DEVELOPMENT OF SHOEBOX BPM FOR Xi`an PROTON APPLICATION FACILITY

M.W.Wang [1]†, S.X.Zhen , H.Y.Zhang, Z.Yang, X.L.Guan,W.H.Huang,X.W.Wang, Engineer Physics Department, Tsinghua University, Beijing 100084, China
M.T.Qiu,Z.M.Wang, [1] also at State Key Laboratory of Intense Pulsed Radiation Simulation and Effect (Northwest Institute of Nuclear Technology), Shannxi 710024, China

Abstract

In this paper, development of the shoebox BPM is presented which can be applied for the measurement of turn-by-turn position data, closed orbit and tune of Xi'an Proton Application Facility (XiPAF). The preliminary design of the physical dimensions including the electrode aperture, the pipe aperture and the gap between the two electrodes is performed by calculating their effects on BPM response respectively with the equivalent circuit model. Furthermore, the mechanical structure of the shoebox BPM is optimized by CST simulation to achieve better performance. The dependency of the BPM sensitivity and zero offset on the frequency is diminished by adding one isolating ring, which decreases coupling capacitance of electrodes and compensates ground capacitance difference of the two electrodes. Finally one prototype of the shoebox BPM has been fabricated and tested offline. Results show that relative position measurement error due to frequency dependency of sensitivity is less than 1% and absolute measurement error due to frequency dependency of zero offset is expected to be less than 0.1 mm.

INTRODUCTION

XiPAF is a proton facility used for radiation effects research. The synchrotron of XiPAF accelerates proton beam from 7 MeV to 230 MeV with 2×10^{11} protons per bunch. The beam diagnostics layout of XiPAF ring is sketched in Fig. 1. There are 12 shoebox BPMs - 6 for horizontal and 6 for vertical respectively. Each BPM is located between a dipole and a quadrupole. BPMs will be installed inside of corrector magnet yoke to save space. Beam positions can be monitored turn by turn with Libera Hadron electronics, fourier analysis of the turn by turn position data indicates tune. Table 1 summarizes the main parameters of beam and specifications of the BPM system.

Table 1: Main Beam parameters and BPM Requirements

Parameter	*Value*	*Unit*
Revolution frequency	1.18~5.78	MHz
RMS beam length	148~9.2	ns
Peak current	85.5~1390	mA
Beam energy	7~230	MeV
Turn by turn resolution	0.5	mm
Closed orbit resolution	0.1	mm
Linear range	60% of aperture	

†Corresponding author: wmw13@mails.tsinghua.edu.cn

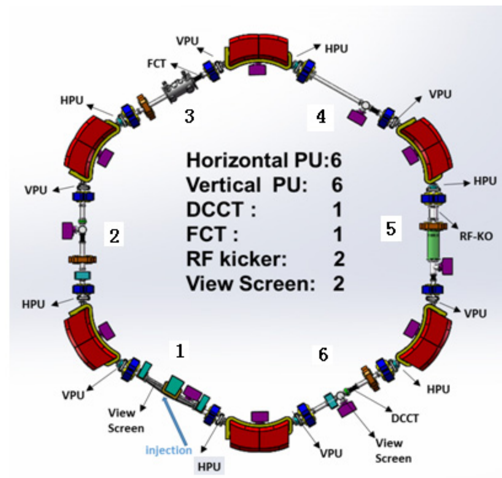

Figure 1: Beam diagnostics layout of XiPAF ring.

THEORY

Due to good linearity and large transfer impedance, shoebox BPM is a good candidate for BPM system of XiPAF. Theory of BPM and equivalent circuit model are shown in Fig. 2 [1]. When a proton beam passes by BPM, an image current, with same density but of inverse polarity, will flow through the electrodes. Seen as a current source, the image current flows through RC parallel circuit. Voltage signals on loads are used for beam position calculation. After simple derivation, we get

$$V(\omega)=Z(\omega)I(\omega)=(1-\frac{x}{a})I_b(\omega)\frac{gl}{v}\frac{i\omega R}{1+i\omega CR}$$

$$\frac{V_l-V_r}{V_l+V_r}=\frac{1}{a}x$$

Where Z transfer impedance, x beam position, a half aperture of BPM, $I_b(\omega)$ beam current, g BPM shape factor, l electrode length, v beam velocity, C electrode ground capacitance and R load impedance.

