Ion Beam Applications
Joint Institute for Nuclear Research

IBA C400 Cyclotron Project for hadron therapy

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Abstract

- Progress of design work on the compact superconducting isochronous cyclotron C400 able to deliver ion beams with a charge to mass ratio of 0.5 is reported. This cyclotron will be used for therapy of cancer using either protons or light ions. $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to energy 400 MeV/amu and extracted by the electrostatic deflector, H_2^{+} ions will be accelerated to the energy 260MeV and extracted by stripping. Computer modeling results on the axial injection, magnetic, accelerating and extraction systems are given. Design of the main systems of the cyclotron and the present status of beam dynamics studies are summarized. Details are presented in some contributions to this conference.

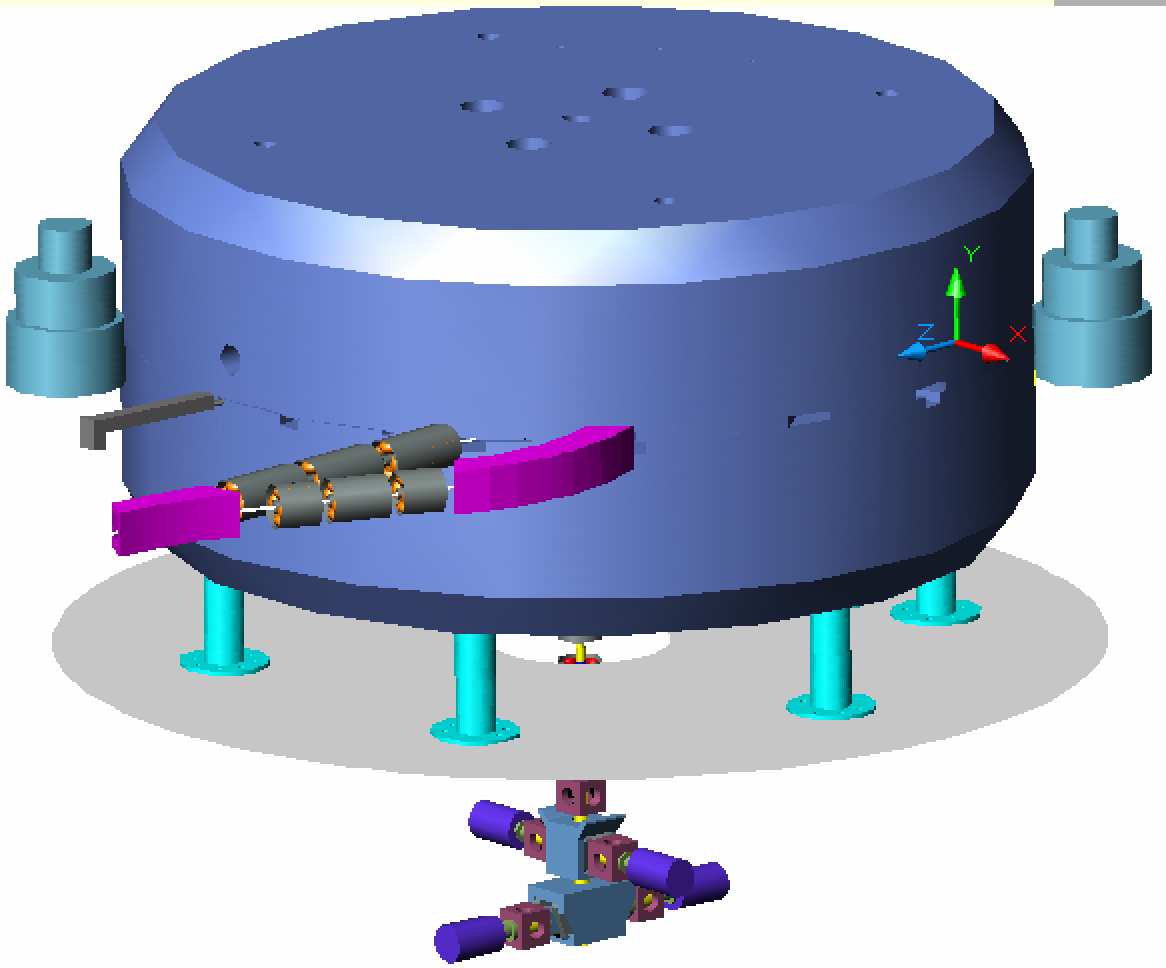
Introduction

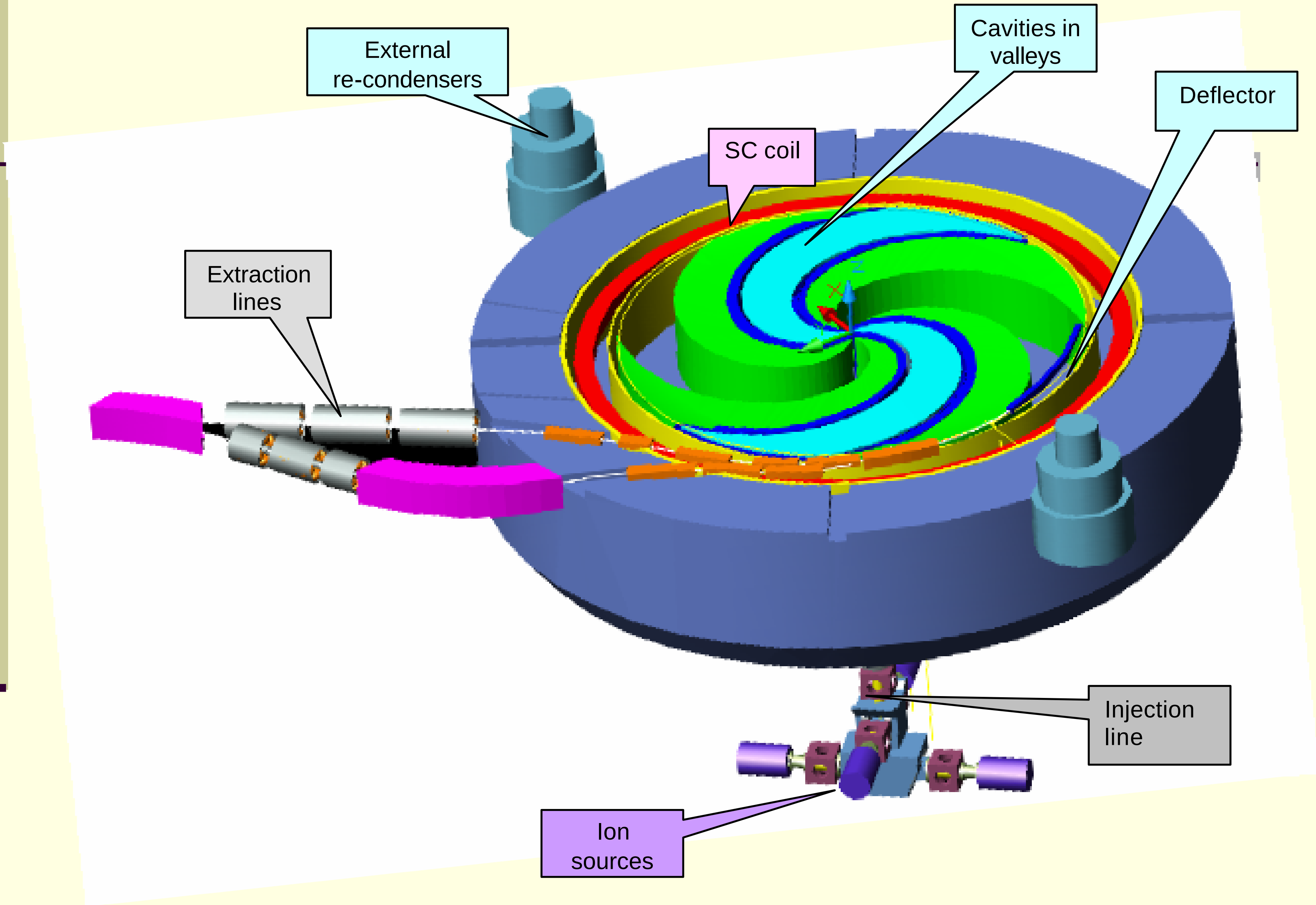
- Today, cancer is the second highest cause of death in developed countries. Its treatment is still a real challenge.
- Protons and light ions allow depositing the radiation dose more precisely in a tumor, greatly reducing the amount of the dose received by healthy tissue surrounding the tumor as compared with electrons and photons. But in addition to the ballistic accuracy of protons, light ion beams, like carbon beams, have an additional advantage in radiation therapy: thanks to their high linear energy transfer, they have a different biological interaction with cells and are very effective even against some types of cancerous cells resistant to usual radiations.
- Over the last 15 years IBA has designed and equipped over half of the clinic-based Proton Therapy facilities in the world. The new C400 cyclotron is based on the design of the current Proton Therapy C235 cyclotron.

