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

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May 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.

Шакун Н.Г. Яковенко С.Л.

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)

Kiyan I.N., Morozov N.A., Samsonov E.V.

In the period from February 2011 to January 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.

Due to the commissioning of a new isochronous cyclotron C–235 the AIC–144 was used as backup cyclotron for the treatment of eye melanoma since February 2016. 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.

In 2016 for the main operation mode of the AIC–144 cyclotron: p, $E_k = 60{,}7 \pm 0{,}2\ MeV$, corrections were made for the amplitude, phase of the first harmonic and the position of the median plane of the cyclotron magnetic field.. As a result, the increase of extraction coefficient of proton beam was fixed on the 15th of June, 2016 from $K_{ext} = 19 \pm 1\ \%$ to $K_{ext} = 34 \pm 1\ \%$.

Реализация режима работы циклотрона АИЦ-144 для протонной терапии меланомы глаза

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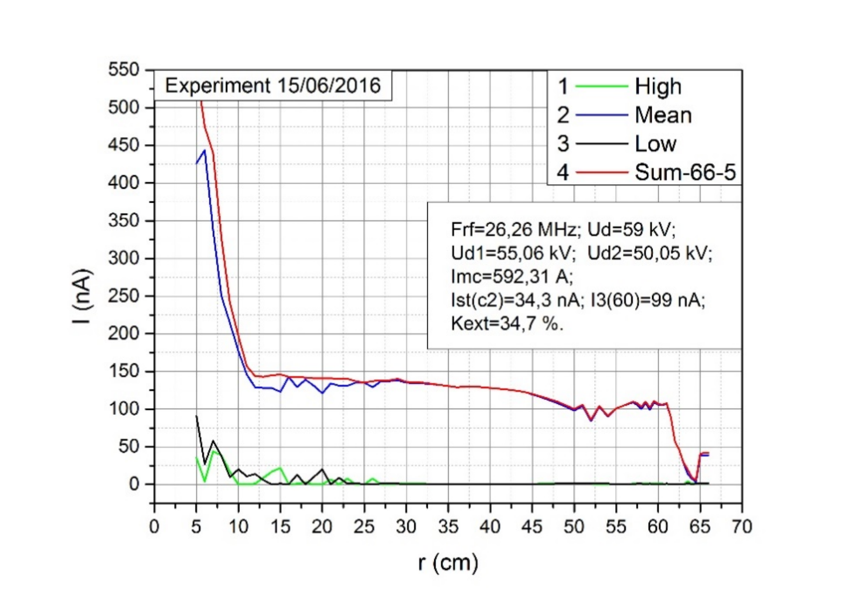
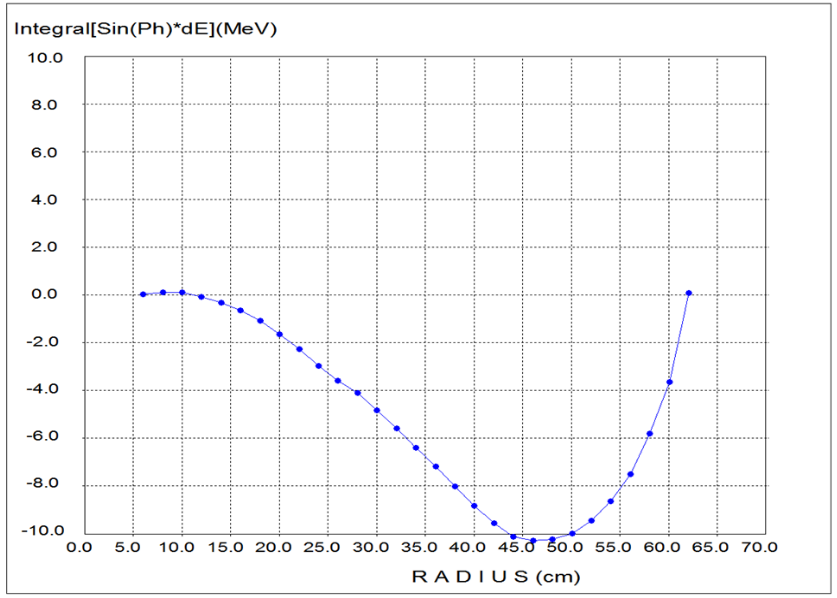
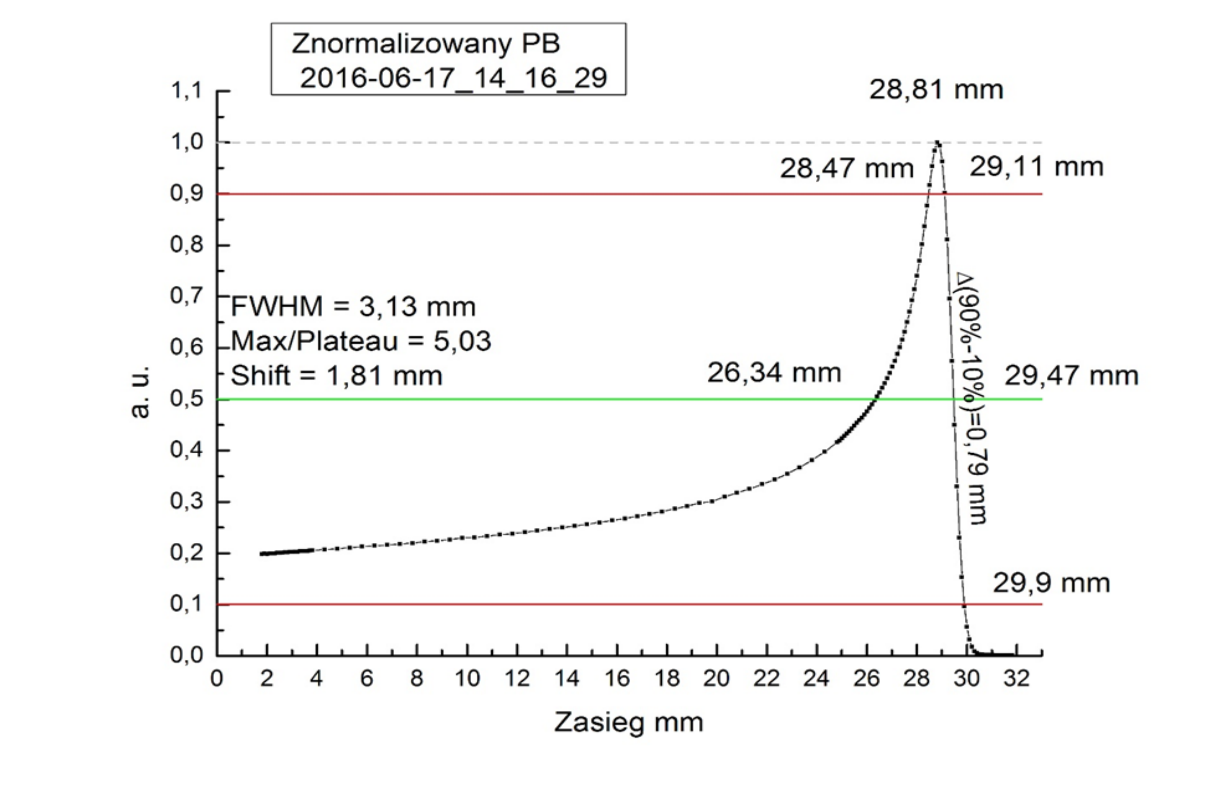




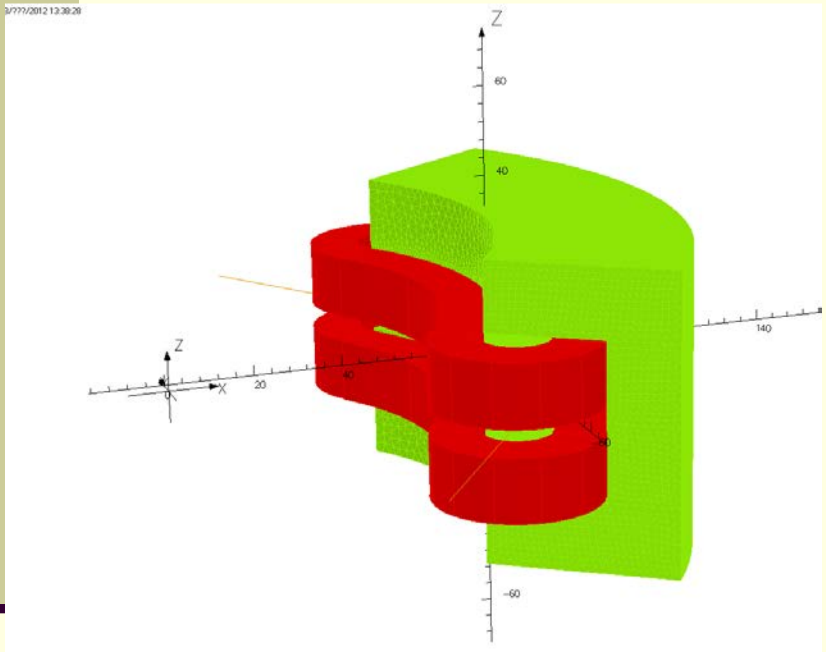
The measured current of proton beam.

The phase–energy integral.



- Maximum of the Bragg peak of protons in water is *L=28,81 mm*. The allowable range of *L* values for the maximum of the Bragg peak at the treatment of eye melanoma using the AIC–144 cyclotron is *L = 28,8±0,18 mm.* The length of the trailing edge of the Bragg peak in the range of 90% to 10% was ΔL = *0,79 mm*. This is the best value for isochronous cyclotrons used for the treatment of eye melanoma by proton beam with kinetic energy of extracted ions: $E_k \sim 60 \div 63\ MeV$.

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

Main results

a) 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).

b) 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.

