IBA-JINR 400 MeV/u SUPERCONDUCTING CYCLOTRON FOR HADRON THERAPY

CYCLOTRONS'10

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During more than 3 years, a team of accelerator physicists was working on the physical design of the cyclotron C400. This study has been summarized into a design report. It has been considered and approved by a commission of experts from the leading cyclotron laboratories of the world.

Carbon therapy

The C400 design project has been executed as the reaction to modern increasing interest to the particle therapy based on carbon ions.

Protons and light ions allow depositing the radiation dose more precisely in a cancer tumor, reducing greatly the amount of dose received by healthy tissue surrounding the tumor as compared with electrons. But in addition to the ballistic accuracy of protons, light ion beams, like carbon beams, have an extra advantage in radiation therapy: they have a different biological interaction with cells and are very effective even against some type of cancerous cells which resist usual radiations.

A cyclotron for 400 MeV/u carbon ions?

- Synchrotrons are today the solution used everywhere for carbon beam therapy
- But this was also the case in 1991 in proton therapy when IBA entered the market
- We believe that the reasons that made the success of cyclotrons in PT will also apply in carbon beam therapy, and that in 10 years the cyclotron will dominate also this market
  - Simplicity (one accelerator, not 3 in series)
  - Lower size and cost
  - Ability to modulate the beam current at kHz frequencies
- In the space and for the cost of a carbon synchrotron, you can install a cyclotron and a compact carbon gantry

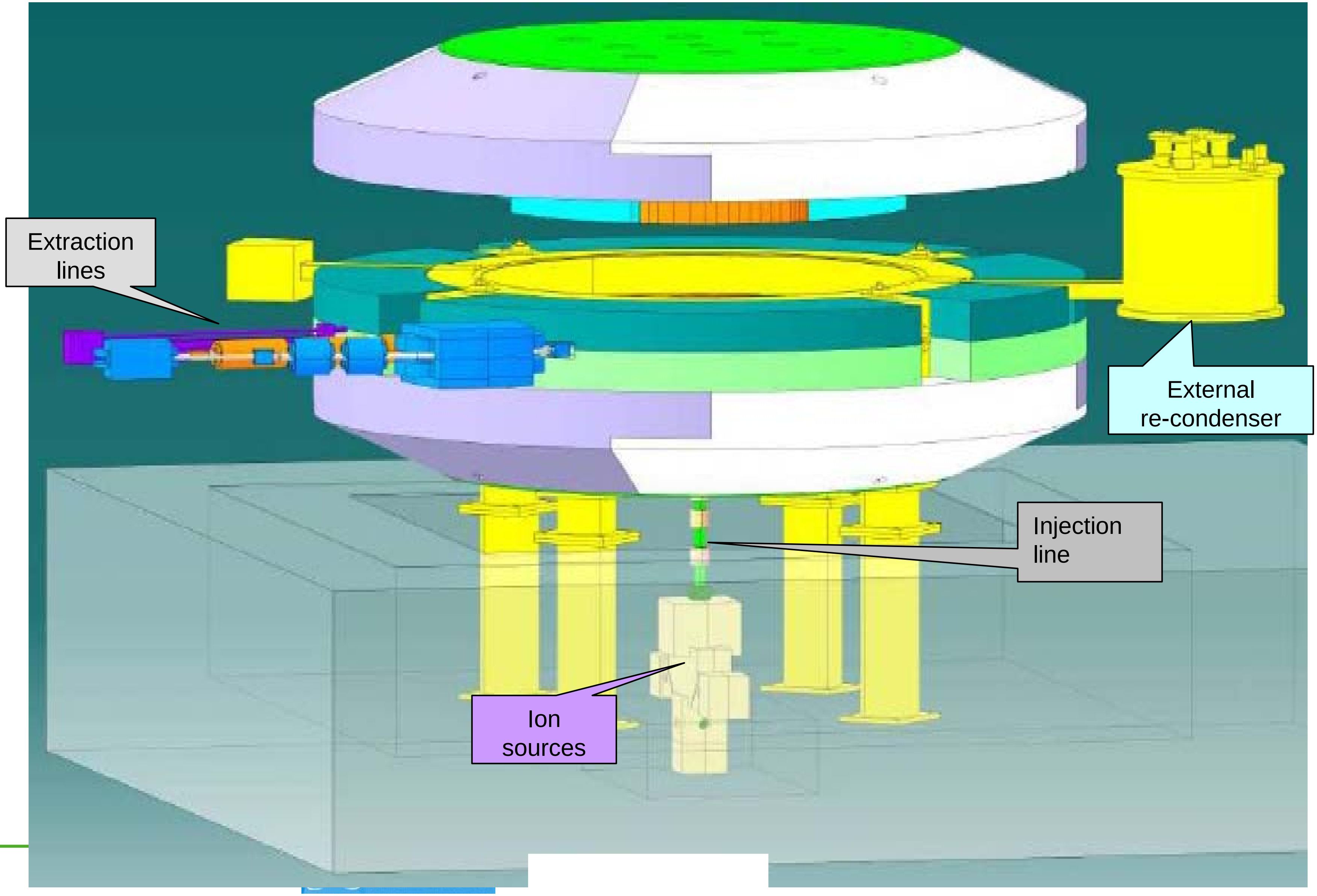
C400 Carbon/Proton therapy facility

- This facility will be based on the technology of the successful IBA proton therapy facility
- By preparing the proposal for design of the cyclotron we were based on technological and design experience of IBA and on experience of workings out and creations of cyclotrons by JINR physicists trying to use a combination of approved simulation and technical decisions
- IBA is collaborating with INFN in the development of a new, improved treatment planning for carbon therapy
- IBA is finalizing the agreement with Archade to install the prototype of IBA Carbon therapy system in Caen

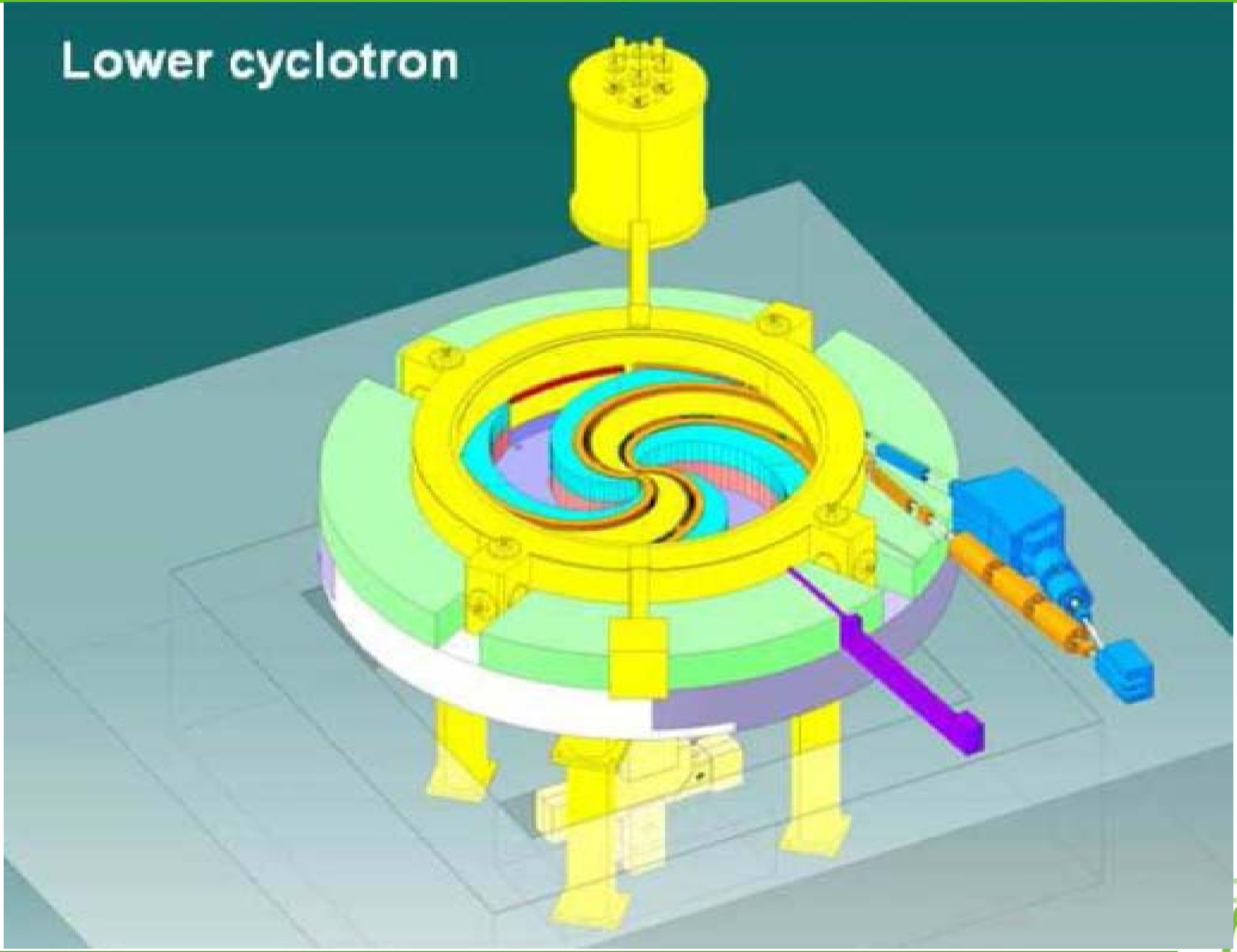
Abstract

- The compact superconducting isochronous cyclotron C400 has been designed by the IBA-JINR collaboration. It will be the first cyclotron in the world capable of delivering protons, carbon and α ions for cancer treatment. The cyclotron construction will start probably this year within the framework of the ARCHADE project (Caen, France). 12C6+ and 4He2+ ions will be accelerated to 400 MeV/u and extracted by the electrostatic deflector. H2+ ions will be accelerated to the energy of 265MeV/u and extracted by stripping. The magnet yoke has a diameter of 6.6 m; the total weight of the magnet is about 700 t. The designed magnetic fields are 4.5 T and 2.45 T respectively in the hills and in the valleys. Superconducting coils will be enclosed in a cryostat. All other parts and subsystems of the cyclotron will be warm. Three external ion sources will be mounted on the switching magnet on the axial injection line located below the cyclotron.
- Cyclotron 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.

