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CSPT: A GPU-ACCELERATED LATTICE DESIGN TOOLKIT ESPECIALLY FOR CCT*

Y. C. Liao[1], R. X. Zhao[2], C. Y. Li[1], X. Liu[1], W. Wang[1], B. Qin[†,1]
[1]State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, China
[2]Shenzhen Institute of Computing Science, Shenzhen, China

Abstract

Canted-Cosine-Thera (CCT) superconducting magnet is a promising alternative for normal-conducting magnets in compact accelerator systems such as large hadron colliders or particle therapy facilities. For the convenience of lattice design with CCT, we develop the CCT Simulation and Particle Tracking (CSPT) toolkit. It's a program that can perform both simulations of the beam dynamic process within particle accelerators and basic electromagnetic harmonic analysis. The charged-particle tracking and electromagnetic calculation process can be accelerated by either CPU multicore or GPU parallel, with a maximum speed-up ratio of 457. The simulation result of the program is well consistent with Opera and COSY Infinity.

INTRODUCTION

In pursuit of high-field magnets, advanced superconducting technology is introduced into the accelerator area. Among the existing superconducting magnets, Canted-Cosine-Theta(CCT) has become quite popular with magnet designers due to it's superior field quality, outstanding mechanical properties and simple winding process [1]. The concept of CCT magnet is based on pairs of conductor wound and powered such that their transverse field components sum up and their axial (solenoidal) field components cancel [2]. As it possesses promising potential in collider, storage ring and particle therapy facility, many laboratories have carried out research on CCT magnets in recent years [3–6].

Thanks to the winding flexibility of CCT magnet, complex multipole field components can be generated. However, few optics and particle tracking software have embedded this type of magnet. Great efforts would be put forward for researchers to accurately simulate and control the beam dynamics in a lattice with CCT magnets. For the convenience of the CCT-related research, we present the CCT Simulation and Particle Tracking (CSPT) toolkit. In this report, the structure of the CSPT toolkit is discussed, and the calculation results are testified with finite element analysis software Opera and optics code COSY Infinity [7].

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† bin.qin@mail.hust.edu.cn

SOFTWARE STRUCTURE

The CSPT toolkit, written in C++17 standard, is compatible with beam dynamic simulation and electromagnetic field analysis within CCT magnet. The structure of the toolkit is shown in Fig. 1.

Fundamental Classes

The gray block at the top of the structure contains the fundamental (low-level) classes of the toolkit that users are not supposed to call directly. The *P2/P3* class characterizes points or vectors in two or three dimensions. The *Coordinate System* class, composed of *P3* vectors, denotes the position of each element and particle.

In CSPT, lines in two dimensions are needed for every magnetic element, so that the position of a particle can be defined in the curvilinear coordinate system. The *Line2* class, which can generate lines in arbitrary curvature, is the base class of 2D lines. It's made up of *P2* points. The *Straight Line* and *Arc line* classes are the derived class of *Line2*. The ideal orbit of a lattice in the toolkit consists of several 2D lines with the vertical axis $y \equiv 0$. Each 2D line belongs to a magnetic element.

Magnetic Elements

At present, only magnetic elements are supported in CSPT toolkit. The *Uniform Magnet* and the *Multipole Magnet* generate ideal fields within the element regions (hard-edge). The *Multipole Magnet* can combine fields from dipole to octupole. To describe a complex field shape, the *Input Magnet Table* class shall be applied. And the class supports the Opera field format. The field calculation process of *CCT* is based on Biot-Savart Law. The field shape of the CCT magnet can be adjusted by modifying the path function of the windings. The CCT model in the CSPT can also be loaded to Opera as conductors. Besides, common harmonic analysis programs are provided for the magnetic classes so that users can check the field quality in the lattice space.

High-level Classes

Above all, the Particle classes and *Beamline* are the highest-level classes in the toolkit. They can be directly called by users. A type of particle with specific values of mass and charge can be defined in *Particle type* class. Then, the toolkit provides two methods to produce running particles. Users can generate a particle with position (x, y, z) and velocity (V_x, V_y, V_z) of a chosen type in *Particle Source*, or

