# DESIGN OF THE ENERGY SELECTION SYSTEM FOR PROTON THERAPY BASED ON GEANT4*

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*Abstract*

Huazhong University of Science and Technology (HUST) has planned to build a proton therapy facility based on an isochronous superconducting cyclotron. The 250 MeV/500 nA proton beam is extracted from a superconducting cyclotron. To modulate beam energy, an energy selection system is essential in the beamline. The simulation based on Geant4 has been performed for the energy selection system and its result will be discussed in this paper. This paper introduces the variation rules of the beam parameters including the beam energy, beam emittance, energy spread and transmission. The degrader's gap and the twiss parameter are proven to be effective ways to reduce the emittance after degrader.

## INTRODUCTION

Huazhong University of Science and Technology (HUST) has proposed to construct a proton therapy facility, which includes two rotating gantries and one fixed beam treatment room [1,2]. To modulate the proton beam energy for treatment, an energy selection system (ESS) is located in the beam-line. The beam energy can be modulated by the interactions between the energetic particles and the degrader's material. The ionization process with the electrons, the multiple Coulomb scattering with the nucleus and the nuclear reaction are the mainly components of the interactions, which will contribute to the energy degradation, the emittance growth and the secondary particles' production.

The energy selection system consists of an energy degrader, a set of collimators, and a double bend achromatic (DBA) section with an energy selection slit. An overview of the conceptual layout is shown in Fig. 1, and the main parameters of the beam are listed in Table 1. The energy degrader is aimed at the energy modulation by controlling the thickness of the degrader. The emittance collimators are designed to suppress the beam emittance significantly increased in the degrader. And the energy slit in DBA section is used to limit the energy spread.

This paper mainly describes the variation rules of the beam parameters including the beam energy, beam emittance, energy spread and transmission. And furthermore, the degrader's gap and the twiss parameter are illustrated to be effective ways to reduce the emittance after degrader.

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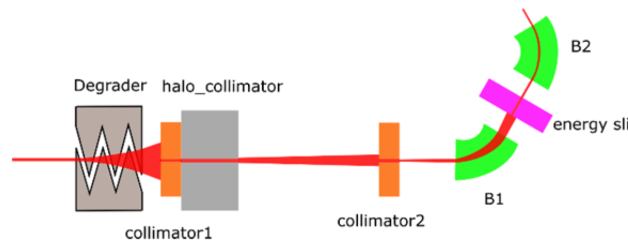


Figure1: Overview of the energy selection system (ESS).

Table 1: Main parameters of the beam

| Location | Parameter | Design value |
|---|---|---|
| Before ESS | Energy | 250MeV |
| | Current | 500nA |
| | Emittance | 5 π mm · mrad |
| | Energy spread | 0.5% |
| After ESS | Energy range | 70~250MeV |
| | Transmission | 0.2% |
| | Emittance | 5 π mm · mrad |
| | Energy spread | ±0.5% |

## THEORY AND SIMULATION

To simulate the passage of particles through matter, the model of ESS is built in Geant4 [3].Geant4 toolkit consists of many kinds of physical package. For example, the QBBC physical package is effective tool for the simulation of interactions between 250 MeV proton and the material. The detailed model parameters are presented in Table 2 [4]. Therefore, the beam parameters can be obtained from the simulation result.

Table 2: Model parameters of ESS

| Object | Material | Central position (mm) | Length (mm) |
|---|---|---|---|
| Degrader | Graphite | 0 | 200 |
| Col1 | Copper | 167.5 | 35 |
| Halo_col | Graphite | 300 | 60 |
| Col2 | Copper | 1187.5 | 35 |

### *Energy Selection*

Energy degrading is the main purpose of the energy selection system based on the Bethe-Bloch formula [5] shown in Eq. (1).

