Design and optimization of beam optics for a superconducting gantry

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Abstract

A lightweight superconducting gantry applied to proton therapy is studied at HUST. In this paper, we presented a first order beam optics design of a SC gantry. Considering the large momentum offset beam and field complexity of AG-CCT magnets, realistic magnetic fields of AG-CCT are calculated. The effect of CCT curvature is observed and a method is proposed to minimize the distortion of the magnetic field . High order aberrations of beamline is under researched with COSY Infinity.

INTRODUCTION

The novel superconducting (SC) gantry has become a research hotspot with the tendency of compact proton therapy system. The footprint and weight of the gantry can be significant reduced by using SC magnets, and alternating gradient field of local achromatic bending sectors provides large momentum acceptance which means the magnetic field of SC magnets can remain fixed during tumor treatment. The schematic layout of HUST SC is shown in Fig. 1.

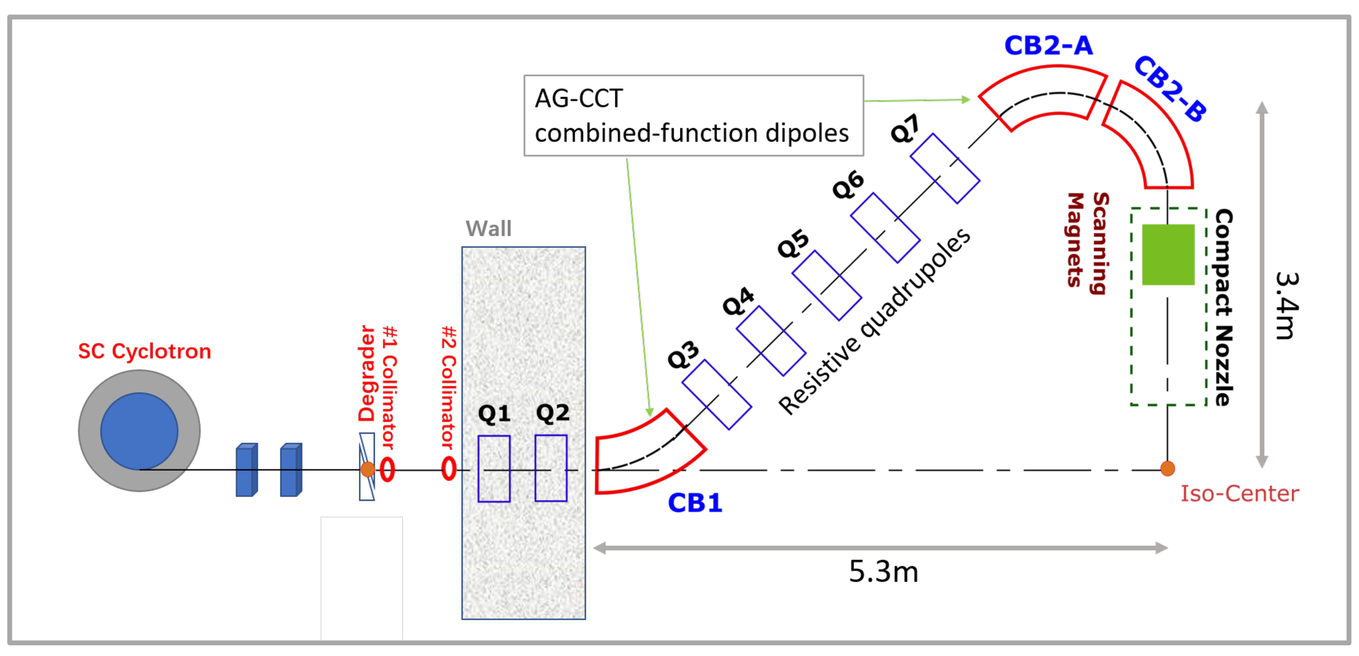

Figure 1: Schematic view of the HUST SC downstream scanning gantry

- AG-CCT combined function magnets are used for 2 bending sections: CB1 45 deg. ; CB2-A , CB2-B 67.5 deg. Local dispersion suppression are used to achieve +/-14% momentum acceptance. Max. dipole field 2.43 T with curvature 1 m.
- Q1-Q7 are resistive quadrupoles with small aperture.

LINEAR OPTICS CALCULATION

Linear optic is designed with TRANSPORT and shown in Fig. 2. Considering the balance of the envelope range and maximum field strength, the 45 deg CB1 AG-CCT is divided into 3 parts (DFD) as a locally achromatic banding section. The 135 deg bending section is split as two identical achromatic segments to suppress the maximum chromatic dispersion at the midpoint. Result shows +/-14% momentum acceptance.