A cyclotron for 400 MeV/u carbon ions



A cyclotron for 400 MeV/u carbon ions



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Main parameters of the C400 cyclotron

General properties	
accelerated particles	H_2^+, $^4He^{2+}$(α), ($^6Li^{3+}$), ($^{10}B^{5+}$), $^{12}C^{6+}$
injection energy	25 keV/Z
final energy of ions, protons	400 MeV/u 265 MeV/u
extraction efficiency	~70 % (by deflector)
number of turns	~2000

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Main parameters of the C400 cyclotron

Magnetic system	
total weight	700 t
outer diameter	6.6 m
height	3.4 m
pole radius	1.87 m
valley depth	0.6 m
bending limit	K = 1600
hill field	4.5 T
valley field	2.45 T

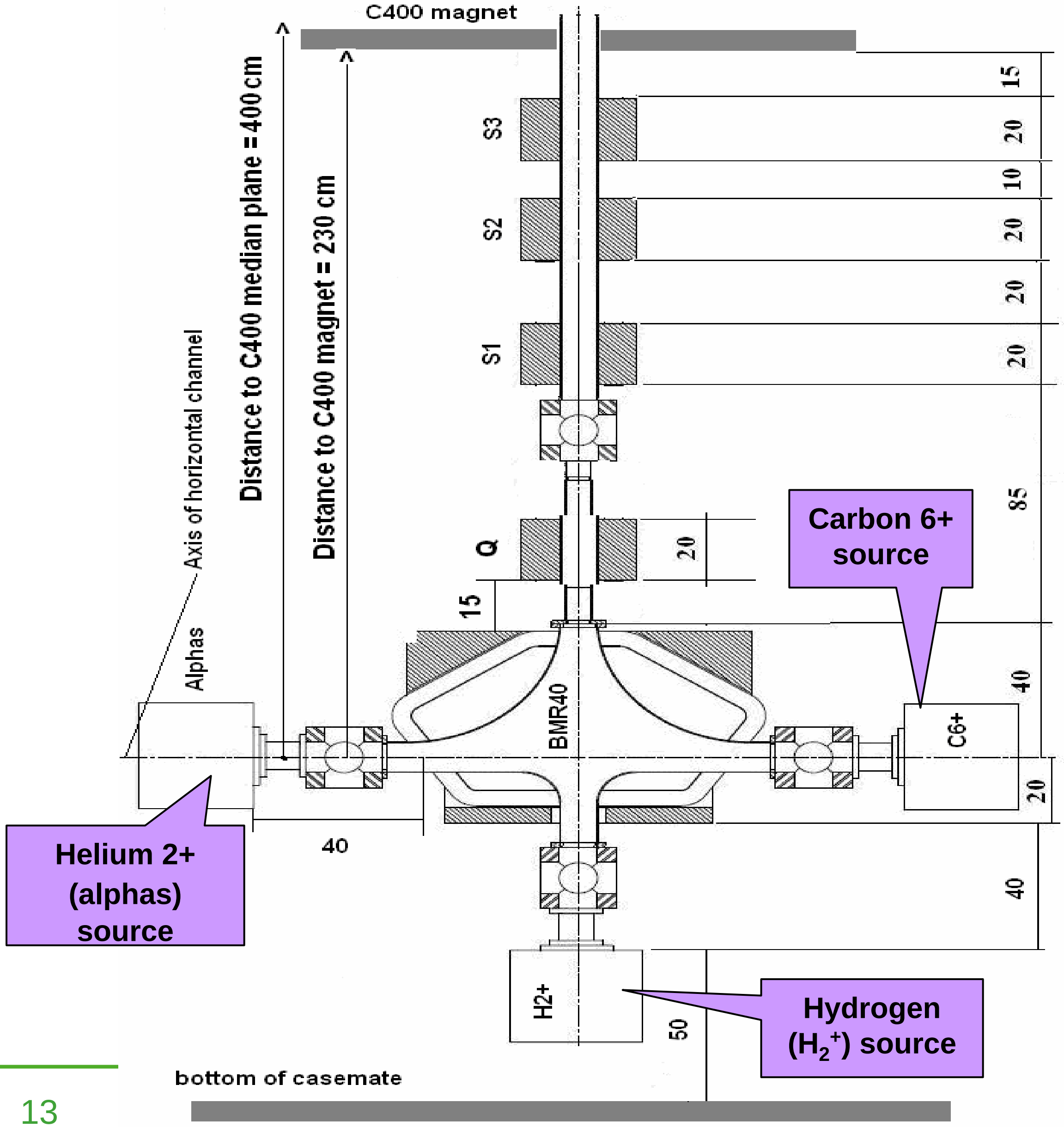
Main parameters of the C400 cyclotron

RF system	
number of cavities	2
operating frequency	75 MHz, 4th harmonic
radial dimension	1.87 m
vertical dimension	1.16 m
dee voltage: center extraction	 80 kV 160 kV

INJECTION AND ION SOURCES

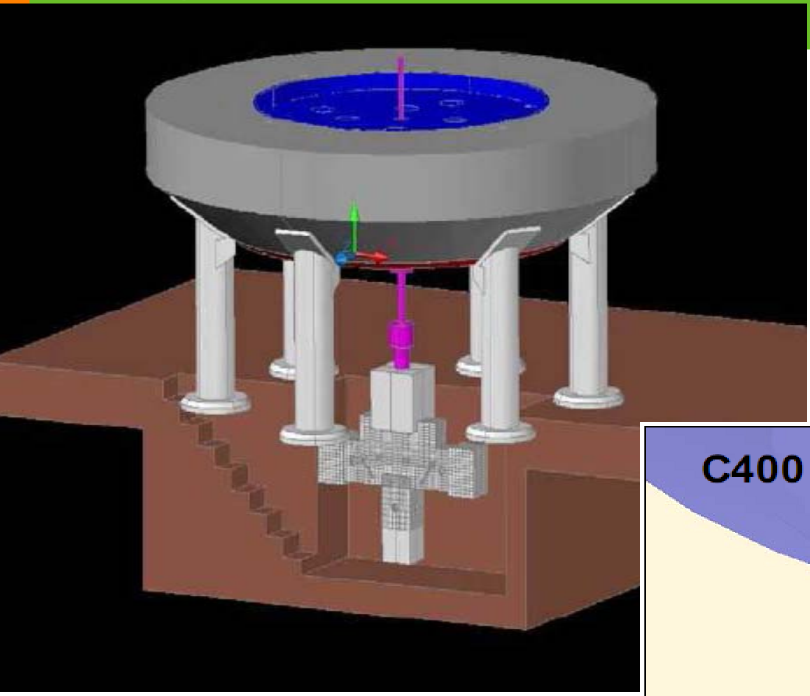
- 3 ECR sources (2 Supernanogan from Pantechnik) producing C6+, He2+, and one simpler ECR source producing H2 are located under the cyclotron
- A 2 x 90° magnet allows to select rapidly the ion species
- One quadrupole is used to restore the X-Y symmetry of the horizontal beams
- The beam is focused into a small circular spot at the inflector entrance by three solenoid lenses, and by the cyclotron magnetic field
- Beam simulations shows that using two phase selection slits, the injection efficiency is equal to 12% for ions with amplitudes of radial oscillations less than 4 mm

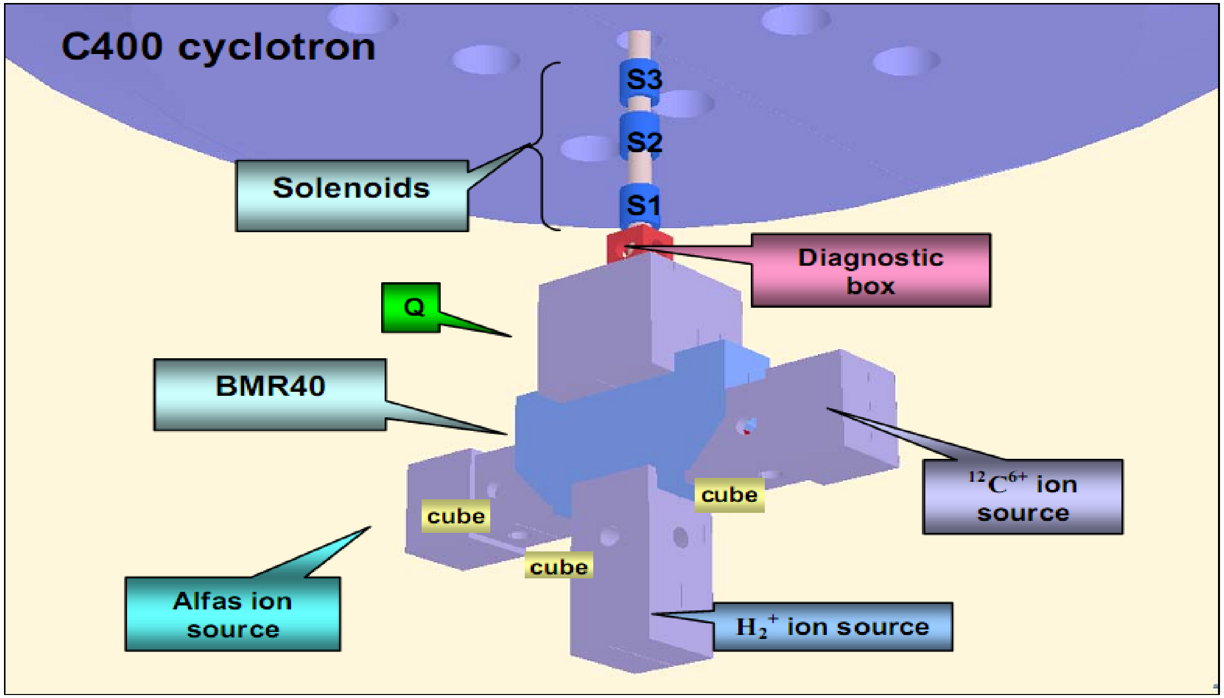
INJECTION AND ION SOURCES



Focusing in the channel is provided by three solenoid lenses (S1 … S3), the rotational symmetry of the beam is reestablished with the help of one quad Q placed just behind the BMR40 bending magnet. The 90º bending magnet has two horizontal entrances, one vertical entrance, and one exit for the ion beams. The bending radius of the magnet BMR40 is equal to 40 cm. The maximum magnetic field corresponds to 0.75 kG, gap height is 70 mm. The maximum magnetic field of the solenoids does not exceed 3 kG, a good field region is of 80 mm. The maximum quadrupole lens gradient does not exceed 100 G/cm.

3 ion sources are located below the cyclotron





Conclusion

- **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.**
- **Only losses due to charge exchange with the residual gas will occur. The simulations show that vacuum requirements for the injection system are determined by $^{12}C^{6+}$ ions. Losses will be about 2 % for the residual gas pressure $2*10^{-7}$ torr.**

CENTRAL REGION DESIGN

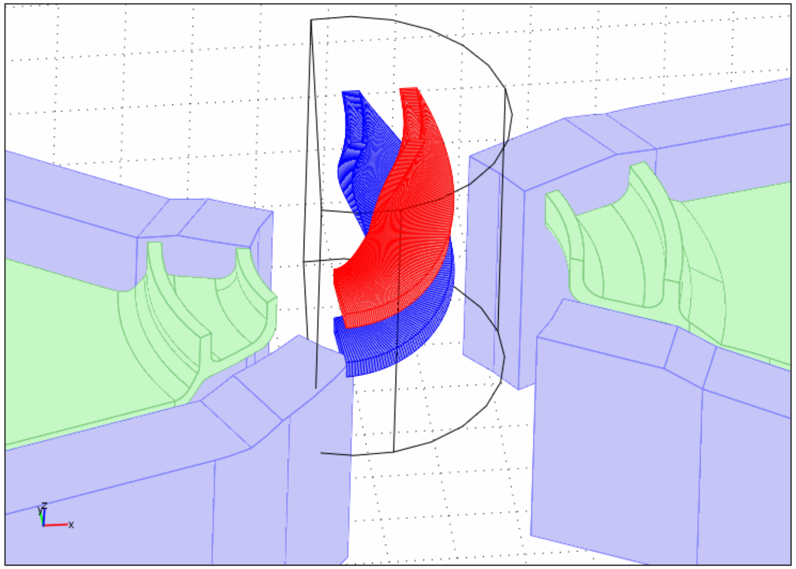
The principal requirements to the central region design were:

- **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.

