PROGRESS OF BEAM INSTRUMENTATION IN J-PARC LINAC

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Abstract

J-PARC, one of the high intensity proton accelerators, achieved the output power of 300 kW at the downstream rapid cycling synchrotron with the beam energy 181 MeV and the beam current 15 mA. When an upgrade of an ion source which can provide 50 mA and the installation of the additional acceleration cavities for the energy upgrade up to 400 MeV are completed, output power reaches 1 MW. To meet with the requirements of the high intensity beam instruments, we prepare several measures against high intensity proton related issues. Following subjects have been reported among many subjects: development of strip-line type beam position monitors, beam current monitors, phase monitors and transverse profile monitors. And the subjects of the beam instruments for the energy upgraded Linac including the longitudinal beam profile monitor and the developing laser based profile monitor are mentioned. A big earthquake occurred on March 11, 2011. J-PARC had a big damage, but we successfully resumed a commercial operation. This paper also mentions the influence of the quake on the J-PARC Linac.

INTRODUCTION

J-PARC (Japan Proton Accelerator Research Complex) Linac aims to provide high intensity beams of peak current 50 mA, beam energy 181 MeV, pulse width 0.5 mA and repetition rate 25 Hz using an RFQ, three DTL cavities and 15 SDTL cavities and two beam transports which have two debuncher cavities include the matching points to inject the downstream rapid cycling synchrotron (RCS) [1]. Beam parameters of Linac are listed in table 1.

In the energy upgrade project since 2013, present two debuncher cavities are replaced to SDTL section as the 16th acceleration cavity. Twenty one ACS (Annular-Coupled Structure Linac) cavities will be installed in the present A0BT subsection. To meet with this project, the beam instruments for the future ACS and L3BT section

Table 1: Operational Beam Parameters of Present and Upgraded Linac

Particle	Negative hydrogen ion
Peak Beam Current	5 - 50 mA
Source Energy	180 - 400 MeV
Typical Bunch Length	1 - 2 deg. (rms)
Typical Transverse Side	1 - 2 mm (rms)
Pulse Width	0.5 msec
Bunch Repetition Frequency	324 MHz, 972 MHz for New ACS cavities
Operational Repetition Rate	1 - 25 Hz
Chopper beam-on ratio	56 %
Beam power	36 kW (133 kW after upgrade)

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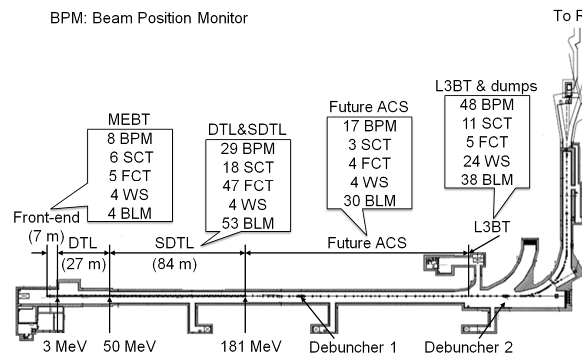

Figure 1: Delivery of beam instruments in the J-PARC Linac.

for the beam commissioning are newly designed and fabricated [2]. The goal of 133 kW beam power and hand-on maintenance will place significant demands on the performance and operational reliability of accelerator diagnostics systems.

COMMISSIONING TOOLS

Number of the Commissioning Tools in Linac

As delivery of beam instruments and parts on the beam line are not at a time, the sensors of beam instruments are installed in the following order in subsection of LINAC.