BASIC DESIGN CONCEPT

- Most of the operating parameters of the C400 cyclotron are fixed. It is relatively small (6.9 m in diameter) and cost effective. It offers very good beam intensity control for ultra-fast pencil beam scanning (PBS). But it requires an energy selection system (ESS) in order to vary the beam energy. However, the efficiency of the ESS for carbon is better than for protons due to less scattering and straggling of carbon ions in the degrader.

View of the cyclotrom




External re-condensers
Cavities in valleys
Deflector
SC coil
Extraction lines
Injection line
Ion sources

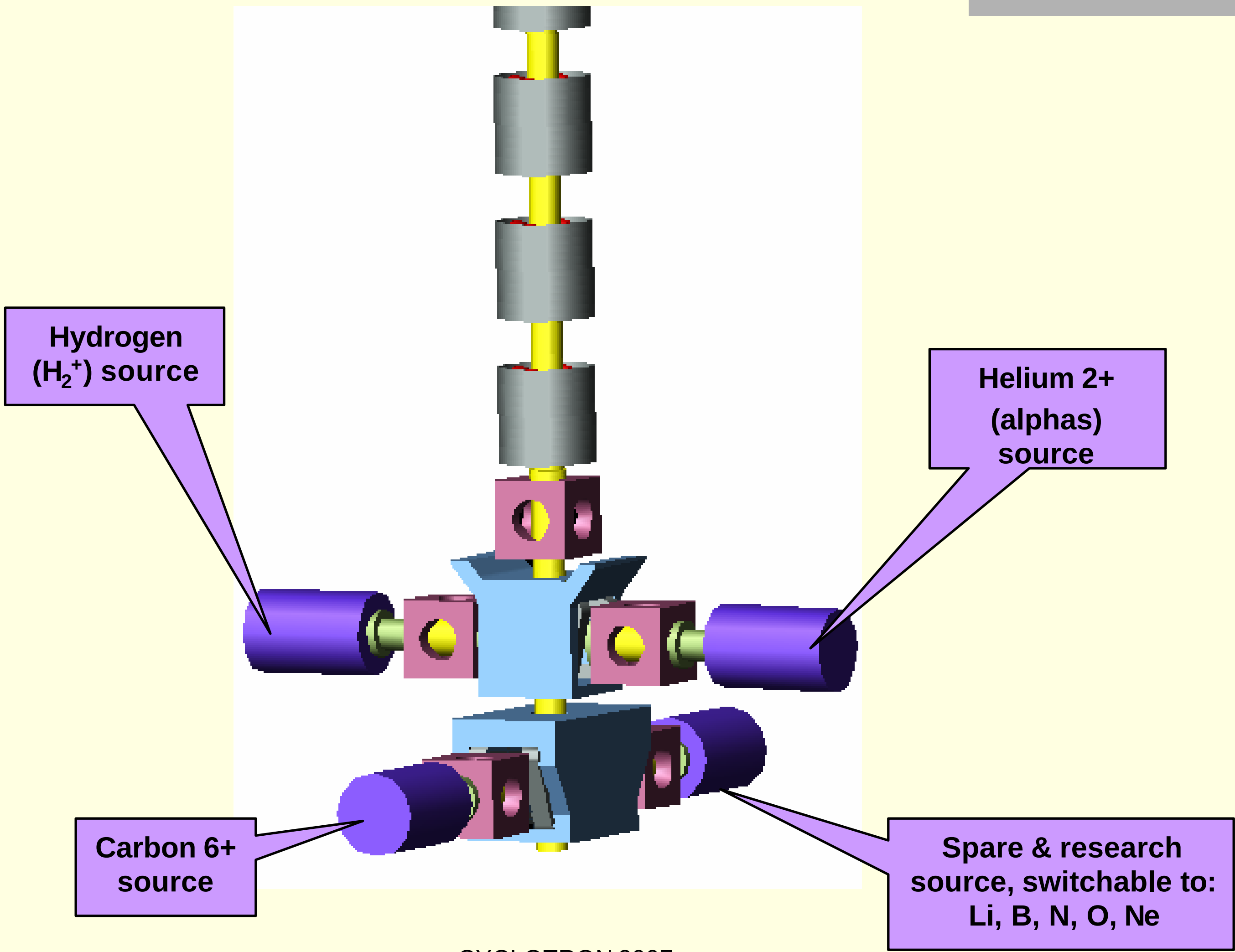
Main parameters of the C400 cyclotron

type	compact isochronous
accelerated particles	H_2^+, $^4He^{2+}$, ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
ion sources	ECR, ECR, multicusp
injection	axial with spiral inflector
injection energy	25keV/Z
final energy of ions, protons	400 MeV/amu 260 MeV/amu
extracted ions, protons	by deflector by stripping
extraction efficiency	70 % (by deflector)
number of turns	~1700

The present status of the C400 design:

- the isochronous magnetic field with adequate focusing characteristics and optimized extraction is obtained by computer simulation with the 3D TOSCA code;
- beam dynamic simulations have been done with multiparticle tracking codes for the acceleration and extraction regions;
- axial injection design and beam dynamic tracking in the injection line have been performed;
- inflector and central region design and beam dynamic tracking have been performed
- RF cavity design by the CST Microwave Studio is currently being performed;
- ion losses due to residual gas interaction have been calculated.

INJECTION AND ION SOURCES



INJECTION AND ION SOURCES

- Three external ions sources are mounted on the switching magnet on the injection line in the bottom of the cyclotron. $^{12}C^{6+}$ are produced by a high performance ECR, alphas are also produced by the ECR source, while H^{2+} are produced by a multicusp ion source. If needed, an additional ion source could be used to produce $^{6}Li^{3+}$.
- In order to allow a quick change between ion species, all three ion sources are kept in operation. All species have a Q/M ratio of 1/2 and all ion sources are at the same potential, so that small retuning of the frequency and magnetic field change achieved by different excitation of 3 parts in the main coil are needed to switch from H^{2+} to alphas or to $^{12}C^{6+}$. We expect that the time to switch species can be not more than two minutes, as long as the time needed to retune the beam transport line between different treatment rooms.

