Design of a fast energy degrader for a compact superconducting gantry with large momentum acceptance

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Abstract

Aiming at the light weight gantry beamline with a large momentum acceptance, we proposed a compact superconducting gantry employing a fast energy degrader, combined-function AG-CCT magnets and downstream scanning nozzle. This paper presents the design of a fast energy degrader with sperate structure, which has lighter weight and higher motion speed. The beam transmission can also be increased nearly 40%~50% in the low energy range compared with a multi-wedge scheme. Benefit from the large momentum acceptance of the beamline, less energy steps can be used to create a uniform Spread-Out Bragg Peak(SOBP) dose curve.

INTRODUCTION

A new compact superconducting gantry is proposed by Huazhong University of Science and Technology(HUST), and this gantry beamline can be configured in the single-room or multi-room PT facility. This SC gantry contains an independent fast energy degrader, three AG-CCT dipoles, seven resistive quadrupoles and a compact downstream scanning nozzle. To reduce the secondary neutrons on the iso-center, a fast degrader The overall length of this gantry will less than 6m and the radius is hopefully limited to 3.4m. The schematic layout of HUST SC gantry is shown in Fig. 1.

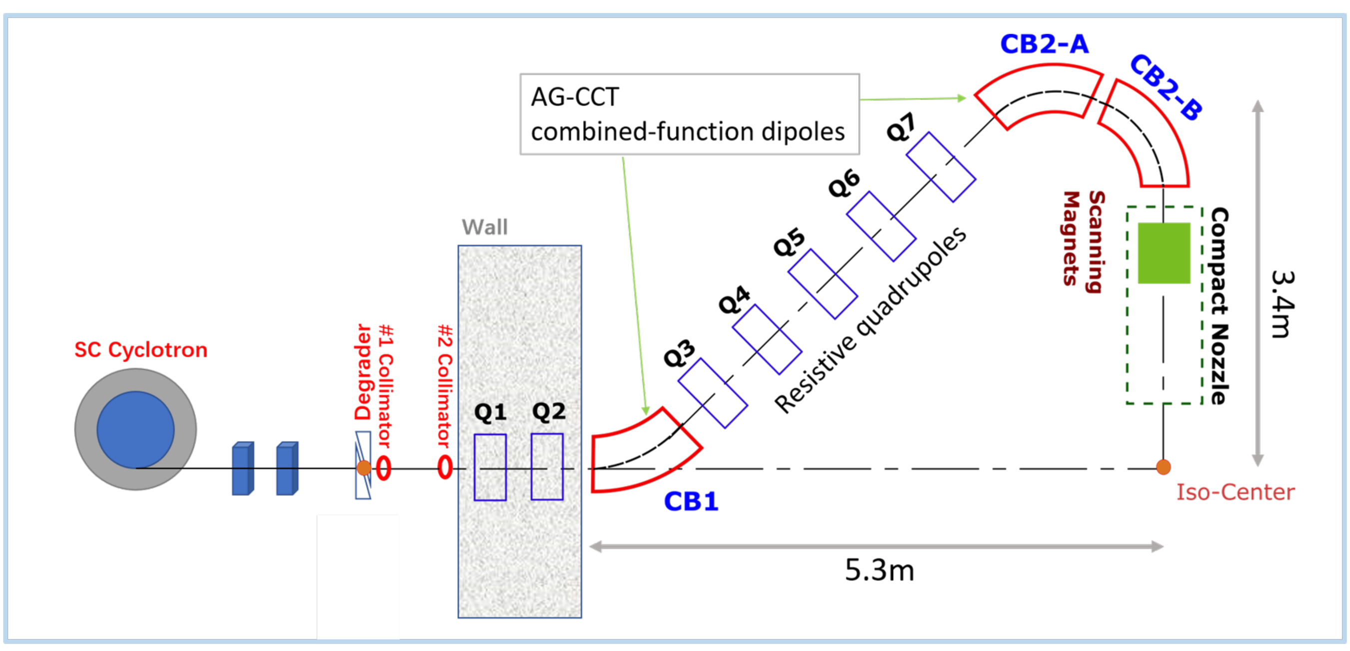


Figure 1: Schematic view of the HUST SC downstream scanning gantry

The SC gantry beamline shall has a large momentum acceptance due to the slow current change for the superconducting magnets. In the linear optics design of HUST SC Gantry, three AG-CCT dipoles have local dispersion suppression schemes to achieve +/-14.0% momentum acceptance.

