COMPUTER MODELING OF MAGNETIC SYSTEM FOR C400 SUPERCONDUCTING CYCLOTRON*

Y. Jongen, D. Vandeplassche, S. Zaremba, IBA, Louvain-la-Neuve, Belgium
G. Karamysheva, N. Morozov, E. Samsonov, JINR, Dubna, Russia.

Abstract

The superconducting cyclotron (C400) [1] is designed at IBA (Belgium) to accelerate carbon ions to 400 MeV/nucleon. By computer simulation with the 3D TOSCA code, principal parameters of the cyclotron magnetic system were estimated (pole radius 187 cm, outer diameter 606 cm, valley depth 60 cm, height 276 cm). The required isochronous magnetic field was shaped with an accuracy of +/- 2 mT. Four-fold symmetry and spiral sectors with an elliptical gap (minimum 12 mm at extraction) provide stable beam acceleration to a distance of 15 mm from the pole edge.

CYCLOTRON OVERVIEW AND IT'S PARAMETERS

In order to respond to the increasing interest (especially in Europe) in particle therapy based on $^{12}C^{6+}$, the IBA company has started development of a dedicated carbon therapy facility. This facility will be based on the technology of the successful IBA proton therapy facility. The main C400 cyclotron design characteristics:

- Compact design similar to the existing IBA C235 cyclotron
- Fixed energy, fixed field and fixed RF frequency
- Bending limit K=1600
- Accelerated particles: Q/M=1/2 ⇒ 400 MeV/amu
  - H_2^+, $^4He^{2+}$, ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
- Superconducting coils enclosed in cryostat, all other parts are warm
- Axial injection using a spiral inflector
- Extraction with an electrostatic deflector
- Extraction by stripping (H2+) is investigated

EXPECTED C400 MAGNET CHARACTERISTICS AND DESIGN GOAL

The simulation and design of the C400 magnetic system was based on its main characteristics:

- Four-fold symmetry and spiral sectors
- Deep-valley concept with RF cavities placed in the valleys
- Elliptical pole gap
  - 120 mm at the center decreasing to 12 mm at extraction
  - Accelerate 15 mm from the pole edge ⇒ facilitate extraction
- Pole radius = 187 cm
- Outer diameter = 606 cm
- Valley depth = 60 cm
- Height = 276 cm
- Hill field = 4.5 Tesla, valley field = 2.45 Tesla
- Weight about 700 tons

During the magnet simulation the following design goals were achieved:

- Optimization of the magnet size
- Realization of the vertical focusing (Q_z) at the extraction region as close to 0.5 as possible (to decrease the vertical beam size and minimize the median plane effects)
- Last orbit kept as close to the pole edge as possible
- Minimization iron weight, keeping the stray field at an acceptable level
- Avoiding resonances

MAGNET SYSTEM SIMULATION

The preliminary choice of the magnet system parameters was provided by 2D codes (POISSON [2] and OPERA-2D [3]). At this stage the basic magnet system dimensions and elliptic gap parameters were estimated. The optimization of the spiral sector parameters and final choice of the magnet design was made with TOSCA, the magneto-static module of OPERA-3D. To speed up the iteration procedure for optimization of magnet parameters the following TOSCA options were used:

- The models were built with the OPERA "Modeller" pre-processor
- The models did not use the symmetry option (azimuth and median plane). This a symmetry option involved the simulation of the cyclotron median plane errors too
- As few elements as possible were used, only one pair of sectors had the fine meshing for providing the magnetic field map suitable for the beam dynamic simulation . This option resulted in no more than 2×10^6 mesh elements and ~ 180 min of the time solution (2 GHz processor)

At the each step of magnet optimization TOSCA-simulated magnetic field maps were analyzed by the beam dynamic codes and the beam extraction procedure was studied too [4].

The C400 cyclotron model views are in Fig.1-2. The ultimately optimized sector parameters are as follows:

- Spiral parameter Nλ=77 cm for sector axis line
- Sectors axial profile – ellipse with 60/1874 mm semi-axis
- Sectors angular width 35 deg. with variation ±6 deg. (Fig.3).

*Work supported by IBA company
http://www.iba.be

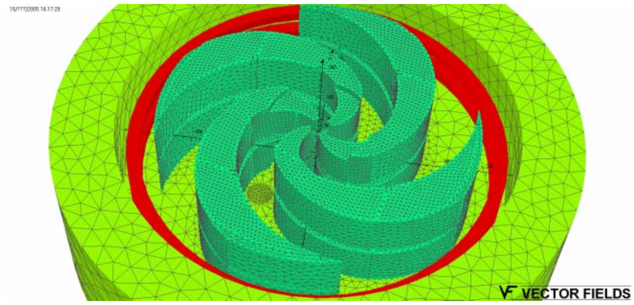

Figure 1: Layout of the TOSCA model of C400 cyclotron.

