# BEAM TRACKING SIMULATION FOR SC200 SUPERCONDUCTING CYCLOTRON

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*Abstract*

The SC200 superconducting cyclotron for hadron therapy is under development by collaboration of ASIPP (Hefei, China) and JINR (Dubna, Russia). The accelerator will provide 200 MeV proton beam with maximum current of 1μA in 2017-2018. The cyclotron is very compact and light, the estimate total weight is about 35 tons and extraction radius is 60 cm. We have performed simulations of all systems of the SC200 cyclotron and specified the main parameters of the accelerator. Average magnetic field of the cyclotron is up to 3.5 T and the particle revolution frequency is about 45 MHz, these parameters increases the requirements for accuracy of the beam dynamics studies. We have designed and performed beam tracking starting from the ion source. Codes and methods used for the beam tracking are presented.

## BEAM DYNAMICS SIMULATIONS

Presently, research and development studies of every accelerator starts with computer simulations. For the SC200 cyclotron we build computer models of the major systems, which effect the beam dynamics in the accelerator. Modern computers performance allows to perform accurate particle tracking from the ion source to the extraction point with high accuracy. Also, one of the most important study is the conventional analysis of betatron oscillations. We use both methods to design the SC200 cyclotron. In order to perform those studies we use various commercial codes such as ANSYS, CST, OPERA-TOSCA and COMSOL Multiphysics to simulate the magnetic field and RF electro-magnetic field.

## CENTRAL REGION STUDIES

Internal PIG proton source will be used in our cyclotron, so our simulations start from the inside of the source. We have built a 3D model of the source and the central region, shown in Fig. 1. The geometry of the ion source used in the simulations is similar to those commonly used in accelerator physics. It consists of a "chimney" with a hole for the protons to come out. In order to increase the efficiency of the extraction of the protons from the source the first accelerating gap between the tip of the RF dee and the source should be kept as small as possible. However, sparking must be prevented, so we need to provide safe distance in both vertical and horizontal directions. The compact size of the accelerator is the major challenge in the design of the central region. Ideally, we would use accelerating voltage of about 100kV in the central region, as on the first turn the beam should get enough energy to bypass the chimney of the source.

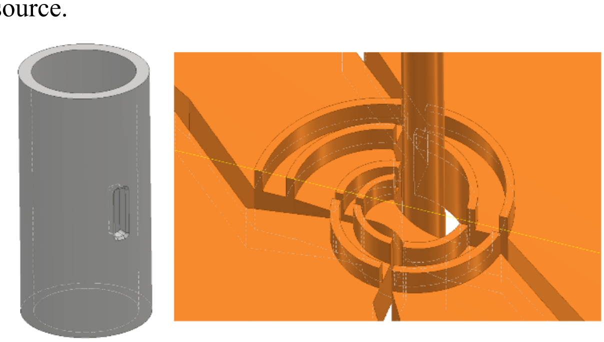

Figure 1: 3D model of the source and central region.

However, such voltage would require at least 1.5cm vertical gap between the RF dee and the "plug" of the magnet and in this case it would be difficult to achieve the area of decreasing magnetic field (also known as "bump") for the initial turns, which is required to help with the focusing of the beam. Central region of the magnet and the average magnetic field are shown in Fig. 2 and Fig. 3.

Figure 2: 3D model of the magnet, central "plug" (steel cylinder connecting the sectors) is 6cm in diameter.

The cylinder, connecting the sectors in the central region has to be as small as possible in diameter, so the magnetic field variation can start at the smaller radius to help with the focusing, but also has to be big enough and close enough to the median plane to provide the area with the decreasing magnetic field (so-called “bump”) shown in Fig. 3.

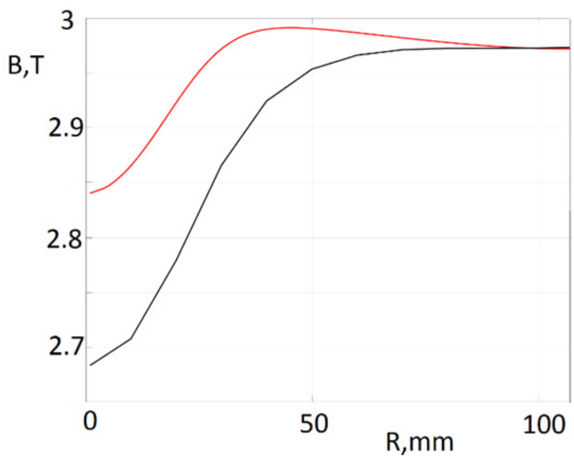


Figure 3: Average magnetic field along the radius in the central region, red line – with d=60 mm plug, black line – without plug.