(1) MEBT1 (Medium Energy Beam Transport)
(2) DTL (Drift-Tube Linac) & SDTL (Separated DTL)
(3) A0BT (Beam Transport from ACS to Beam Dump)
(4) L3BT (Beam Transport from Linac to RCS)

After the instruments had been tested in the DTL commissioning in KEK site, installation of all instruments had conducted. Each of the instruments is handled and supervised by J-PARC staffs all through the installation. In the present beam line, 38 beam current monitors (SCT: slow current transformer), 61 phase monitors (FCT: fast current transformers), 36 beam profile monitors (WSM: wire scanner monitor), 102 beam position monitors (BPM) and 124 beam loss monitors (BLM) are employed for the beam operation [3-4] (Fig. 1). In the upgrade project, 24 SCTs, 51 FCTs, 4 WSMs, 49 BPMs and 30 BLMs are replaced from those of present beam line. And three bunch shape monitors (BSM) are newly employed.

Beam Position Monitor (BPM)

J-PARC Linac employs over a hundred of BPMs which have about 40 - 180 mm diameter and 4-stripline electrodes with one end shorted by 50 Ω terminations [5]. Electrostatic computations are used to adjust the BPM cross-section parameters to obtain 50 Ω transmission lines. BPMs are sustained by pole edge of quadrupole magnet and designed to reduce the offset between quadrupole

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magnet and BPM electrical centers of less than 0.1 mm. A procedure of beam based alignment to evaluate the displacement of Linac BPMs was examined [6]. The BPM electronics employs conventional log-ratio method [7]. Prototype of BPM system was tested in KEK test stand.

Phase detection using 4-stripline BPM was also examined with the real beam [8]. It was confirmed the signal level of converted sum signal from 4-stripline is enough high for the phase measurement.

Slow/Fast Current Transformer

Two types of current transformers have been developed to measure beam current and phase. The SCT for the current measurement has dynamic range of 0.1 - 80 mA, a droop of 3% for a pulse width of 500 μs and time response under 50 ns. The SCT has been chosen with 50 turns and additional winding to provide a calibration input capability. The FCT for the phase measurement have a good response of relative bunch phase under 1 %. To measure the beam energy at every accelerator cavity and injection point of RCS, phase differences of two FCTs are used (time-of-flight), and 10^{-4} order energy resolutions can be expected.

We compare the signal level of FCT with that of BPM at the acceleration frequency. FCT would be used for the higher frequency, because the signal level of FCT marked a good performance. And the output level is still stable until 3.0 GHz.

The signal revel of 4-stripline BPM is also acceptable to be used for the phase measurement, but FCT has superiority at the acceleration frequency [9].

In the beam commissioning, the RF set-point tuning of DTL has been performed with a phase-scan method, where the output beam energy from the DTL tank is monitored using two downstream FCT's. The phase-scan results show a reasonable agreement with the design set-point, but the tuning accuracy is required 1 deg in phase and 1 % in amplitude [10-11].

Beam Loss Monitor

To prevent from the activation and heat load by intense beam loss, fast response of loss signals is required for the beam loss detection. The beam loss monitor (BLM) system is composed of Ar+CO_2 gas filled proportional counter, which detect γ-ray, neutron and charged particles induced by lost particle and γ-ray sensitive scintillator and [12-16]. It is necessary to measure wide dynamic range of loss intensity for various beam energies.

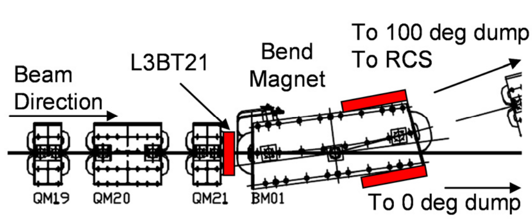

Figure 2: Gas proportional BLMs are installed to measure the beam loss caused by protons. Red bars are location of BLMs.

In the beam commissioning, we found the protons in the accelerated beam during the beam operation. We additionally installed the gas proportional BLMs at the both sides of first bend magnet (Fig. 2). When the negative hydrogen beam is bended to RCS direction, the protons are bended to the outer side of the magnet yoke, BLM set on the outer yoke can detect the beam loss from protons. Measured beam loss and residual radiation on the bend magnet explained the existence of protons in the accelerated beam [17].

