LONGITUDINAL BEAM DIAGNOSIS WITH RF CHOPPER SYSTEM

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Abstract

The RF chopper system is one of the key items for the upcoming 400 MeV and 50 mA upgrade of the injection linac of Japan Proton Accelerator Research Complex (J-PARC). The system scrapes unnecessary beams for the following 3 GeV Rapid Cycling Synchrotron (RCS). Since the remnant beam causes a beam loss in RCS, it is required to maintain the sufficient elimination power for the stable operation after the upgrade. The elimination power heavily depends on the beam width in the phase direction at the RF chopper cavity. The confirmation of the present status is important for the consideration of the upgrade properly. Therefore, we obtained the beam width from the measurements of the RCS beam loss with varying the RF settings of the chopper. In this paper, we discuss the measurement method and results.

INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) is a high intensity proton accelerator facility designed for a MW-class beam. The accelerator complex is currently comprising a 181 MeV linac, a 3 GeV Rapid Cycling Synchrotron (RCS) and a 30 GeV Main Ring (MR). A 3 GeV beam is also transported to Materials and Life Science Experimental Facility (MLF). In the injector linac, The design peak current is 30 mA, the macro pulse is 0.5 msec with the repetition rate of 25 Hz. 50 keV negative hydrogen ions (H^-) are extracted from an ion source (IS), then they are accelerated by a 3 MeV Radio Frequency Quadrupole (RFQ), a 50 MeV Drift Tube Linac (DTL), and a 181 MeV Separate-type DTL (SDTL) [1]. All cavities are operated at the frequency of 324 MHz.

A 3 MeV beam transport line so-called MEBT1 is a 3 m long transport line connecting the 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 (CTs), beam position monitors (BPMs) and wire scanner monitors (WSMs) [2] throughout MEBT1. The other issue is a shaping of a macro pulse. The RF frequency of RCS is 0.938 MHz and it is different from the frequency of the linac. If a macro pulse is injected to RCS without any shaping, a part of the macro pulse stays out of the RF bucket and it is lost in the middle of acceleration. The beam loss causes a serious radioactivation of accelerator components. It is the key issue for the stable operation to mitigation of the beam loss, i.e. the rejection of the beam out the RF bucket for RCS. Therefore, we configure another pulse structure to a macro pulse so-called medium pulse. The RF chopper system in MEBT1 conducts the forming of the medium pulse. The system is comprised from a RF deflector cavity and a scraper. During RF on, beam is horizontally deflected by sinusoidal RF wave in the cavity, and then the beam is absorbed in the scraper as shown in Fig. 2. The detail of the RF chopper system is introduced in the next section.

The linac has a plan to extend the peak current to 50 mA from currently 30 mA by the replacement of the front-end part (IS and RFQ) in the next summer. The simulation of new RFQ by LINACSrfqSIM indicates that the longitudinal beam emittance in the 50 mA operation increases more than 20 percent from the present operation of 15 mA [3], i.e. beam width in phase direction at 50 mA operation is wider than present. Since the RF becomes smaller as the synchronous phase shifts from 0 deg (for cosine wave), the increase of beam width in phase direction causes an insufficient deflection for beam elimination at beam envelope. Therefore, we need to confirm whether the 20 % emittance enhancement is problem for the RF chopper system or not. And if the chopper system cannot sustain the 50 mA operation, we must upgrade the chopper system with the reasonable estimation. For the estimation, the understanding of present status is absolutely imperative. However there is no monitor to measures a longitudinal beam profile in MEBT1. It motivates us to measure the beam width in phase direction by existing apparatus.

RF CHOPPER SYSTEM

The RF chopper system is comprised from an RF chopper cavity and a scraper which is located at 0.72 m downstream from the cavity. The beam is horizontally deflected by the chopper cavity during the RF on, and then the deflected beam is absorbed in the scraper.