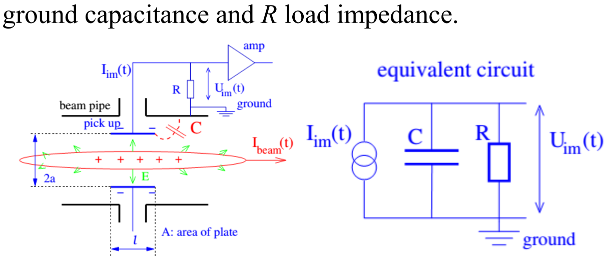

Figure 2: BPM theory diagram and equivalent circuit.

 ISBN 978-3-95450-147-2

Take coupling between electrodes into consideration, equivalent circuit should be modified as shown in Fig. 3. BPM response can be written as follows[2].

$$\frac{V_l - V_r}{V_l + V_r} = \frac{\frac{2}{i\omega R}+C_1+C_2}{\frac{2}{i\omega R}+C_1+C_2+4C_{12}+\frac{x}{a}(C_1\text{-}C_2)}\cdot\frac{x}{a}+\frac{C_1\text{-}C_2}{\frac{2}{i\omega R}+C_1+C_2+4C_{12}+\frac{x}{a}(C_1\text{-}C_2)}$$

Where C_1 and C_2 are ground capacitance of a pair of electrodes respectively and C_{12} is coupling capacitance between electrodes.

As can be seen from the above equation, BPM sensitivity and zero offset have a dependency on frequency caused by coupling capacitance and unequal ground capacitance of the two electrodes.

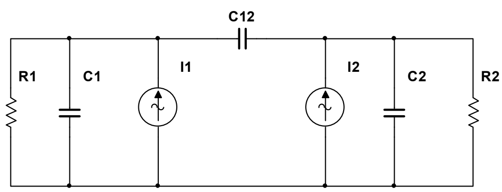

Figure 3: Equivalent circuit including coupling.

DESIGN PROCEDURES

Geometric Design

Geometric design contains six physical dimensions:

- BPM inner half aperture w × h
- BPM outer half aperture W × H
- Gap between electrodes b
- Electrode thickness t
- Electrode length l

Study the relations between each physical dimension and BPM sensitivity *S*, transfer impedance *Z*, ground capacitance *C* and coupling capacitance C_{12} respectively. In order to keep boundary continuity, BPM inner half aperture is chosen the same to beam pipe. BPM outer half aperture decides gap between electrode and ground. The gap has a significant impact on *C*. The relation between BPM outer half aperture and BPM response when other dimensions are fixed is shown in Fig. 4.

Similarly, relations between other dimensions and BPM response can be calculated. The design goal is high sensitivity, high transfer impedance and low coupling capacitance. Although it is impossible in physics to reach all the above demands, we can achieve an optimized compromise with above relations. After an optimization, BPM geometric dimensions are determined to be: w × h = 102 mm × 48 mm, t = 1.5 mm, b = 6 mm, l = 120 mm

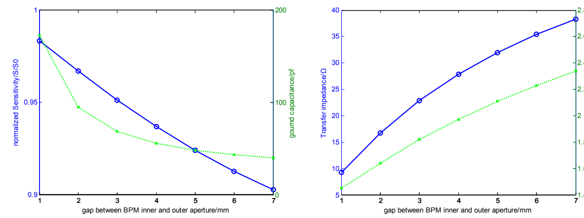

Figure 4: Relation between BPM outer pipe and response.

