



Improvement of the JINR Phasotron and Design of Cyclotrons for Fundamental and Applied Research

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Report on the theme 03-2-1102-2016/2020

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- ▶ **Improvement of the JINR Phasotron and beam channels.**
 - ▶ Shakun N.G. Yakovenko S.L.
 - ▶ **Design and modernization of the cyclotrons for medical purpose.**
 - ▶ Karamysheva G.A.
 - ▶ **Research and development of the superconducting cyclotron for proton therapy for IPP CAS (Hefei, China).**
 - ▶ Shirkov G.D.
 - ▶ **Investigation of the high-current beam acceleration in cyclotrons.**
 - ▶ Vorozhtsov S.B.

Improvement of JINR Phasotron and the beam channels.

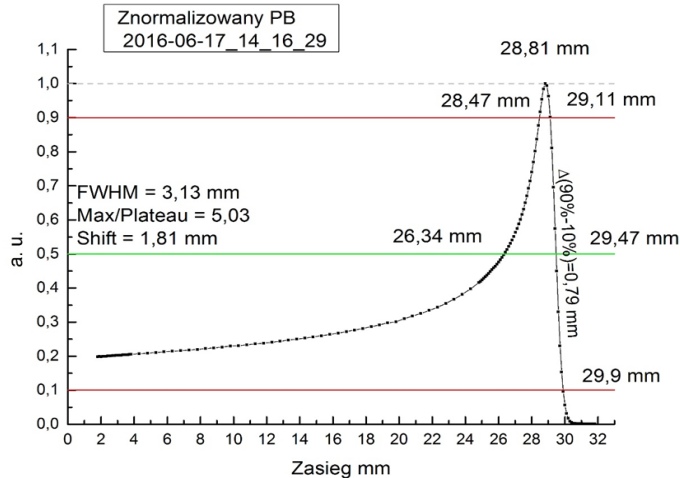
- Improving of the power supply system of the Phasotron and beam tracts was performed. Modern semiconductor converters feeding the magnetic systems instead of the motor generators have been put into operation;
- Automatic control system for the transport line has been implemented together with improvement of regulation and stabilizing system by replacing electronic equipment and new software development.
- All switching devices were replaced with modern ones in the power supply systems of the beam lines;

As a result of the modernization, the energy savings amounted to about 900 kW. In 2016-2019, Phasotron operated an average of 1000 hours per year. Of these, 80% were spent for medical research, for experiments PHASE, BURAN - 13% and 7% of the time for the needs of the accelerator. In 2020, the planned Phasotron operating time is 500 hours per year. Mostly for radiobiological research.

Cyclotron AIC-144 (INP PAS, Krakow, Poland)

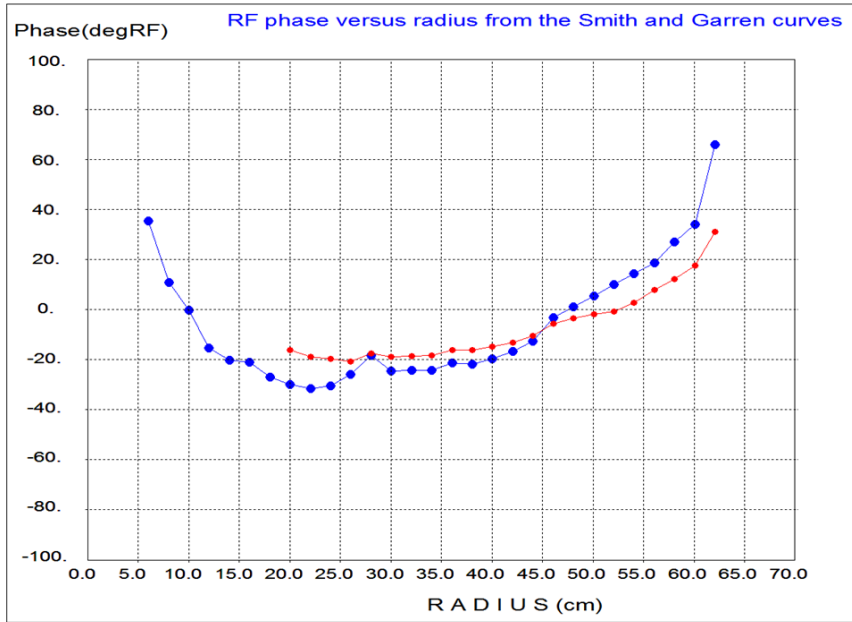


In the period from 2011 to 2016 proton therapy of eye melanoma was performed on the cyclotron AIC-144. Since 2016 the AIC-144 was used as backup cyclotron for the treatment of eye melanoma due to the commissioning of a new isochronous cyclotron C-235. Every two months the quality control of proton beam extracted from the AIC-144 cyclotron was performed regularly. In addition, the accelerator was used for production of radioisotopes.

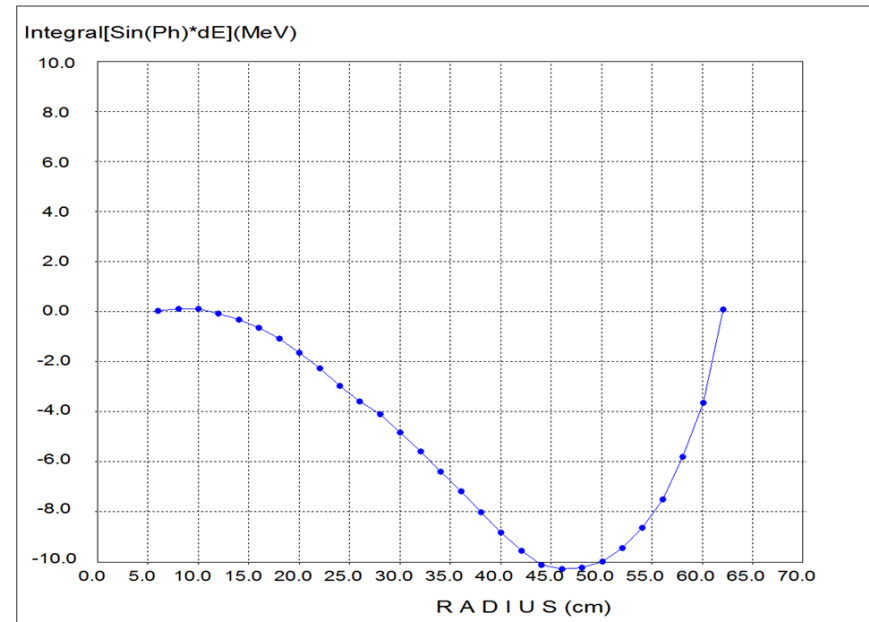


Beam tests

Based on automated control system of the AIC-144 cyclotron the Smith-Garren's curve measurements were carried out. The phase motion and the phase-energy integral were calculated.



The phase motion.