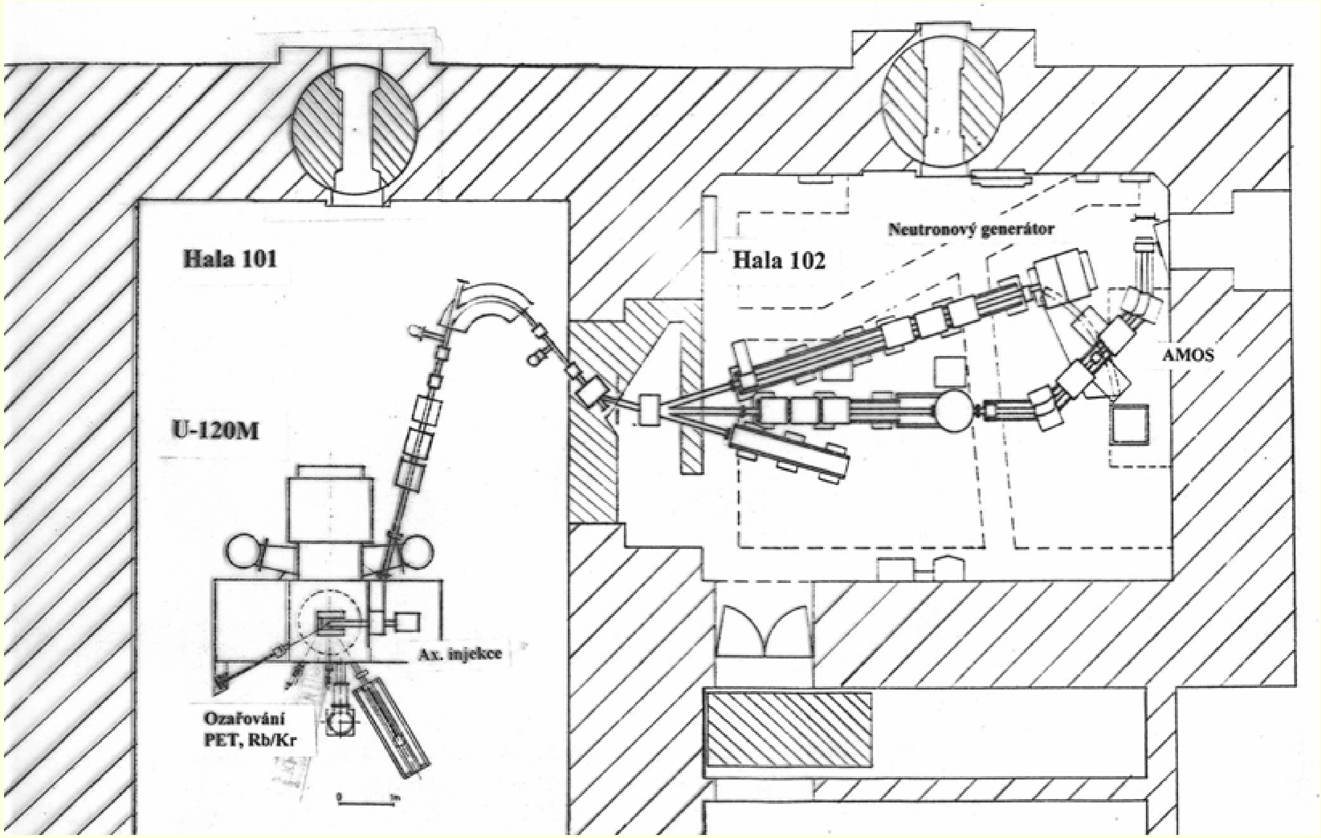
c) It was received stable irradiation by proton beam on the position of patients with optimal run in water. This allows the irradiation of tumors located inside of the eye in a maximal range from 29.1 mm to 29.9 mm (from 90 % to 10 % of the Brag peak's back front), this corresponds to the energy of beam's 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.

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

e) Manufacturing yoke of the M1 magnet and manufacturing accessories for the M1 and M2 magnets in JINR (Dubna) factory started in the IV quarter of 2016 (at present time).

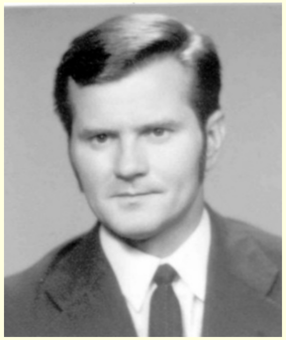
Cyclotron U-120M, Řež,Czech Republic

Tomas Matlochka



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

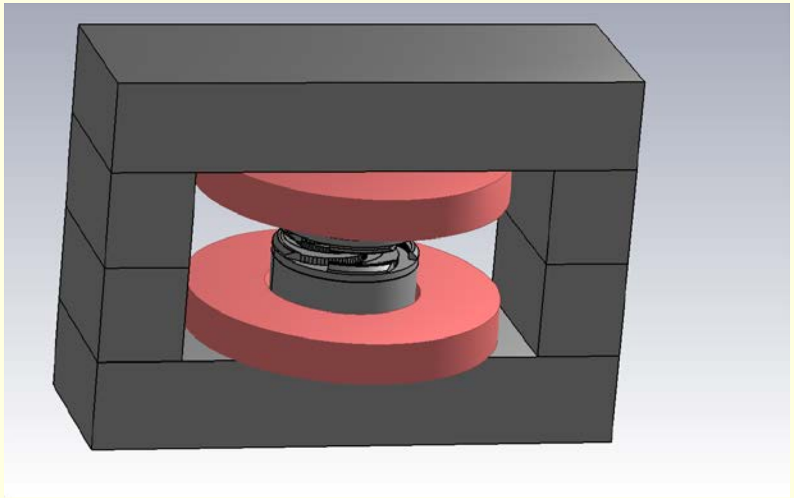
V.P. Dmitrievskij, L.M. Onischenko

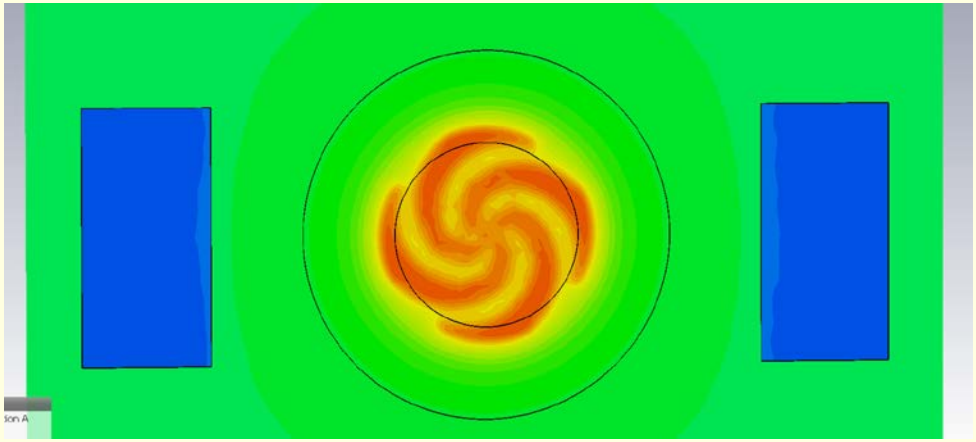


Zdeněk Trejbal, Miloslav Křivánek, Milan Čihák, Josef Šinágl

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

Computer model of the magnet





Magnetic field distribution

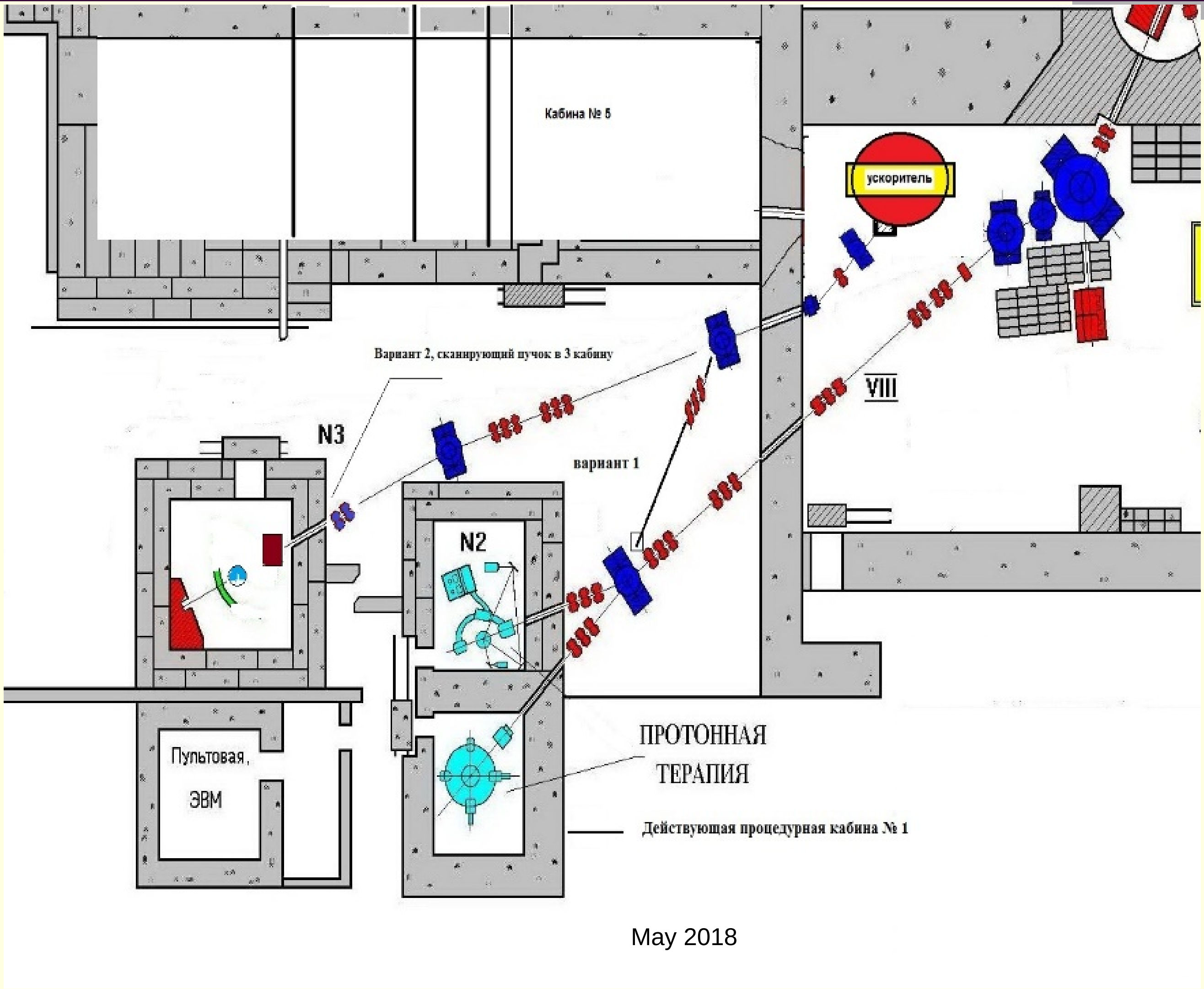
We plan to help to correct extraction of positive ions by electrostatic deflectors. For this purpose computer simulations of the magnetic field and beam dynamic simulations during extraction are under way.

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

Схема демонстрационного центра протонной терапии на базе сверхпроводящего синхроциклотрона и медицинской кабины МТК ЛЯП.



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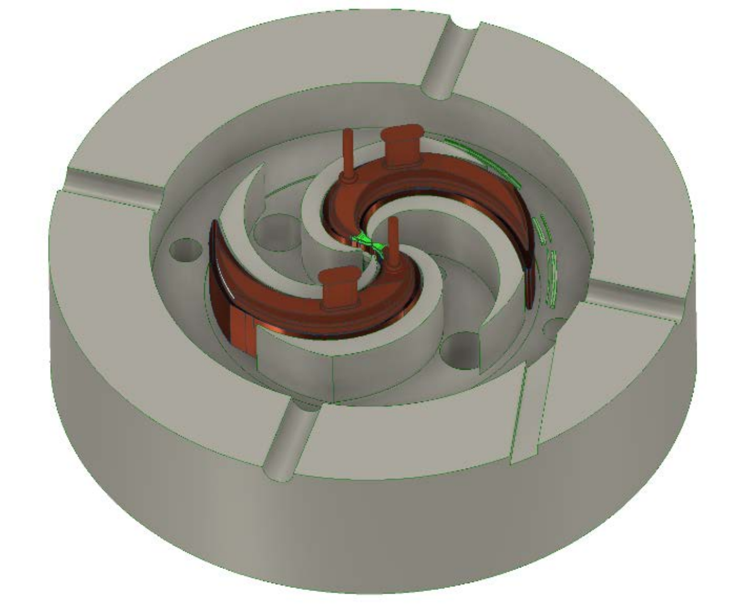
Main characteristics of the magnet:

