DESIGN AND SIMULATION OF A CAVITY BPM FOR HUST PROTON THERAPY FACILITY*

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Abstract

In a proton therapy facility, non-destructive beam diagnostic devices are essential for the promise of precise beam dose to a patient during treatment. A high dynamic range of beam intensity, which varies from the order of nano-ampere to micro-ampere, is required to meet the clinical requirement. However, it creates challenges to the design of non-destructive beam diagnostics system particularly for the extremely weak beam current. A cavity-type beam position monitor (BPM) device is being developed for the Huazhong University of Science and Technology Proton Therapy Facility (HUST-PTF), which has the advantage of high shunt impedance and can induce sufficient diagnostic signal. The device consists of three cavities, a reference cavity and two position-cavities placed orthogonally. Both CST Microwave Studio and Particle Studio are used to achieve an optimum design.

INTRODUCTION

With more and more success of proton therapy reported, attention to proton therapy has dramatically increased in recent years. Compared with traditional radiation therapy, proton therapy shows a clear advantage of improving clinical outcomes for cancer patients because of the Bragg peak of proton dose distribution [1]. A dedicated cyclotron based proton therapy facility, Huazhong University of Science and Technology Proton Therapy Facility (HUST-PTF), is being developed [2]. As shown in Fig.1, it mainly consists of a 250MeV superconducting cyclotron, an energy selection system, one fixed treatment room, two rotatable gantries, and the corresponding transport lines.

An energy degrader and selection system must be employed to obtain variable energy beams from the cyclotron for treatment, which reduces the beam intensity remarkably. Tab.1 shows the key beam parameters after the energy selection system. In order to ensure the precise dose delivery to the tumor volume, high sensitive BPMs are needed to monitor the beam accurately while it is being delivered to the patient. Currently, the ionization chambers are widely used to monitor the beam position with such low intensity. However, excessive ionization chambers in the beamline will cause beam scattering leading to worse beam quality. Non-destructive beam diagnostics with high sensitivity are preferable in such cases to avoid deteriorating the beam performance.

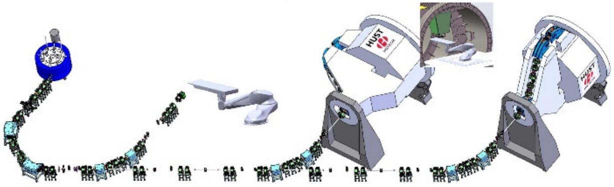

Figure 1: Layout of HUST-PTF.

A cavity-BPM device with the capability of monitoring the feeble proton beam is being developed, which consists of one reference-cavity and two position-cavities placed orthogonally. The reference-cavity is used to measure the charge-dependent signal to normalize the position signal, and the two orthogonal positioned cavities are used to measure the transverse beam position directly.

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

THEORETICAL BASIS

When a bunch passes through a cavity, a series of eigenmodes will be excited, which can be extracted by a coupler. The output signal is given by [3]:

$$V_0 = \frac{1}{2} q\omega \sqrt{\frac{Z}{Q_{ext}}(R/Q)} \exp\left(-\frac{\omega^2\sigma_z^2}{2c^2}\right)$$

(1)

where q is the bunch charge, ω is the working mode frequency, Z is the impedance of the detector, R is the shunt impedance, Q is the quality factor of the cavity itself, Q_{ext} is an external quality factor, c is the speed of light and σ_z is the bunch length. In case of multiple bunches, if the signal decay time τ of a single bunch is

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longer enough than the bunch interval t_b, the output signal is the superposition of every single bunch. The superposition pattern is determined by the working mode frequency and bunch interval. In case of $\omega t_b = 2\pi N + \pi$, where N is an integer, the signal would cancel out. In the case of $\omega t_b = 2\pi N$, the output signal will sum up and the sum would be [3]:

$$V_{out} = V_0 + V_0 e^{-\frac{t_b}{2\tau}} + V_0 e^{-2\frac{t_b}{2\tau}} + \ldots = \frac{V_0}{1 - e^{-\frac{t_b}{2\tau}}} \quad (2)$$

According to Eq. (1) and Eq. (2), if we select a mode sensitive to the beam offset and set the working frequency to be a harmonic of the bunch frequency, the beam position can be monitored effectively.

POSITION CAVITY DESIGN

Two key issues that must be dealt with in the design of cavity-BPM used in HUST-PTF, which is low working frequency and ultra-low intensity. The low frequency will lead to a larger cavity size, and in case of ultra-low intensity, a large shunt impedance is indispensable. Conventional cavity-BPM, such as circular cavity-BPM and rectangular cavity-BPM, works in dipole mode (TM110). Although the dipole mode shows an ideal linear variation in the central area, the R/Q is quite small near the beam axis so that the output signal is very weak when the beam current is extremely low. Moreover, the intensity of the monopole mode (TM010) is much higher than the intensity of the dipole mode near the beam axis, so the rejection of the monopole mode is a great challenge. In the case of the elliptical cavity, the strong monopole mode itself is used, which results in the stronger output signal and higher signal-to-noise ratio [4]. In an elliptical cavity, the fall-off of R/Q is more dramatic along the minor axis than that along the major axis, so the beam pipe is deliberately offset to the minor axis.

