

Superconducting gantry design for a carbon ion medical accelerator

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Summary

During my stay at the Summer School 2019 at CERN, I have worked together with my colleagues on the design of a new medical facility based on accelerator technology, as part of the SEEIST initiative (South East European International Institute for Sustainable Technologies, see http://seeiist.com/wp-content/uploads/2018/05/SEE-Hadron-Therapy-and-Research-Facility-HTR_11.09.18.pdf). This initiative refers to the collaboration of South East European countries (including Montenegro) with the goal of designing and constructing a new medical ion accelerator facility to be used for treatment and research purposes. Under the supervision of Elena Benedetto (TERA Foundation) and Maurizio Vretenar (CERN), I have worked as part of a team in charge of producing a new synchrotron and gantry design. In this report, I will provide a detailed overview of my work and contribution to the project.

Introduction

Hadron therapy is one of the possible treatment methods for various types of cancer, with proton therapy being more widespread, and light and heavy ion therapy still in earlier stages of development. This particular project has the final goal of designing a new ion accelerator facility. The facility design, in short, consists of a synchrotron to accelerate carbon ions (and other light ions) to a maximum energy of 430 MeV/u (Mega-electron-volt per nucleon), several beam delivery lines for treatment and research, as well as a superconducting gantry that would allow the beam to be delivered to the patient from different angles. The superconducting magnet technology aims to make use of high magnetic fields (up to 4 T) to reduce the size and cost of the facility. A comparison with already existing ion accelerator medical facilities can be seen below.

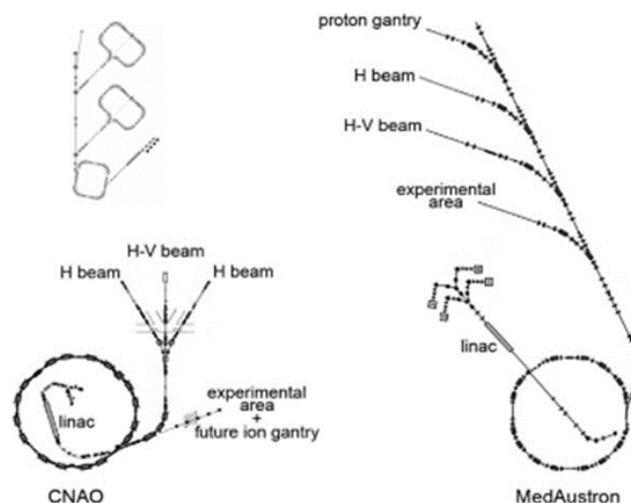


Figure 1: The planned medical ion facility (top left) compared to already existing ones

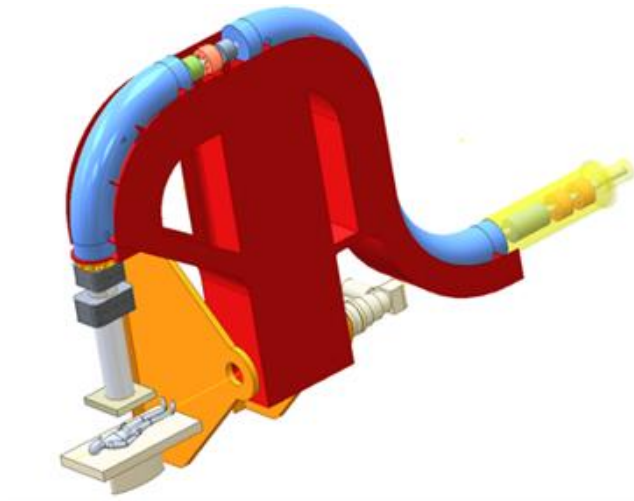


Figure 2: Gantry design

I was given the task of producing a model for the gantry magnets using the software Opera-3D, specifically the version 18R2 (<https://operafea.com/>). The task consisted of creating a 3D model for the magnet and the iron yoke, and then subsequently calculating the relevant magnetic fields. The magnetic field maps would then be used for simulating the gantry elements in other software and for particle tracking.

As a secondary objective, I was given the task of finding a way to track a multitude of particles through the magnet using Opera 3D and then graph and compare this data in a $x-x'$ phase space graph. The particle tracking module for Opera 3D have been added only recently, and this project was a good opportunity to test Opera 3D's tracking against other software.

Methodology

For the purposes of this project, I have done most of my work in Opera 3D. I have used Opera 3D's Modeller to prepare the 3D mesh to be calculated, using its built-in functions to generate all the necessary geometry, material properties, as well as boundary and symmetry conditions. After the model was finished, a database would be prepared for the software to analyze, which would on average take about 15 hours, depending on the mesh properties.