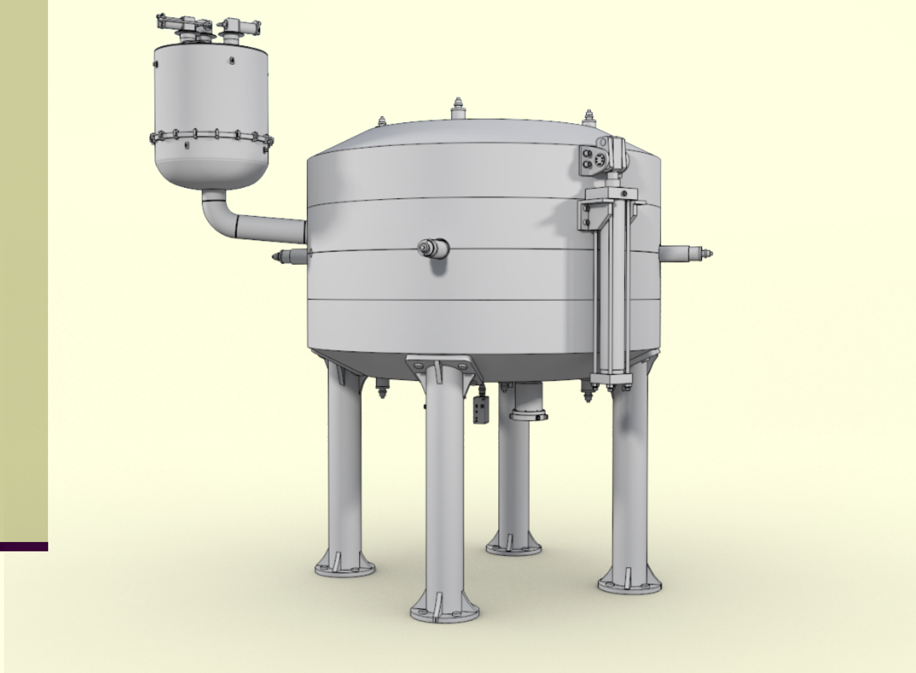
- Four-fold symmetry and spiral sectors
- Deep-valley concept - valley depth = 27 cm with 2 RF cavities placed in the opposite valleys
- Small sectors gap near beam extraction
  - Accelerate ~5-7 mm from pole edge $\Rightarrow$ facilitate extraction
- Vertical focusing in the center (from R = 4 to 8 cm) is provided by bump of magnetic field
- Pole radius = 61 cm
- Outer diameter = 250 cm
- Height = 170 cm
- Hill field = 4.75 Tesla, valley field = 3 Tesla
- Weight about 55 tons

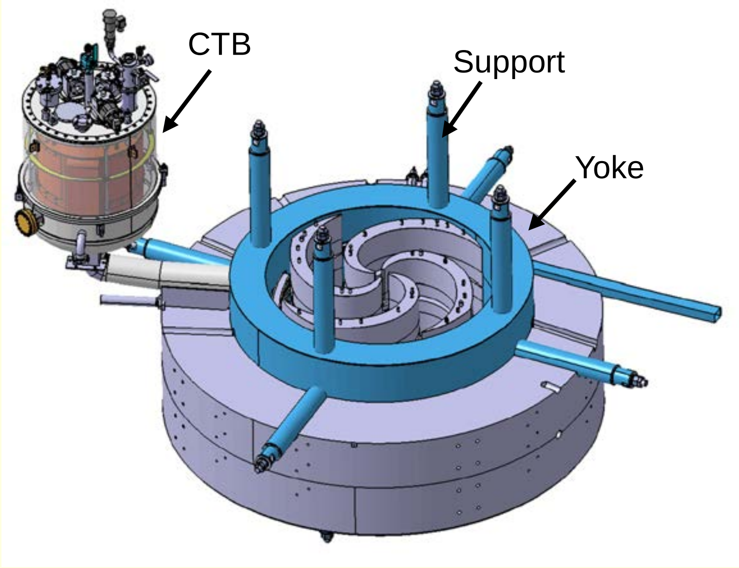
SC202 Основные параметры циклотрона



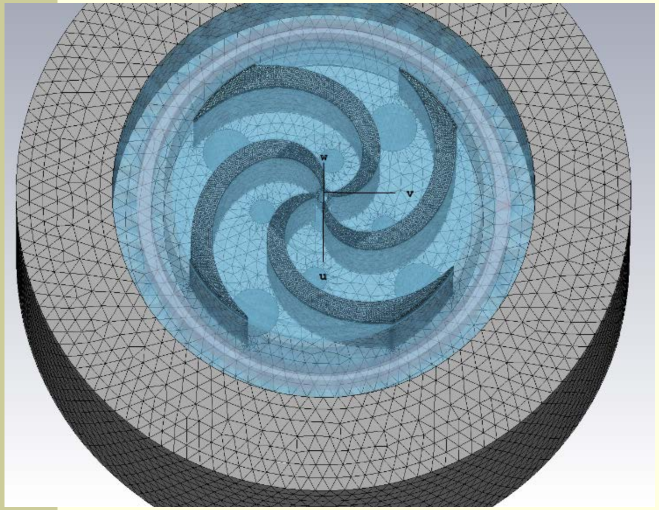
Mass	55 Tonn
RF Freq	91.5 MHz
Coil current	720 kA
Ion source	PIG
Sector azimuthal length	20-35 deg
Vertical gap between sectors	38->9 mm Decreasing to extraction. Not elliptical!
Valley depth	250mm

SC202 магнитная система

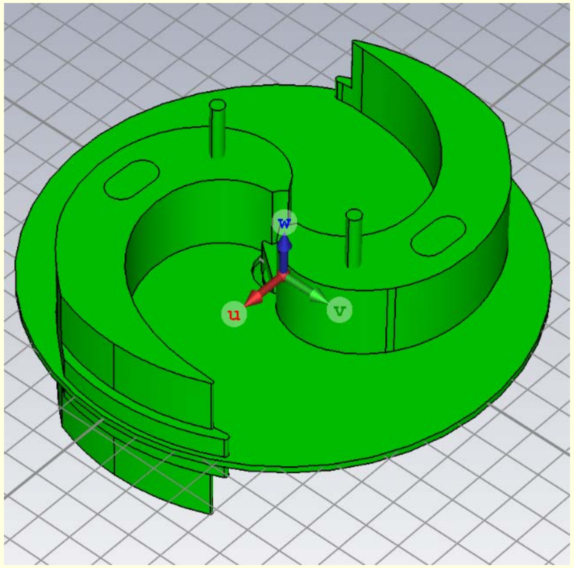




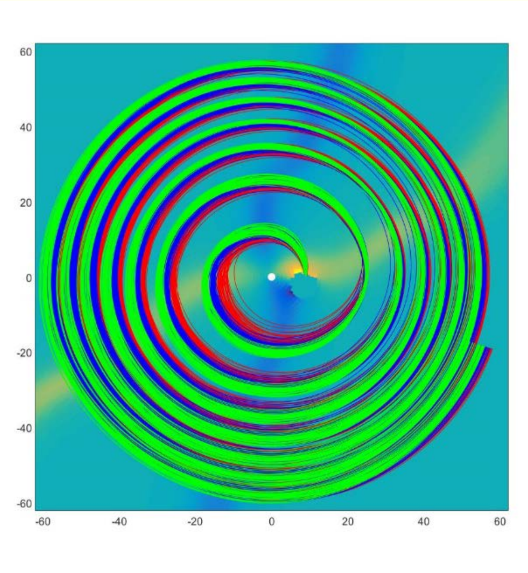
Project is successfully finished



Magnet



RF cavity



Beam dynamics

Магнитное поле

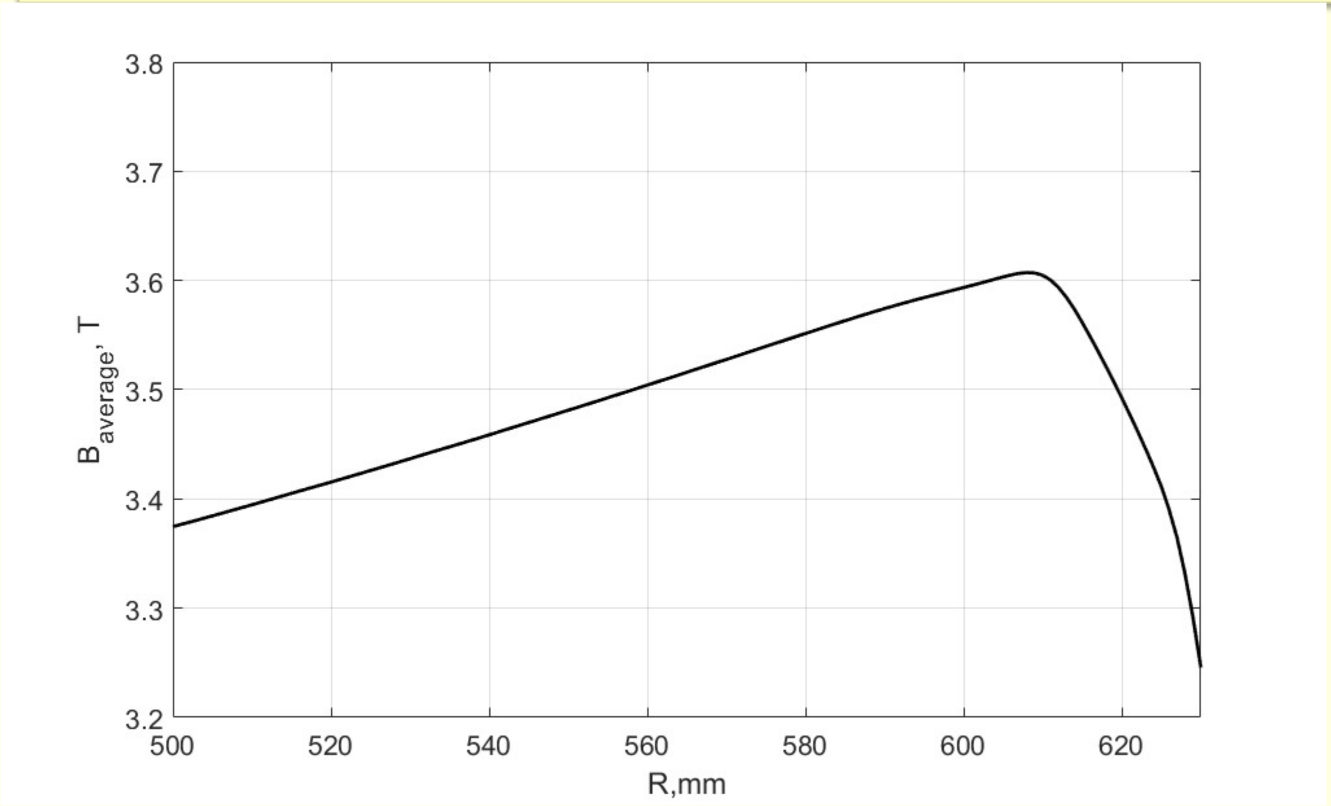
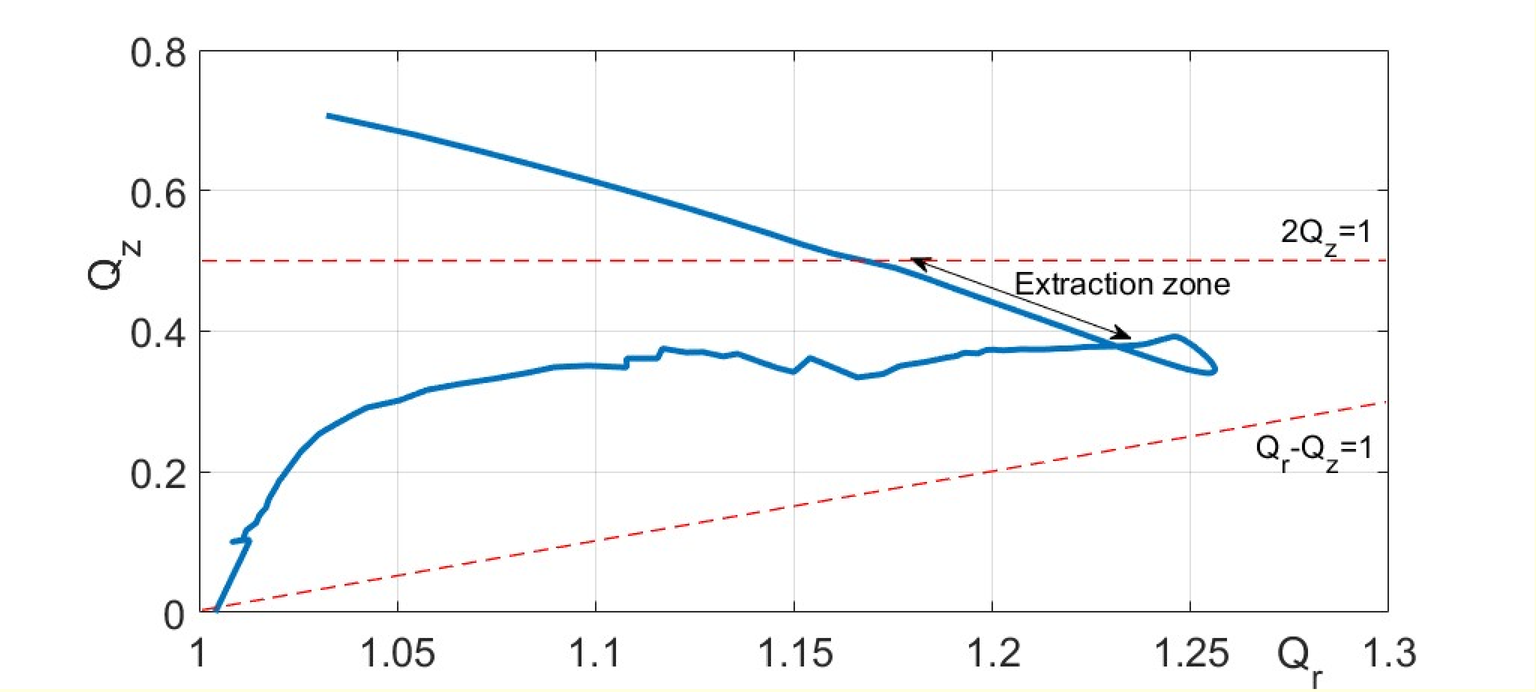
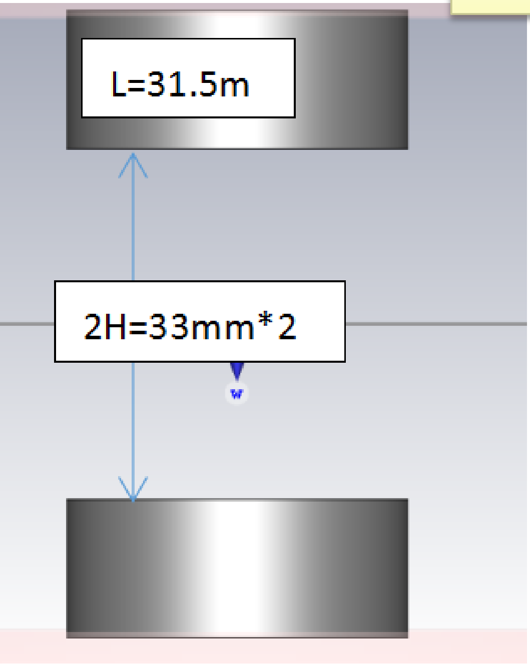


