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ARTICLE

Development of non-destructive large-aperture beam monitor

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A non-destructive large-aperture beam position monitor has been developed to measure the beam position of the 150 MeV Fixed Field Alternating Gradient (FFAG) accelerator at Center for Accelerator and Beam Applied Science of Kyushu University. The results of the performance test of a prototype of the new beam position monitor with multi-electrodes are described.

KEYWORDS: beam monitor, FFAG accelerator, non-destructive, multi electrodes, position resolution

I. Introduction

The 150 MeV Fixed Field Alternating Gradient (FFAG) accelerator[1-10] is under construction at Center for Accelerator and Beam Applied Science of Kyushu University. This accelerator is planned to be devoted to education and investigations in various fields such as nuclear, medical, biological, environmental science and technology.

In a FFAG accelerator, a radius of the beam orbit shifts during acceleration since the magnetic field is static. Therefore, a high-resolution beam monitor that covers much wider range of the horizontal area than that used at ordinary synchrotrons is required for the beam diagnostics. In addition, a non-destructive beam monitor is necessary to prevent the radioactive contamination.

Figure 1 shows the schematic layout of the 150 MeV FFAG accelerator, and its main parameters are summarized in **Table 1**. The beam radius which shifts from 4.47 m to 5.20 m imposes an aperture of the beam position monitor to be over 730 mm. Since the revolution frequency swings between 1.5 MHz to 4.2 MHz during acceleration, the broad frequency bandwidth to cover this frequency range is also requisite to the monitor. Further, the monitor is desired to provide position information with an accuracy of less than 10 mm to optimize the operation of the accelerator. However, the non-destructive beam monitor to meet these requirements has not been developed hitherto, so that the destructive one has been applied for the beam diagnostics of the FFAG accelerator.

We have developed a new non-destructive beam position monitor of electrostatic pick-up type with triangle electrodes. In this paper, the results of the performance test are described.

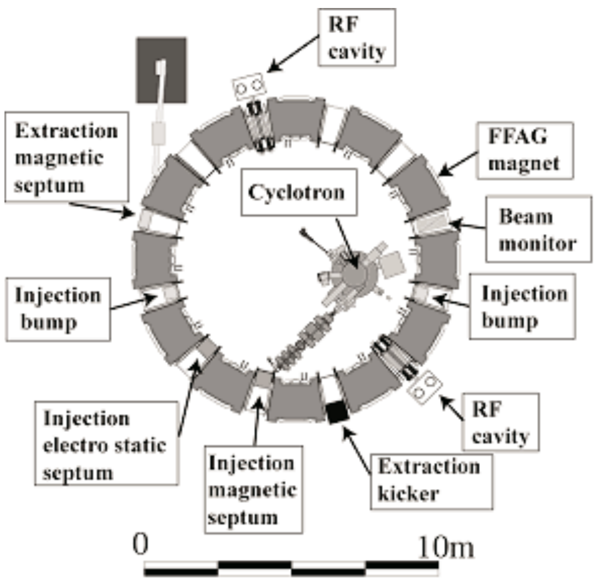

Fig. 1 Schematic view of 150 MeV FFAG accelerator.

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Table 1 Designed parameters of 150 MeV FFAG Accelerator.

Type of Magnet	Triplet Radial（DFD-triplet)
Number of Sector	12
k-value	7.62
Beam Energy(MeV)	12 to 150 (10 to 125)
Average Radius (m)	4.47 - 5.20
Betatron Tune (at injection)	Horizontal 3.69 - 3.80 Vertical 1.14 - 1.30
Rf frequency	1.5 - 4.2 MHz

II. Principle

At proton synchrotrons, the electrostatic pick-up type beam position monitor with triangle electrodes is often installed due to its excellent position linearity and large signal strength. A typical geometry of the beam monitor is shown **Fig. 2**[11, 12]. In the figure, x denotes the distance of a beam from the edge of the left electrode. The amount of electric charge (q_1, q_2) induced on the surface of electrodes is in principle proportional to the pass length of the beam trajectory between the electrodes (l_1, l_2)[11]. q_1 and q_2 are observed as the pick-up voltage (V_1, V_2) generated between the electrodes and a vacuum chamber. Since the left and right electrodes can be considered to have the same capacitance to the chamber, x is expressed as

$$x = \frac{W}{2}\frac{V_2 - V_1}{V_1 + V_2} + \frac{W}{2} = L\frac{V_2}{V_1 + V_2}\tan\phi \,, \quad (1)$$

where W and L are the horizontal and longitudinal lengths of the monitor[12] and $\phi$the angle denoted in Fig. 2.

