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CONSIDERATION OF USING NON-DESTRUCTIVE DETECTORS IN THE BEAMLINE OF A PROTON THERAPY FACILITY*

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Abstract

Ionization profile monitors (IPM) are a kind of nondestructive monitors mostly used in accelerators of high intensity pulsed beams. As for particle therapy accelerators, either based on cyclotrons or synchrotrons, the extracted beams are very weak, usually on the level of nano-Amperes. Up to date, the commonly used detectors in such low current machines are all destructive, such as fluorescent screens and gas ionization chambers. In this paper, we proposed for the first time to use a residual gas ionization monitor to measure the beam profiles in a proton therapy facility based on a superconducting cyclotron. The feasibility of such a scheme and some basic issues are discussed in this paper.

INTRODUCTION

There is a proton therapy facility based on a superconducting cyclotron under construction in the Huazhong University of Science and Technology (HUST-PTF) [1,2]. The HUST-PTF uses an energy degrader to modulate the beam energy from the cyclotron to match the clinical requirements [3]. The beam parameters from the superconducting cyclotron are summarized in Table 1. The layout of HUST-PTF is shown in Fig. 1.

Table 1: Beam parameters from the SC cyclotron.

Parameter	Value
Frequency	73 MHz (CW mode)
Energy	250 MeV
Energy spread	<0.5%
Intensity	60 ~ 500 nA

The proton beam extracted from the cyclotron has a fixed energy of 250 MeV and then is modulated to 70 ~ 230 MeV with an energy degrader, followed by three collimators to constrain the emittance and a momentum slit in the middle of the DBA section to restrict the energy spread [4]. Taking all the beam loss into consideration, the transmission rates of different beam energies vary dramatically, which is not acceptable in clinical treatment. So it is demanded that the cyclotron has the ability to output different intensity beams in accordance with the working energy points. According to our optimization result, the beam intensity from the cyclotron is divided into three levels (Fig. 2) and the final intensity for clinical treatment is shown in Fig. 3.

ANALYSIS OF THE IONIZATION PROFILE MONITOR

Nondestructive detection is always preferred in an accelerator. However, as the first attempt to build such a proton machine, the traditional fluorescent screen and strip ionization chamber are the two primary detectors used in the beamline [5]. Even so, the residual gas monitor, or ionization profile monitor (IPM), is considered as a potential candidate in the future upgrade. IPM is a kind of nondestructive detector, which collects the secondary particles produced from the interaction between the incoming high energy particles and the residual gas molecules [6–8]. The biggest challenging of using an IPM in our machine is the extremely low signal due to the nA-level beam current. In the following, some basic issues are discussed to investigate its performance.

Gain Analysis

Gain is the first issue that needs to be considered. The process of producing an ion-electron pair is evaluated with the Bethe-Bloch formula:

$$-\frac{dE}{dx} = (4\pi N_a r_e^2 m_e c^2)\rho \frac{Z}{A}\frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2\right) \quad (1)$$

The gain is calculated from the energy of proton beams deposited in the residual gas and the ionization energy of the gas. The parameters used in our simulation is displayed in Table 2. As it is hard to tell the ingredient of the residual gas at the 10^{-4} Pa level, both the hydrogen and the nitrogen cases are calculated and the results are shown in Fig. 4.

Table 2: Simulation parameters for the gain of Hydrogen and Nitrogen.

Parameter	Value
Pressure	10^{-4}Pa
Temperature	298.15K
Detector length	10cm
Ionization energy	36eV of H_2, 36.4 of N_2

It is easy to conclude from the Bethe-Bloch formula and the simulation results that the hydrogen curve gives a lower gain, so it is reasonable to use the hydrogen curve to estimate the gain of the detector.

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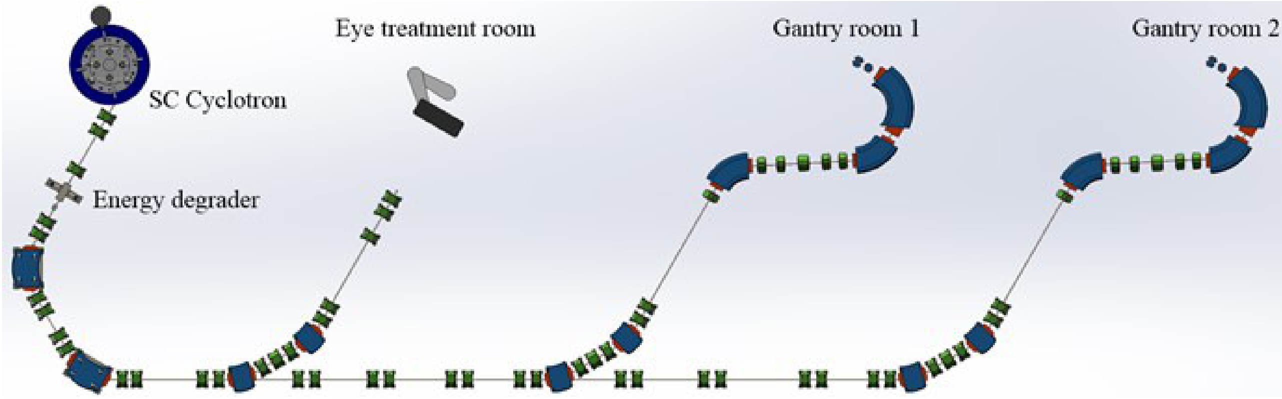

Figure 1: The beamline layout of the HUST-PTF.