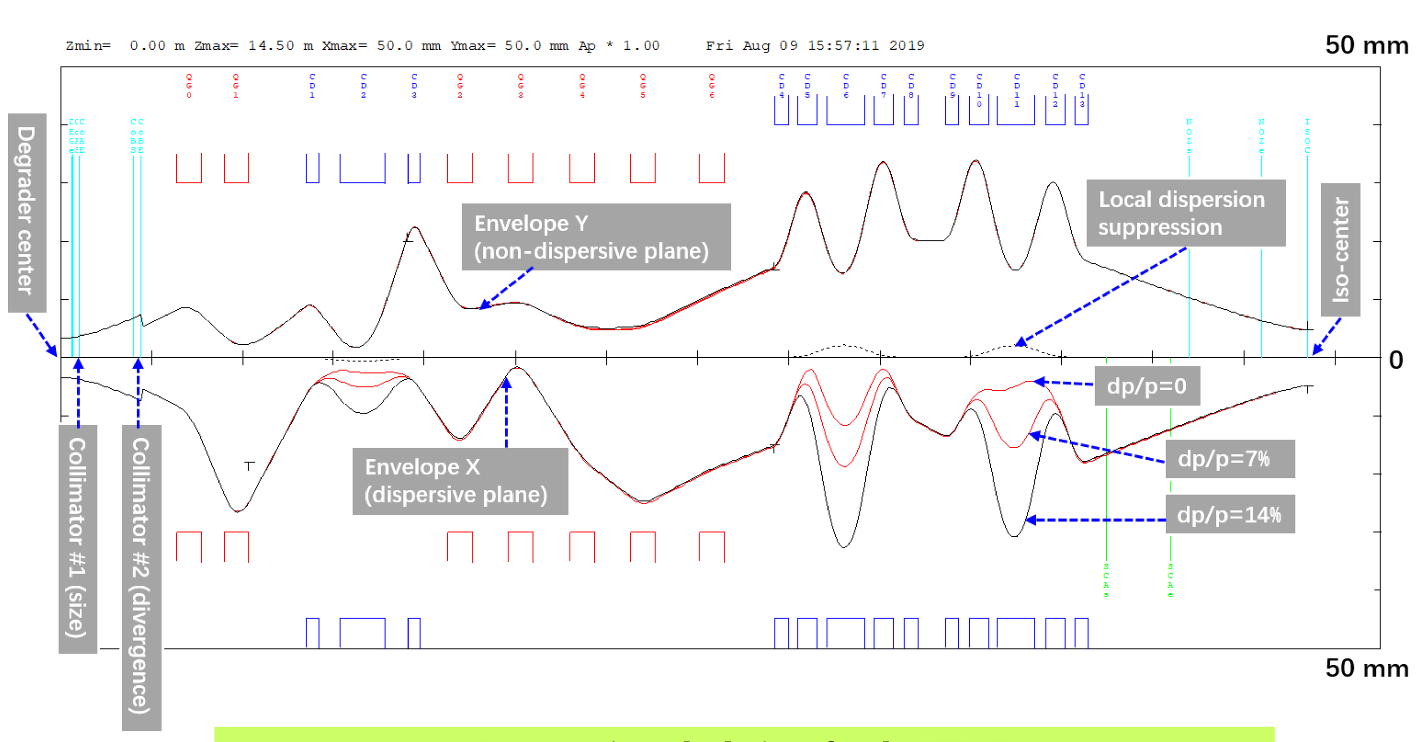

Figure 2: Beam optics calculations for the HUST SC Gantry

AG-CCT modelling and field calculation

Based on Biot-Savart Law, a set of CCT coil modeling and analysis tools have been developed to avoid time-consuming finite element analysis such as OPERA-3D. Parametric modeling provides a fast method of optimization with necessary accuracy. The transformation matrix computation builds a bridge between linear optic and realistic model.

The 135 deg AG-CCT modelling and magnetic field distribution are shown in Fig. 3.