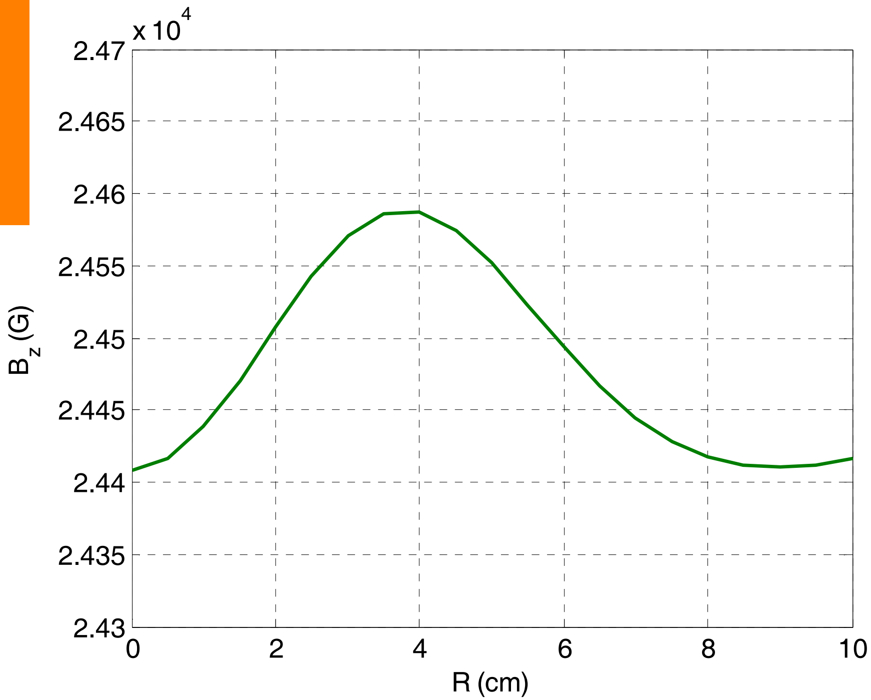
Spiral inflector

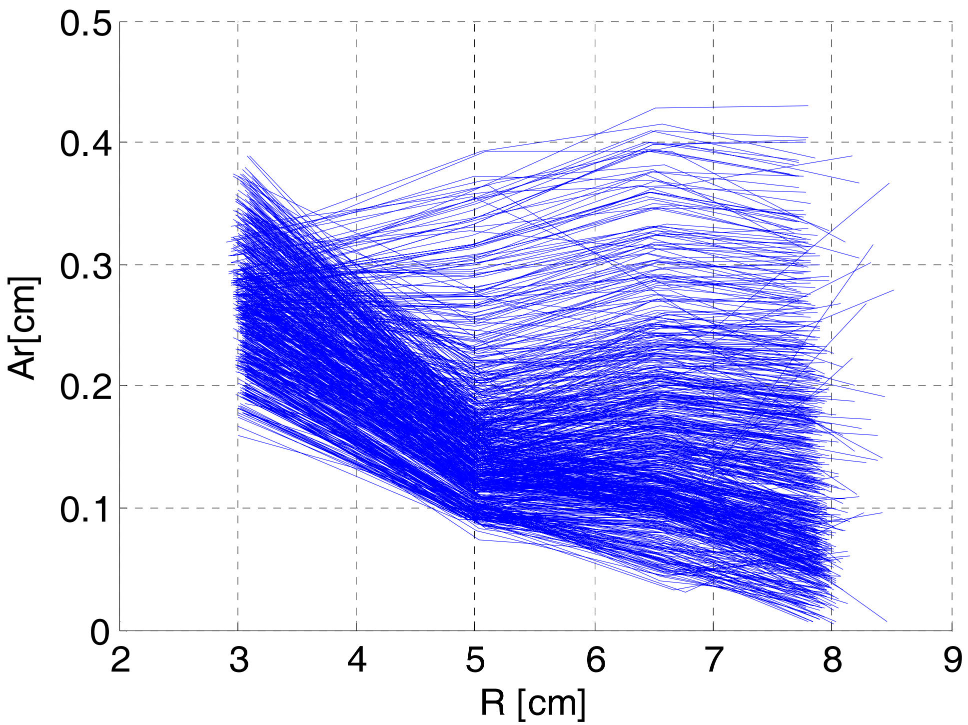
- The electric field of the inflector was chosen to be 20 kV/cm. Thus, the height of the inflector is equal to 2.5 cm. The gap between the electrodes was taken to be 6 mm. The aspect ratio between the width and the spacing of the electrodes was taken to be equal to 2 to avoid the fringe field effect. Computer model of the inflector with tilt parameter 0.1 was developed. The inflector was placed in the grounded housing. The distance between the grounded housing and the twisted electrodes was 4mm.



Inflector parameter	
Electric radius (height of the inflector) (mm)	25
Width of the electrodes (mm)	12
Voltage on the electrodes (kV)	±6
Gap (mm)	6
Tilt parameter	0.1

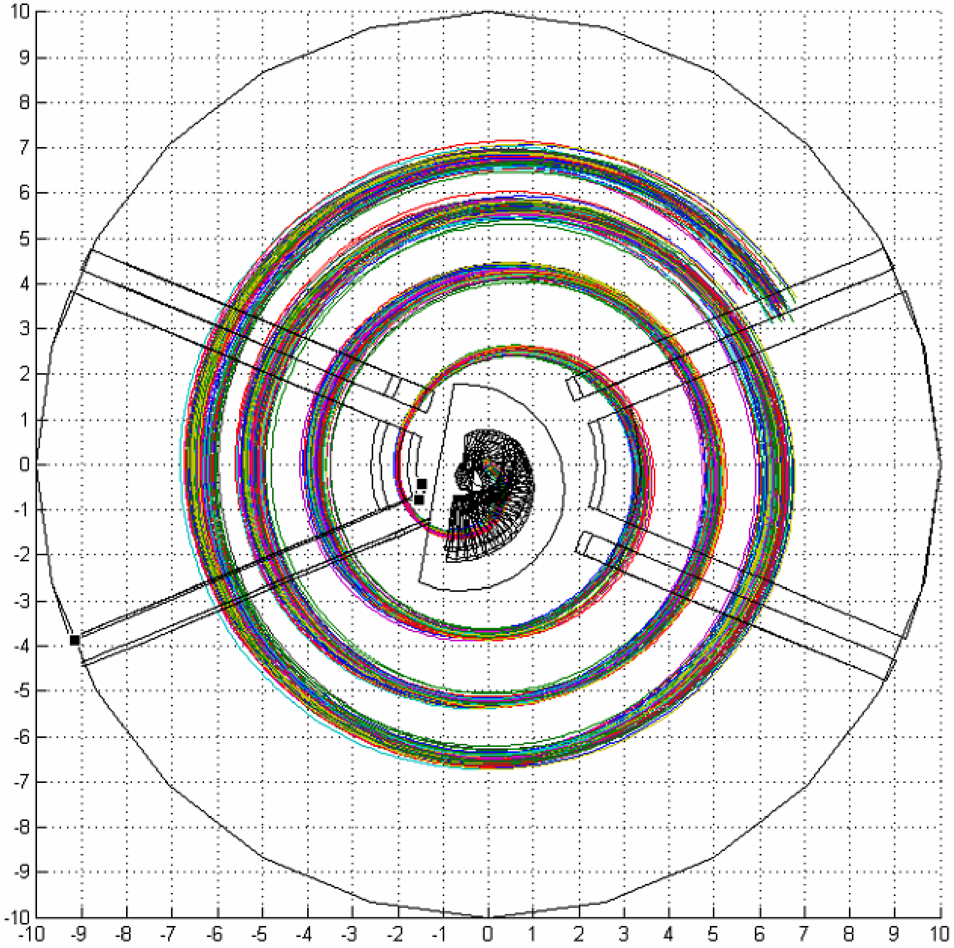
Amplitudes of radial betatron oscillations





Axial focusing is provided by electric focusing. Magnetic field bump do not provide vertical focusing.

First turns



CENTER REGION DESIGN
Conclusion

- **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 4mm. Using of the buncher will increase injection efficiency in about 2 times.**

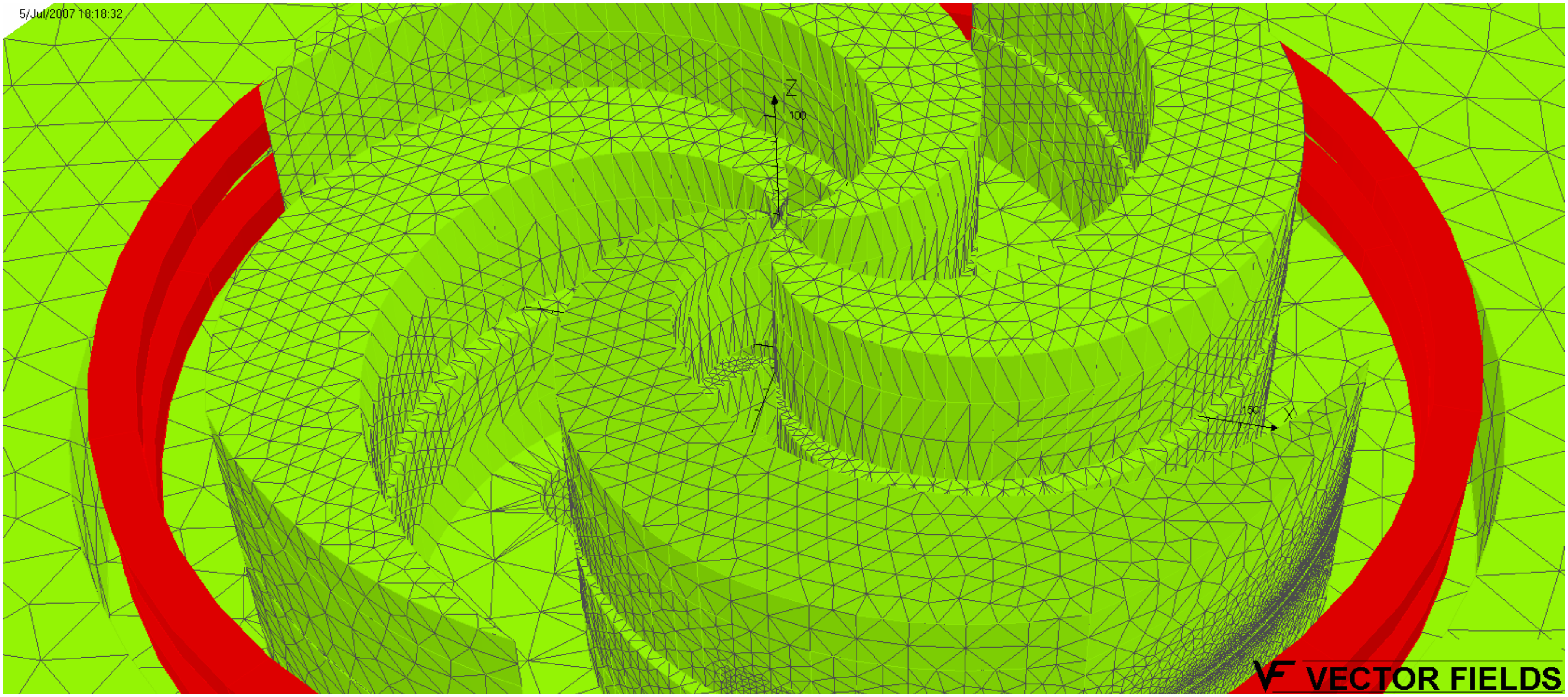
MAGNETIC SYSTEM (design goals)

- **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 13-15 mm from the pole edge $\Rightarrow$ facilitate extraction
- **Pole radius = 187 cm**
- **Magnetic induction inside yoke less 2-2.2 T**
- **Weight less 700 tons**

