A novel intensity compensation method to achieve energy independent beam intensity at the patient location for cyclotron based proton therapy facilities

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Abstract. In cyclotron-based proton therapy facilities, an energy selection system is typically used to lower the beam energy from the fixed value provided by the accelerator (250/230 MeV) to the one needed for the treatment (230-70 MeV). Such a system has the drawback of increase beam emittance and introducing an energy-dependent beam current at the patient location, resulting in energy dependent beam intensity ratios of about 10^3 between high and low energies. This complicates treatment delivery and challenges patient safety systems. As such, we propose the use of a dual energy degrader method that can reduce beam intensity for high-energy beams. The first degrader is made of high Z material and the second is made of low Z material and are placed next to each other. For high energies (190-230 MeV), we use only the first degrader to increase beam emittance after the degrader and thus lose intensity in the emittance selection collimators. For intermediate energy beams (110-190 MeV) we use the combination of both degraders, whereas for low energy beams (70-110 MeV), only the second degrader limits the increase in emittance. With this approach, energy-independent beam intensities at the patient location can be achieved, whilst localizing beam losses around the degrader.

1. Introduction

Proton therapy provides better dose distribution conformity and also better spares healthy tissues when com-pared with equivalent photon plans. Therefore, proton therapy has become a credible option in radiotherapy to treat certain types of cancers.

In proton therapy, based on the size and location of the tumor, proton beams with different energies are required to deliver the dose in the target volume. The energy required for patient treatments is typically in the range of 70-230 MeV.

Most proton therapy facilities use a cyclotron. Since a cyclotron produces beams of fixed energy (250 MeV for the PSI COMET cyclotron [1]), to modulate the energy of the beam, a degrader with an adjustable thickness is required. Unfortunately, beam scattering in the energy degrader increases the beam size, divergence, and energy spread beyond the beamline and gantry acceptance. It is unavoidable to use one or more collimator systems and an energy selection system (ESS) to cut these quantities to those that fit in the acceptance of the following beam transport system, to prevent unwanted beam losses along the beamline. This limited acceptance depends on the energy, the geometrical layout of the beam transport system, and the setting of the magnets in the beamline. At PSI, for example, for the highest energies (200-230 MeV), transmission through the beamline is about 30 %. However, for the lowest energies (70-100 MeV), transmission through the beamline is below 0.1 % [2-5].

The beam intensity at the patient would be strongly dependent on beam energy, due to this energy-dependent transmission. It may result in significant change in beam current at patient location and could have consequences for safety, due to a limitation of reaction times. Therefore, an intentional beam loss for higher energies is necessary to obtain the similar beam intensity for all energies.
This can be done by adjusting the intensity in the cyclotron, but one could also design a beamline setting with energy-dependent controlled beam losses at dedicated collimators in the beam-transport system.

In this study, we report a new way to do intensity compensation for high-energy beams using two degraders made of different materials. For the proof of principle simulation study, by using two degraders, we tried to achieve the similar transmission from the cyclotron to the end of the ESS beamline.

2. Methods and materials

2.1. Dual energy degrader method

To intentionally lose the intensities of the high energy beams, we designed an ESS beamline using two degraders (as shown in figure 1). We used two degraders made of different materials, Aluminium (D1) and Carbon (D2).