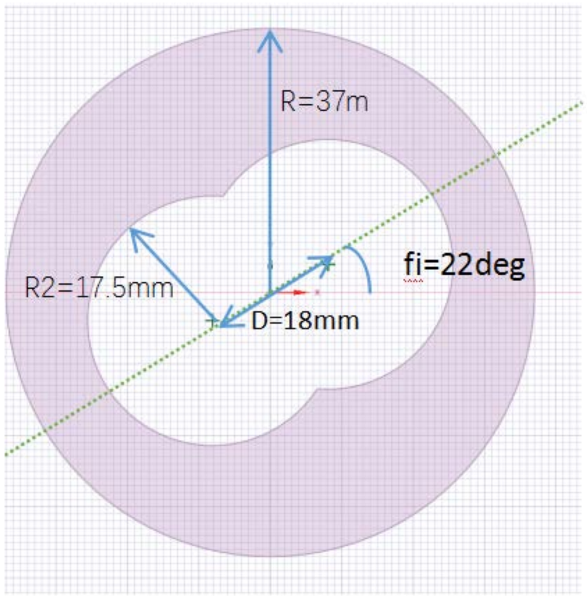
Диаграмма частот



Central region

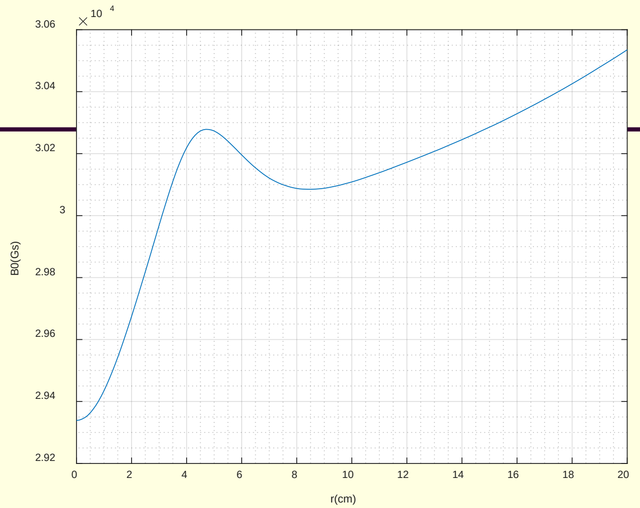


Lateral view

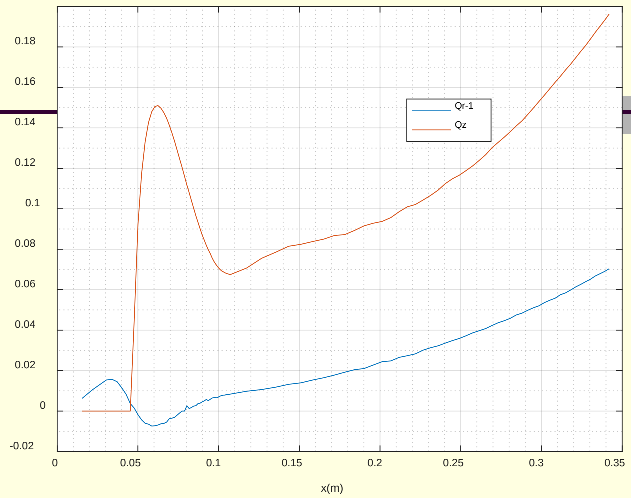


Top view

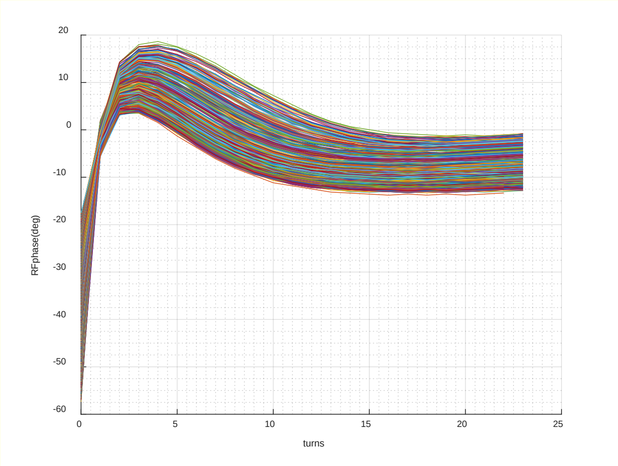
Parameter	Value
Material of Iron	Tested B-H
Distance to midplane H（mm)	33
Outer radius R （mm)	37
Thickness L（mm)	31.5
Distance between two Centre of the Ion Source Hole D（mm)	18
Rotating angle （deg)	-22
inner Radius R2 （mm)	17.5



× 10 4
3.06
3.04
3.02
3
2.98
2.96
2.94
2.92
B0(Gs)
0 2 4 6 8 10 12 14 16 18 20
r(cm)



0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
Qr-1
Qz
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
x(m)

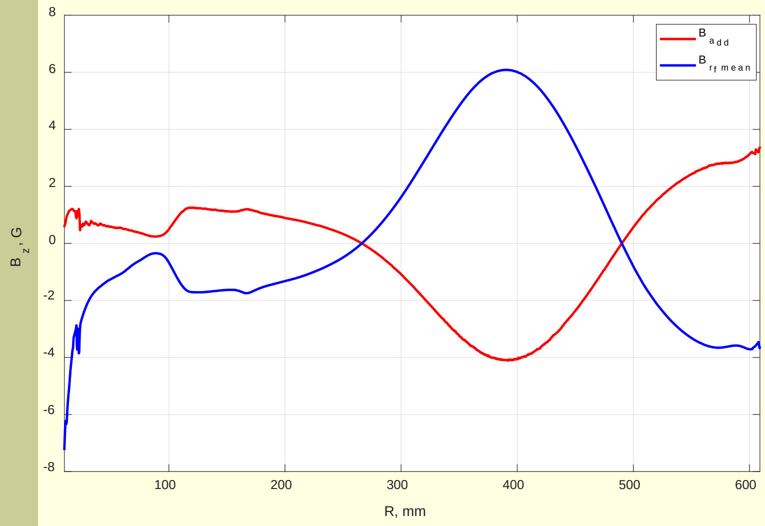


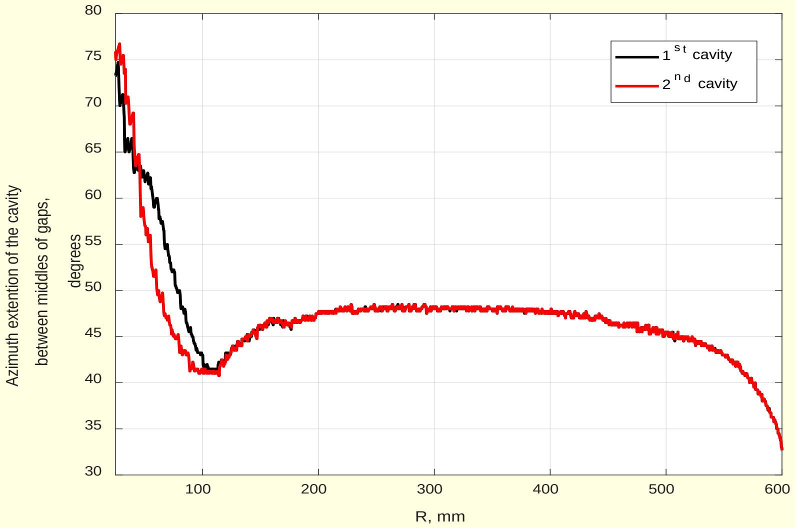
20
10
0
-10
-20
-30
-40
-50
-60
RFphase(deg)
0 5 10 15 20 25
turns

