# SIMULATION STUDY ON THE LONGITUDINAL BUNCH SHAPE MEASUREMENT BY RF CHOPPER AT J-PARC LINAC

T. Maruta*, J-PARC center, Japan Atomic Energy Agency, Tokai, Ibaraki, Japan
M. Ikegami, High Energy Accelerator Research Organization, Tsukuba, Ibaraki, Japan

*Abstract*

We propose to measure the longitudinal rms beam size by existing apparatuses in MEBT1 at J-PARC linac. The RF chopper cavity horizontally deflects beam particles at the frequency of 324 MHz, which is the same frequency as other accelerator cavities. By setting an adequate driving phase of the chopper, a horizontal deflection is proportional to relative phase difference from the centroid of a beam bunch. Then, the deflected beam distribution is measured by a wire scanner monitor. It is also possible to measure the longitudinal rms emittance by varying the amplitude of a buncher upstream. In this paper, we confirm the feasibility of the measurement scheme with particle simulation.

## 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 a 181 MeV Separate-type DTL (SDTL). There is a medium energy beam transport section (MEBT1) between the RFQ and DTL. We place an RF chopper system in the middle of MEBT1 to shape a macro pulse configuration in accordance with RF frequency of following 3 GeV rapid cycling synchrotron (RCS).

In the J-PARC linac, a beam intensity upgrade project is currently underway. The project will replace the front end part (IS to RFQ) for the extension of the peak current to 50 mA in the next summer. A simulation study indicates that the longitudinal beam emittance in the 50 mA operation is 20 % larger than present one. The beam rejection power of the RF chopper system is inversely correlated to a beam width in phase direction, it motivated us to consider a reinforcement of the chopper. It is important to understand the current beam width for an inquest of the reinforcement. However, we have no monitors for the beam width measurement, and moreover, there is no space to install an additional monitors in MEBT1.

We devise a beam width measurement method only with an existing apparatus in MEBT1 to overcome the situation. Then we evaluate the feasibility with a three dimensional particle-in-cell code IMPACT [1].

## MEBT1

MEBT1 is a 3 m long transport line between RFQ and DTL as shown in Fig. 1. There are two major issues. One is a matching of the beam to the DTL acceptance in both longitudinal and transverse phase space by eight quadrupole magnets and two buncher cavities while transferring the beam to DTL. To measure the beam qualitatively, we place beam current monitors (CT), beam position monitors (BPM) and wire scanner monitors (WSM) [2] throughout MEBT1. The other issue is a shaping of a macro pulse in accordance with the RF frequency of following RCS. The RF chopper system is involved in the shaping. It is comprised from an RF chopper cavity and a scraper which is located at 0.72 m downstream from the cavity. Unnecessary beam bunches are horizontally ($x$) deflected by the cavity and then they hit to the scraper.

### *RF Chopper Cavity*

We employ an RF deflector (RFD) for beam chopping [3]. The RFD is operated in a $TE_{11}$-like mode with the frequency of 324 MHz, which is same as RFQ and DTL. The deflection angle of a RF gap is 6 mrad at the electric field of 1.6 MV/m of which an RF power is 22 kW. There are two RF gaps in the cavity at intervals of $3\beta\lambda$, where $\beta$ is the velocity of beam normalized by the speed of light and $\lambda$ is RF wave length. The two RF gaps are currently connected in series via a coaxial tube with length of $2\lambda$ to supply an RF from a single semiconductor amplifier. In this summer, we modify the configuration to individually supply an RF to each RF gap by introduction of an additional amplifier. It enable us to tune an asynchronous phase and an amplitude of each RF gap individually. The current amplifier stably supply an RF power up to 35 kW which corresponds a gap field of 2.0 MV/m. Moreover, we have a plan to upgrade the amplifier to 60 kW in the next summer.

## MEASUREMENT METHOD

In the measurement, we use the RF chopper cavity, the upstream buncher and a WSM downstream of the chopper cavity. The measurement is comprised of two steps. In the first step, we measure the beam width in phase direction by the chopper cavity and the WSM. Then, the second step measures a longitudinal emittance and a Courant-Snyder parameter by adding the buncher to the beam width measurement. This measurement is similar to a transverse emittance measurement so-called "Q-scan" [4] in principle.

### *Beam Width in Phase Direction*

In the nominal operation of J-PARC linac, the chopper is tuned to give a maximum deflection to a beam bunch. It is equivalent that we adjust the RF to be maximum when a beam bunch arrives at the middle of an RF gap as shown in Fig. 2(a). The integrated RF of a beam particle gradually attenuates in accordance with a phase difference from the

