

BUNCH SHAPE MONITOR DEVELOPMENT IN J-PARC LINAC

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Abstract

In the linac at the Japan accelerator research complex (J-PARC), we decided to use bunch shape monitors (BSMs) as phase-width monitors. Both centroid-phase set point at the frequency jump from SDTL (324 MHz) to ACS (972 MHz) and phase-width control are key issues for suppressing excess beam loss. BSM was designed and developed at the Institute for Nuclear Research, Russia. Because the BSM was first used between acceleration cavities, we need to improve it to protect it from the leakage-magnetic field of the quadrupole magnets and from outgassing impacts on the cavities. In this paper, we introduce these improvements to the BSM for the adoption of the location nearby the acceleration cavities.

INTRODUCTION

The linac at Japan accelerator research complex (J-PARC), which serves as the injector for the downstream 3-GeV synchrotron (RCS: Rapid Cycling Synchrotron), accelerates a negative-hydrogen-ion beam (H⁻). The linac comprises an ion source, radio-frequency quadrupole linac (RFQ), drift tube linac (DTL) and separated-type DTL (SDTL). For the energy upgrade to achieve 1 MW beam power from RCS, we upgraded the beam energy and increased the output energy to 400 MeV by adding annular-ring coupled structure linac (ACS) cavities downstream of the SDTL. We use an accelerating frequency of 324 MHz for the accelerator cavities of RFQ, DTL, and SDTL and 972 MHz for ACS. Because there is a three-fold frequency jump at the SDTL-ACS transition (from 324 to 972 MHz), proper matching at that point is crucial to suppressing excess beam loss. We have decided to use three bunch shape monitors (BSMs) installed periodically at the entrance of the ACS section [1]. The amplitudes of two bunchers located between SDTL and ACS are adjusted so that the measured rms phase-widths with the BSM array become the same [2].

Since the BSM developed by A. Feschenko (INR: Institute for Nuclear Research, Russia) has been used by many accelerator facilities [3], we have developed a BSM in collaboration with INR. The development was completed in 2012. The BSMs were commissioned along with the beam, and their operability was demonstrated [4].

We have encountered some problems with the BSM measurements. The first problem involves the influence of the quadrupole magnetic fields on the ability to focus the secondary electrons. This is because the BSMs are located between and close to the quadrupole doublets. The second problem involves degradation of vacuum during measurement [5]. After we overcame above mentioned problems, we remounted one BSM in front of

the area upstream of the ACS cavities. We have used the BSM and the proposed tuning method at 40 mA for peak beam current operation [6]. Because the BSM was first used between acceleration cavities, we need to protect the leakage magnetic field from the quadrupole magnets and outgassing effects on the cavities. This paper focuses on the two problems and the associated countermeasures for the BSM installed near the acceleration cavities.

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Principle of Bunch Shape Measurement

A device for longitudinal beam-width (phase-width) measurement was designed on the basis of the observation of secondary electrons from a single wire intersecting the beam, as described in [3, 4]. A series of bunches of the beam under measurement was made to intersect a target wire of 0.1 mm diameter, and low-energy secondary electrons were emitted owing to the beam-wire interaction. The wire was held at a typical negative potential of -10 kV. The secondary electrons moved almost radially and entered the RF deflector through collimators.

System Configuration of Bunch Shape Monitor

The BSM comprises a body, an RF deflector, a steering magnet, an actuator, and electron detector, as shown in Fig. 1. The BSM body was designed for installation between the quadrupole doublets, which are located between the acceleration cavities. The RF deflector and the actuator that holds the target wire were installed vertically against the beam axis. The secondary electrons pass through the collimators of the RF deflector and the duct connected to the electron detector. The collimators and the structural parts degrade the pumping conductance. During the BSM measurement, we applied a high bias voltage to the static lens and the target wire, and controlled the RF power input as the main parameter. They are the main factors influencing the vacuum condition.

The RF deflector is composed of a pair of electrodes. We applied a constant DC voltage typically -8.45 kV to focus the trajectories of the secondary electron. The secondary electrons accelerated away from the target wire with a negative potential because -10.0 kV was applied to the collimator in front of the bending magnet.

Installation Layout

Because of vacuum degradation, we installed one BSM downstream of the last SDTL (SDTL16) and ACS-type buncher cavities (Bunchers 1 and 2). Accelerating frequency jumps between SDTL16 and Buncher 1. The

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distances from SDTL16 and Buncher 1 to the BSM are 8.4 m and 16.9 m, respectively (Fig. 2). Clear dependence of the amplitude and phase-width of Buncher 2 cannot be obtained because the distances are too short to obtain the phase-width within the phase resolution of BSM.