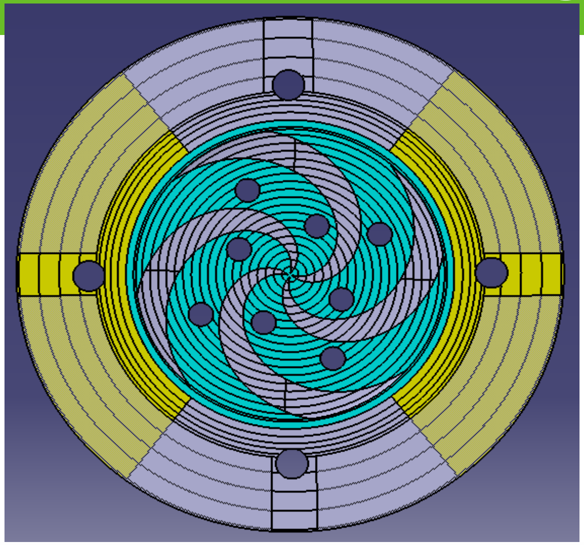
Achieved goals

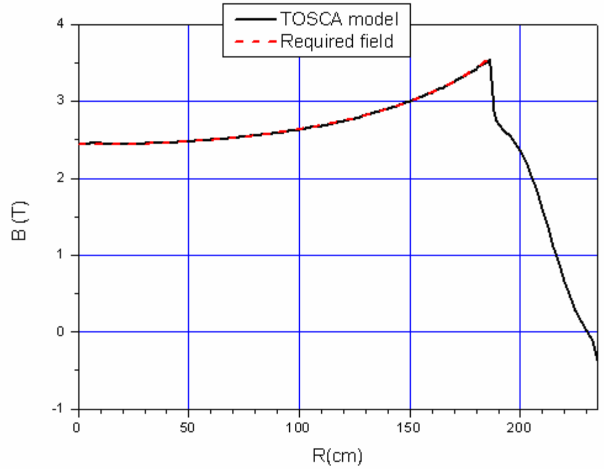
- Optimization of the magnet sizes
- Realization of the vertical focusing (Qz) at the extraction region as close to 0.45 as possible (to decrease the vertical beam size and minimize the median plane effects)
- Keeping optimal value of the spiral angle of the sectors (minimize total sectors angle turn)
- Average magnetic field shaping by variation of the sectors azimuth width
- Last orbit kept as close to the pole edge as possible (~13 mm)
- Minimization iron weight, keeping the stray field at an acceptable level
- Avoiding resonances (most dangerous)
- Optimal solution for SC coil design
- Finding the optimal design solution for C12/H2 magnetic field switch
- Realization of optimal design for C and p extraction channels

TOSCA model for the sectors design with azimuth profiling

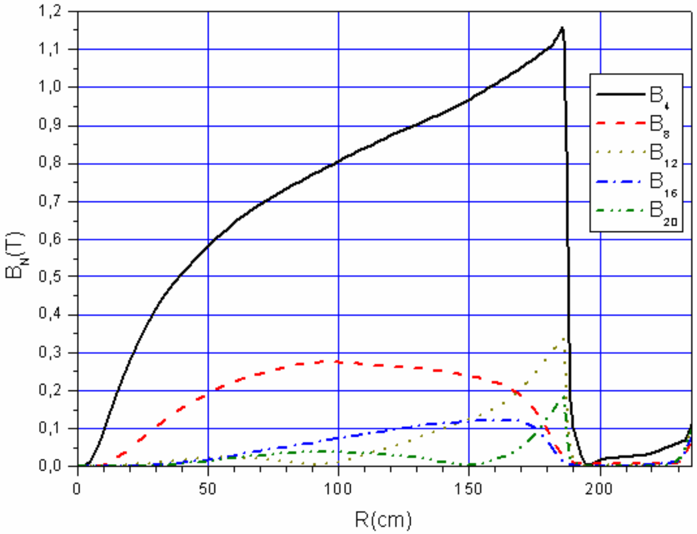


Magnetic field properties

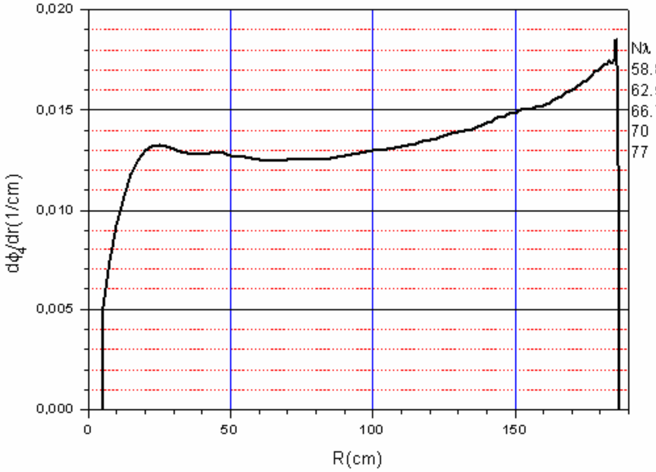




Average field



Main harmonics



Derivative of 4-th harmonic phase

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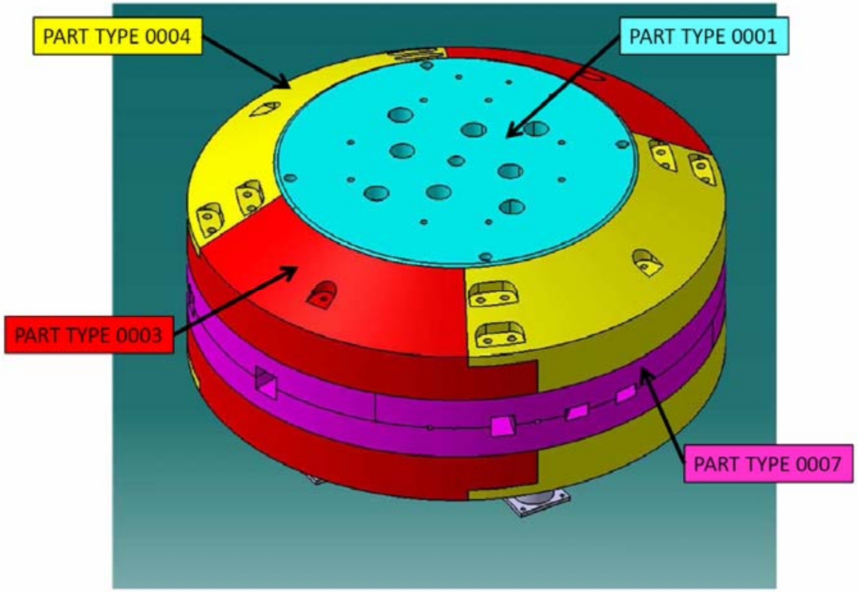
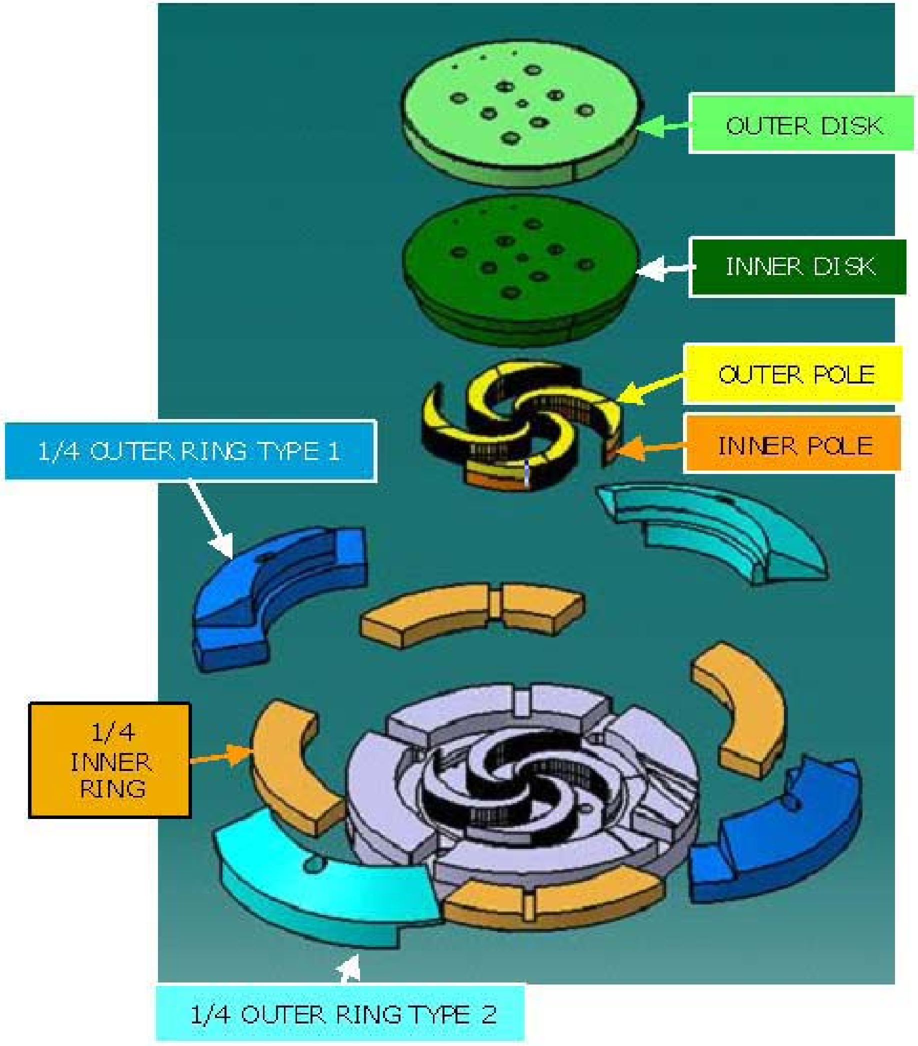
C400 magnet design

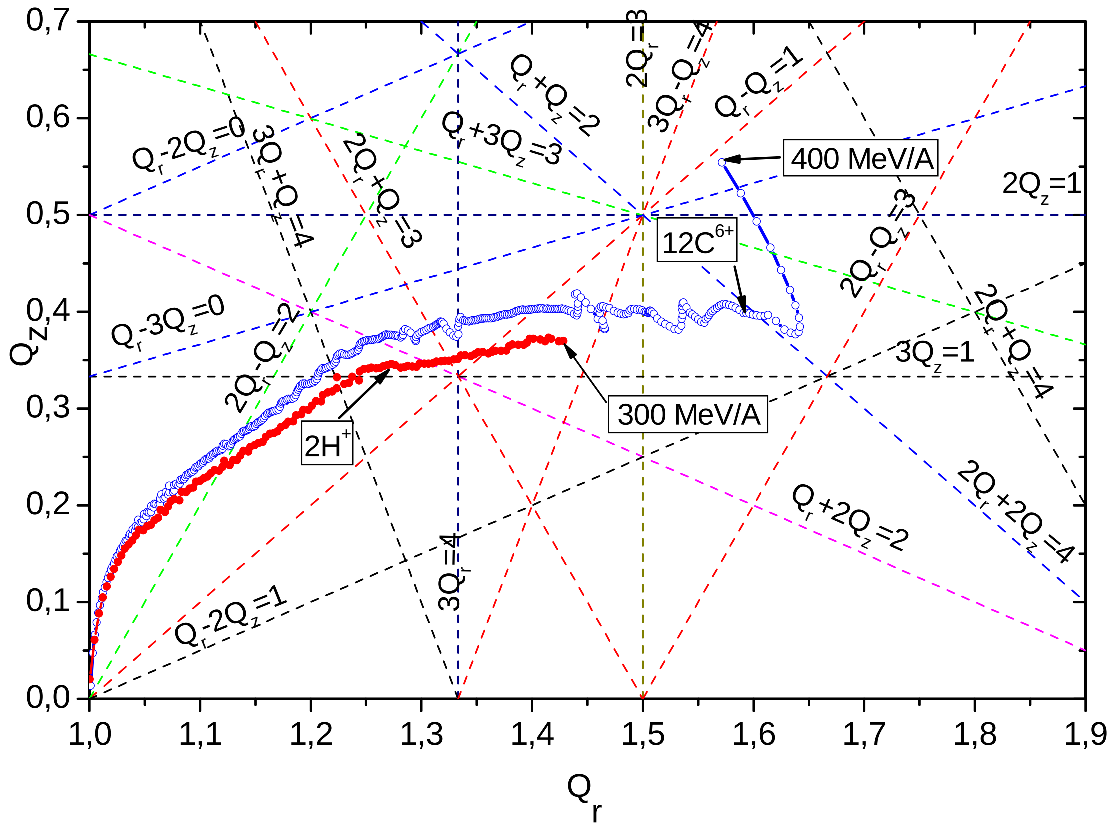




Top part of horizontal yoke (part 0001)	2*58.4 t
Central disk of the horizontal yoke with sectors (part 0002)	2*(64.4+20) t
Outer ring of the horizontal yoke Part 0003 Part 0004	 4*38.1 t 4*36.7 t
Return yoke	4*26.8 t
Total weight	694 t

Beam dynamics

- During a whole range of acceleration the carbon beam crosses the lines of 17 resonances up to 4th order. The working diagrams have been computed via an analysis of the small oscillations around the closed orbits. All resonances can be subdivided into two groups. The first group consists of 6 internal resonances (nQr±kQz=4, n, k=0, 1, 2, 3, 4, n+k≤4) having the main 4th harmonic of the magnetic field as a driving term. The second group includes 11 external resonances (nQr±kQz=m, m=0, 1, 2, 3) that could be excited by the magnetic field perturbations.