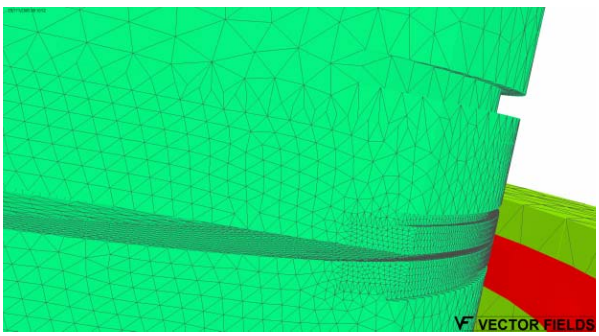

Figure 2: TOSCA model of the C400 cyclotron near the extraction region.

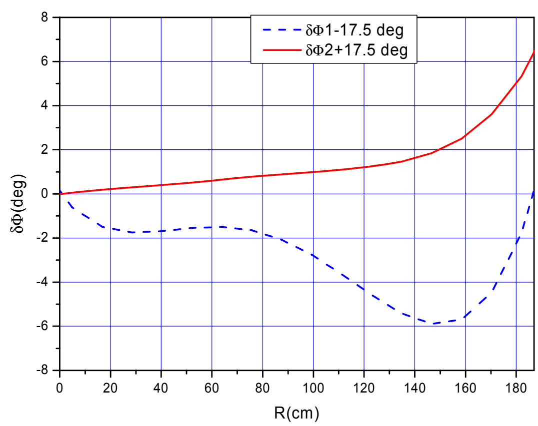

Figure 3: Spiral sector azimuth profile (variation from 35 deg. width).

The required isochronous magnetic field was shaped with accuracy ±2 mT by axial and azimuth profiling of the sectors and by additional grooves and sector shims. The average field simulated by the TOSCA model is presented in Fig.4 and the accuracy of the required field shaping in Fig.5. The basic number Fourier harmonics are shown in Fig.6 and the fourth harmonic phase derivative in Fig.7 (the latter figure demonstrates the real spiral parameter Nλ of the sector magnetic field).

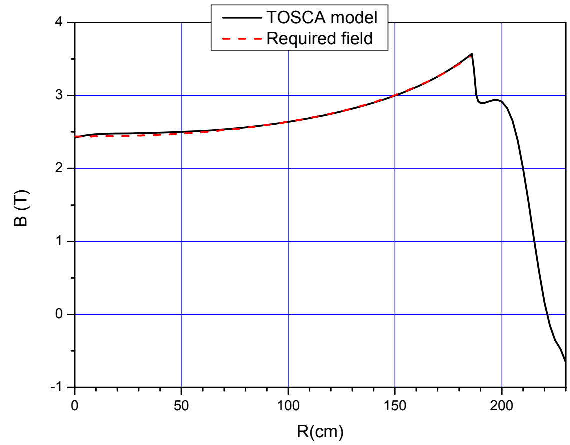

Figure 4: Average magnetic field.

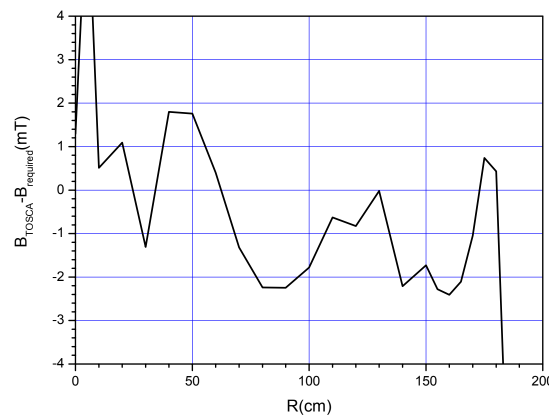

Figure 5: Accuracy of the required magnetic field shaping.

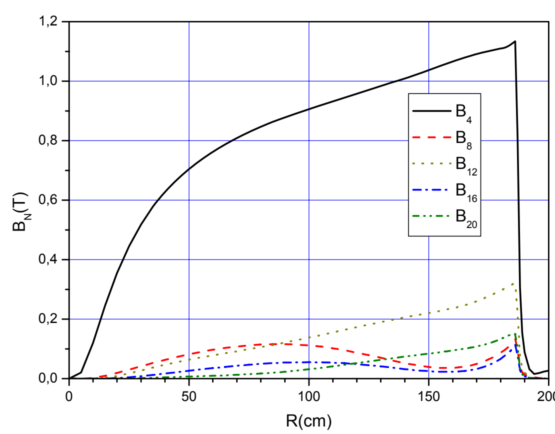

Figure 6: N-number Fourier harmonics of the cyclotron magnetic field.