Particle Simulation

To estimate BPM response more accurately. The 3D EM-Field calculation software CST[3]is used to calculate BPM signal level, sensitivity and linear range. The results are shown in Fig. 5. BPM signal peak value is about 20 mV at the beginning of acceleration and 1.5 V at the end of acceleration. BPM response is linear within almost 80% of aperture. The high cut off frequency is 60 MHz, which means BPM response factors should be as insensitive as possible to frequency within the range. Unfortunately, BPM sensitivity and zero offset have a great dependency on frequency, resulting from coupling capacitance and unequal ground capacitance of the two electrodes respectively. In the original design, coupling capacitance is 3 pF. In the optimized structure, a 4 mm length isolating ring is added to decrease coupling capacitance. As shown in Fig. 6, the optimized structure has higher sensitivity and less frequency dependency. As for zero offset, 3 pF ground capacitance difference of a pair of electrodes is created deliberately by adjusting the distance between one electrode and ground in simulation. Zero offset is a function of frequency and the maximum is about 0.9mm. After adding external 3 pF lumped capacitance to compensate the difference, zero offset drift with frequency is reduced significantly, just about 0.12 mm.

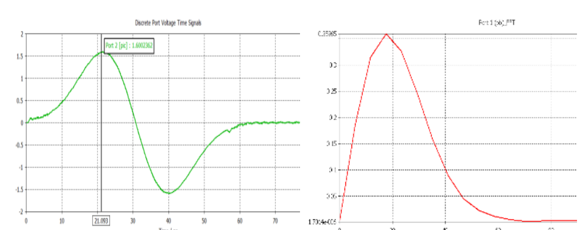

Figure 5: BPM output signal and spectrogram.

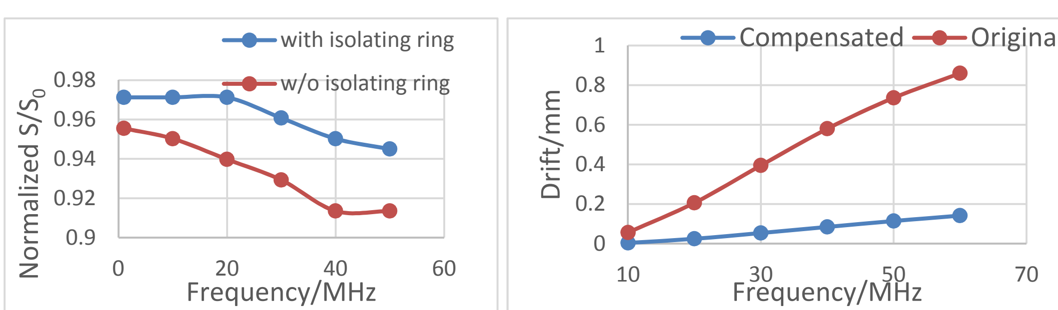

Figure 6: Frequency dependency of sensitivity and zero offset.

OFFLINE TEST

Ground capacitances of the two electrodes measured by using Vector Network Analyzer are 73.5 pF and 74.6 pF respectively. Difference of two electrodes is -1.1 pF, and the coupling capacitance is 0.86 pF, much less than the original design. As shown in Fig. 7, coupling factor is less than -35 dB within the whole frequency range. A wire test bench is also constructed to verify BPM response.

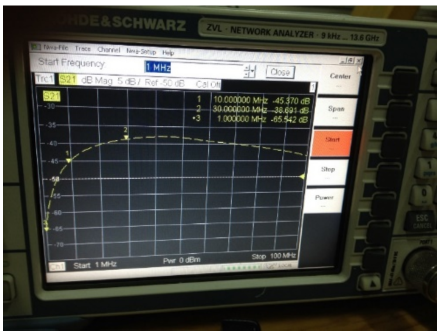

Figure 7: Coupling of the two electrodes.

