# BUNCH LENGTH ANALYSIS OF NEGATIVE HYDROGEN ION BEAM IN J-PARC LINAC *

A. Miura#, N. Hayashi
J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki, JAPAN
T. Maruta, Y. Liu, T. Miyao,
J-PARC Center, High Energy Accelerator Research Organization, Oho, Tsukuba, JAPAN
S. Fukuoka
Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki, JAPAN

*Abstract*

We used bunch shape monitors (BSMs) to measure the longitudinal bunch length of a negative hydrogen ion beam in the J-PARC linac. Because we experienced a vacuum degradation to suspend a beam operation during the BSM operations, BSMs were once dismounted for vacuum conditioning. We installed one BSM again in the beam line with additional vacuum equipment. We stared to measure the 191-MeV beam again to tune the buncher amplitude after checking a functioning BSM by comparing its results with those of a simulation. To evaluate the measurement errors with peak beam current increasing, we observed waveforms with various beam currents. Therefore, the RMS bunch length depends on the peak beam current and the bending at the pulse head grows with the peak beam current. Furthermore, to avoid the thermal stress, we compared the data taken at an off-center beam with the ones taken at an on-center beam, because a target wire will be exposed to a higher peak beam current. In this study, we introduced the peak beam current dependence of the bunch length waveforms, and an effect of on-/off-centering of the wire position. Finally, the new buncher tuning method using one BSM is discussed.

## INTRODUCTION

In the 1-MW upgrade project at the J-PARC at the experimental laboratories connected to the downstream of the linac and the rapid cycling synchrotron (RCS), we have two big projects, particularly, the energy upgrade from the 181-MeV linac to the 400-MeV linac and the front-end improvement using a new RF ion source and replacing it with the upgraded radio frequency quadrupole (RFQ) linac cavity. To meet with the 400 MeV of the linac, 21 ACS cavities have been developed and installed in the beam line; we have developed the beam monitors for the ACS cavity tuning. Because the acceleration frequency of ACS cavities is 972 MHz, which is three-fold higher than that of upstream RF cavities, we need to take longitudinal matching at the upstream part of the new ACS beam line.

We started the development of a bunch shape monitor (BSM) for the J-PARC linac. Three years into the project, three BSMs were fabricated. In the summer of 2012, prior to the installation of ACS cavities, we installed all three BSMs at the upstream of the new ACS section to conduct some test measurements using 181-MeV beams [1]. During the BSM measurements, a problem with the degradation in vacuum conditions was found. A major reason for this problem was outgassing from materials when the high voltage and RF power were supplied. To mitigate this problem, BSMs were dismounted from the beam line and the off-line conditioning with outgas analysis was performed. The impacts of the bias voltage to the target wire and static lens and the RF power to the deflector were examined in the vacuum test [2].

The improved arrangement of the vacuum system for installing the BSM was also proposed. We installed a BSM in at the upstream of the ACS again in the summer of 2014 with the additional vacuum arrangement. We started to use the BSM to conduct the buncher amplitude tuning. In the study on space-charge driven transverse–longitudinal coupling resonance, we measured the longitudinal emittance with the BSM. The results are expected to contribute to the design of the beam operational parameters for the energy-upgraded linac. The high-intensity linac design follows the equipartitioning (EP) condition. Fortunately, J-PARC linac could find its EP solution as the baseline design without sacrificing hardware efficiency. It also has the applicability for a wide range of off-EP conditions, offering opportunities not only for investigating the basic beam physics principles but also for further optimizing the machine operation [3].

To evaluate the measurement errors in the high-intensity beam operation, we observed waveforms with various beam currents. We discuss the longitudinal bunch length taken at an off-center position to avoid the thermal stress from the higher peak beam current. Finally, we introduce a proposal for the new buncher tuning method with one BSM.

## STRUCTURE OF BSM

A BSM comprises the body, RF deflector, steering magnet, actuator, and electron detector as shown in Fig. 1. An RF deflector and an actuator which holds a target wire are vertically installed against the beam axis on the body. Secondary electrons that pass through the collimators on the RF deflector travel to the pipe connected to the electron detector [4]. Finally, secondary electrons pass

* amiura@post.j-parc.jp

through some collimators and the bending magnet before reaching the electron multiplier.