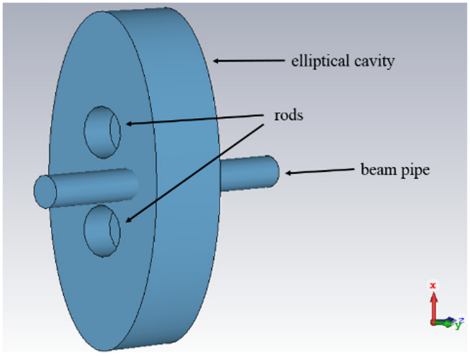

Figure 2: The schematic of position-cavity.

We use CST Microwave Studio and Particle Studio to perform the simulation [5]. Fig. 2 shows the elliptical cavity model, and Tab. 2 lists the dimensions of the cavity. The cavity with lower working frequency has the benefits of higher signal level [6], with the cost of larger size, however, which makes it difficult for manufacturing. Finally, we select the fourth harmonic as the working frequency. What' more, there are two symmetrical rods in the cavity. Although the field pattern of the working mode is slightly distorted because of the rods, the cavity becomes more compact. A relatively large gap of 200 mm is designed to improve the output signal. The electric field intensity distributions of TM010 in the transverse direction are shown in Fig .3, which indicates that the fall-off of electric field intensity is dramatic along the minor axis. So we set the beam pipe to the minor axis and calculate the R/Q distribution along the pipe diameter as shown in Fig. 4.

Table 2: Position Cavity Dimensions

Parameters	Value
Major axis	384.7mm
Minor axis	175.6MHz
Cavity gap	200mm
Rod radius	59mm
Pipe radius	37mm

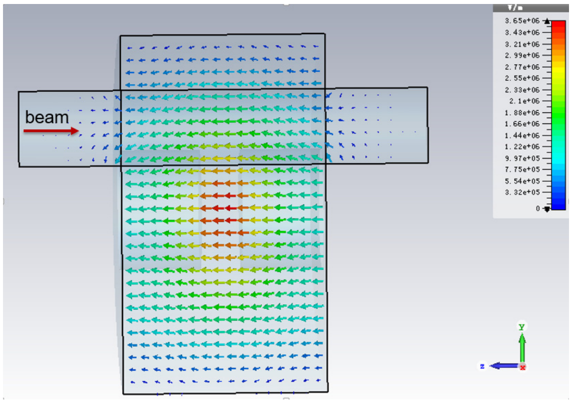

Figure 3: Electric field intensity distributions of TM010.

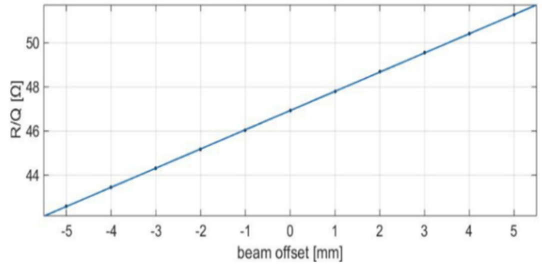

Figure 4: R/Q distribution along the pipe diameter.

A coupling loop is designed to extract the position signal. The coupling loop is positioned at the plane where

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the dipole mode is zero to improve the signal to noise ratio. Compared with conventional couplers, such as an antenna coupler, the external coupling quality of the coupling loop is bigger so that the coupling loop can extract stronger position signal. According to the beam parameters in Tab.1 , an elliptical cavity-BPM was loaded with the virtual beam in CST Particle Studio. In order to evaluate the weakest-signal case, a proton beam of 70MeV/0.4nA is used in our simulations, the output signals of the time domain and frequency domain are shown in Fig. 5 and Fig. 6, respectively. According to Fig. 5 and Fig. 6, the signal power is weak and is concentrated at the fourth harmonic in the frequency domain. To amplify the weak voltage signal with little distortion, we plan to use a commercial lock-in amplifier to process the signal, then the lock-in amplifier will be connected to the EPICS control system.

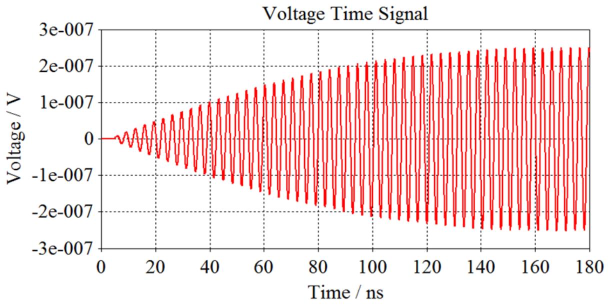

Figure 5: Output signals of position cavity.

