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

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G.A. Karamysheva

June 2018

Report on the theme 03-2-1102-2016/2018

- **Improvement of the JINR Phasotron and beam channels.**
- **Design and modernization of the cyclotrons for medical purpose.**
- **Research and development of the superconducting cyclotron for proton therapy for IPP CAS (Hefei, China).**
- **Investigation of the high-current beam acceleration in cyclotrons.**

Improvement of JINR Phasotron and the beam channels.

The main task of the topic 1102 is maintenance of the Phasotron and modernization of the accelerator and beam tracts. During the period from 2015 to 2018 the following works on the modernization of the Phasotron and beam tracts were performed:

- Automatic control system for the transport line has been implemented (ACS TL) together with improvement of regulation and stabilizing system by replacing electronic equipment and new software development.
- Improving of the power supply system of the Phasotron and beam tracts was continued. Modern semiconductor converters based on the SVAROG ARS -400, 630 feeding the magnetic system of the VIII tract instead of the motor generators (reducing the power consumption of about 200 kW) have been developed and put into operation;
- Modernization of the correcting system of the median surface position of the proton beam accelerated inside Phasotron has been carried out.
- The accelerating system (duant) of the accelerator was modernized.

Currently, Phasotron operates an average of 1000 hours per year. Of these, 80% are spent for medical research, for experiments PHASE, BURAN - 13% and 7% of the time for the needs of the accelerator.

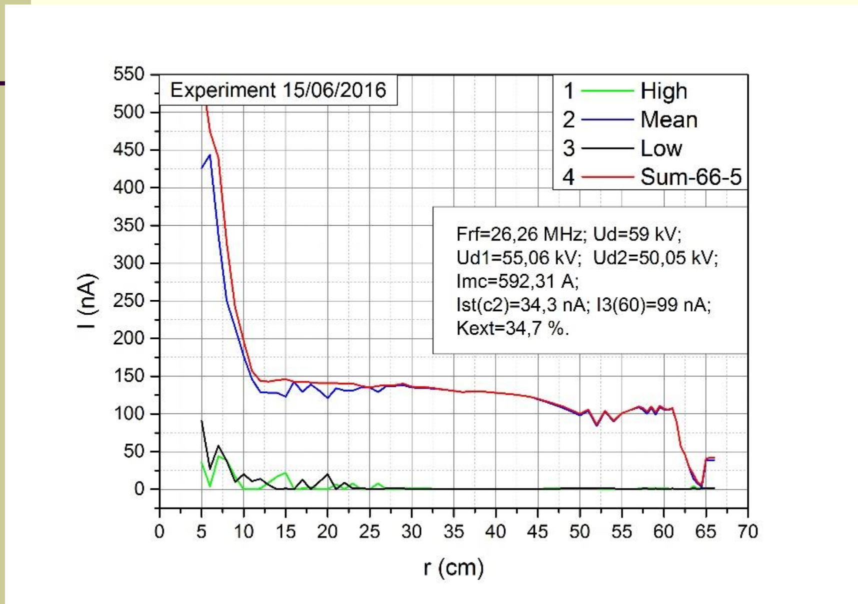
C235 V3 cyclotron (IBA, Belgium)

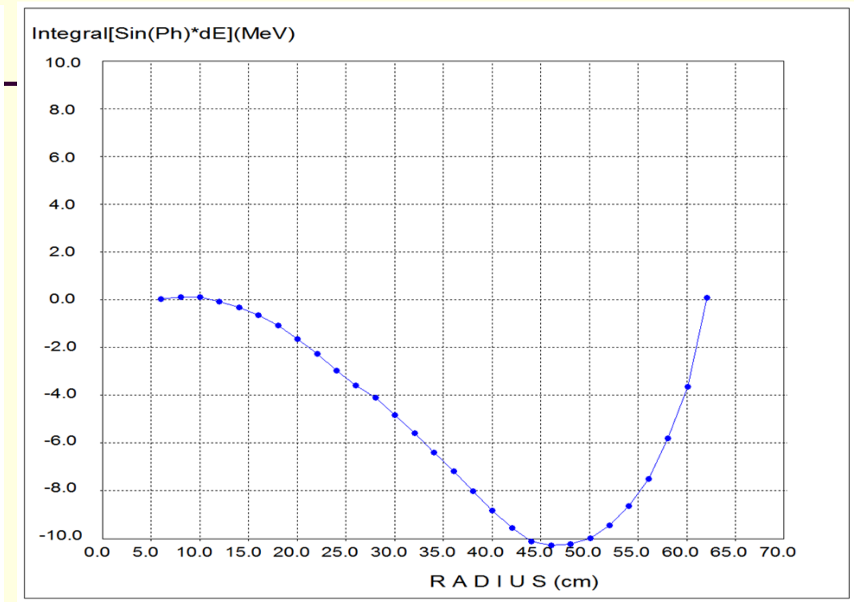
Today, the first hospital center of radiation medicine is being founded in Dimitrovgrad (Russia) under the guidance of the Federal Medical and Biological Agency for practical application of advanced radiation therapy methods in domestic medical radiology. The C235 V3 cyclotron outperforms IBA's medical cyclotrons installed in leading oncologic clinics worldwide. This refers primarily to the efficiency of acceleration and proton extraction.

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

In the period from 2011 to 2016 proton therapy of eye melanoma was performed on the multipurpose isochronous cyclotron AIC–144.
In total, 128 patients were successfully treated during this period.

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



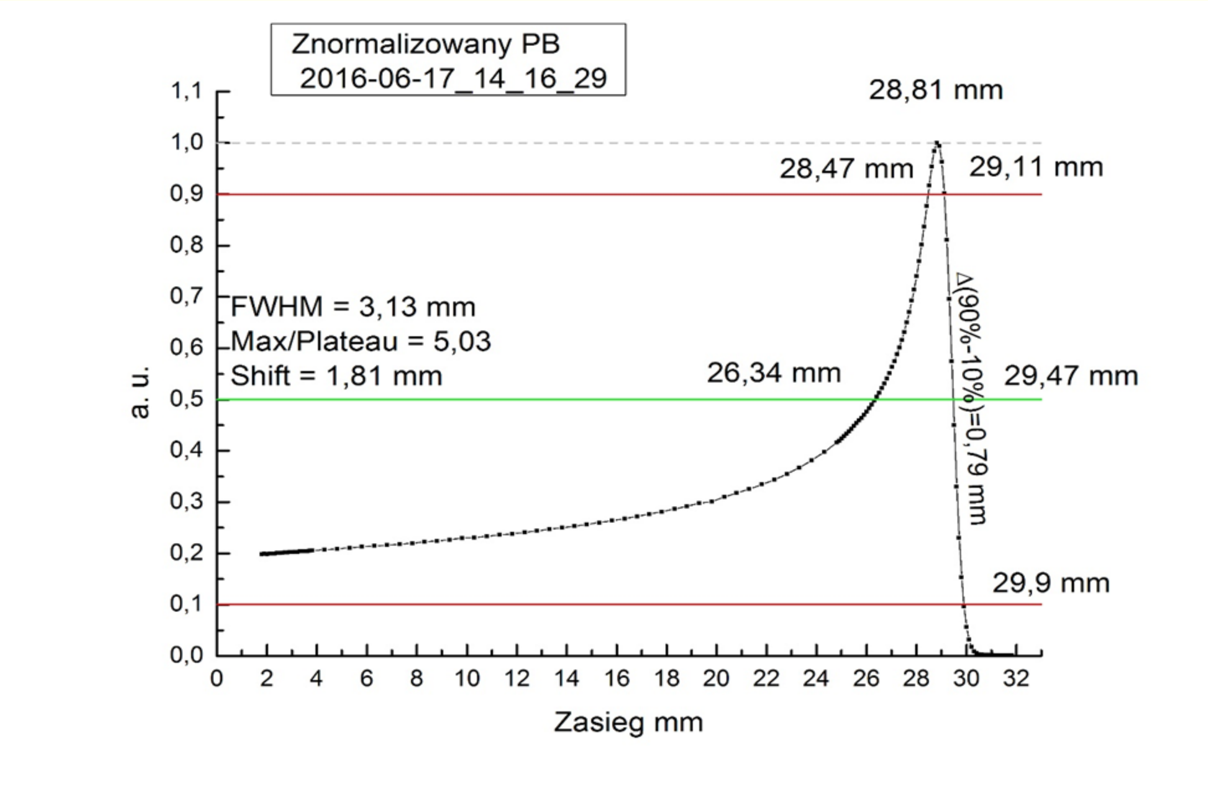


The measured current of proton beam.

The phase–energy integral.

The beam dynamics was calculated and the settings of harmonic coil currents were optimized for the AIC–144 cyclotron. The median plane of the magnetic field was levelled for the main operation mode of the AIC–144 cyclotron (p, Ek~60,5 MeV, Frf=26,26 MHz). 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 Kext=35 % was achieved.

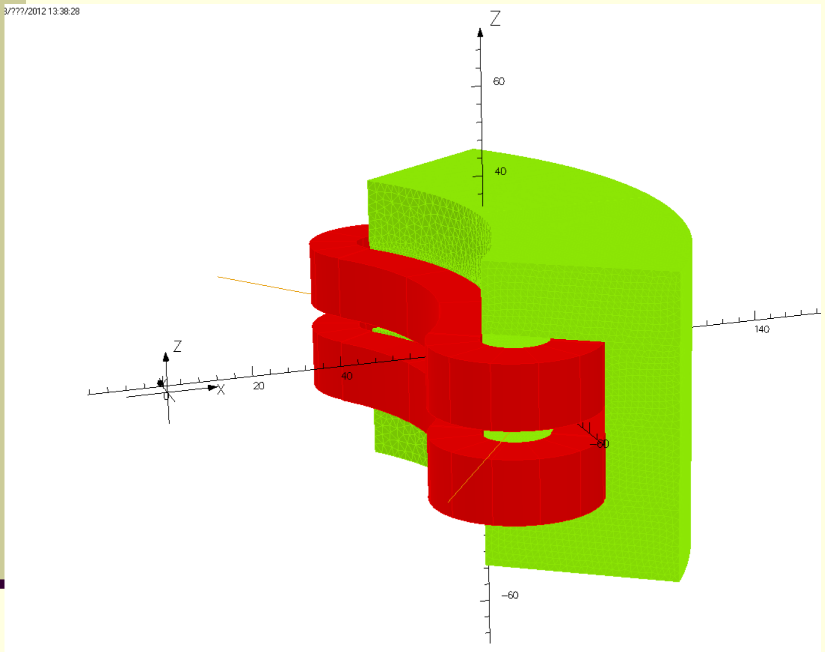
Cyclotron AIC-144 (INP PAS, Krakow, Poland)



It was received stable irradiation by proton beam on the position of patients with optimal run in water. This allows the irradiation of tumors located inside of the eye in a maximal range from 29.1 mm to 29.9 mm (from 90 % to 10 % of the Brag peak's back front), this corresponds to the energy of beam's protons at the exit of the AIC–144 cyclotron approx. 60,7±0,2 MeV. Obtained results are fully satisfactory, fulfilling the tasks of this work.