During a BSM operation, we set the wire position at the beam center by observing the beam loss signals at the downstream beam loss monitor. The stroke of the wire reaches about 5.0 mm from the duct center (to the right in Fig. 1). It means that the wire is relatively closer to the detector.

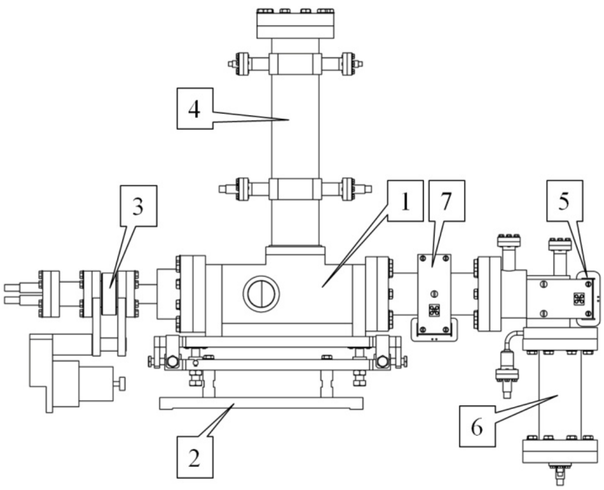

Figure 1: Overview of BSM (1: body, 2: support, 3: target actuator, 4: RF deflector, 5: bending magnet, 6: electron detector, and 7: steering magnet).

Installation layout of the BSM is shown in Fig. 2. The BSM locates at the downstream of SDTL16 and ACS-type bunchers. The specification of the measured beam is 5–30 mA for the peak beam current, 191 MeV for the beam energy, and 100 μs for the longest pulse duration.

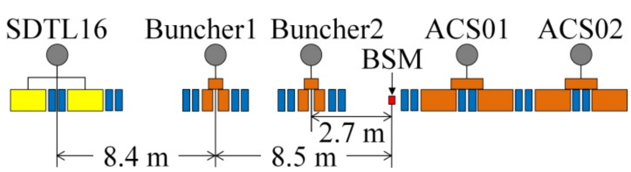

Figure 2: One BSM installation layout after SDTL16 with their distances shown.

## EFFECT OF THE RF FEED FORWARD SYSTEM

When the beam operation started, we usually tuned an RF feed forward (FF) system for the compensation of the RF power loss due to the passing of charged particles to the RF cavity. To investigate the behavior of the pulse head, we took waveforms at various peak beam currents. In the 30-mA operation, the peak beam current can be squeezed by the scraper in the upstream of linac to make 5–30 mA with 5-mA intervals.

The electrical field in an RF cavity is caused by the travelling electrical field induced by the charged beam pulse. The strength of the field directory depends on the travelling electrical field, i.e., the peak beam current. The field counteracted the beam pulse, particularly, by slowing down the beam particles.

Figure 3 shows the waveforms affected on the beam pulse. In the figure, pulse heads are on the left and the tails are on the right. The color contour means the intensity of the signal. At 5 mA, phases were not affected by the travelling field and the profiles were almost straight. When the peak beam current increased, pulse heads were effectively bent. This is usually compensated by the RF FF system; if there is no compensation, then it is usually difficult to calculate pulse width accurately. These results suggest the importance of RF FF adjustment to compensate the electrical field for the measurement at the high peak beam current operation.

RMS bunch lengths are calculated using the last half of the measurement results, because the effect of the RF FF system is negligible in the last half. The calculated RMS bunch length grows with beam current. It is considered that the cause of the growth is due to the space-charge effect.

