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DEVELOPMENT OF 16-ELCTRODES BEAM-SIZE MONITORS FOR J-PARC MR

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Abstract

For J-PARC Main Ring(MR), 16 electrodes beam-size monitors are developed aiming at measuring the beam sizes of high intensity beams up to 1.3 MW in 1.2 s cycle operation of the MR. Furthermore, with high accuracy measurements of beam sizes, the injection mismatch from the RCS is to be decreased. In the beam test in February 2019, the signal-noise ratio (SNR) of the 1st 16-electrodes monitor in bunch-by-bunch measurements was nearly 40 dB and lower than the design value 50 dB. To improve the SNR, we considered to develop new LPFs for anti-aliasing and attenuators system. In addition, the second monitor was installed in August 2019 and will be tested with beams in November.

INTRODUCTION

In 2018, the beam power of J-PARC MR is 490 kW and scheduled to be upgraded to 1.3 MW in 2021. For this, it is necessary to reduce beam losses and understand it. Therefore, the developments of new beam profile monitors are important.

Beam-profile monitors such as a Flying Wire Monitor [1] and an Ionization Profile Monitor [2] are already installed in MR. However, the two monitors have issues in measuring higher intensity beams. The former is that the wire gets easily burned out and the latter is that there is a sign of the saturation by a space charge effect. Therefore, we are developing 16-electrodes monitors (Figure 1) aiming at measuring the beam sizes of high intensity proton beams up to 4.2×10^{13} protons per bunch, which corresponds to 1.3 MW in 1.16 s cycle operation of the MR.

Measurements of Beam Sizes

The relation between induced voltage V_i ($i = 0, 1, \ldots, 15$) in the electrode of ch i and transverse moments $Q, Q\langle x\rangle, Q\langle y\rangle, Q\langle x^2-y^2\rangle, Q\langle 2xy\rangle, \ldots$ is given by:

$$\begin{pmatrix} g_0 V_0 \\ g_1 V_1 \\ \vdots \\ g_{15} V_{15} \end{pmatrix} = A \times \begin{pmatrix} Q \\ Q\langle x\rangle \\ Q\langle y\rangle \\ Q\langle x^2-y^2\rangle \\ Q\langle 2xy\rangle \\ \cdots \end{pmatrix} \quad (1)$$

$\langle\rangle$ and Q show weighted mean of the charge distribution of beams and total charges.. The matrix A is calibration matrix 16×16 and obtained by wire calibration. The value g_i is the gain of ch. i and obtained by Beam Based Gain Calibration

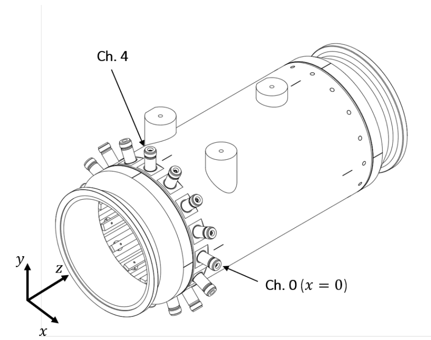

Figure 1: The drafting of 16-electrodes monitor by TOYAMA Co.,Ltd. The size is 500 mm length, 195 mm in outer diameter and 165 mm in inner diameter. Transverse moments of beam are calculated from induced voltages in 16 electrodes which are 320 mm long, 9.85 mm wide and 5.0 mm thick.

which is discussed later. In areas where dispersion functions are zero, the quadrupole moment $\langle x^2-y^2\rangle$ is given by:

$$\langle x^2-y^2\rangle = \langle (x-\langle x\rangle)^2 - (y-\langle y\rangle)^2\rangle + \langle x\rangle^2 - \langle y\rangle^2 \quad (2)$$

$$= \beta_x\epsilon_x - \beta_y\epsilon_y + \langle x\rangle^2 - \langle y\rangle^2 \quad (3)$$

where β_i ($i = x, y$) is the beta function and the ϵ_i is emittance. Hence, we could calculate transverse emittance from measurements of quadrupole moment in two locations which meet $\frac{\beta_{x,1}}{\beta_{x,2}} \neq \frac{\beta_{y,1}}{\beta_{y,2}}$ [3].

Signal Processing

Readout circuits for 16-electrodes monitors are consist of FPGA (VC707 evaluation board) and ADCs (LTM9011-14, 14-Bit, Input Range 2 Vp-p) [4]. The clocks of ADCs are synchronized with the 52th harmonic 88 MHzof the Acc. RF frequency (1.7 MHz). In bunch-by-bunch measurements, the Fourier amplitudes in the 2nd harmonic 3.4 MHz of the Acc. RF frequency are extracted by Goertzel algorithm [5] and used for calculations of transverse moments in FPGA. The frequency band of aliasing noises is 85 MHz. For the attenuations of these noises, low-pass filters (LPFs) are installed before ADC.