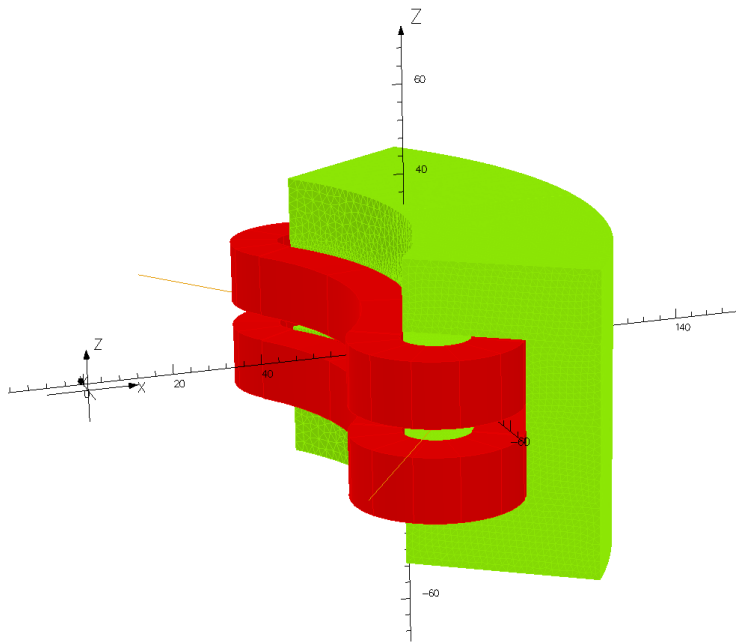


The phase-energy integral.

The acceleration and extraction of proton beam from the AIC-144 cyclotron were executed by use of a new current settings in the harmonic coils. The maximal stable value of the beam extraction coefficient $K_{\text{ext}}=35\%$ was achieved.

Development of the magnets for the beam transport line.

1/777/2012.13.38.28



The design documentation has been developed, the yoke has been produced and the galettes for two half-windings of the M1 turning magnet, designed to work in the beam transportation line of the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland), have been reeled up on the LNP machine.

A general view of the proposed design of the magnet

The yoke of the M1 turning magnet.



The galettes.



Two tetrodes (GU92A – Russian production) for RF generator of the AIC-144 cyclotron have been purchased. (Contract of delivery No 1003/397-200/1680).



C235 V3 cyclotron (IBA, Belgium)

Today, the hospital center of radiation medicine is founded in Dimitrovgrad for practical application of advanced radiation therapy methods. The C235 V3 cyclotron is manufactured in Belgium and improved by specialists from the JINR. The cyclotron was mounted, its magnetic field was properly configured, acceleration conditions were optimized, and beam extraction tests were carried out in JINR after which it was supplied to Dimitrovgrad.

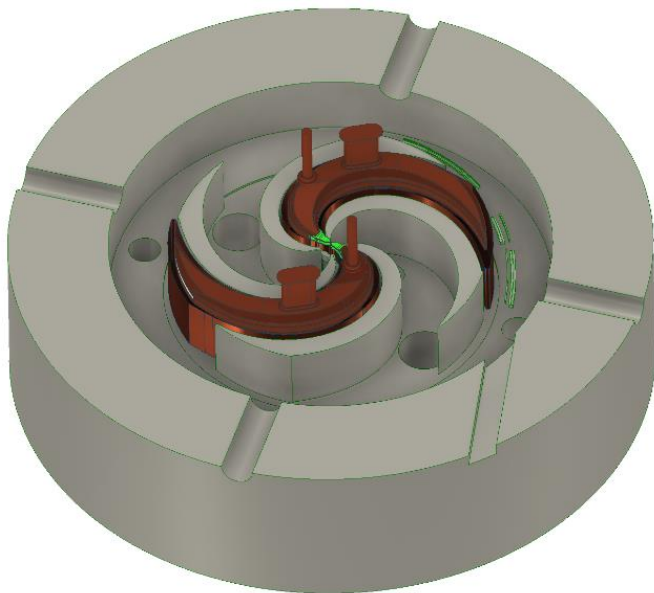


Research and development of the superconducting cyclotron for proton therapy for IPP CAS (Hefei, China).

Main cyclotron SC200 characteristics:

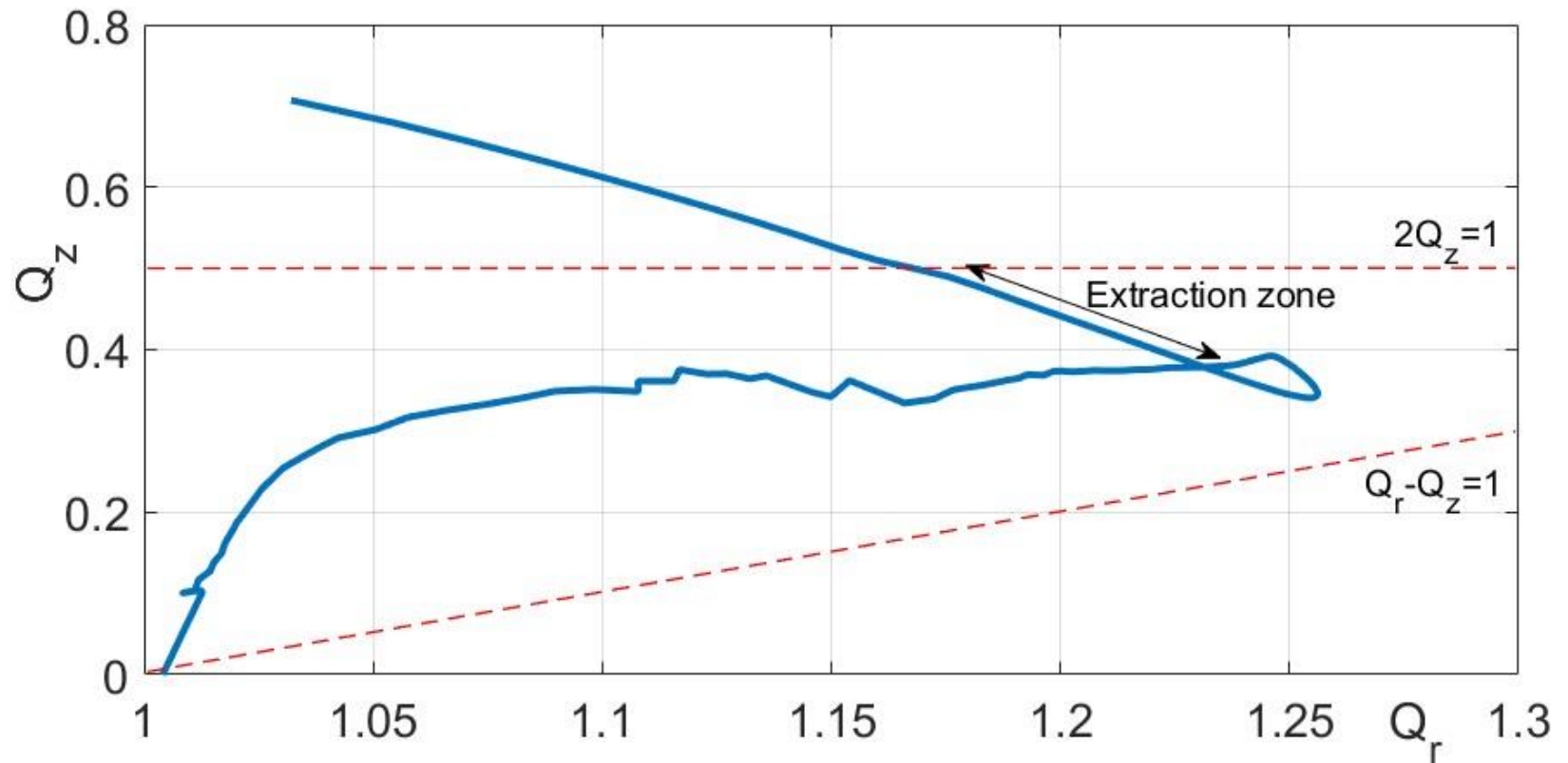
- Compact design
- Fixed energy, fixed field and fixed RF frequency
- Bending limit $W=200$ MeV
- Accelerated particles: protons
- Superconducting coils enclosed in cryostat, all other parts are warm
- Injection by PIG ion source
- Extraction with an electrostatic deflector and passive magnetic channels

