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DEVELOPMENT OF WIDEBAND BPM FOR PRECISE MEASUREMENT OF INTERNAL BUNCH MOTION

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Abstract

To suppress intra-bunch oscillations and to reduce particle losses, the intra-bunch feedback (IBFB) system has been developed in 2014 for the J-PARC Main Ring (MR). A new BPM was also installed to the MR for the IBFB system. This BPM has a sufficient frequency response and position sensitivity. (up to 1.5GHz within 15% fluctuation.) However, the performance needs to be further improved, particularly at high frequency, for more precise analysis of internal motions (e.g. due to electron clouds). We report the development of the BPM and precise measurement results of the BPM characteristics. We also show simulation studies of the digital equalizer which helps to reconstruct the beam shape from beam signals.

INTRODUCTION

The J-PARC is composed of three proton accelerators: the 400MeV linear accelerator (LINAC), the 3GeV Rapid Cycling Synchrotron (RCS), and the 30GeV Main Ring (MR) Synchrotron. At the J-PARC MR, transverse instabilities have been observed at the injection and during the acceleration. To suppress these instabilities, intra-bunch feedback system (IBFB) (Fig. 1) has been developed since 2014. It performs well in supressing instabilities and reducing beam losses [1].

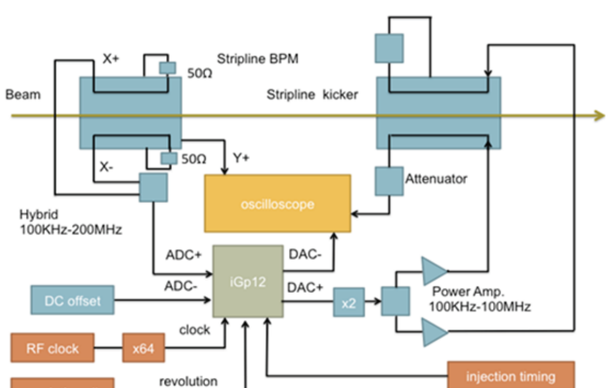

Figure 1: Schematic of the intra-bunch feedback system.

EXPONENTIAL TAPERED COUPLER

Exponential tapered couplers (ETC) [2] have been used for IBFB. They have a wider frequency response than a normal rectangular coupler. The details are described in Ref [1]. The ETC transfer function can be written as Eqs. (1) and (2). Measurement results agree with Eq. (1) within

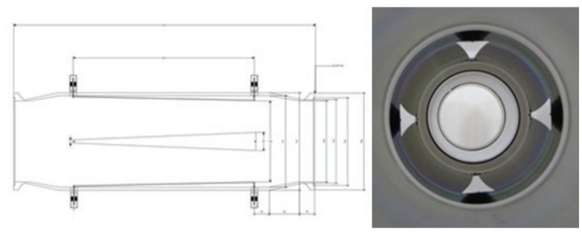

Figure 2: Side (left) and front (right) views of BPM.

15% fluctuation up to 1.5GHz (the blue line in Fig. 7). But a wider and flatter frequency response will be needed in future for more precise analysis of internal motions. In this paper, we report the development of the BPM to match measurement with theoretically designed response accurately.

$$|F(\omega)| = \frac{\frac{K\omega l}{c}}{\sqrt{a^2 + \frac{4\omega^2 l^2}{c^2}}} \left(1 + e^{-2a} - 2e^{-a}\cos\frac{2\omega l}{c}\right)^{\frac{1}{2}} \tag{1}$$

$$Arg(F(\omega)) = \arctan\left(\frac{\frac{2\omega l}{c}\sin\frac{2\omega l}{c} + a(e^a - \cos\frac{2\omega l}{c})}{\frac{2\omega l}{c}(e^a - \cos\frac{2\omega l}{c}) - a\sin\frac{2\omega l}{c}}\right) \tag{2}$$

NEW DESIGN OF BPM STRIPLINE

Impedance Matching

The fluctuation in the frequency response seems to be caused by the impedance mismatching in the BPM electrodes and some problems in the measurement method. The black line in Fig. 4 shows the impedance of electrodes measured by Time Domain Reflectometry (TDR). The two large peaks appear at the feed-through positions, and the fluctuation between them corresponds to impedance of the electrodes. The characteristic impedance of BPM is determined by the width and thickness of electrodes and their position. As the width is changed exponentially, the thickness or the distance from the chamber wall should be changed proportionally to the change in the width.

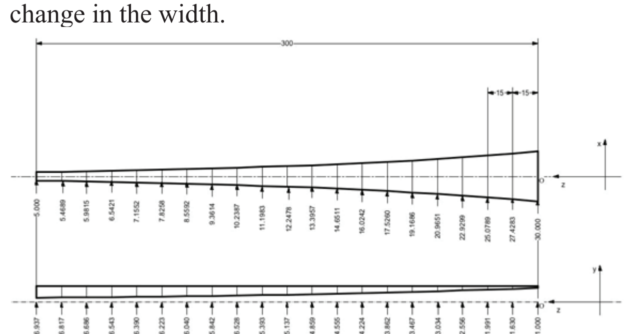

Figure 3: Design of new electrodes.

