# RECENT PROGRESS OF BEAM COMMISSIONING AT J-PARC LINAC

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*Abstract*

To recover the beam energy to the original design of 400 MeV, the J-PARC linac was conducted large upgrade in year 2013. The main upgrade is the installation of annular-ring coupled structure (ACS) cavities at SDTL downstream. The first beam commissioning after the upgrade was started at December 16, 2013. And then we successfully realized 400 MeV acceleration at January 17, 2014. The user operation had been stably operated from February 16 to the end of June with the peak current of 15, which is equivalent to the beam power of 300 kW at the extraction of 3 GeV Rapid Cycling Synchrotron (RCS). In this paper, we discuss the progress of beam commissioning.

## INTRODUCTION

The J-PARC linac is comprised from a 50 keV negative hydrogen ($H^-$) ion source (IS), a 3 MeV Radio Frequency Quadrupole (RFQ), a 50 MeV Drift Tube Linac (DTL) and an 191 MeV Separate-type DTL (SDTL) and a 400 MeV Annular-ring coupled structure (ACS) as shown in Fig.1 [1]. The beam transport sections are placed from RFQ to DTL (MEBT1), from SDTL to ACS (MEBT2) and ACS to 3 GeV RCS (L3BT), respectively. The RF frequency is 324 MHz for RFQ to SDTL and threefold higher frequency of 972 MHz for ACS. In the beam commissioning of linac alone, three beam dumps are available. The 0 degree dump (0BD) is on the extended line of straight section, the 30 degree dump (30BD) line is branched in the middle of the 1st arc section and the 100 degree dump (100BD) locates in the middle of the 2nd arc section.

The construction of the J-PARC linac is separated to two stages. In the first stage, beam energy is 181 MeV by installing IS to SDTL in the beam line. SDTL is designed for the acceleration to 191 MeV. The last two cavities, however, are placed in L3BT to divert them into debuncher cavities. The operation of the J-PARC linac was started in 2008 at beam current of 5 mA. Since then, we continuously conducted the beam commissioning to improve the beam quality and to increase the beam power. The peak current of the user operation was finally achieve to 15 mA, which is equivalent to 300 kW at the extraction of 3 GeV RCS [2]. For the construction of the second stage, ACS had been developed in parallel with user operation. With a significant effort of the R&D and fabrication, ACS is successfully installed on the beam line in year 2013.

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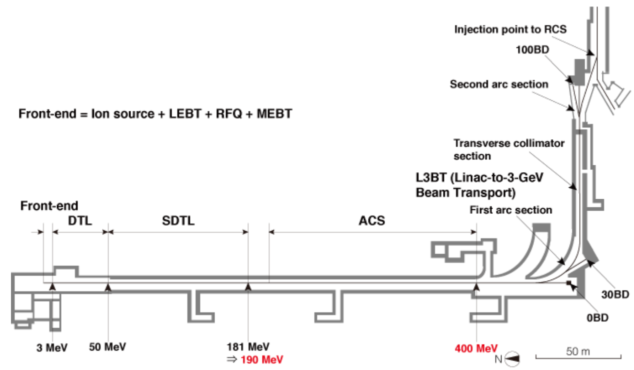


Figure 1: Outline of the J-PARC linac. In the initial stage, the linac had been operated at 181 MeV by the installation of IS to SDTL on the beam line as shown in black character. The ACS accelerator was installed at second stage to extend the beam energy to 400 MeV (red).

## BEAM COMMISSIONING AFTER THE ACS INSTALLATION

The linac beam commissioning was started on December 16, 2013, and it continues till January 30, 2014. The main purpose of the beam commissioning is the establishment of 400 MeV acceleration, tuning of 15 mA beam for user operation and tuning of 25 mA beam for high power test.

### *Achievement of 400 MeV Acceleration*

After the front-end (from the IS to MEBT1) tuning, we started the tuning of RF cavities. RF amplitude and driving phase for each cavity is determined by a phase scan method [3] one by one from upstream. The output beam energy from a cavity is calculated by time-of-flight method. We place phase detectors (FCTs) to measure the flight time. When a beam bunch passes thought the upstream (downstream) FCT at the phase of $\phi_1$ ($\phi_s$), the flight time in the phase coordinate system is calculated as

$$\Delta\phi = \phi_2 - \phi_1 + 360 \times n, \quad (1)$$

where $n$ is number of turns and it is estimated from the distance of two FCTs. It is around 21 for the FCT pairs in SDTL, and around 17 for the paris in ACS. The phase scan is conducted with peak current of 5 mA. Because the output beam energy varies during a phase scan, the beam could be lost on the way to a beam dump due to the mismatch of transverse focusing power. In addition, an unexpected beam loss may occur in the upgraded ACS section. We choose 5 mA beam to minimize the beam loss even when such situation happens. It is the lowest peak current for the J-PARC linac to operate stably. The phase scan of DTL and

SDTL section smoothly proceeded. We achieved 181 MeV acceleration on December 20.