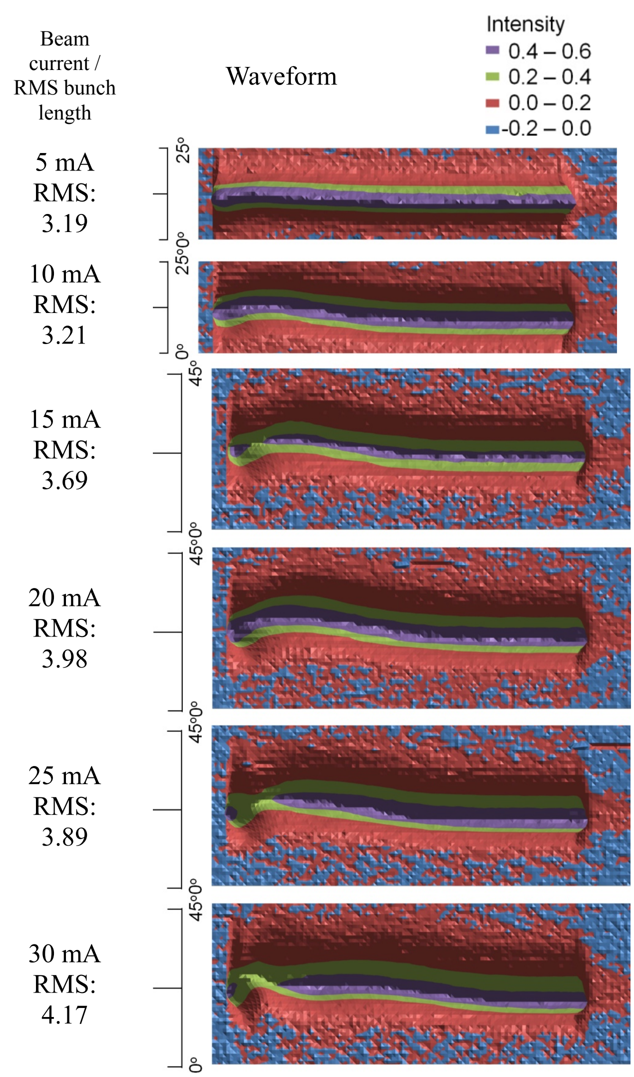

Figure 3: Effect of the FF system on waveform of bunch length.

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## EFFECT OF OFF-CENTERING BEAM

When the peak beam current is increasing, a target wire will be exposed to a higher peak beam current and the thermal stress will become serious. The misalignment with the beam axis should be evaluated. Several measurements were conducted for different horizontal wire positions scanning from −2 mm to +2 mm in steps of 0.5 mm as shown in Fig. 4. Here the positive position means the wire is inserted to the right of the detector in Fig. 1. To control the thermal stress, we evaluated the data taken at an off-center beam with those taken at an on-center beam. The minimum phase spread can be seen at −1.0 mm where the maximum signal was detected by the electron multiplier and the Gaussian fitting is shown to underestimate the actual RMS bunch length. This tendency agrees with the frontend bunch length of the 3-MeV beam measured at Linac4 at CERN [5]. The absolute bunch length of the 3-MeV beam is quite larger than that above 191 MeV in J-PARC. The signal level shift with wire position is considered to be caused by the mechanical structure.

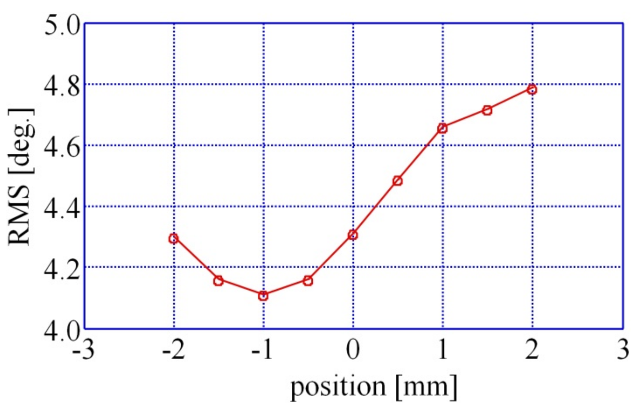

Figure 4: RMS phase spread at different horizontal wire positions.

Because the BSM is a type of wire scanning device, the possibility of using it as a horizontal profile monitor is incidentally discussed [5]. However, the signal level is a function of the wire position; therefore, the measurement results include the functional errors. We usually defined the wire position of the beam center by the beam loss signal taken at the downstream beam loss monitor. When the beam hits the wire, secondary particles are generated and lost to the transport. A part of the lost particles are detected by the beam loss monitors, and the signal levels depend on the beam intensity. We usually obtained the horizontal beam profiles by the beam loss signal with the horizontal wire scan.