We employ an RF deflector (RFD) for the beam chopping [4]. The RFD is operated in a TE_{11}-like mode with the frequency of 324 MHz, which is same frequency as the other cavities. Since no higher order harmonic is supplied, the RF wave is sinusoidal. There are two RF gaps in the cavity at a interval of $3\beta\lambda$, where β is the velocity of beam normalized by the speed of light and λ is RF wave length. For the supplement of RF from the single amplifier, the two RF gaps are connected in series via a coaxial tube with length of 2λ in order to deflect a beam at the same RF phase by two gaps. The design deflection angle of each RF gap is 6 mrad at the electric field of 1.6 MV/m of which an RF power is 22 kW. The power source of the chopper cavity is

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ISBN 978-3-95450-118-2

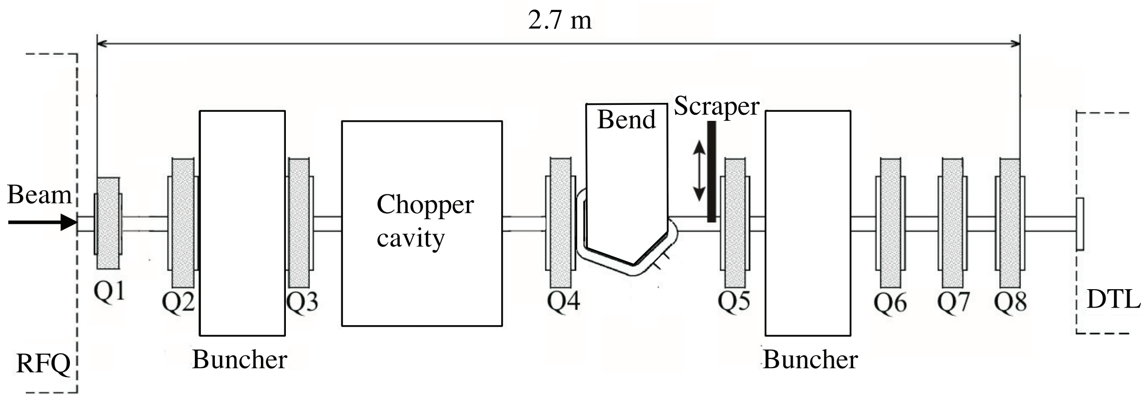

Figure 1: Layout of MEBT1. The RF chopper system, which is comprised from an RF chopper cavity and a scraper, is placed at the middle of MEBT1.

a semiconductor amplifier, which is possible to stably supply the RF power up to 35 kW which corresponds the gap field of 2.0 MV/m.

Beam Extinction

The beam extinction level of the RF chopper system had been measured at MLF with a probe of the neutron flux [5]. In MLF, The neutron beam is produced by injecting the 3 GeV beam into a mercury target. More than twenty secondary beamlines are radially constructed around the target to carry the neutron beam to outward. In the measurement, we had counted the neutron flux at one of the secondary beamlines so-called BL10. Since the neutron counter saturates at the RCS beam power of 120 kW which was nominal power for user operation at that time, The calibration of the counter was conducted by weak beam of 1 and 0.5 kW which is produced by thinning out a macro pulse in the linac. The chopper RF amplitude is 2.0 MV/m. We measured the neutron flux with two driving phase, one is the phase of maximum deflection angle and the other is shifted by 20 deg. The ratio of the neutron flux with and without the chopper RF, then it is scaled to 120 kW beam. We obtained the extinction level with the phase at the maximum deflection is 1.13×10^{-7} for 120 kW. The level is still 7.8×10^{-7} after shifting the driving phase by 20 deg. The required level is in the range of $< 10^{-4}$ for J-PARC [6]. The results indicates that the RF chopper system achieves 10^3 higher performance than the request. Moreover, the deterioration of the extinction level is less than one order of magnitude even if the driving phase is shifted by 20 deg.