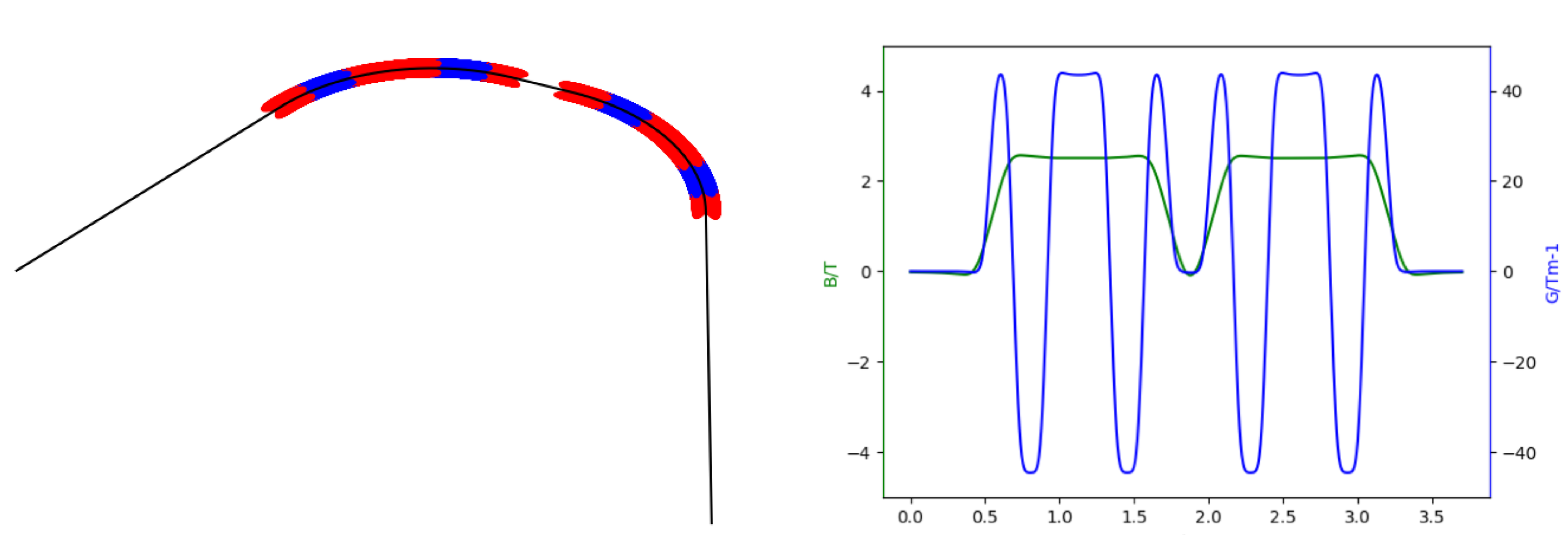

Figure 3: 135 deg AG-CCT modelling and magnetic field distribution

Dipole and quadrupole field distortion in curved CCTs

Curvature of curved CCT will break field symmetry along the radius in cross section where there are different current densities, and lead to (1) Small inherent quadrupole field, from dipole CCT

$$b_2^{inh} \approx b_1/(2 \cdot \rho)$$

(2) For quadrupole field of AG-CCT → center deviation & focusing difference in outside and inside radius → nonlinear distortion on beam phase space

The symmetric distortion of quadrupole field is shown in the Fig. 4. There is a positive association between the curvature of CCT and the degree of symmetric distortion.

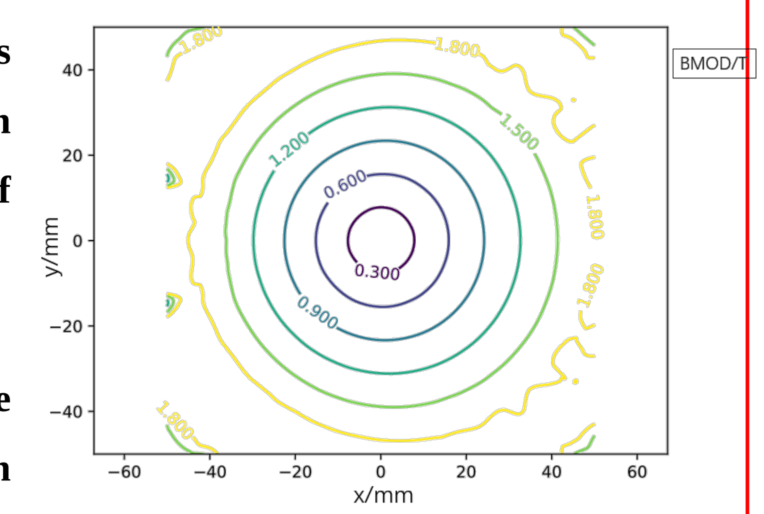

Figure 4: Field Distribution in Cross Section

Quadrupole field center point / ideal particle trajectory digresses from the CCT center axis with residual bipolar field component. See Fig. 5, using separate tracks of modelling to obtain 0 field along ideal particle trajectory.

