.1 % in momentum.

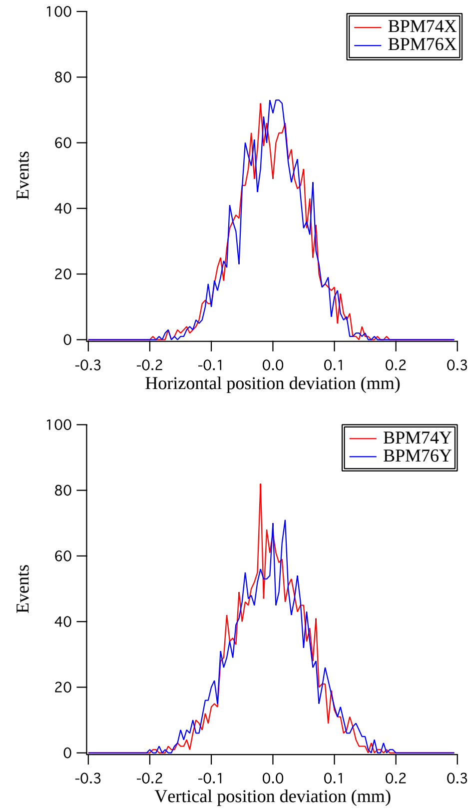

Figure 4: Beam position jitter for the last two BPM's in L3BT. Top: horizontal, bottom: vertical.

MACHINE ACTIVATION

The machine activation is often the limiting factor for the achievable beam power for a high-intensity accelerator. In spite that the average beam power is mostly kept very low at present, we have already experienced some machine activation due to uncontrolled beam losses.

We have narrow sections at two debunchers installed in L3BT, because the last two SDTL tanks are temporarily utilized for debunchers in 181-MeV operation. Machine activation is mostly localized in the vicinity of the debunchers. We experienced the highest activation when we performed the fine phase-scan tuning for SDTL cavities for the first time with the beam power of 0.12 kW. In that run, the residual radiation level reached 250 μSv/h at the second debuncher with contact to the vacuum chamber 6-hour after beam shutdown. Conducting precise tuning of machine parameters, the radiation level was gradually reduced. Then, the typical radiation level at the debunchers became 10 to 40 μSv/h at the end of the initial commissioning in spite of the increased beam power to around 0.6 kW. We also see slight activation in the beam transport line between two debunchers and the arc section after the second debuncher, but it was typically kept below 10 μSv/h.

After the commencement of the RCS commissioning, the radiation level has been reduced with the factor of several to ten. However, most of the reduction in the machine activation might be attributable to the single-shot or low-duty factor operations totally employed in the recent runs. As we are entering the stage where we seek beam power ramp-up, we plan to carefully monitor the trend of machine activation in the forthcoming stable beam operations. It is expected to provide valuable information to predict the activation level with the nominal operation with higher beam power.

BEAM-POWER RAMP-UP

We are now entering the stage where we seek higher beam power in tandem with the further RCS tune-up. The neutron production run will be started in December 2008 with a 20-kW beam delivered from RCS. In the present plan for the beam power ramp-up, the immediate goal is to deliver a 100-kW beam from RCS until February 2009. Then, the next goal is 250 kW until June 2009. The corresponding linac beam power is 6 kW for February 2009 and 15 kW for June 2009. In the present planning, 20 %

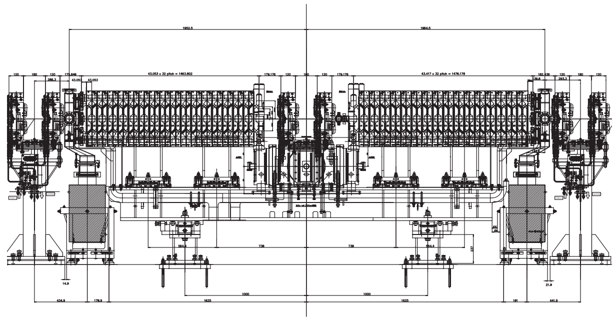

Figure 5: The layout of an ACS module. Two ACS tanks are connected with a bridge coupler. Quadrupole doublets are placed between ACS tanks to provide the transverse focusing.

of the goal beam power is considered to be the minimum requirement for each stage.

The limiting factor for the available beam power is currently the authorized beam dump capacity, and it is to be increased to accommodate the above beam power goals. The machine activation levels and its build-up should also be carefully monitored with a long-term operation.

UPGRADE PATH

To achieve the final beam power of 1 MW from RCS, we plan to take a phased approach. In the first phase, we start the beam operation of the linac with the lower energy of 181 MeV and the lower peak current of 30 mA. In this phase, the design output beam power from linac is 36 kW and that from RCS is 0.6 kW. We are currently in the beam commissioning stage of this phase.

In the second phase, the linac beam power is increased to 133 kW to achieve the beam power of 1 MW from RCS. The linac output energy is increased to 400 MeV in this phase, and the linac peak current to 50 mA. Instead of moving up to the second phase at a stretch, we plan to take intermediate steps toward the second phase to smoothly ramp-up the output beam power as discussed below.