INJECTION AND ION SOURCES

- The length of the vertical part of the injection channel is about 5 m from the carbon ECR axis to the median plane of the C400 cyclotron. For all types of ions the beam envelopes at the entrance of the spiral inflector do not exceed 2 mm. Therefore the particle losses in the inflector will be absent.

INJECTION AND ION SOURCES

- Gradients of the quadrupole lenses have been fitted for all types of ions. To reduce the coupling in the longitudinal magnetic field, the quadrupoles are turned around the longitudinal axes by required angles. The rotation angle of the quadrupole lenses should be found only at the initial stage of operation only for one sort of injected ions. These rotation angles are the same for all other types of the ions with the charge to mass ratio 1/2 and should not be changed during the routine operation. The maximum gradient in the quadrupole lens is about 300 G/cm.

INJECTION AND ION SOURCES

- The system of injection allows transportation of $^{12}C^{6+}$, $^{4}He^{2+}$, and H^{2+} ion beams from ion sources to the median plane of cyclotron with a 100% efficiency.

CENTER REGION DESIGN

The principal requirements to the central region design are:

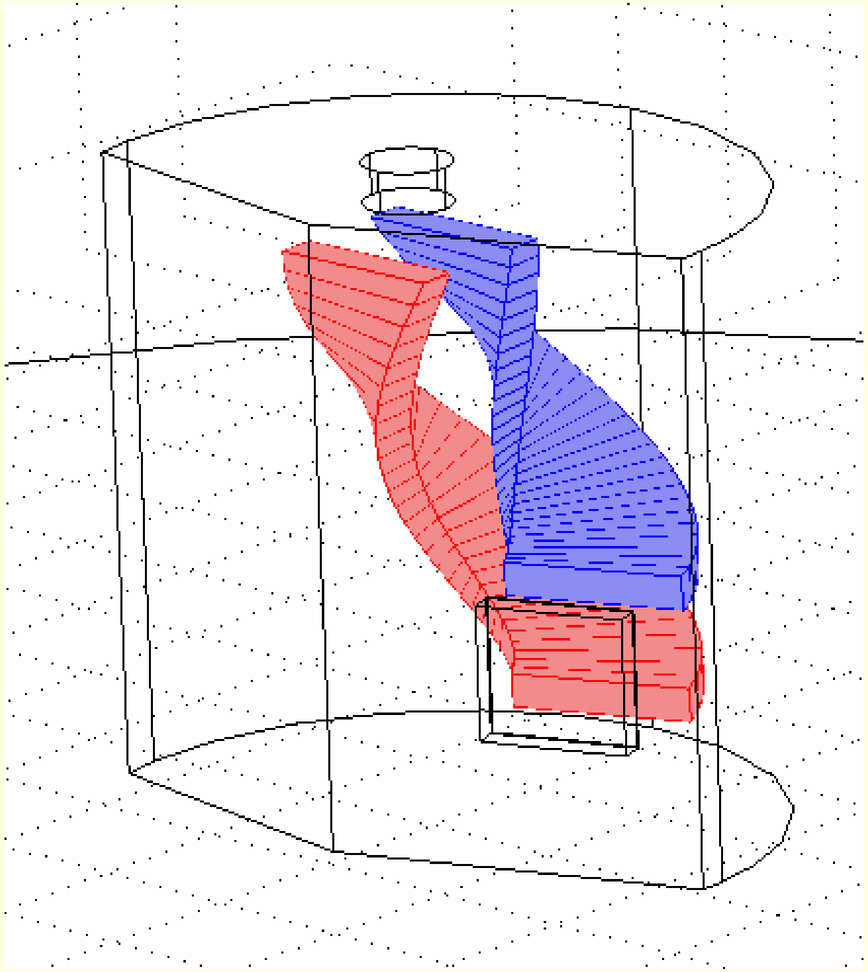
- acceleration of the beam in a well-centered orbit with respect to the geometrical center
- fine tune electric vertical focusing

A model of the dee geometry at the cyclotron center with the inflector housing was developed. Dee tips have vertical aperture 1.2 cm in the first turn and 2 cm in the second and further turns. In the first turn the gaps were delimited with pillars reducing the transit time.

Spiral inflector

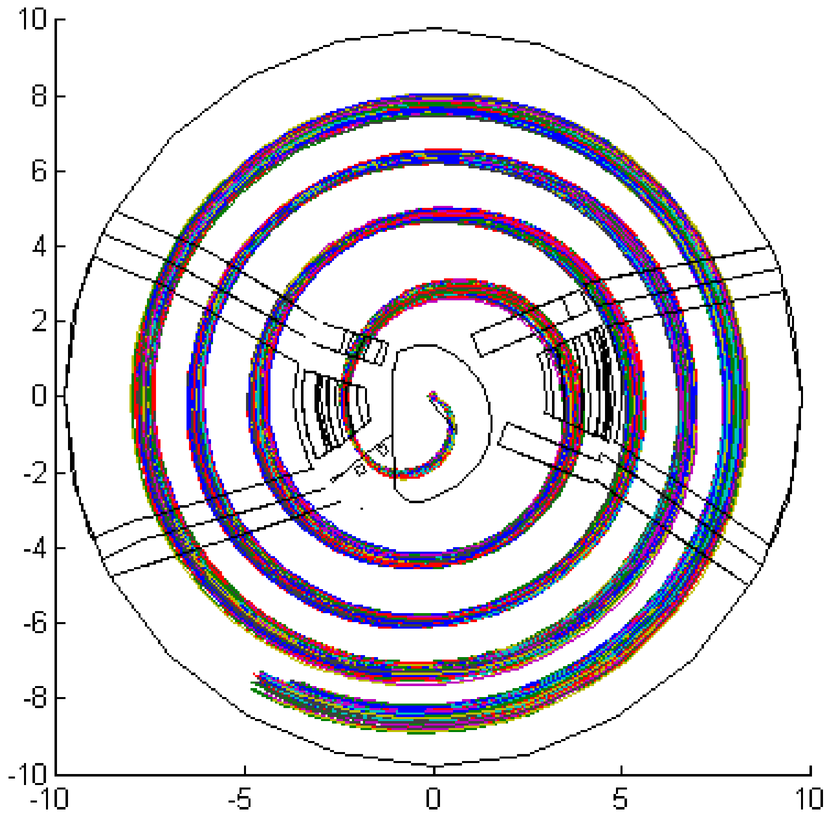
- The electric field of the inflector was chosen to be 20 kV/cm. Thus, the height of the inflector is equal to 2.5 cm. The gap between the electrodes was taken to be 6 mm. The aspect ratio between the width and the spacing of the electrodes was taken to be equal to 2 to avoid the fringe field effect. Computer models of the inflector with different tilt parameters were developed. The inflector was placed in the grounded housing. The distance between the grounded housing and the twisted electrodes was 0.5 cm.