* tmaruta@post.j-parc.jp


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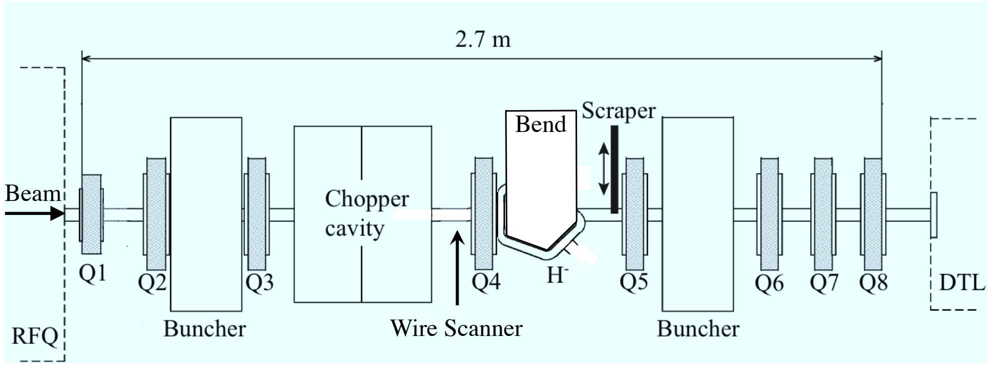


Figure 1: Layout of MEBT1. We use the chopper cavity, the upstream buncher cavity and the wire scanner between the chopper cavity and Q4 for the measurement.

centroid of a beam bunch. The earlier and later particles than the centroid are deflected in same amount if the phase deference is same. Consequently, it is hard to extract the beam width in phase direction from an $x$ plane measurement.

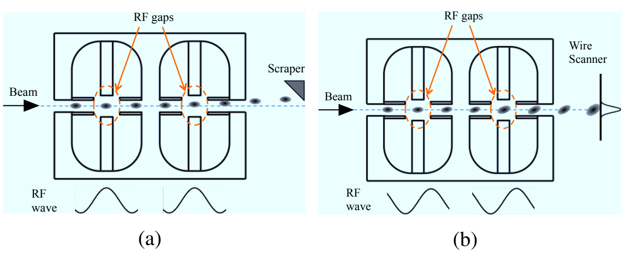


Figure 2: The RF setting and a beam bunch behavior — (a) In the nominal operation (b) In the measurement.

If we set the RF phase shifted by $\pi/2$ from the nominal operation, the centroid of a beam bunch is not deflected at an RF gap, because the centroid passes through a gap at zero-crossing. Whereas, particles away from the centroid are deflected in accordance with the relative phase difference from the centroid ($\Delta\phi$). Consequently, a beam bunch rotates on the $x' - \phi$ phase space as shown in Fig. 2(b). If the transverse emittance is negligibly small, the $x$ position after the deflection is a function of $\Delta\phi$. We can obtain a beam distribution in phase direction by the measurement of the $x$ distribution downstream of the chopper. Unfortunately, the beam is a finite transverse emittance. Instead we obtain a root-mean-square (rms) beam width ($\sigma_\phi$).The deflected rms beam width on the $x$ plane at the distance of $D$ is

$$< (x + D\theta(\Delta\phi))^2 >=< x^2 > +D^2 < (\theta(\Delta\phi))^2 >, \tag{1}$$

where $< x^2 >$ is square of rms beam size without deflection and $\theta$ is deflection angle of each particle. This equation shows that we can obtain the $\sigma_\phi$ from the measurement of $x$ distribution with and without the deflection.

Originally, this method is considered by Prof. Naito from KEK [5]. Although it is important to adjust the asynchronous phase of both RF gaps to a zero-crossing, the ambiguity of phase difference due to the series connection of RF gaps is an obstacle for an accurate measurement. The introduction of the additional amplifier in this summer resolves the ambiguity. Consequently, it is possible to conduct the measurement.

### *Emittance*

The $\sigma$-matrix at the chopper ($\sigma^C$) is expressed from the $\sigma$-matrix at the upstream buncher ($\sigma^B$) and the transfer matrix between them ($R$) as $\sigma^C = R\sigma^B R^T$. The element $\sigma_{55}$, which is equivalent to the square of $\sigma_\phi$, $\sigma^C_{55}$, is written as

$$\sigma^C_{55} = (\sigma^C_\phi)^2 = \varepsilon\left(\beta^B R^2_{55} - 2\alpha^B R_{55}R_{56} + \gamma^B R^2_{56}\right), \tag{2}$$

where $\varepsilon$ is the emittance, and $\alpha^B$, $\beta^B$ and $\gamma^B$ are Courant-Snyder parameters at the buncher, respectively. The lattice is RF gap + Quadrupole + Drift. The matrix elements without impulse from the space charge forces are $R_{55} = 1 + kL/\beta\gamma^3$ and $R_{56} = L/\gamma^2$, where $k$ is an electric field of the buncher and $L$ is the length of the lattice. Substituting them into Eq. 2 and deforming it with focusing on $k$, Eq. 2 is expressed as

$$(\sigma^C_\phi)^2 = \frac{\varepsilon\beta^B L^2}{\beta^2\gamma^6}\left(k + \frac{\beta\gamma^3}{L} - \frac{\alpha^B}{\beta^B}\beta\gamma\right)^2 + \varepsilon^2\frac{L}{\gamma^2}\frac{1}{\varepsilon\beta^B}. \tag{3}$$

Therefore, $(\sigma^C_\phi)^2$ is the second order polynominal function of $k$, and the minimum width is equivalent to the square of $\varepsilon^2 L/\gamma^2\varepsilon\beta^B$. Since $\varepsilon\beta^B$ can be calculated from the coefficient of $k^2$, it is possible to extract the $\varepsilon$ from the correlation of the $\sigma_\phi$ and the $k$. The Courant-Snyder parameter also evaluate from Eq. 2. The $R$ elements vary when we change $k$. Measurements at three $k$ result three equations in three unknowns.