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

Development of the magnets for the beam transport line



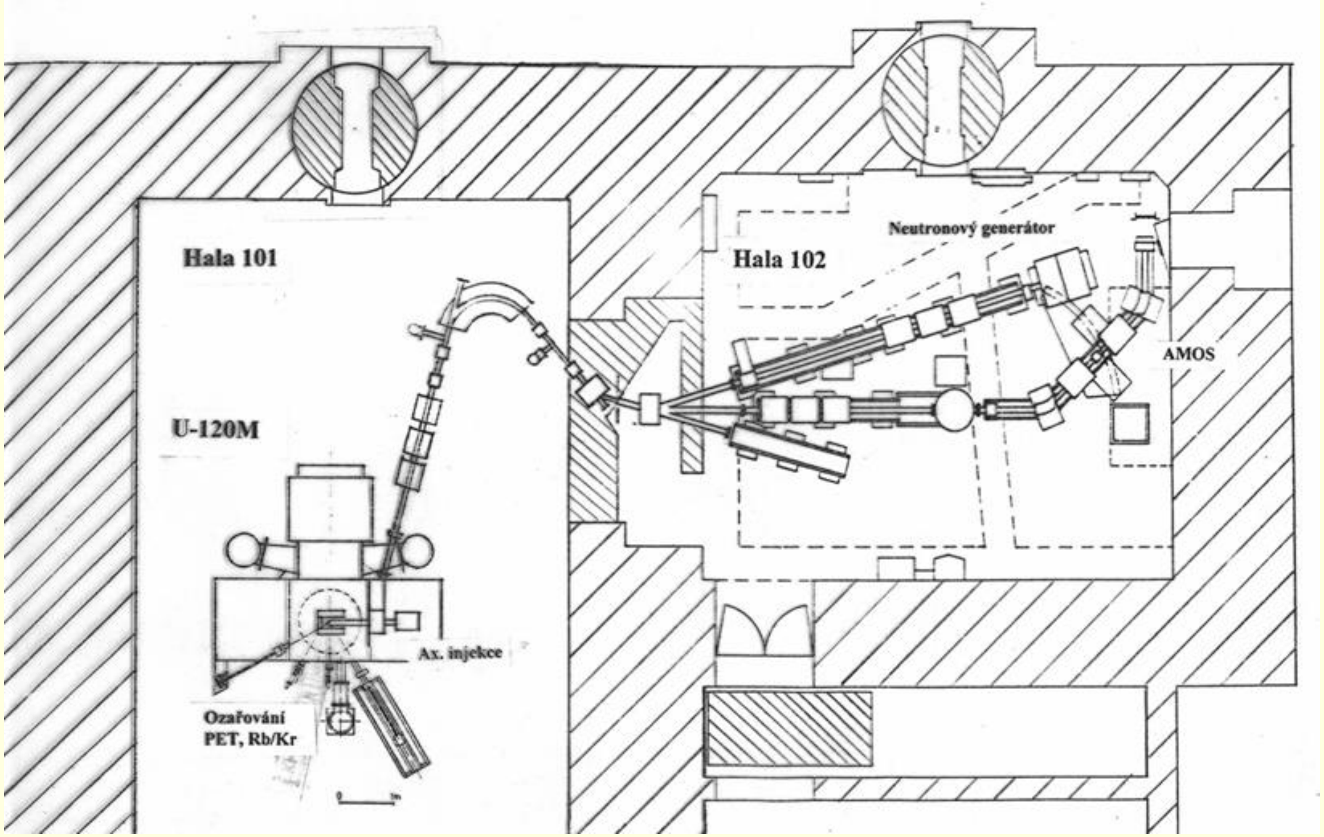
At present, the New Accelerator Department is working on the production of two bending magnets for the cyclotron transport line AIC-144.

Magnet M1 is located in the transport line of the proton beam with energy up to 60.5 MeV, extracted from the cyclotron AIC-144. The magnet should replace the old magnet and ensure the bending of the proton beam by 68 degrees.

A general view of the proposed design of the magnet

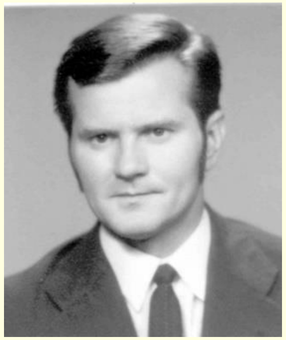
Cyclotron U-120M, Řež,Czech Republic

Tomas Matlochka



U-120M build in Dubna in 1971 – 1977 under supervision of:

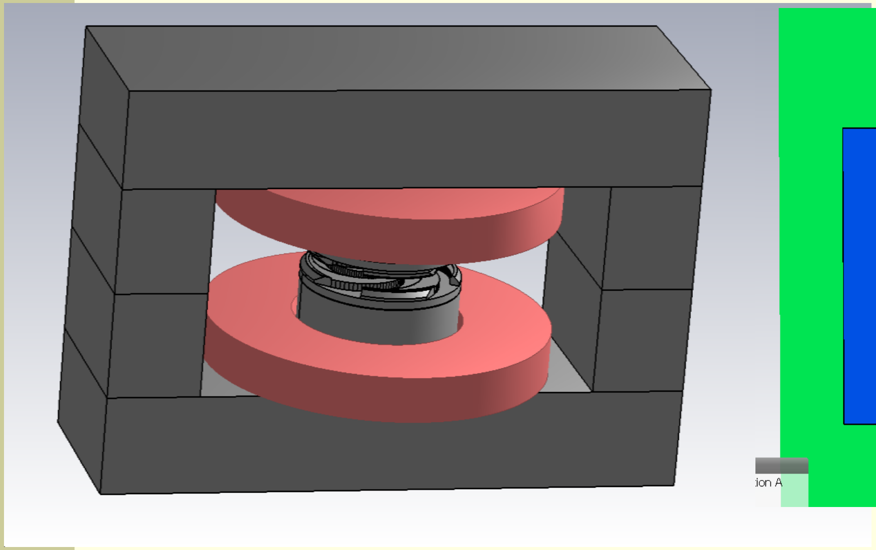
V.P. Dmitrievskij, L.M. Onischenko

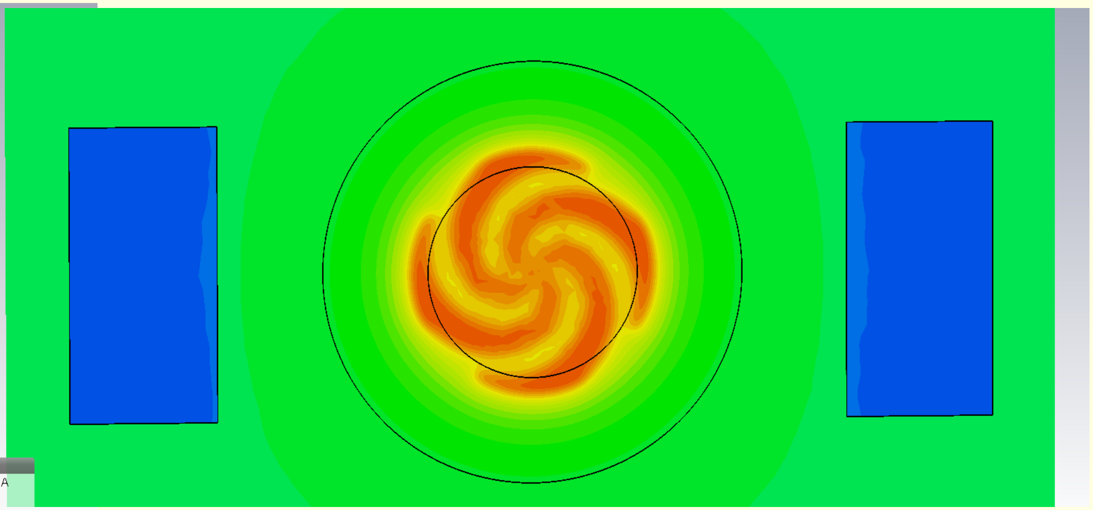


Zdeněk Trejbal, Milan Čihák, Miloslav Křivánek, Josef Šinágl

Taken from "30 years of U-120M" anniversary presentation of Milan Čihák.

Computer model of the magnet U-120M





Magnetic field distribution

We plan to help to correct extraction of positive ions by electrostatic deflectors. For this purpose computer simulations of the magnetic field and beam dynamic simulations during extraction are under way.

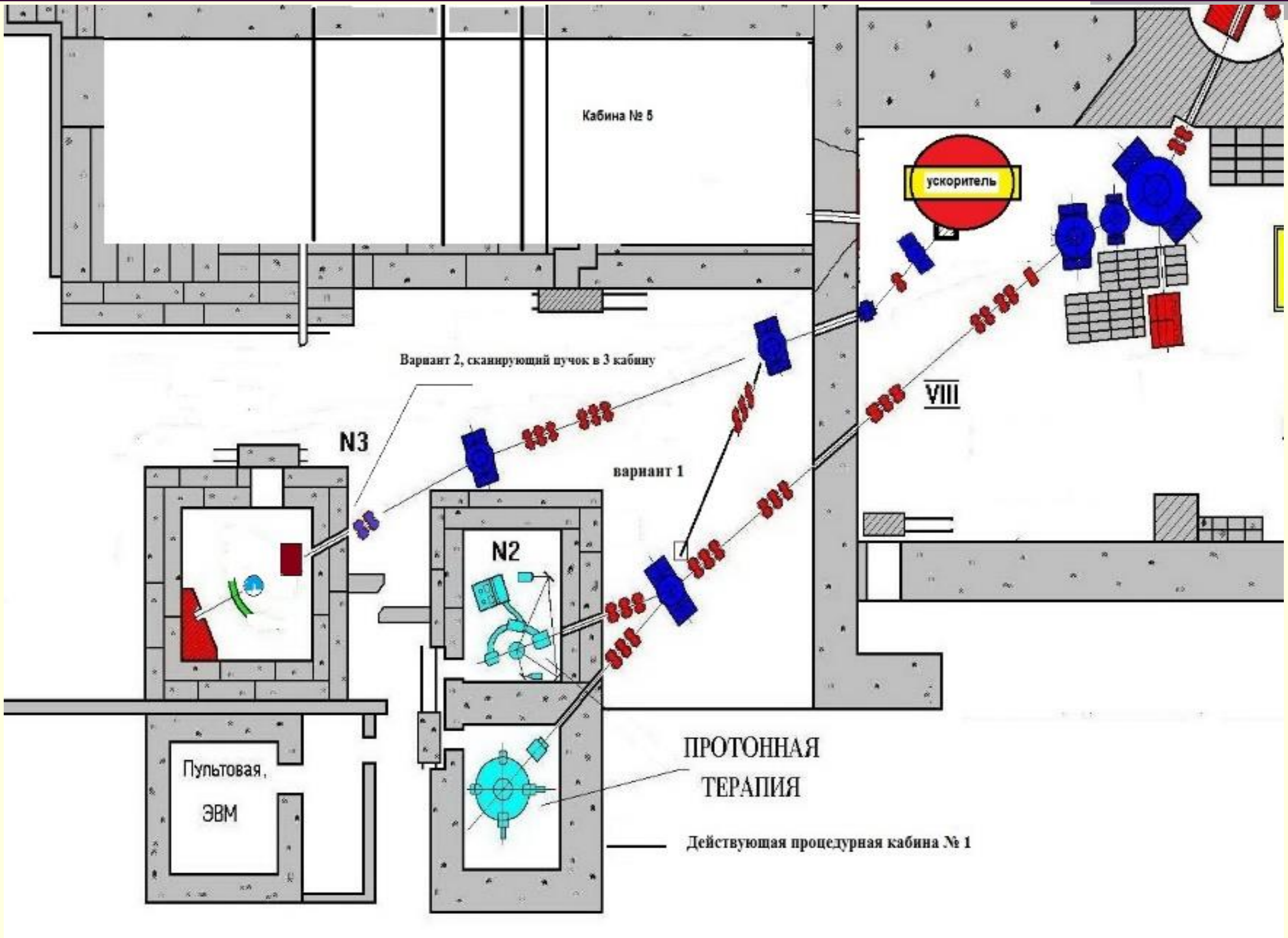
Research and development of the superconducting cyclotron for proton therapy for IPP CAS (Hefei, China).

Shirkov G.D.

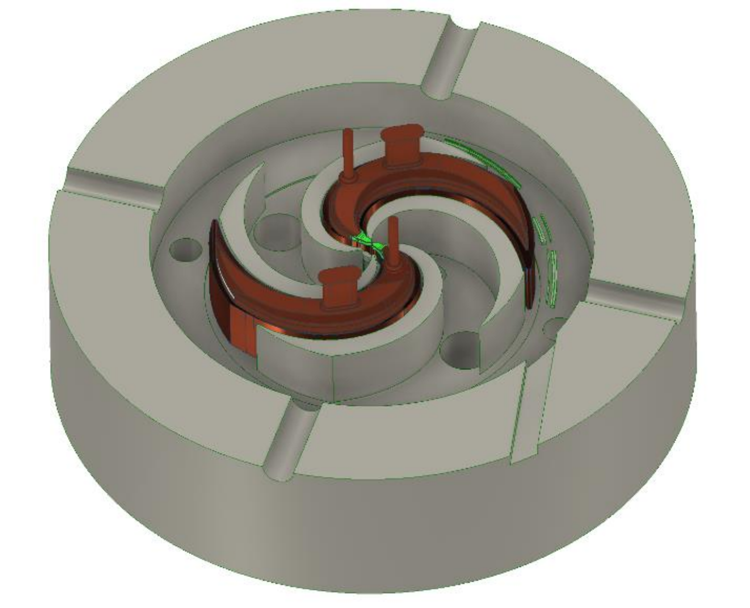
Main cyclotron design characteristics:

- 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

JINR Medico-technical center.



