THE ALIGNMENT OF THE ENERGY DEGRADER APPLIED IN THE PROTON THERAPY *

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Abstract

A new proton therapy facility based on a 250MeV/500nA superconducting cyclotron has been under construction in Huazhong University of Science and Technology (HUST) in Wuhan, China. Due to the fixed beam energy extracted from the cyclotron, an energy degrader is essential for the proton beam with variable energy to reach various tumour depths in human body. Because of the interaction between the protons and the energy degrader material, the beam emittance and the energy spread will be increased while the beam current will be significantly decreased. The alignment accuracy will have an obvious impact on the performance of the degrader. This paper will discuss how the beam energy, beam emittance and beam losses are influenced by the alignment accuracy including the positional accuracy, the angular accuracy, the coaxiality and others. Moreover, the detailed alignment program will be proposed.

INTRODUCTION

The proton therapy facility proposed by Huazhong University of Science and Technology (HUST) includes two rotating gantries and one fixed beam treatment room. An energy degrader is located after the 250MeV/500nA superconducting cyclotron to modulate the energy ranging from 239MeV to 70MeV. Because of the Coulomb interactions between the incident protons with the target atom, the beam emittance growth, the momentum spread and beam loss will take place after the energy degrader. The collimators and the double bend achromatic (DBA) section will be located downstream after the degrader (see Fig. 1) in order to restrict the beam emittance and the momentum spread respectively. But they will further increase the beam loss. Therefore, the energy selection system (ESS) including the degrader, collimators and DBA section will have a significant impact on the beam parameters [1].

The mechanical deviation of the energy selection system will bring out the deviation of the beam parameters. The mechanical deviation of the energy degrader will lead to the error of the overlap thickness and then cause the deviation of the beam energy. The mechanical deviation of the collimators will lead to the deviation of the stopping proton number and then cause the deviation of the beam current. However, the accuracy of the beam energy determines the accuracy of the treatment location due to the Bragg peak position changed with the beam energy. The deviation of the beam current will change the therapeutic dose and then influence the therapeutic effect. Therefore, the alignment of the degrader and collimators will be really important for the design of proton therapy. The alignment of the DBA section is not mentioned in this paper which includes not only the mechanical alignment but also the magnetic field alignment. In this paper, the requirement of alignment tolerance and the alignment program of the system including energy degrader and collimators will be detailed discussed.

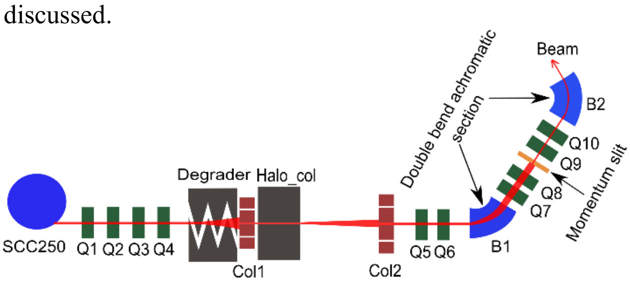

Figure 1: Layout of energy selection system (ESS).

ALIGNMENT TOLERANCE

Alignment tolerance of the energy degrader

The energy degradation process by the energy degrader results from the interactions between the incident protons and the degrader material. In this process, the energy loss is determined according to the Bethe–Bloch formula (see e.g. [2]), given in Eq. (1).

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

We can conclude from it that the energy loss is proportional to the overlap thickness of the energy degrader. Combined with the results of Geant4 simulation (see Fig. 2), the energy degradation gradient will be larger when the energy is lower. The energy degradation gradient with the overlap thickness is 1.48 MeV/mm at 70 MeV when the graphite density is 1.95 g/cm³ as the degrader material. According to the geometry of the energy degrader, the alignment deviation will result in 2.68 times overlap thickness deviation. The one-sided alignment tolerance of the energy degrader is set to 0.1mm and then the maximum energy deviation is 0.4 MeV when the beam energy is 70 MeV.