Figure 3 shows the equivalent circuit schematic of the beam position monitor. V, i, R and C are the pick-up voltage, the beam current, a termination resistance and the coupling capacitance between the chamber and electrodes of the monitor, respectively. A circuit equation is written by

$$\frac{dV}{dt} + \frac{V}{CR} = \frac{1}{C}\frac{dQ}{dt} \,. \quad (2)$$

A solution of eq. (2) includes differential time constant. This shows that the equivalent circuit serves as a Low-Cut Filter. Therefore, the beam position can not be measured if the revolution frequency is lower than a cutoff frequency. The cutoff frequency is given by

$$f = \frac{1}{2\pi RC} \,. \quad (3)$$

In the monitor with triangle electrodes, the position resolution (Δx) can be expressed as

$$\Delta x = \sqrt{(\partial x/\partial V_1)^2 \sigma_{V_1} + (\partial x/\partial V_2)^2 \sigma_{V_2}}$$
$$= f(V_1, V_2, \sigma_{V_1}, \sigma_{V_2}) L \tan\phi, \quad (4)$$

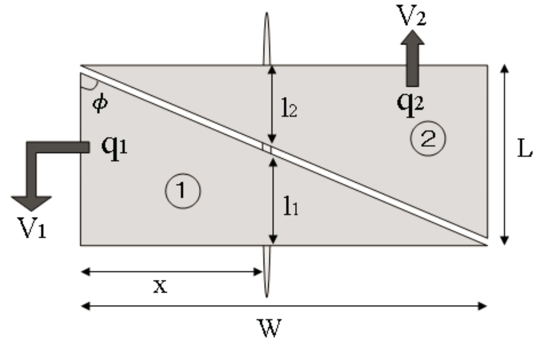

Fig. 2 Top view of an typical beam position monitor with triangle electrodes.

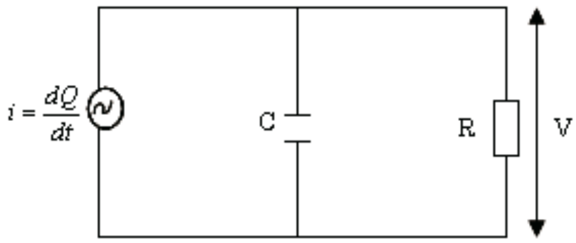

Fig. 3 Equivalent circuit schematic of the beam position monitor.

where σ represents an uncertainty in the measured voltage. The accuracy of position determination becomes higher as the angle ϕ becomes smaller. If L is to be constant, an increase of W results in worse accuracy in position determination. Most simple prescription to assure good accuracy for wide W may be to place the monitors with small ϕ side by side. Since, however, the monitor with triangle electrodes is known to provide inaccurate position information for the side edge region, the beam position around the borders between the adjacent monitors would not be determined accurately. Therefore, the development of the multi-electrode monitor with the configuration of the electrodes to assure accurate position determination for whole of the beam transit region is of importance.

We have proposed a new design concept of a multi-electrode beam monitor, as shown in **Fig. 4**, which has the possible ability to give accurate position information at around the border of the successive regions. The beam position is determined by the pick-up voltages at two pairs of the electrodes in each region by

$$x = \frac{V_{k+1}}{\frac{C_k}{C_{k+1}}V_k + V_{k+1}} L\tan\phi + (K-1)L\tan\phi \quad (5)$$

where k and K are respectively the number of electrodes and a region number, as shown in Fig. 4. The symbol C represents the capacitance between the electrodes and the chamber.

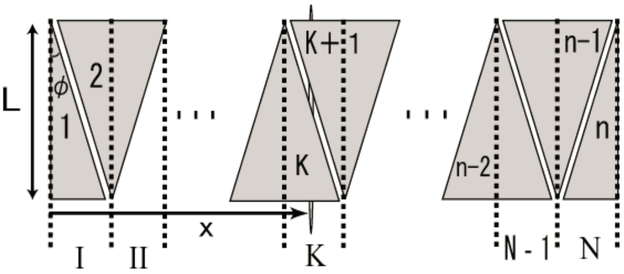

Fig. 4 Top view of a proposed beam position monitor with multi-electrodes.

