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DESIGN AND SIMULATION OF STRIPLINE BPM FOR HUST PROTON THERAPY FACILITY

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Abstract

Proton beams used in Huazhong University of Science and Technology Proton Therapy Facility（HUST-PTF）have extreme low currents of the order of nanoampere，which is a great challenge to beam diagnostics due to low signal level. Conventional destructive beam diagnostic devices will affect the quality of the beam and cannot work online during the patient treatment, so a non-destructive stripline beam position monitor (BPM) is designed. This study will introduce some analysis and simulation results of the stripline BPM, such as the coupling between the electrodes, impedance matching, signal response, etc. We also discussed how to increase the output signal by geometry optimization.

INTRODUCTION

Huazhong University of Science and Technology Proton Therapy Facility（HUST-PTF）is a dedicated proton therapy facility [1]. As shown in Fig. 1, it is made up of a 250_MeV superconducting cyclotron, an energy selection system, two rotating gantries, the beam line and a fixed treatment room. The beam current becomes ultra low after the proton beam passes through a degrader, which is a great challenge to measure the beam position. The beam main parameters after the degrader are described in Tab.1. Conventional measurements, such as using an ionization chamber, will introduce some degradation of the beam energy dispersion. From experience of iThemba LABS [2], we plan to design a stripline BPM for HUST-PTF.

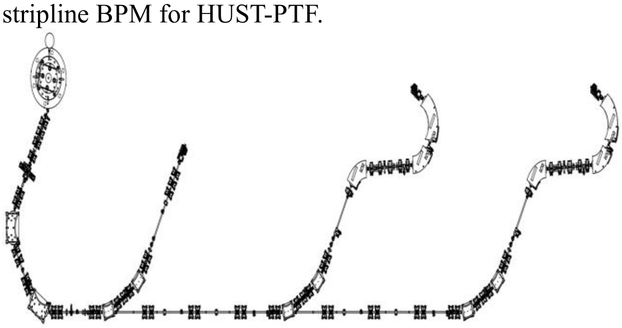

Figure 1: Layout of HUST-PTF.

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Table 1: Beam Parameters After a Degrader

Parameters	value
Bunch length	~200mm
Bunch frequency	73MHz
Bunch radius	2-10mm
Beam energy	70-230Mev
Average current	0.4-4nA

The stripline BPMs can be regarded as transmission-line circuits in microwave engineering. The schematic of stripline BPM is shown in Fig. 2. It is suited for short bunch measurement because the signal propagation is considered. When a Gaussian bunch passes through the BPM, the voltage signal of the upstream port is:

$$V_U(t) = \frac{\phi Z}{4\pi}(\exp(\frac{-(t+l/c)^2}{2\sigma^2}) - \exp(\frac{-(t-l/c)^2}{2\sigma^2}))I_b(t) \quad (1)$$

Where σ represents bunch length. l represents electrode length. ϕ represents electrode radius. The frequency domain expression of the output signal can be written as:

$$V_U(\omega) = \frac{\phi Z}{\sqrt{2\pi}} I_b(\omega)\sin\left(\frac{\omega l}{c}\right) \quad (2)$$

$V_U(\omega)$ is made up of a series of maximum for $f=(2n-1)c/4l$. For a given electronic device the first voltage maxima is located at $l=c/4f$. Because of Libera Single Pass [3] we plan to work at 500_MHz ± 5_MHz in frequency domain, the electrode length is 150_mm to get the voltage maxima at 500_MHz.

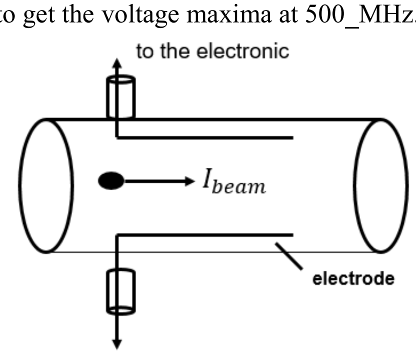

Figure 2: Schematic of stripline electrodes.

IMPEDANCE MATCHING

From Fig. 3 it is clear that the stripline BPM has four electrodes, which support four independent TEM modes, namely a sum mode, two dipole modes (horizontal dipole and vertical dipole), and a quadrupole mode. As shown in Figs. 4 and 5, the electrodes and vacuum pipe can be

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regarded as transmission-line circuits, which can be handle by even-odd mode analysis method.