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



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Where E is the particle energy, $x = X \cdot \rho$ is the reduced medium thickness, $r_e$ is the classical electron radius, $m_e$ is the static electronic mass, c is the light speed, z is the change of the particle, Z/A is the charge mass ratio of the degrader material, $\beta$、$\gamma$ are the velocity and the mass, I is the ionization potential, $\delta/2$ represents the density effect which can be ignore for 250 MeV protons because of the lower energy. The theoretical and simulated results are shown in Fig. 2

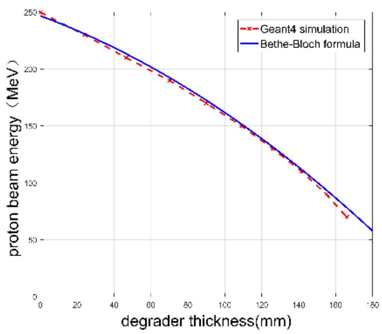


Figure 2: The proton beam energy varies with the degrader thickness.

The result of the Fig. 2 indicates that:

- The degrader thickness ranges from 0 to 166 mm while the beam energy ranges from 250 MeV to 70 MeV.
- The maximum error between the theoretical and simulated result is 3.3% when the energy after degrader is 70 MeV.
- The maximum energy change rate is about 1.46 MeV/mm when the energy is 70 MeV. This means the degrader requires high position accuracy especially when the energy after degrader is low.

## *Emittance Growth*

The emittance growth comes from the multiple Coulomb scattering in the degrader. The multiple Coulomb scattering will lead to the beam divergence angle increase which is the main reason of the emittance growth in the degrader. The multiple scattering angle and the exiting beam emittance can be calculated by Eq. (2) and Eq. (3) [6].

$$\theta_0 = \frac{13.6z}{\beta cp}\sqrt{\frac{L}{L_0}} \times \left(1 + 0.038\ln\left(\frac{L}{L_0}\right)\right) \cdot \tag{2}$$

$$\varepsilon_{\text{deg}} = \varepsilon_0 + \beta\theta_0^2 . \tag{3}$$

Where p is the incident momentum, L is the reduced medium thickness, $L_0$ is the material radiation length, $\varepsilon_0$ is the initial beam emittance before degrader and the $\beta$ in Eq. (3) is the beam twiss parameter instead of the velocity in Eq. (1). The Eq. (2) and Eq. (3) illustrate that the twiss parameter and the material radiation length are the two main factors that influence the emittance growth.

The proton therapy requires low emittance so that some collimators must be added to reduce the emittance after the degrader. The formula of the emittance after the collimators is as followed [7].

$$\varepsilon_{\text{col}} = \frac{2r_1 \cdot r_2}{L} \tag{4}$$

Where $r_1$ and $r_2$ are the incident and exiting aperture of the collimators and L is the whole length from the first collimator to the last.

After the energy slit, the emittance will be further reduced. The simulated result of the emittance for the whole system is shown in Fig. 3.

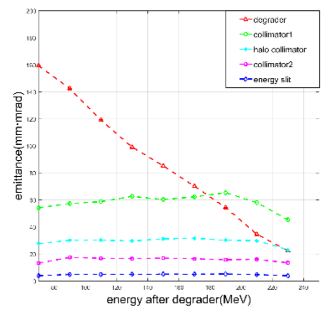


Figure 3: The emittance's variation of the whole system.

Based on the above simulation, some conclusion can be derived.

- The degrader will bring about the emittance growth. The emittance is proportional to the degrader's thickness corresponding to the energy after degrader.
- The collimators can significantly reduce the emittance and maintain a lower value about 5 π mm · mrad.
- The energy slit can further reduce the emittance to a stable value about 5 π mm · mrad while it's aimed to decrease the energy spread to 0.5%.

## *Energy Spread Increase*

The energy spread will increase after the degrader. Besides, the energy spread will be larger when the energy after degrader is higher. The simulation result of the exergy spread after the degrader is shown in Fig. 4.