Requirements to the field imperfections imposed by the dangerous resonances will be able to be provided in practice at today's level of cyclotron technology

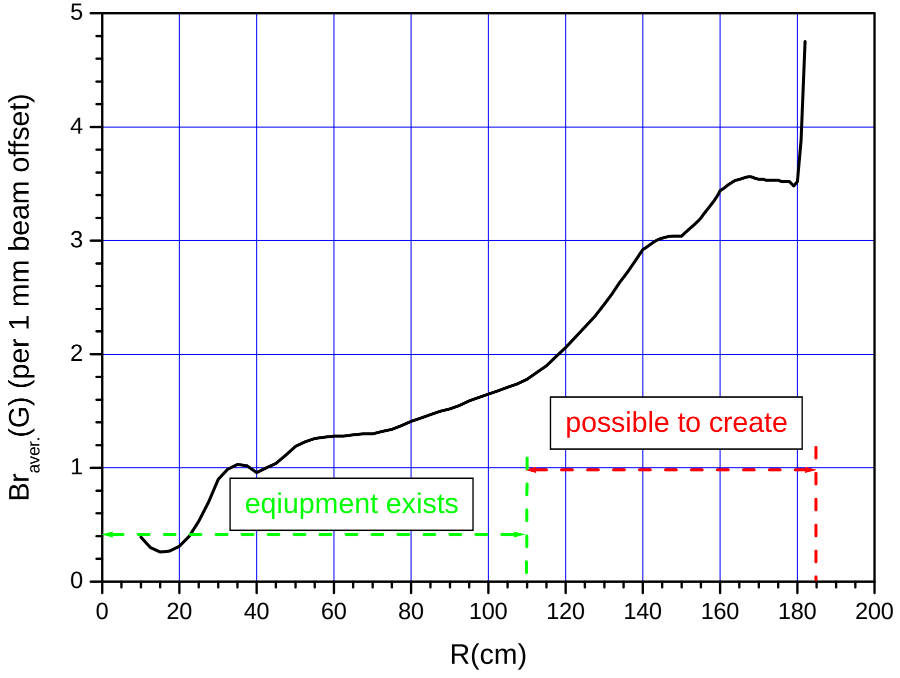
Table of resonances

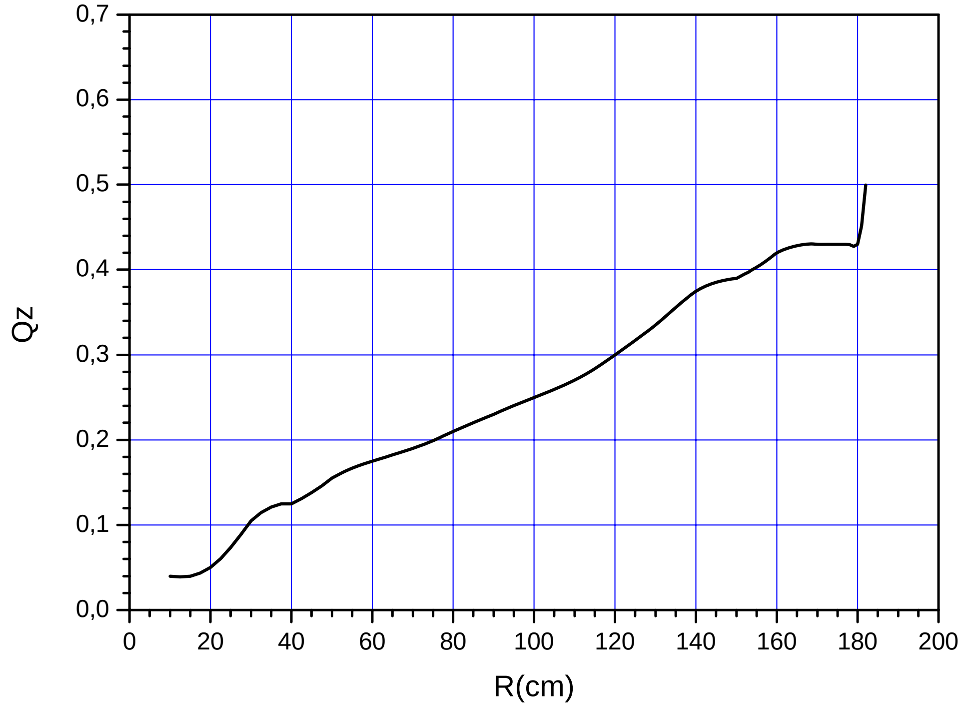
No.	Resonance	Radius (cm)	Driving term	Description, tolerances	Level of danger
1	$Q_r = 1$	2-10	B_{z1}	Increase in radial amplitudes $B_{z1} < 2\text{-}3$ G	Dangerous
2	$4Q_r = 4$	2-10	B_{z4}, ϕ_{z4}	Weak influence on radial motion at acceleration	Not dangerous
3	$2Q_r - Q_z = 2$	110	B_{z2}, B_{r2}	Increase in axial amplitudes $B_{z2} < 200$ G, $B_{r2} < 50$ G	Not dangerous
4	$3Q_r + Q_z = 4$	131	B_{z4}, ϕ_{z4}	No influence up to A_z, $A_r = 5\text{-}7$ mm	Not dangerous
5	$Q_r - Q_z = 1$	145	B_{r1}	Increase in axial amplitudes $B_{r1} < 5\text{-}7$ G	Dangerous
6	$3Q_r = 4$	154	B_{z4}, ϕ_{z4}	Increase in radial amplitudes beginning from $A_r = 1.5$ mm. Can be corrected by average field perturbation.	Dangerous
7	$2Q_r + Q_z = 3$	157	B_{r3}	Increase in axial amplitudes $B_{r3} < 10$ G	Not dangerous
8	$Q_r + 2Q_z = 2$	162	B_{z2}	Increase in axial amplitudes $B_{z2} < 20$ G	Not dangerous
9	$3Q_z = 1$	167	B_{r1}	Increase in axial amplitudes $B_{r1} < 20$ G	Not dangerous

Table of resonances (cont.)

10	$3Q_r - Q_z = 4$	167	B_{z4}, ϕ_{z4}	Increase in radial amplitudes. No influence if no axial amplitudes increase on $3Q_z = 1$ due to B_{r1}.	Not dangerous
11	$2Q_r = 3$	172	B_{z3}	Increase in radial amplitudes. $B_{z3} < 10$ G	Not dangerous
12	$Q_r + Q_z = 2$	177	B_{z2}, B_{r2}	Increase in radial and axial amplitudes. $B_{r2} < 10$ G	Not dangerous
13	$2Q_r + 2Q_z = 4$	177	B_{z4}, ϕ_{z4}	No influence	Not dangerous
14	$Q_r + 3Q_z = 3$	179	B_{z3}	Increase in axial amplitudes $B_{z3} < 10$ G	Not dangerous
15	$2Q_r - Q_z = 3$	180	B_{z3}	Increase in axial amplitudes $B_{z3} < 10$ G	Not dangerous
16	$2Q_r + Q_z = 4$	181	B_{z4}, ϕ_{z4}	Increase in axial amplitudes. Requires proper deflector positioning.	Not dangerous
17	$2Q_z = 1$	181	B_{z1}, B_{r1}	Increase in axial amplitudes. $B_{r1} < 10$ G	Not dangerous

Median plane effects





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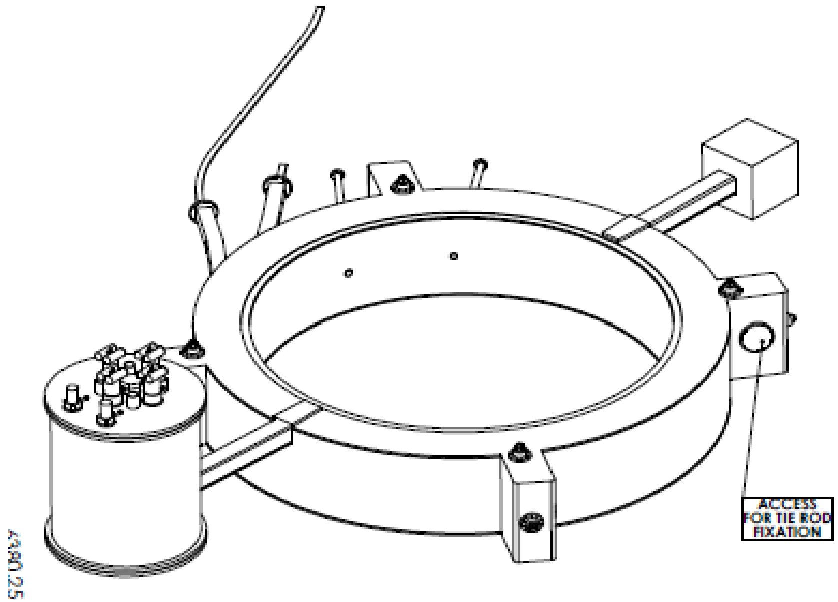
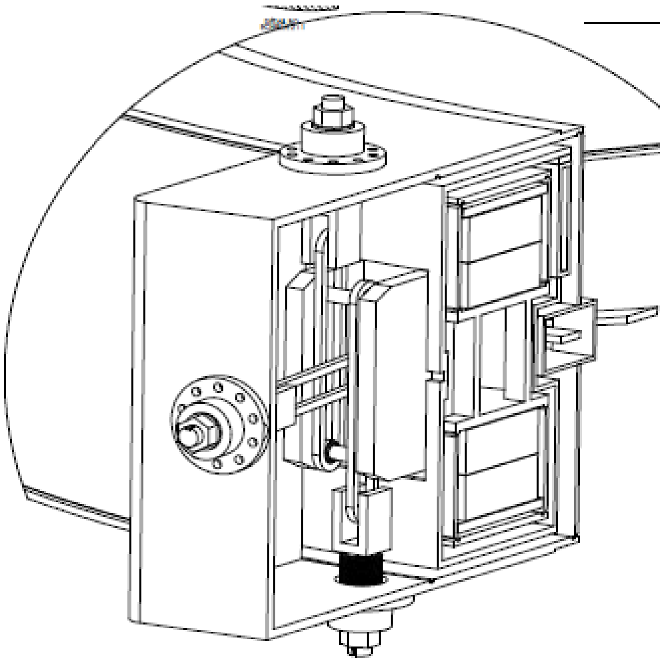
SC coils design

- Four companies (ANSALDO, BNG, SIGMAPHI, TESLA) were participating in tender for design and fabrication of SC coils for C400
- SIGMAPHI was selected
- SC coils design conception is under the last modification.
- The cryostat outer diameter is 4.7 meter for a total weight of 25 tons. The whole system provided by Sigmaphi will include the superconductive coils, the cryostat, service turret with cryocoolers, power supplies, monitoring instrumentation and quench protection electronic system