## SIMULATION

We use a three dimensional particle-in-cell code, IMPACT, for an evaluation of the feasibility. In the simulation, the initial particles are launched at the entrance of MEBT1. Then, we track these particles to the WSM which we use in the measurement. The output distribution from PARMTEQM [6] is taken as the initial distribution. The electro-magnetic field inside the chopper cavity is calculated with a finite element method (FEM) code, Micro Wave Studio (MWS) [7]. We treat the RFDs as two single cavity in MWS and obtain an electric field distribution at the frequency of 324 MHz.

We measure the deflection at the several electric fields to confirm the reproducibility of a simulation with the MWS field distribution. The horizontal beam distribution at the electric field of 0, 0.33, 0.50, 0.95 and 2.0 MV/m are measured by the WSM. Here we define the deflection as the displacement of the centroid of the distribution from the centroid without excitation. Figure 3 shows the comparison of the measured deflection with the simulation. The simulated deflection shows a linear correlation to the electric field. The measurements are well gathered around the simulation in the region less than 1 MV/m. Concerning to the 2.0 MV/m, we observe a decline of a beam current at the chopper downstream. It is supposed that a part of a beam bunch hits to an aperture inside the chopper and it becomes an obstacle for the calculation of the deflection properly.

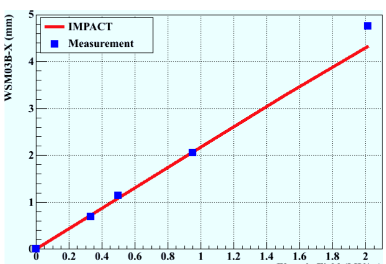


Figure 3: Correlation of the chopper electric field and the deflection at the WSM.

Figure 4(a) shows the $\sigma_\phi$ at each RF gap as a function of the buncher $E_0$TL. Red points are $\sigma_\phi$ at the upstream gap (#1) and blue points are that at the downstream (#2). Both distributions have a minimum $\sigma_\phi$, and the $E_0$TL of minimum $\sigma_\phi$ at the gap #2 is lower than the gap #1. It is consistent that the $k$ at minimum $\sigma_\phi$ is inversely proportional to $L$ shown in Eq. 3. The $\sigma_\phi$ of the gap #2 is minimum at $E_0$TL of 0.19 MV. Since the maximum $E_0$TL is currently 0.17 MV, we may need to upgrade the semiconductor amplifier of the buncher to observe the minimum $\sigma_\phi$.

Next, we calculate the boundary condition on the $\phi - E$ phase space at the buncher. From the measurement in Fig. 4(a), we extract the boundary of the ellipse at the buncher by using the $R$. We use a Trace3D [8] for the calculation of the $R$ for each $E_0$TL. Figure 4(b) shows the boundaries and actual ellipse by IMPACT. Here we shows the boundaries at the buncher $E_0$TL of 0, 0.085 and 0.17 MV. Since an emittance growth is not taken into account to the Trace3D, the reproducibility of the boundaries becomes worse as the emittance growth being large. The calculated boundaries are close to the ellipse well. The effect of the emittance growth between the buncher to the chopper is supposed to be negligibly small. We consider to upgrade the semiconductor amplifier of the buncher currently. After the upgrade,It is expected to observe the minimum $\sigma_\phi$ in Fig.3 and to give more tight constraint for the ellipse in Fig. 4(a).

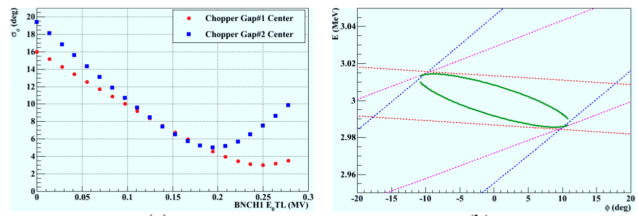


Figure 4: The simulation results — (a) $\sigma_\phi$ at both RF gaps of the chopper as a function of the buncher $E_0$TL (b) The ellipse and the boundaries obtained by $\sigma_\phi^C$ measurement. The dotted lines are the boundary at 0 (red), 0.085 (magenta) and 0.17 MV (blue), respectively.

## SUMMARY AND FUTURE PROSPECTS

Because of the introduction of another semiconductor amplifier for the chopper, it is possible to measure the beam width in phase direction. Moreover, we also measure longitudinal beam emittance and Courant-Snyder parameters by adding the flexibility of the buncher amplitude to the beam width measurement. The data-taking is scheduled at the beginning of October. We confirm the feasibility of the measurement and evaluate the longitudinal beam profile.

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