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



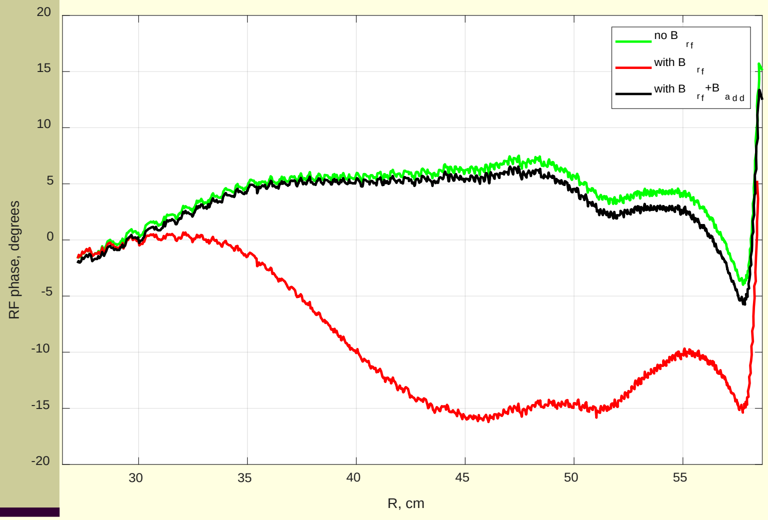


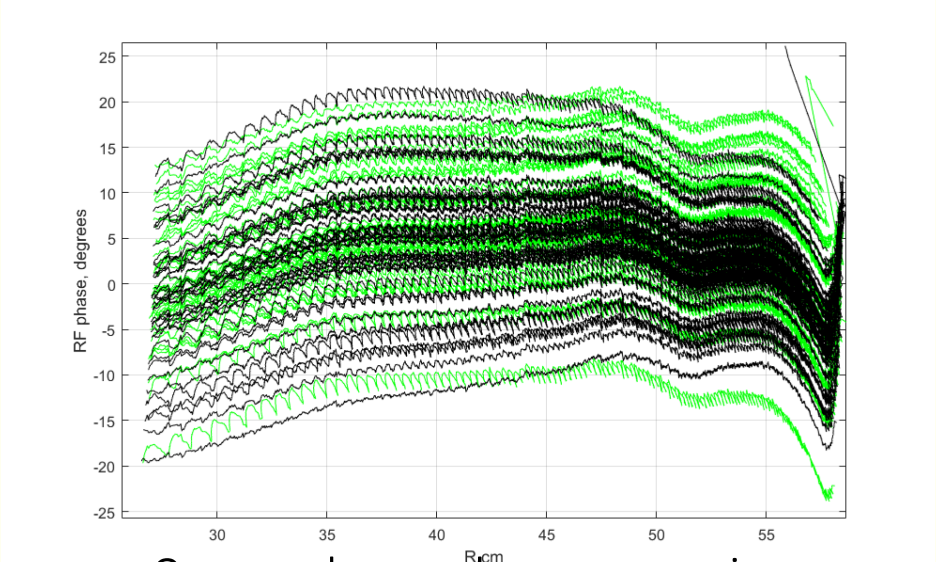
Mean value of B_{rf} field (blue line) and additional field (red line) versus radius. Isochronous field should be increased at R=40 cm by 4 G and decrease at R=60 cm by 3 G according to red curve for the designed voltage 70 kV at R=70 mm.

Azimuthal extension between the maximums of the field distribution

Popov D.V.

Phase motion with Brf compensation



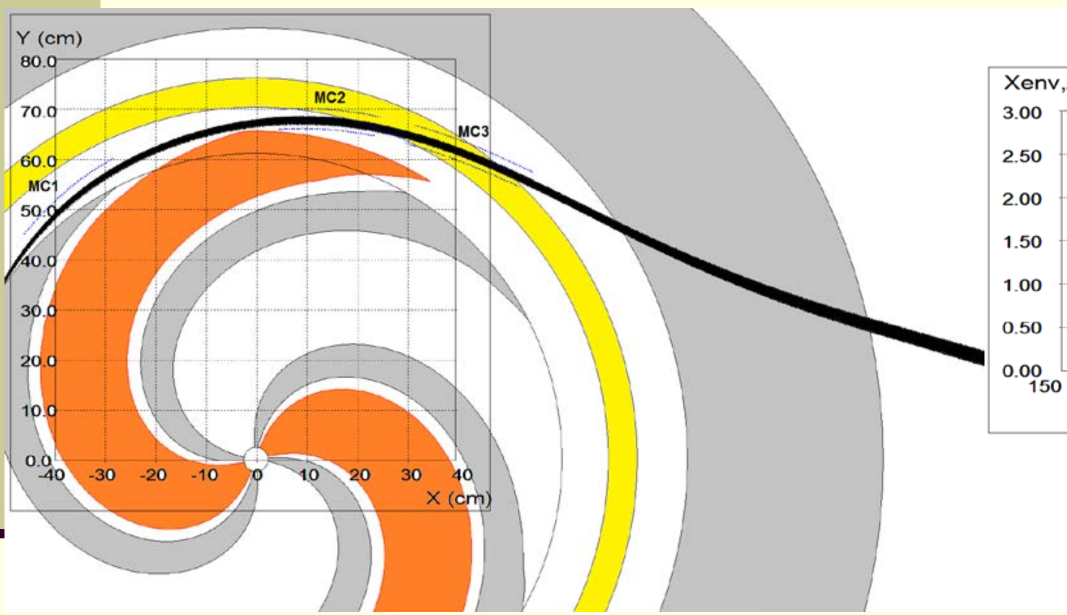


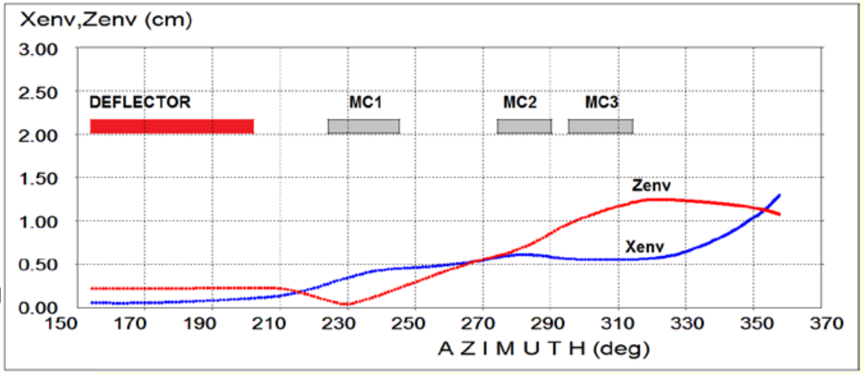
Phase motion of the central particle neglecting B_{RF} (green line) taking into account RF magnetic field (red line) and with B_{RF} +compensation (black line) for magnetic field from Dubna cyclotron and

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

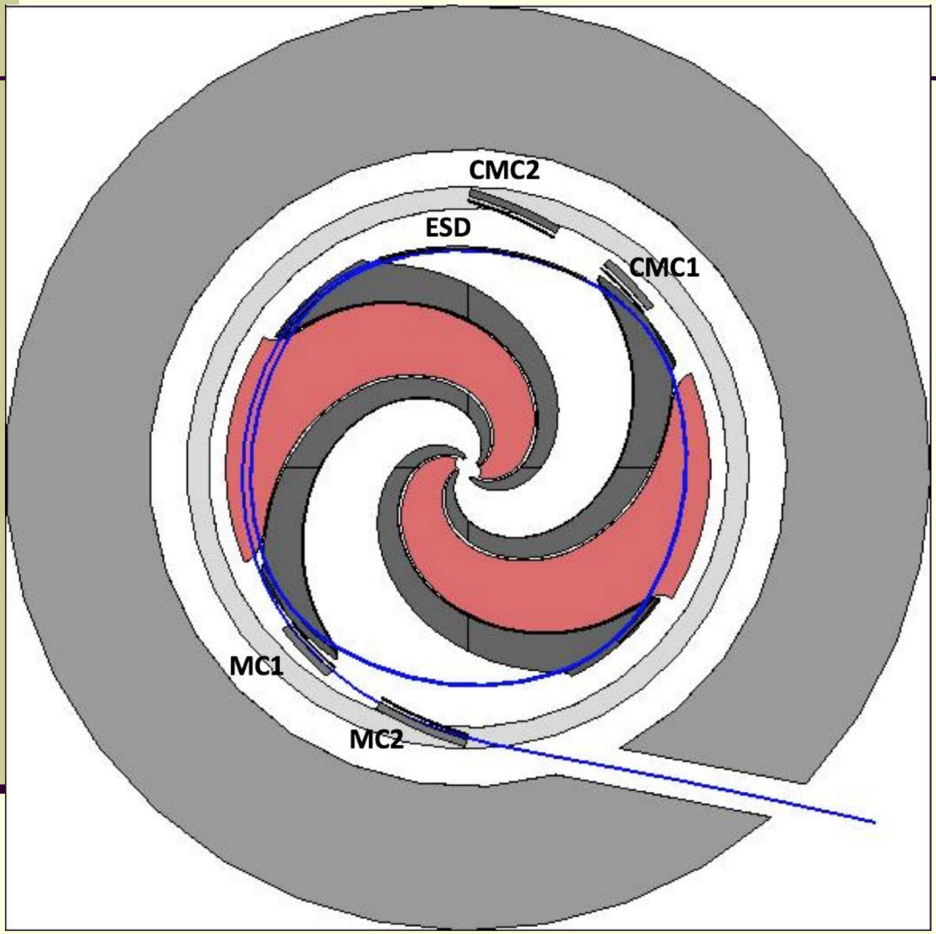
Karamysheva G., Malinin V.