Using the d=6cm plug would require to place it 25mm from the median plane. In such way it would not be possible to use 100kV on the Dee in the central region as it would result in vertical sparking. There could be two solutions of this problem: place the plug higher or decrease the voltage. We have chosen to use 50kV in the central region, and in this case the major problem was to bypass the source on the first turn. In order to do so, we had to shape the dee tips in the centre in such way to provide optimal acceleration rate. Our RF cavities operate on $2^{nd}$ harmonic mode, the revolution time is about 45MHz and the RF frequency is 90MHz. In order to achieve optimal acceleration, we need the dee azimuthal length to be equal to 90degrees. The azimuthal length of the sectors of the magnet is 40 degrees, which gives us 50 degrees for the RF system. However, in the central region we are not limited by the sectors, so may vary the gap positions, as we need.

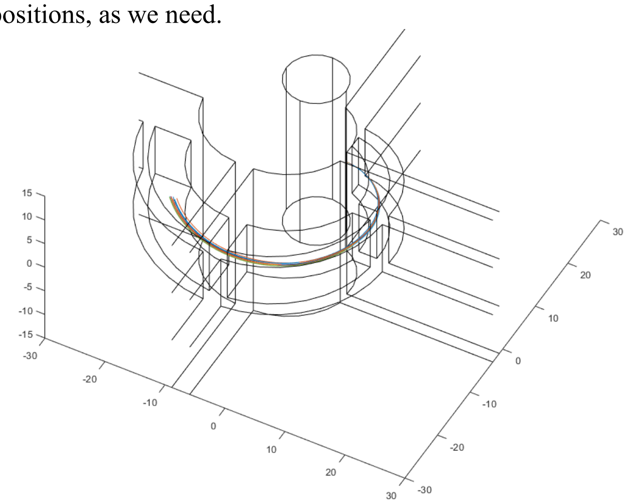

Figure 4: Beam tracking on the first turn.

In Fig. 4 it is clear that azimuthal length of the Dee tips is about 90 degrees.

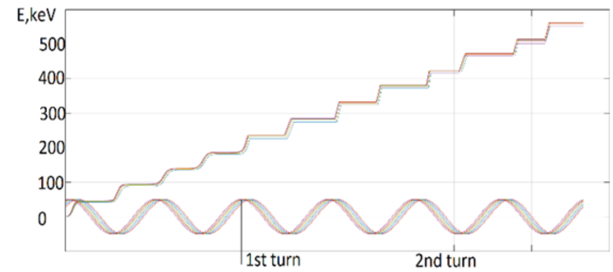


Figure 5: Energy gain in the central region.

We have used our 3D model of the RF system and the magnet in order to simulate the particle trajectories in the central region. It is clear that the energy gain is good enough, however further work is required to optimise the performance and to solve centring and focusing issues.

## BEAM DYNAMICS IN THE CYCLOTRON

Particle tracking is a good choice for the central region studies and extraction region studies, however for the beam dynamics in the main accelerating region the CYCLOPS procedure is widely used to perform the isochronising of the magnetic field map and to calculate the betatron tunes. For this procedure the magnetic field simulation is required.

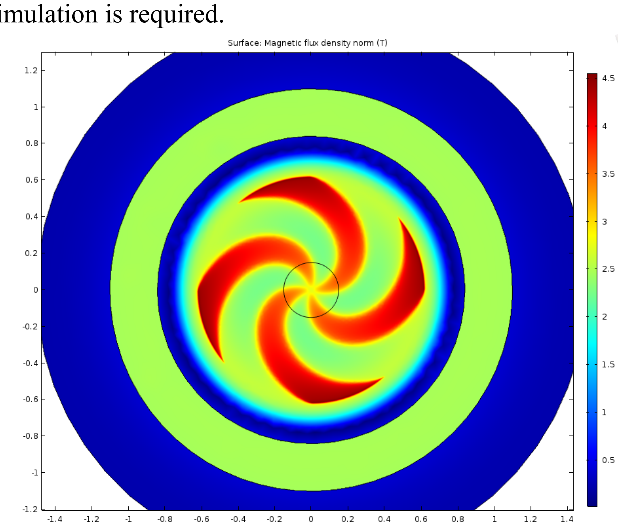


Figure 6: Magnetic field of the SC200 cyclotron in the median plane.

As we are going to use just 2 RF cavities operating on $2^{nd}$ harmonic mode, each 50 degrees in azimuthal length, the acceleration is going to be relatively week on each turn. So avoiding resonances is crucial for the design of the SC200 cyclotron.

Working diagram of the cyclotron is shown in Fig. 7. Many efforts have been done to avoid the most dangerous resonances during acceleration 2Qz=1 and Qr-Qz=1. One can see that the first resonance is avoided completely while the second one is crossed at the end of acceleration. Future study will show us how many protons lost in vertical plane due to this resonance crossing. We are




ISBN 978-3-95450-147-2

going to continue as well our efforts to avoid this resonance crossing by changing form of the spiral sectors at edge region.