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It is not really practical to change the electrode's distance from the chamber wall exponentially, since an accuracy of a few micro-meters is required for correct set-up. Instead, we built electrodes whose side thickness along the electrode is changed so that the impedance becomes a constant (see Fig. 3). The actual thickness was determined by 2D boundary elementary method (BEM) [3] at each point.

Feed-through

The present feed-throughs have impedance of about 90-Ohm, which causes the large two peaks in Fig.4. To reduce these peaks, copper tapes were wound around the feed-throughs to make their impedance to 50 Ohm.

Measurements by TDR

Figure 5 shows the characteristic impedance of electrodes measured by TDR. The two large peaks are reduced and the impedance fluctuation along the electrode is now within 2-Ohm. The remaining peaks at the feed-throughs can be further reduced by fine tuning of the inner conductor radius.

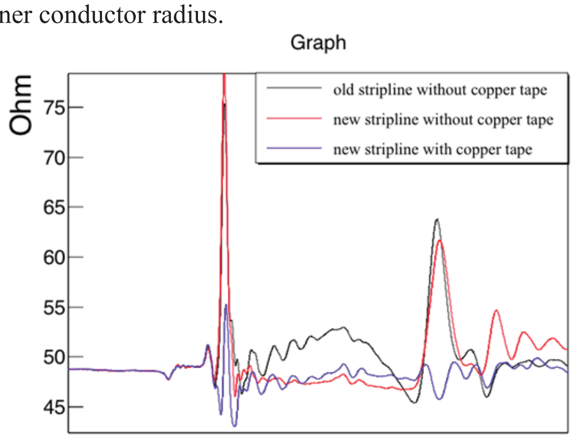

Figure 4: Characteristic impedance. Black line: old electrode. Red: new electrode without copper tape. Blue: new electrode with copper tape.

Tapered Ducts

The ETC characteristics were measured by the stretched wire method [4]. This method suffers from a reflection signal from an insertion device due to the impedance miss-matching. To avoid reflection signals, we used Time Domain Gate (TDG) method [5]. But even if the TDG method is applied, some reflection signals will still remain and we need another measure to reduce reflection signals further.

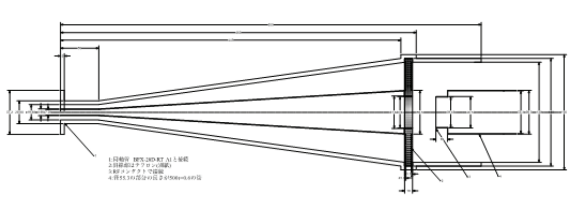

Figure 5: Overview of the tapered duct.

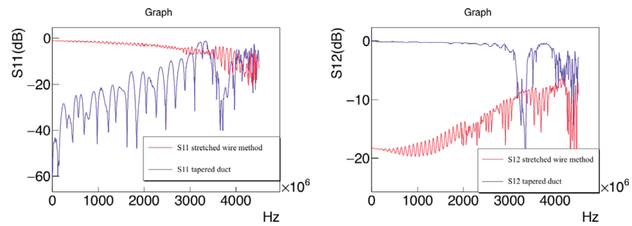

Figure 6: S-parameters of tapered ducts: left S11, right: S12.

We fabricated tapered ducts (Fig. 5) to match impedance in all sections by changing both outer and inner radii of the conductors. Some reflection signals still remain, but we can measure the BPM characteristics with -20dB reflection up to about 1.8GHz (Fig. 6).

Measurement of Longitudinal Transfer Impedance

The blue and the black lines in Fig.7 show the previous measurement result (by the wire method in combination with TDG), and the new result with the tapered ducts, respectively. The red line is the theoretical fit of the new result by using *a,l,K,c* in Eq. (1) as a free parameters. Some spikes are visible in the plots over 1.0GHz, but the deterioration of frequency response at high frequency is improved, and the measurement results agree with the theory up to 3.0GHz.

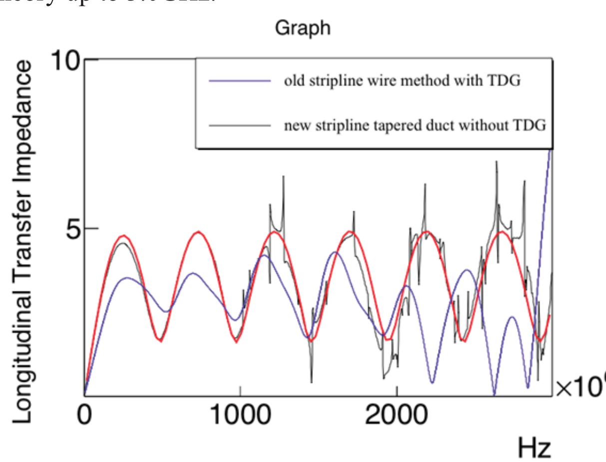

Figure 7: Longitudinal transfer impedance. Blue: the previous result. Black: the new measurement.