SC200 cyclotron parameters

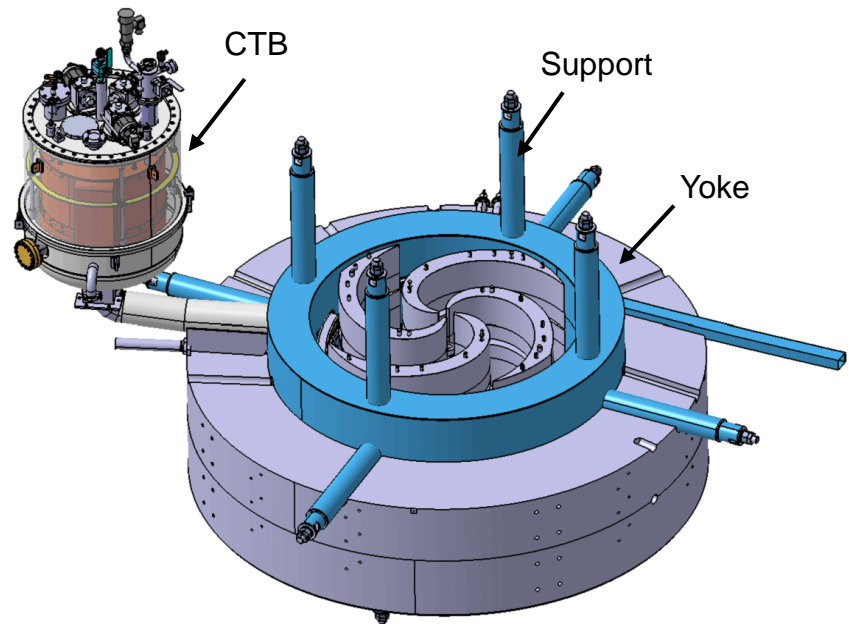


Mass	55 Tonn
RF Freq	91.5 MHz
Coil current	720 kA
Ion source	PIG
Sector azimuthal length	20-35 deg
Vertical gap between sectors	38->9 mm Decreasing to extraction. Not elliptical!
Valley depth	250mm

Working diagram

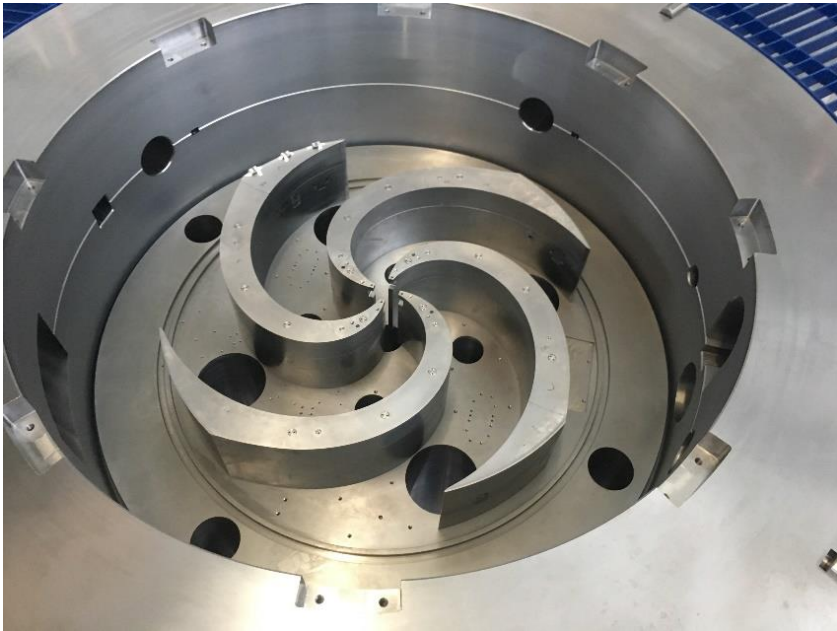


SC200 cyclotron manufacture



Magnet

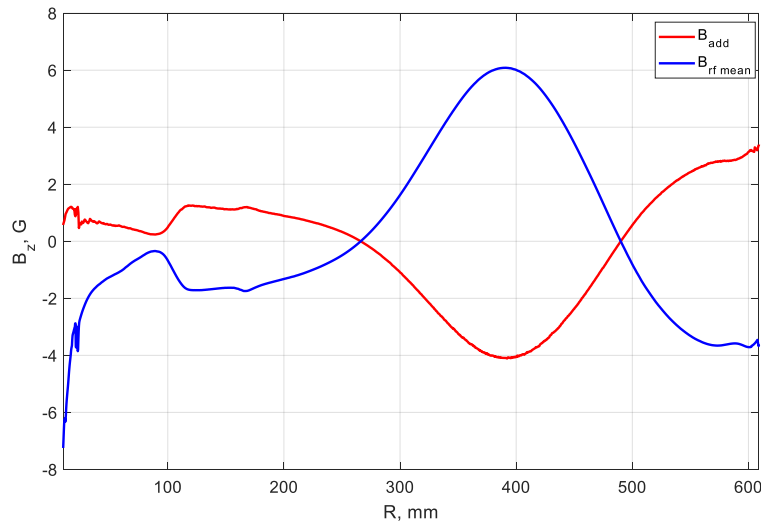
Accelerating Cavity



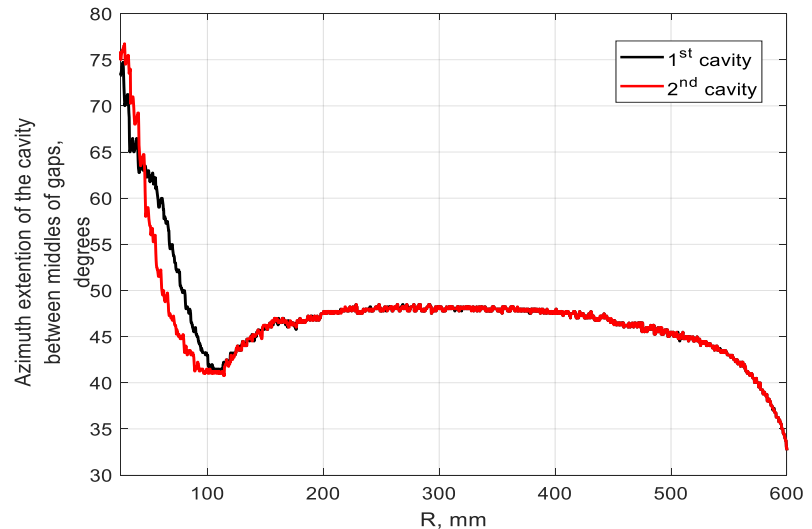
About compensation of the action of the magnetic field B_{RF} of the accelerating system

$$B_{add} = -B_{rf\,mean} * \cos(\theta_{cav})$$

θ_{cav} - azimuthal extension between the maximums of the accelerating field distribution