MEASUREMENT

In the experiment, we have conducted two kinds of measurements. One is chopper amplitude scan. In order to provide a clear idea, we explain the measurements with a simple sketch in top of Fig. 3. The horizontal axis shows the RF phase of the chopper with respect to the phase at the RF peak ($\Delta\phi_s$), and vertical axis is the chopper electric field. Here, we assume that the beam centroid is perfectly

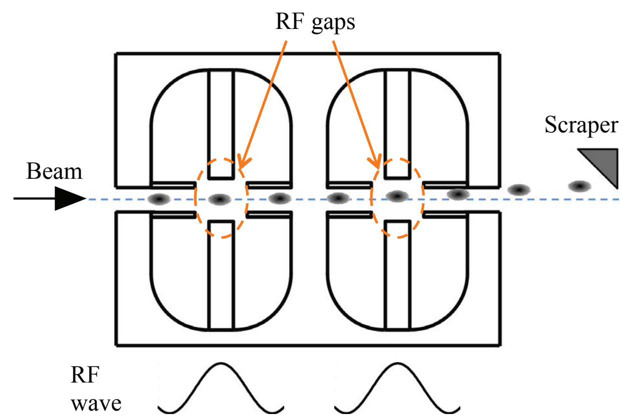

Figure 2: The outline of the chopper cavity. Two RF gaps are in the cavity for the horizontal deflection. The deflected beam is absorbed in the scraper. The RF phase is adjusted as the beam is deflected at an RF peak.

adjusted at the RF peak and the beam is certainly eliminated from the beamline where the RF is higher than the threshold (a^{th}). Here we call the phase region in which RF amplitude is higher than the a^{th} as effective region. The effective region at the amplitude of a^1 is for $\pm\phi_1$, and the effective region is shrink to $\pm\phi_2$ when the amplitude decline by Δa. If the effective region at a^1 fully covers the beam, no beam loss is observed in RCS. When the beam loss appears when we change the amplitude from a^1 to a^2, it means that a portion of the beam is in $-\phi_1$ to $-\phi_2$ or in ϕ_2 to ϕ_1. And the signal height indicates the amount of the beam in the regions. While the signal height is low when the beam halo splits out of the effective region, the signal drastically increases in the case of splitting out of the beam core. Therefore, the RF amplitude scan introduces us how far the halo and the core distribute from the beam centroid. The other measurement is chopper phase scan. When the driving phase of the chopper is shifted by $\Delta\phi$ as shown in top of Fig. 4, the effective region also shifts by same amount. If the effective region at $\Delta\phi = 0$ deg sufficiently

ISBN 978-3-95450-118-2

covered the beam distribution, the situation is equivalent to the transverse profile measurement by beam collimation with a one-side movable jaw. The projection axis is perpendicular to the phase direction. The beam profile in the negative phase side is supposed to be obtained by analyzing the data of the phase shift to positive phase and vice versa.

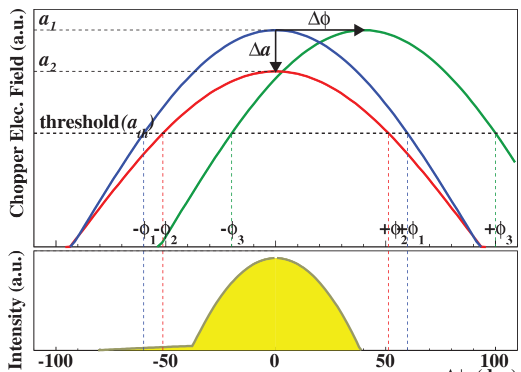

Figure 3: (Top) the chopper RF wave form at various conditions. (Bottom) Supposed beam distribution from the phase scan. The vertical axis is logarithmic scale.

Tuning of the Chopper Driving Phase

Before the data-taking, we tune the driving phase of the RF chopper by our nominal procedure. We use a WSM to probe the remnant beam. The wire of the WSM in SDTL is inserted to the beamline, and then we measure the WSM signal with varying the driving phases. If the remnant H^-s hit the wire, the electrons composing of H^- are absorbed inside the wire and then we can observe the electrons as a signal. Since a read-out circuit can amplify the signal by factor of 100 (factor of 1 in a beam profile measurement), the sensitivity of the remnant beam is improved to less than 10^{-3} [7]. The signal declines with the phase closing to $\Delta\phi_s = 0$ deg due to the increasing in the proportion of absorbed beam. Then the extinction level goes beyond the WSM sensitivity and no signal is observed in the certain phase region. The phase of $\Delta\phi_s = 0$ deg is expected to be the center of no signal region. In order to obtain the center of the region, we fit the correlation of the driving phase with the signal around the no signal region by a quadratic function. Then we set the driving phase at the peak of the function.