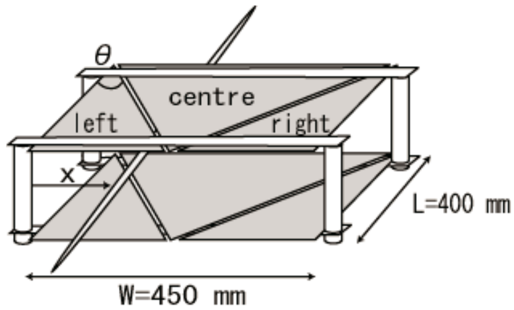

Fig. 5 Schematic view of a beam position monitor with new type electrodes. The electrodes are supported by FRP plates.

III. Experiments

A prototype beam position monitor (n = 3) based on the principle given in Sect. II was designed and built to investigate basic performances of the monitor; a frequency bandwidth and an accuracy of position determination. **Figure 5** shows the schematic layout of the developed monitor. The monitor consists of three pairs of the triangle electrodes which are mechanically supported by FRP plates. In the case n = 3, the beam position can be calculated using the following equation;

$$x = L\tan\theta\left(\frac{V_{right}}{\frac{C_{centre}}{C_{right}}V_{centre}+V_{right}}-\frac{V_{left}}{V_{left\,t}+\frac{C_{centre}}{C_{lef\,y}}V_{centre}}\right)+L\tan\theta, \quad (6)$$

with no need of identification of the left or right region.

Figure 6 shows the experimental setup to examine the prototype beam monitor. The monitor was placed at the center of the vacuum chamber. A copper wire which has a diameter of 5 mm was located on the center plane of the monitor. A voltage waveform generated by a function generator was applied to the wire to simulate the electric field around the beam. The wire was terminated to the ground through a 50 Ohm resister. The pick-up voltage was measured by an oscilloscope.

The frequency of a sine wave voltage applied to the wire by the function generator was varied from 100 Hz to 10 MHz in order to measure the frequency responses and the bandwidth of the monitor. The wire was placed at x = 330 m for the measurements of V_{right} and V_{centre} and at x = 120 mm for those of V_{left}. The applied peak voltage was set to 5.0 V to generate sufficiently high pick-up voltage to observe.

The position dependence of the response of the monitor has also been investigated. The position x of the wire was varied from 15 mm to 425 mm with an interval of 10 mm to investigate the position dependence of the monitor. The pick-up voltage was measured at each wire position A square wave voltage was applied to the wire. The applied voltage, the frequency and duty cycle were 5.0 V, 1.5 MHz and 4%, respectively.

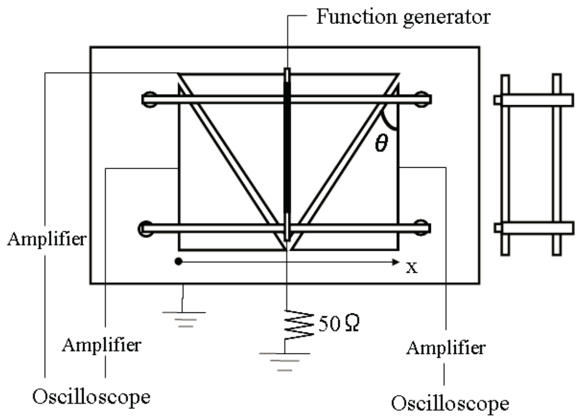

Fig. 6 Setup of experiments.

IV. Results and Discussion

4.1 Frequency bandwidth

Figure 7 shows the pick-up voltages at the individual electrodes relative to the applied voltage to the wire as a function of the frequency. It is shown that the frequency responses of the individual electrodes are almost the same: cutoff frequencies are 800 Hz, sufficiently lower than the revolution frequencies of a proton beam in the 150 MeV FFAG accelerator, and the pick-up voltages are nearly constant in the range of 10^3 to 10^7 Hz. This result indicates that the developed monitor has a wide frequency bandwidth to meet the requirement for the beam diagnostics in the 150 MeV FFAG accelerator.

4.2 Accuracy of position determination

Figure 8 shows the pick-up voltages at the individual electrodes as a function of the position where the wire is set. Three curves have good linearity in the region covered by the respective electrodes, except in the ranges of x smaller than 40 mm and greater than 410 mm. The loss of linearity at around the edge of the monitor is presumably due to the electric field leaks. It is to be noted that three electrodes show a linear response in a wide range including the region around center of the monitor.

