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DESIGN OF A STRIPLINE BPM FOR CSNS-II INJECTION UPGRADE*

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Abstract

The China Spallation Neutron Source (CSNS) accelerator complex is upgrading the injection area to improve the beam-loss control during beam injection and acceleration in the Rapid Cycling Synchrotron. The linac beam energy will be increased from 80 MeV to 300 MeV employing a new superconducting accelerating section, and the beam power at the spallation target will be 500 kW. To accomplish these requirements, a stripline-type beam position monitor(BPM) has been designed with a large aperture and 50 Ω stripline electrodes. This BPM has an inner diameter of 52 mm and is used to detect the beam with a current of 10-30 mA and a pulse width of 100-500 µs. Several geometrical and electrical parameters have been optimized with numerical simulation. This paper will describe the design and optimization of the stripline-type BPM in detail, and simulation results are discussed.

INTRODUCTION

The China Spallation Neutron Source (CSNS) complex is designed to provide a multidisciplinary platform for scientific research and applications by national institutions, universities, and industries [1]. The accelerator of CSNS consists of a low-energy linac, a Rapid Cycling Synchrotron (RCS) and two beam transport lines. For CSNS-II, the accelerator will be upgraded to 500 kW beam power with a beam energy of 1.6 GeV and a repetition rate of 25 Hz. This upgrade involves increasing the linac beam energy from 80 MeV to 300 MeV by using a new superconducting accelerating section [2]. This paper presents the optimization and design of a stripline-type beam position monitor (BPM) with large aperture and 50 Ω stripline electrodes through numerical simulation, while also including error analysis.

BEAM POSITION MONITOR (BPM)

The stripline BPM serves as a broadband coupler, with its pickups operating on the principle of image currents. For the off-centred beam in a beam pipe, the beam charge at the position ($x = r\cos\varphi$, $y = r\cos\varphi$) distributes wall charges in the beam pipe [3], as shown in Fig. 1.

By solving the equivalent 2-dimensional electrostatic image charge problem, the solution can be expressed as a series expansion in Eq. (1).

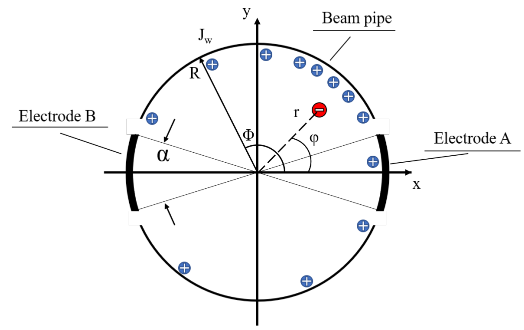

Figure 1: Cross section of BPM pick up model used for calculations.

$$J_w(R,\Phi,r,\varphi) = -\frac{I_{\text{beam}}}{2\pi R}\left[1+\sum_{n=1}^{\infty}\left(\frac{r}{R}\right)^n \cos n(\Phi-\varphi)\right] \quad (1)$$

Consequently the BPM electrode covering an arc α generates a wall current, as is shown in Eq. (2).

$$I_{\text{elec}} = R\int_{-\alpha/2}^{+\alpha/2} J_w(R,\Phi,r,\varphi)\mathrm{d}\Phi \quad (2)$$

Utilizing Eq. (2) and considering the identical BPM pickup electrode transfer impedance, the horizontal position characteristic with x/R being the normalized horizontal beam position can be deduced[3]:

$$\begin{aligned}\frac{\Delta}{\Sigma} = \frac{A-B}{A+B} &\simeq \frac{4\sin(\alpha/2)}{\alpha}\frac{x}{R} + \text{higher order terms} \\ &= \text{hor. position} \approx \frac{2}{R}x\end{aligned} \quad (3)$$

For the strip design of BPM, it is crucial to have impedance matching of vacuum feedthrough and stripline electrode to prevent the beam signal reflection. The impedance of the stripline can be calculated using the following equation[4]:

$$Z = \frac{Z_0}{4\pi}\ln\left\{1+4\left(\frac{h}{w_{eff}}\right)\left(8\left(\frac{h}{w_{eff}}\right)+\sqrt{64\left(\frac{h}{w_{eff}}\right)^2+\pi^2}\right)\right\} \quad (4)$$

where

$$w_{eff} = w + \left(\frac{t}{\pi}\right)\ln\left\{\frac{4e}{\sqrt{\left(\frac{t}{h}\right)^2+\left(\frac{t}{w\pi+1.1t\pi}\right)^2}}\right\} \quad (5)$$

Figure 2 shows the parameter. w is the width of the stripline determined by its angle due to the fixed inner electrode diameter. e is the natural constant (=2.718). h is the

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gap distance between the stripline and the vacuum chamber, and Z_0 is the free space impedance (=376.73 Ω) [5].