Spiral inflector

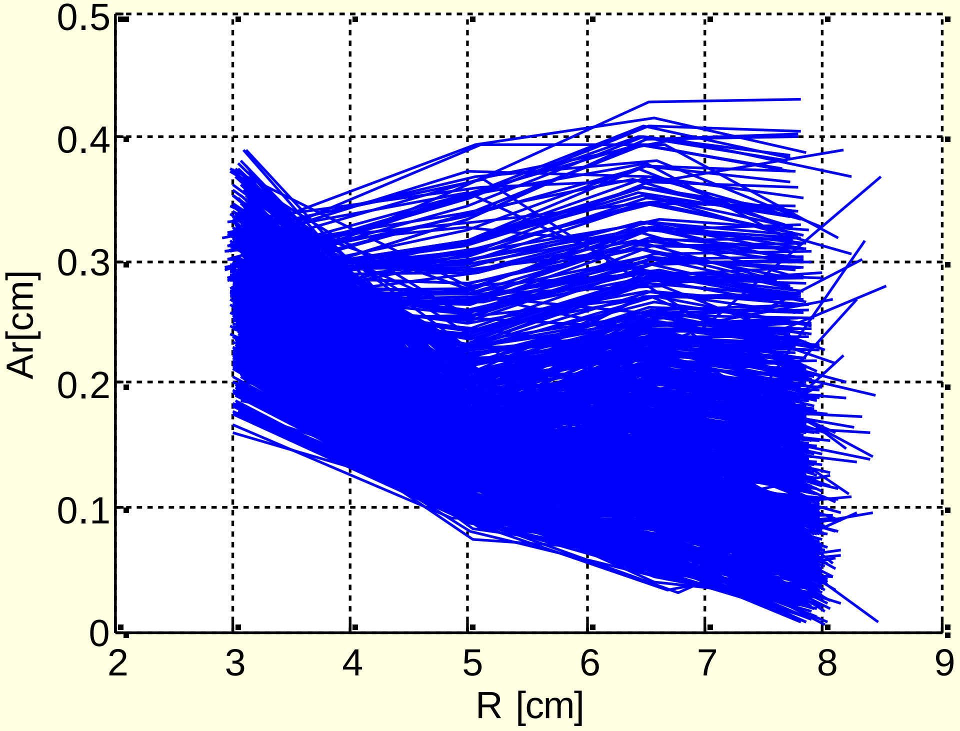


- Beam dynamics simulations were made for particles with initial distributions in transverse phase planes obtained from the axial injection line simulation.
- A continuous beam simulation shows that when we use two phase selection slits, the injection efficiency is equal to 12% for ions with amplitudes of radial oscillations less than 0.4 cm.

First turns at the center



Amplitudes of radial betatron oscillations



MAGNETIC SYSTEM

- Two possible optional mechanical designs are proposed for the C400 magnet:
- 1.The initial design with the yoke of diameter 6.06 m. In this case the background magnetic field at R=11.5 m from the magnet center is more than 20 G and this field can be screened by additional iron plates. The total weight of the magnet is 490 t. The working excitation of one coil current is 1420000 A.
- 2. The magnet design with the yoke of diameter 6.9 m. In this case the background magnetic field less than 10 G. Total weight is 660 t. The main coil current is 1320000 A.

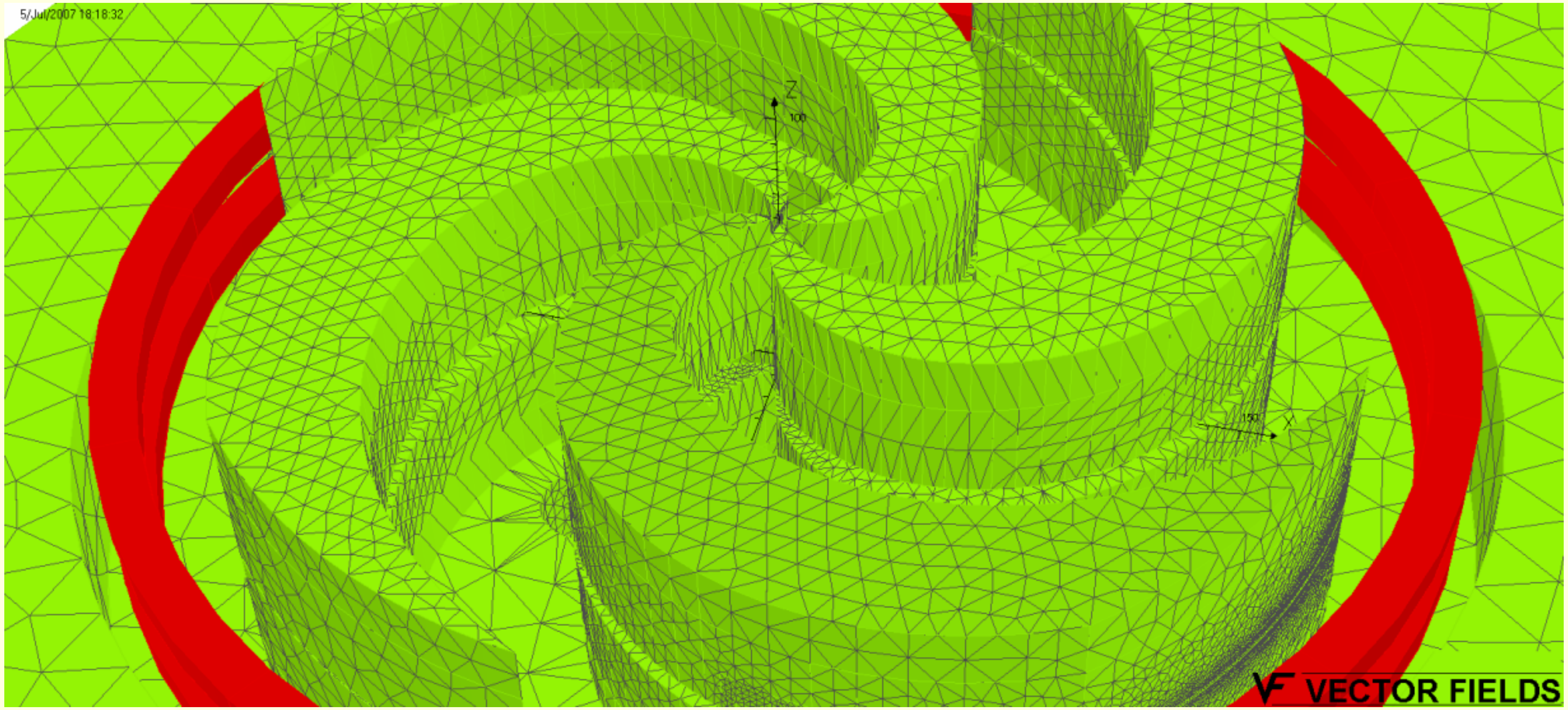
MAGNETIC SYSTEM

- Superconducting coils will be enclosed in a cryostat, all other parts are warm.
- The required isochronous magnetic field was shaped by azimuth profiling of the sectors. Four-fold symmetry and spiral sectors with an elliptical gap (120 mm at the center decreasing to 12 mm at the extraction) provide stable beam acceleration up to 15 mm from the pole edge. Keeping the last orbit as close as possible to the pole edge facilitates extraction.