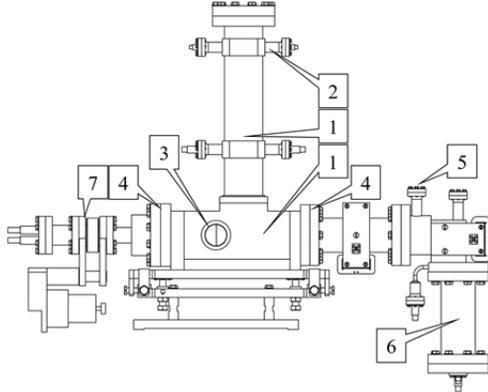


Figure 1: BSM Outline (1-Body and RF deflector, 2-SHV connector, 3-Beam duct, 4-Flange to connect body and pipe, 5-View port, 6-Detector, 7-Actuator).

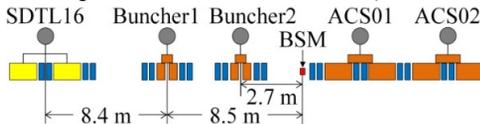


Figure 2: BSM Installation Layout after SDTL16 with Their Distances Shown.

DEFOCUSING BY QUAD FRINGE FIELD

Visual observations of the focusing of thermal electrons from the view ports with the turned-on doublet quadrupoles immediately revealed a strong influence of the quad-fields. Increasing the quadrupole current resulted in an increase in electron beam size at the output collimator installed in bending magnet. We considered the relationship between the quadrupole current and focusing voltage applied to the collimator. The typical focusing voltage was -8.45 kV, and a rapid decrease in the focusing voltage can be seen in Fig. 3 (no shield). With a current of 30 A, the focusing voltage had to be decreased to zero. Therefore, we concluded that the compensation effect facilitated the focusing/defocusing

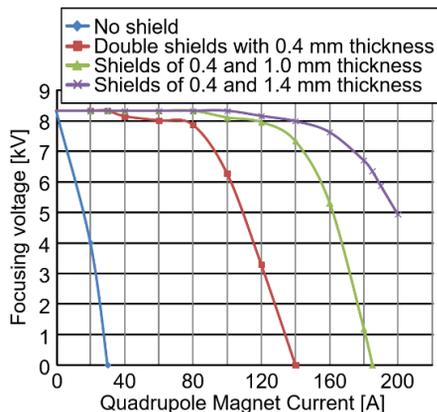


Figure 3: Focusing Voltage Dependence on the Electrical Current of Quadrupole Magnet.

effect of the quad-fields. It became clear that BSMs cannot work with the recent nominal doublet current to say nothing of higher currents needed.

The limits of BSM operability depend on the thickness of steel shields and are estimated to be as follows:

- two 0.4-mm-thick shields for up to 100 A,
- 0.4-mm-thick shield and 1.0-mm-thick shield for up to 150 A, and
- 0.4-mm-thick shield and 1.4-mm-thick shield for up to 180 A.

Based on the magnetic simulation, which treats the secondary electron trajectories affected by the excess quad-field [7], we decided to decrease the quads-fields by mounting steel shields measuring 0.4 mm in thickness on the BSM body and 1.0-mm-thick steel plates vertically near the coils (Fig. 4).

After installation of the shields, focusing of the thermal electrons was reproduced (Fig. 3). To evaluate the influence of the shield on the quad-field around the beam path, we measured the beam profile downstream of the beam transport by using wire scanners (WSM). The rms beam sizes in the transverse profile with magnetic shields are about 1.0% larger than those without the shields. According to an INR estimate, the magnetic shield reduced the GL product (product of the gradient of magnetic field and the length of magnet poles) by about 1.5%, which is in good agreement with the estimation.

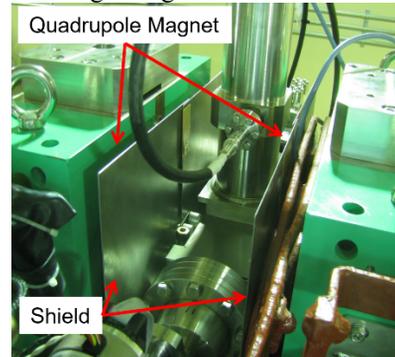


Figure 4: Installation of Shields in Quadrupole Doublets between Acceleration Cavities.

VACUUM DEGRADATION

During the BSM measurement, a problem related to the influence on the vacuum was encountered. Before BSM installation, vacuum pressure in the upstream part of the ACS section was slightly under 1.0×10^{-6} Pa. However, a vacuum of over 1.0×10^{-4} Pa, which is the interlock level required to stop beam operation immediately after supplying RF power, is essential.