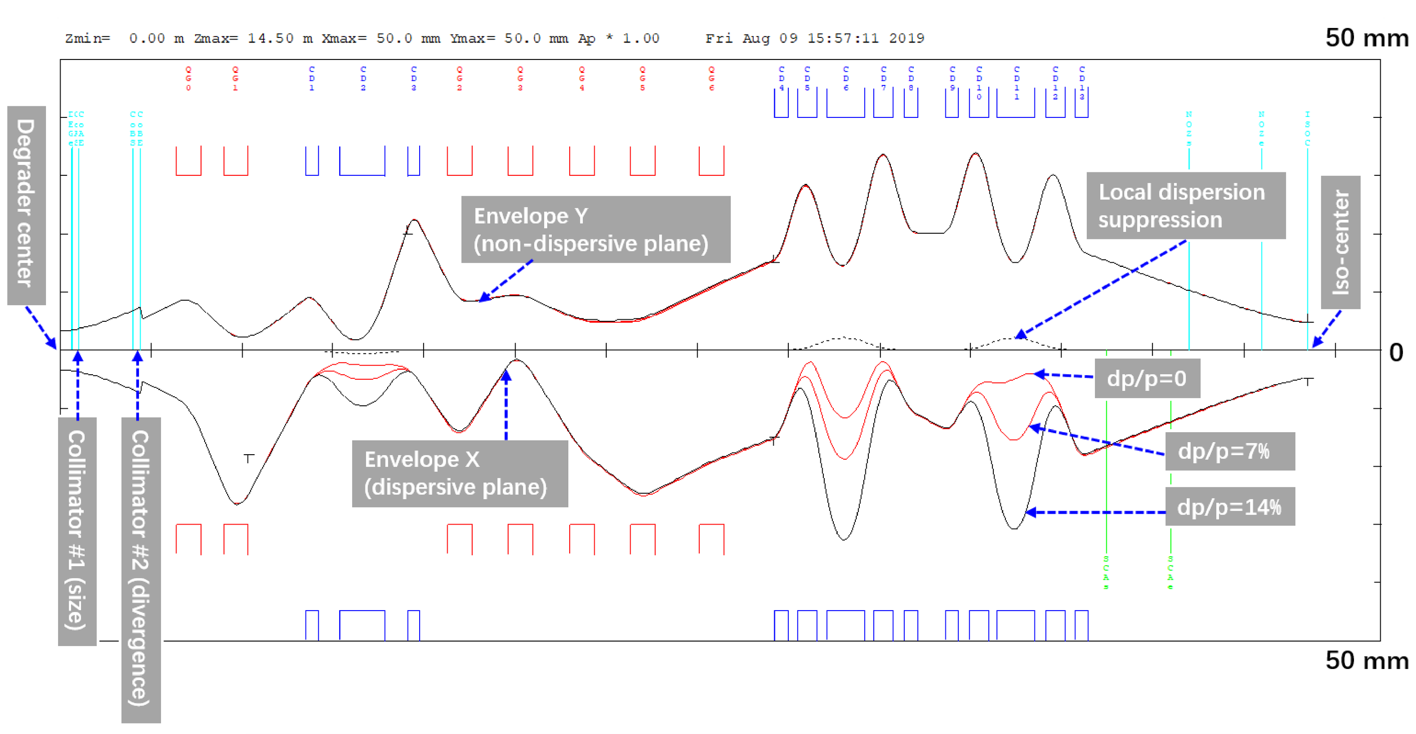


Figure 2: Beam optics calculations for the HUST SC Gantry

CONCEPT DESIGN OF A FAST DEGRADER

Considering some aberration effects, such as fringe fields and high-order optics, the final momentum acceptance can more than +/-10%. Thus we can divide into four levels to cover therapic beam energy 70MeV-240MeV, as listed in Table 1. In any range, the magnet settings are keep same, only the beam energies are needed to change.