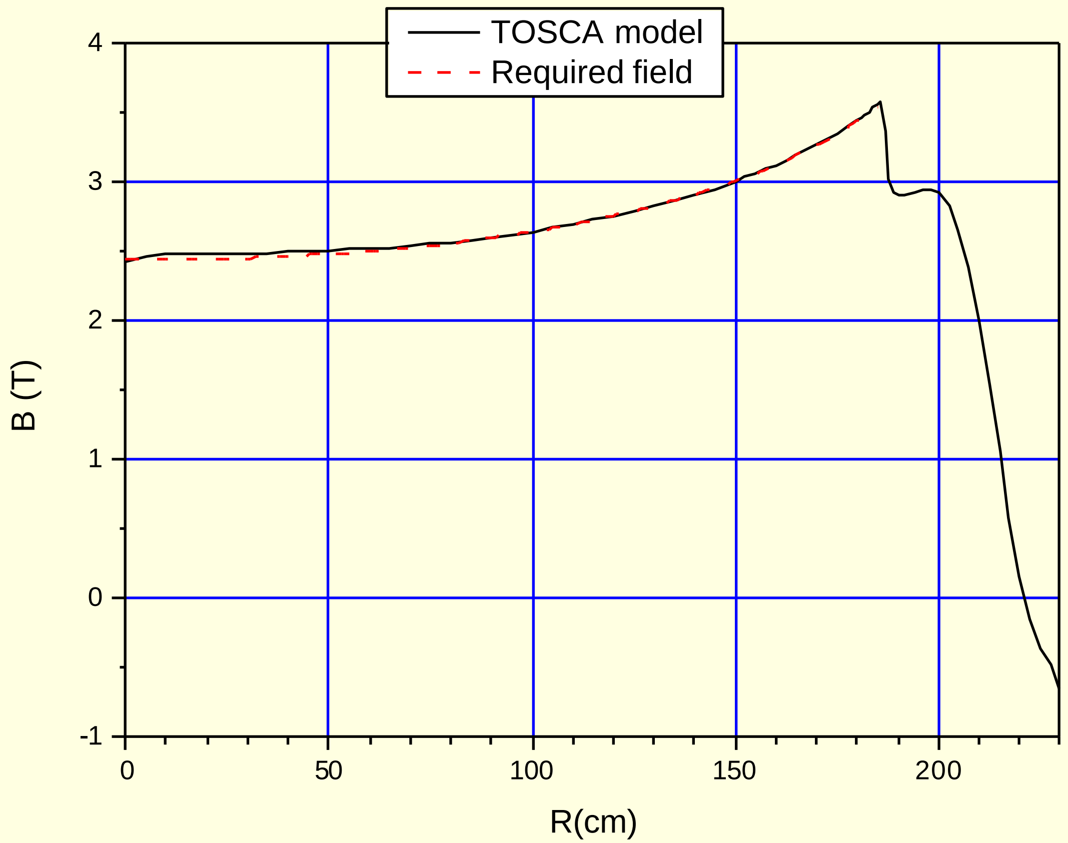
MAGNETIC SYSTEM

total weight	660 tons (490 tons)
outer diameter	6.9 m (6.06m)
height	2.76 m
pole radius	1.87 m
valley depth	60 cm
bending limit	K = 1600
hill field	4.5 T
valley field	2.45 T

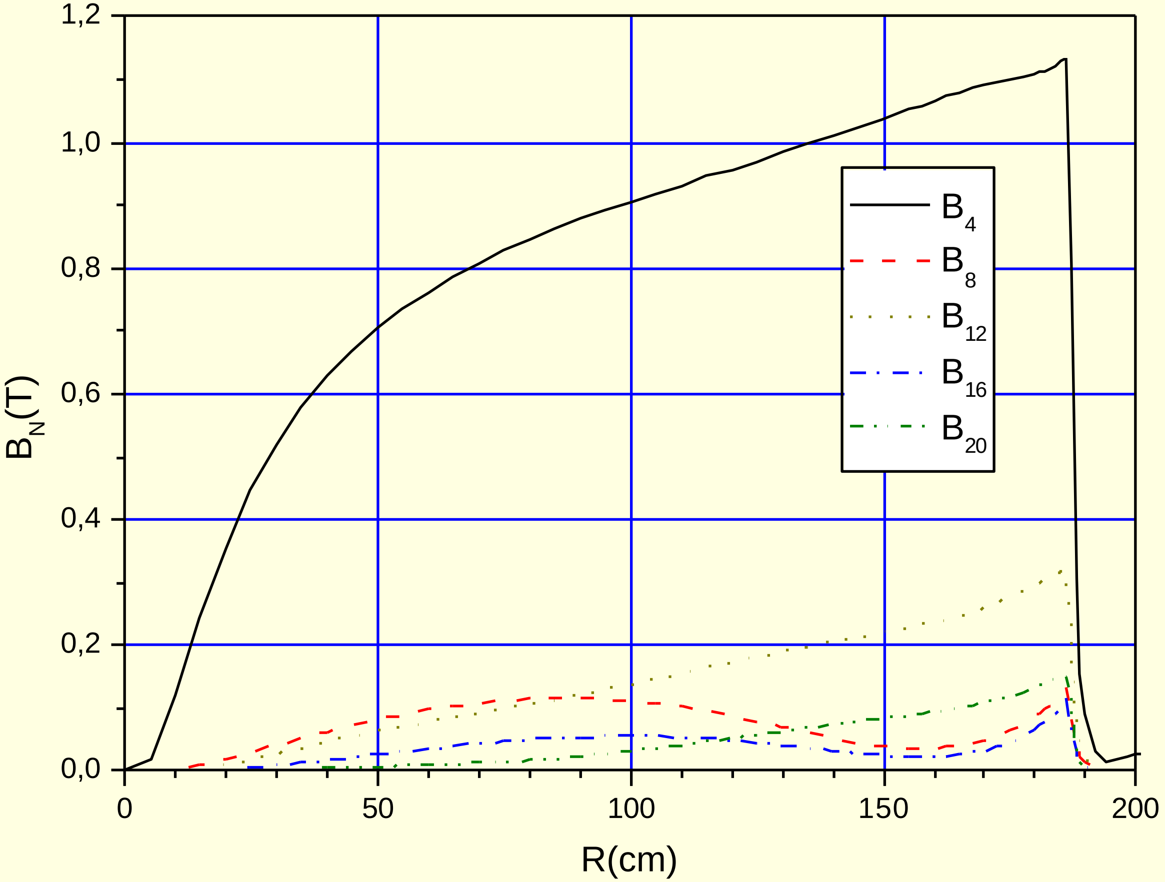
TOSCA model for the sectors design with azimuth profiling