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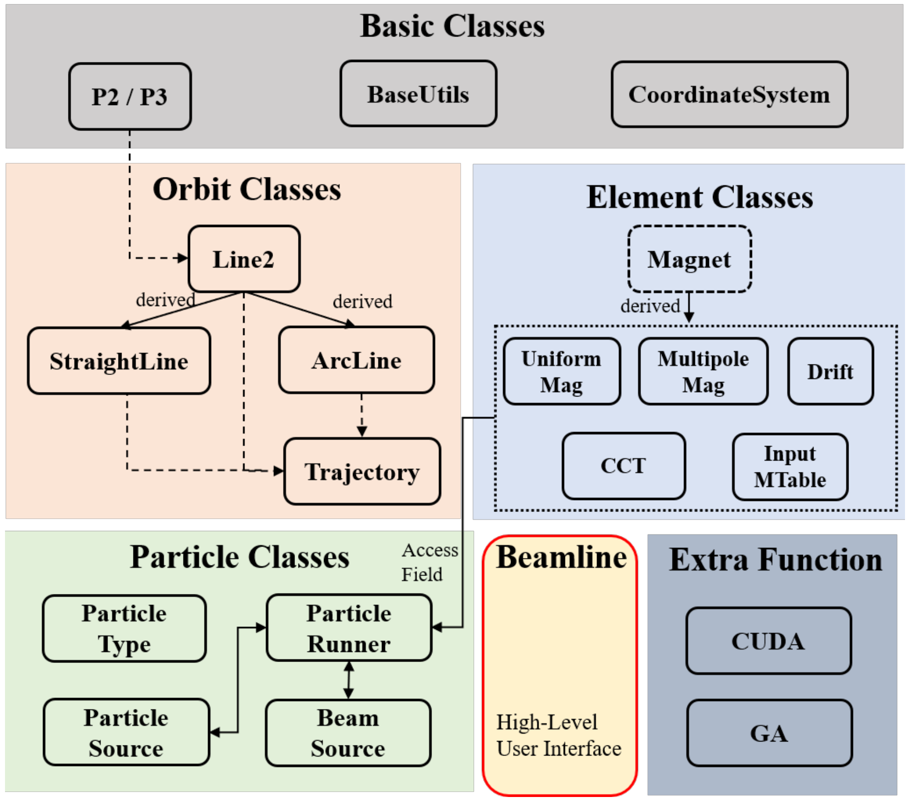

Figure 1: The structure of the CSPT toolkit. Each rectangle with round corners represents a C++ class in the toolkit.

define a beam of a specific number of particles with Gaussian or uniform distribution in *Beam Source*, which is a more useful way in a practicle simulation. The beam can be defined both in twiss or sigma parameters. The *Particle Runner* is responsible for calculating the Lorentz force and movement of each running particle in a small time step. Runge-Kutta45 is adopted for the particle tracking calculation.

To build a beam lattice easily, the *Beamline* class adopts MAD-style syntax. Users can simply define a magnetic element with several parameters, and the element would be directly jointed at the end of the present lattice. The program will calculate the position and direction of the element, and produce a *Line2* orbit for it automatically. What's more, the *Beamline* class offers several common particle tracking programs, so that users don't have to pay attention to the Particle classes.

To be noticed, the CSPT toolkit does not cover the calculation of particle-matter interactions. But the toolkit allows the user to input the particle information from Geant4 using the *Particle Factory* class. To accelerate the calculation speed of particle tracking and magnetic field (especially for CCT magnets), CPU multicore (OpenMP) and GPU parallel (CUDA) technology are applied. Besides, a Genetic Algorithm (GA) package is developed so that users can conduct lattice design and optimization just in the toolkit.

RESULTS

To prove the accuracy of CSPT results, we pick widely-used optics software COSY-Infinity as a reference for particle tracking results within ideal multipole elements, and finite element analysis software Opera as a reference for CCT magnetic field calculation results.

Validation of Beam Optics Calculation

A beamline lattice of HUST-PTF gantry [8] is generated in CSPT and COSY Infinity, respectively. And a particle is emitted at the start of the lattice and collected at the end. Phase space results of the particle in the programs are compared. We carried out 10 times of experiments. And for the first 5 experiments, the magnets parameters are changed randomly. For the last 5, the initial parameters of the particle are changed. Figure 2 shows the maximum error of the phase space results in the experiments. There is a well consistency of the CSPT toolkit with the optics software, with a maximum relative error of 0.92% and a maximum absolute error of 0.056 mm.