SC202. Main Parameters.

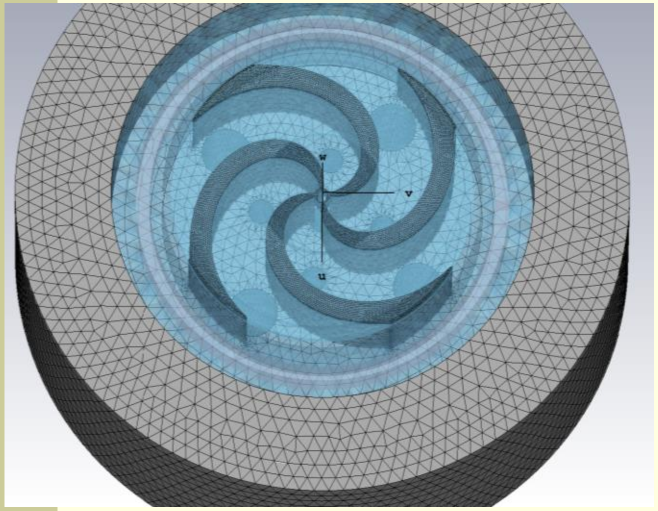


Mass	55 Tonn
RF Freq	91.5 MHz
Coil current	720 kA
Ion source	PIG
Sector azimuthal length	20-35 deg
Vertical gap between sectors	38->9 mm
Valley depth	250mm

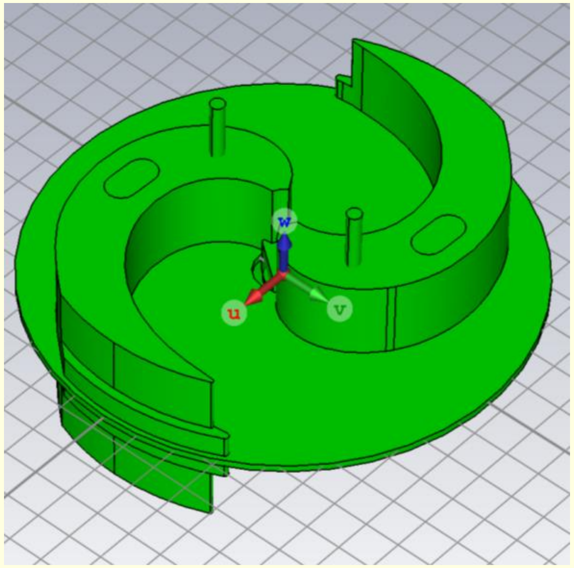
The next goals were achieved:

- Isochronous field in whole accelerating range
- Proper vertical focusing in the whole range
- Avoid dangerous resonances
- Keep last orbit close to pole edge 5-7 mm
- Keep the stray field at an acceptable level

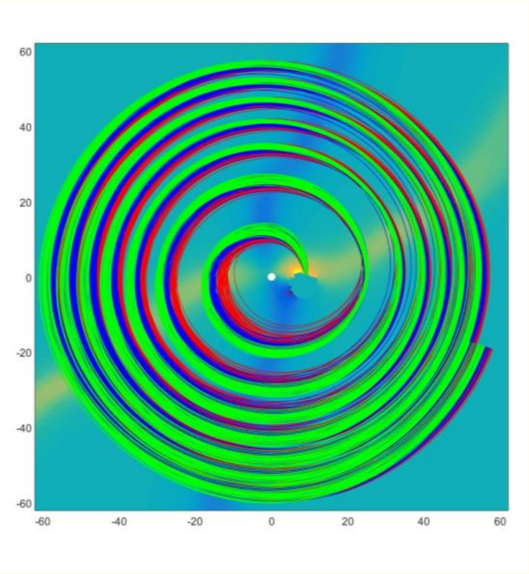
Project is successfully finished.