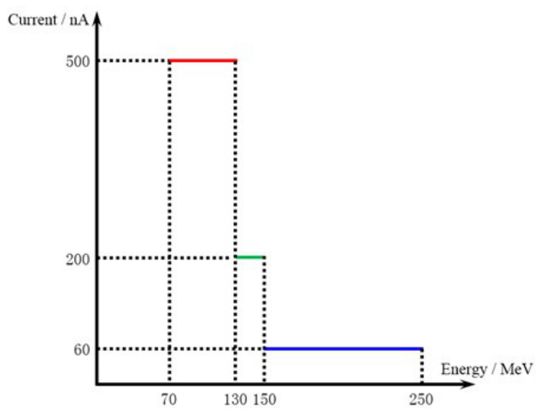

Figure 2: Beam intensity from the cyclotron under different working points.

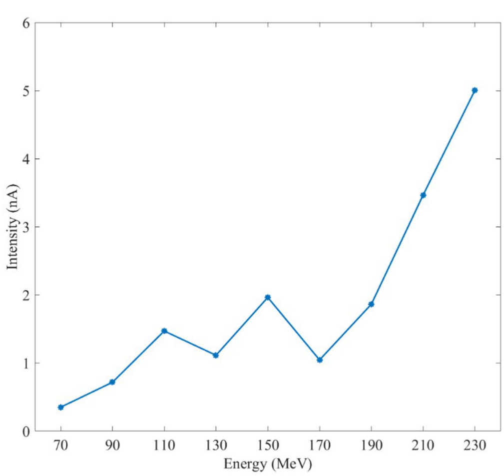

Figure 3: Beam intensity for clinical treatment under different working points.

Figure3 indicates the beam intensity increases with the beam energy while Fig. 4 indicates the gain decreases with the beam energy. Combining the results in Figs. 3 and 4, the lowest ionization signal occurs at the 70 MeV point, which corresponds to 1009 ion-electron pairs per second. It should be emphasized that the time resolution is not an important issue in the beam diagnostics of our machine and only the average parameters are concerned. With the help of a typical two-stage MCP with a gain of $10^6 \sim 10^7$, we feel confident in applying such an IPM detector in our machine.

Structure of the Detector

The main components of the IPM include the electrodes, MCP and readout electronics (Fig. 5). It includes the following key components. Electrodes: We are unable to make a choice on the collection particles, ions or electrons. Their difference and engineering challenges are not clear. As for the guiding B field that is necessary in many high intensity proton accelerators, I do not see its necessity in our case due to the ultralow incident beam current. MCP: A gain of 107 is not challenging for a commercial two-stage MCP, such as the Hamamatsu products. Readout: Compared with an anode scheme, a phosphor screen combined with a CCD camera is easier to obtain a better spatial resolution. The exposure time of the camera should be set to 1 s or larger.

Steering Effect

The transverse electrical field of the IPM may influence the transport of the proton beam. Take the 70 MeV proton beam for example. The kick angle imposed by the IPM is

$$\theta = \frac{\Delta p_x}{p_z} = \frac{qE_cL}{m_pc^2\gamma\beta^2} \qquad (2)$$

where E_c is the cage E field of the IPM, L is the detector length. E_c = 5kV/cm, L = 10 cm. Then, the kick angle associated with the 70 MeV proton beam is 0.37 mrad. The steering effect is not a serious problem and can be compensated by the corrector magnets.

SUMMARY

Although the fluorescent screen and stripped ionization chamber are the primary detectors in the current configuration, we have been looking for appropriate nondestructive instruments. Cavity-BPM and IPM are the two candidates. The Cavity-BPM has advantage in spatial resolution, but its volume is relatively large. The IPM has a smaller insertion length compared to the Cavity-BPM, but there is