The analysis of the model was conducted in the Analyzer of the Opera 3D package, using its graphing and plotting functions. The Analyzer was also used for particle tracking, and I used its output trajectory files to produce the relevant $x-x'$ graphs for the beams. The $x-x'$ graphs were produced and finalized in Microsoft Excel.

The Model

At the beginning of my work, I was provided with a set of premade conductor files that described the magnet coils for the gantry bending magnets. The coils were separated into two layers that, when put together, created a dipolar magnetic field. The magnetic coils were wound in a specific fashion called CCT

(Canted Cosine Theta, see figure below), and the magnet itself was curved by 90 degrees, with a curve radius of 1.65m.

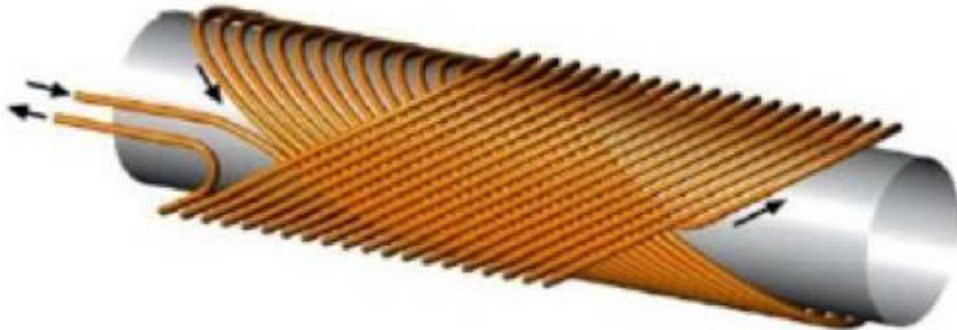


Figure 3: Canted Cosine Theta (CCT) coils, Courtesy L. Brouwer, LBNL

My first task was to get familiar with the software itself, its modeler and post-processor, and then use my skills to create a working model for the superconducting coils. During my first week, I got acquainted with the software, and learned how to produce various coils, 3D bodies of air and iron, as well as how to impose the needed symmetry and boundary conditions. After that, I have created a working 3D model for the gantry bending magnet.

The steps in producing the model

To produce the required geometry for the model, I have made use of cylinders and tubes of various diameters. The model consists of 2 air cylinders (one with a very fine mesh, only enveloping the coils; another enveloping the rest of the model), and one tube that represents iron. All the elements were first generated using the 'Create Cylinder' command, and then bent in a rotated global coordinate system so as to match the curve of the magnet. The length of the iron was made to match that of the magnet, while the air body has a linear continuation, so as to facilitate low-field regions for particle tracking purposes. The figure below shows the dimensions of the cross-section of the model.

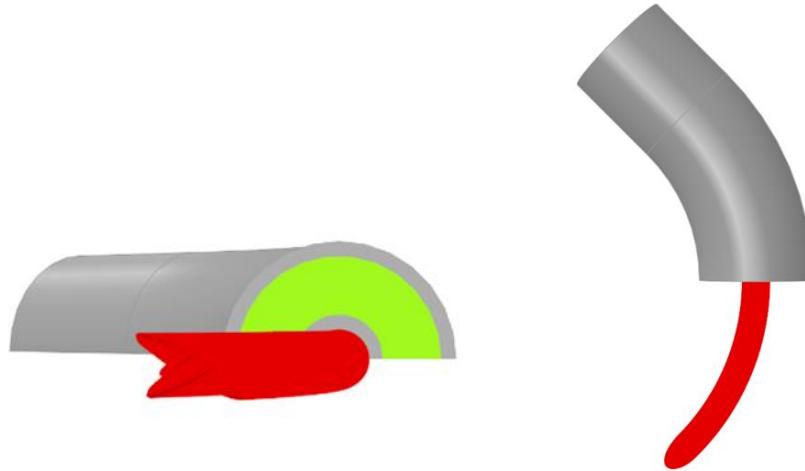


Figure 4: 3D model of the magnet with the coils in red, air in gray, and iron in green

Once the model was completed, it needed to be modified and optimized.

Model modification and optimization

My first goal in modifying the model was to find a satisfying current density and reach a field strength of 4 T inside the magnet, taking into consideration the effect of the iron yoke. After a couple of iterations, I have settled on a current density of 267 A/mm².

The second objective was to complete a convergence study for the mesh of the model. In other words, I had to calculate the magnetic fields for various number of mesh elements, and decide on a number of mesh elements that was high enough to guarantee good accuracy, but low enough so that the calculation of the model takes reasonably short.

Throughout my work with the model mesh, I have come to recognize the importance of the mesh properties when conducting any study on a 3D model, as it can have a substantial impact on the results of any analysis. In particular, poor mesh can induce artificial spikes with very high field inside the geometry. To investigate the properties of the mesh and possibly fix the problems in the model, I have conducted a convergence study, and in three ways.

