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DESIGN OF A LARGE MOMENTUM ACCEPTANCE GANTRY BASED ON AG-CCT FOR LIGHTWEIGHT PROTON THERAPY FACILITY*

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Abstract

Superconducting (SC) gantry can be applied to proton therapy with significantly reduced footprint and weight. However, the relatively lower ramping limit of the SC magnetic field becomes a bottle-neck for fast energy change and beam delivery. Designing a large momentum acceptance (LMA) beam optics can mitigate this issue, which would, meanwhile, bring potential applications for advanced treatment schemes with high beam transmission. In this contribution, we present the design of an LMA gantry using strong focusing AG-CCT SC magnets and symmetrical achromatic lattice. A fast degrader is combined in this design so that the gantry can perform rapid energy switches during the treatment. The AG-CCT design process and beam transport simulation are all performed with our homemade integrated code CSPT, which has interfaces to Geant-4 and Opera, and can reach a maximum speed-up ratio of 450 by applying parallel computation technique. The multi-particle tracking result proves that the gantry has a large momentum acceptance of ~20%.

INTRODUCTION

Hadron therapy is known to have superior physical characteristics, namely Bragg-Peak. It decreases the deposit dose to surrounded normal tissues and thus holds the potential of reducing the toxicity of organs at risk. Gantry, as an attractive tool in particle therapy, can further expand the ability of conformal treatment by irradiating the beam from different angles. However, the relatively large magnet rigidity, with respect to that of electrons in photon therapy, leads to massive facility size and weight. Most of the gantries running for proton therapy weigh over 100 tons with their length exceeding 10 m [1]. The figure would be much larger when it comes to carbon-ion facilities. Therefore, a cost-effective hadron therapy facility with a smaller gantry is one of the major interests of hospitals and research centers.

Utilizing superconducting (SC) technology enables the magnet to excite a higher magnetic field, which, in consequence, can make the gantry significantly lighter. The main drawback of the SC magnets is their slow ramping rate. The momentum modulation process in the steps of $\Delta p/p = 1\% \sim 2\%$ is performed with a ramping time of 0.1 ~ 2.0 s per step, corresponding to the momentum of the beam [2]. Designing a gantry lattice with large momentum acceptance (LMA) can mitigate this issue so that the field of magnets maintains while the beam with various momentum can still be transported to the iso-center. This contribution presents the design of an LMA gantry for proton therapy using alternating gradient canted cosine theta (AG-CCT) magnets. The beam lattice with a fast degrader component and a compact nozzle design is introduced in the paper. For the convenience of the gantry design, a simulation toolkit based on parallel computation technology is developed. A preliminary design of the AG-CCT magnet is displayed at the end.

OPTICS DESIGN OF THE LMA GANTRY

The overview of the LMA gantry is presented in Fig. 1, which is a cyclotron-based design. A fast degrader component is placed in the middle of the gantry for momentum modulation. The degrader adopts a pair of high-density graphite wedge for continuous momentum modulation, and 2 B_4C blocks for step modulation, since the low Z material can suppress the growth of beam emittance. Linear motors could be equipped for fast energy switches. Two copper collimators lie in sequence, right after the degrader, for emittance restriction. At this stage, only one set of collimator configuration is applied to form a beam with the emittance of 10π mm mrad for the following beamline. The Monte Carlo (MC) simulation suggests that the overall transmission efficiency at the nominal energy 70 MeV is about 0.91%, which is about 53% higher than the traditional multi-wedges degrader.

On either side of the degrader component are the 2 bending sections, among which only the second bending section is demanded to have a large momentum acceptance of >16% to ensure a sufficient range of momentum variation with a fixed field of the SC magnet. Considering such a large momentum offset, high-order aberration should be taken into account. AG-CCT is introduced in the design as a main achromatic method [3], and its magnetic field is symmetrically arranged. Due to its flexibility of combining the dipole with multipole fields, the quantity of the magnet in the gantry is reduced. A strong alternating quadrupole field is embedded in the magnet for restricting the beam of different nominal momentum within the bore. Weak sextupole is added for high-order achromaticity. The optics design and optimization process is carried out on COSY Infinity [4]. The optics result of the second bending section is presented in Fig. 2, a stable rounded beam spot is formed at the iso-center, which proves that the gantry is capable of delivering the beam with a momentum range of -9.5%~+10.5%. The main restriction of the momentum acceptance is the good