We estimated the causes of this degradation, and the relevant countermeasures are given below [5].

- Dark electron current from a target accelerated by bias potential was a candidate because the effect was observed immediately after supplying high voltage potential. We conditioned a target wire applying a bias voltage to it for several days continuously.
- We examined the vacuum test with and without the BSM parameters at the beam line to estimate the

contributions of BSM parameters and to estimate the pumping speed based on the vacuum trends. We decided to remove the BSMs from the beam line for off-line tests and for vacuum conditioning.

Without any BSM conditioning, vacuum speed was evaluated using an off-line setup. Based on a test that ran for a week (about 100 h), the time to reach an operational level of 5.0×10^{-7} Pa (in Fig. 5) was estimated to be 2,000 h. This means that more than a week is required to exchange a broken target wire after pumping.

We conducted baking with an additional turbo-molecular pump installed on top of the RF deflector. Notably, the RF arrangement, which is an extension of an RF deflector, affects the RF characteristics. After cooling, we measured vacuum speed and RF parameters to adjust the resonance frequency by changing the length of the deflector electrode. The required time was reduced to almost half the original time after conditioning. Therefore, effective conditioning during pumping results in quicker recovery. This means that online conditioning after installation is important to minimize the recovery time. In addition, the time for the vacuum impact to the acceleration cavities can be avoided.

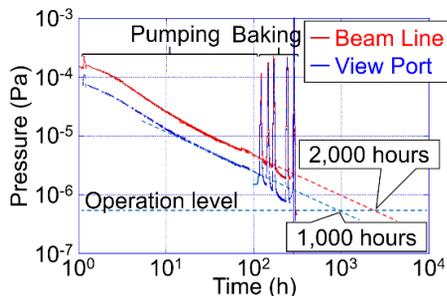


Figure 5: Initial pumping Speed of BSM and Acceleration Time for Achieving Target Vacuum Level.

PHASE WIDTH TUNING BY LONGITUDINAL TRANSVERSE COUPLING

We remounted one BSM in front of the area upstream of the ACS cavities (in Fig. 2) to propose a tuning method. Buncher 1 is used as the knob for amplitude scan at the location of BSM. The amplitudes of SDTL16 and Buncher 1 were scanned to obtain the curves shown in Fig. 6. Based on the Q-scan method for matching transverse beam profiles, we proposed a tuning method that employs amplitude scan curves and the Twiss parameters obtained from transverse profiles [6, 8]. In the method, we use the following formula;

$$\sigma_{\text{BSM}}^2 = \varepsilon_z [(1 + Lk)^2 \beta_B - 2L(1 + Lk)\alpha_B + L^2 \gamma_B] \quad (1)$$

where ε_z is phase-width emittance; L is drift length; α_B , β_B , and γ_B are Twiss parameters at the BSM position; and k is the longitudinal focusing force. We substituted σ_{BSM}^2 and k obtained from Fig. 6. These free parameters of ε_z , α_B , and β_B , were obtained by iterated calculation, and γ_B was obtained by 3D-PIC simulation. These parameters were adapted to the buncher and quadrupole settings, as well as the total beam loss measurements, and proper settings for minimum beam loss were determined.

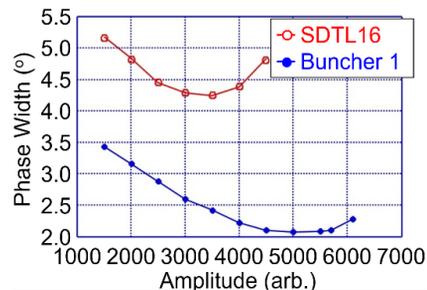


Figure 6: Amplitude Scan by SDTL16 and Buncher 1.

CONCLUSION

BSMs were installed between the quadrupole doublets. Therefore, we considered the influence of the quadrupole magnetic fields on the operational settings. We overcame the problems of the defocusing of static lens and vacuum degradation to maintain the required super-high vacuum level during BSM operation. A vacuum system with an online baking scheme was proposed to operate BSMs without significant vacuum degradation.

Presently, we use BSMs for resonance studies [9, 10] to determine the equipartitioning (EP) condition. BSM measurement has the advantages of being able to measure longitudinal (phase-width) emittance, which is useful for determining the EP-set point. In addition, we have commenced modification of the BSMs to be installed additionally upstream of the ACS section with deep consideration of the effect of vacuum, because we consider back to the policy to take matching of buncher cavities using three BSMs.

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