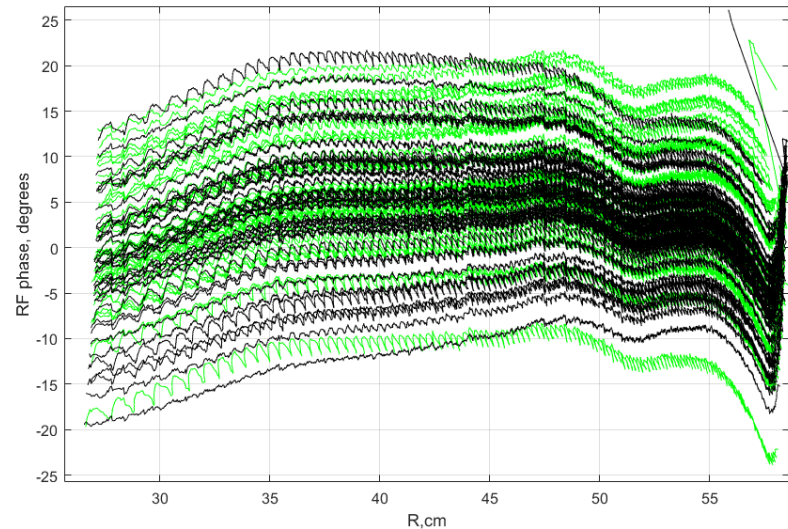
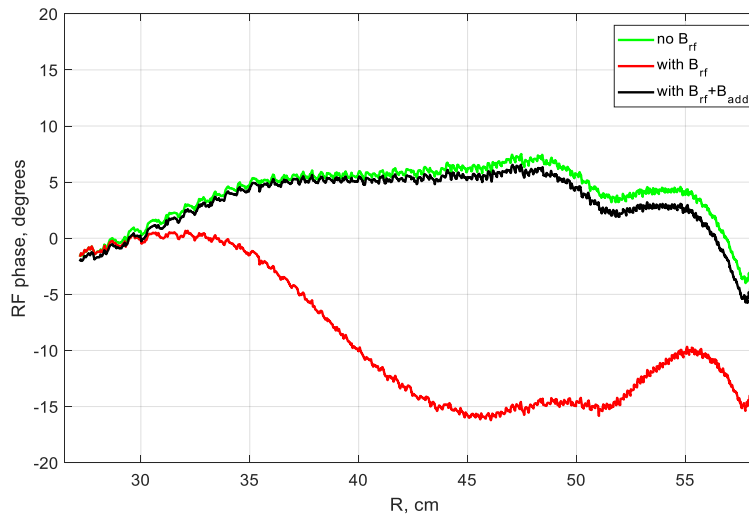


Mean value of B_{RF} field (blue line) and additional field (red line) versus radius. Isochronous field should be increased at $R=40$ cm by 4 G and decrease at $R=60$ cm by 3 G according to red curve for the designed voltage 70 kV at $R=70$ mm.



Azimuthal extension between the maximums of the field distribution

Phase motion with B_{RF} compensation

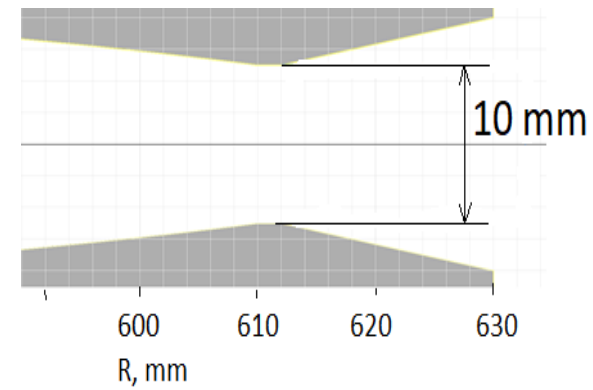
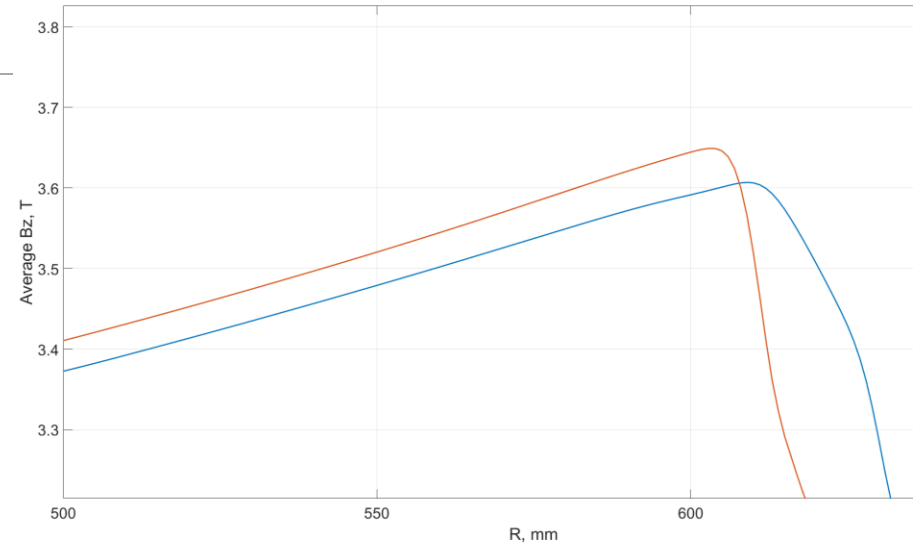
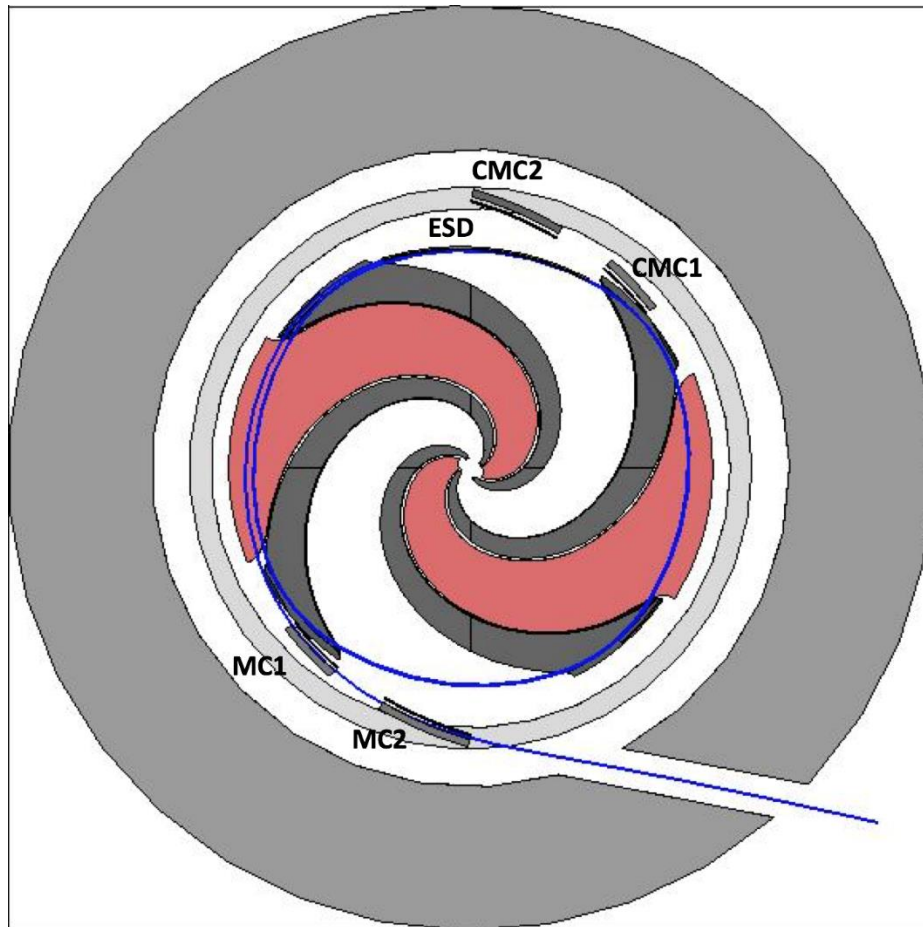