PEFORMACE

Beam Test in February 2019

Beam test was done for Beam Based Gain Calibration (BBGC) which is discussed later. Beam parameters and waveforms in this time are given by Table 1 and Figure 2.

Signal-noise-ratio (S/N) was low, so flactations of quadrupole moment was large. (Table 2) In this time, the

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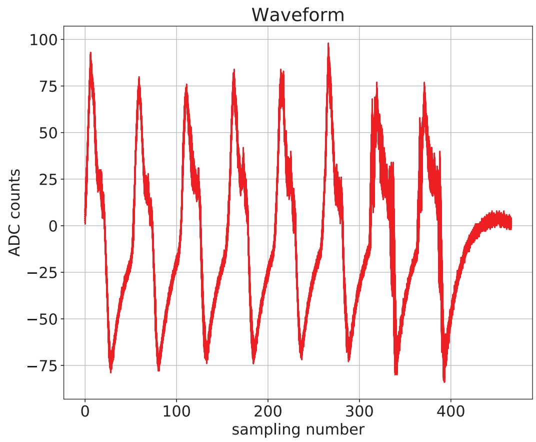

Figure 2: Waveform from ch.0 which is overwriten by turn. It shows 9 buckets by 52 × 9 samples.

Table 1: Beam Parameters

Bunch	8
Thining Ratio	28 / 32
protons per pulse	5.87e+13
Beam Power	5.42 kW
MR Cycle	5200 ms
Acc. mode	3 GeV DC mode

beam was in a steady state, because it measured after ~ 1.5 s from the injection to MR. Threfore, these fluctations are from statsical errors of 16-electrodes monitor. That is because used LPFs whose 3 dB rejection is > 800 kHz attenuated the desirable signal in 3.4 MHz. In the S/N evalutions, the noises are estimated with the data when the acc. RF and magnet power supplies were all powered on but no beam. The errorsis calculated from standard deviation of 1300 turns. For improvements of accuracies, we considered new LPFs & attenuators system (Figure 3) which switches the attenuation from 6 to 20 dB depending on the number of protons per bunch. (The cutoff frequencies of these LPFs are 12 MHz.)

Table 2: Quadrupole Moment and S/N

	$\sigma_x^2 - \sigma_y^2$ [mm^2]	S/N [dB]
1 Bunch	-29.3 ± 11.0	37.4 ± 1.0
8 Bunches	-30.0 ± 3.2	50.7 ± 1.7

Estimations of SNR and Protons/Bunch

From the frequency characteristics of LPF and 16-electordes monitor (Figure 4) which was measured by Network analyser and taper pipe for impedance matching, waveforms of output signals was calculated. Figure 5 shows the expected SNR and peak-to-peak voltages in each proton per bunch.

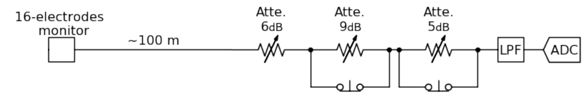

Figure 3: New LPFs & attenuators system (6, 15, 20 dB). LPFs are EF515 [7] whose 3 dB rejection is > 12 MHz. The values of attenuator are optimazed by peak-to-peak voltages which are expected from the frequency characteristics of LPF (EF515) and 16-electrodes monitors. (Figure 5)

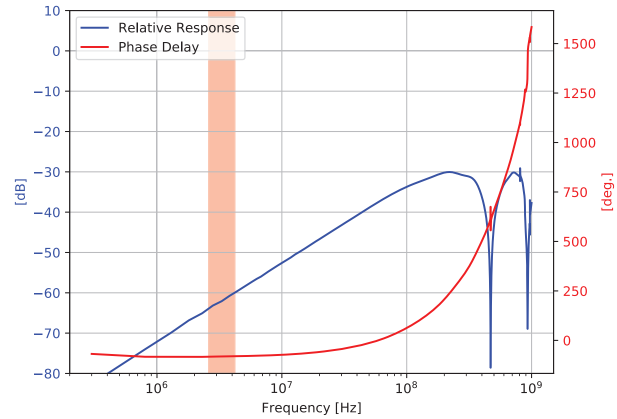

Figure 4: The response of 16-electrodes monitor measured with taper-pipe for impedance match. Blue line is relative response and red line is phase delay. The signal region around 3.4 MHz is presented as red zone. The frequency spectrums of output signals have peaks in the 2nd harmonic of the ACC. RF frequency ~ 3.4MHz.