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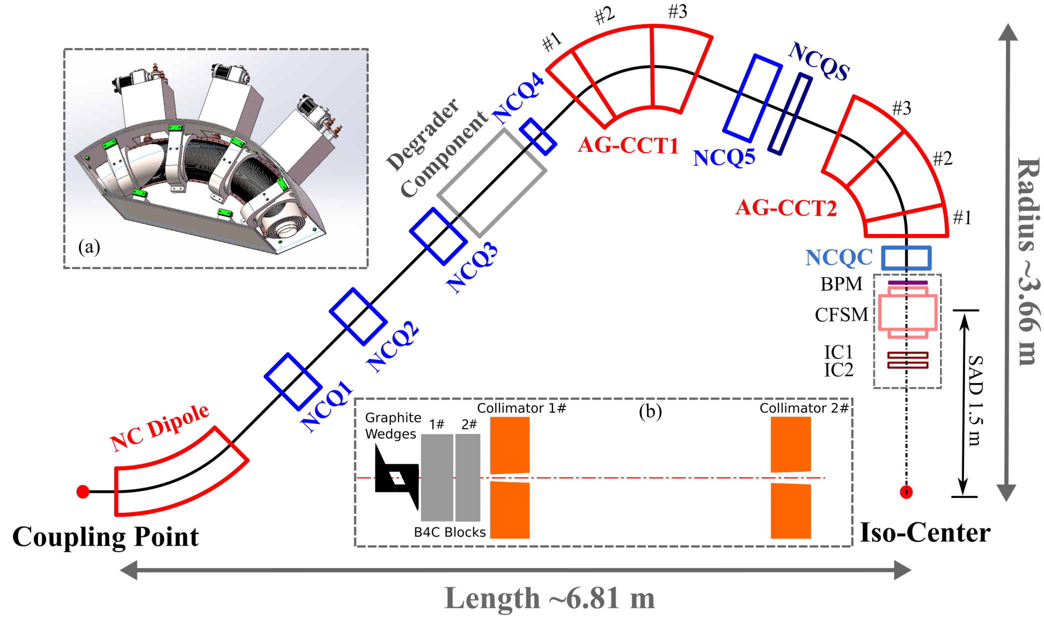

Figure 1: The overview of the LMA gantry. (a) The AG-CCT magnet model; (b) The layout the degrader component.

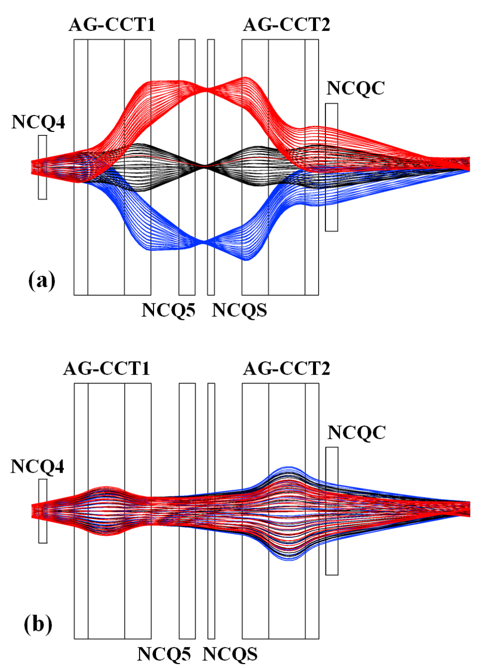

Figure 2: Beam envelope of the second bending section, (a) in the horizontal plane; (b) in the vertical plane. The red, black and blue lines in the figure represent the particle trajectories with the momentum offset of -9.5%, 0%, +10.5%, respectively. The black boxes denote the boundaries of the magnets.

field region (GFR) of the AG-CCT magnet, which is set to 90 mm in this contribution. A compact nozzle component, with a combined-function scanning magnet CFSM, is right after the second bending seciton, and the SAD is set to 1.5 m in this design.

TOOLKIT FOR GANTRY DESIGN

The field shape of the AG-CCT magnet is greatly affected by the winding geometry, and can hardly be abstracted to a transfer map. The beam tracking with a realistic field offers the best accuracy, which, however, often involves interaction between electromagnetic simulation software and beam optics software. For the convenience of gantry design, we developed a lattice design toolkit using C++, named CSPT [5]. The structure of the toolkit is shown in Fig. 3.