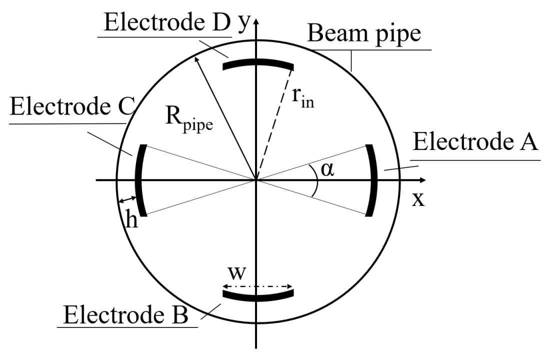


Figure 2: Schematic of stripline BPM with circular cross-section.

The impedance of the stripline increases with an increase in the parameter h, whereas an increase in w results in a decrease of the impedance. To optimize the resolution and signal strength, an angular orientation of 54 degrees was selected. To accurately calculate the impedance of the stripline electrode, which was targeted to be 50 Ω, numerical simulation code CST [6] was employed. Through an optimization process, a final height of 6.1 cm for the stripline electrode was achieved.

In the time-domain reflectometer (TDR) measurement, the time represents the electrical length, including the feedthrough and strip electrode. The rise time given by the Gaussian pulse of the TDR measurement is 32.7 ps, and the points between 0.4 and 1.65 ns correspond to the stripline electrode. The characteristic impedance of the electrode is approximately 50 Ω as shown in Fig. 3.

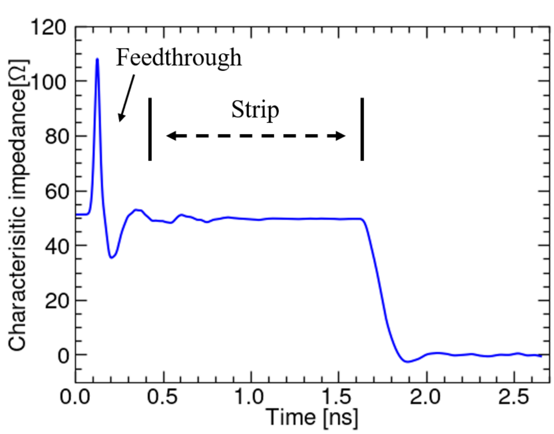


Figure 3: TDR simulation results for stripline BPM.

SIMULATION RESULTS

BPM Calibration

We have simulated the behavior of charge particles for different injection beam energy, i.e., 80 MeV and 300 MeV.

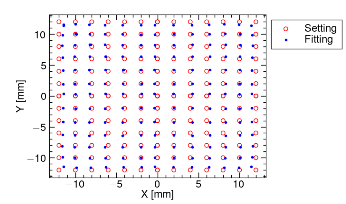
According to Eq. (3), the peak-to-peak value of the stripline signal was utilized to calculate the beam position (X_{raw} and Y_{raw}) in Eq. (6), as follows:

$$X_{\mathrm{raw}} = \frac{U_A - U_C}{U_A + U_C}, Y_{\mathrm{raw}} = \frac{U_B - U_D}{U_B + U_D} \tag{6}$$

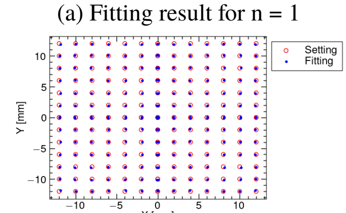
where U_i (i=A, B, C, D) is the peak-to-peak amplitude of the output signal. By using a polynomial of X_{raw} and Y_{raw}, the actual position of the beam can be estimated as

$$\begin{cases} x_{\mathrm{bpm}}^{\mathrm{2D}} = \sum_{i,j=0}^{p,q} (c_{ij} x_{\mathrm{raw}}^{i} y_{\mathrm{raw}}^{j}) \approx x \\ y_{\mathrm{bpm}}^{\mathrm{2D}} = \sum_{i,j=0}^{p,q} (c_{ij} y_{\mathrm{raw}}^{i} x_{\mathrm{raw}}^{j}) \approx y \end{cases} \tag{7}$$

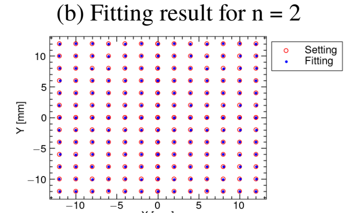
where q and p are the maximum powers for x and y when mapping and fitting by a two-dimensional surface polynomial [3]. The 2D polynomial fit of position characteristic returns a matrix of order p, q with the polynomial coefficients C_{ij}. In this simulation, the particle beam is positioned at intervals of 2 cm, moving along a quarter of the pipe from 0 cm to 12 cm. During mapping, we modify the polynomial order (1, 2, 3) to fit the BPM position. In Fig. 4, the setting position indicates the beam position at CST. The term fitting refers to the position that is fitted based on the signal value. The average fitting error decreased from 393 µm to 100 µm, and then to 19 µm as the polynomial order decreased.