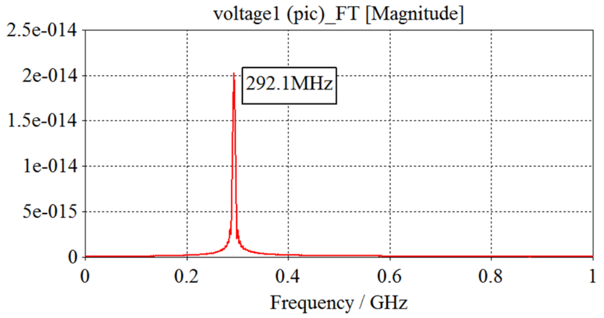

Figure 6: Output signal of position cavity in frequency domain.

REFERENCE CAVITY DESIGN

According to Eq. (1) and Eq. (2), the output signal is not only determined by R/Q, but also determined by the bunch charge. So a reference cavity is necessary for the whole cavity BPM system. A reentrant cavity is designed as the reference cavity, and its dimensions are listed in Tab. 3. Compared with a circular cavity, if they work at the same frequency, the reentrant cavity is more compact. However, the quality factor of the reentrant cavity is smaller than that of a circular cavity, which results in a broadening of the resonance curve [7]. The broadening resonance curve will reduce the dependence of output signal level on frequency drift so that the machining difficulty of the cavity will be reduced. The working mode of the reference cavity is also TM010 mode and the working frequency is also the fourth harmonic frequency. We use CST Microwave Studio to perform the simulation. The reference cavity model is shown in Fig. 7 and the dimensions of it are listed in Tab. 3. The R/Q distribution of the TM010 mode is shown in Fig. 8. According to Fig. 8, the R/Q remains almost constant within +-5 mm, which indicates that the beam position has little effect on the output signal. The coupling method used in the reference cavity is similar to that used in the position-cavity, a coupling loop is placed at a plane where the magnetic field of the monopole mode is concentrated on.

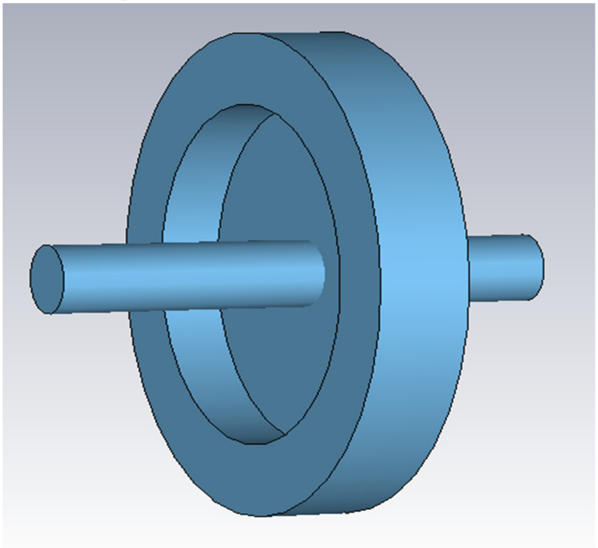

Figure 7: Schematic of the reference-cavity.

Table 3: Reference Cavity Dimensions

Parameters	Value
Cavity radius	384.7mm
Gap length	175.6MHz
Pipe radius	37mm

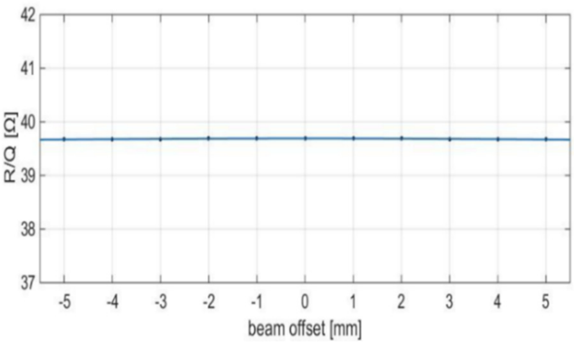

Figure 8: R/Q distribution along the cavity diameter

CONCLUSIONS

In this article, we have presented an electromagnetic design of a cavity BPM system consisting of a reference cavity and two position cavities placed orthogonally for HUST-PTF. This design utilizes the monopole mode in the elliptical cavity, which results in the stronger output signal and higher signal-to-noise ratio. The position cavity was loaded with a virtual proton beam of 70MeV/0.4nA to evaluate the weakest signal. It is proved that the weakest output signal can be processed by lock-in amplifier effectively so that the monopole cavity resonator can be a promising candidate at the low proton beam intensities used in proton therapy.

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