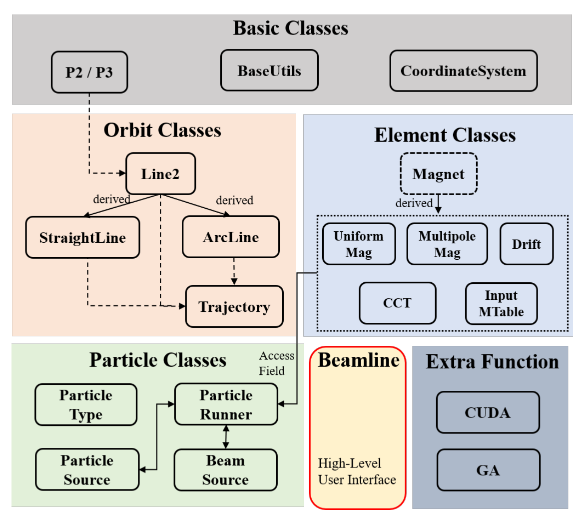

Figure 3: The structure of the CSPT toolkit. Each rectangle with round corners represents a C++ class in the toolkit.

The toolkit is capable of dealing with beam tracking with various initial distributions in the electromagnetic field. The toolkit provides basic optical elements such as dipole, quadrupole and combined-function magnets. The geometry of the CCT magnet can be defined by a winding path

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function, and its magnetic field can be calculated with the Biot-Savart law. The toolkit provides interfaces to Geant4 and Opera, so that the simulation can be carried out with input electromagnetic field and complicated beam distribution after a series of particle-matter interactions. Parallel computation technology is applied in the toolkit for fast simulation. The GPU parallel performs a maximum speed-up of 457 times faster than the single thread CPU calculation, exchanged with merely a 0.32% relative error increase.

AG-CCT MAGNET DESIGN

Due to the large bore aperture of the magnet for LMA beam delivery, the field pattern of the AG-CCT bending magnet can't be taken as cylindrical distribution in approximation. But the relation between the curved winding geometry and toroidal field pattern is complicated. In this contribution, simply the field derivatives are applied to define the field pattern, which also is consistent with the Taylor expansion for particle motion around the nominal trajectory in the transfer map. Ref. [6] discusses the relationship between the winding path of the CCT magnet and its derivative field, which is integrated into our magnet design procedure.

The design of the winding path needs iterative optimization because there are inherent fields that depend only on the geometrical parameters and the current of the magnet. The final derivative field of the AG-CCT magnet is demonstrated in Fig. 4. The integrated harmonic is limited below 5 units, and the main tilt angle of the magnet is set to 40° for a sharp fringe field ramp. A thin ironic shield is used in the magnet design to ease the overshooting of the fringe field.

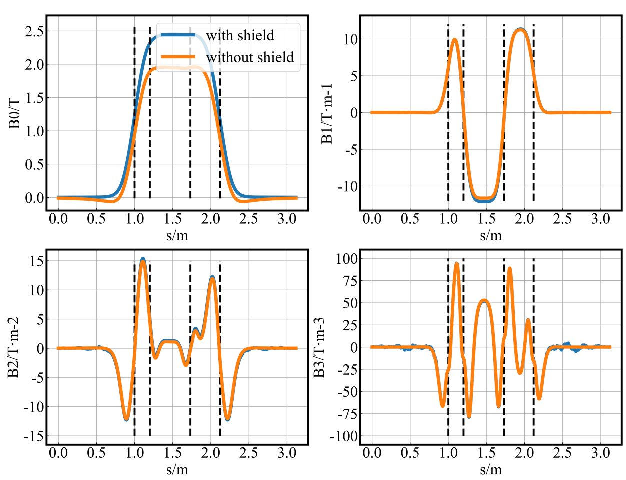

Figure 4: The distribution of the derivative field along the magnet. The black dashed lines in the figure represent the boundaries of each AG section.

CONCLUSION

Proton therapy has attracted much attention worldwide. Gantries utilizing SC magnets are in demand for more cost-effective and robust treatment facilities. In this contribution, a systematic design of the LMA gantry with AG-CCT SC magnets is proposed. Benefiting from the strong alternating focusing characteristic of the AG-CCT magnet and symmetrical achromatic lattice design, the LMA gantry achieves a large momentum acceptance of -9.5%~+10.5%. For such a large momentum range, in combination with a fast degrader component, the transmission of the lattice at the iso-center is significantly raised, which improves the efficiency of treatment and would bring potential advantages for advanced treatment schemes. A homemade toolkit CSPT is developed for LMA gantry and CCT magnet design. With interfaces to Geant4 and Opera, the toolkit can conduct more realistic multi-physics simulations. More detailed studies, such as the quench protection design of the SC magnet and error analysis, are still ongoing before the LMA gantry comes to the manufacturing stage.

Table 1: Integrated Derivative Fields of the AG-CCT Magnet

Order	Section 1#	Section 2#	Section 3#
B0	10000.000	10000.000	10000.000
B1	3247.147	3587.687	3567.178
B2	1.035	4.739	3.428
B3	1.945	2.334	1.103
B4	2.262	0.377	1.058
B5	0.535	0.497	0.345

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