

CONTINUOUS BEAM DYNAMICS SIMULATION IN COMSOL MULTIPHYSICS

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Abstract

The classic way of beam dynamics simulation in a cyclotron is to separate it into many different stages from the ion source to the extraction (or even further), this was absolutely necessary to fit the calculations into any reasonable time in a cost of influence of some operation devices from one stage, on beam dynamics of another (next or previous mostly) stage. We've managed to perform beam dynamics from ion source through a solenoid to the center region in a single model in COMSOL, using several fields simultaneously: external magnetic (the magnet), calculated magnetic (the solenoid) and alternating and stationary electric fields in the center region.

INTRODUCTION

The main purpose of cyclotron design is to conduct successful beam dynamics simulation from the ion source to the extraction. In general, beam dynamics depends on EM-fields in the cyclotron (but there are some additional factors like beam losses on structure elements and space-charge effect of the beam). To obtain this EM-fields with high precision, one needs to thoroughly simulate numerous cyclotron elements, which effect the beam along its way.

There are some of these elements, in order of beam encounter:

- Injection line:
 - Ion Source(s)
 - Bending Magnet(s)
 - Focusing Solenoid(s)
- Center region:
 - Inflector(s)
 - Magnetic Field
 - RF-system
- Acceleration region:
 - Main Magnet
 - RF-system
- Extraction system:
 - Magnetic Channel(s)
 - Deflector(s)
- And numerous elements of delivery system...

The limitations in power of computational hardware formed the conventional approach – to simulate every (or almost every) of these elements separately to combine their influence in their region, and then, to calculate the beam dynamics, separately for every region. This approach allows to obtain neat EM-field maps but it also have some disadvantages:

1. An element could bring unintended distortion to a field. For instance, in our SC200 cyclotron the RF-system affects beam dynamics with its magnetic field, altering effective mean magnetic field and causing phase compression effect [1].
2. An element could affect the operation of another element with its field.
3. Beam dynamics calculation in one region can omit the effect of some elements from another region.
4. Beam dynamics values could be transferred not fully from region to region.
5. The beam losses on structure elements are additional task to calculate.

In pursuit of avoiding this we have tried the opposite approach – to conduct continuous beam dynamics simulation in a single COMSOL model.

CONTINUOUS BEAM DYNAMICS IN COMSOL

The first thing to clarify is that COMSOL's "model" includes "components" each with its own geometry, but one can transfer entities (results, fields, geometry parameters, physical quantities, etc...) from one "component" to another. (So, in common words, a "model" is more like a project and a "component" is more like a model. But we will stick to COMSOL's terminology in this paper.)

The Description of the Simulated Cyclotron Elements

In our case the first goal was to create a correctly operating COMSOL model with 5 elements of some cyclotron from our former working project.

The elements (Fig. 1):

1. Ion Source: H_2^+ ions with initial energy of 25 keV.
2. Focusing Solenoids: produce fields up to 0.19 T and 0.4 T along beam direction.
3. Spiral Electrostatic Inflector: voltage of 5.6 kV.
4. RF-system: a uniform structure from the center region to the acceleration area, alternating voltage of 50 kV.
5. Main Magnet: magnetic field in the center – 1.22 T.

COMSOL Model's Description

The model consists of two components: one is purely for calculation of the magnetic field of the main magnet (Fig. 2, Top), the other (Fig. 2, Bottom) calculates the rest of the fields, imports the field from the first component, through General Extrusion operator, and preforms particle tracing.

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In the second component: the magnetic field calculation is restricted to the solenoid area, whereas the electric field calculation proceeds in the rest of the model.

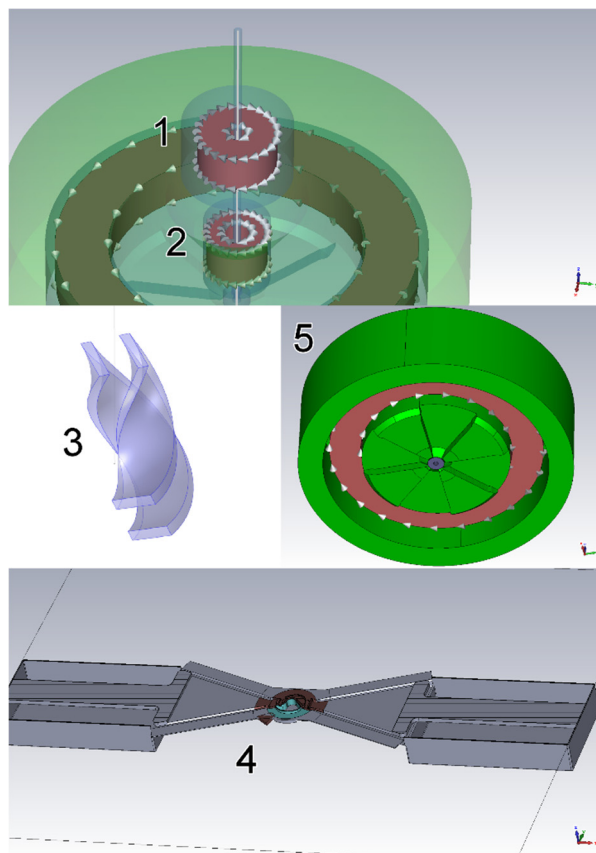


Figure 1: The elements of the cyclotron. 1,2 – the focusing solenoids; 3 – the inflector; 4 – the RF-system (cut in half); 5 – the main magnet (cut in half).