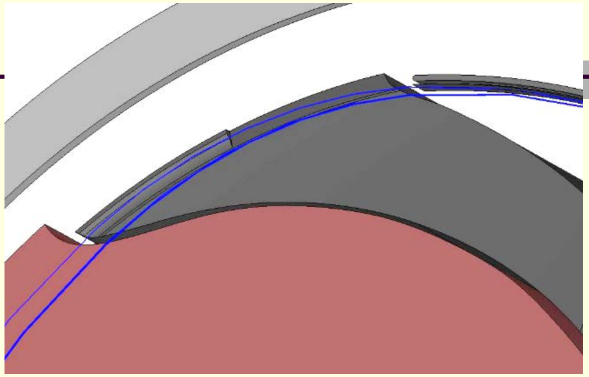
Extraction

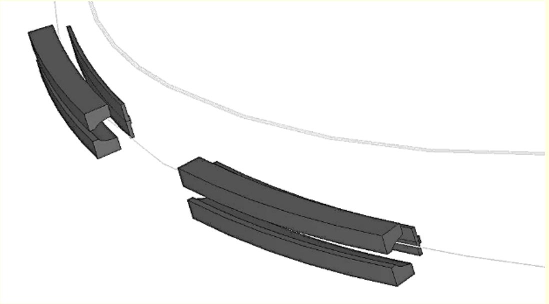


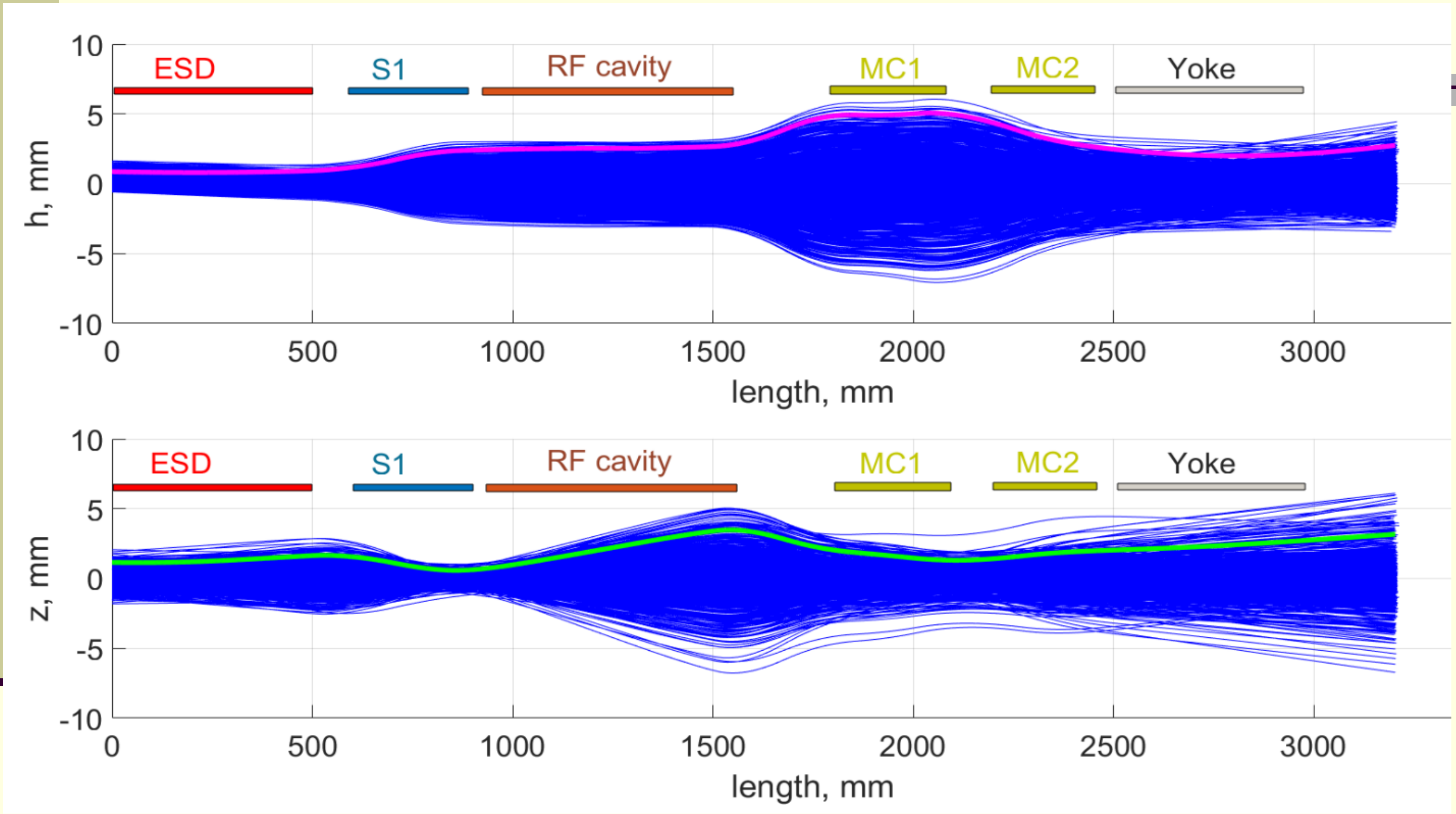


Beam envelopes in extraction system

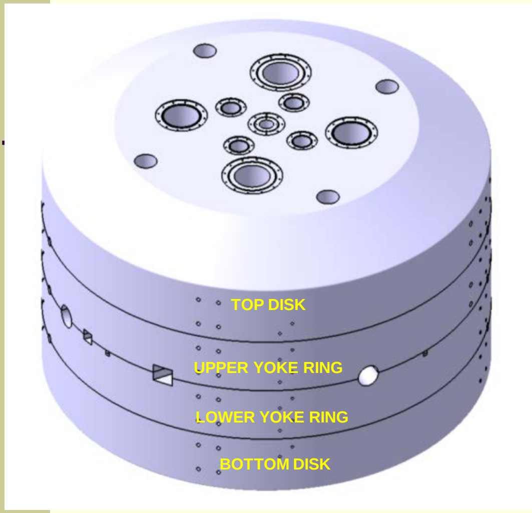

CMC2
ESD
CMC1
MC1
MC2

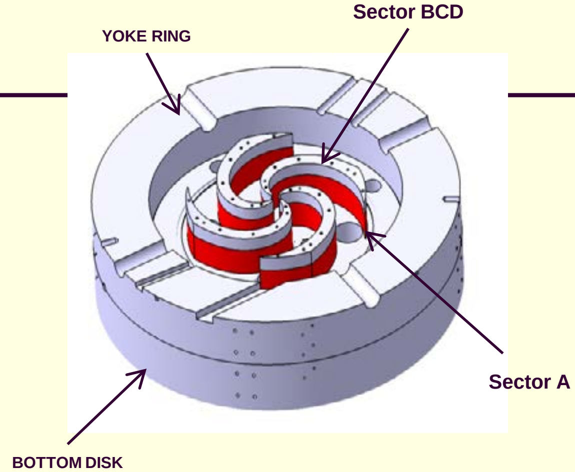


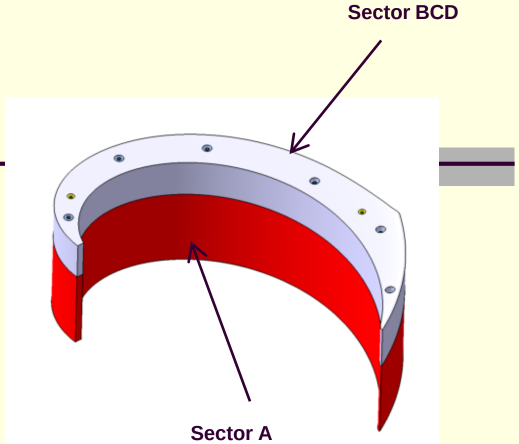


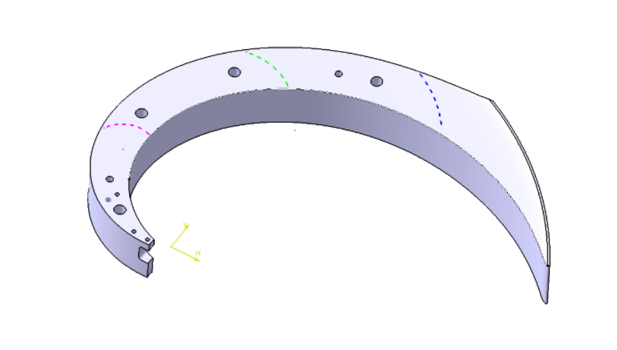


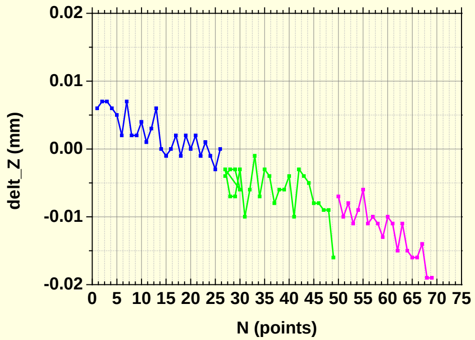
ESD
S1
RF cavity
MC1
MC2
Yoke
h, mm
length, mm
ESD
S1
RF cavity
MC1
MC2
Yoke
z, mm
length, mm