Table 1 Four energy levels for +/-10% momentum deviation

Central Energy/MeV	dP/P	dE/E	Emin/MeV	Emax/MeV
75	10.00%	19.26%	60.56	89.44
105	10.00%	18.99%	85.06	124.94
145	10.00%	18.66%	117.94	172.06
205	10.00%	18.21%	167.68	242.32

The time for energy change is an important parameter for the beam transport system. Fast energy switch can reduce the total treatment time, which are benefit for the volumetric rescanning. To achieve this goal, we propose a separate degrader structure employing a multi-wedge and two blocks. The material of wedge is pure graphite with the density of $1.92 g/cm^3$, and the blocks are chosen as boron carbide to increase beam transmission. Unlike the energy range segmentation for the momentum dispersion, the degrader only has three configurations:

- 170MeV~240MeV: Only change the overlaps of multi-wedge;
- 120MeV~170MeV: Insert the Block1, and change the overlaps of multi-wedge;
- 70MeV~120MeV: Insert the Block1 & Block2, and change the overlaps of multi-wedge;

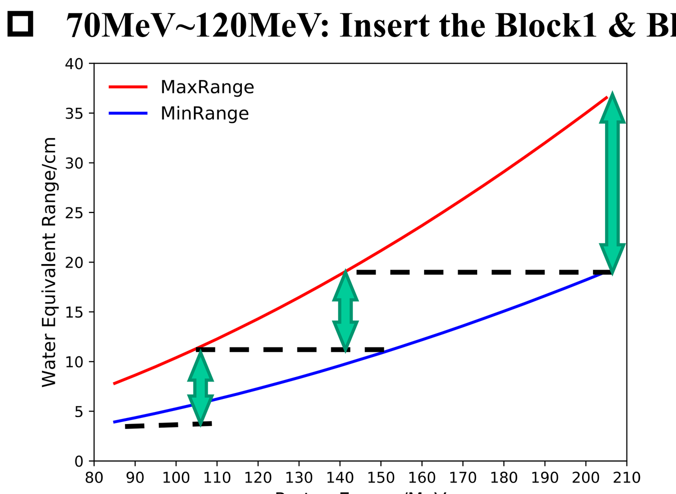


Fig. 2 Three adjustment energy ranges

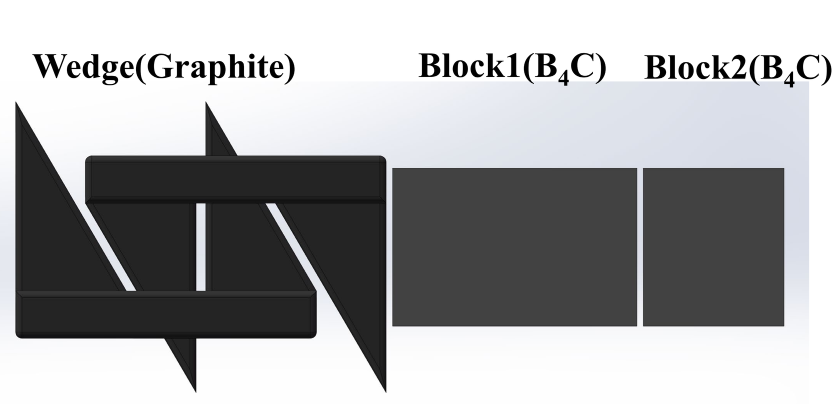


Fig. 3 Layout of the new separate degrader

DEGRADER SYSTEM SIMULATION

Due to the multiple coulomb scattering in the degrader, the beam divergence and emittance are rapidly increased. To limit the beam size and define the beam emittance, two collimators are placed downstream after the degrader. The position of each components is shown in Fig.4.