Phase motion of the central particle neglecting B_{RF} (green line) taking into account RF magnetic field (red line) and with B_{RF} + compensation (black line)

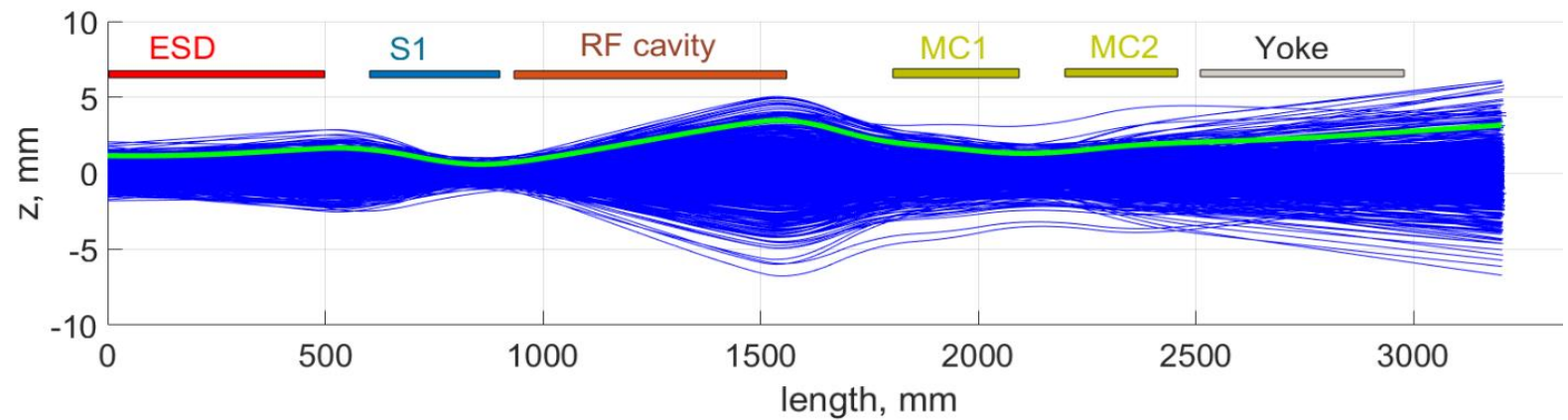
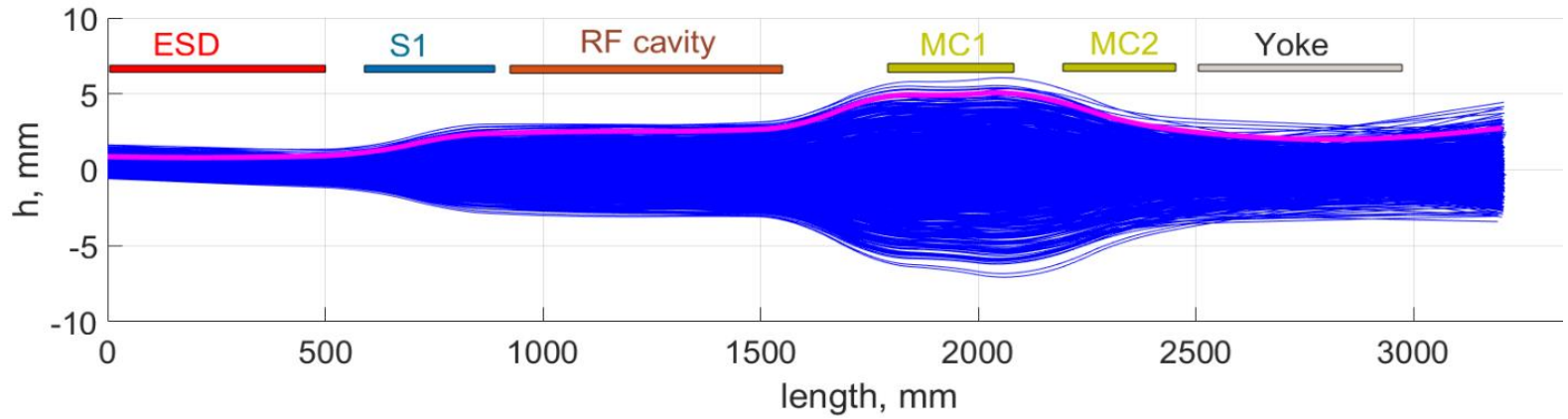
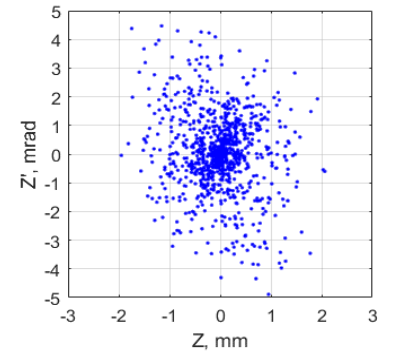
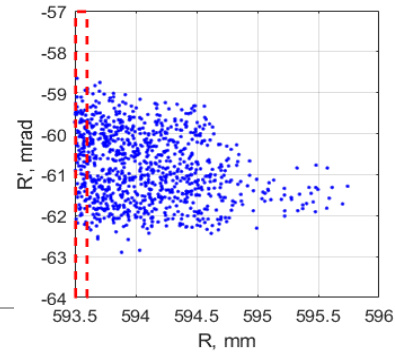
One can observe phase compression effect (it is positive).

Extraction scheme

Magnetic field in the extraction zone.



Beam tracking



SC200 Conclusion

Design of the cyclotron was finished.

We obtain proper model of magnet.

We obtain proper model of plug dimensions and dee tips geometry in the center.

We test accelerating field distribution.

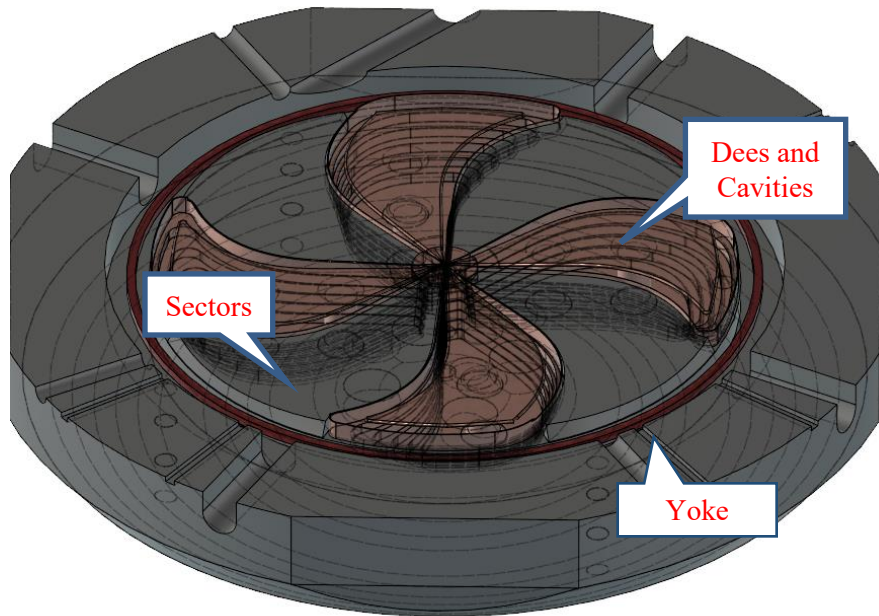
Beam dynamics shows sufficient quality of the center region and in acceleration zone.