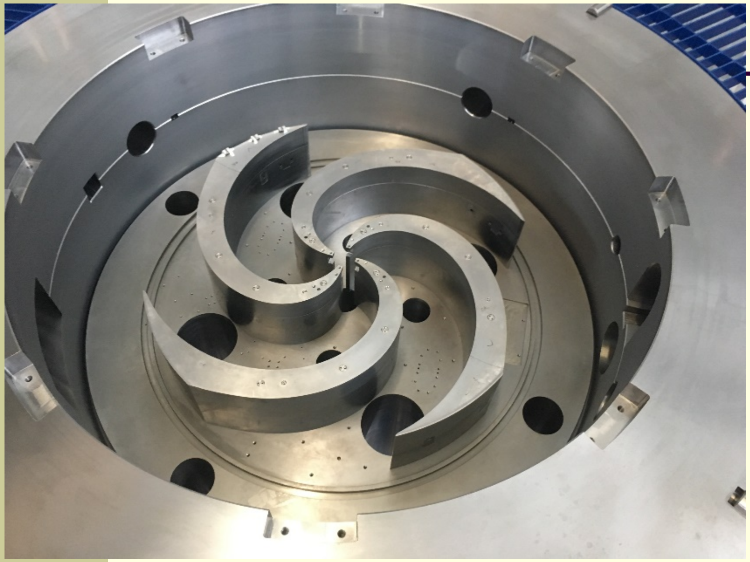

TOP DISK
UPPER YOKE RING
LOWER YOKE RING
BOTTOM DISK

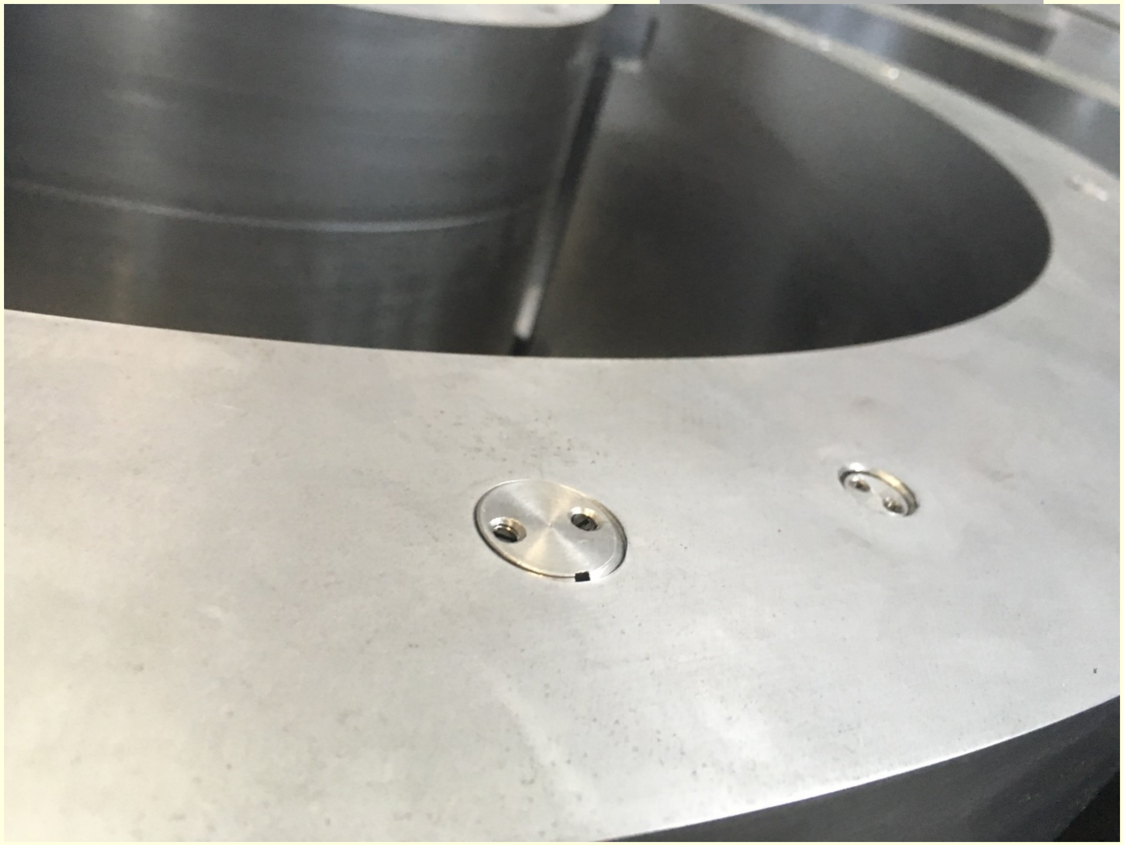

YOKE RING
Sector BCD
Sector A
BOTTOM DISK


Sector BCD
Sector A

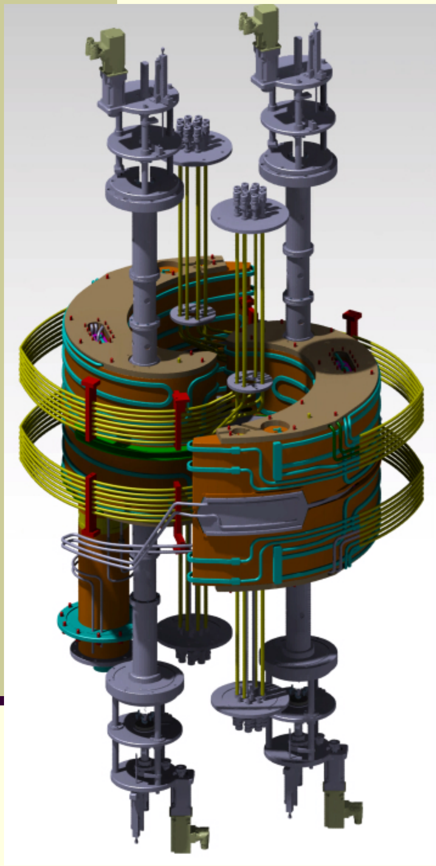


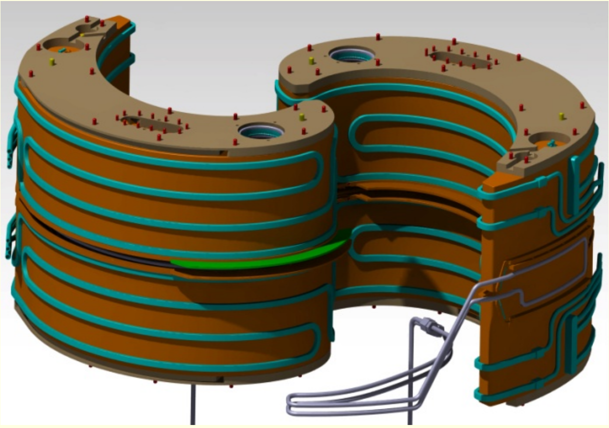

0.02
0.01
0.00
-0.01
-0.02
delt_Z (mm)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
N (points)





The Engineering desining of Cavity

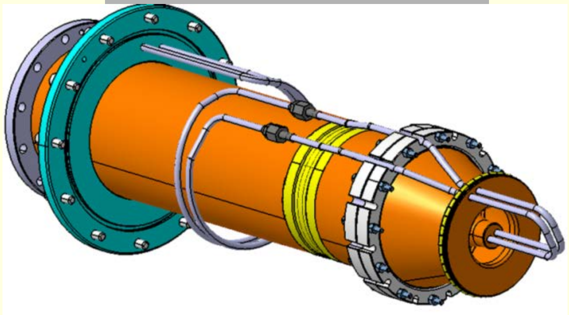




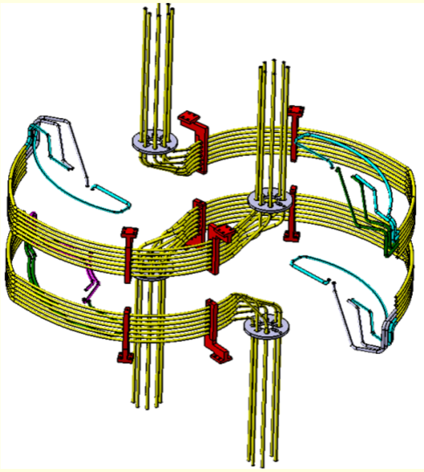
Cavity model

¼ Dee & Stem model

Tuning model

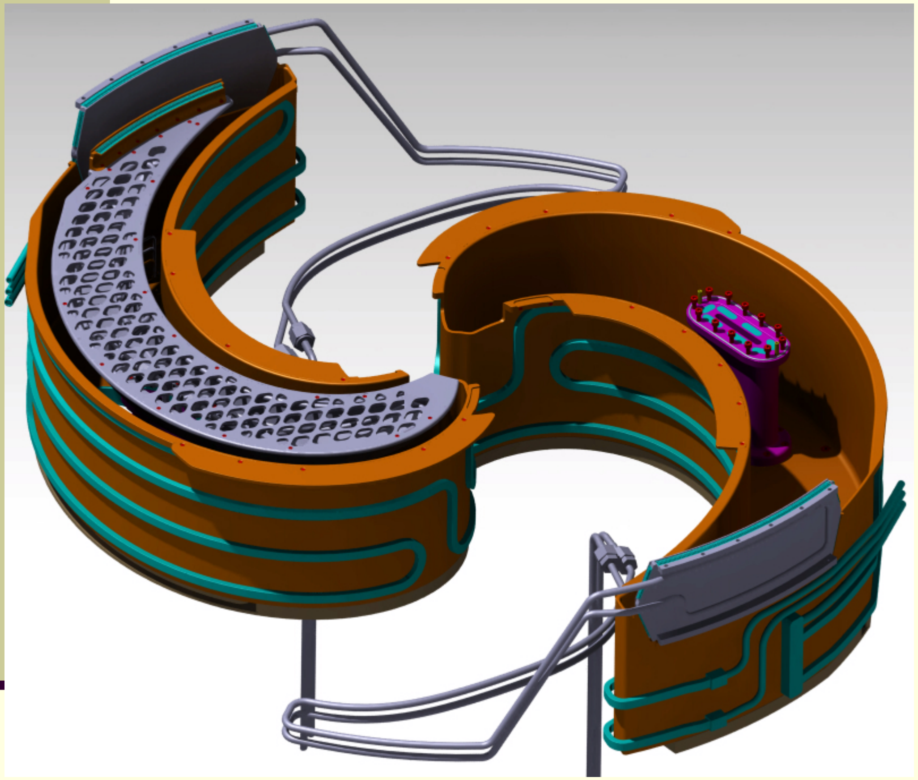


Coupling loop model

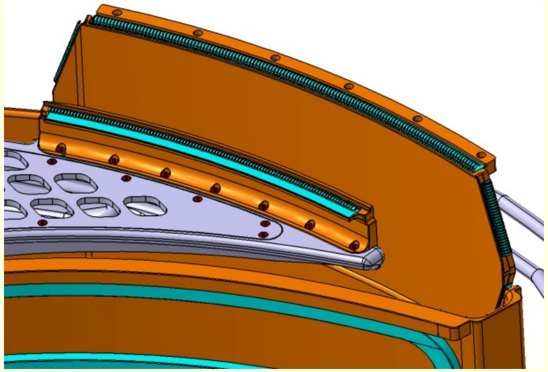


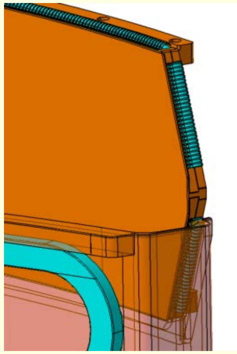
Cooling pipes model

The Engineering desining of Cavity



Cavity model





RF contact finger between upper and bottom cavity

RF cavity is consist of cavity ,dummy Dee,cooling pipes and RF connector. The key points are :