RF CAVITY
Specifications for the RF cavity

- **Magnetic field modeling and beam dynamics have determined orbital frequency of the ions equal to 18.75MHz. As RF cavities will be operated in the 4th harmonic mode resonance frequency must be 75 MHz.**

- **Voltage value must be equal 80 kV in the center and about twice higher in the extraction region. It is important to have high value of voltage beginning from about R=150 cm before resonance $3Q_r=4$ crossing.**

- **The active tuning system must be designed to bring the cavities on frequency initially to compensate detuning for temperature variations due to RF heating and to provide frequency difference 450kHz for C^{6+} and H_2^+ ions acceleration**

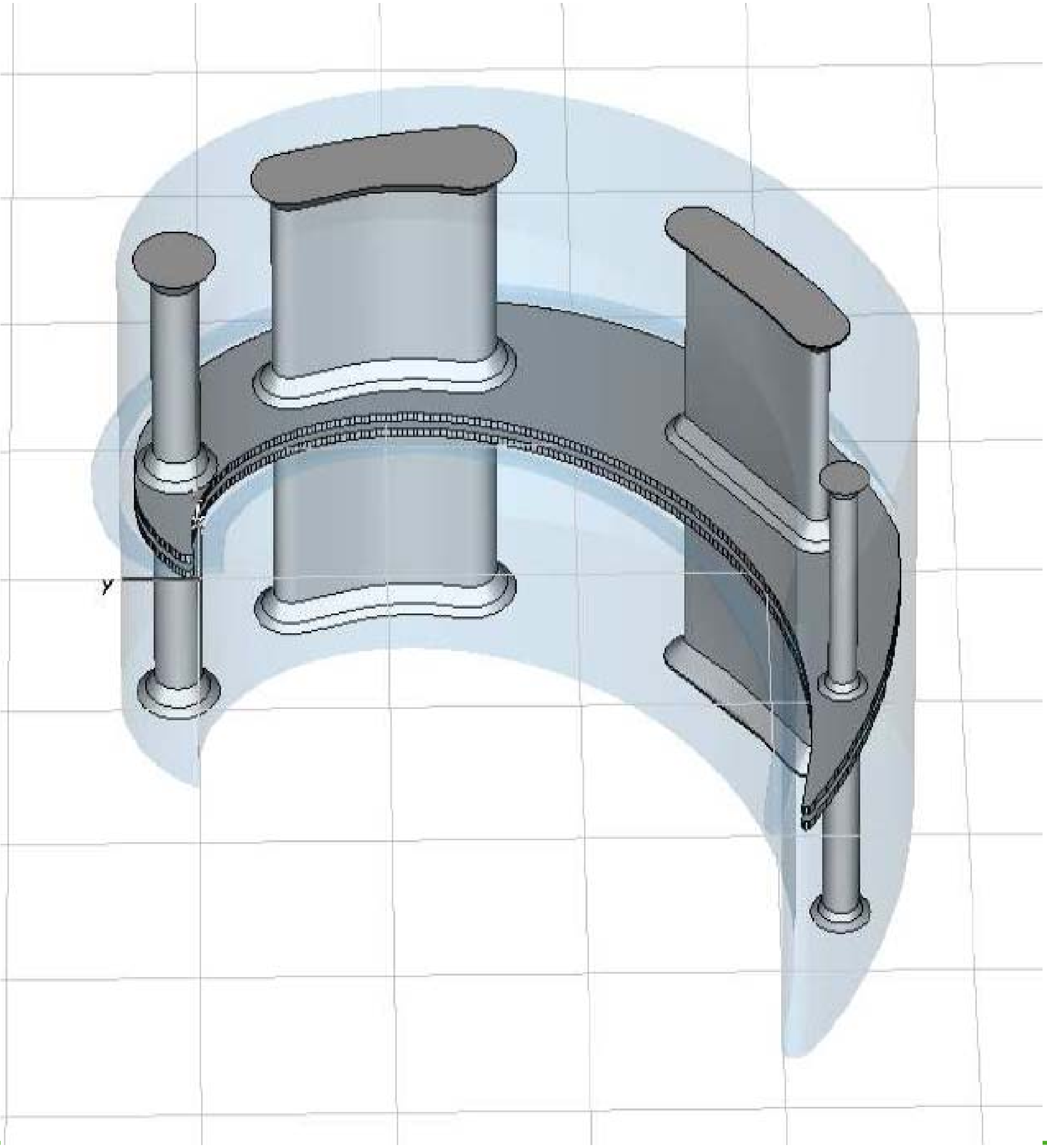
- **Fitting of the frequency of the cavity**

Geometry of the RF Cavity

Parameters of the cavity

Total height of the cavity	116cm.
Radial length of the cavity	186cm.
Dee height	2 cm;
Vertical aperture	2 cm.
Accelerating gap width in the center in the extraction radius.	 6 mm 80 mm;
The distance between the dee and the back side of the cavity	55mm
The distance between sector side and cavity	1.5 cm.

View of the cavity model



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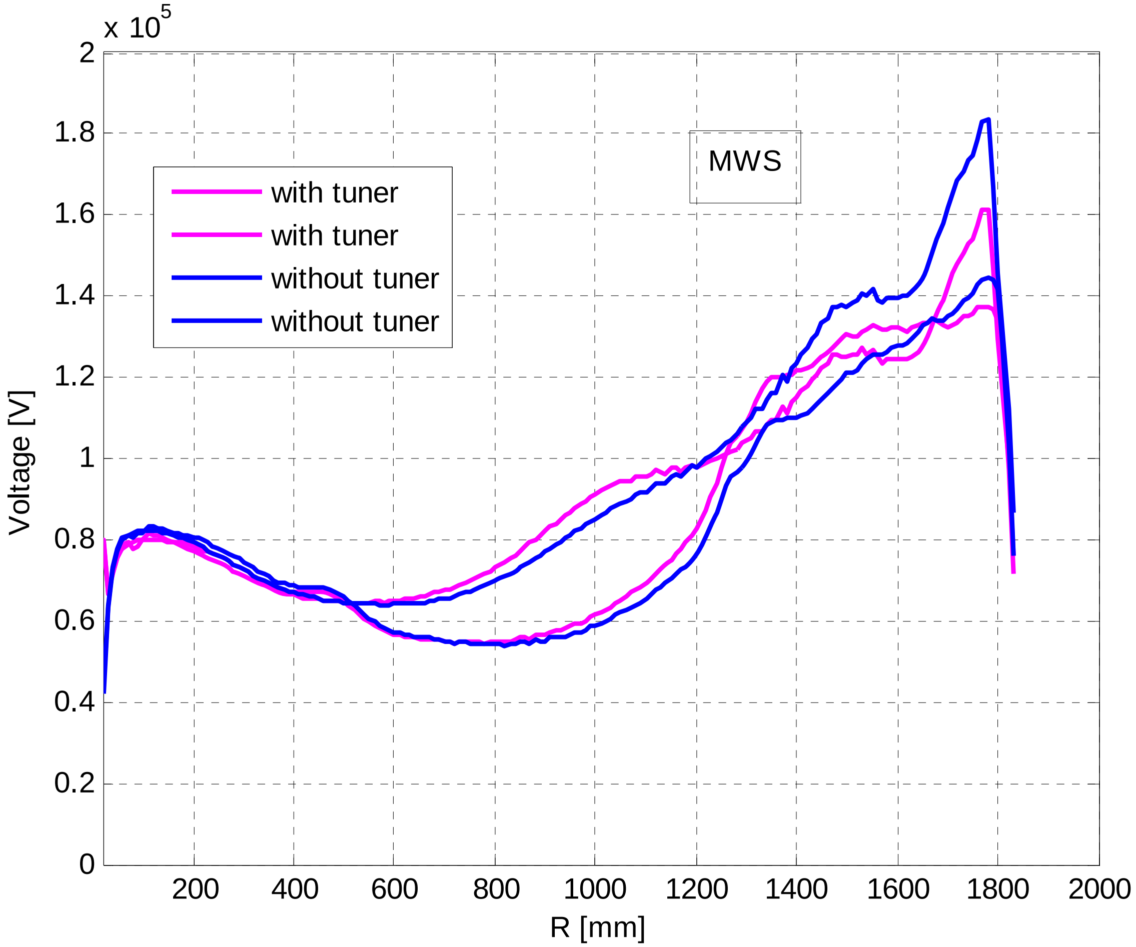
MWS simulations

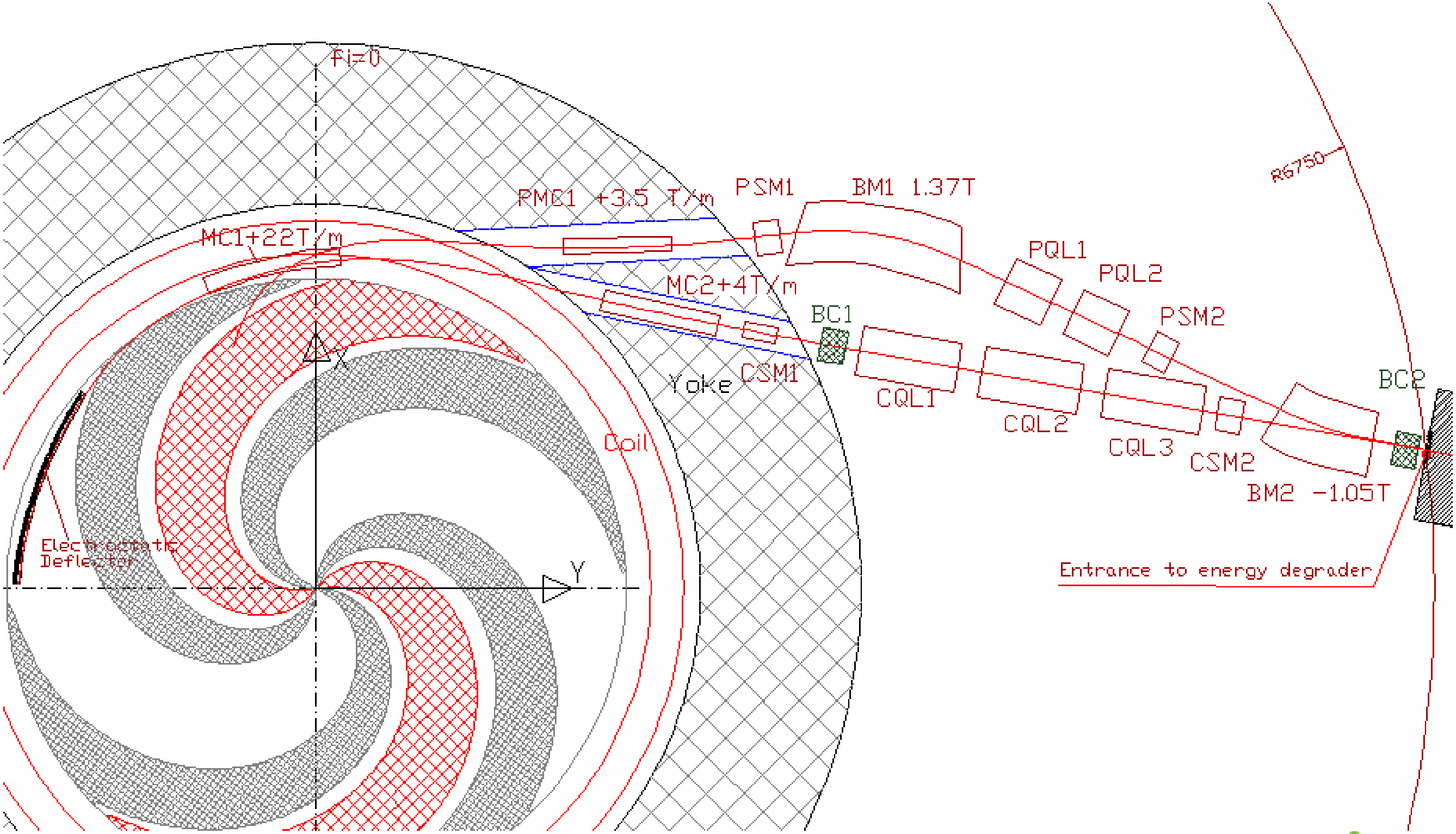


Voltage distribution along the gap in the models with and without tuners

Beam extraction

- All ions other than protons are extracted without resonance but with high efficiency using a classical ESD
- Thanks to the elliptic gap, the extraction is very fast: the beam is extracted in around 100° !
- The ESD is located in the valley, like in the present IBA PT cyclotrons. The field in the ESD is 150 kV/cm (180 kV/cm in IBA PT cyclotrons)
- After the ESD, the beam is refocused by 2 passive gradient correctors
- The protons are extracted by stripping around 265 MeV, (100% eff.) and do 2 turns in the cyclotron before exiting
- To exit the cyclotron, carbon ions and protons follow different paths. The trajectories recombine at the degrader