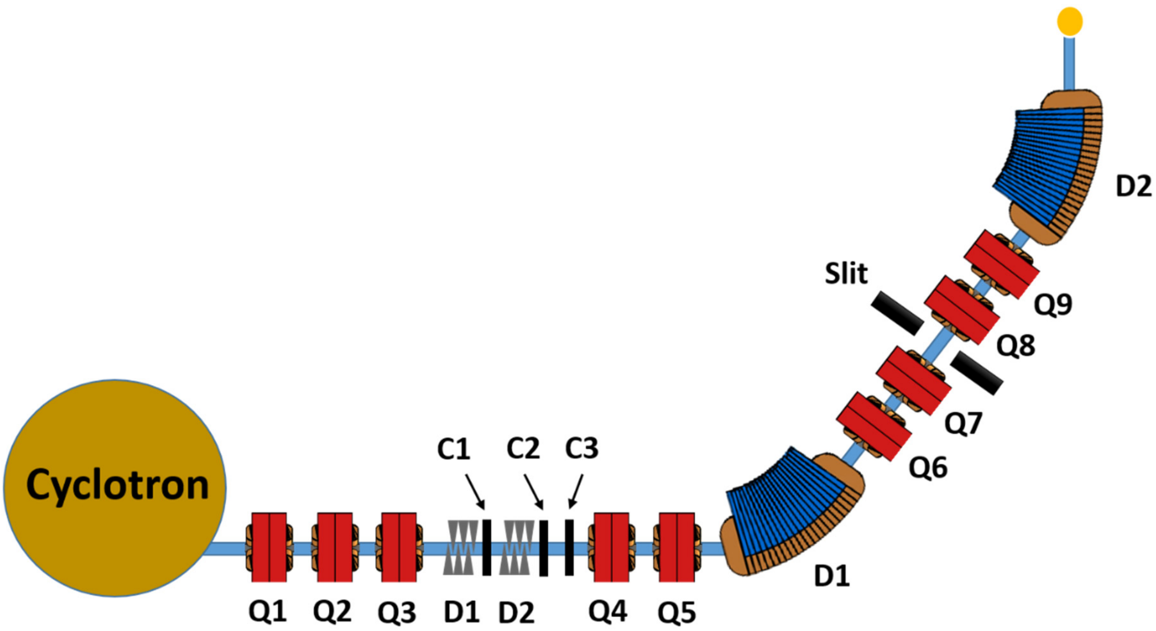

Figure 1. Schematic of the ESS beamline. (Q1-Q9: Quadrupole magnets, D1-D2: Dipole magnets, D1-D2: Degraders C1-C3 collimators).

To achieve efficient intensity compensation, we divide the energy degradation in three parts.

- High energy beams (190-230 MeV): we use degrader (D1) to choose the beam energy, collimator (C1) to choose beam size, and collimator (C2) to choose the beam divergence.
- Intermediate energy beams (110-190 MeV): we use the combination of degrader (D1) and degrader (D2) to achieve almost similar transmission at the end of ESS. Additionally, we use collimator (C2) to choose beam size and collimator (C3) to choose the bema divergence.
- Low energy beams (70-110 MeV): we use degrader (D2) to choose the beam energy, collimator (C2) to choose beam size, and collimator (C3) to choose the beam divergence.

2.2. Specification of degraders and collimators
The first degrader (D1) is made of Aluminium (Al) (assuming a density of 2.7 g/cm^3) and the second degrader (D2) is made of carbon (assuming a density of 1.7 g/cm^3), placed in the beam line as shown in figure 1. Due to the high atomic number, Aluminium provides higher scattering power compared to carbon. Table 1 summarizes the apertures of the collimators.

Table 1. Dimension of collimators.

	Radius in X-plane (mm)	**Radius in Y-plane (mm)**
C1	1.5	1.5
C2	4	4
C3	15	15

2.3. Beam optics and Monte Carlo simulation
The matrix formalism code TRANSPORT has been used to design new beam optics of the ESS beamline (see figure 2). The transmission of the beam was calculated with fast and light-weight Monte-Carlo beam optics code for the proton beamlines of the Paul Scherrer Institute, MinT [6]. MinT can compute the effects of beam degradation, multiple scattering, beam collimation and beam transmission. Additionally, it allows to do fitting.

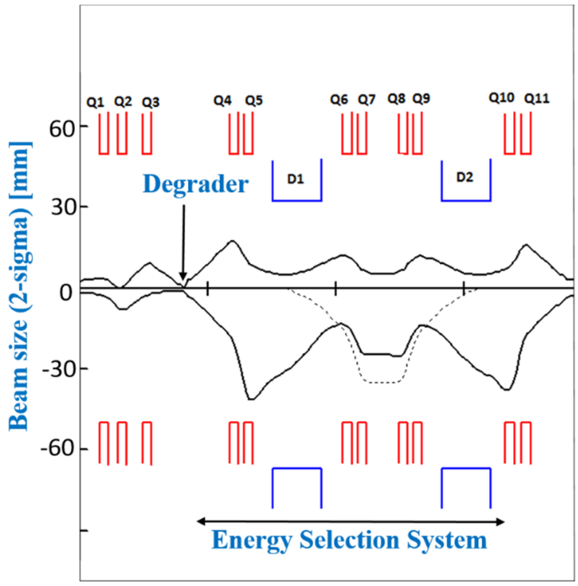

Figure 2. The new beam optics of ESS. The beam envelopes show the beam size in 2-sigma values and the dispersion (dashed line) along ESS beam line. The lower half of figure shows beam envelope in X-plane (bending plane) and the upper half shows envelope in Y-plane.

3. Results

3.1. Simulation results
For low energy beams (70 MeV), the transmission through the ESS is about 0.1 %. If we try to achieve the same 0.1 % transmission to all energy beams, the beam currents at the patient location will be very

low. There-fore, to achieve reasonable beam currents at the isocenter, for the first proof of principle simulation study, we decided to do intensity compensation for energies higher than 110 MeV.