Beam Profile Monitor (Wire Scanner Monitor)

Beam profile measurements are used to determine the beam emittance of a matched beam in a periodic focusing lattice. The thin sensing carbon wire with 7 μm for low energy part and tungsten wire with 100 μm for higher energy part are scanned to obtain a beam profile. Dynamic range of the wire scanner monitors (WSMs) employed in J-PARC Linac reaches over 10^4 order magnitudes (Fig. 3) [18-19].

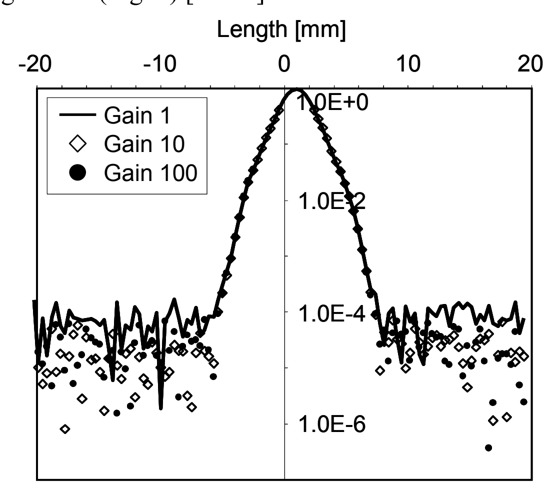

Figure 3: Vertical beam profile at ACS03. RMS spot size is almost 1.0 - 2.0 mm and dynamic range reaches 10^4.

UNIQUE APPLICATION OF COMMISSIONING TOOLS

SDTL Longitudinal Acceptance Using SCT and BLM

There has been an argument that the longitudinal loss could be a cause of the beam loss at the downstream beam transport, which motivated us to conduct an experimental investigation on the margin between the longitudinal acceptance of the Linac and the actual beam distribution. In the experiment, we scanned the tank level to measure the margin of beam acceptance of first SDTL cavity in the energy direction using SCT and BLMs. Combining the tank level scan with the conventional phase scan method, the longitudinal acceptance of SDTL has been studied. The measurement has confirmed that we have sufficient margin both in the phase and energy directions with the nominal tank parameters. The measurement can provide us with valuable information on the width of longitudinal halo [20].

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H0 Particle Measurement Using Wire Scanner

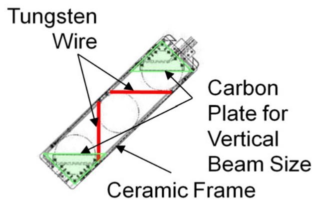

Figure 4: Head of Wire Scanner. Beam size can be measure by the wide carbon plate.

Wire scanner monitor has the wide carbon plate to measure the beam size (beam size monitor). Because the plate is more sensitive to detect the small amount of beam particles, it is employed for the H^0 particle detection (Fig. 4).

When the accelerated beam is bended to RCS, main beam is transported to RCS but H^0 particles travel to straight beam dump (Fig. 5).

Because the beam-on-duty of chopped beam is almost half of that of no-chopped beam, integrated signals are almost corresponded to the beam-on-duty. Figure 6 shows the top half of the H^0 beam, because the beam size monitor can be inserted until the beam centre. Obtained data have a reasonable agreement with the operational situation [19].

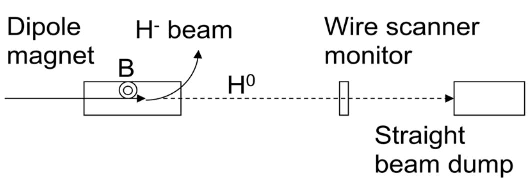

Figure 5: Method of H^0 particle measurement. H0 was observed with carbon plate in wire scanner at the straight beam dump with a bending magnet on.