No resonances were observed in the whole accelerating region in beam dynamics simulations.

We can extract beam with accuracy upto 70 %.

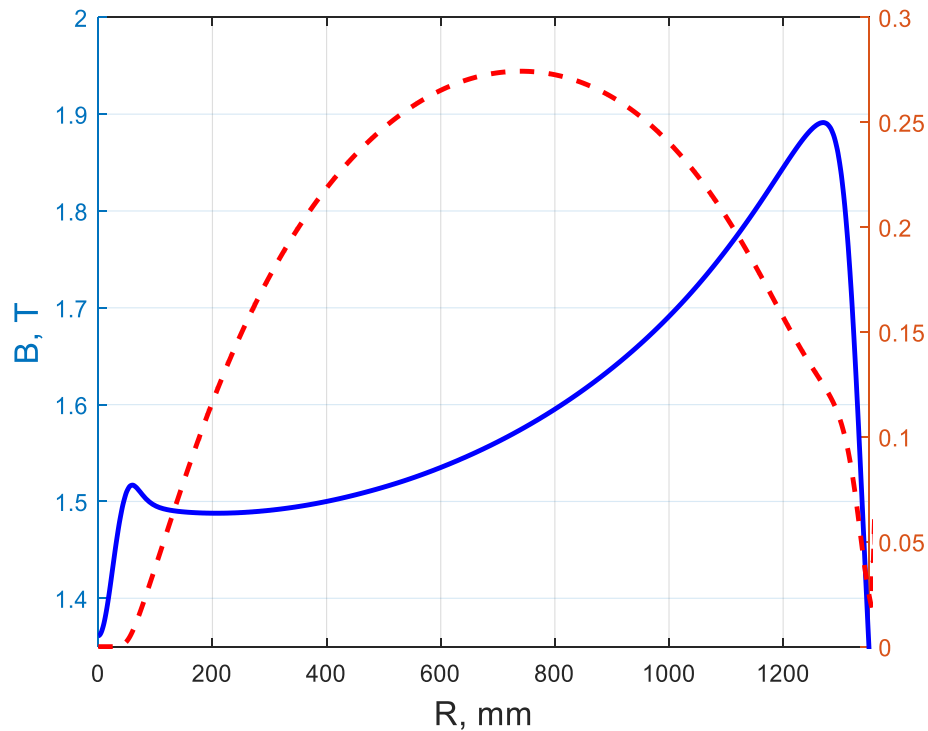
Cyclotron is manufactured. Assembling, shimming and starting up works are under way.

SC-230 superconducting cyclotron

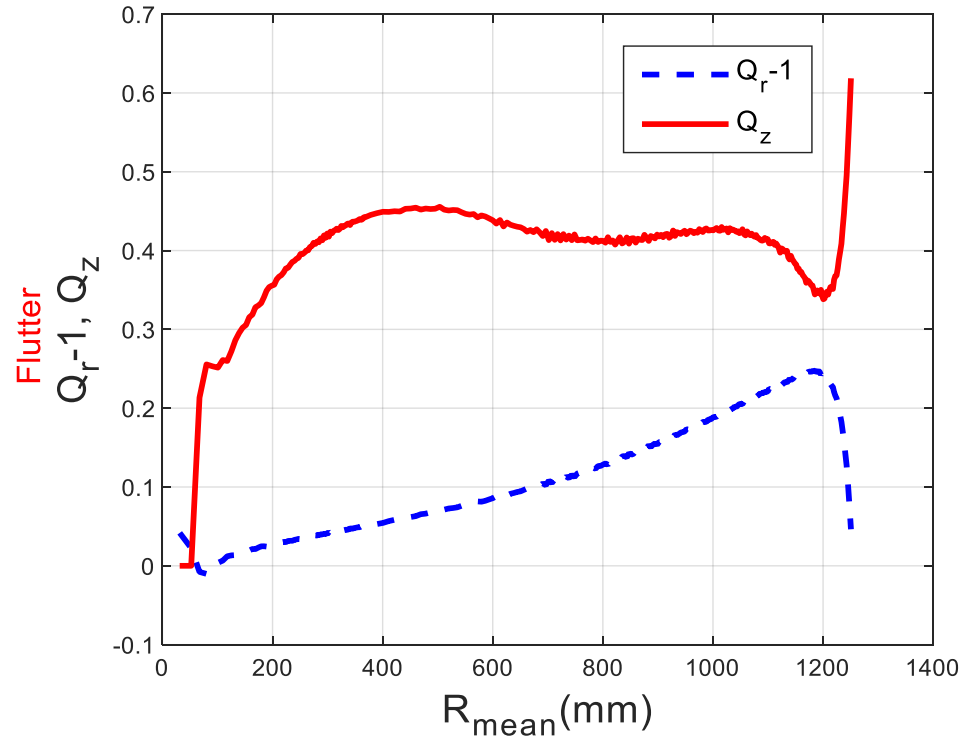


Magnet type	SC coil, warm yoke
Ion source	PIG
Final energy, MeV	230
Pole radius, mm	1350
Mean magn. field (center), T	1.5
Dimensions (height×diameter), m	1.7 × 4
Weight, tonnes	130
Hill/Valley gap, mm	50/700
A*Turn number	170 000
RF frequency, MHz	91.5
Harmonic number	4
Number of RF cavities	4
Voltage, center/extraction kV	35/90
RF power, kW	40
Number of turns	600
Beam intensity, μA	1.0
Extraction type	ESD

Computer simulations of the magnet

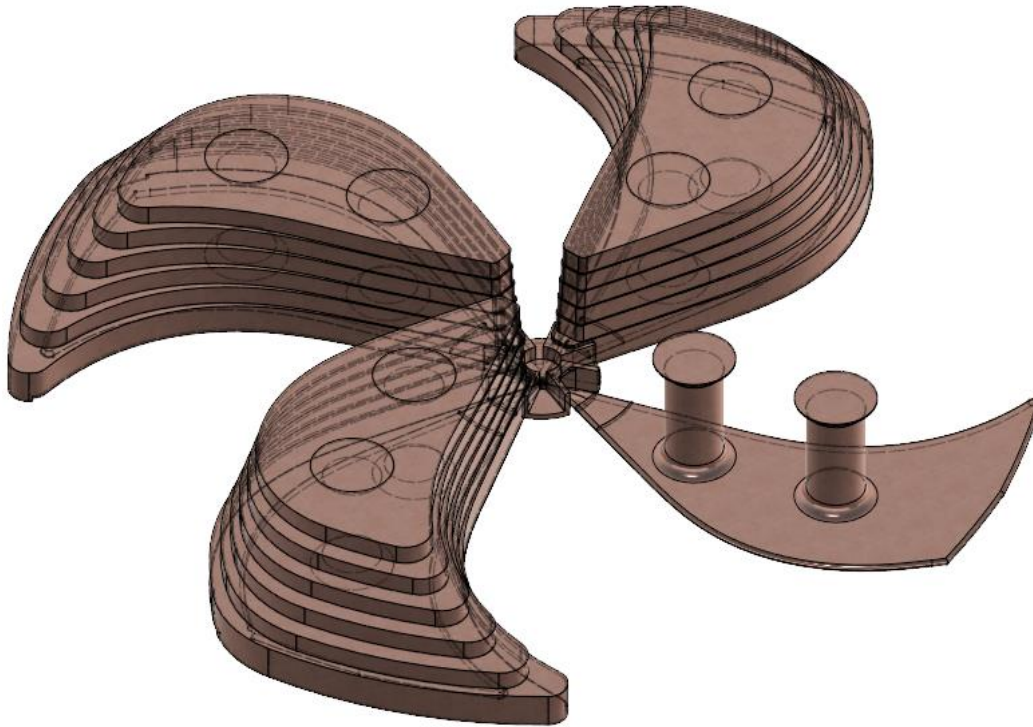


Average magnetic field and flutter along the radius.