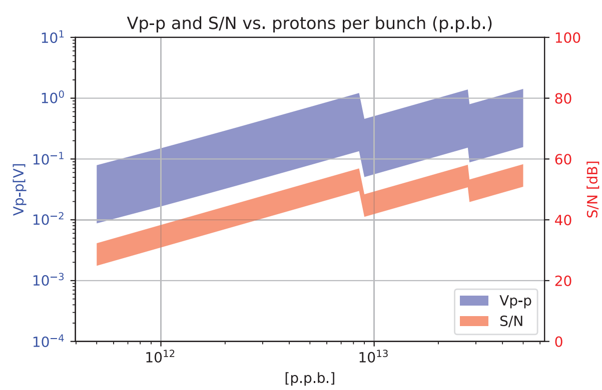

Figure 5: The expected SNR and peak-to-peak voltages in new LPFs and attenuators system (Figure 3). The blue and red zone show peak-to-peak voltages and S/N. The colour bands mean before and after acceleration. It shows S/N reaches 50 dB in high p.p.b > 5×10^{12}.

Resolution of Quadrupole Moment and Emittance

From emittance 17 πmm mrad in user's operations, the relation between S/N and the resolution of quadrupole moments $\sigma_x^2 - \sigma_y^2$ was calculated and given by the blue line of Figure 6. Furthermore, the resolutions of emittances

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ϵ_x, ϵ_y are given by the red lines in Figure 6. $(\beta_x^1, \beta_y^1) = (39.7,\ 5.9)$[m], $(\beta_x^2, \beta_y^2) = (14.6,\ 30.6)$[m] were used as beta functions of the two 16-electrodes monitors. From Figure 6, if S/N is 50 dB, the resolutions of emittances come up to desirable value nearly 3% emittances 17 πmm mrad.

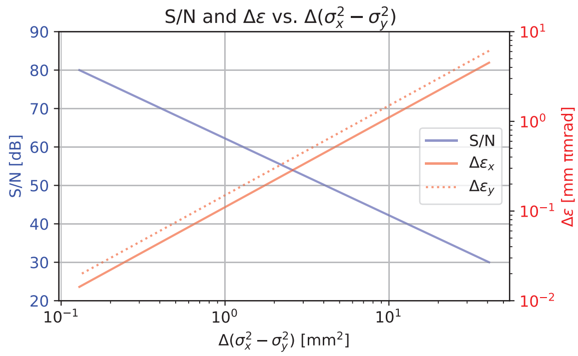

Figure 6: The expected resolution of quadrupole moments $\sigma_x^2 - \sigma_y^2$ and emittances ϵ_x, ϵ_y. The blue and red lines show S/N and the resolutions of emittaces. No change were seen in S/N v.s. $\Delta(\sigma_x^2 - \sigma_y^2)$ from the differeces of beta functions. It shows the results of the last beam test (Table 2) is indicated in error ranges.

Wire Caliration

The matrix A in Eq. (1) was obtained by Wire Calibration. The wire was moved in monitors and applied an electrical current by Network Analyser. The setups are Figures 7 and 8. The output signals from electorodes of monitors are fit by Eq. (1).

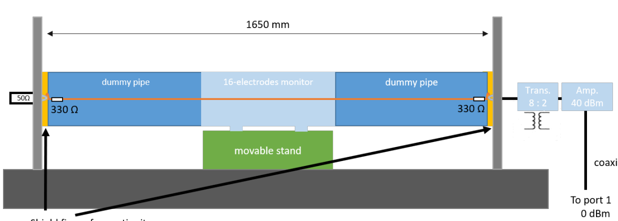

Figure 7: The setup of wire calibration.

The accuracy of wire positions was ~30 µm and used wire was 260 µm in diameter. The number of positions was 97. The resistors 330 Ω and transformer is used for impedance matching between 50 Ω and 386 Ω, impedance of the wire and monitors. Figure 9 shows the differences between calculated moments from wire positions and reconstructed moments. These values could be systematic errors. In the area $R < 30$ mm which beams are exist, the maximum of differences are shown in Table 3 below. From this table, if S/N is > 60 dB, systematic errors from wire calibration come up to statitic errors (Figure 6). The differeces of positions are almost as much as the accuracy of wire positions.

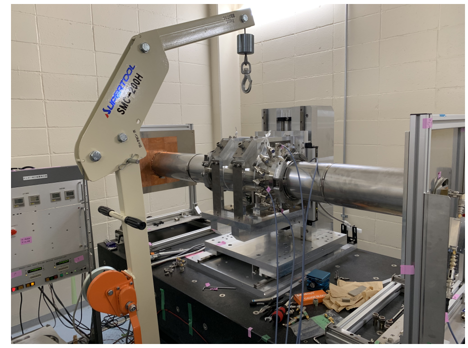

Figure 8: The setup picture of wire calibration. Wire mapping setup for the 2nd 16-electrodes monitor.

Table 3: The maximum of differences between calculated moments from wire positions and reconstructed moments in the area $R < 30$ mm.