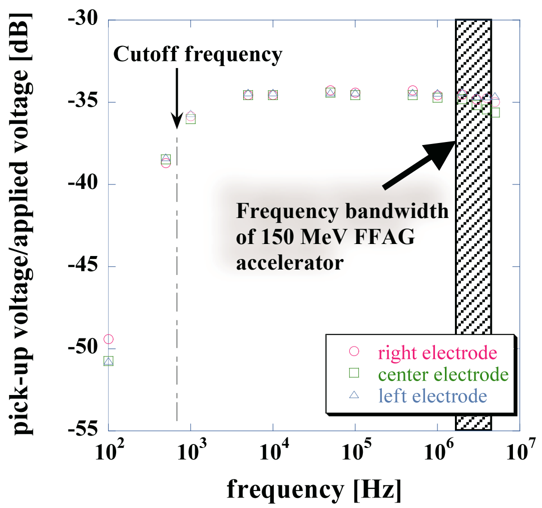

Fig. 7 Pick-up voltages relative to the voltage applied to the wire as a function of frequency.

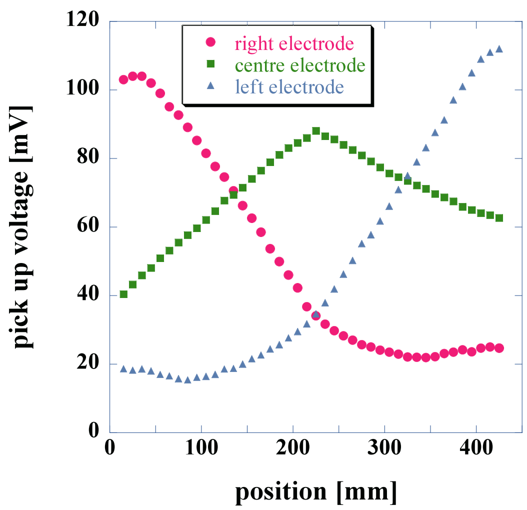

Fig. 8 Pick-up voltages versus wire position.

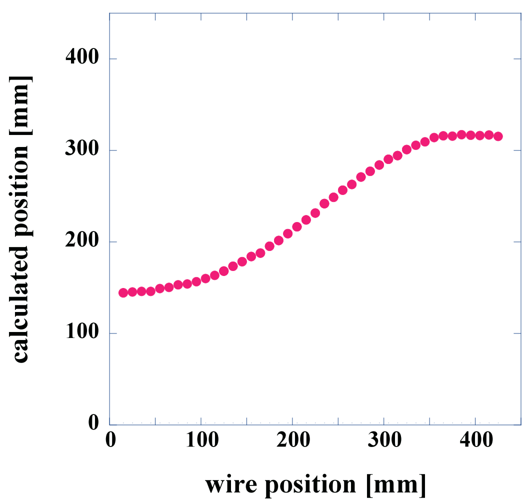

Fig. 9 Position calculated from the measured the pick-up voltages using eq. (6).

Figure 9 shows the calculated position with eq. (6) versus the position of the wire. It can be seen in the figure that the monitor has excellent position linearity in the center region of the monitor. The standard deviation of the calculated position from the linear fit in the range of 125 mm to 325 mm is 3.1 mm. This corresponds to an accuracy of 4.7 mm in standard deviation in determination of the beam position, less enough than 10 mm requisite for the monitor of the 150 MeV FFAG accelerator.

The non-linearity becomes worse if the distance between the wire and the center of the monitor is increased to be more than 100 mm. This is because that the finite pick-up voltage is generated at the electrodes when the wire is set apart from the electrodes, in contrary to the assumption in eq. (6). To extend the range of good linearity for position measurement to meet the requirements for monitoring the beam in the 150 MeV FFAG accelerator with fixing the longitudinal length of the monitor and the θ value of the electrodes, the monitor of proposed design (shown in Fig. 4) is to be composed of more than 5 pairs of the electrodes.

V. Conclusions

The new type of non-destructive beam position monitor has been started to be developed for the beam diagnostics of the 150 MeV FFAG accelerator. The result of the experiments shows that the prototype beam monitor has excellent position linearity except for the edge regions. In addition, the frequency bandwidth of the monitor is shown to cover the repetition frequencies of a proton beam in the 150 MeV FFAG accelerator. Based on the results, we are going to develop a full-scale monitor for practical application.

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