Coupling Between a Beam and Electrodes

Though the behaviour of the frequency response is improved at high frequency, the ringing is increased from the old case. This may be due to change in the coupling between the electrodes and a beam. Figure 8 shows the transfer impedance of electrodes at each point calculated by the 2D BEM. The transfer impedance of the old electrode is approximately proportional to the width due to the constant thickness. But the transfer impedance of new one depends not only on the width but also on the thickness, and as a result that the coupling with a beam is increased. That corresponds to a larger a in Eq (1).

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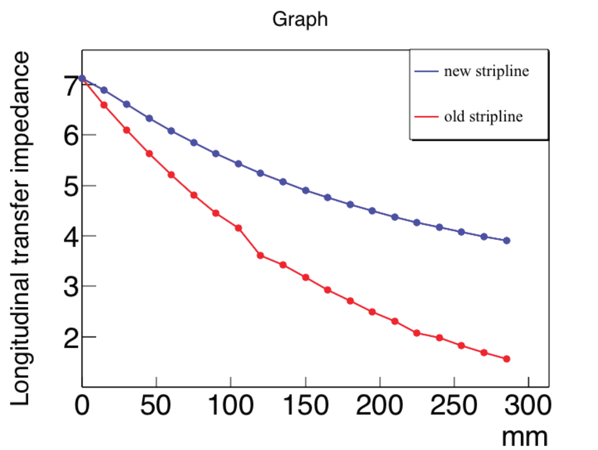

Figure 8: Transfer impedance calculated by BEM. Blue: new electrode. Red: previous electrode.

Correction of BPM Characteristics and Cable Dispersion

BPM signals contain both beam current signals and BPM characteristics. So we need to correct BPM signals to get right beam signals out of them. Right now, the beam current is reconstructed by integration. But integration is valid only below 200MHz. To equalize these effects, we are considering a new digital equalizer. One example is a 50tap Finite Impulse Response (FIR) filter with 2.0GHz clock frequency. The FIR filter coefficients are determined by applying FFT to the function shown in Fig 10.

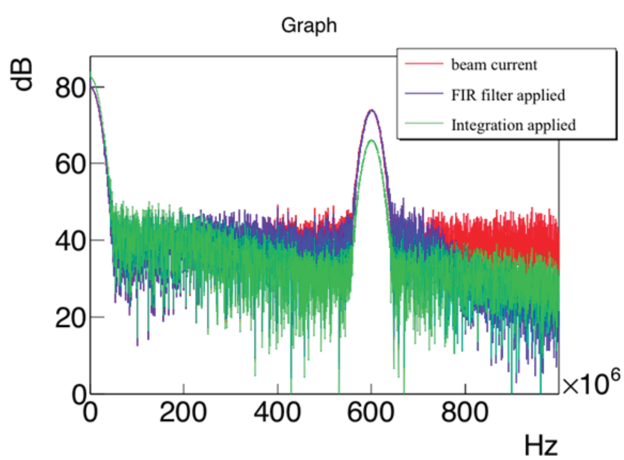

Figure 9: FFT amplitude. Red: beam current. Blue:After FIR filter applied. Green: Integration applied.

After a FIR filter is implemented, the reconstruction of the beam current will be more accurate than the integration method (see Fig. 9). We should also improve the cable dispersion. We are using ~300m long coaxial cables (the outer radius=2.9mm, and the inner radius= 3.0mm). For example, a 600MHz signal will attenuate by about –25dB in this cable. This effect also can be equalized by the digital filter.

CONCLUSIONS

To improve the frequency response at high frequency, we developed a new type of exponential electrodes with changing width and side thickness to keep impedance constant along the electrode. For more accurate measurements, we also built tapered ducts to reduce reflection signals. With these new improvements, the deterioration of frequency response at high frequency is significantly mitigated up to 3.0GHz, though the ringing of the frequency response is worsened due to an increase of the coupling with a beam. Several improvements for better frequency response are under consideration.

For more improvements, a digital equalizer for BPM and the cable dispersion is under consideration.

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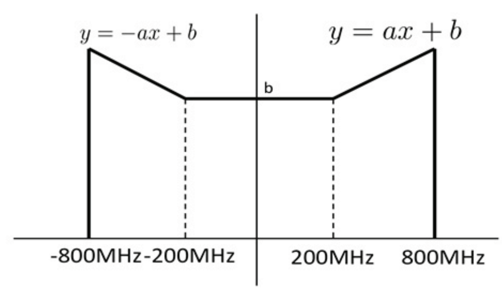

Figure 10: Desired frequency response for BPM.

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