We perform another measurement after the tuning in order to confirm whether the above tuning really adjusts the driving phase to $\Delta\phi_s = 0$ deg. The horizontal displacement from the beam line at the chopper downstream is maximum when the beam centroid is adjusted to $\Delta\phi_s = 0$ deg. We scan the horizontal beam position at the middle of Q4 in MEBT1 (see Fig. 1. The black square points in Fig. 4 show the position for ±50 deg with respect to the tuned phase. The fitting by a quadratic function written by the red line indicates that the phase of maximum displacement is 0.29 deg. Consequently, we confirm the nominal phase tuning successfully adjusts the driving phase to at the phase of the maximum deflection.

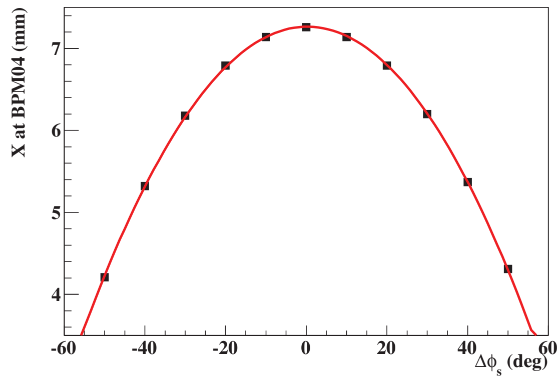

Figure 4: The correlation between the RF phase of the chopper and the beam position at Q1 in MEBT1. The horizontal axis shows the difference of the phase which is obtained by nominal tuning. The red line is the fitting result by quadratic function.

Amplitude Scan

In the experiment, we record the time evolution of one BLM signal in RCS as shown in Fig. 5. Because the measurement is conducted with the chopper being on, the beam loss in RCS comes only from the remnant beam in the beamline due to the insufficient deflection by the chopper. Most of the beam out of the RF bucket is considered to be lost at arc sections during the acceleration due to the transverse mismatch of the magnetic field of bending magnets. We select one BLM, C08arc, placed near the arc. The BLM is a proportional counter produced by Toshiba Electron Tunes & Device Co. Ltd. [8]. The signal is recorded by a 9-bit and 250 kHz sampling digital oscilloscope after an amplification and filtering in a read-out circuit. The time range of 40 msec is equivalent to the inverse of the repetition rate of 25 Hz. It takes about 20 msec for the beam injection, acceleration and extraction. In the figure, the acceleration starts at 3 msec. Since the shape peak around 23 msec is the noise coming from the excitation of the extraction magnets, we can see the beam is extracted soon after the peak. And the enhancement around the 24 msec is also noise from extraction related apparatus. In the figure, we plot the BLM signals with three amplitudes of the chopper RF, 1.2, 1.4 and 2.0 MV/m. The significant beam loss is observed in early acceleration stage of 5 to 10 msec and the signal is large as the RF amplitude is low. The signal of 1.2 MV/m shows a flat top shape due to the signal saturation. Therefore, the beam loss at 1.2 MV/m is beyond the dynamic range of the BLM. Meanwhile, A baseline shift is observed of the signal in 1.2 MV/m after 12 msec. Since the signal after 12 msec is same shape except for the base line shift, we decide to integrate the signal from 3 to 12

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msec in the analysis.

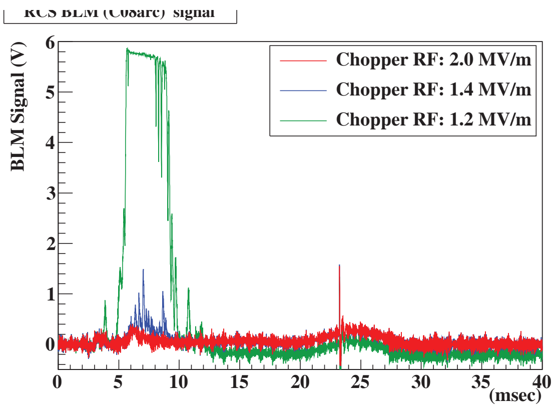

Figure 5: Time evolution of the BLM (C08arc) signal for one acceleration cycle of RCS. The acceleration starts soon after the beam injection at 3 msec, and then the beam is extracted at 23 msec. The signal distributions at the RF amplitude of 2.0 (red), 1.4 (blue) and 1.2 MV/m (green) are plotted. We integrate the BLM signal from 3 to 12 msec for the evaluation of beam loss.