Average magnetic field



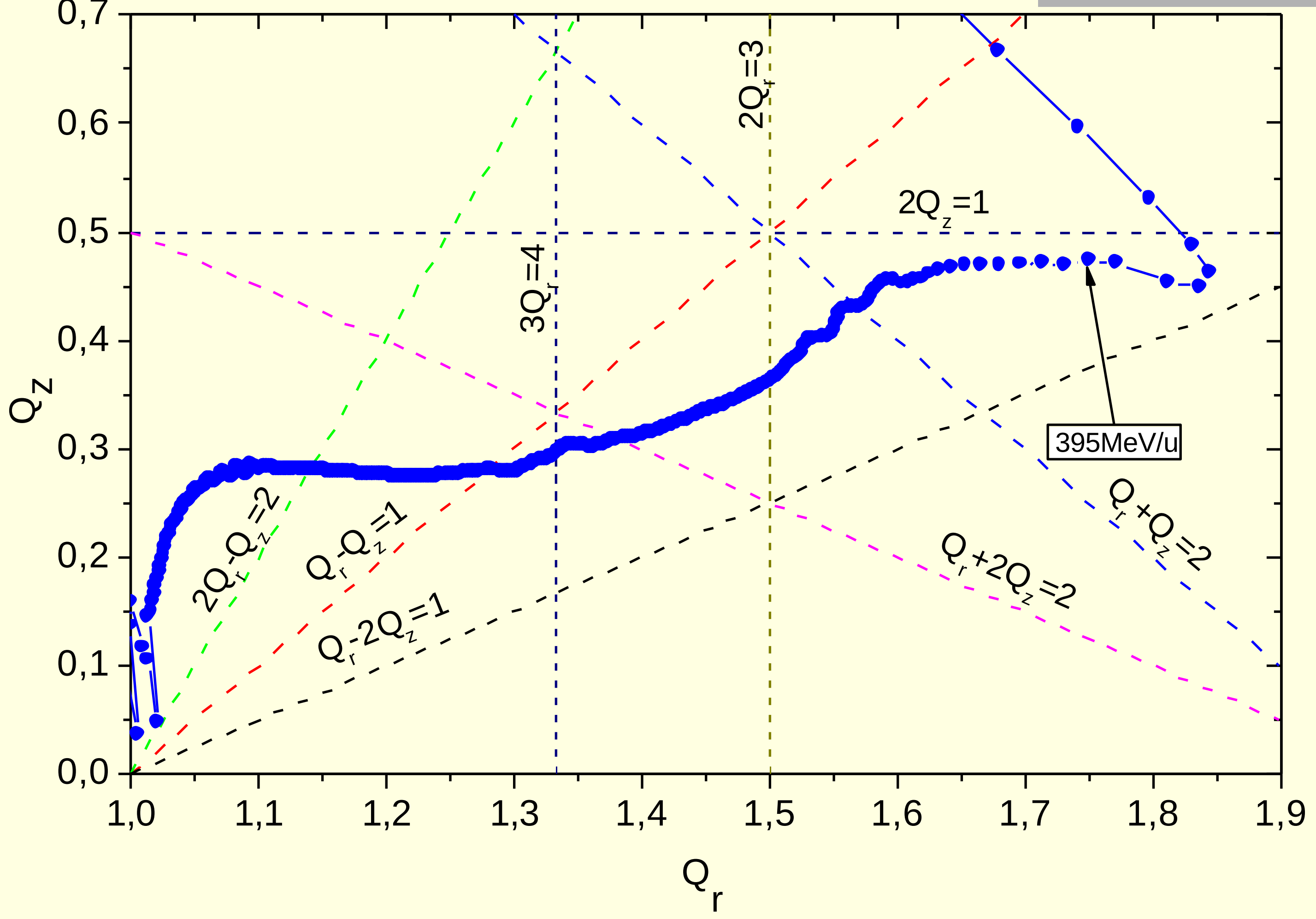
Fourier harmonics of the cyclotron magnetic field



Beam dynamics

- The optimized sector geometry provides vertical focusing ν_z ~ 0.3 in the acceleration region. The vertical focusing (ν_z) at the extraction region made as close to 0.45 as possible, decreases the vertical beam size and minimizes the median plane effects. Special attention was paid to avoiding dangerous resonances. Detailed dynamics simulations were performed to be sure that resonances crossed during acceleration did not cause significant harmful effect to the beam.
- The conditions which provide intersection of the most important resonances Q_r=1, 3Q_r=4 and Q_r-Q_z=1 without essential worsening in the quality of the beam are determined.

Working diagram of the cyclotron



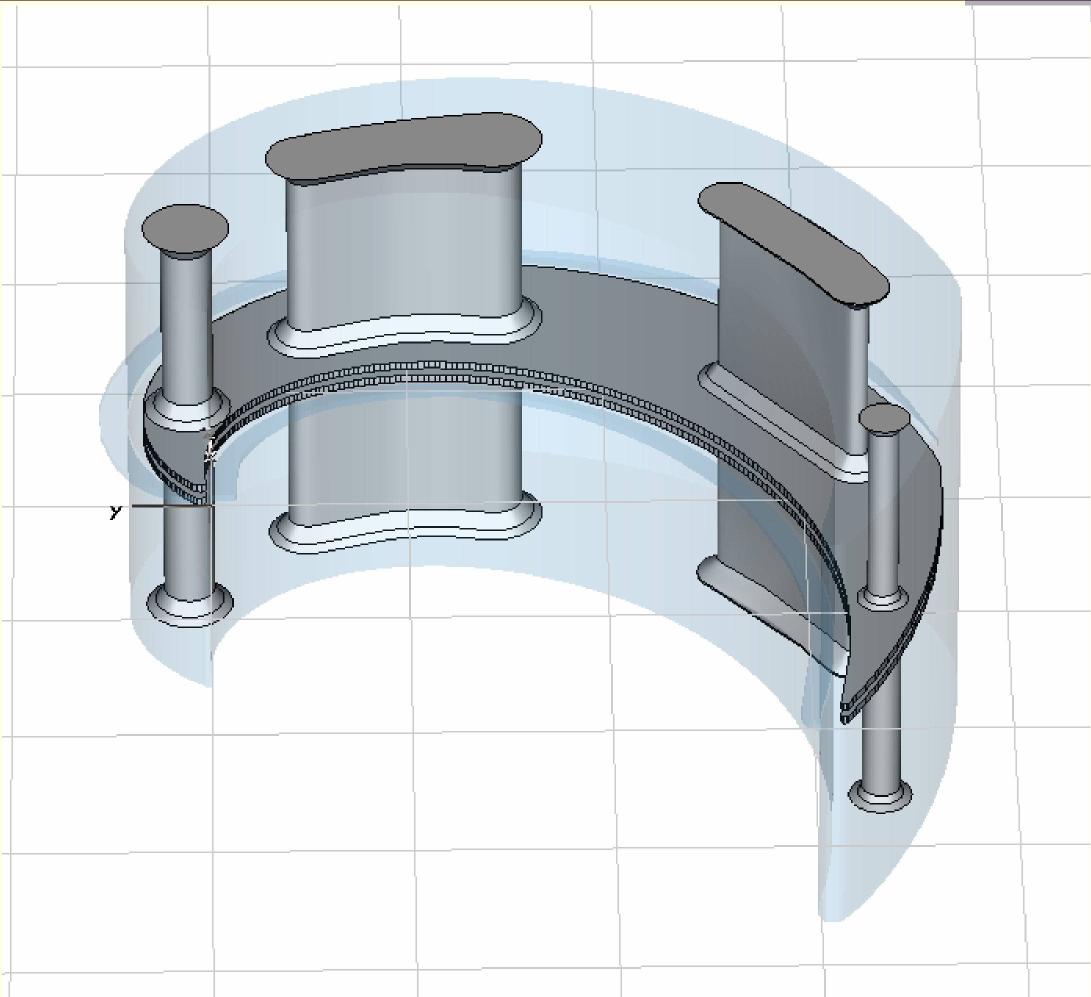
Accelerating system

- Acceleration of the beam will occur at the fourth harmonic of the orbital frequency, i.e. at RF=75 MHz.
- The acceleration will be obtained through two cavities placed in the opposite valleys. Two 45° dees working at the fourth harmonic will guarantee the maximum acceleration. The dee voltage increases from 80 kV at the center to 200 kV at the extraction region, resulting in an average of about 600 kV/turn.

Accelerating system

- A geometrical model of the double gap delta cavity housed inside the valley of the magnetic system of the C400 cyclotron was developed in the Microwave Studio. The depth of the valley permits accommodation of the cavity with the total height 116cm. The vertical dee aperture was equal to 2 cm. The accelerating gap was 6mm at the center and 40 mm in the extraction region.
- The cavities have a spiral shape similar to the shape of the sectors. We inserted four stems with different transversal dimensions in the model. We investigated different positions of the stems to insure increasing voltage along radius.