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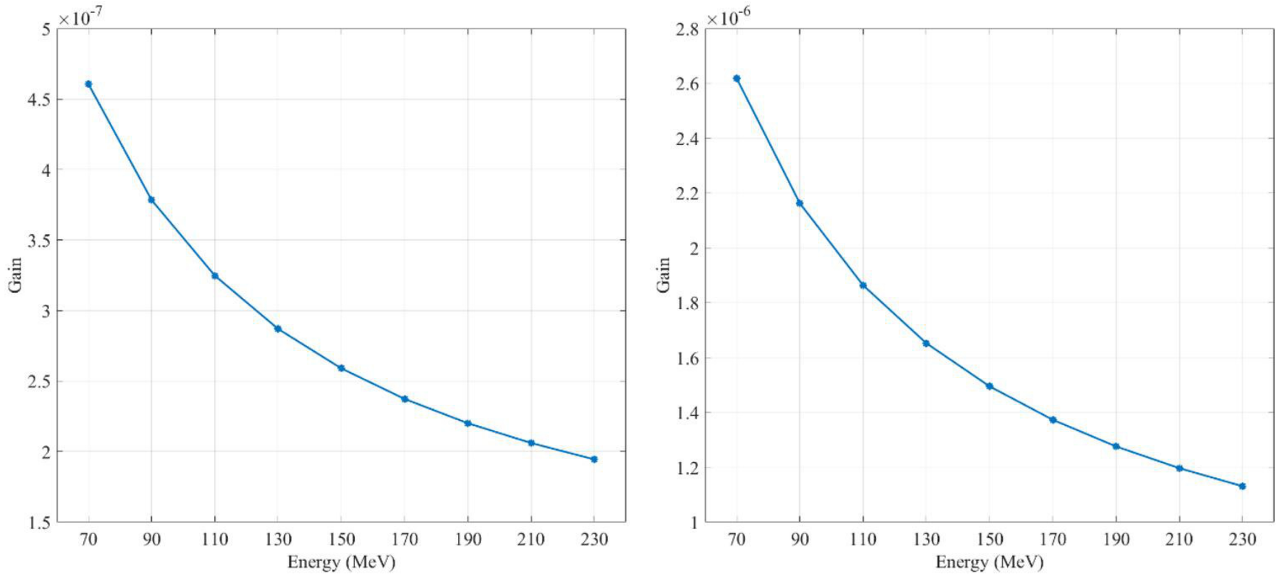

Figure 4: Gain curves of the hydrogen (Left) and the nitrogen (Right) at 10^{-4} Pa.

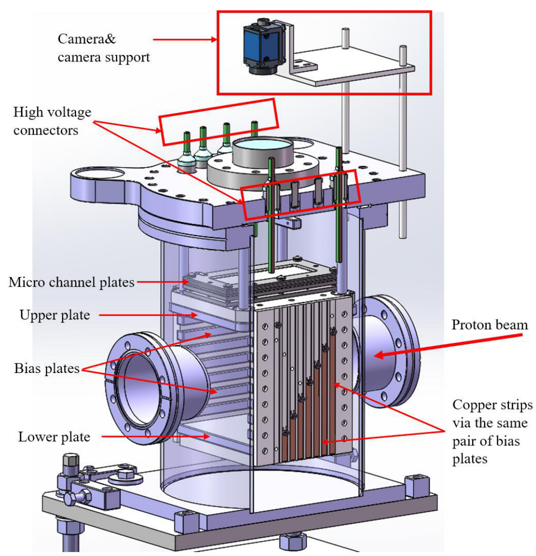

Figure 5: Schematic view of the IPM.

still much uncertainty in its output signal. Besides, the mechanical structure, high voltage supply, radiation protection of the CCD camera, signal distortion, etc. still need to be considered with more details.

REFERENCES

[1] Bin Qin *et al.*, "Design and development of the beamline for a proton therapy system", *Nucl. Sci. Tech.*, vol. 31, p. 138, 2021. doi:10.1007/s41365-021-00975-y

[2] S.Hu, K. Fan, L. Zhang, Z. Mei, Zhiyuan, X. Li, and Z. Zeng, "Beam loss issue study on the extraction system of a superconducting cyclotron at HUST", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 911, pp. 87–93, 2018. doi:10.1016/j.nima.2018.09.126

[3] Wei Chen *et al.*, "Transmission calculation and intensity suppresion for a proton therapy system", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 881, pp. 82–87, 2018. doi:10.1016/j.nima.2017.10.04

[4] Xu Liu *et al.*, X. Liu, W. Wang, Z. Liang, R. Zhao, K. Liu, and B. Qin, "Design of a light and fast energy degrader for a compact superconducting gantry with large momentum acceptance", *Physica Med.*, vol. 73, pp. 43–47, 2020. doi:10.1016/j.ejmp.2020.04.008

[5] Aote Chen *et al.*, "Prototype development of the beam diagnostic system of a proton therapy facility based on a superconducting cyclotron", *Nucl. Instrum. Methods Phys. Res. A*, vol. 998, p. 165208, 2021. doi:10.1016/j.nima.2021.165208

[6] C. D. Johnson and L. Thorndahl, "Non-destructive proton beam profile scanners for the CERN Proton Synchrotron, based on the ionization of residual gas in the beam vacuum chambers", in *Symposium on Beam Intensity Measurement*, Daresbury, Apr. 1968, pp. 227–237.

[7] H. Ishimaru, Z. Igarashi, K. Muto, and S. Shibata, "Beam profile measurements for KEK 12 GeV proton synchrotron", *IEEE Trans. Nucl. Sci.*, vol. 24, no. 3, pp. 1821–1823, 1977. doi:10.1109/TNS.1977.4329099

[8] T. Hardek, W. Kells, and H. Lai, "Very low intensity storage-ring prpofile monitor", *IEEE Trans. Nucl. Sci.*, vol. 28, no. 3, pp. 2219–2221, 1981. doi:10.1109/TNS.1981.4331642