Δx	11 µm
Δy	13 µm
$\Delta(x^2 - y^2)$	1.21 mm²

Beam Based Gain Calibration

The gain g_i in Eq. (1) is different for each channel $i (i = 0, 1, ..., 15)$ due to the characteristics of connectors and cables. It could distort beam profiles. Therefore, it is necessary to correct with beams. The method which is planned is below:

- To measure stable beams 10 times in 13 positions by bump orbits (The total of shots is 130.)
- To split 16-electrodes into two pairs of 8-electrodes
- To fit as pairs of transverse moments are equal

It assumed that tranverse distributions of stable beams are 2D gaussian. In this fitting, the free parameters are $g_i, x_k, y_k, (\sigma_x^2 - \sigma_y^2)_k$, where i, k are the channel number $i = 0, 1, 2, ..., 15$ and the shot number $k = 1, 2, ..., 130$. In simulations of 2D electrostatic field, the accuracies of gains are less than 0.3 %.

INSTALLATION OF THE 2ND MONITOR

The 2nd 16-electrodes monitor was installed in MR on 4th September 2019 (Figure 10). The alignment errors will be measured by a laser tracker.The performance of the two 16-electrodes monitors will be checked in November 2019.

CONCLUSION

From the results of last beam test, we evaluated S/N, resolutions of the 1st 16-electrodes monitor and the elements of systematic errors (gain error and wire calibration errors). Furthermore, we considered new LPFs and attenuators system. In this system, desirable S/N 50dB will be archived in the wide range of protons per bunch. The expected errors of emittaces ϵ_x, ϵ_y are Table 4:

The errors of Wire Calibration and BBGC are systematic errors. There are room to improve the method of BBGC

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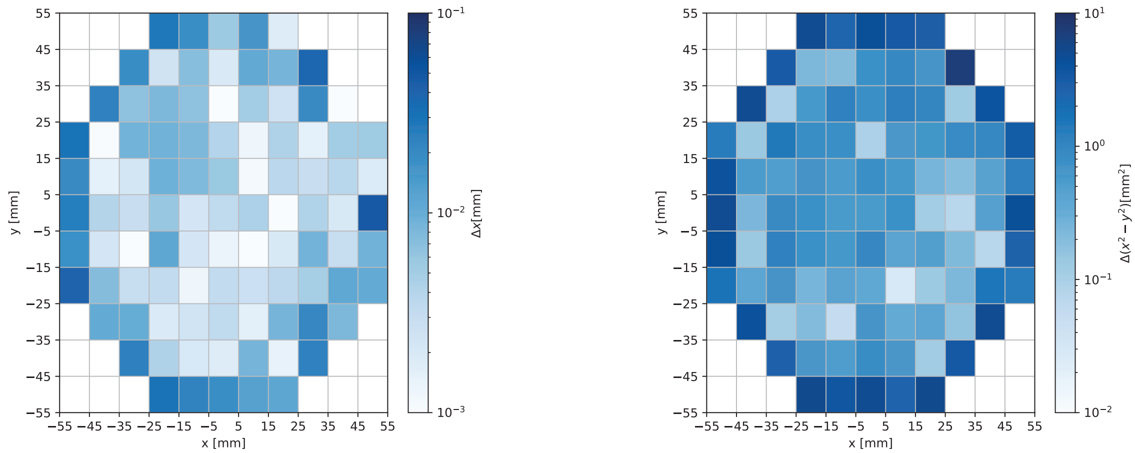

Figure 9: The differences in x, $x^2 - y^2$ which calculated from wire positions and reconstructed. The number of wire positions is 97.

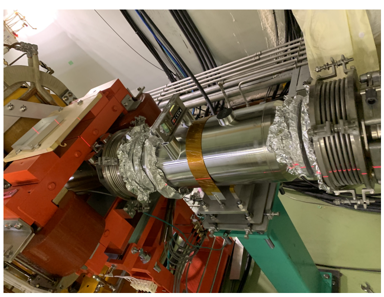

Figure 10: The installation of the 2nd 16-electrodes monitor with the laser ink makers.

Table 4: The Expected Performances $\Delta\epsilon$ [π mm rad]

	$\Delta\epsilon_x$	$\Delta\epsilon_y$
Statistics error (S/N = 50 dB)	0.45	0.61
Statistics error (S/N = 45 dB)	0.80	1.09
Wire Calibration	0.13	0.18
BBGC	< 0.42	< 0.58

and to evalute errors from BBGC. The wire mapping results may give the same calibration matrix A as the beam case, if the output voltages are normalized by the sum of the output voltages [8]. Nevertheless numerical confirmation of the validity of the wire calibration for this monitor will be performed with the simulations.

Two 16-electodes monitors have been installed in MR already. From now on, we will check performances and study the effects of injections mismatch from RCS to MR and tune spreads [9].

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