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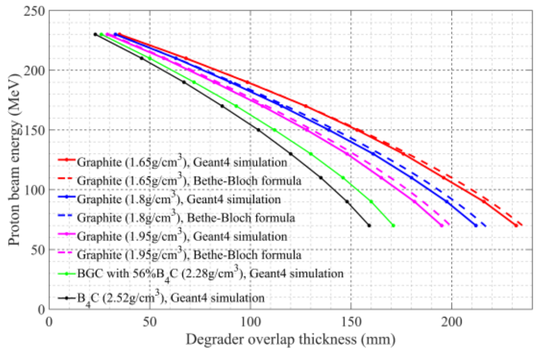

Figure 2: Beam energy varying with the degrader overlap length.

Alignment tolerance of the collimators

Besides the energy degradation, the beam emittance increases considerably due to the multiple Coulomb scattering during the degradation process. When the beam energy is degraded from 250MeV to 70MeV by the energy degrader, the rms beam emittance will increase to 214π mm·mrad from initial emittance of 5π mm·mrad. Therefore, a set of collimators (Col1, Halo_col and Col2) placed immediately behind the degrader is used to restrict the emittance. Collimators with various aperture sizes are used to define the accepted emittance, given in Eq. (2) [2].

$$\varepsilon_{col} = \frac{2r_1 \cdot r_2}{L_{col}} \quad (2)$$

Where r_1 and r_2 are the radii at the entrance and exit of the collimators respectively, and L_{col} is the overall length of the collimators. The positional deviation of the collimators will result in the errors of the beam central position, the beam emittance and the beam current. The alignment tolerance of the collimators is set to 0.2mm.

ALIGNMENT PROGRAM

The energy degrader and collimators are contained inside a vacuum box. Therefore, the alignment objects should include the vacuum box, the energy degrader and collimators. The alignments of the energy degrader and collimators are after the alignment of the vacuum box. The laser tracker is used to calibrate the vacuum box while the alignment telescope is chosen for the alignment of the energy degrader and collimators. The laser tracker is a fast 3D measuring instrument that uses the laser interference principle to measure the slant range and guarantees high precision [3]. In contrast to the laser tracker, the alignment telescope is designed specifically to perform the coaxiality measurement that can measure the deviations of the components from the reference axis [4].

Alignment of the vacuum box

The alignment of the vacuum box is accomplished by the laser tracking measurement system which is generally composed of a laser tracker, a reflecting ball, a controller, a computer, and other accessories. When calibrating, the reflecting ball will be placed in the reference targets fixed on the calibrated object. The laser is reflected back to the tracker by the reflecting ball to measure the distance. The coordinate system of the component could be established by the measurement of multiple targets [5].

Four reference targets are welded to the upper surface of the vacuum box (see Fig. 3). The targets are symmetrically distributed along the centreline of the vacuum box to counteract the influence by temperature, and the position between them should be as far as possible to reduce the influence by measurement error. The reference target is designed as a conical surface structure and matched with a reflecting ball with a diameter of 38.1 mm (1.5 inches) (see Fig. 4). The reflecting ball is movable and the placement repeatability is generally better than 0.01 mm.

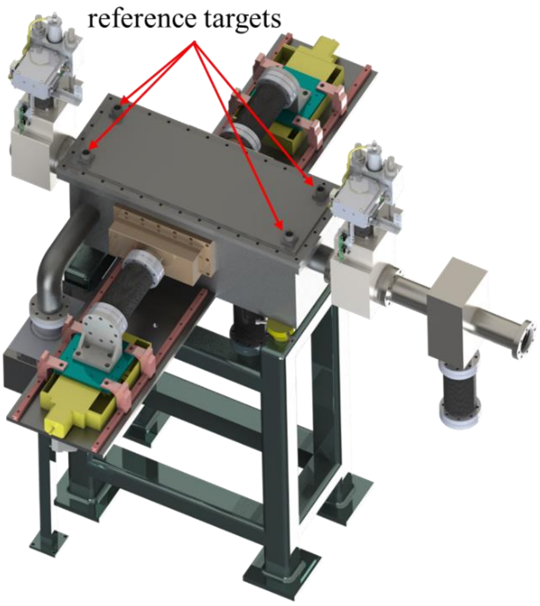

Figure 3: Reference targets of the vacuum box.