Magnet

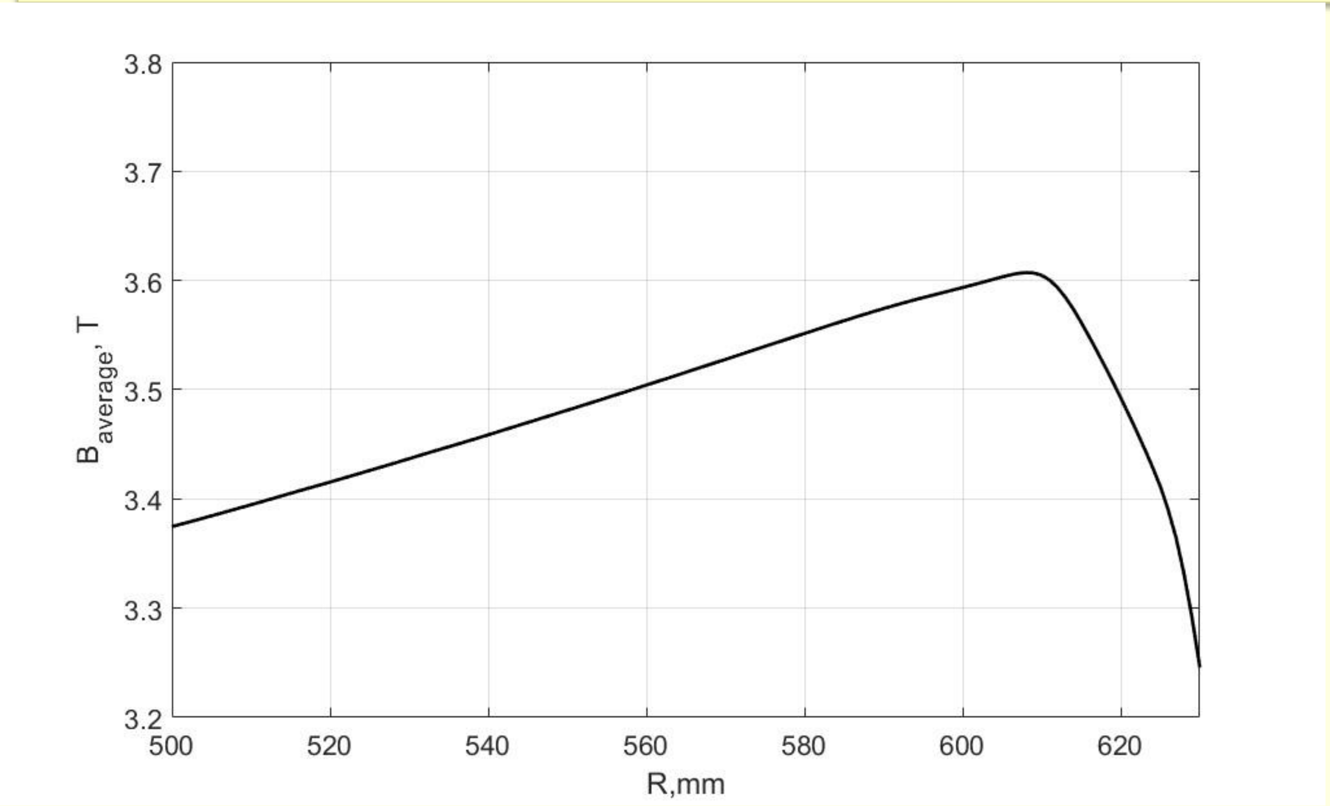


RF cavity

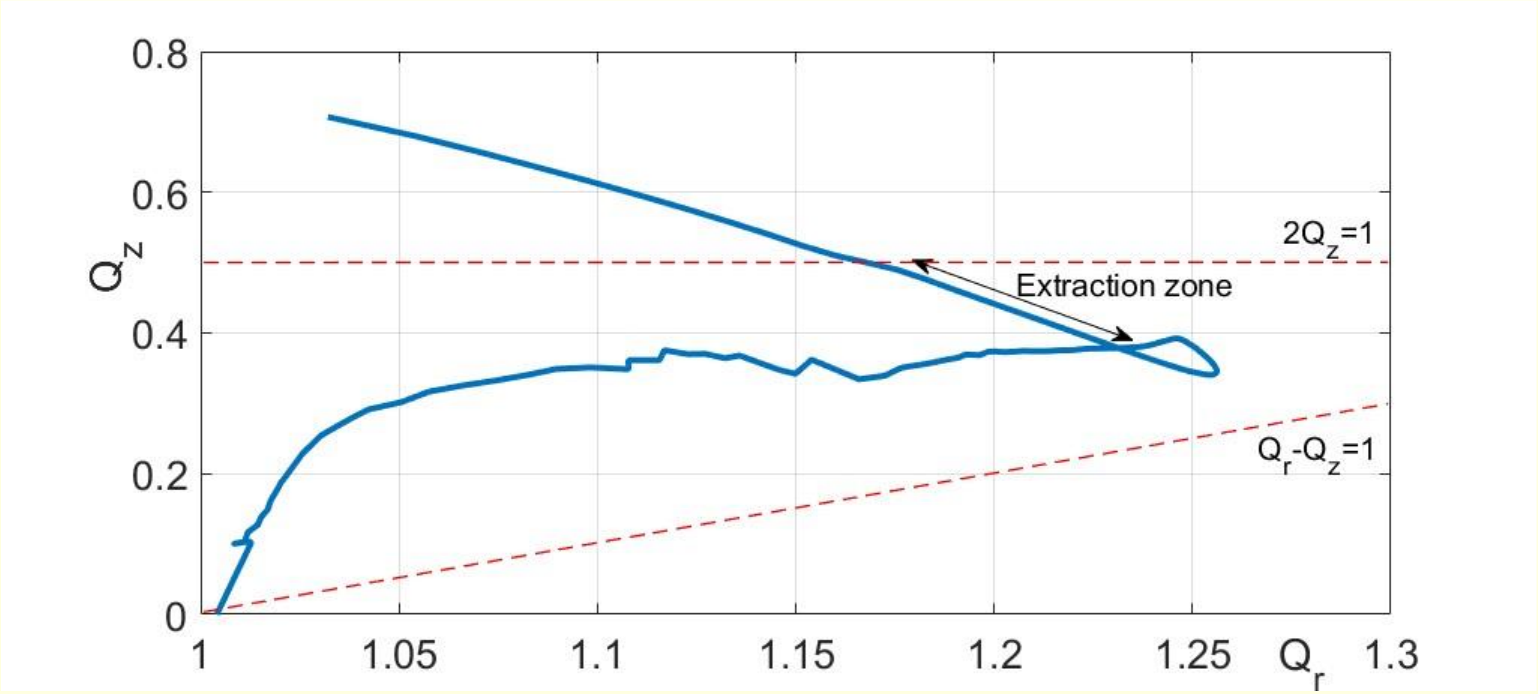


Beam dynamics

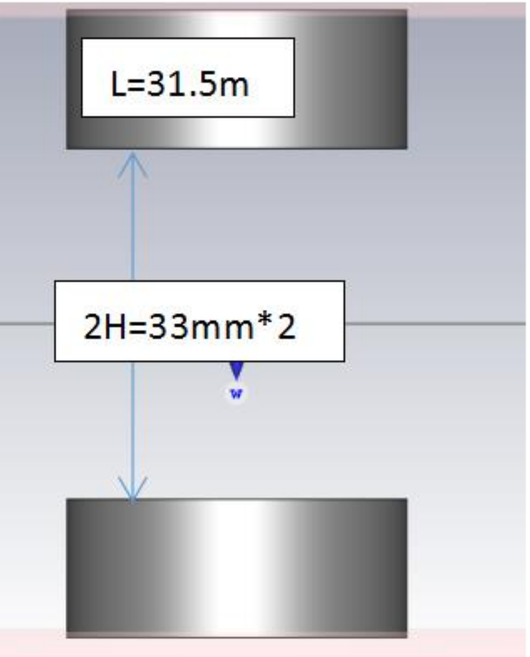
Magnetic field



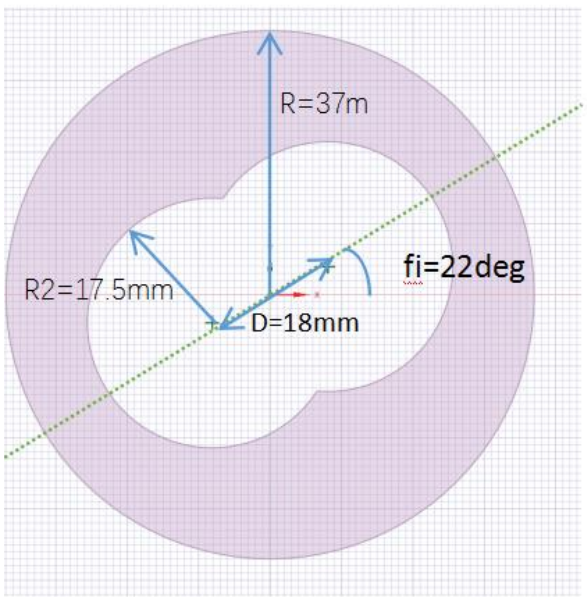
Working diagram



Central region



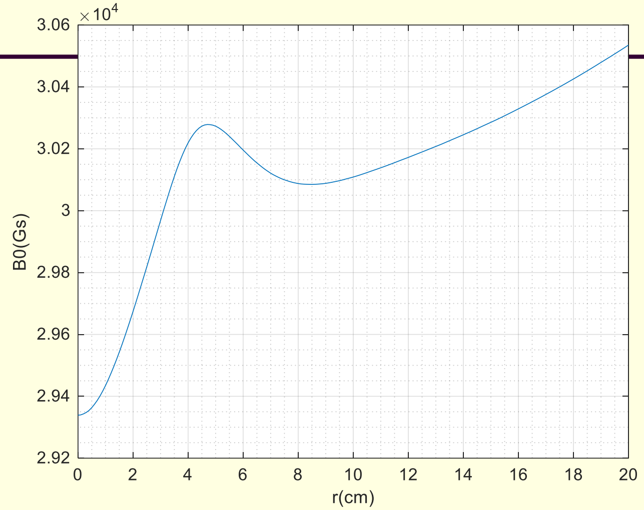
Lateral view

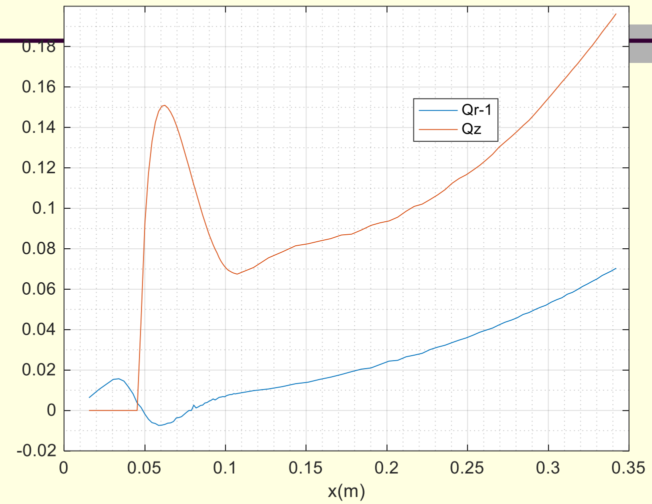


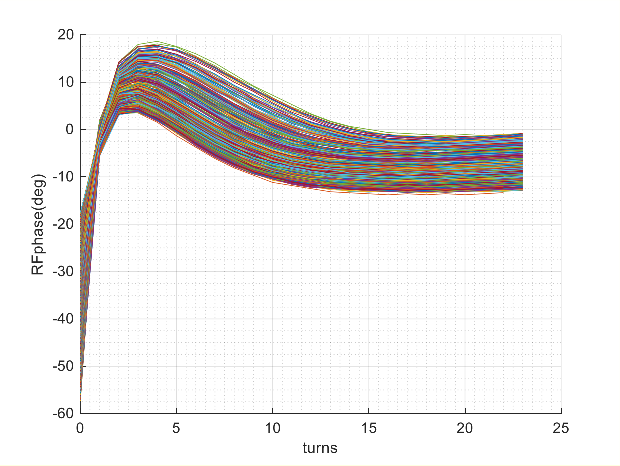
Top view

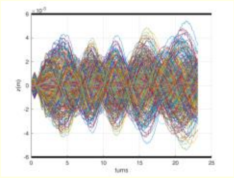
Parameter	Value
Material of Iron	Tested B-H
Distance to midplane H（mm）	33
Outer radius R （mm）	37
Thickness L（mm）	31.5
Distance between two Centre of the Ion Source Hole D（mm）	18
Rotating angle （deg）	-22
inner Radius R2 （mm）	17.5

Central region







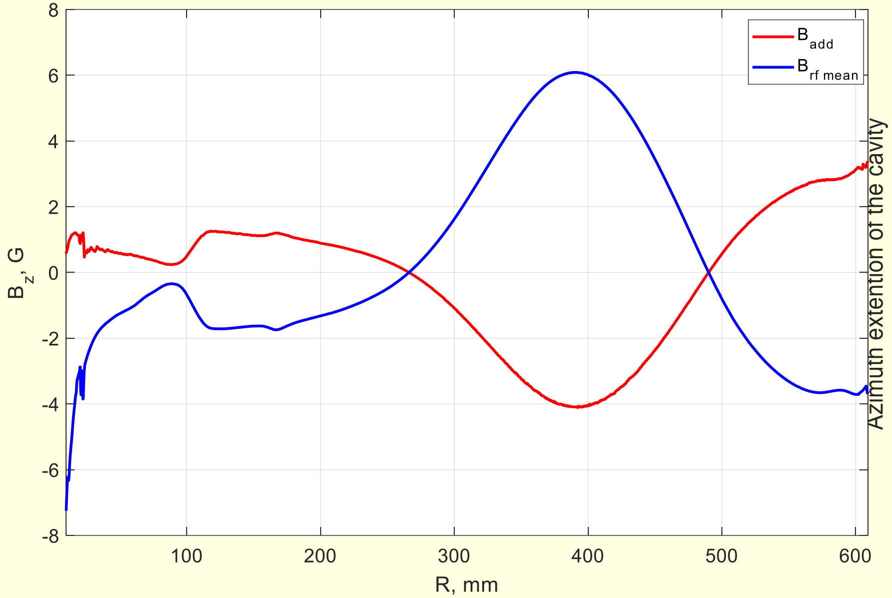


June 2018

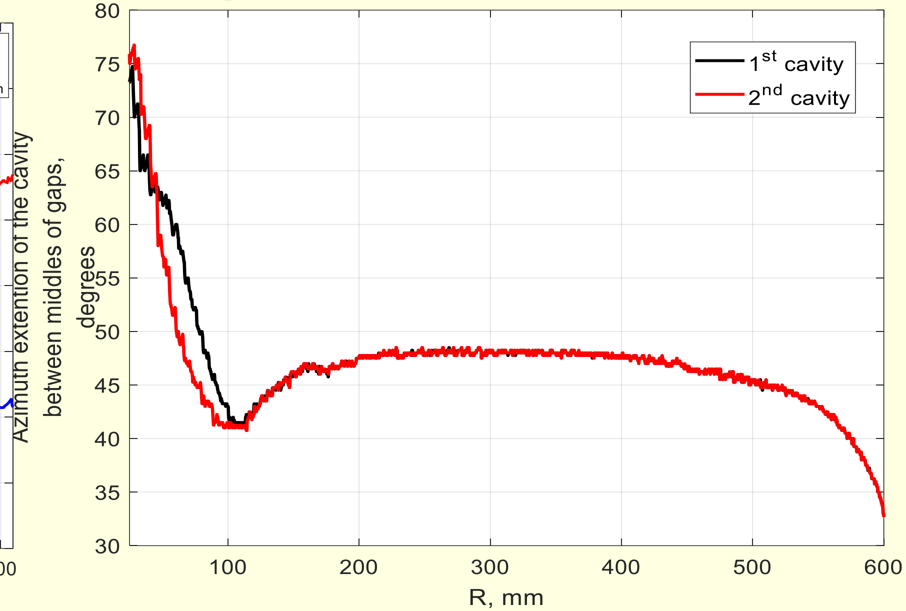
About compensation of the B_{rf} action

$$B_{add} = -B_{rfmean} * \cos(\theta_{cav})$$

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

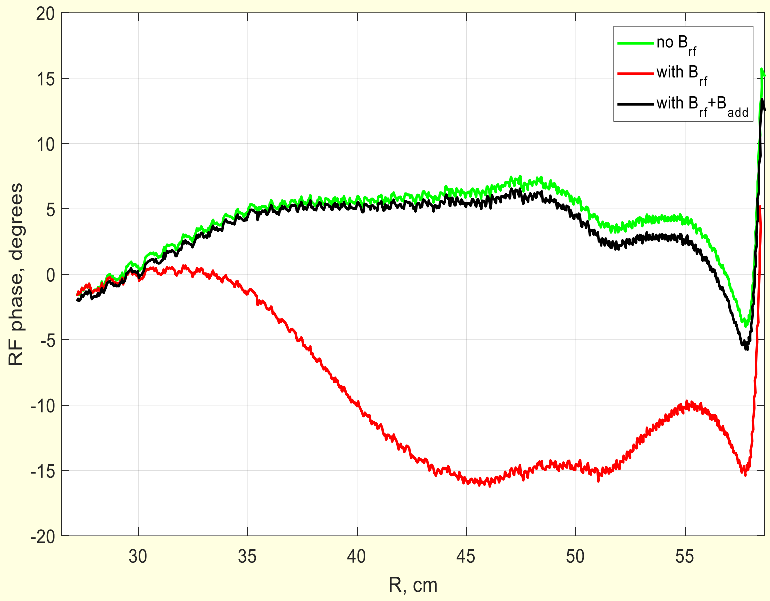


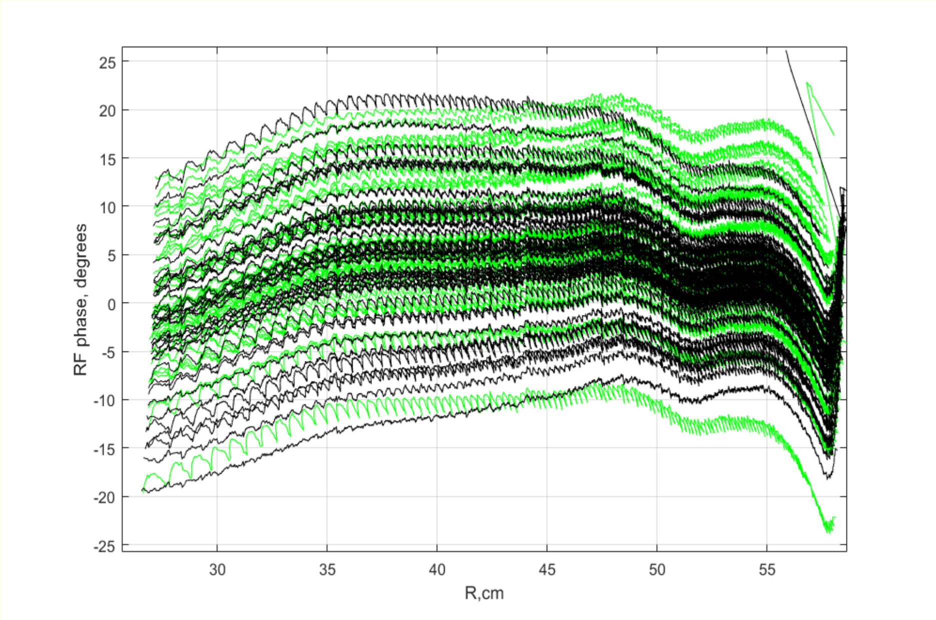
Mean value of B_{rf} field (blue line) and additional field (red line) versus radius.