Beam extraction



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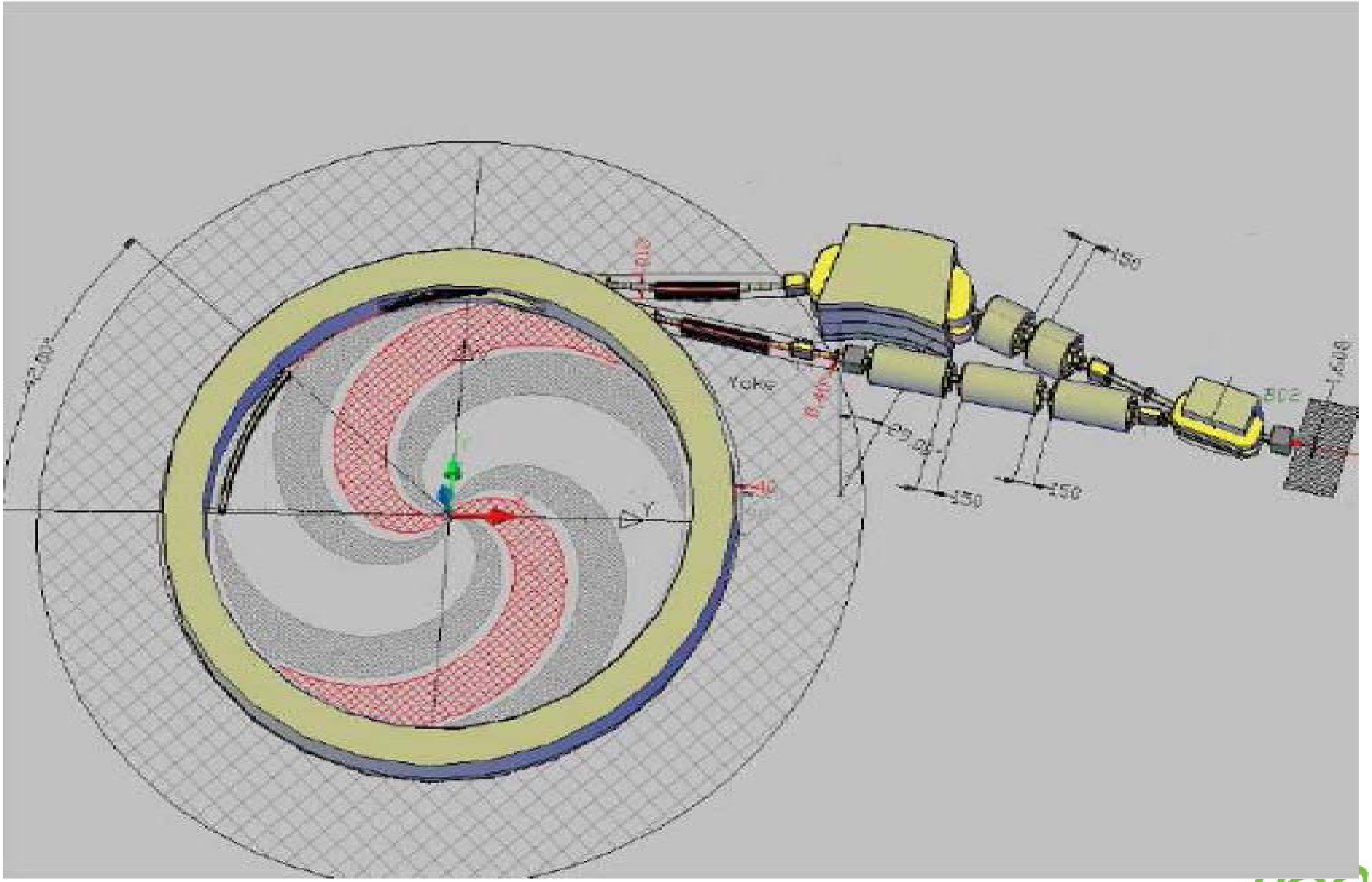
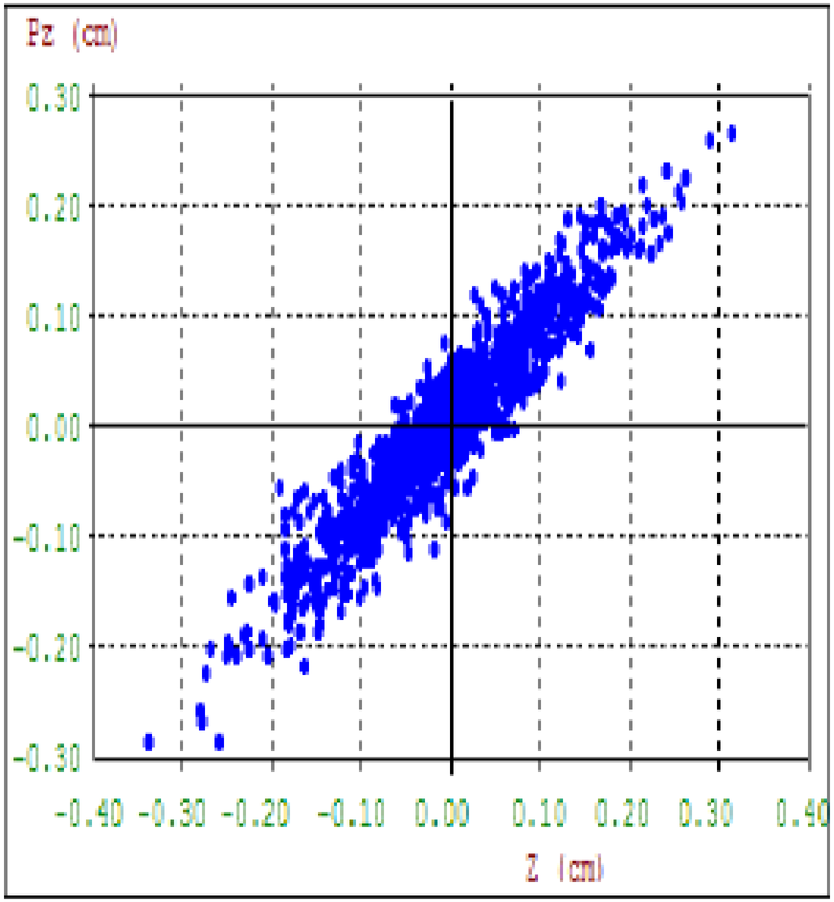
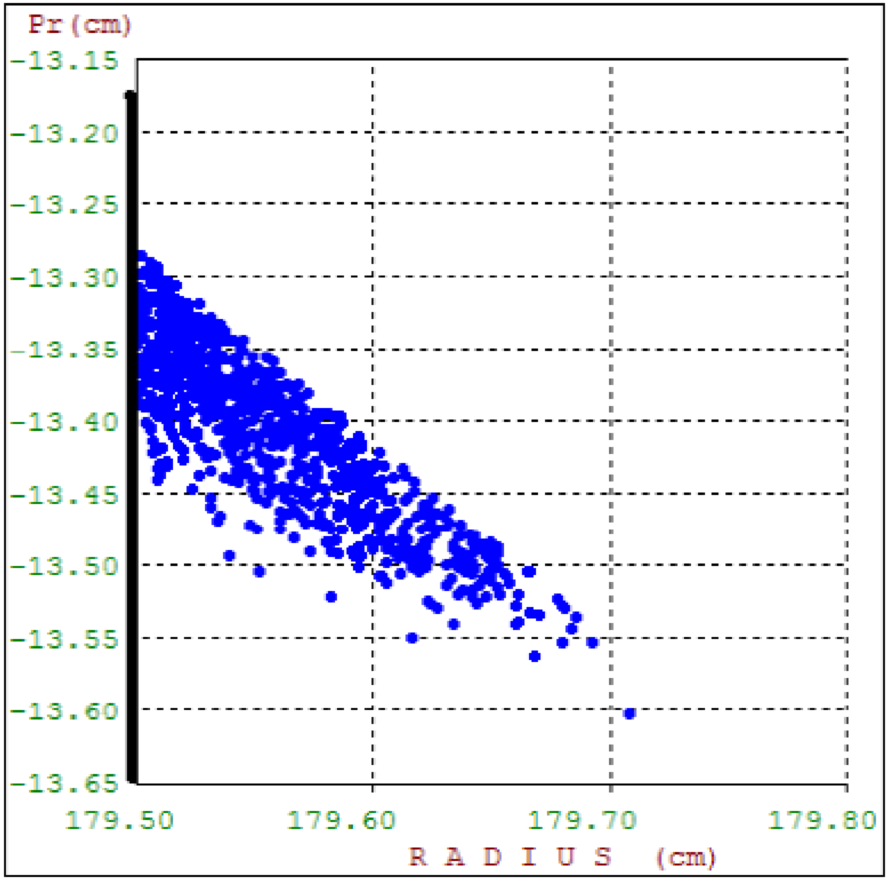
Proton & Carbon extraction elements



Extraction
Carbon beam

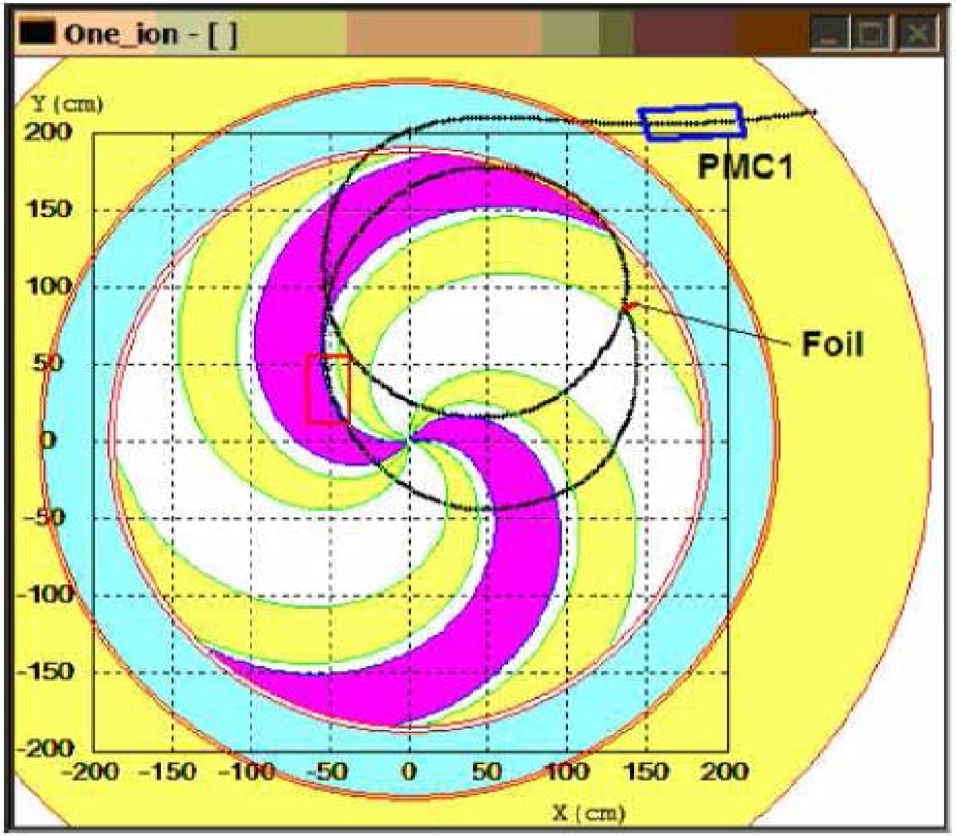
- It is possible to extract Carbon beam using **140-150 kV/cm** electric field strength inside the deflector
- Computed extraction efficiency is 84%