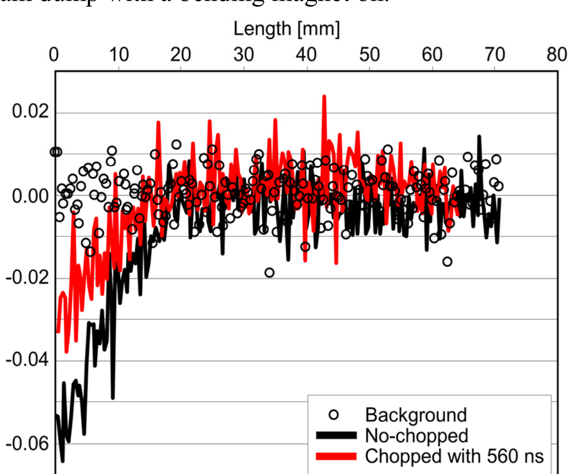

Figure 6: Signal from H^0 taken by carbon plate in wire scanner.

Chopper Tuning using Wire Scanner

In the J-PARC commercial operation, a macro pulse with several hundred micro seconds is shaped into a pulse with medium bunch structure of about one MHz by an RF chopper. When the chopper is detuned, a small fraction of the beam pulse is remained and accelerated. Then, we measured the remaining fraction of the beam pulse using a wire scanner with scanning of the chopper phase. Measured values are taken into hyperbolic approximation to obtain the optimal phase. An RF chopper is tuned by this method and remaining fraction of the beam pulse is less than 0.1 % of the operating beam pulse [21].

BEAM INSTRUMENTS FOR ENERGY UPGRADED

Scintillation Beam Loss Monitor

Because the $Ar+CO_2$ gas proportional counter is sensitive to background X-ray emitted from RF cavities, the plastic scintillator with less X-ray sensitivity is tested to measure the beam loss with suppression of the background. We used photo-multiplier and the plastic scintillator.

We successfully measured clear beam loss signals with low noise and confirmed the high time resolution by scintillator (Fig. 7) [15].

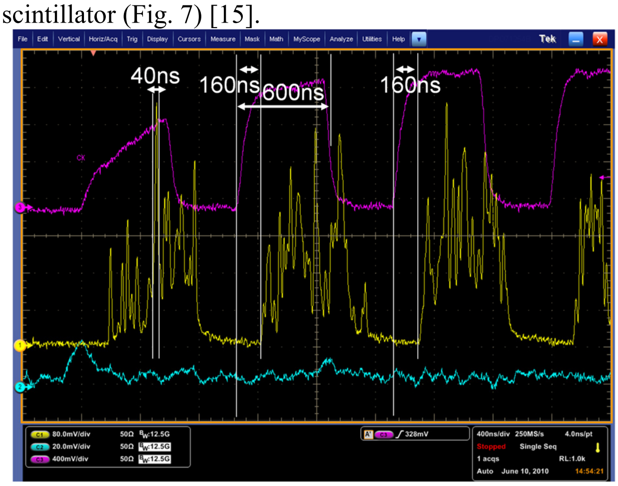

Figure 7: Signals from a gas proportional monitor (blue) and plastic scintillation monitor (yellow) at SDTL13 section, during beam operation with chopped beam. Time scale is zoomed up to 400nsec/div. The beam current signal with a current transformer is also shown (magenta).

Beam Loss Measurement at DTL Section

After resuming the operation by big earthquake, higher residual radiation was marked at the surface of drift tube Linac (DTL) cavity by radiation survey, we installed scintillation beam loss monitors (BLMs) at some points with particularly high radiation to investigate the cause of the radiation. Although the DTL section is low energy part of the Linac, fine structure of the beam loss was observed by the scintillation BLM. We also measured the beam loss occurred at the DTL varying the beam orbit.

As the results of the beam loss measurement using scintillator, beam loss occurs at DTL depends on the beam orbit which pass through the cavity inside. Because the serious beam loss had not been seen in this section, but the residual radiation and beam orbit dependence of beam loss show the important lessons for beam commissioning. Also, the scintillation BLM would become an essential beam commissioning tool, based on the development of electrical circuits which has the functions of high speed beam loss detection system, qualification of the beam loss events and high accuracy. The beam loss measurement system using scintillator with the optimal integrated

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circuit to evaluate the amount of beam loss quantity to the future beam line, the system will be developed [16].