Energy Upgrade

In 181-MeV operation, we are aiming at the output beam power of 0.6 MW from RCS. However, this goal is challenging because the space-charge effect is significant in the injection period in RCS. Actually, the space-charge effects in this case is more profound than that in the final stage, where the beam power of 1 MW is aimed with the injection energy of 400 MeV. A simple energy scaling of the space-charge effect results in the beam power of 0.33 MW with 181-MeV injection. Then, we anticipate to face with significant beam losses in achieving 0.6 MW with the injection energy of 181 MeV.

To avoid the potential beam loss problems, we plan to upgrade the linac energy as an intermediate step before proceeding to the second phase. In the energy upgrade, the linac output energy is increased to 400 MeV to ease the space-charge effects in the injection period. Then, the linac output power is increased to 80 kW to achieve the beam power of 0.6 MW from RCS.

The energy upgrade is to be realized by adding an ACS (Annular Coupled Structure linac) section after the existing SDTL section [13]. The ACS is a variation of CCL (Coupled-Cavity Linac), where the emphasis is put on the axial symmetry of its geometry. The J-PARC ACS has been developed based on the former JHF-ACS [14] after an extensive optimization studies with regard to the frequency change [15].

The operation frequency of 972 MHz is adopted for ACS. Then, a 16-m long beam matching section with two buncher modules is to be provided between SDTL and ACS. The primary objective of this matching section is to smoothly absorb the transitional effects due to the three-fold frequency jump [13].

The ACS section consists of 21 ACS modules, and each ACS module is comprised of two ACS tanks. Each ACS module is to be driven by a 3-MW klystron. Figure 5 shows the layout of an ACS module. Three prototype ACS modules have been fabricated and high-power-tested to date [16]. The remaining one and half prototype modules are currently in the final stage of their fabrication. In parallel with the trial manufacturing, the design polishing for the mass production is now under way [17]. Three prototype 972-MHz klystrons have also been fabricated and high-power-tested successfully [18].

We have a four-year plan to fabricate and install ACS modules in the energy upgrade. In the current upgrade plan, it is supposed to take three years to mass-produce the ACS modules. The 972-MHz RF systems, utilities, and cables can be installed during nominal shutdown periods with little interruption of the 181-MeV operation. The ACS modules will be installed in the tunnel during an extended shutdown period. The assumed duration of the extended shutdown period is eight months including that for the following cavity aging and the beam commissioning.

A fraction of the construction budget for ACS has been approved this fiscal year, and we are seeking a government approval of the full construction budget.

Intensity Upgrade

After the energy upgrade, we plan to increase the peak current from 30 mA to 50 mA. Accordingly, the linac output beam power is increased to 133 kW to deliver a 1-MW beam from RCS. The intensity upgrade involves a replacement of the ion source and RFQ. It is also likely to be accompanied with a significant modification of MEBT to accommodate chopper improvement. With increased peak current, the heat load for the chopper system is supposed to be a crucial issue.

As for the 50-mA RFQ, a prototype has been fabricated and low-power-tested successfully [19]. In the trial manufacturing, the upstream one third of the RFQ module has been fabricated.

The 50-mA ion source is naturally the most essential component for the intensity upgrade, for which an extensive R & D has been continued. The peak current of 70 mA has been achieved with a cesium-seeded ion source [20]. However, the available peak current is currently limited to 38 mA without cesium seed [21]. We are continuing the effort to increase the peak current with a cesium-free ion source to avoid potential undesirable effects to the following RFQ.

Further Energy Upgrade

In the second phase of the project, it is also foreseen to add an SCL (Super-Conducting Linac) section after ACS to increase the linac output energy to 600 MeV. The 600-MeV beam is not assumed to be injected into RCS, but it will be dedicated to the fundamental studies for ADS (Accelerator-Driven nuclear-waste transmutation System). The 400-MeV beam from ACS will be shared between RCS and SCL. We are planning to increase the linac repetition to 50 Hz, and to utilize 25 Hz of them for ADS studies without reducing the RCS beam power. A prototype cryomodule for SCL has been fabricated and high-power-tested successfully [22].

SUMMARY

The beam commissioning of J-PARC linac has been started since November 2006, and its initial phase has been completed in October 2007. In October 2007, we started to provide a beam to downstream facilities for their beam commissioning. Since then, the emphasis of the linac operation has been put on providing stable beams to downstream facilities.

In a high-power demonstration for a limited period of time, the beam power of 12.7 kW has been achieved in the linac, which corresponds to 210 kW from RCS. The beam stability and availability of the linac have already reached the sufficient level, and we are entering the stage where we seek beam power ramp-up in tandem with further RCS tuning. We have already experienced a certain machine activation due to uncontrolled beam losses. However, its level is kept sufficiently lower than the tolerable limit.

In J-PARC project, a phased approach is taken to achieve the final goal of 1-MW beam power from RCS and 0.75 MW from MR. In the upgrade path toward the final phase, we plan to take a few intermediate steps for the linac upgrade to smoothly ramp-up the beam power on target. The upgrade is to be started with an energy upgrade by adding ACS section after SDTL. Then, it is followed by an intensity upgrade and another energy upgrade with SCL cavities. Extensive R & D studies are now underway for every front of the staged upgrades. A fraction of the ACS construction budget has been approved this fiscal year, and we are seeking an approval of its full construction.

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