Azimuthal extension between the maximums of the field distribution

Phase motion with Brf compensation

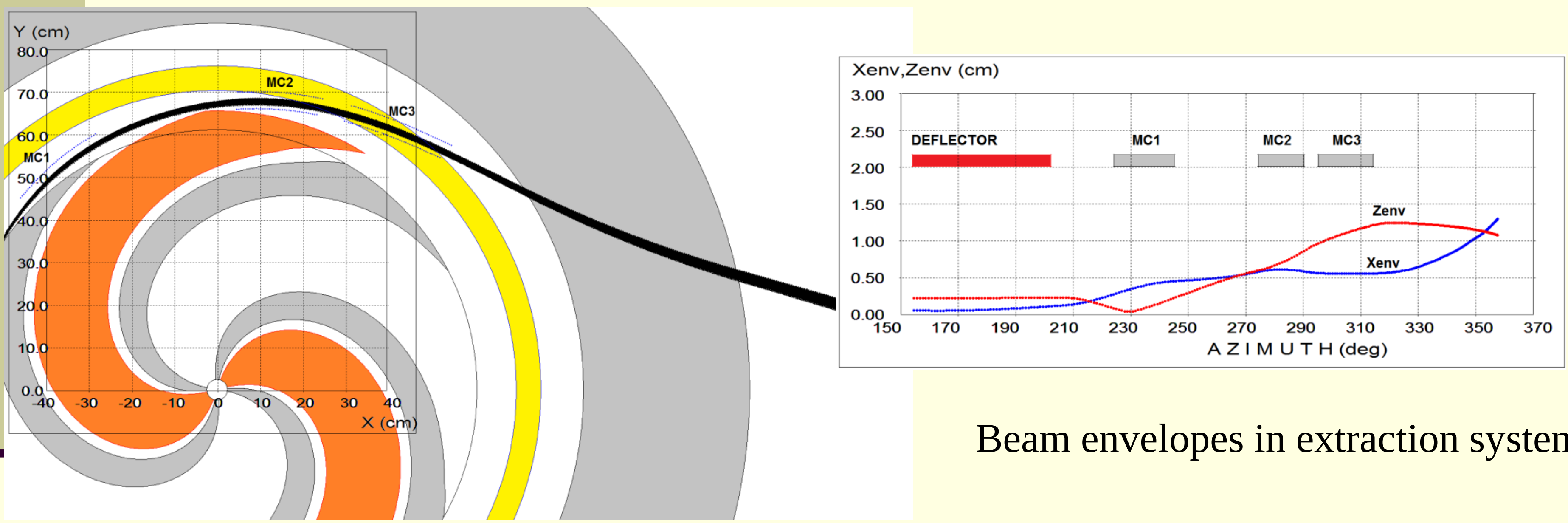




Phase motion of the central particle neglecting B_{RF} (green line) taking into account RF magnetic field (red line) and with B_{RF} +compensation (black line)

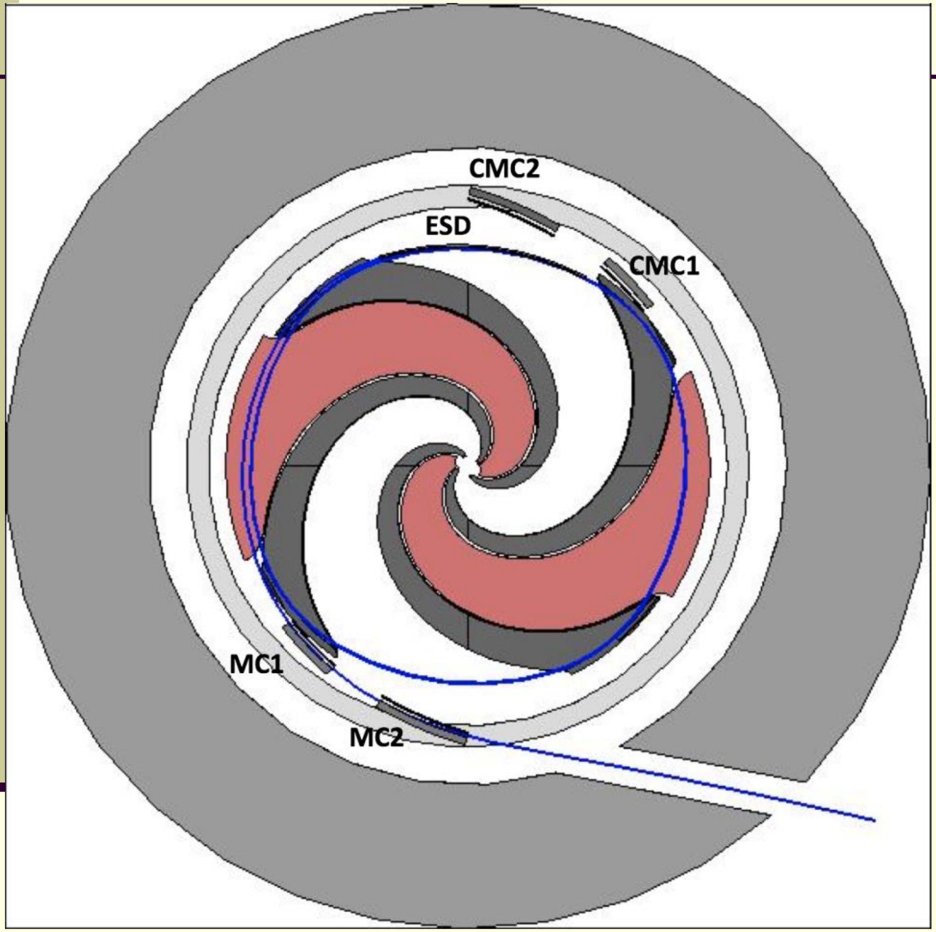
One can observe phase compression effect.