The integrated BLM signals are plotted in Fig. 6 as a function of the chopper electric field. We measure the BLM signal at five electric fields: 1.2, 1.4, 1.5, 1.6 and 2.0 MV/m. The signal increase as the electric field is low, especially a sharp enhancement is observed from 1.4 to 1.2 MV/m. Since the beam loss at 1.2 MV/m is underestimated due to the signal saturation, actual enhancement is more drastically. Therefore, it is considered that a part of the beam core is split out from the chopper effective area in 1.2 MV/m. The signal also increases from 2.0 to 1.6 MV/m. However, we supposed that the beam is perfectly eliminated from the beamline at design of 1.6 MV/m. The small enhancement of the signal from 2.0 to 1.6 MV/m indicates that the beam halo distributes wider than our estimation in phase direction. Consequently, we find that the full width of the beam core is smaller than the effective region at 1.4 MV/m, whereas beam halo distributes beyond the effective area at 1.6 MV/m.

Phase Scan

Next, we have measured the phase dependence of the beam loss for two amplitudes, 1.6 and 2.0 MV/m, as shown in Fig. 7. The scan region is in $\Delta\phi_s = \pm 30$ deg with every 5 or 10 deg. The blue line shows the beam loss at 2.0 MV/m and the red line is that at 1.6 MV/m, respectively. The beam loss at 1.6 MV/m is higher beam loss than 2.0 MV/m in all over the region. In the positive phase side, the beam loss gradually increases as the phase is away from the $\Delta\phi_s = 0$ deg, and the beam loss of two amplitude is similar level. It indicates that the particle density between the edges of their effective regions is very low and the small fraction continues at $\phi_s = 15$ deg. Therefore the beam halo widely distributes in the negative phase region. On

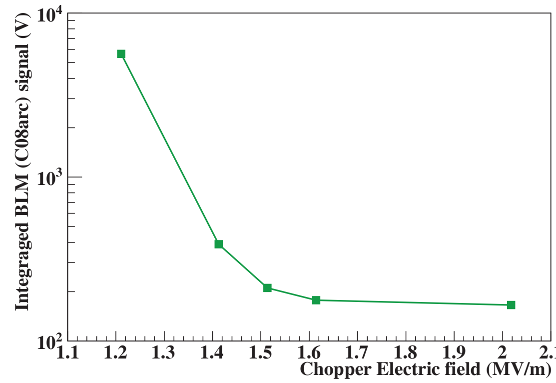

Figure 6: The integrated BLM signal as a function of chopper RF amplitude. The driving phase of the chopper is adjusted at the maximum deflection angle.

the other hand, the beam loss distribution in the negative phase region is completely different from the other side. The beam loss declines from 0 to -10 deg in 2.0 MV/m. It indicates that the beam halo in the negative phase side continues out of the effective region and a part of the halo goes inside the effective region by -10 deg shift. It also shows the margin of the effective area in the positive side is between 10 to 20 deg, because another -10 deg shift (-20 deg in total) causes a significant enhancement of the beam loss. A portion of the beam in the positive side splits out from the effective region. The beam loss out of -20 deg increases drastically due to the slop-over of the beam core. Consequently, we obtain the qualitative beam profile shown in the bottom of Fig. 7; the beam halo continues out of the effective region in the negative phase side, and there is about 10 deg margin from the edge of effective region and beam core in the positive phase side.