In the first study, a fine mesh was used around the coils, with the surrounding air having a rougher mesh. The mesh of the iron was then varied to produce models of 300K, 500K, 1M, 1.5M and 2M mesh elements. Unfortunately, this did not yield the desired results.

In the second study, the mesh size was varied uniformly for all bodies, and results were observed for 40K, 100K, 250K, 300K, 500K and 600K mesh elements. Although these models brought no new insights, it was obvious that uniformly varying the mesh size yielded only long calculation times, as only the mesh part directly around the coils need to be precise, while the rest of the model simply added to the calculation time without improving the results themselves.

A final attempt consisted of creating a model with a very fine mesh around the coils only. The mesh elements were made to be small enough to 'see' individual brick nodes of the conductors. This new model had 3.25M elements.

Interpretation of the results

The figures below show the magnetic field in the magnet cross section and on the axis. The magnet produces a very homogenous vertical field of 4 T in the central aperture. The field in the iron is still quite high, especially in the parts above and below the magnet, where it can reach up to 1.85 T. Therefore, the thickness and shape of the iron will need to be further optimized to avoid iron saturation.

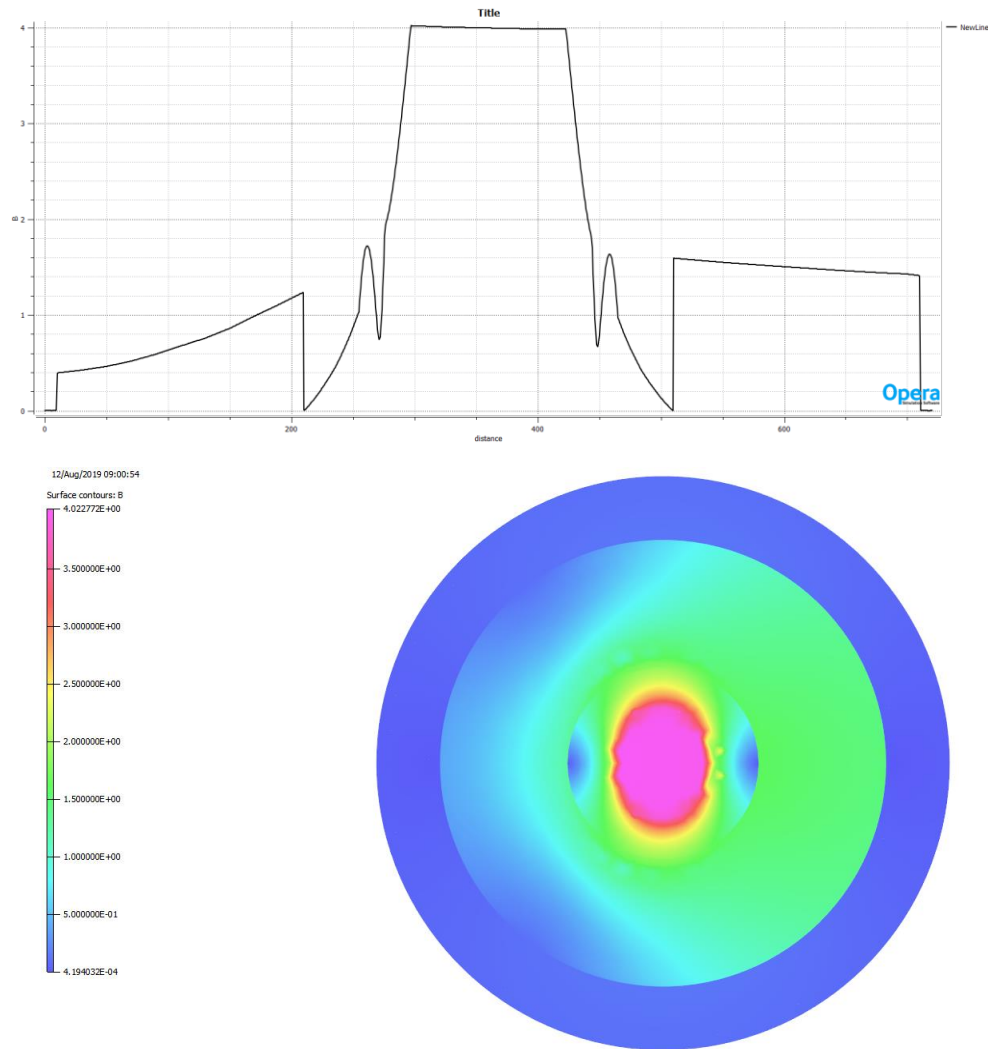


Figure 5: Examples of the cross-section graphs for the magnet

Particle Tracking

The particle tracking task consisted of three parts:

1. Find the appropriate parameters for tracking a single particle in Opera (energy, direction, mass, electric charge etc.)
2. Write a code that can produce a 2D Gaussian distribution of particles for Opera to track

3. Write a second code that can analyze Opera's output file and produce a set of starting and ending x - x' coordinates to be graphed

The end goal of this task was to produce and track the evolution of a given particle distribution through the superconducting magnet. The evolution of this distribution, i.e. the beam ellipse orientation would provide data for the calculation of the Twiss parameters. The summer student lectures given by Dr. M. Schaumann provided with the necessary theory to understand and analyze the beam dynamics inside the magnet.