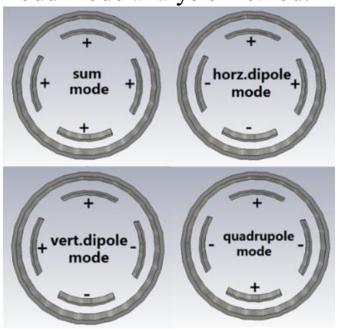

Figure 3: A typical 4 conductors BPM electrode.

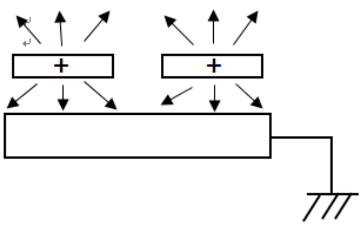
Figure 4: Even mode of coupling transmission line.

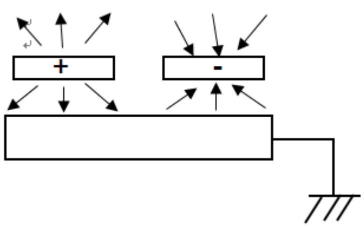
Figure 5: Odd mode of coupling transmission line.

The characteristic impedances of two dipole modes are identical because of the symmetric structure. Calculations shows that the pick-ups are optimally matched to the cable when the following conditions are satisfied [4]:

$$\sqrt{Z_{\text{sum}} Z_{quad}} = Z_{dipole} = R_0 \tag{3}$$

$R_0 = 50\ \Omega$ is the transmission line impedance.

CST EM Studio can calculate the capacitance/length and field energy [5]. A simple electrode model is built in Fig. 6. Then the solution for the impedance follows directly by the relationship $Z = \frac{1}{cC}$. The calculated impedances of every mode are:

$$\begin{aligned} Z_{sum} &= 66.26\Omega \\ Z_{quad} &= 43.59\Omega \\ Z_{dipole} &= 49.81\Omega \end{aligned} \tag{4}$$

Then the solution follows:

$$\sqrt{Z_{sum}.Z_{quad}} \approx \sqrt{Z_{horz}.Z_{vert}} \approx 50\Omega \tag{5}$$

From the calculation, the impedances matching is ideal.

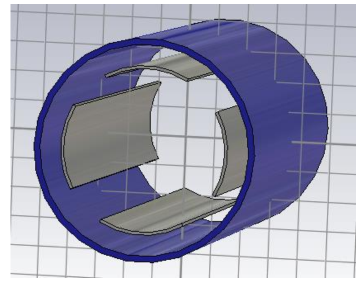
Figure 6: The electrode model in CST EM Studio.

ELECTRODE COUPLING ANALYSIS

Excessive coupling will affect the BPM sensitivity, so it is necessary to calculate the coupling between electrodes. The electric field is concentrated in the transverse direction when the beam passes through the BPM, so the coupling analysis can be done by analyzing electrostatic field [6]. The coupling coefficient can be written as:

$$\begin{aligned} K_{12} &= C_{12} / C_{10} \\ K_{13} &= C_{13} / C_{10} \end{aligned} \tag{6}$$

CST MWS can be used to analyze the coupling between the electrodes. As shown in Fig. 7, a current source is placed on the port 1 and then other port's currents are observed.

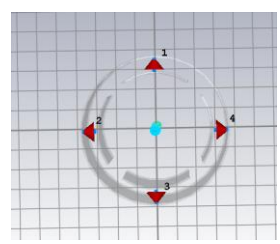
Figure 7: A BPM model in CST MWS.

Figures 8 and 9 show that current signal at port 1 and other ports respectively. The coupling coefficients between adjacent electrodes are $K_{12} = K_{14} = 3.70\%$ .The coupling coefficient between opposite electrode is $K_{13} = 1.45\%$. The adjacent electrode coupling coefficients are larger than the opposite electrode coupling coefficient because of the shielding effect of the adjacent electrodes.

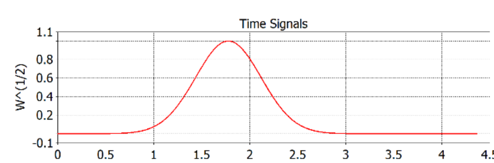

Figure 8: The current at port 1.

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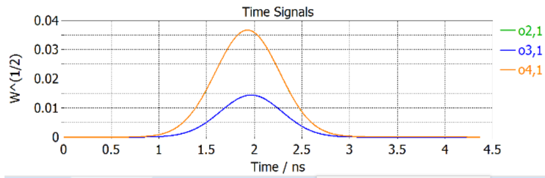

Figure 9: The currents at other ports.