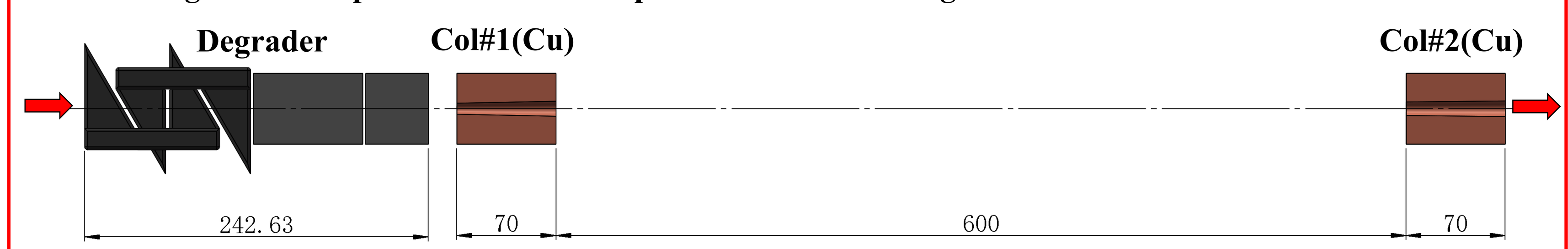


Figure 4 Layout of the whole degrader system

The incident beam energy is 250MeV with energy spread of ±0.1%. Ten millions protons are used for MC simulation, which is carried out in TOPAS. The results are shown in Fig.5-Fig.7:

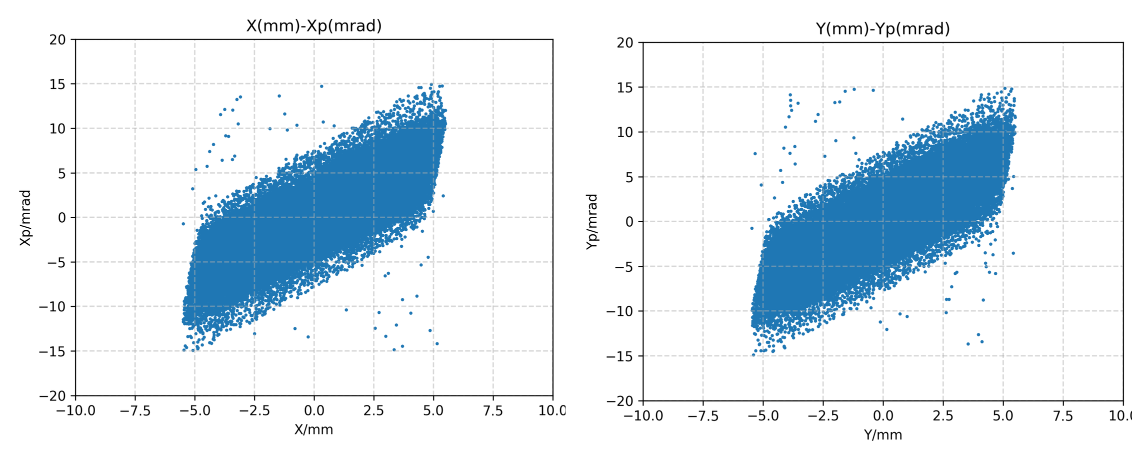


Figure 5 Beam phase space after the Col#2 for 70MeV. The output beam emittance is 7.2pi mm*mrad.