I was provided with a C++ routine that produced a 2D Gaussian distribution, and have implemented it in my code. The executable file, when run, produces a .txt file that can be loaded into Opera 3D as a command script. Opera would then execute these commands and track the particles. The required format and parameters for the commands were found beforehand by trying out the particle tracking function manually in Opera 3D.

The second code reads the Opera 3D output file (which contains x , y and z coordinates of the position and velocity of each particle for each step of its trajectory), calculates the starting and ending x and x' coordinates, and writes them down in a separate .txt file. This data can then be analyzed with any graphing software, and I have in this case used Excel.

For the preliminary test, I have used a beam of 100 particles. The x - x' graphs showed a clear rotation of the beam emittance ellipse. The emittance did not change after the beam passed through the magnet (as expected), and the statistically calculated beam emittance matched the one obtained from the input parameters.

A problem that immediately presented itself, though, was the file size. The output file that Opera 3D produced for 100 particles (each making about 40000 steps) had a size of 400 MB. This signified that going to larger particle numbers was not feasible, as the file sizes would get too big.

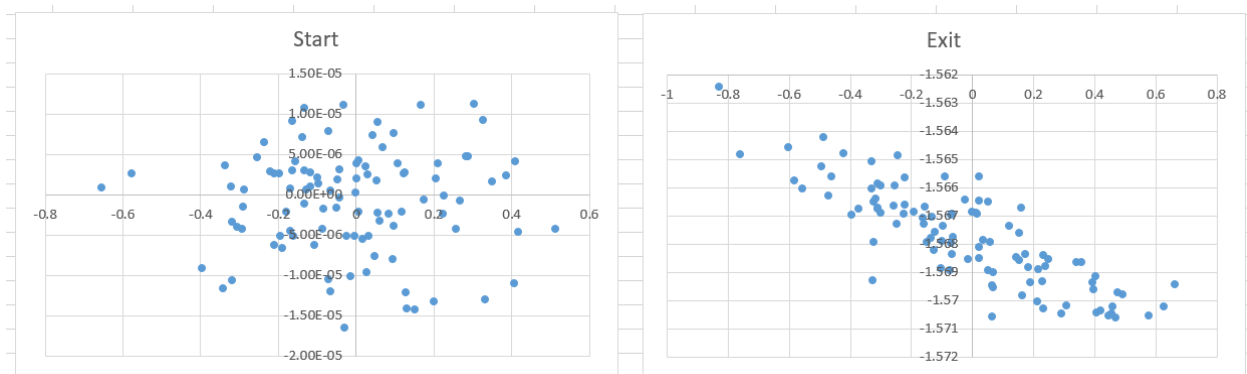


Figure 6: Beam emittance phase space graphs (x - x')

Open points and next steps

The main open points that are left unfinished are the convergence study and the particle tracking. More specifically, the convergence study has to be completed, both for the purposes of finding the right mesh as well as investigating the origin of the field strength spikes inside the coils. As for the particle tracking, a number of tasks remain. Namely, the vertical motion of the particles still have not been analyzed (beam evolution in the y - y' phase space), and the emittance and Twiss parameters of the beam still need to be computed and checked against the input parameters. Besides these points, a certain amount of effort will also need to be devoted to cross-checking the units for all the data and graphs, as Opera often switches between SI and cgs units.

After these points have been closed, the next logical step would be to introduce two new layers of coils responsible for the quadrupole (focusing) component of the magnetic field. Once this has been done, a new model can be calculated, and the particle tracking process would need to be redone. This would provide new data and illuminate the effect that the quadrupole component of the magnetic field would have on the particle beam and its evolution.

Conclusion

During my stay at the CERN Summer School of 2019, I have worked in the Accelerator Technology sector and produced a 3D model for a superconducting bending magnet to be used in a gantry and subsequently tracked particles through it. This is part of a project to design and build an innovative hadron therapy facility in the South Eastern Europe region, to which my home country belongs. I have gained valuable experience with regards to working in a team, as well as under supervision, and also gained insight into how a project of this type and level of importance is to be handled and worked on. I have learned how to use a new software, how to correctly study a 3D model, and have found an interest in a field of physics I previously did not consider when making long-term academic plans.