Before start the phase scan for newly installed RF cavities, we checked specification of monitors, FCT and beam position monitors (BPMs). One monitor is FCTs. We adopt same phase scan scheme of DTL and SDTL to ACS [4]. FCTs were installed in MEBT2 to ACS section in accordance with the installation of the ACS linac. Since it is first time to calculate beam energy with their detectors, we have to confirm whether the measurement accuracy satisfies our requirement. We calculate beam energy for all FCT pairs by passing 181 MeV beam to ACS downstream in order to estimate the accuracy for each FCT pair. Therefore, we estimate the accuracy by checking the difference the energy from 181 MeV. The accuracy of FCT itself is about 60 ps, which is equivalent to 0.05 % in momentum and 0.1 % in kinetic energy. In the measurement of 181 MeV beam, we found that beam energy of some pairs were more than 5 % far from 181 MeV. Such large difference occurs only when there are radical mistakes. Therefore, we suspended the beam commissioning and investigated the reason of this large difference, and it is found that their conversion factors from a detector signal (voltage) to a phase (degree) were wrong. After the re-calibration of the factors, we again calculate beam energy for all FCT pairs with 181 MeV bean. The root-mean-square (RMS) of energy distribution of all FCT pairs become about 0.2 % which is comparable with the pairs in the SDTL section.

We resume the phase scan for SDTL downstream cavities after finishing these monitor check, and we continue it until the morning of December 30. The phase scan of the 14th ACS cavity and its output beam energy is 325 MeV.

The beam commissioning of January started on the morning of the 7 but we suspended the phase scan from 7 to 15. Since some 972 MHz circulators in the ACS section often discharged electricity [5], they were under repairment in a factory. We did a tuning of the front-end to the SDTL section for 15 mA operation from 7 to 9, and then we spent time in conditioning of ACS cavities. The phase scan was resumed at 16 and we successfully achieved 400 MeV acceleration on the evening of the 17th. We confirm the 400 MeV acceleration by two methods. The first method is Time-of-Flight which is used for the energy calculation of the phase scan. The phase scan result of the last ACS cavity is shown in Fig. 2 and it shows an achievement of 400 MeV. As already described, the accuracy of calculated beam energy is about 0.1 %. However, this method has an ambiguity of number of phase rotation, i.e. ambiguity of the $n$ in Eq. 1. One difference of the $n$ is equivalent to momentum difference of about 5 % and kinetic energy of about 10 %. To compensate this ambiguity, we employed the second method: the measurement of beam transmission and orbit to 30BD. The 30BD is located in the middle of the first arc section as shown in Fig. 1. There are two bending magnets in the upstream of 30BD and their magnetic field are set to bend 400 MeV beam. Therefore, if the beam energy is substantially lower than 400 MeV, the beam transmission may be low or zero. The beam transmission to 30BD is 100 % as shown in Fig. 3 and no significant beam loss is observed on the way to the 30BD. Moreover, the beam orbit also measured in the arc section to measure the beam energy more accurately. Some beam position monitors (BPMs) are placed where momentum dispersion is about 0.55 m. We can estimate the momentum difference from the displacement of the beam orbit from the beam line. The displacement of the beam orbit from the beam line, the beam energy is consistent to 400 MeV within 0.08 %.

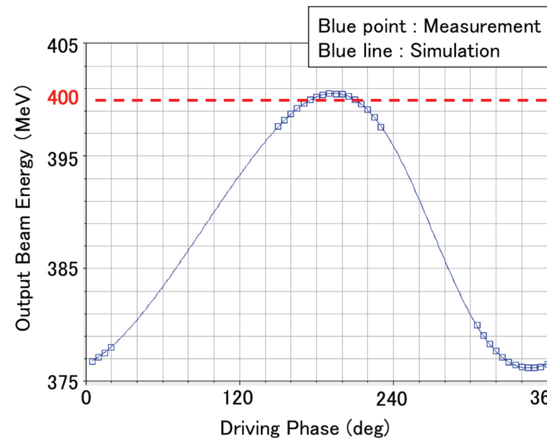


Figure 2: The phase scan curve of the last ACS cavity.

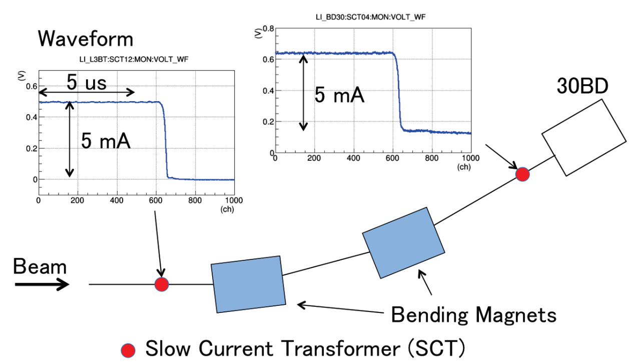


Figure 3: Beam transmission to the 30BD.