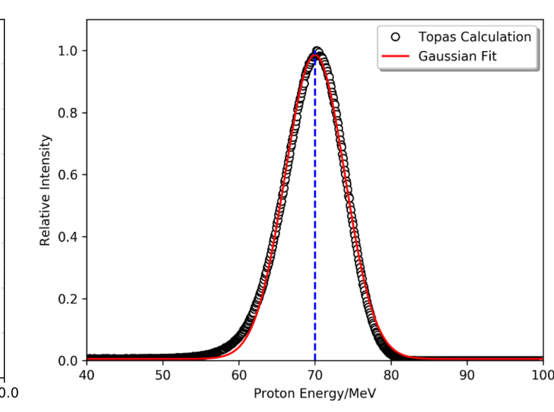


Figure 6 Energy distribution after the degrader (70MeV, dE/E=2.82%)

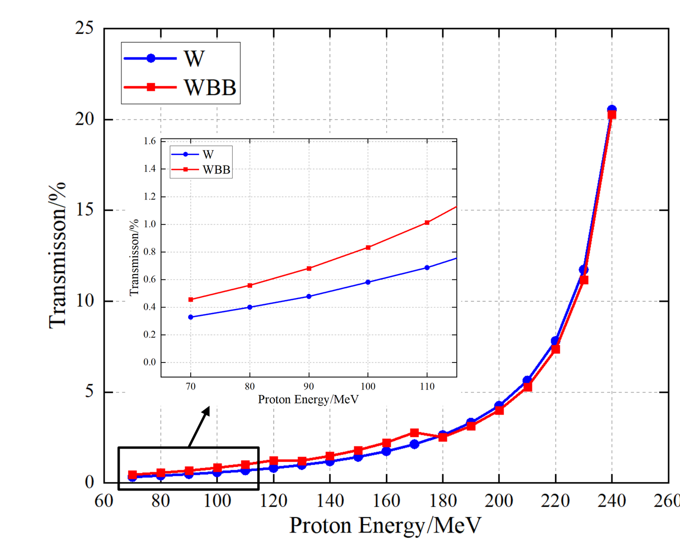
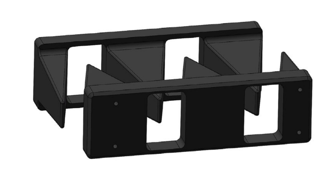


Figure 7 Beam transmission after the Col#2



Compared with multi-wedge scheme:

- Pros: 39~50% increase(relatively) for 70-120MeV
  24~30% increase(relatively) for 130-170MeV
- Cons: 4%~6% decrease(relatively) for 180-230MeV, due to the long drift (~143mm) between the wedge and Col#1.

Beneficial:

- ✓ Higher transmission, for low-z materials usage of B1,B2 (B_4C)
- ✓ Lighter wedge (~1/4 of full wedge), higher motion speed

SPREAD-OUT BRAGG PEAK

The relationship between proton range in water and proton beam momentum is approximately expressed as:

$$dR/R = 3.3\ dP/P$$

The maximum accepted change in beam momentum (dp/p=±10%) covers a variation water range of almost dR/R=±33% with respect to the nominal momentum. Benefit from this properties, we can increase the distance between successive energy layers and reduce the times of energy change, resulting the total treatment time decreased.