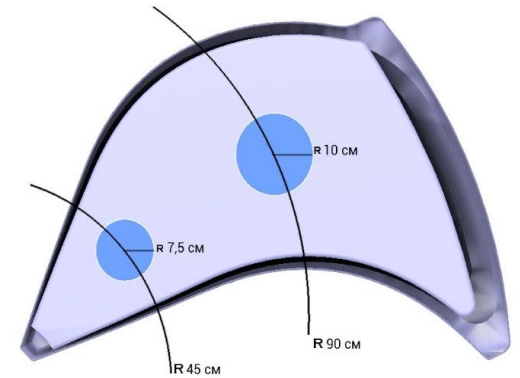


Vertical and radial betatron tunes in SC230.

Accelerating system design

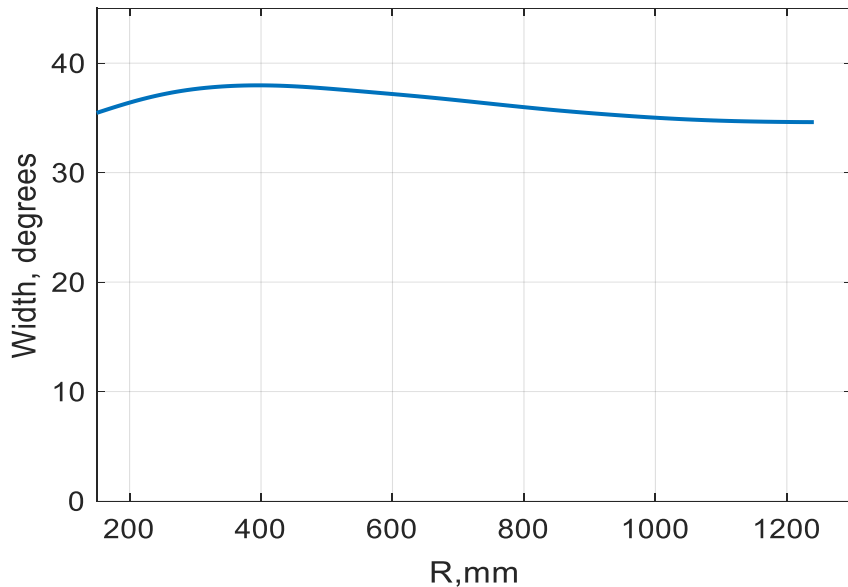


Overview of 3D model of RF system.

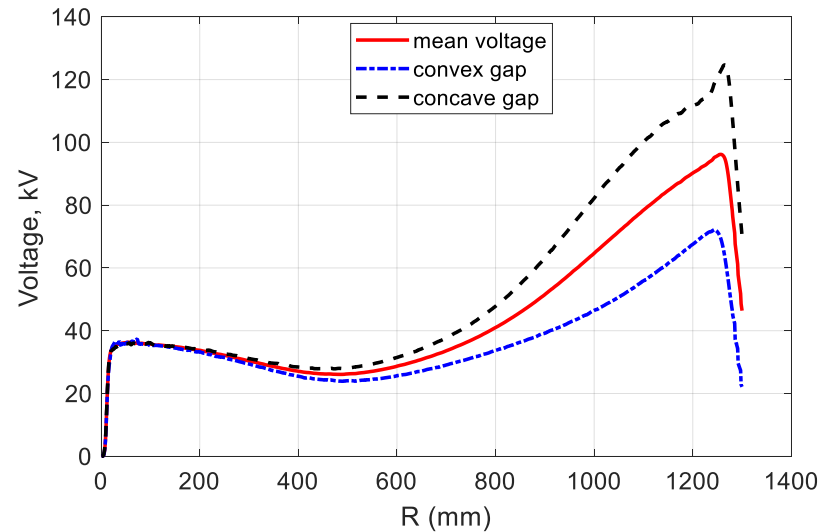


View of the model of the cavity.

Accelerating cavity simulation



Azimuthal extension of the cavity



Accelerating voltage along radius.

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8 \cdot 10^7$ 1/(Ωm). The quality factor was about 13800 and power losses of all cavities were: for storage energy 1 joule voltage in the center/extraction 35-95 kV, thermal losses are 43 kW.

Extraction from this cyclotron will be performed by electrostatic deflector. The height of the deflector is 50 mm, which makes it possible to place it in an axial gap between the sectors. The ESD voltage, required for extraction is just 100 kV/cm.

As a result, we have a design of cyclotron with:

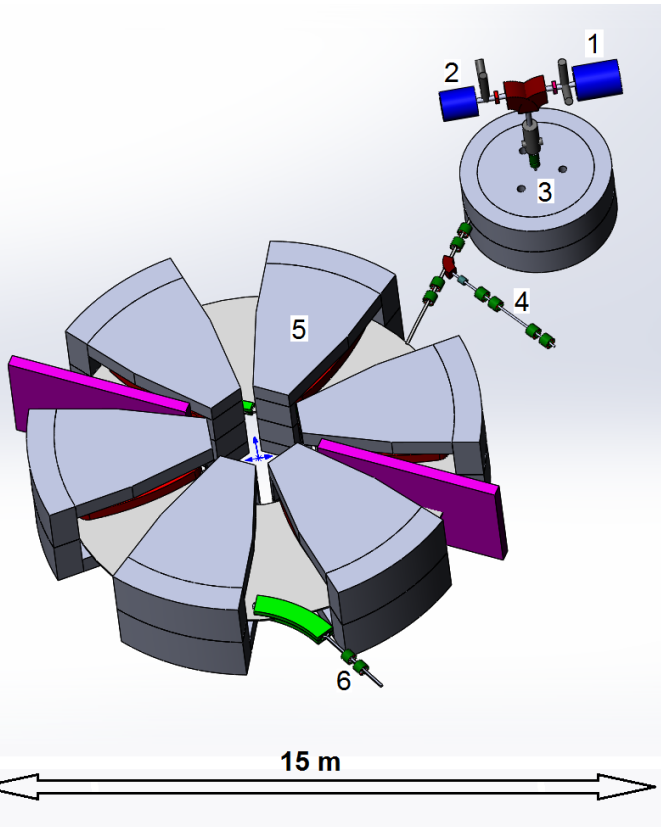
- Low power consumption.
- High quality of the beam.
- Minimum engineering efforts and challenges.
- Reasonable size and weight.

SC-230. Conclusion

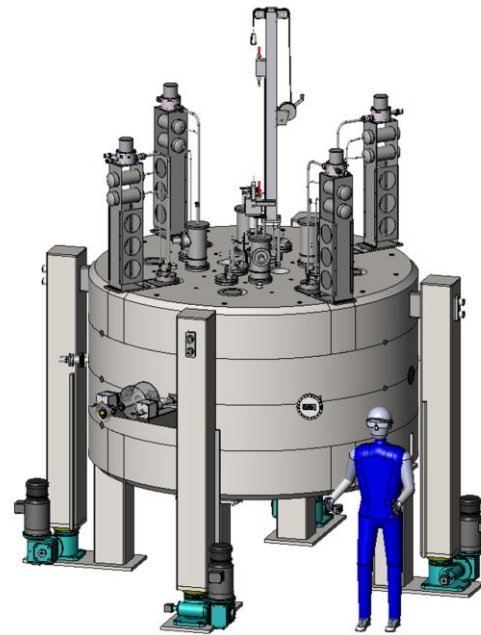
Project has conservative and well-established solutions. The use of innovative solutions, such as the non-circular shape of the coils, leads to a cyclotron for proton therapy with a weight comparable to the VARIAN superconducting cyclotron, while cheaper and more energy-efficient due to the low energy consumption of the accelerating system and superconducting winding. The low power consumption of the SC coils makes it possible to use high-temperature superconductors (HTSC).