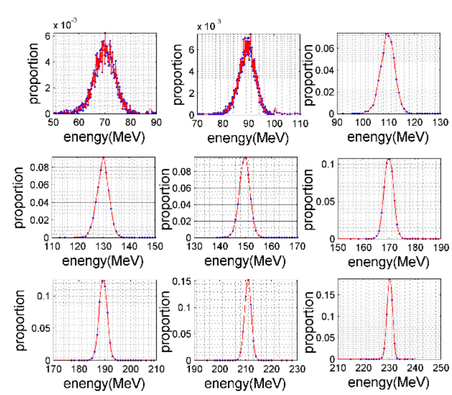


Figure 4: The energy spread after the degrader varies with the energy after degrader.

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The energy spread will maintain a stable value about ±0.5% by using the DBA section and the slit. Proton beam with different energies will deflect in different radius through the bending magnet. Thus, only the protons with proper radius can go through the energy slit.

### *Transmission*

Transmission of the proton beam directly relates to the beam current. The beam losses of the energy selection system are much more significant than other places in the proton therapy equipment. Figure 5 illustrates the transmission of the whole energy selection system.

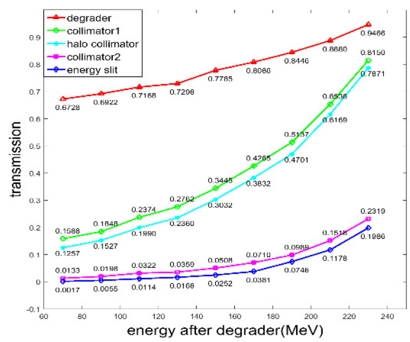


Figure 5: The transmission varies with the energy after degrader.

## OPTIMIZATION

To obtain higher transmission efficiency, lower emittance growth after the degrader is essential. According to Eq. (3), the emittance growth is mainly determined by the multiple scattering angle $\theta_0$ and the twiss parameter $\beta$ . Therefore, on the one hand, material with smaller material radiation length $L_0$ is chosen such as graphite and beryllium whose atomic number is pretty low. In this paper, due to the virulence of the beryllium, the graphite is used instead. On the other hand, it's effective to locate the center of the degrader at the beam waist or keep the degrader compact so that the twiss parameter $\beta$ can be smaller. Because the degrader is wedge-shaped, the gap between the dentation structures should be as smaller as possible. Figures 6 and 7 show the simulation result after enlarging the gap so that the degrader length varies from 200 mm to 260 mm.

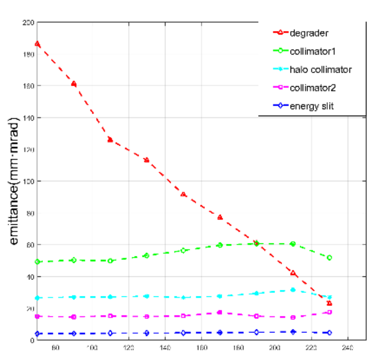


Figure 6: Degrade length becomes 260mm. Showing the emittance.

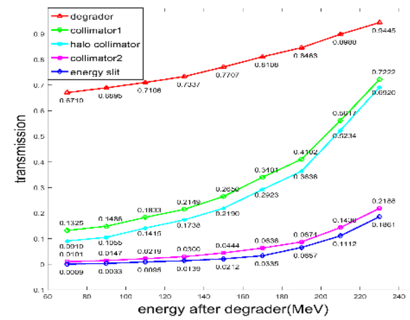


Figure 7: Degrade length becomes 260mm. Showing the transmission.

Compared to Fig. 3 and Fig. 5, some conclusions can be obtained.

- The emittance after degrader will increase when the degrader gap increases.
- The transmission of the whole ESS will decrease when the degrader gap increases.

## CONCLUSION

The energy selection system consists of the energy degrader, the emittance collimator, the energy slit and the control component, radiation protection. Owing to the space for the monitor or the cooling, the length of energy degrader is set to 200 mm. The beam parameters can be obtained: 5 π mm · mrad，0.17% as the transmission when the energy spread is ±0.5%.

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