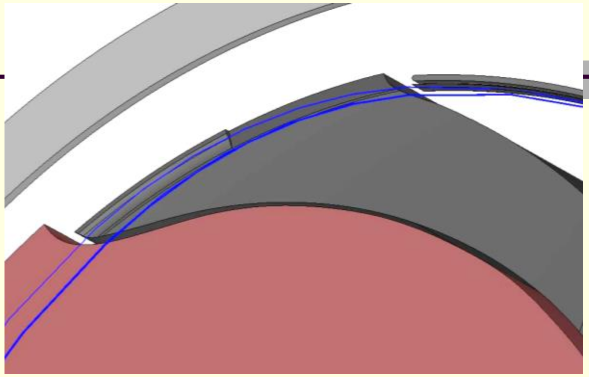
Extraction

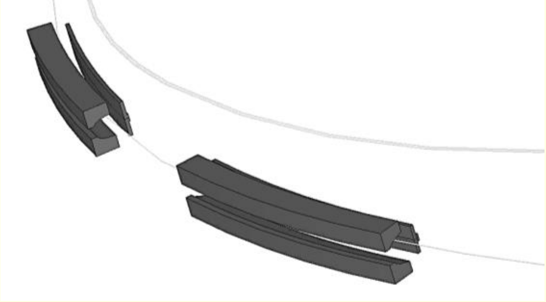


Beam envelopes in extraction system

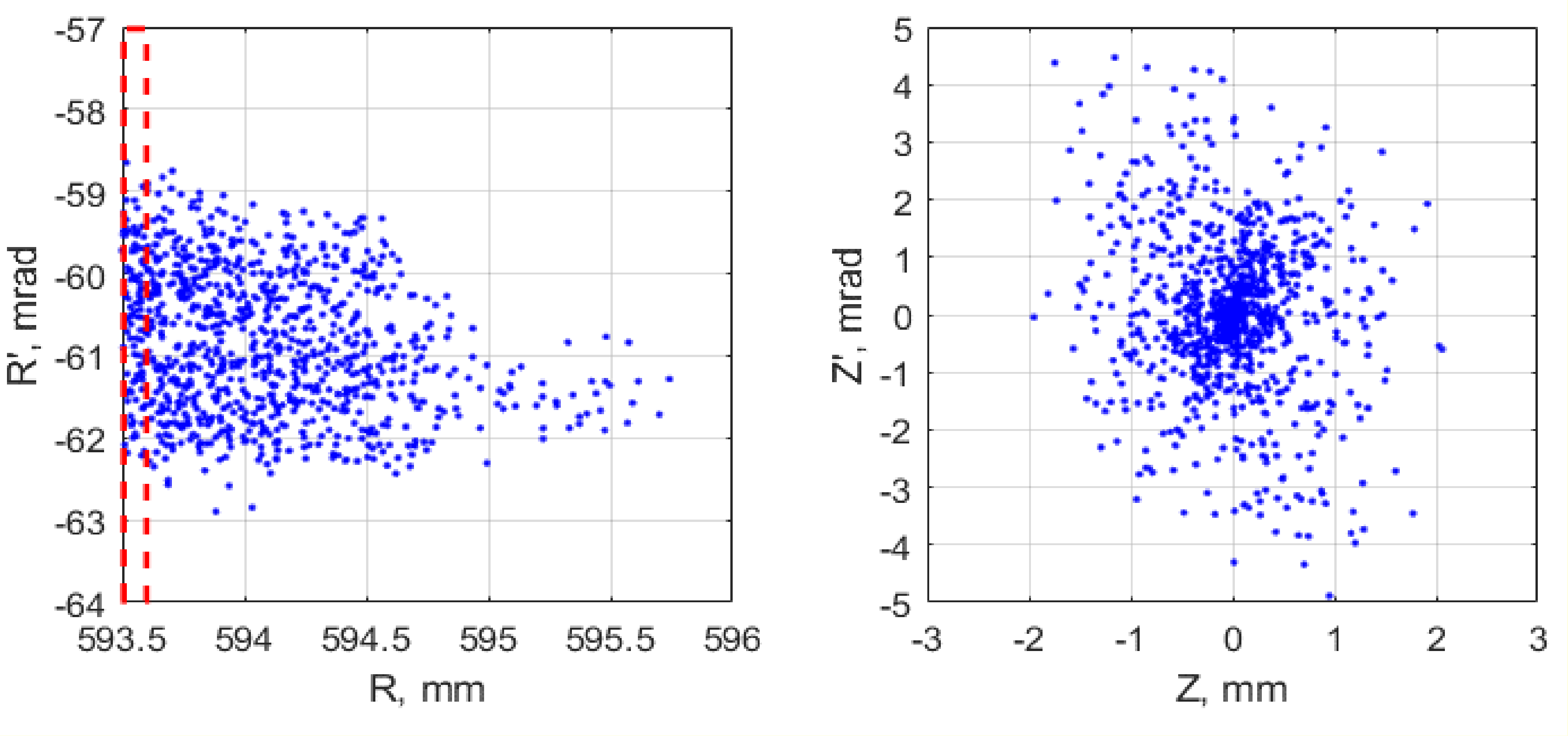
Extraction



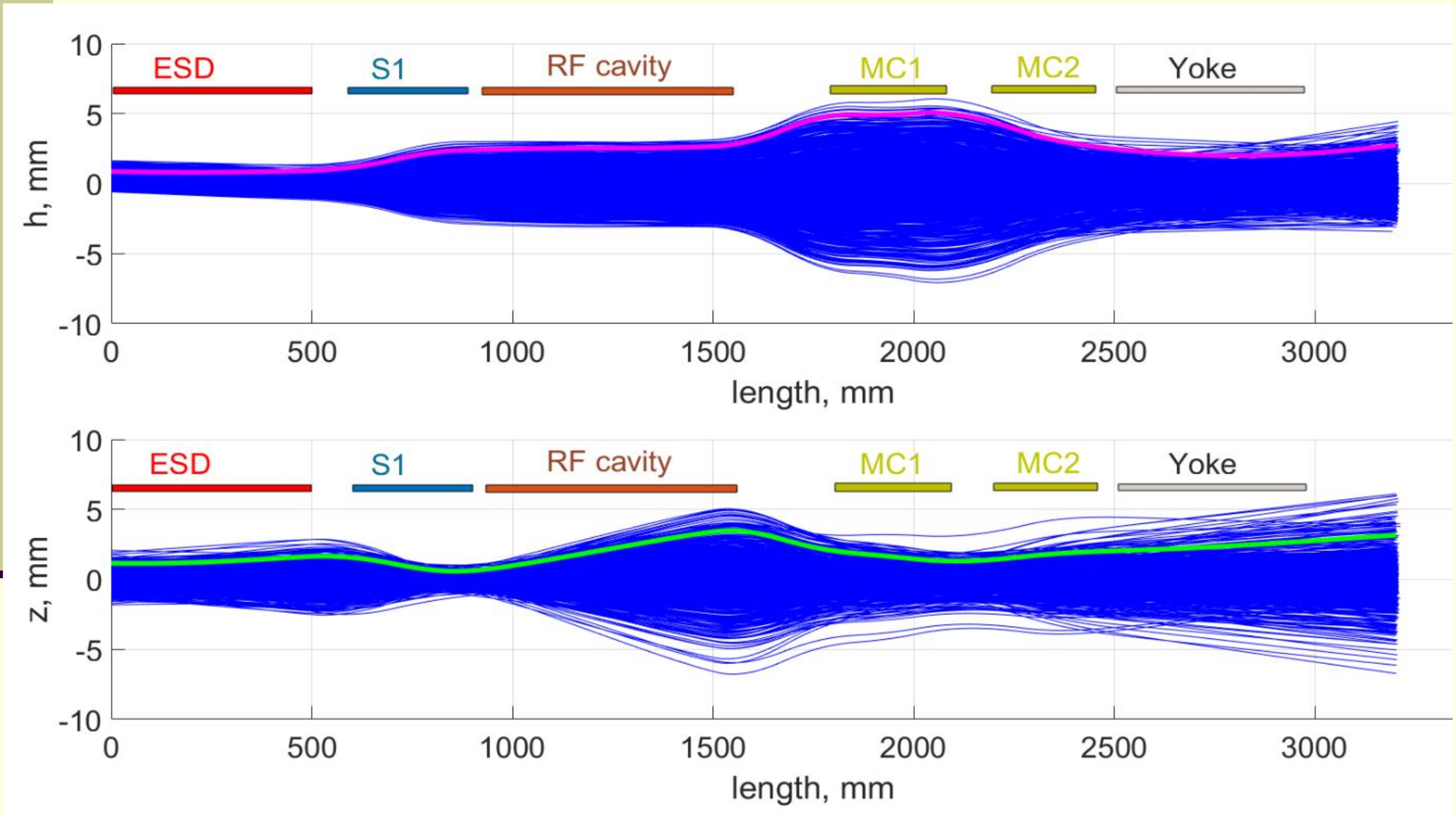




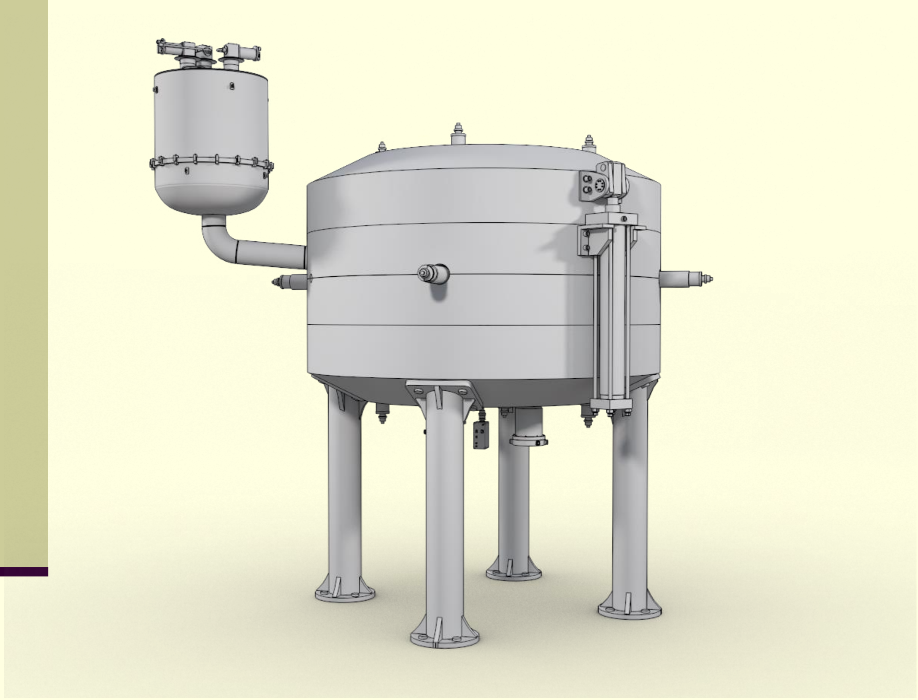
Beam distribution at the deflector entrance. Septum width 0.1mm is marked by red dashed line

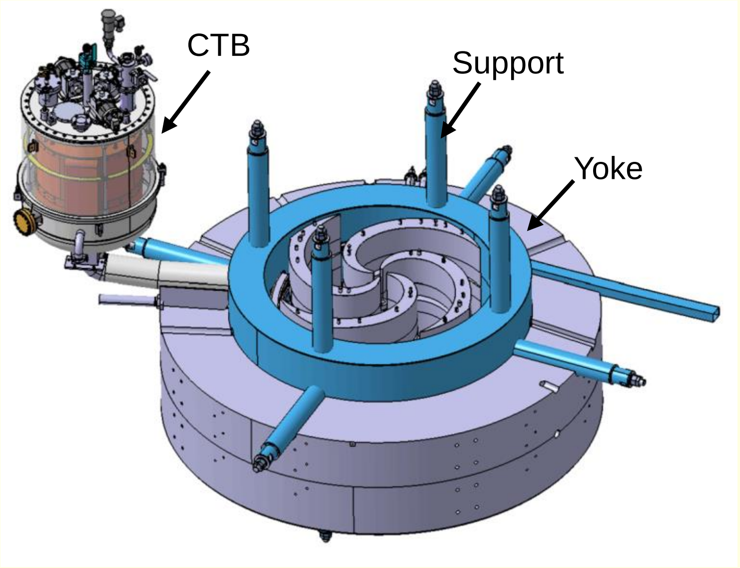


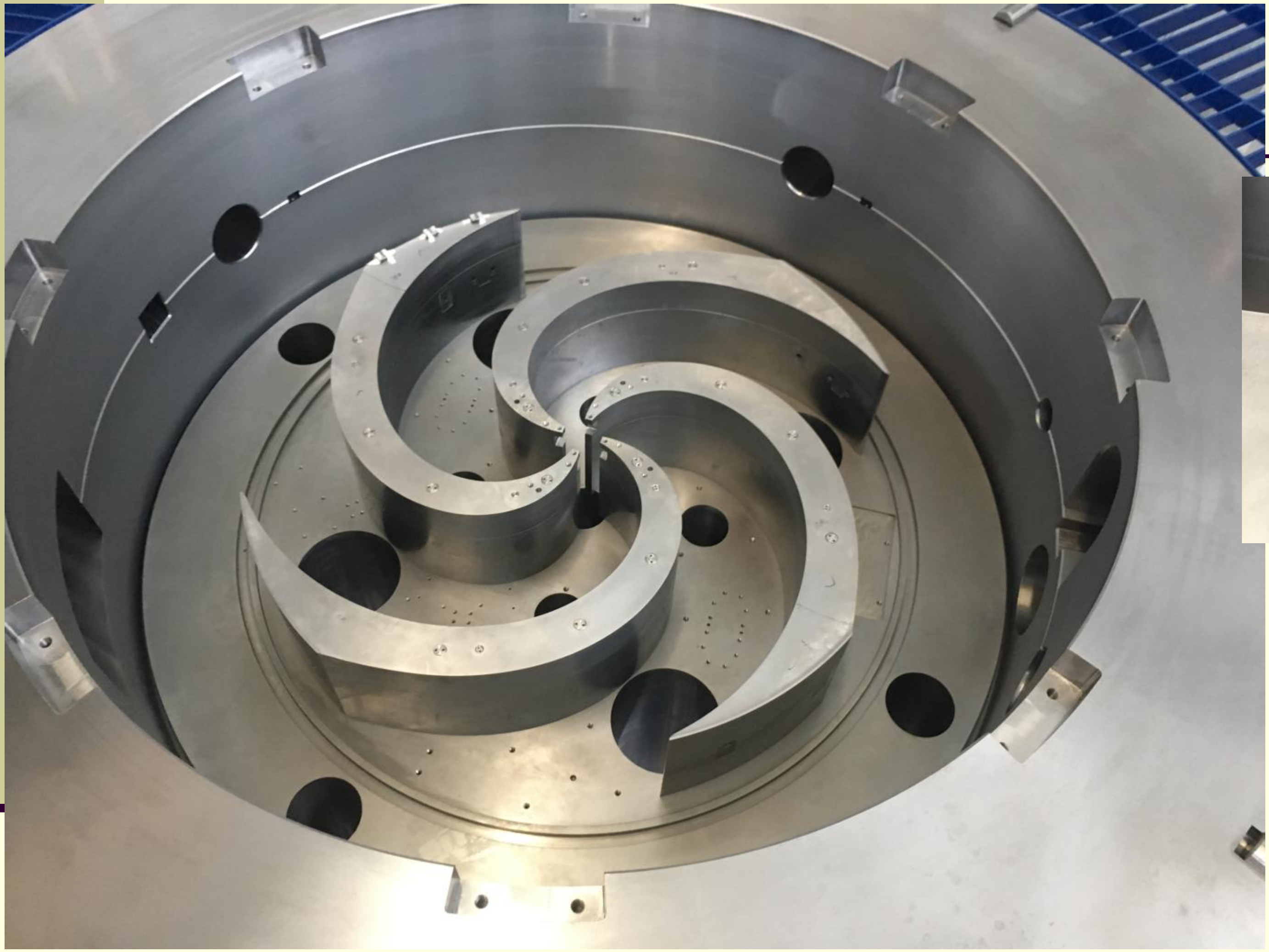
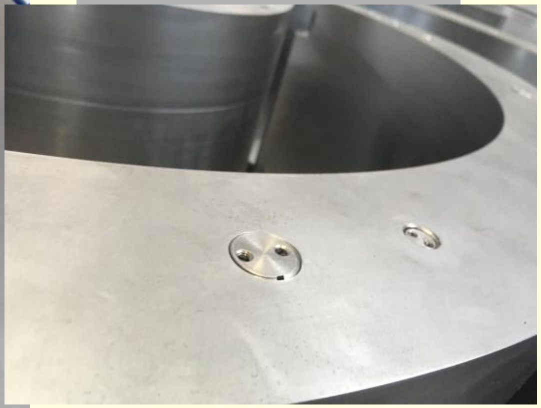
Horizontal and vertical motion of the beam during extraction, thick lines - 2σ envelopes



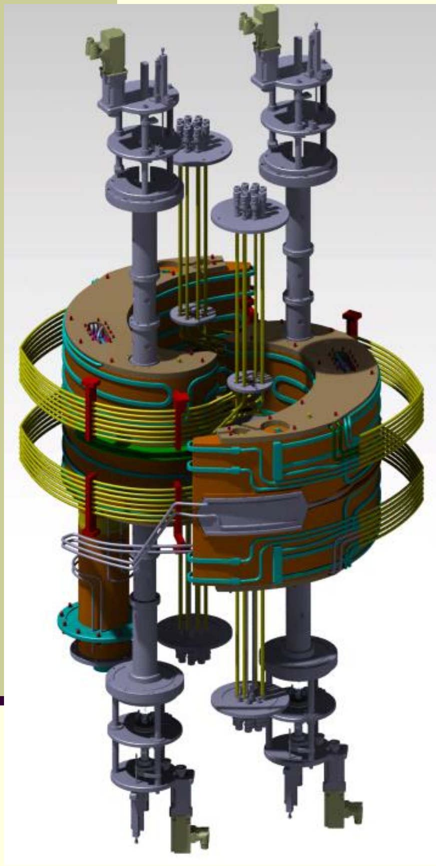
SC202. Magnet system.