Validation of Field Analysis

A CCT magnet with 4 layers is generated in the CSPT toolkit. And the conductor model is then loaded to Opera. The multipole component distribution on the reference orbit is shown in Fig. 3. The dipole and quadrupole results show well consistency between the two programs. Differences on sextupole and octupole at the entrance and exit of the

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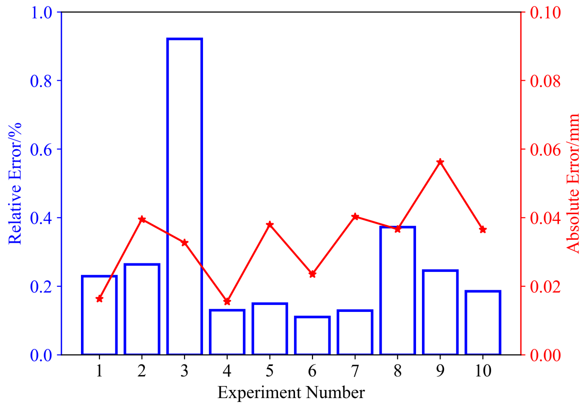

Figure 2: The error of the CSPT tracking results with respect to COSY Infinity.

magnet, which would lead to no significant divergence in the particle tracking results, are mainly due to the numerical error during the fast Fourier transform process. Figure 4 is the tracking result of an ideal particle in the CCT magnet in CSPT toolkit and Opera. The maximum difference between two programs, at the end of the lattice, is about 0.1 mm.

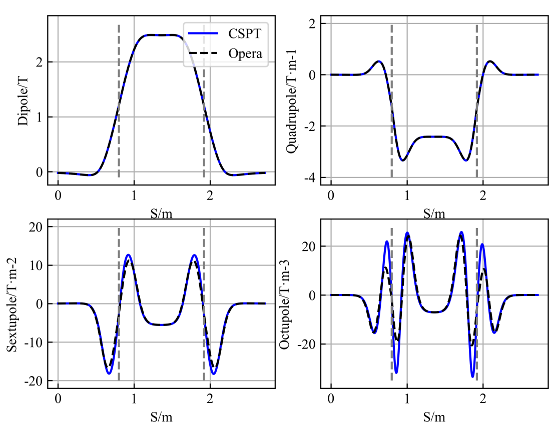

Figure 3: The field component of a 4 layers CCT magnet on the ideal orbit. The blue lines represent the results of CSPT toolkit, the black lines in dash are the Opera's results.

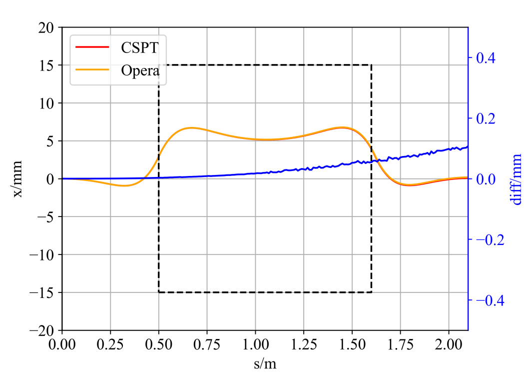

Figure 4: A particle tracking result of CSPT and Opera. The black box in dash line represents the CCT magnet.

Calculation Speed

The calculation speed of CCT magnetic field dominates the efficiency of lattice design and particle tracking, to a considerable extent. The field calculation with Biot-Savart Law is a very time-consuming process, because there are an enormous number of current units in a CCT manget. To alleviate the problem, CPU multicore and GPU parallel technology are applied in the toolkit. In Table. 1, the tracking time of 250 particles in a beamline with 2 CCT magnets is investigated. The GPU parallel enables the toolkit to calculate a maximum of 457 times faster than the single thread CPU version, exchanged with merely a 0.32% relative error increase.

Table 1: Calculation Time of 250 Particles in a Beamline under Different Settings

Method	**Total time**	**Speed-up ratio**
CPU (1 core)	77 298 sec	-
CPU (12 cores)	13 318 sec	5.8
CUDA (double)	531 sec	145.6
CUDA (float)	169 sec	457.0

CONCLUSION

CCT magnet, as a promising alternative for the next generation accelerator facilities, has drawn much attention over the world. But few optics software support accurate simulation of this kind of magnet. In this paper, we present a newly-developed program called the CCT Simulation and Particle Tracking toolkit (CSPT). It's capable of dealing with particle tracking and field analysis tasks. The experiment shows that the toolkit can produce accurate results with a relative error below 1.0% in a considerably short calculation time. Together with rich built-in functions, it's a simple and effective toolkit for lattice design with CCT magnet. Due to limited time, the Graphic User Interface(GUI) and lattice error analysis module are still ongoing.

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