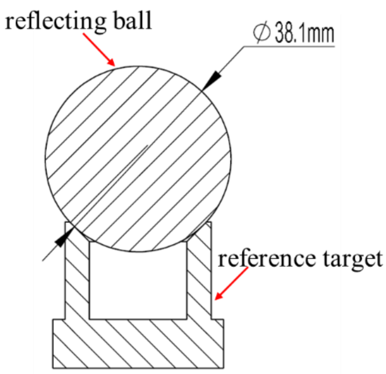

Figure 4: Sectional view of the reflecting ball and reference target.

Alignment of the energy degrader and collimators

Once the vacuum box is calibrated, the alignment of the energy degrader and collimators by the alignment telescope will be the next. The deviations of the energy degrader and collimators from the reference axis of the proton beam could be observed by the cross-hairs on the objective lens mounted on the alignment object through the alignment telescope. The objective lens must be mounted in a hole of the alignment object while there are no holes in the energy degrader and collimators. Therefore, the backup degrader and collimators made of aluminium with holes could be adopted in the alignment of the real degrader and collimators. The reset pins could ensure the repeated accuracy when the real degrader and collimators are installed once the backup degrader and collimators were aligned well. The alignment procedures are as follows:

(a) The alignment telescope is aligned with two objective lens mounted on the central flanges of the vacuum box to establish a line of sight along the reference axis of the proton beam (see Fig. 4).

(b) The backup double-wedge degrader with holes is aligned separately on each side. The objective lens matches with the hole in one-sided wedge. Once the one side is aligned, the other side is aligned with the same method (see Fig. 5).

(c) The backup Col1, Halo_col and Col2 are machined with the stepped cylindrical holes which will be matched with the objective lens. The alignments of the collimators are completed from upstream to downstream according to the beam axis direction.

(d) Once the backup degrader and collimators were aligned well, the real degrader and collimators will be installed. And the whole alignment of the system is completed.

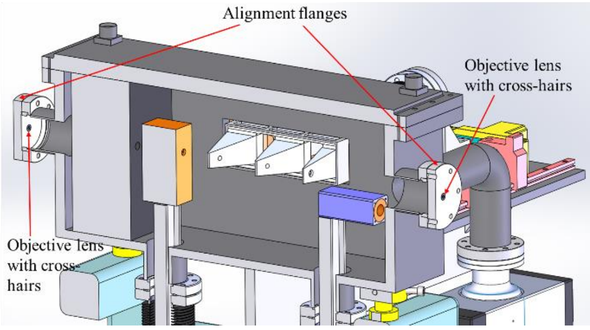

Figure 4: The alignment telescope is aligned with two objective lens mounted on the central flanges of the vacuum box to establish a line of sight along the reference axis of the proton beam.

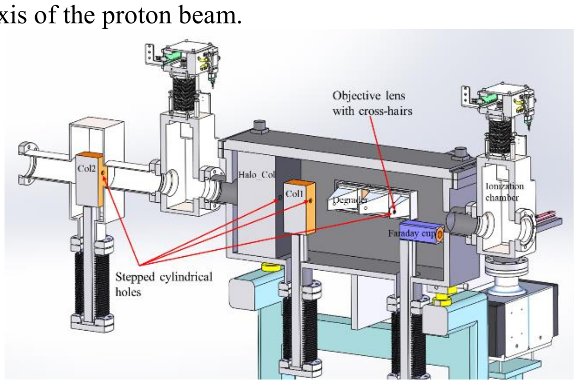

Figure 5: Alignment diagram of the energy degrader and collimators. The objective lenses are placed on the the energy degrader, Col1, Halo_Col and Col2 in turn.

CONCLUSION

The alignment of the energy degrader applied in the proton therapy has significant influence on the beam parameters including the beam energy, beam emittance, beam central position and beam current. According to the empirical formulas and the simulation results by the Geant4 Monte-Carlo toolkit, the one-sided alignment tolerance of the energy degrader is set to 0.1mm and the alignment tolerance of the collimators is set to 0.2mm. The alignment of the vacuum box is carried out by the laser tracking measurement system while the alignment of the energy degrader and collimators is accomplished by alignment telescope.

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