DISCUSSION

We analyze the phase scan data shown in Fig. 7 in order to obtain the quantitative beam distribution on the phase direction. In the 2.0 MV/m result, we observe weak beam loss in the range of -20 deg $< \Delta\phi_s < 20$ deg. However, the beam extinction ratio in this range is in the order of 10^{-7} according to the above-mentioned beam extinction measurement at MLF. As our target is to achieve the beam extension of $< 10^{-4}$, we here neglect the extremely thin halo in defining the edge of the beam tail while it is still noteworthy that the thin halo is observed beyond the defined tail edge. On the other hand, the beam loss outside of ± 20 deg drastically increases. Meanwhile, the result of 1.6 MV/m shows the similar distribution in the negative phase; the beam loss for $\Delta\phi_s > -15$ deg is less than 1 kV and it quickly increases at -20 deg. Assuming the enhancement comes from the leakage of the beam tail from the effective areas within which the particle feels sufficient deflecting field to be eliminated. The edges of the effective regions are at the edge of the beam tail when the RF is

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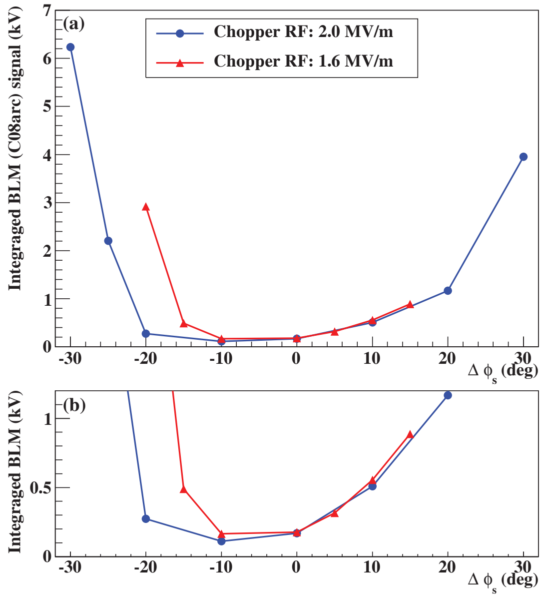

Figure 7: (a) The integrated BLM signals as a function of driving phase with respect to the angle with maximum deflection angle. The RF amplitude is set to 2.0 (blue) and 1.6 (red) MV/m. (b) Same as (a) but expansion of low beam loss region.

2.0 MV/m with $\Delta\phi_s = -20$ deg and 1.6 MV/m with -15 deg as shown in Fig. 8, At the edge of the effective are, the threshold deflection field is felt by the particles. Then, the threshold should be the same in the positive and negative phase sides. Therefore, the half beam tail width, $\delta\phi$, satisfies the equation,

$$2.0\cos(-20+\delta\phi) = 1.6\cos(-15+\delta\phi), \qquad (1)$$

where $\delta\phi$ is full width of the beam core. Consequently, we obtain the $\delta\phi$ to be 50 deg.

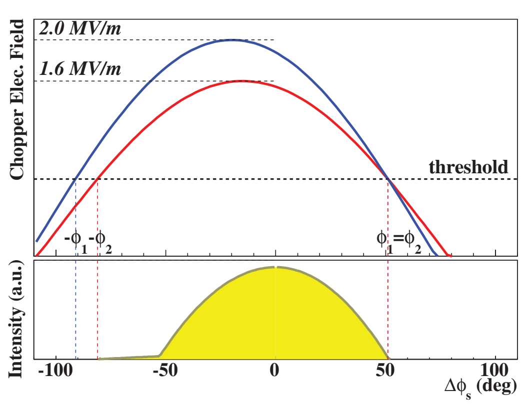

Figure 8: RF wave of 2.0 MV/m at $\Delta\phi_s = -20$ deg (blue) and 1.6 MV/m at -15 deg (red). Assuming the crossing-point is equivalent to the edge of the beam core in the positive phase side, we obtained half width to be 50 deg.

SUMMARY

The performance of the RF chopper system is one of the key issues for the beam intensity project of the linac of J-PARC. The measurement of the beam width at the chopper cavity is important parameter to consider the upgrade of the system. We successfully obtain the beam profile on the phase axis by measuring the beam loss in RCS with various RF settings of the chopper cavity. The result indicates the different beam shape in each side. In addition to the full beam width is about ± 50 deg, the beam halo widely distribute in the negative side.

ACKNOWLEDGEMENTS

The authors would like to thanks P.K. Saha for helpful supports for the data-taking of the RCS beam loss. We also thank S. Meigo for the analysis of the beam extinction measurement.

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ISBN 978-3-95450-118-2