Fig. 6 also shows the distortion of phase ellipse passing CCT. It is interesting that the ellipse recovers far away CCT field.

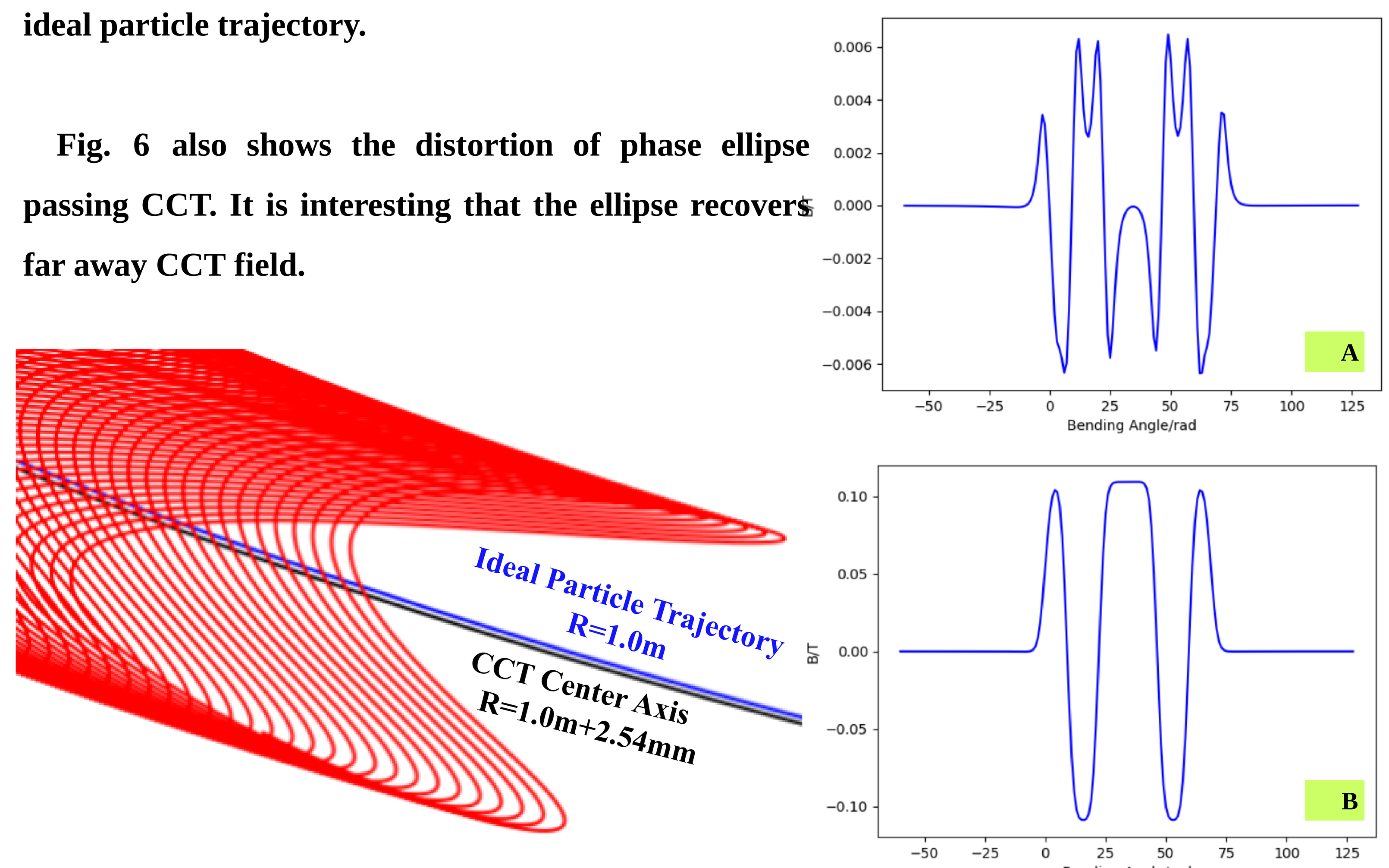

Figure 5: Magnetic Central Deviation and Distribution along Ideal Particle Trajectory(A) and CCT Center Axis(B)