Sensitivity and Linearity Measurement

Because Libera Hadron is under construction, an oscilloscope is used to measure the BPM signal instead. Considering that signal is not that stable in experiment, we take an average of ten measurements as output. Shown in Fig. 8, linear range is at least 60% of aperture and sensitivity S is 0.019/ mm, which is close to the simulation result 0.0189/ mm. The frequency dependency of S arises as expected. Although *S* is almost independent of frequency below 20 MHz, it decreases with frequency at higher frequency, which is also consistent with simulation. The maximum relative difference of sensitivity is 1% which corresponds to a less than 1% position error. X-Y coupling is also measured, X-Y direction is almost independent within ±5 mm, but nonlinear effect becomes significant at larger deviation.

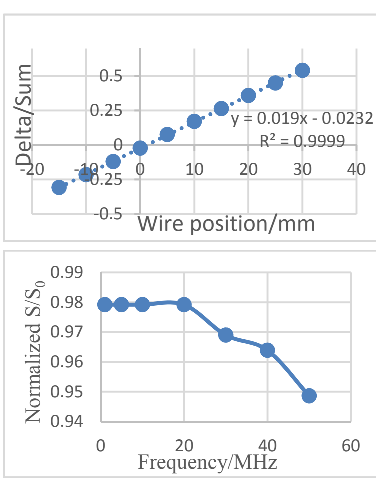

Figure 8: Relation of delta/sum and wire position (top). and normalized sensitivity as a function of frequency (bottom).

Frequency Dependency of Zero Offset

As we analyze above, zero offset has a dependency on frequency due to different capacitances of two electrodes. The prototype original ground capacitances of two electrodes are 73.5 pF and 74.6 pF respectively. Difference is -1.1 pF. Since round hole rather than waist-shape hole in the current isolating ring, it's not easy to compensate the capacitance difference by adjusting isolating ring. We add a lumped 5 pF capacitor at electrode1 instead, leading to capacitance difference 3.9 pF. Zero offset change from a decrease to an increase with frequency and zero offset drift is severer due to larger capacitance difference. We have verified that compensating capacitance difference of two electrodes can really decrease frequency dependency of zero offset.

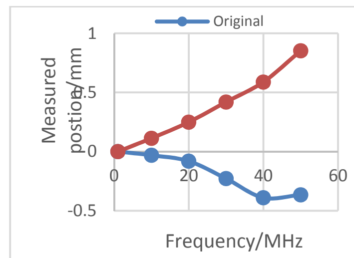

Figure 9: Zero offset drift on frequency for the original prototype and after adding 5 pF capacitor at electrode 1 corresponding to capacitance difference of –1.1 pF and 3.9 pF respectively.

SUMMARY AND CONCLUSION

In this paper, a shoebox BPM for measuring XiPAF beam closed orbit and turn-by-turn position is designed. A preliminary structure is determined by equivalent circuit model. BPM response is optimized by simulation with CST. With isolating ring and compensation capacitor, measurement error of BPM due to frequency dependency of BPM sensitivity and zero offset is decreased to less than 0.2 mm. A prototype of shoebox BPM has been fabricated and the offline test results show the linear range is at least 60% of aperture. The frequency dependency of BPM sensitivity is indeed reduced by an isolating ring. X-Y coupling is negligible within ±5 mm. Zero offset drifting on frequency can be reduced by compensating capacitance difference of the two electrodes. A new isolating ring with waist-shape holes will be fabricated to complete the experiment.

REFERENCES

[1] P.Forck, P.Kowina and D.Liakin,"Beam position monitors". CAS - CERN Accelerator School: Courseon Beam Diagnostics, Dourdan, France, (2008).

[2] H.Y.Bi, T.G.Xu and S.N.Fu, "Design of Linear-Cut Beam Position Monitor in Rapid Cycling Synchrotron of China Spallation Neutron Source". Atomic Energy Science and Technology, vol. 5, pp. 600605. (2011).

[3] https://www.cst.com/