Increasing the distance between adjacent electrodes can decrease the coupling, so can the sensitivity be improved. But large distance between adjacent electrodes also means that electrode radius is small, which will decrease output signal amplitude. A compromise should be made between the coupling coefficients and the output signal amplitude.

BPM MODELING

CST Particle Studio is used to design the stripline BPM. The length of the electrode 150_mm is determined by the electronics of the BPM. The BPM geometry is determined by transmission line impedance, coupling between the electrodes and output signal amplitude. There is a positive correlation between electrode angle and output signal amplitude. However, excessive electrode angle will enlarge the electrode coupling, which will reduce BPM sensitivity. Together with the aforementioned considerations, the parameters of stripline BPM are chosen: φ=60 （φ represents the electrode angle）, $\phi = 27.5mm$, $R = 37mm$ （R represents the pipe radius）. The BPM model is shown in Figure.10.

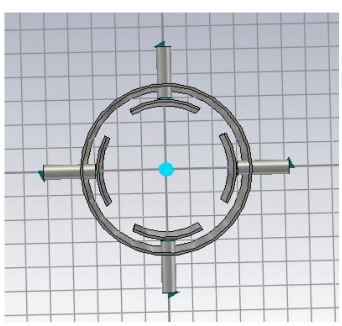
Figure 10: A BPM model in CST MWS.

Table 2: Geometry Parameters of the BPM

Parameters		value
Electrode radius		27.5mm
Electrode angle		60°
Pipe radius		37mm
Pipe thickness		1mm

A proton beam of 70_MeV/0.4_nA and 230_MeV/4_nA are used in our simulations, the output voltage signal are 19nV and 0.35uV, respectively（see Fig.11 and Fig.12）. According to the experience of iThemba LABS，the voltage of the order of nanovolt can be used to detect beam position by a specified electronic equipment [7].

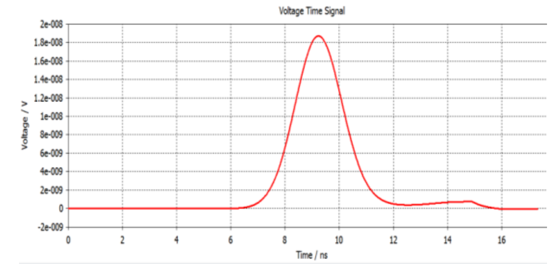

Figure 11: Time-domain output signal at 70Mev/0.4nA.

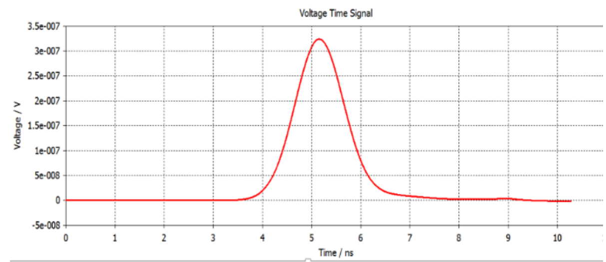

Figure 12: Time-domain output signal at 230Mev/4nA.

CONCLUSIONS

A stripline BPM is designed for HUST-PTF. The even-odd mode analysis method is used to calculate the BPM impedance and make it match optimally to the cable. Then electrode coupling is calculated by CST MWS. Finally, a proton beam of 70_MeV/0.4_nA and 230_MeV/4_nA are simulated by CST Particle Studio, the output signal are 19_nV and 0.35_uV respectively, which can be used to detect beam position by the specific electronic system.

REFERENCES

[1] B. Qin *et al.*, “Progress of the beamline and energy selection system for HUST proton therapy facility”, in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, paper THPVA112, pp. 4719-4721.

[2] D.T. Fourie et al., “Non-destructive beam position measurement in a proton therapy beam line”, in *Proc. DIPAC’09*, Basel, Switzerland.

[3] Matjaz Znidarcic, Libera_brilliance_Single Pass_User_Manual_v_2.00[R], Instrumentation Technologies Company, 2009.

[4] C. Deibele, “Synthesis and Considerations for Optical Matching to a Beam Position Monitor Circuit Impedance” SNS-NOTE DIAG31,2002.

[5] CST - Computer Simulation Technology, http://www.cst.com..

[6] Suwada T, Kamikubota N, Fukuma H, *et al.*, Stripline-type beam-position-monitor system for single-bunch electron/position beam[J]. Nuclear Instruments and Methods in Physics Research, 2000, A440:307-319.

[7] J.L. Conradie et al., “Beam Phase Measurement in a 200 MeV Cyclotron”, in *Proc. EPAC’06*, Edinburgh, June 2006, TUPCH077, p. 1187 (2006); http://www.JACoW. org.