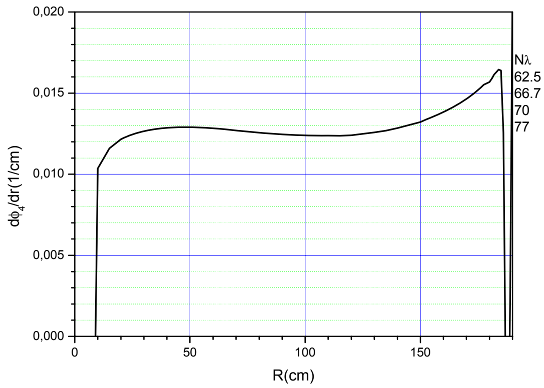

Figure 7: Derivative of the fourth harmonic phase.

The optimized sector geometry provides vertical focusing Q_z~ 0.3 before the cyclotron extraction region. Near extraction Q_z was shaped as close to 0.5 as possible (Fig.8). Such Q_z leads to smaller vertical beam size and not so hard tolerance condition for horizontal components of the magnetic field in the median plane of the cyclotron. The azimuth magnetic field distribution for three cyclotron radii R=140, 180 and 186 cm is shown in Fig.9.

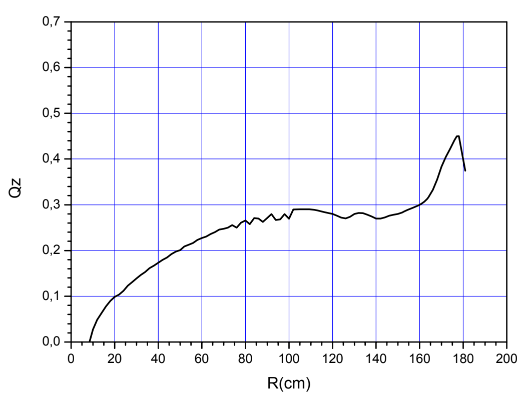

Figure 8: Vertical betatron frequency for the shaped cyclotron magnetic field.

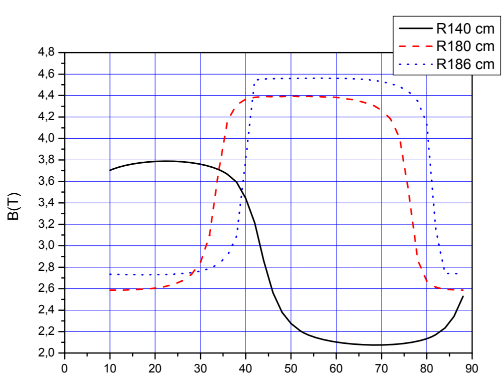

Figure 9: C400 magnetic field for R=140, 180, 186 cm.

In the cyclotron C400 the beams are injected throw axial holes with diameter 50 mm in the sectors and 200 mm in the horizontal yoke. Axial beam injection dynamic [5] was simulated on the bases of the axial magnetic field computed by the TOSCA model. Cyclotron axial magnetic field dependence upon radius is presented in Fig.10.

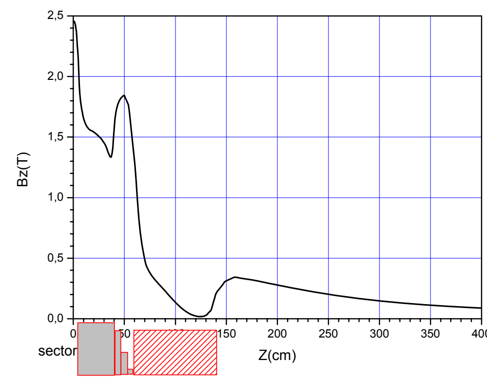

Figure 10: C400 axial magnetic field.

CONCLUSION

The computer modeling of the magnet system for the C400 superconducting cyclotron was performed by the TOSCA code. The fine optimization of the magnet yoke and spiral sector parameters was carried out in the cyclotron compact design. The TOSCA model provided field maps which allowed feasibility of a superconducting carbon cyclotron of energy to 400 MeV/amu to be verified by beam dynamics simulation.

REFERENCES

[1] W. Kleeven et al. "Design of a K=1600 compact superconducting cyclotron for therapy by carbon beams", XXXIV European Cyclotron Progress Meeting, Belgrade, Serbia and Montenegro, October 2005, http://www.tesla-sc.org/ecpm/ecpm.htm.

Y.Jongen et al. "Design Studies of the Compact Superconducting Cyclotron for Hadron Therapy", this conference.

[2] POISSON/SUPERFISH User's Guide, LA-UR-87-115, Los Alamos Accelerator Code Group.

[3] OPERA 2D and 3D, Vector Fields, UK, www.vectorfields.com.

[4] Y. Jongen et al. "Simulation of Ions Acceleration and Extraction in Cyclotron C400", this conference.

[5] V. Shevtsov et al. "Design Study of the Axial Injection System of C400 Cyclotron", this conference.