Figure 3 shows the transmission between cyclotron to end of ESS for different energy beams using the two de-grader method.

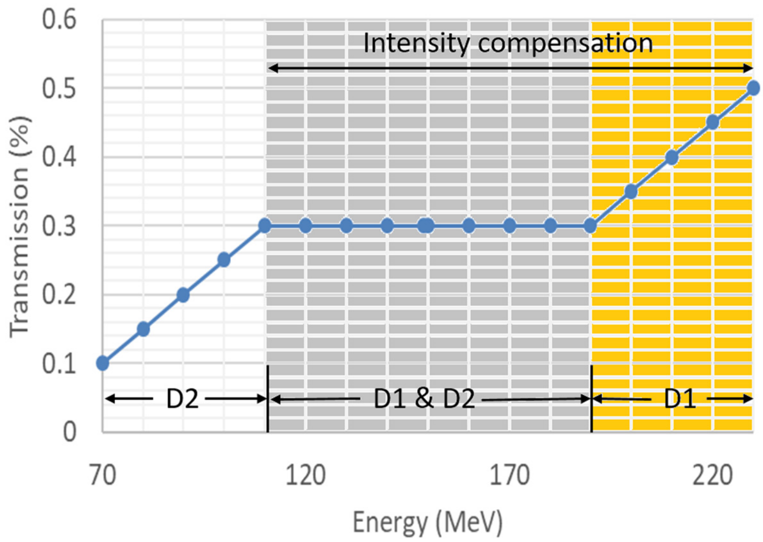

Figure 3. Beam transmission using two degrader method.

To achieve maximum beam loss for high energy beams (190-230 MeV beam) we used only the high Z degrader D1 made of Aluminium. Therefore, for high energy beams, the scattering through the degrader D1 was high and the emittance after the degrader was significantly high compared to low Z degrader material. Additionally, by using a smaller aperture of beam size selection collimator C1, we lose significant beam loss at C1 and achieve only 0.3 to 0.5 % transmission for high-energy beams.

For intermediate energy beams (110-190 MeV), our aim was to achieve almost the same transmission. Therefore, we used the combination of two degraders. We choose the thickness of both degraders by the iterative process using the fit function in MinT. We define the transmission at the end of ESS as a fitting constraint. The fitting function tries to find the thickness of two degraders to match the transmission value. The beam will lose part of the energy in degrader D1 and part of the energy in degrader D2 in a way that we achieve 0.3 % transmission at the end of ESS for all energies from 110 to 190 MeV.

For low energy beams, we used only degrader (D2) to achieve the maximum possible transmission through the ESS. As shown in figure 3, we achieved transmission of 0.1 to 0.3 for low 70 to 110 MeV beams.

4. Discussion

We have demonstrated that with the use of the two de-graders made of different materials, it is possible to achieve flat intensity compensation curve. However, for the proof of principle study, we tried to achieve the same transmission (from the cyclotron to the end of ESS) for 110 to 190 MeV beams. However, it is possible to achieve the same transmission from cyclotron to isocenter for all energy beams.

With this new intensity compensation method, we localized all the losses next to the degrader and avoid the need for an additional collimator along the beamline for intensity compensation. This helps in better shielding the design of the facility. Additionally, with this method, just by changing the degrader thickness of the two degraders, we can achieve any type of intensity compensation scheme based on the clinical need.

A few recent beam optics studies show that by using an asymmetric collimator or by transporting asymmetric emittance through the beamline with scattering foil, it is possible to achieve almost 1 % transmission for a 70 MeV beam. In this case, as the beam transmission for low energy is higher, by using two degrader methods, one could easily achieve the same 1 % transmission for all clinical energy range (70-230 MeV). With an asymmetric collimator, it is important to use two different apertures of the collimator (a larger aperture for low energy beams and a smaller aperture for high energy beams). However, the change of collimator during the treatment will increase the treatment delivery time. To avoid the use of different apertures of the collimator, one could defocus the beam before the degrader for high-energy beams.

One of the disadvantages of the method is that it will increase the length of the beam line by 0.7 to 1 m. How-ever it will reduce the shielding requirement in down-stream part of the beamline as there are no additional beam losses in coper collimators.

We did not look directly into the implement ability of this method. Further studies with different degrader materials would be essential to choosing the degrader material which could produce less long-lived radioactive isotopes.

5. Conclusion

In this proof of principle work, we have demonstrated that by using two degrader intensity compensation methods, it is possible to achieve almost the same transmission for all energy beams while localizing the beam losses of high energy beams around the degrader region. Additionally, it will reduce the shielding requirement for downstream beamline as there are no additional beam losses in downstream collimators for intensity compensation purposes.

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