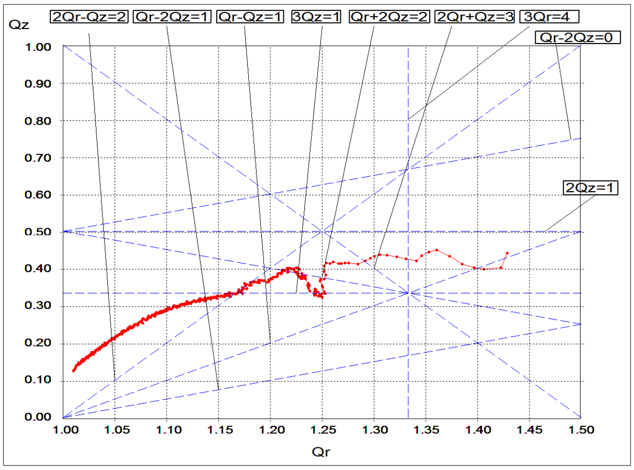


Figure 7: Vertical and radial frequencies in SC200.

## RF SYSTEM

Two RF cavities, connected in the centre will be working on the 2nd harmonic on approximately 90MHz.

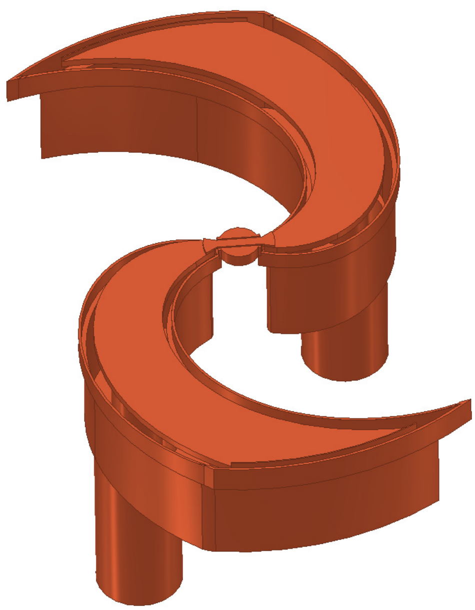

Figure 8: Overview of 3D model of RF system.

From the beam dynamics point of view the choice of 2nd harmonic is not the best solution, as the acceleration rate will be lower compared to 4th harmonic which seems like a natural choice for a cyclotron with 4 sector structure. However operating on 180MHz would raise problems with the extraction of particles from the ion source and the generators on 180MHz are not widely available as compared to 90MHz ones. As we avoid all critical resonances and extraction scheme does not require high acceleration rate we are able to use just 2 cavities on 2nd harmonic.

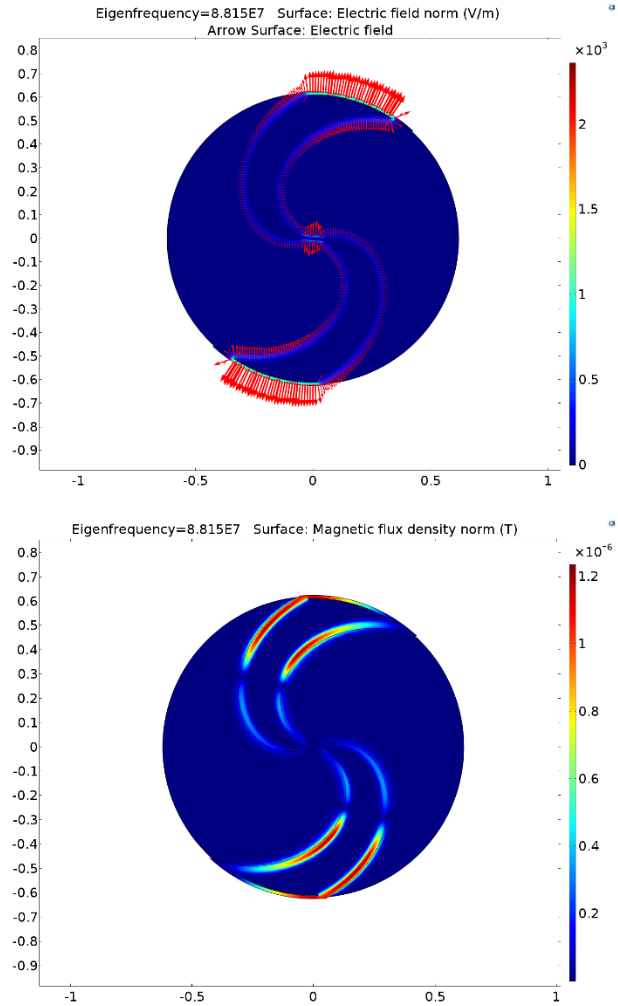


Figure 9: RF electric and magnetic field of the accelerating system.

The electric and magnetic components of the field are presented in Fig. 9.

## EXTRACTION

Simulations show that the extraction can be provided by deflector with electric field 170 kV/cm and two magnetic channels MC1 and MC2 focusing the beam in horizontal plane. MC2 is arranged inside the hole in yoke.

No need of the channel to focus the beam in vertical plane. This is provided by drop of edge magnetic field. The collimator will be used to match the beam parameters with requirements imposed by a transport system.

## CONCLUSION

Computer simulation of the beam dynamics for SC200 cyclotron has been performed. We are going to continue simulations in the center and extraction regions.

The technical design of the cyclotron will be finished in 2016.