Bunch Shape Measurement

Bunch shape monitors (BSM) have been developed under collaboration with INR (Institute for Nuclear Research: Russia) for the measurement of the longitudinal distribution [22]. Three BSMs were installed in the summer of 2012 in the beginning of ACS section in order to tune the longitudinal matching, because the acceleration frequency of 324 MHz until the end of SDTL is jumped to 972 MHz of ACS cavities.

The design of BSMs was started since 2009 and the fabrication of three BSMs was started since 2010 (Fig. 8). The BSM beam commissioning had started since Oct. of 2012. Preliminary data have been accumulated through the commissioning (Fig. 9).

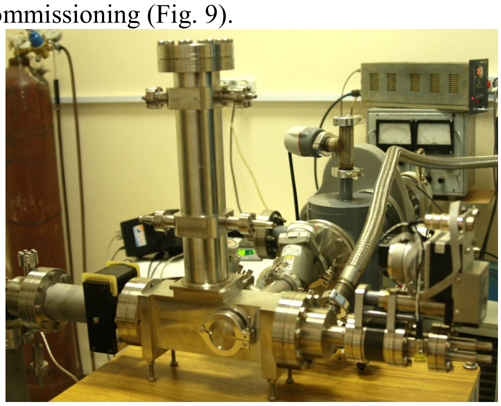

Figure 8: Bunch shape monitor for J-PARC Linac. The monitor was tested in INR test stand.

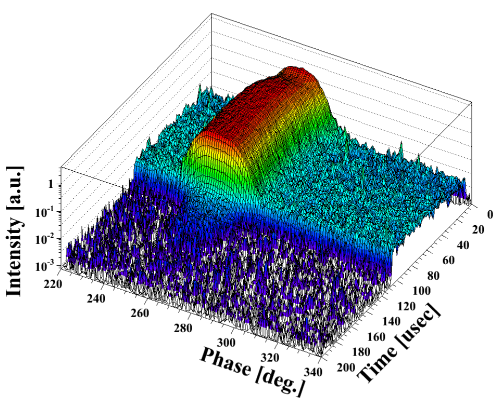

Figure 9: First beam data of J-PARC 181 MeV longitudinal distribution taken at the beam commissioning in Oct. 2012.

Non-Destructive Profile Monitor (Laser-based)

The laser wire scanner using a pulse width of 20 nsec, beam energy of 500 mJ (repetition rate of 25 Hz) Nd: YAG laser have been installed in MEBT1 test stand to measure current profile of high intensity negative hydrogen beam. It was confirmed that the photo detached electron signal corresponds to the reduction of FCT current signal at downstream. The results of transverse profile measurements are also consistent of wire scanner signals of upper and downstream. The negative hydrogen beam components intercepted by 0.8 mm height laser beam have been estimated by transverse profile measurement, and agree with photo detached fraction (Faraday cup and FCT reduction signal). The calculation results also show the complete neutralization ratio with 130 mJ Nd: YAG laser for 3 MeV negative hydrogen beam. Thus the almost complete photo neutralization fraction for a 130 mJ (repetition frequency of 5 Hz) 1064 nm Nd: YAG laser pulse on a 15 mA, 3 MeV negative hydrogen beam could be confirmed practically. The difficulty of practical construction of laser system, for example the stability of optical transport line and/or laser oscillator, should be investigated in future [24-25].

DIAGNOSTIC DEVICES FOR BEAM PHYSICS

For the continual beam operation, a major operation goal is to decrease the beam loss. It has been recently suggested that intra-beam-stripping contributes significantly to beam losses in an H^- Linac. Contribution of intra-beam-stripping was tested experimentally at SNS by accelerating a proton beam with an inverse optics. SNS presented that this experimental results are in good agreement with the theoretical estimates with emphasis on understanding beam loss in terms of intra-beam-stripping.