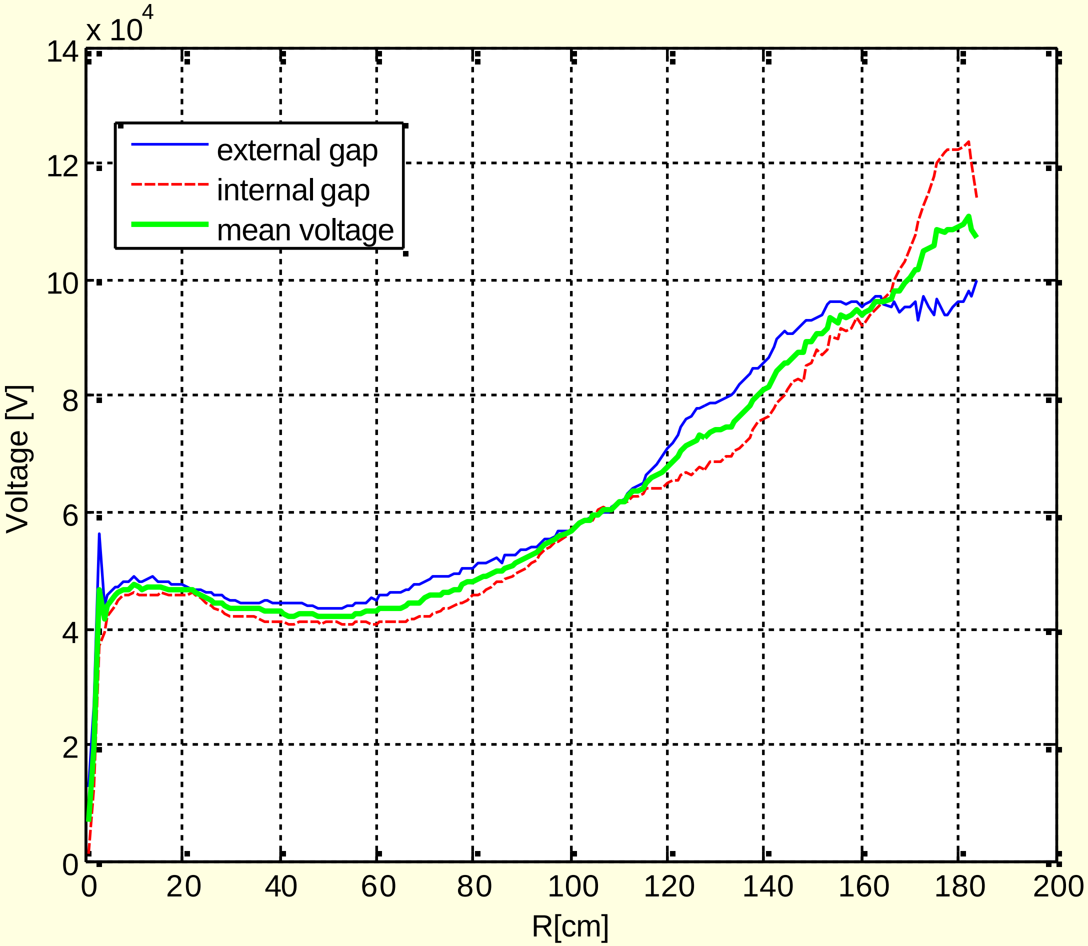
View of the cavity model



Accelerating system

radial dimension	180 cm
vertical dimension	116 cm
frequency	75 MHz
operation	4^{th} harmonic
number of dees	2
dee voltage: center extraction	80 kV 200 kV

Voltage distribution along the gap: the internal gap-red line, the external gap-blue line, average voltage-green line



Extraction
Proton beam

- Extraction of protons is supposed to be done by means of the stripping foil. The main purpose of the preliminary computations was to find the minimal values of the protons energy which could be provided by the 1-turn and 2-turn schemes of extraction.
- It was found that 320 MeV is the minimal attainable energy of protons which can be extracted during 1-turn after the stripping foil and 260 MeV is the minimal energy of protons for 2-turn extraction. The latter variant was chosen as the optimal one because the energy of the 2-turn extracted protons is essentially closer to the normally used energy for the proton beam treatment.
- A set of computations was carried out to optimize the extracted proton trajectory. The optimal position of the stripping foil was found.

Extraction
Carbon beam

- The average magnetic field in the C400 cyclotron is about 3.6 T at the final radii. Due to decreasing gap of the magnetic system, the isochronous field expands very close to the pole edge and just outside the pole there is an essential field drop. In such a magnetic field rapid beam extraction by means of the electrostatic deflector seems to be most effective.

Extraction
Carbon beam

- It is possible to extract the beam by means of one electrostatic deflector (which is located in the valley between the sectors) with a 140 kV/cm field inside. The septum of the deflector (septum thickness 0.3mm, deflector aperture 3mm) was located on the radius 180.2cm for tracking simulation. Under these conditions the total losses just before extraction are 31.6%.