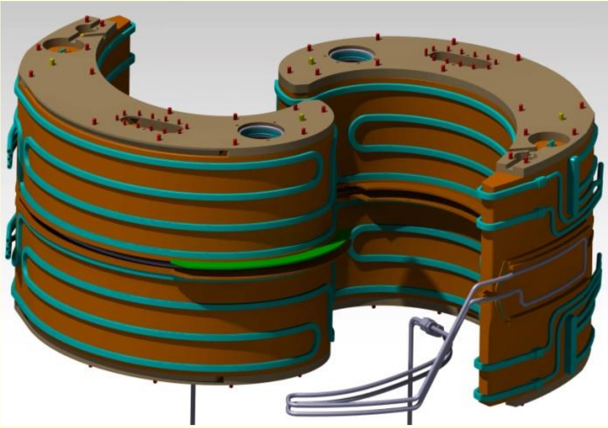




The Engineering desing of Cavity

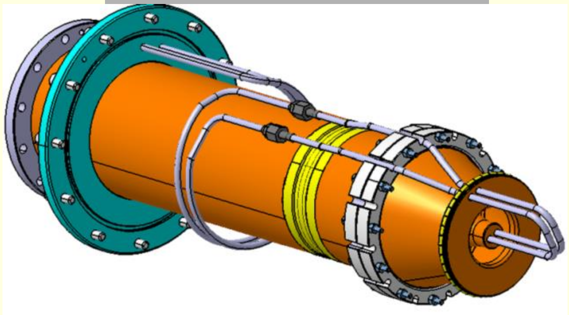




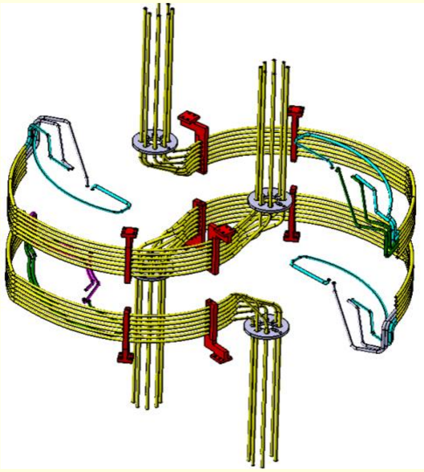
Cavity model

¼ Dee & Stem model

Tuning model

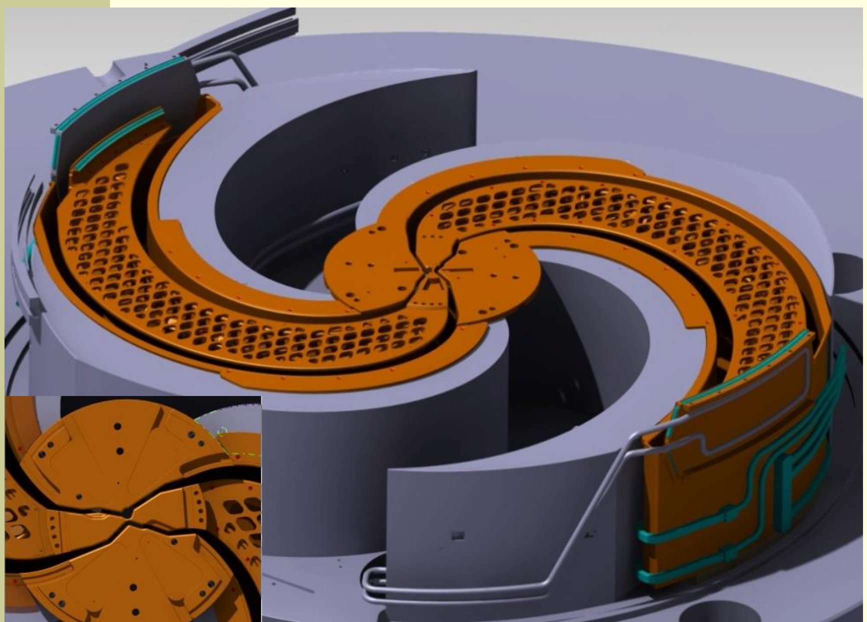


Coupling loop model

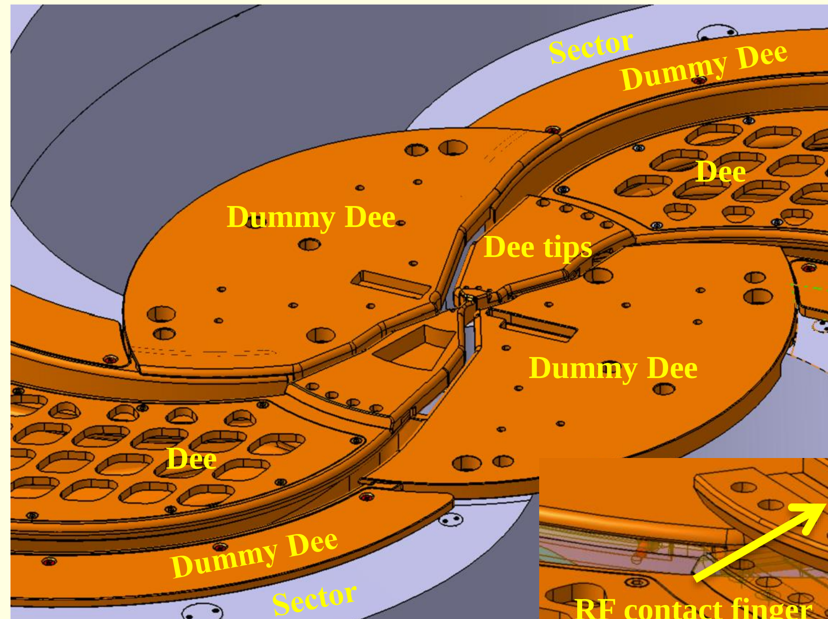


Cooling pipes model

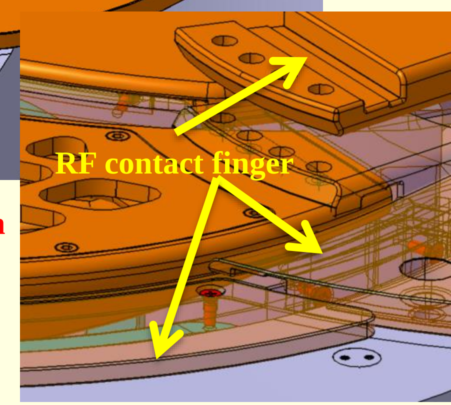
The Engineering Designing of Cavity



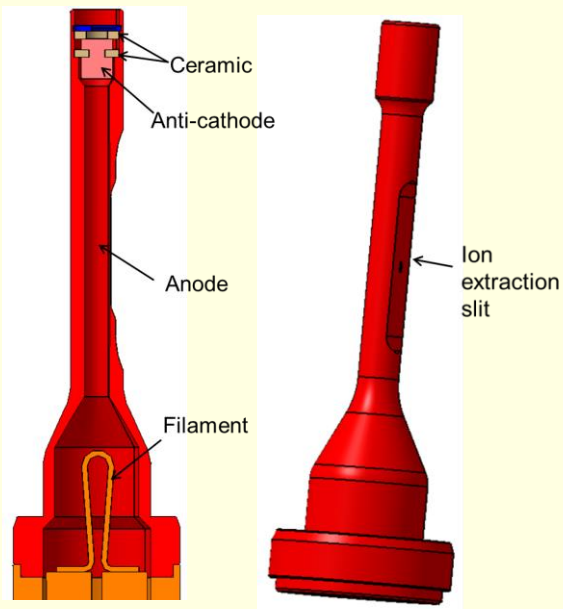
Bottom cavity and center region

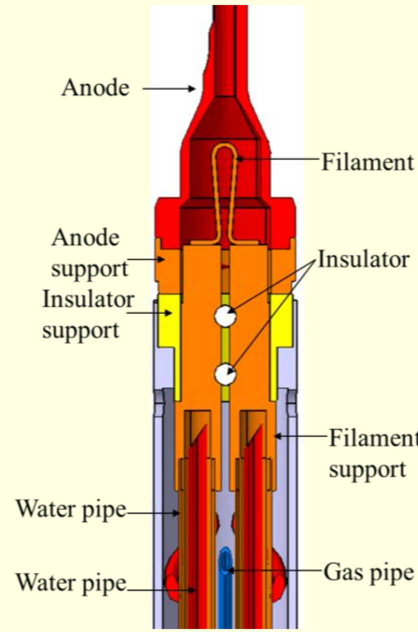


Detail view of bottom center region

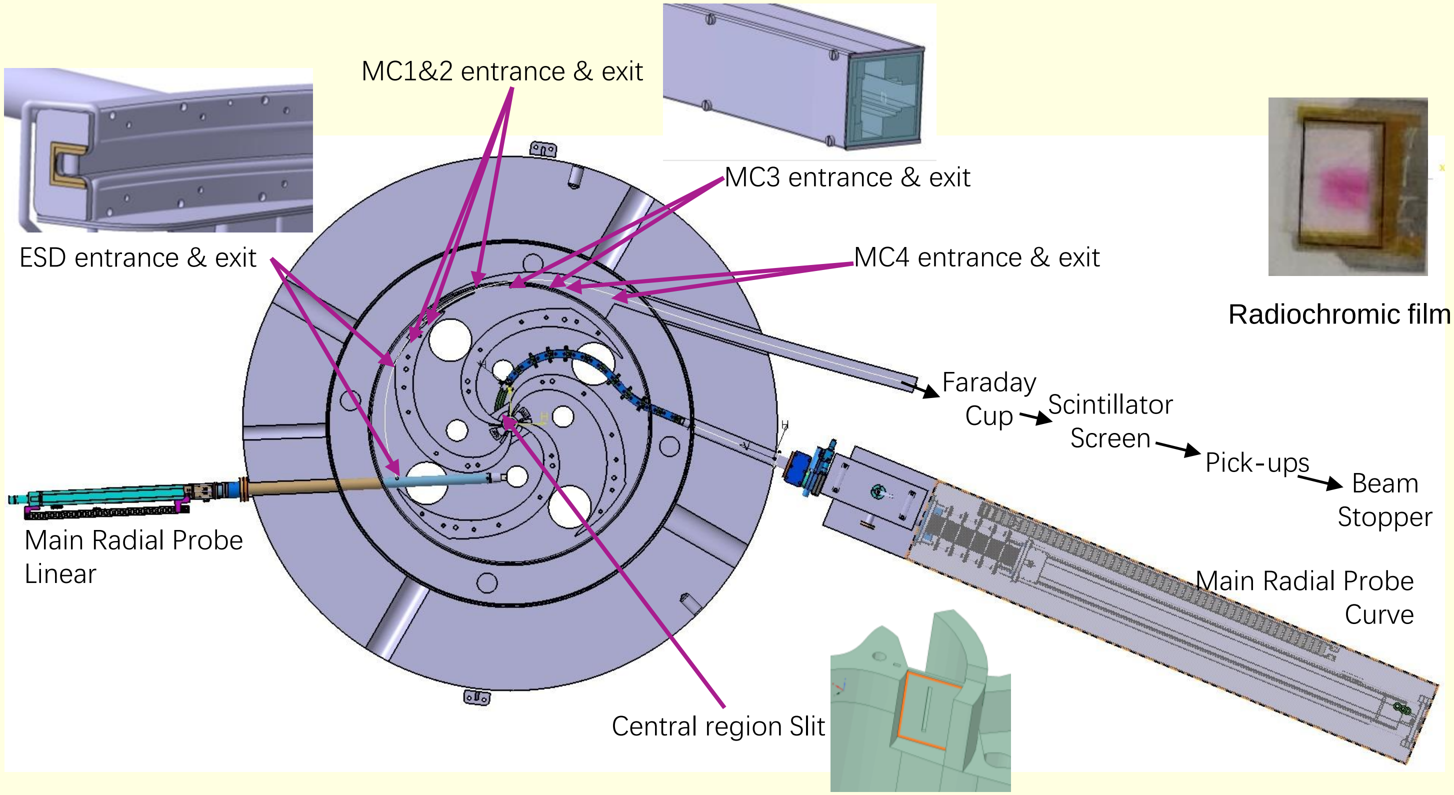


Source


Ceramic
Anti-cathode
Anode
Filament
Ion
extraction
slit

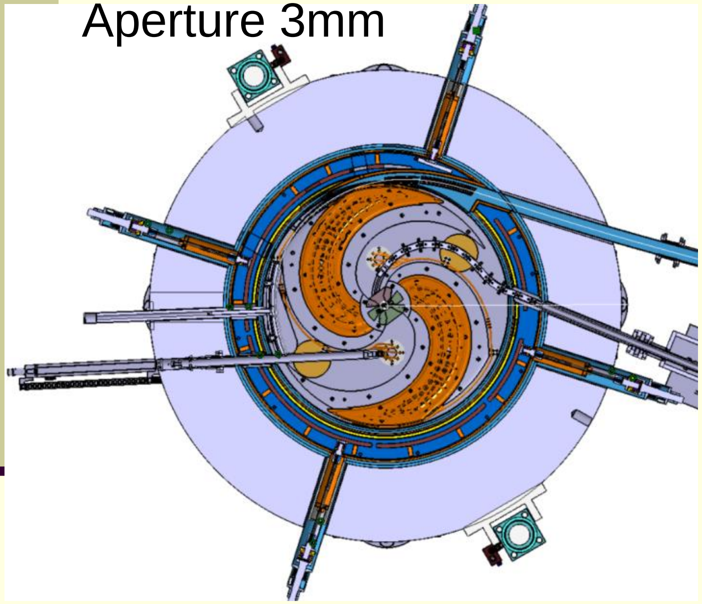

Anode
Filament
Anode
support
Insulator
Insulator
support
Filament
support
Water pipe
Water pipe
Gas pipe