At J-PARC Linac, highest beam loss has been observed at the ACS section. The primary source of beam loss is considered to be H^0 produced by an interaction of H^- beams with remnant gas. The H^0 hits the beam duct, converted to H^+, and escapes from the beam duct. To detect the proton's and evaluate the absolute magnitude of the beam loss, we developed a detector system, which consists of 6 planes of hodoscopes made of 16 scintillation fibers with 64 x 64 mm^2 area. In the ACS section, two planes to measure horizontal positions are installed, and at about 1.1 m downstream positions, two planes for horizontal and two for vertical measurements are placed (Fig. 10). We reconstruct charged particles passing through all the 6 planes, and measure the velocity by time-of-flight and energy loss to identify particle species.

We measured charged particle tracks using scintillating fiber detectors with a fast trigger scheme [26]. The clear time-of-flight peaks at 73 - 115 MeV assuming protons, which are consistent with proton energies in the simulation are confirmed. And the data showed the very good timing resolution '~ 400 psec.) and excellent signal to noise ratio (~ 1.5) at the track angles from 3.6 deg. to 5.0 deg.

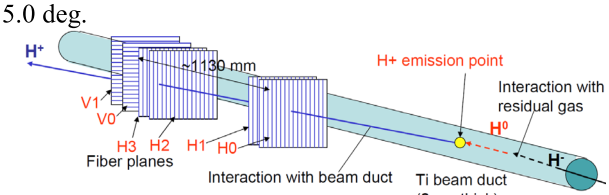

Figure 10: Beam loss tracking system by fast trigger scheme.

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DAMAGE AND RECOVERY FROM THE EARTHQUAKE

On March 11, 2011, the big Tohoku quake occurred. One week after the quake, some delegations accessed to the accelerator tunnel to check the accelerator and its related infrastructures. At the time, no collapse of the accelerator components was found but approximately 10 cm depth of the water flooding was found. According to the detail inspection, we found the deformation of the several beam monitors and bellows welded with beam transport pipes (Fig. 11). Because the alignment of the acceleration cavities and the beam monitors should be required, the devices installed in the drift space which is located between the cavities were dismounted. Vacuum leakage of all removed devices is inspected by helium leak test. Corrosion due to the flooding water was observed on the several pre-amplifiers which were on the floor. Based on the chemical analysis result, the distilled water had strong alkali property which was originally from the concrete contents [27].

After the earthquake, we resumed the beam operation in December 2011. After two series of Linac beam tuning extending to 14 days in total, we succeeded in resuming the user beam operation with the Linac beam power of 7.2 kW in January 2012. The beam power was increased to 13.3 kW on March, which is the same with that just before the earthquake [28].

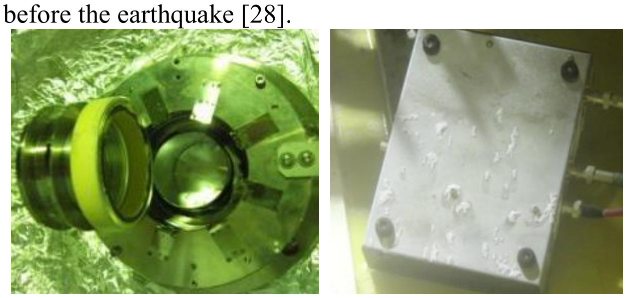

Figure 11: Detachment of the brazing section between the ceramic tube and stainless duct of S/FCT monitor (left). And corroded pre-amplifier boxes on the floor by strong alkaline (right).

SUMMARY

This paper describes the beam instrumentation devices for the present and future J-PARC Linac. Sometimes the beam instrumentations already installed in the beam line were employed for the other propose. This means developed instrumentations have high potential to measure the beam properties. To meet with the big project to increase the beam energy and output power, we still continue the development the new devices to measure and make a diagnosis of the upgraded beam.

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