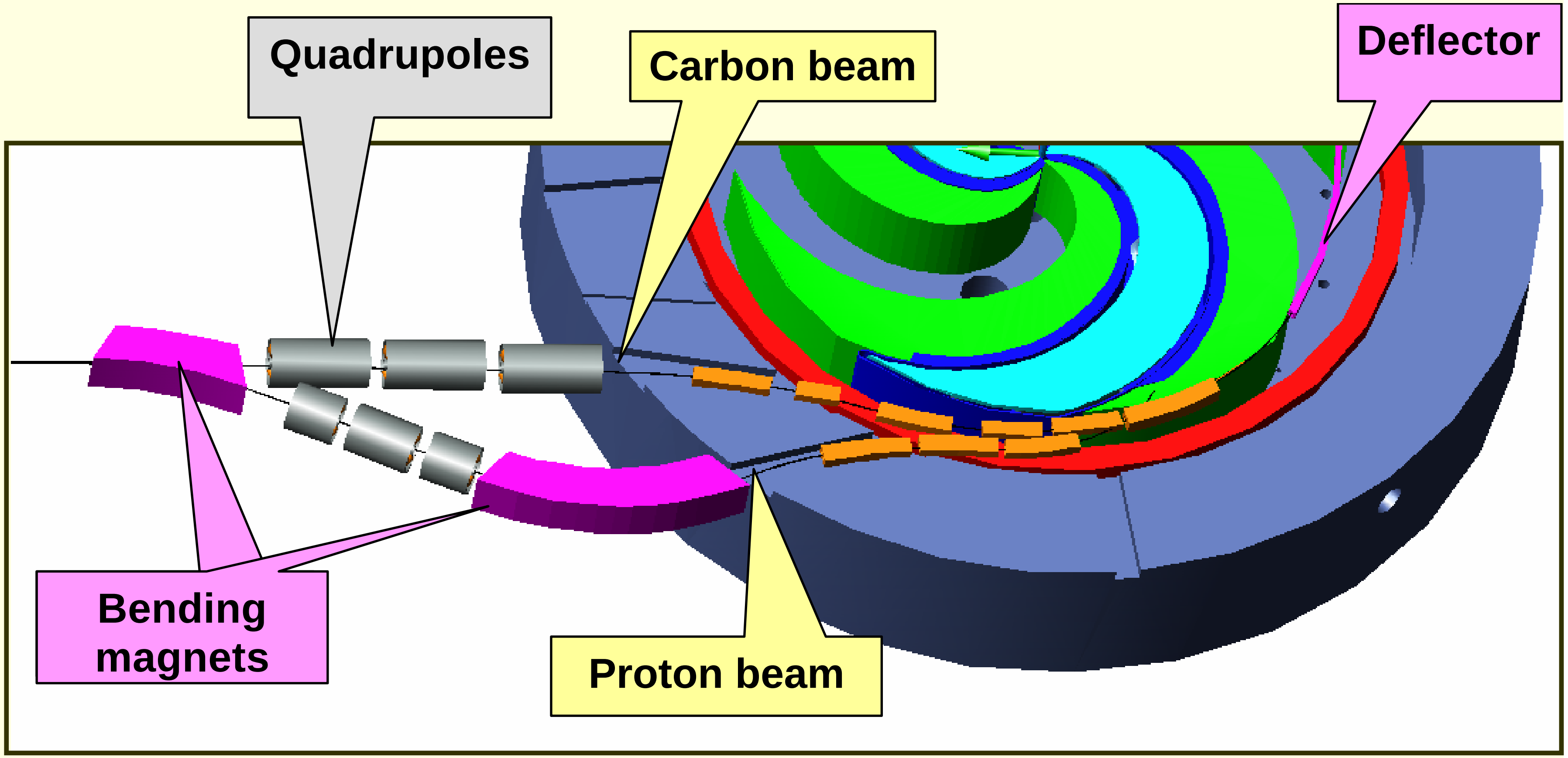
Extraction line optics

- Modelling of action of different focusing elements in both carbon and proton extraction systems was carried out to avoid large beam divergence during the extraction. Necessity of precise alignment of two beams at ~3 m from the cyclotron just before the energy degrader to provide the ~1-2mm beam spot at this point for both beams was taken into account.

Extraction line optics

- During these simulations an attempt was made to use partly the same extraction channel for both beams. The results showed that in this case it was impossible to provide acceptable beam spots before the degrader and the beams had also rather large transverse size (sometimes up to 6-8cm) during the extraction. Therefore, extraction of the carbon and proton beams through separate channels and their further alignment by the bending magnets outside the cyclotron was chosen as an acceptable variant.

View of the extracted carbon and proton beams and elements of the extraction lines



Beam losses by residual gas interactions

- Simulations of ion losses in the cyclotron and in the injection line with nitrogen as a residual gas were done.
- The vacuum losses in the injection line were estimated using the experimental cross section data. The simulations show that vacuum requirements for the injection system are dictated by $^{12}C^{6+}$ ions. Losses will be about 2% for the residual gas pressure $2*10^{-7}$ torr.

Beam losses by residual gas interactions

- We used formula calculated from Bohr's formula (for Z_T**>**3) obtained in the free-collision approximation in a classical treatment of electron scattering in the strongly screened field of the target atom:

$$\sigma(E) = \pi a_0^2 Z_T^{2/3} \frac{v_0}{v} \sqrt{\frac{I_0}{I}}$$

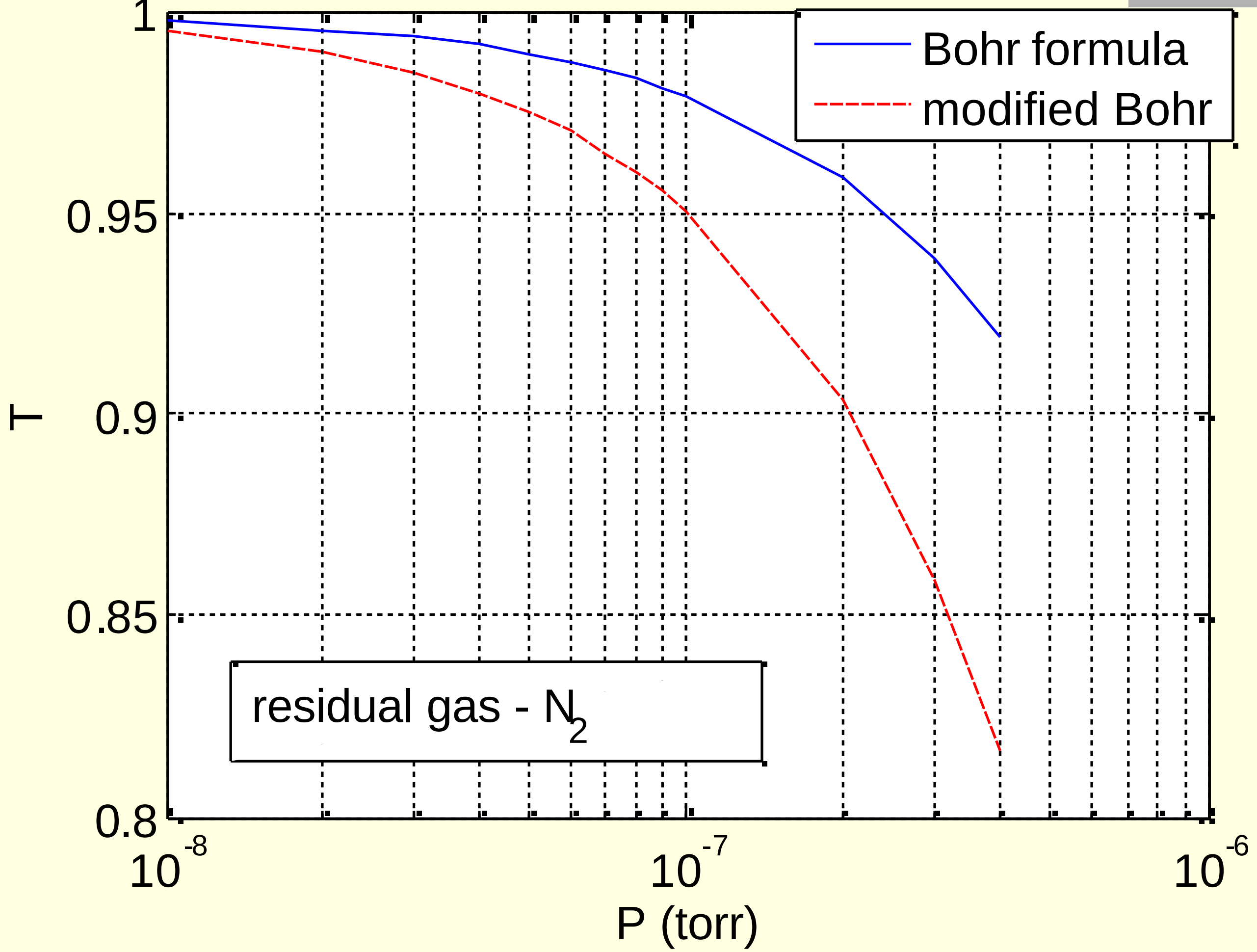
Beam losses by residual gas interactions

- The modified Bohr formula:

$$s(E) = 4pa_{m0}^2 \frac{v_0^2}{v^2} \frac{Z_T^2 + Z_T}{Z_i^2}$$

here: v_0 **=**2.19 *****10**8** cm/s, a_0=5.29*10-9 cm and a_{m0}=9*10^{-9} cm are the velocity, the radius of the Bohr orbit and the modified radius respectively, Z_i and Z_T are the atomic number of the incident H^{2+} and of the residual gas respectively, v is the velocity of the accelerated H^{2+}, ***I*** is the binding energy of an ejected electron, and $\boldsymbol{I_0}$ = 13.6 eV.

Transmission efficiency of H^{2+} ions for the C400 cyclotron as a function of vacuum pressure.



CONCLUSIONS

- The detailed computer simulations of the beam dynamics and the main systems of the C400 cyclotron were performed. The results of the simulations show that the energy up to 400MeV/amu (K = 1600) can be obtained with the compact design similar to the existing IBA C235 cyclotron. The C400 cyclotron will also provide a proton therapy beam with energy 260MeV.

Thank you for your attention!