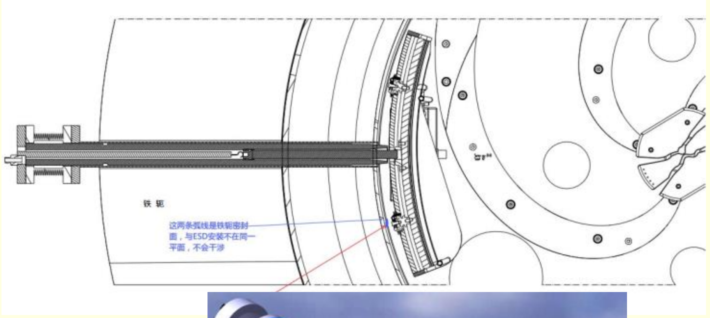
Diagnostics

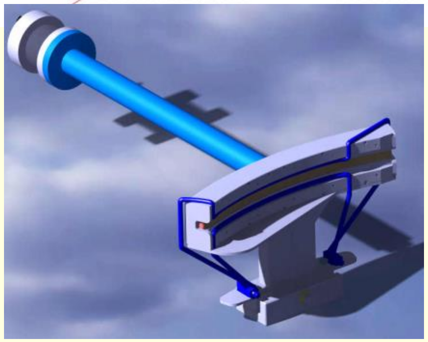


Deflector

Septum electrode:
0.1mm
Aperture 3mm







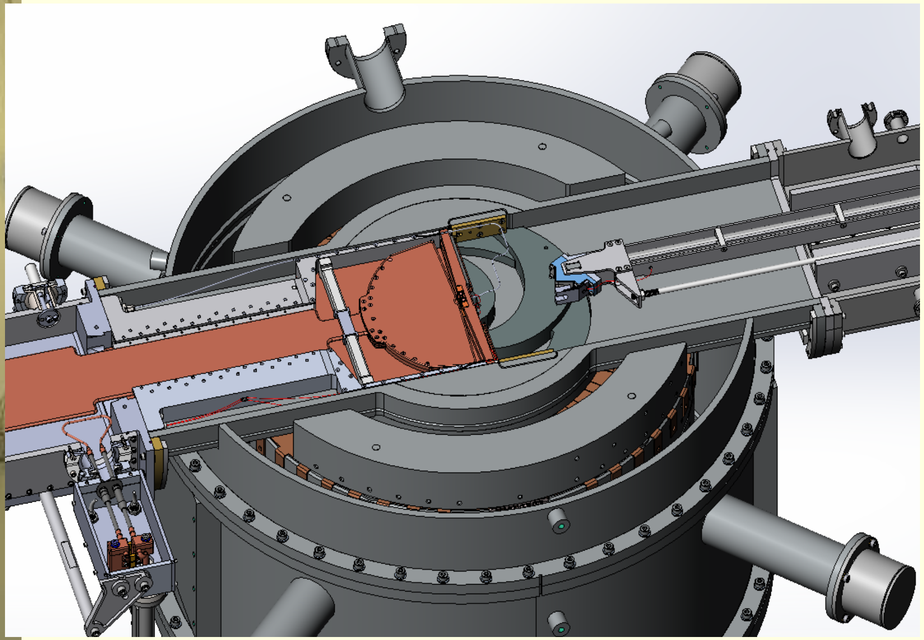
Conclusion

We obtain proper model of magnet, 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 %. Optimization of extraction is under way.

DEVELOPMENT OF THE CYCLOTRON METHOD FOR HIGH-CURRENT BEAM ACCELERATION

Ionetix ION-12SC cyclotron

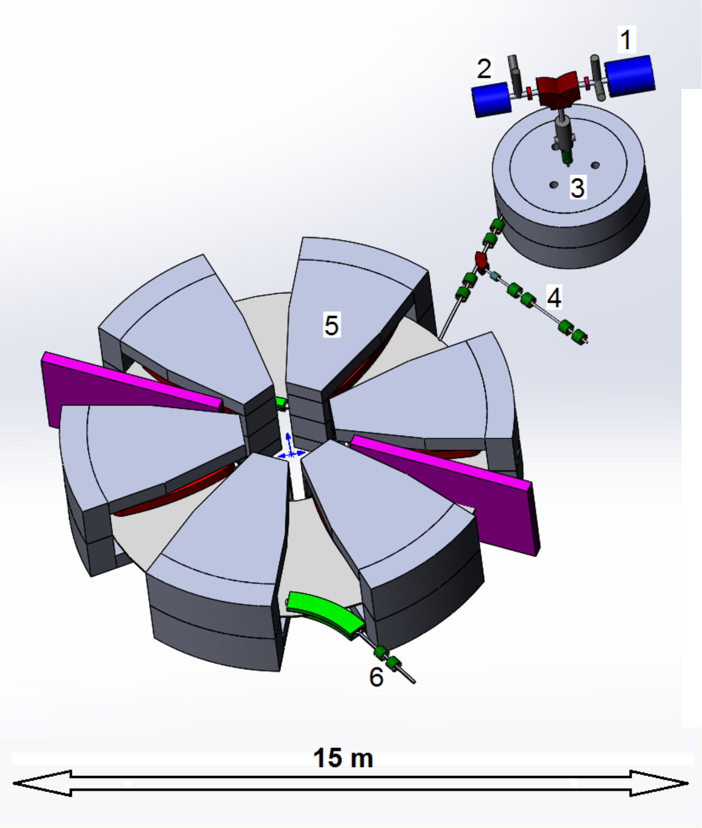


Accelerator in hospital.

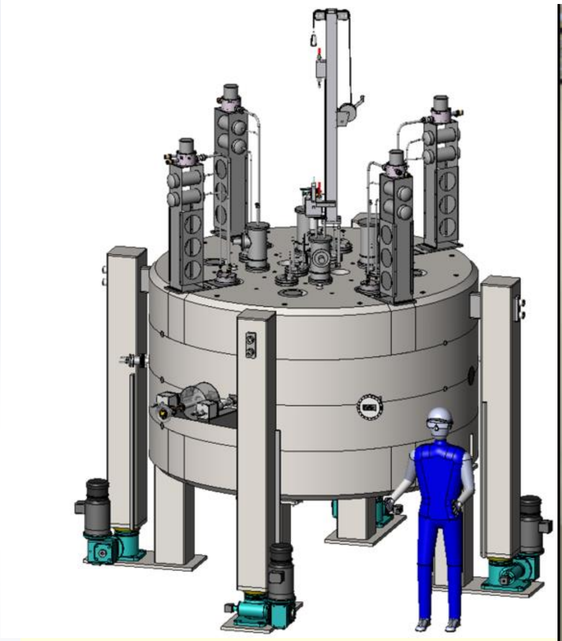
S.B.Vorozhtsov, V.L. Smirnov

Highlights

JINR 400 MeV/u Cyclotron Complex for Carbon Therapy



Pronova K230 superconducting cyclotron for proton therapy



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

June 2018

Tooling

- **SNOP** – Beam Dynamics Analysis Code for Cyclotrons
  - **JINR home-made, installed in:**

1. Russia - JINR
2. USA – MSU, Siemens, Ionetix, ProNova
3. Japan – RIKEN, NIRS, RCNP
4. China – IMP
5. Czech Republic - Nuclear Physics Institute (Řež)
6. Iran - Amirkabir University of Technology

- **Tosca-Opera3D** – *3D electromagnetic field calculations* – **license available**
- **SolidWorks** – *Mechanical design* – **license available**
- **Open access soft**
  - Trace3D – *Beam transport lines*
  - TRANSPORT – *Beam transport lines*
  - DIMAD– *Beam transport lines and circular accelerators*

Applications

N	Person	Center	Facility	Activity status
1	V.L. Smirnov S.B. Vorozhtsov	JINR, Dubna	Cyclotron complex for hadron therapy	Feasibility study
2	A. Jacques	ProNova, USA	230 MeV Superconducting Cyclotron for Proton Therapy	Construction
3	F. Taft	AUT, Iran	18 MeV AVF cyclotron	Simulations
4	J. Vincent	Ionetix, USA	Ultra-Compact superconducting cyclotron for isotope production	Mass production
5	H. W. Zhao H.F. Hao	IMP, China	HIMM 7 MeV/u 12C5+ injecrtor cyclotron	Operational
6	E. Pozdeyev	MSU, USA	FRIB Front End	Implemented Construction
7	A. Goto M. Nakao	NIRS, Japan	NIRS-930 cyclotron	Implemented Operational
8	A. Goto	RIKEN, Japan	RIKEN K-70 AVF Cyclotron	Implemented Commissioning
9	M. Nakao	RCNP, Japan	RCNP AVF cyclotron	Implementation
10	J. Vincent	Ionetix, USA	H- Superconducting Cyclotron for PET Isotope Production	Proposal
11	V.L. Smirnov S.B. Vorozhtsov	JINR, Dubna	Protontherapy FFAG	Proposal
12	P. Zavodszky T. Eriksson	GE Global Research, USA GE Healthcare, Sweden	PETtrace 800 Cyclotron	Proposal

List of activities

1. Modernization of the Phasotron and beam tracts.
2. Design of cyclotrons for medical applications.
3. Development and production of the superconducting cyclotron for SC202 proton therapy in collaboration with IPP (Hefei, China).
4. Development and applications of methods and codes for the design of new cyclotron-type accelerators.

Participating countries, institutes and organizations

Country or Organization	City	Institute or Laboratory	Participants Name, Surname	Status
Poland	Krakow	NINP PAS	Sulikowski J.	Protocol
Czech Republic	Řež	UJV	Matlocha T.	Protocol
Uzbekistan	Tashkent	INP AS RUZ	Umerov R.	Protocol
China	Hefei	IPP CAS	Song Y.	Collaboration
Belgium	Louvain-laNeuve	IBA	Jongen Y.	Collaboration
Japan	Chiba	NIRS	Noda K.	Collaboration
USA	Lansing, MI	IONETIX	Vincent J.	Collaboration

Results expected upon completion of the theme

- Stable work of the Phasotron, modernization of the power supply system and the beam channels of the Phasotron.
- Commissioning of a specialized superconducting isochronous cyclotron SC202 for proton therapy
- Creation of techniques and codes for the design of cyclotron-type accelerators. Applying these techniques and codes in the development of accelerator projects.

Participants from JINR

Laboratory	Name, Surname	№ №	Name, Surname
DLNP	G.A. Karamysheva		S.L. Yakovenko
	N.G. Shakun		G.D. Shirkov
	S.B. Vorozhtsov		V.I. Smirnov
	I.N. Kiyan		V.A. Malinin
	O.V. Karamyshev		S.V. Gursky
	D. Petrov		A.F. Chesnov
	D.V. Popov V.M.Romanov+2pers.		+30 pers.
FLNR	I.A. Ivanenko		+2 pers.
LIT	I.V. Amirkhanov	2	+2 pers.

Total estimated cost of the theme

№№	Activities	Total cost	Costs per years (thousand USD)		
			1st year	2nd year	3rd year
1.	Improvement of JINR Phasotron and the beam channels	630	210	210	210
2.	Design of cyclotrons for medical applications	60	20	20	20
	Total	690	230	230	230

Thank you for your attention