## LONGITUDINAL TUNING

We propose a new buncher tuning method. Because currently we can use only one BSM, we need to consider the new method to tune the longitudinal bunch length. One BSM was installed in front of ACS01 as shown in Fig. 4. We can measure the longitudinal pulse width using SDTL16, buncher 1, and buncher 2. We can obtain the amplitude scan curve as shown in Fig. 5. From previous discussions of EP tuning [3], the EP condition should be far from the resonance region to avoid transverse–longitudinal emittance exchange. We propose a tuning method using the amplitude scan curve and Twiss parameters obtained by transverse profiles.

We use the following formula [6].

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

where $\varepsilon_z$ is emittance, L is drift length, $\alpha_B$, $\beta_B$, and $\gamma_B$ are Twiss parameters at the BSM position, and k is longitudinal focusing force. We substituted $\sigma^2_{BSM}$ and k, which are obtained from Fig. 5. In Fig. 5, blue dots were taken at 30 mA and red ones were at 50 mA. We can obtain the smallest bunch length at 3 MV for the buncher 1 amplitude. This curve means longitudinal focusing and defocusing by the buncher amplitude. The amplitude at the minimum bunch length means the focusing point that is the most important for fitting the simulation results.

We made iterated calculations to obtain a free parameter set of $\varepsilon_z$, $\alpha_B$, $\beta_B$, and $\gamma_B$ estimated by a 3D-PIC simulation. We adopted the above parameter set for the buncher and quadrupole settings and the total beam loss measurements, and we finally decided the proper settings for the minimum beam loss situation.

We obtained the longitudinal beam parameters as listed in Table 1 at the position of buncher 1. The emittance at the RFQ exit from the RFQ simulation is 134.4 [π deg. keV] and the measured emittances at buncher 1 are 149.9 at 30 mA and 224.0 at 50 mA. Emittances glowed approximately 10% and 60% at 30 mA and 50 mA, respectively.

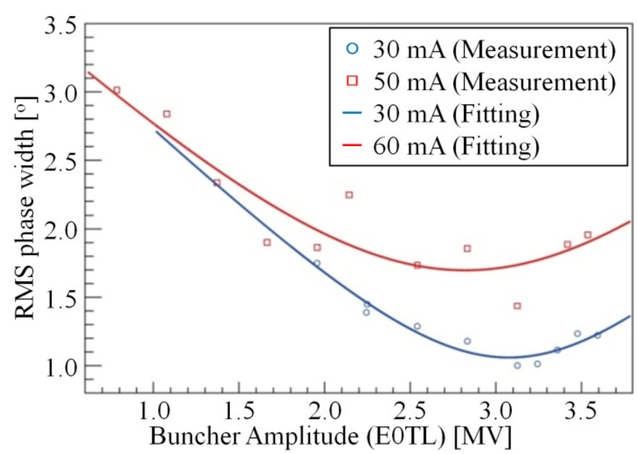

Figure 5: Amplitude scan curve of buncher 1 at 30 (blue) and 50 mA (red). Solid curves are fitted.

Table 1: Measured longitudinal beam parameters at the MEBT2 entrance by buncher 1 amplitude scan [6]

| | Measurement | |
|---|---|---|
| | 30 mA | 50 mA |
| $\alpha_x$ | 0.138 | −0.622 |
| $\beta_x$ [deg./keV] | 0.0182 | 0.0183 |
| $\varepsilon_x$ [π deg. keV] | 149.9 | 224.0 |



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## CONCLUSION

We successfully developed a BSM for the J-PARC linac and used it for the buncher amplitude tuning. The effect of the electric field generated by the travelling charged particles was observed using various beam currents. Furthermore, we showed the RMS phase spread at different horizontal wire positions. One possible cause is the mechanical structure. However, there still mains an unknown beam dynamics cause. The high-intensity linac design follows the EP condition. We measured the longitudinal emittance with BSMs. The results supported minimum beam loss conditions; however, the emittance growth was recognized at 30 and 50 mA. We proposed a new tuning method using one BSM, which is similar to the Q-scan method. We have a plan to develop the BSM for the frontend; there is not sufficient space to install a number of BSMs. In this case, we will install only one BSM and use this method. This method will play an important role in the frontend tuning.

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