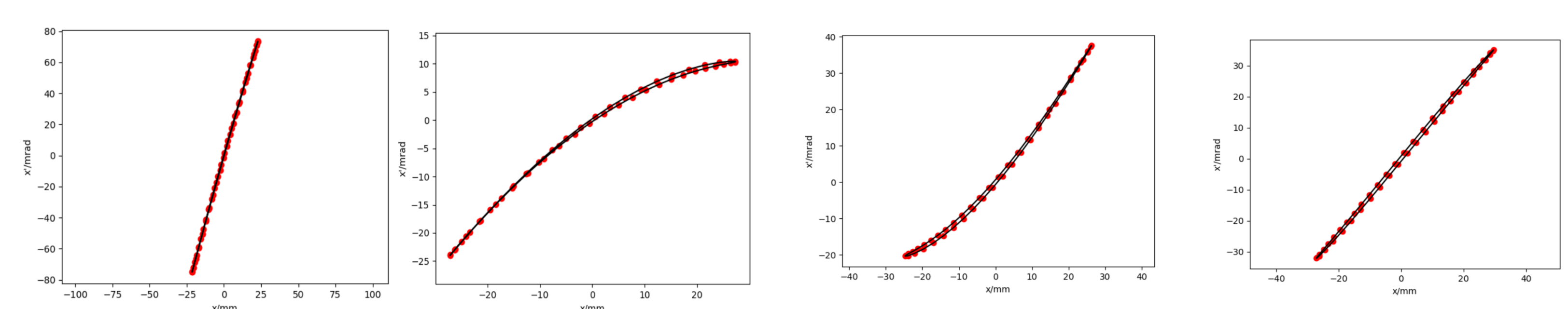

Figure 6: Change of Phase Ellipse passing CCT

Effect of High Order Aberrations

Second order beam optics has been studied in COSY Infinity. Present results show that aberrations have significant influence on beam trajectories, especially for large momentum offset particles. The original linear optics need be re-optimized in high order situation, and sextupole components will be introduced to minimize the second order aberrations.

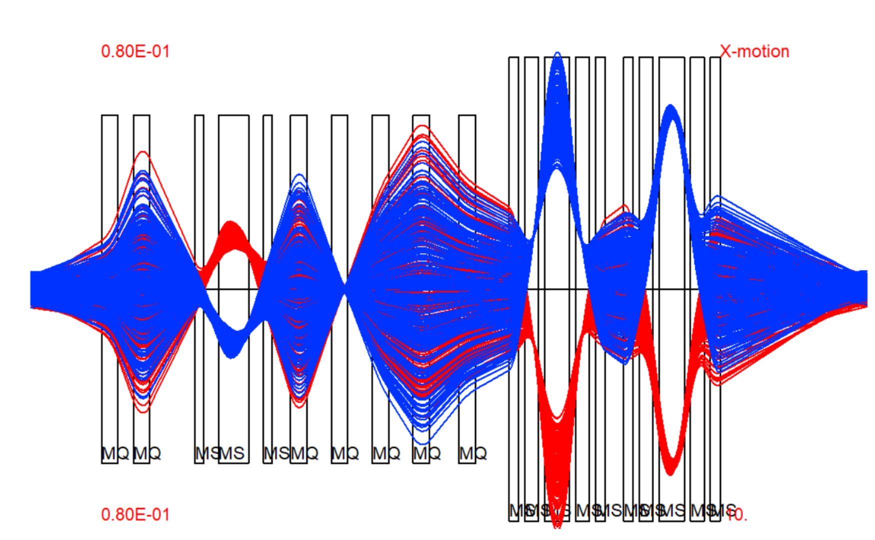

Figure 7: Beam Tracking with Momentum Dispersion in Linear optic

CONCLUSIONS

A superconducting gantry with large momentum acceptance using AG-CCT magnets is under research in HUST. Linear optics with +/-14% momentum acceptance is introduced. Considering magnetic field complexity of AG-CCT, a modelling and calculation code has been developed. COSY Infinity is used to investigate high order aberrations and fringe field effect, and further optics optimization and beamline validation using particle tracking is under-going.

Reference:

[1] B. Qin, X. Liu et al., Comparison of beam optics for normal conducting and superconducting gantry beamline applied to proton therapy, International Journal of Modern Physics A, accepted, 2019.

[2] Lucas Nathan Brouwer, Canted-Cosine-Theta Superconducting Accelerator Magnets for High Energy Physics and Ion Beam Cancer Therapy, PhD Dissertation, UC Berkeley, 2015.

[3] Gerbershagen A , Meer D , Schippers J M , et al. A novel beam optics concept in a particle therapy gantry utilizing the advantages of superconducting magnets. Zeitschrift für Medizinische Physik, 2016:S0939388916300010.