## *Transverse Beam Profile*

Since the RF frequency of the ACS cavities is three times higher than that of the SDTL cavities, longitudinal matching is important to mitigate beam loss and beam halo. For the matching, we preparel two bunched cavities and three bunch shape monitors (BSMs) [6] in the MEBT2 to ACS upstream sections. Whereas the buncher cavities were successfully installed on the beam line, we abandoned the BSMs installation. The BSMs were already installed in the year 2012, one year before the ACS installation, to check their specification [7]. The BSMs were successfully measured a beam profile in phase direction, and we confirm that the BSMs have a sufficient performance for the longitudinal matching [8].

However, we confronted a significant deterioration of pressure level while a BSM measurement due to an outgas from




ISBN 978-3-95450-142-7

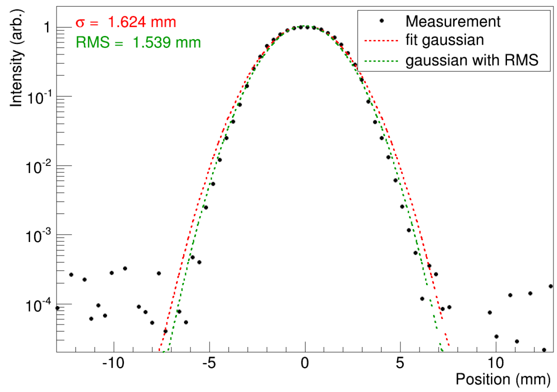


Figure 4: Transverse beam profile at the ACS entrance with peak current of 25 mA and beam energy of 191 MeV. Noise level is order of $10^{-4}$. A red dotted line shows the fitting results by Gaussian function, and a green one is a Gaussian function of which $\sigma$ is RMS of the distribution.

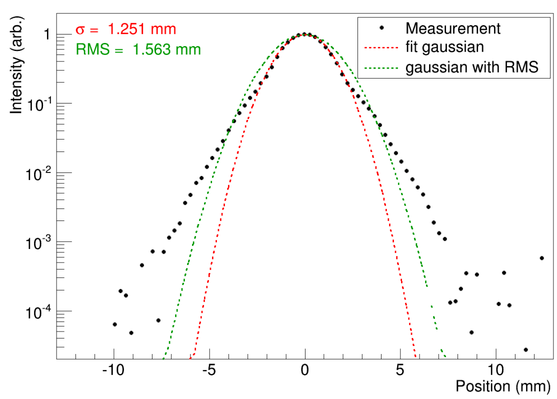


Figure 5: Transverse beam profile at the ACS exit with peak current of 25 mA and beam energy of 400 MeV. the red and green dotted lines are same as those of in Fig. 4.

the BSMs It often exceeds the threshold of a machine protection system (MPS). The ACS cavities was going to install around the BSMs. The outgas is possible to has a bad influence on the cavities. Therefore, we decide to once take the BSMs away from the beam line in order to construct a new vacuum system for BSMs. The RF amplitude of two bunchers is determined from an IMPACT simulation. After finishing the injection beam tuning to the ACS section with peak current of 25 mA, we measured transverse beam profile by wire scanner monitors (WSMs). A typical beam profile at the ACS entrance is shown in Fig. 4. A dotted red line shows a fitting result by Gaussian function, and a green one is a Gaussian function of which $\sigma$ is RMS of the profile. Whereas the $\sigma$ of Gaussian fitting mainly represents a beam core width, the RMS also takes a beam halo component into account. Since the RMS of the ACS entrance in Fig. 4 are almost consistent with the $\sigma$, the beam halo is considered to be small. On the other hand, the RMS of the ACS exit is about 20 % bigger than $\sigma$ as shown in Fig. 5. The increase of the beam energy in the ACS section makes a reduction of transverse emittance by 34 % due to the adiabatic damping. Whereas the $\sigma$ is reasonably decrease, The RMS is comparable due to the growth of the beam halo. We suppose that the beam halo growth comes from the longitudinal mismatch at the ACS entrance. The space charge coupling transfers a longitudinal mismatch to a transverse phase space. We suppose that this halo can mitigate a longitudinal matching after the BSMs installation.

## SUMMARY

On December 2013 to January 2014, the first beam commissioning after the ACS linac installation is conducted. We successfully accelerate the beam to 400 MeV at January 17. The transverse beam profile at the ACS exit shows the significant beam halo which is supposed to come from the longitudinal mismatch at the ACS entrance. We suppose that this halo can mitigate a longitudinal matching after the BSMs installation. The J-PARC linac is now on the way to upgrade the front-end to extend the peak current from 30 mA to 50 mA. It will be ready to realize a design beam power. We will continue the beam commissioning to improve the beam power and beam quality.

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ISBN 978-3-95450-142-7