Development of the cyclotron method for high-current beam acceleration

JINR 400 MeV/u Cyclotron Complex for Carbon Therapy

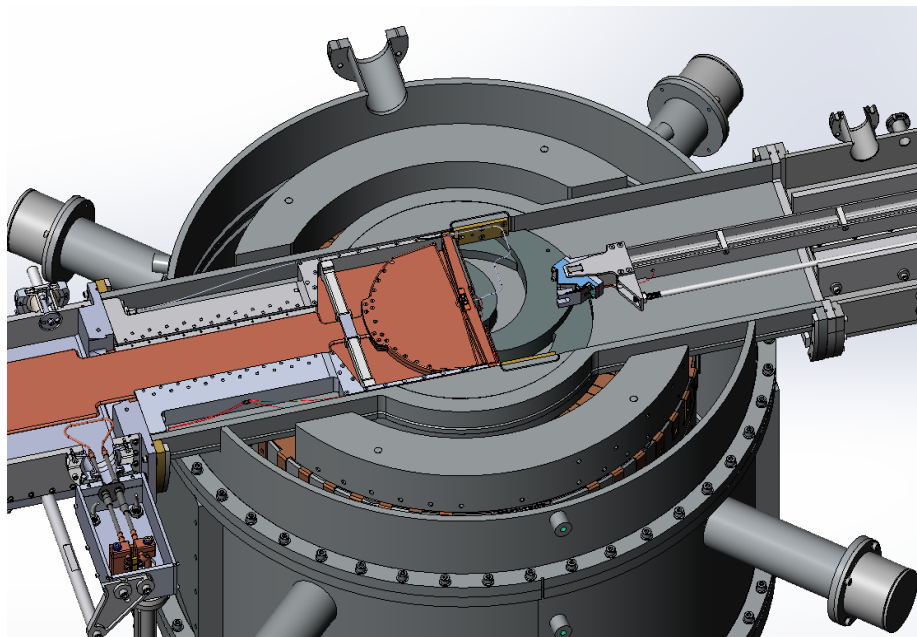


Pronova K230 superconducting cyclotron for proton therapy

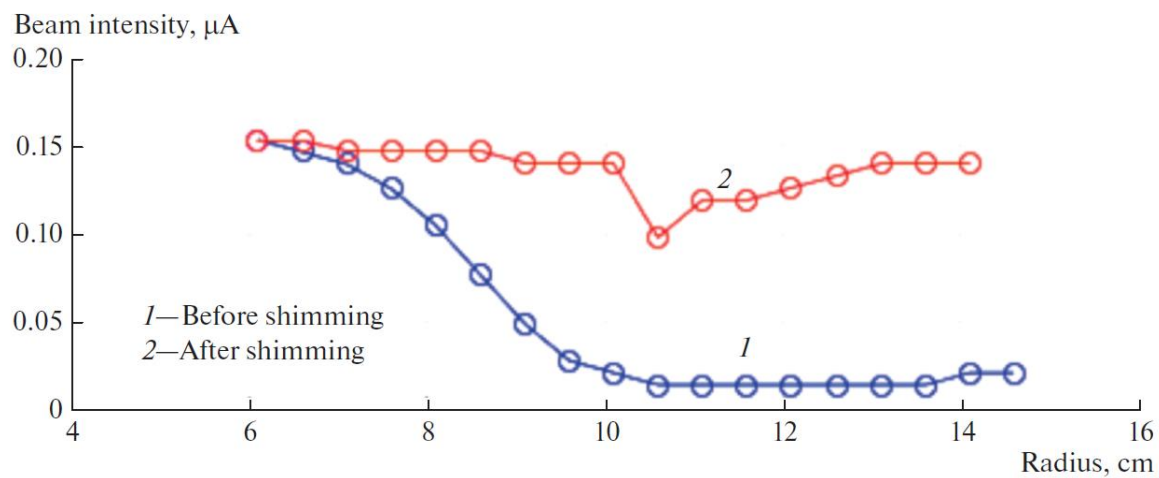


Ionetix ION-12SC The world's smallest superconducting cyclotron for isotope production!



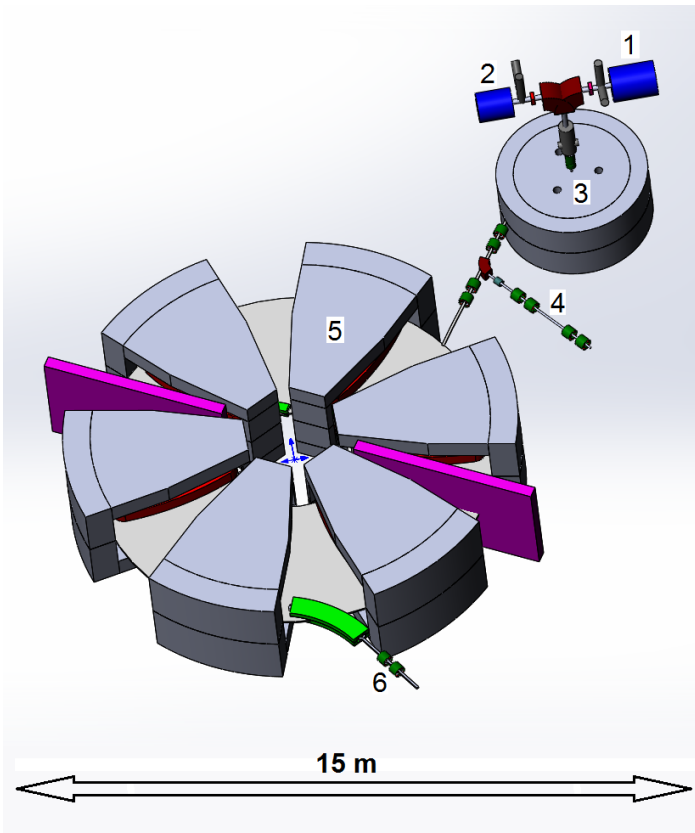


Ionetix ION-12SC cyclotron



Beam intensity
before and after shimming

A Cyclotron Complex for Carbon Ions Acceleration



Acceleration complex including the cyclotron-injector and the booster:
1 – $^{12}\text{C}^{6+}$ ECR, 2 – H_2^+ ECR, 3 – cyclotron-injector, 4 – medium energy beam transport line (proton and carbon 70 MeV/u), 5 – main cyclotron, 6 – heavy energy beam transport line (carbon 400 MeV/u)

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Karamysheva T.V., Kiyani I.N., Lepkina O.E., Lomakina O.V., Liapin I.,
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V.M.,Vorozhtsov S.B., Vorozhtsov A.S., Smirnov V.L., , Shakun N.G.,
Shirkov G.D., Shirkov S.G., Yakovenko S.L.

For 2016-2020 about 25 articles in refereed journals were published. More than 50 reports at international and Russian scientific conferences and meetings were made. One patent for invention No. 2702140 was issued.

Thank you for your attention