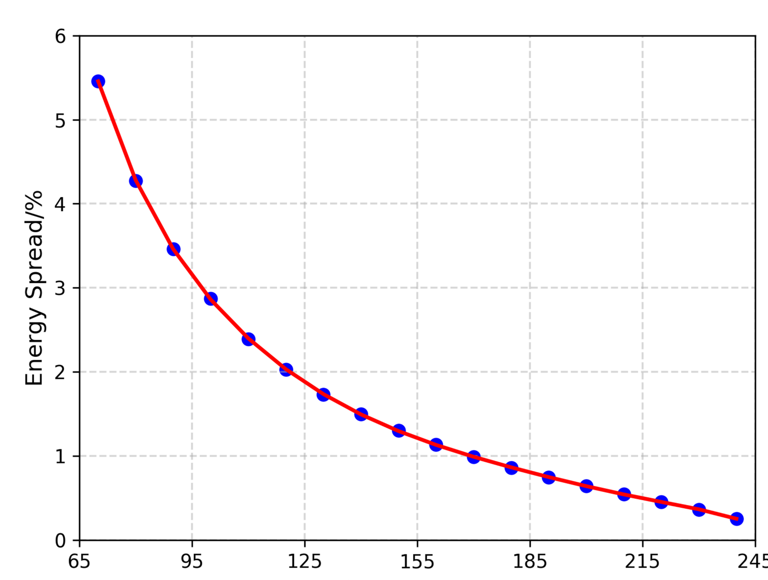


Figure 7 Energy Spread after the Col#2

In the normal proton therapy facility, the maximum momentum acceptance is typically ±0.5%, and energy modulation was done in steps that corresponds to a 5mm change in equivalent water depth. For the superconducting gantry with large momentum acceptance, we can increase the water equivalent steps. For example, we simulated a serious of proton beam with the energy from 120MeV to 170MeV, and the modulation energy step is 10mm to create the SOBP, as shown in Fig.9. The width of SOBP(w98) is 78mm and the deviation in the flat top is less than 2%. While the penumbra width is 6.62mm, which will be careful for some critical organs.

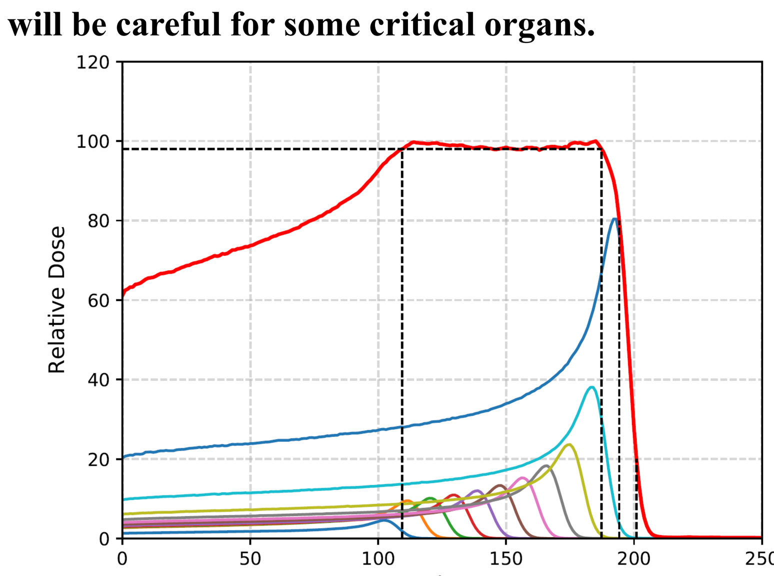


Figure 8 SOBP for 10mm energy step

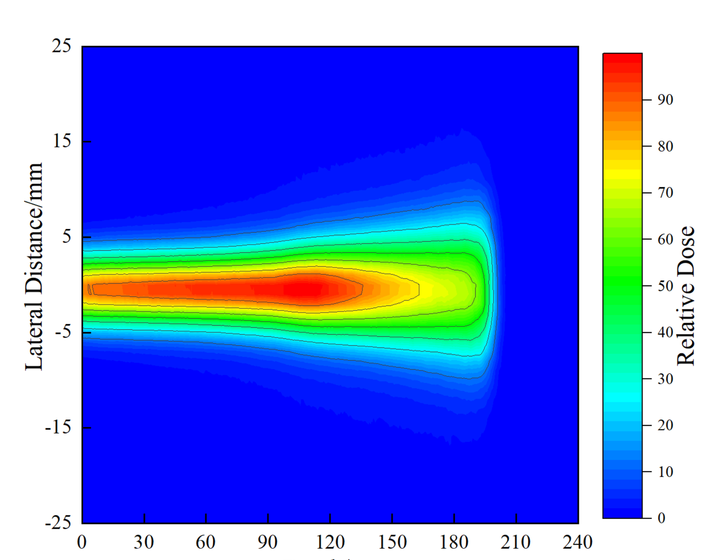


Figure 9 Lateral Distribution of the proton beam

CONCLUSIONS

A new fast degrader with separate structure is proposed for the compact superconducting gantry with large momentum acceptance. This degrader has lighter weight and can achieve higher motion speed. Owing to the usage of low Z material, the beam transmission in the lower energy can increased rapidly.

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