Extraction
Proton beam

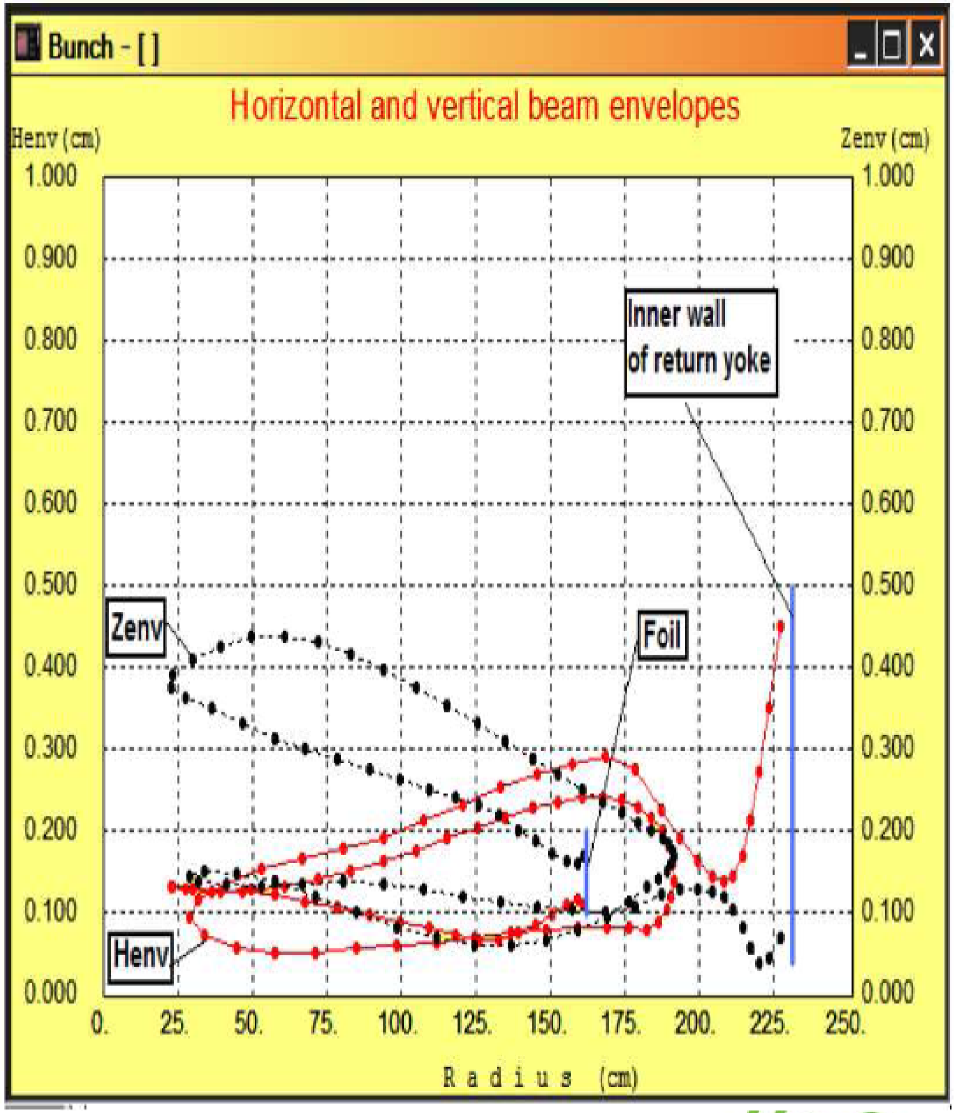
- 100% proton extraction by stripping at 265 MeV



Extraction line optics

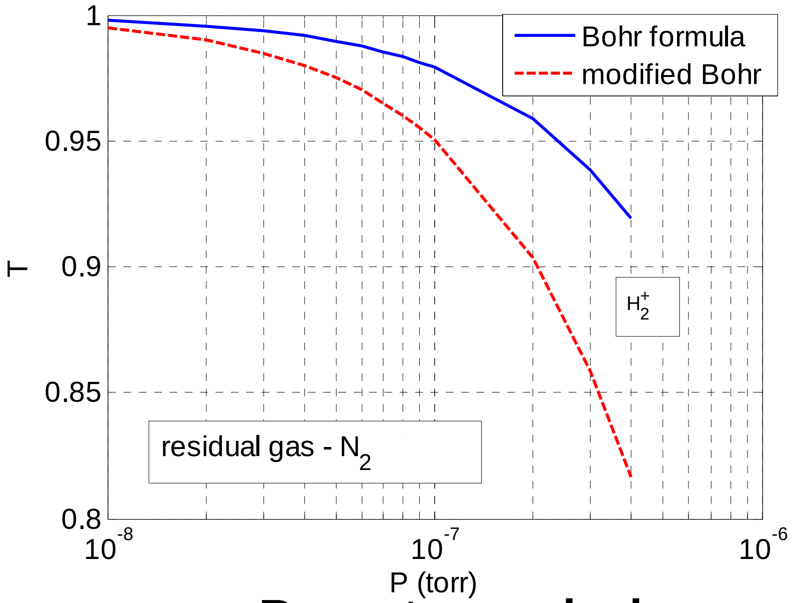
- **During these simulations an attempt was made to use partly the same extraction channel for both beams. The results showed that in this case it was impossible to provide acceptable beam spots before the degrader and the beams had also rather large transverse size (sometimes up to 6-8cm) during the 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.**

- **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 just before the energy degrader to provide the ~1-2mm beam spot at this point for both beams was taken into account.**



VACUUM REQUIREMENTS

- **The vacuum requirements in cyclotron are determined by H_2^+ ions.**
- **For pressure 10^{-7} torr losses estimated with “pessimistic” formula will be about 5 %, with “optimistic” Bohr formula – 2% (in nitrogen as a residual gas),**
- **For pressure $2*10^{-7}$ torr pessimistic estimation - 10 %, optimistic– 4%.**



Beam transmission

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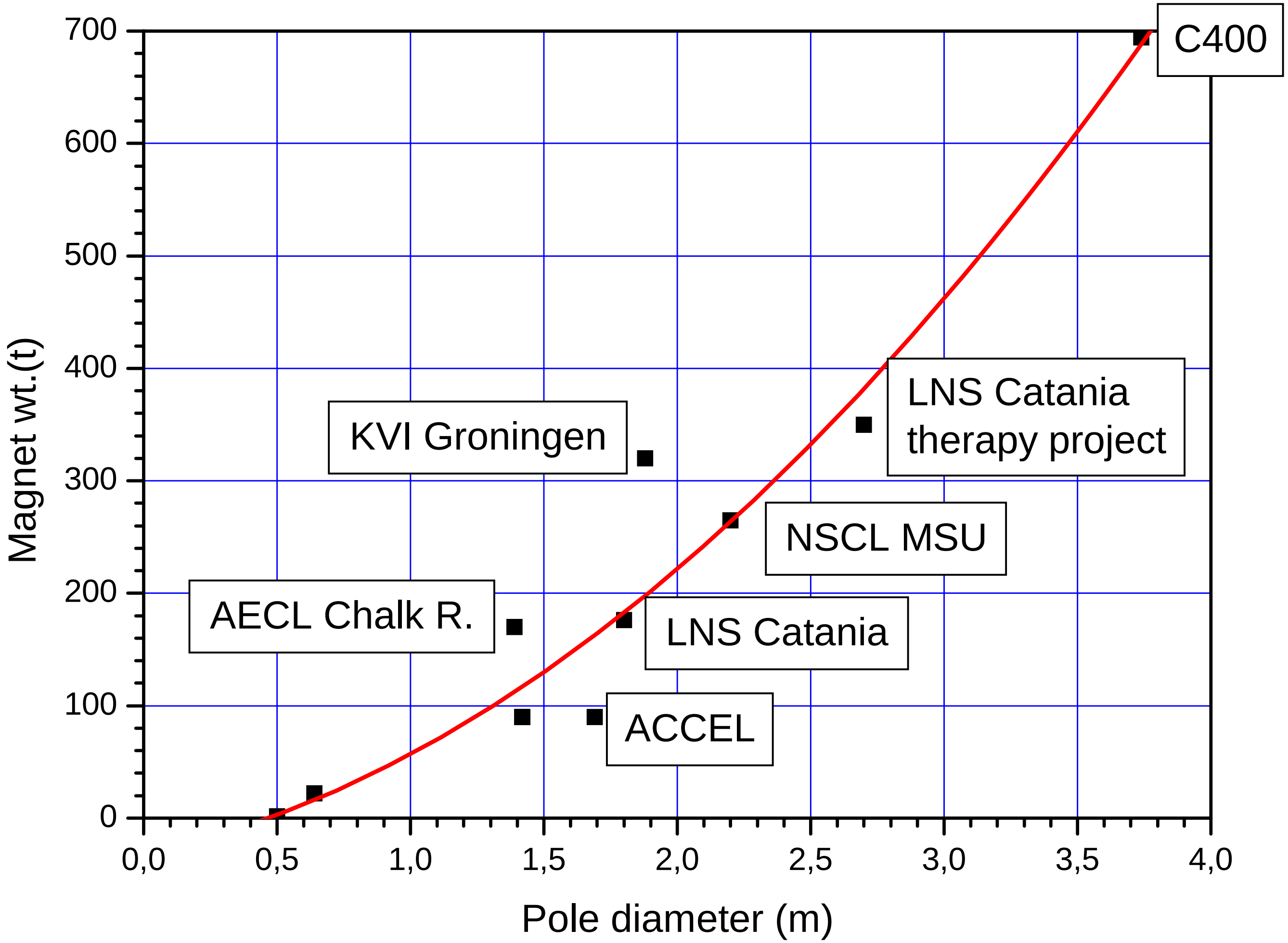
CONCLUSION

- **The detailed computer simulations of the beam dynamics and the main systems of C400 cyclotron have been performed. The results of the simulations show that the energy range up to 400 MeV/amu (K = 1600) can be achieved with the compact design similar to that of the existing IBA C235 cyclotron. The C400 cyclotron will also provide a proton therapy beam with energy 265 MeV.**

Status of the cyclotron

- On April 2009 a team of experts in superconducting cyclotrons from various countries has been provided a deep design review of the cyclotron
- The results of the review were completely positive, and no “show-stoppers” were found
- The design has now reached a stage where long lead items (steel, superconducting coils) can be ordered.
- Contracts for these are ready to be signed
- As soon as the agreement with Archade is finalized, IBA will start the construction of the prototype

Superconducting compact cyclotrons



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Thank you for your attention!