(a) Fitting result for n = 1



(b) Fitting result for n = 2



(c) Fitting result for n = 3

Figure 4: Fitting results for different polynomial order.

Error Analysis

The value of fitting error ($\sqrt{(x - x_{\mathrm{fit}})^2 + (y - y_{\mathrm{fit}})^2}$) with respect to the radius ($R = \sqrt{x^2 + y^2}$) was calculated. Figure 5(a) illustrates that the errors for high-order fittings were

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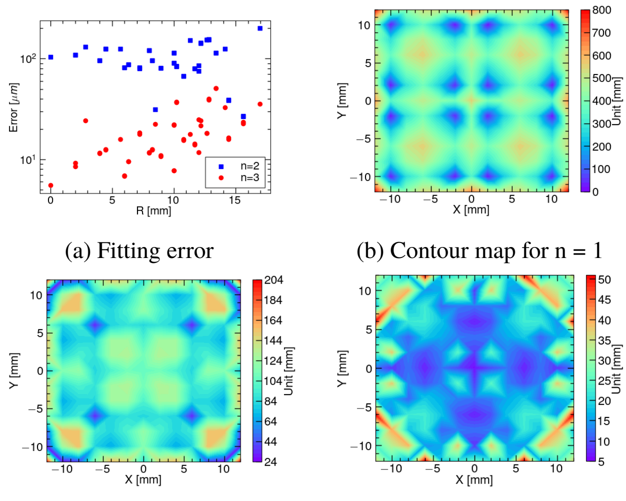
smaller than for low-order fittings. Figure 5(b-d) shows the distribution of fitting errors for n values of 1, 2, and 3. We observed that the error distributions varied with n. The errors in the central region were smaller than those in the edge area. The X_{raw} varies as a function of beam velocity, as shown in Fig. 6. One can see that it is nonlinear, and the higher the beam velocity, the stronger the nonlinear effect.



(a) Fitting error (b) Contour map for n = 1

(c) Contour map for n = 2 (d) Contour map for n = 3

Figure 5: Fitting errors and the contour map for $\beta = 0.65$.

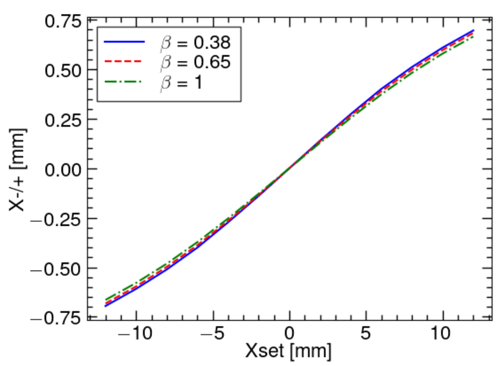


Figure 6: The difference in X_{raw} change with β.

MECHANICAL DESIGN

The final design of the BPM is illustrated in Fig. 7. The length, inner diameter, and open angle of the electrode is 236.48 mm, 52 mm, and 54°, respectively. The length of the beam pipe along with bellows is 340 mm. The gap between electrode and pipe is 6.1 mm, and the height of electrode is 1.5 mm.

CONCLUSION

A stripline-type BPM has been designed for the CSNS-II injection upgrade using numerical simulation code. After optimization, we decided on a 6.1 mm gap between the beam pipe and the strip electrode, an open angle of 54° and an inner diameter of 52 mm. To calibrate the position-measurement

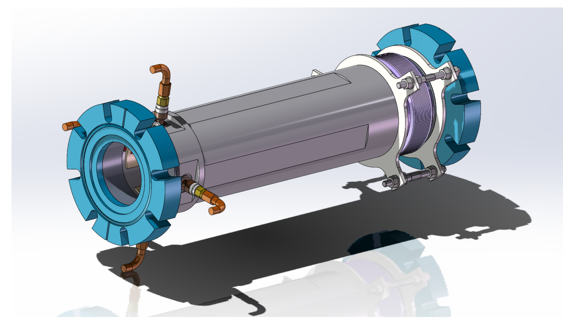


Figure 7: Mechanical design of stripline BPM.

accuracy, we have used the BPM pickup signal to fit the setting position. These results indicate that a higher order of fitting results in a better measurement precision.

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