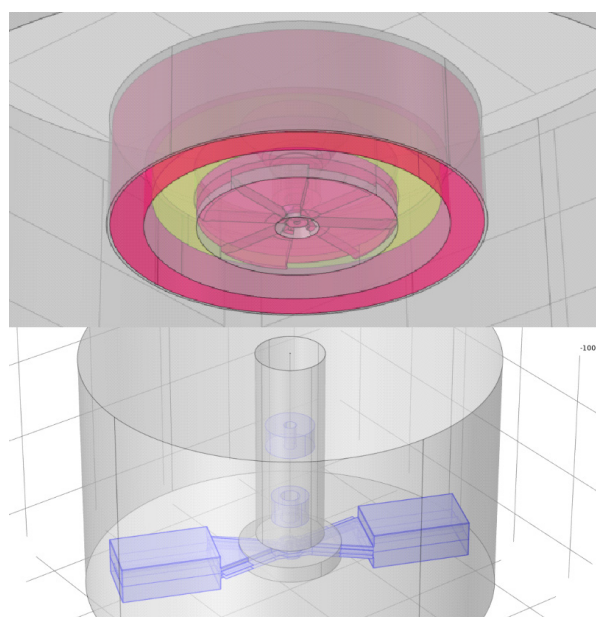


Figure 2: The component's geometries inside one COMSOL model. Top – the main magnet; Bottom – all the other elements (see Fig. 1).

Continuous Beam Dynamics Simulation and Subsequent Design Improvements

The model performed particle tracing as it was intended to: the beam was focused by the solenoids, caught by the inflector, and then, accelerated around by the RF-system, taking into account the magnetic field (Fig. 3, Left).

Since the magnetic field in COMSOL is often hard to calculate, we developed an option to import external 3D magnetic field into the second component through the Interpolation operator. The magnetic field, calculated in CST Studio Suite, was imported and the particle tracing was performed (Fig. 3, Center). Since CST provides field with great precision for our purposes, we improved the geometry of spiral inflector in this model to achieve good beam dynamics in the center region (Fig. 3, Right).

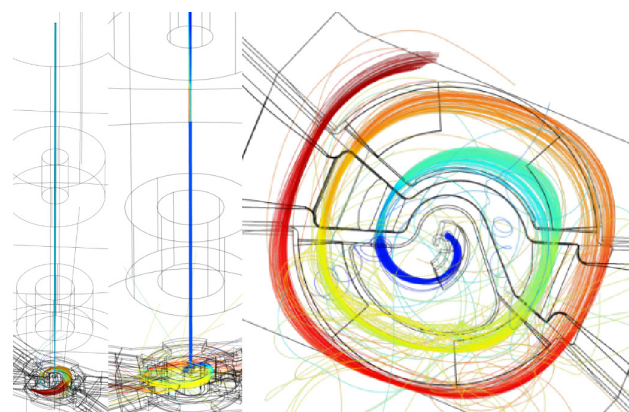


Figure 3: Continuous beam dynamics. Left – the main magnetic field calculated in COMSOL component; Center and Right – the main magnetic field imported from CST; Right – the inflector geometry is improved.

The last useful feature of our approach, that we implemented, was the possibility to assess beam losses on structure elements in a process of particle tracing. COMSOL's one component simulation allows it easily.

To increase beam current of the cyclotron with axial injection, we simulated the double axial injection by two inflectors from two injection lines (Fig. 4, Left). Since all of center structure elements were placed inside a single component, the only thing to do – is to mark required geometry faces as a wall, and the beam losses will be automatically calculated during the particle tracing (Fig. 4, Right).

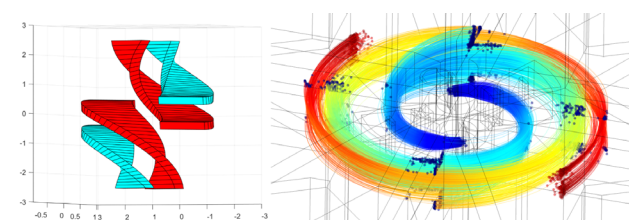


Figure 4: Double injection. Left – the inflectors design; Right – particle tracing with beam losses on the structure.

CONCLUSION

COMSOL's one model simulation brings several significant improvements and provides variety of opportunities to field simulation and tracing procedure:

- Makes it possible to estimate the impact of all elements in your model not only on particle tracing, but on each other.
- Allows you to partition your model, not only in terms of your components, but in terms of physics inside every component.
- And the customization goes even more, by allowing you to import any external 3D-field, if you dislike its COMSOL calculation.

Final Words

COMSOL proves to be a very adjustable tool when it comes to cyclotron design. It could contain the whole machine in one model, which could be neatly customized for every direction you prioritize: whether it would be mesh, physics, solver, particle tracing or even collisions with the structure, and many more...

This approach will be used in our future projects (SC230 cyclotron). The result it provides, along with its new advantages and peculiarities, will be reported in our next work.

REFERENCES

- [1] G. Karamysheva *et al.*, "Influence of the RF magnetic field on beam dynamics in SC200 cyclotron", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 940, pp. 61-65, 2019.
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