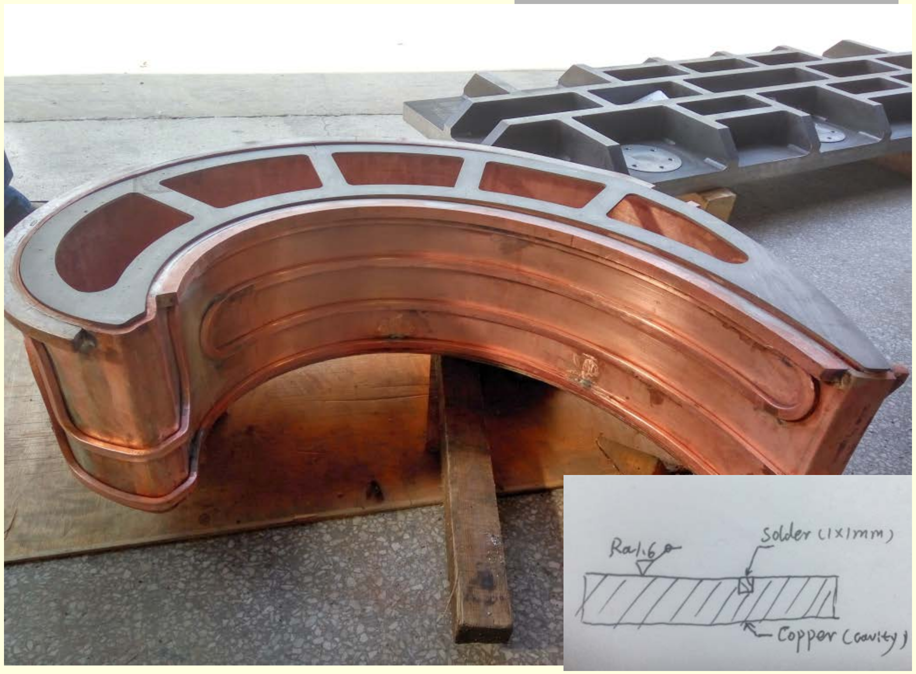
◆The mechanical precision control

◆Good cooling

◆Good roughness

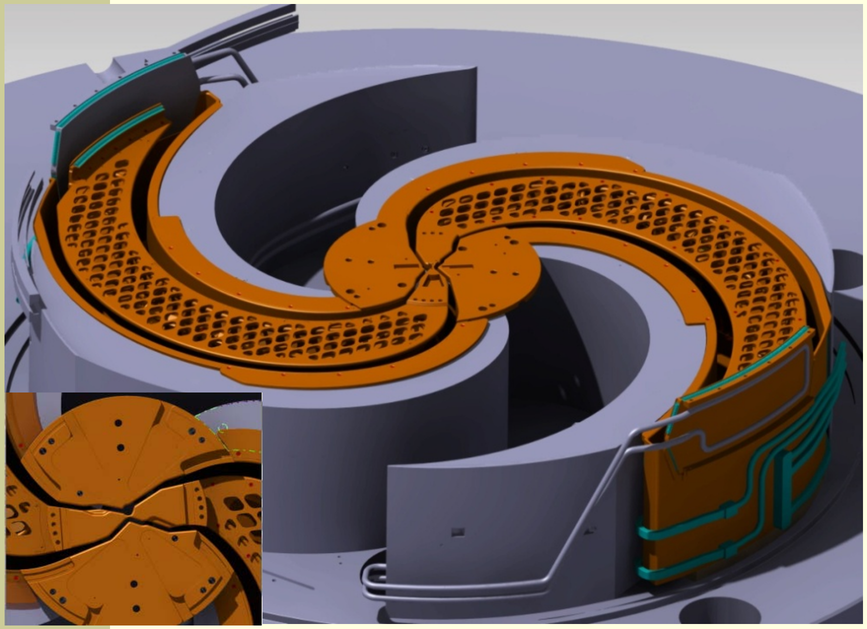
◆Good RF contact finger

The Engineering desining of Cavity

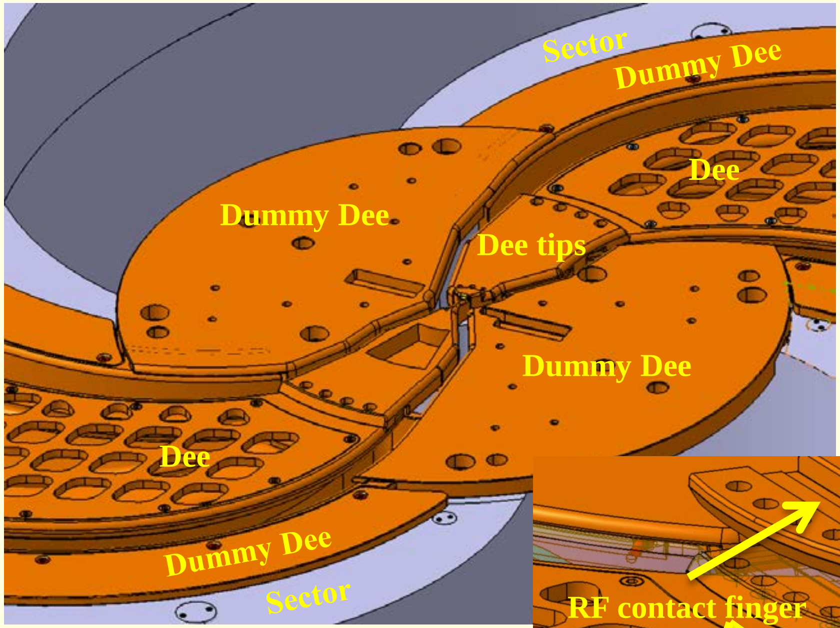


Cooling pipes welding after cleaning

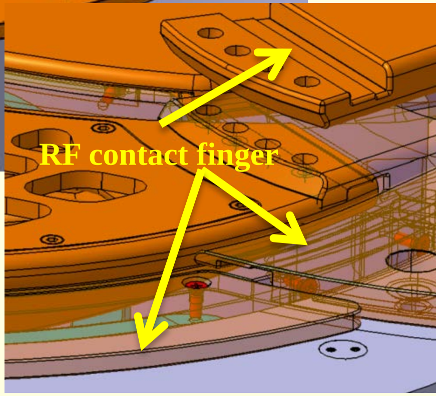
The Engineering Designing of Cavity



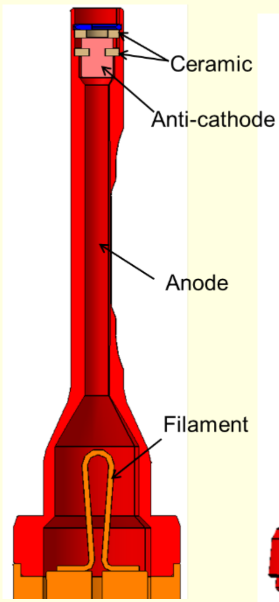
Bottom cavity and center region



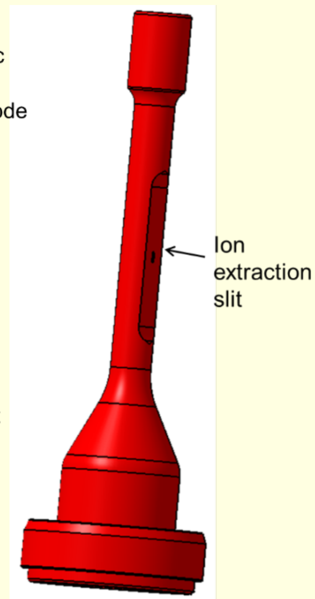
Detail view of bottom center region



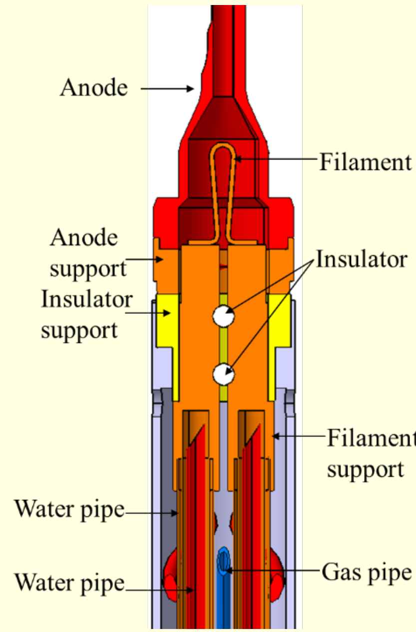
Source



Ceramic
Anti-cathode
Anode
Filament

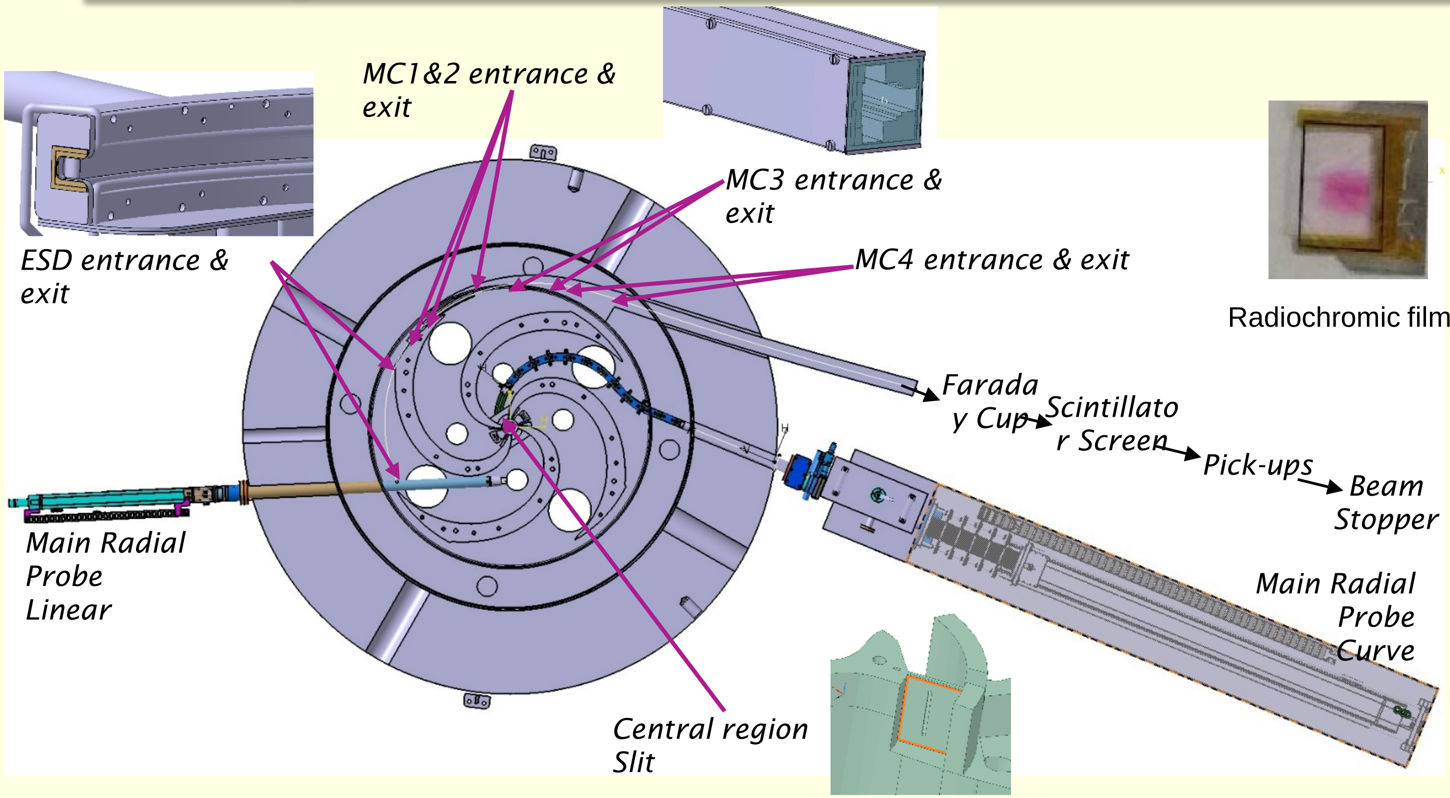


Ion
extraction
slit



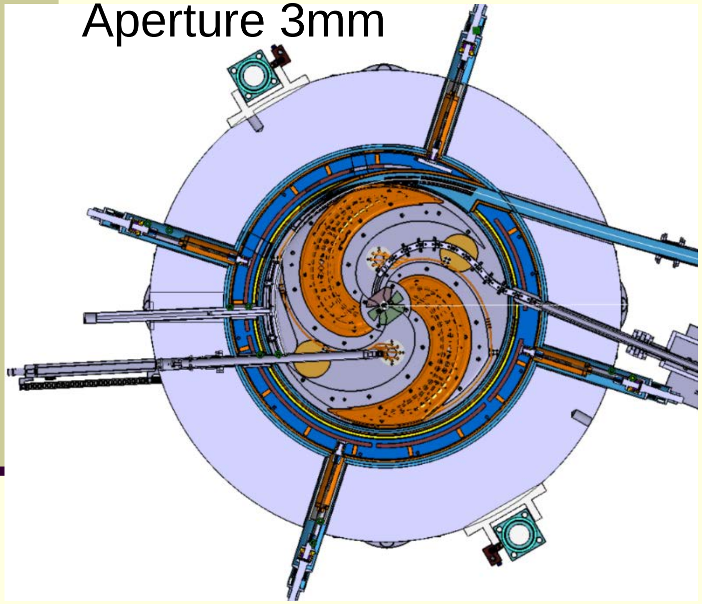
Anode
Filament
Anode
support
Insulator
Insulator
support
Filament
support
Water pipe
Water pipe
Gas pipe

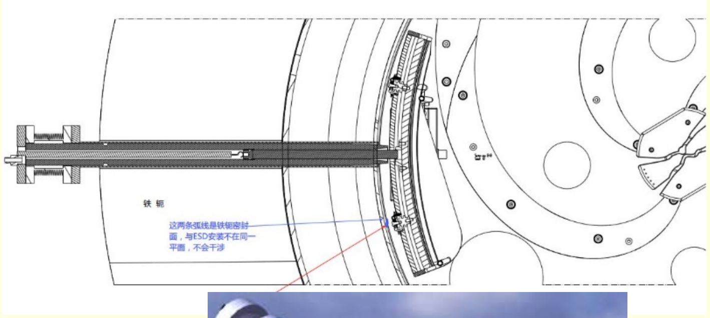
Diagnostics

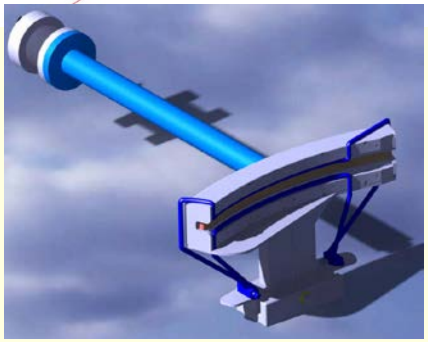


Вывод пучка

Septum electrode:
0.1mm
Aperture 3mm







Conclusion

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 %. Optimization of extraction is under way.

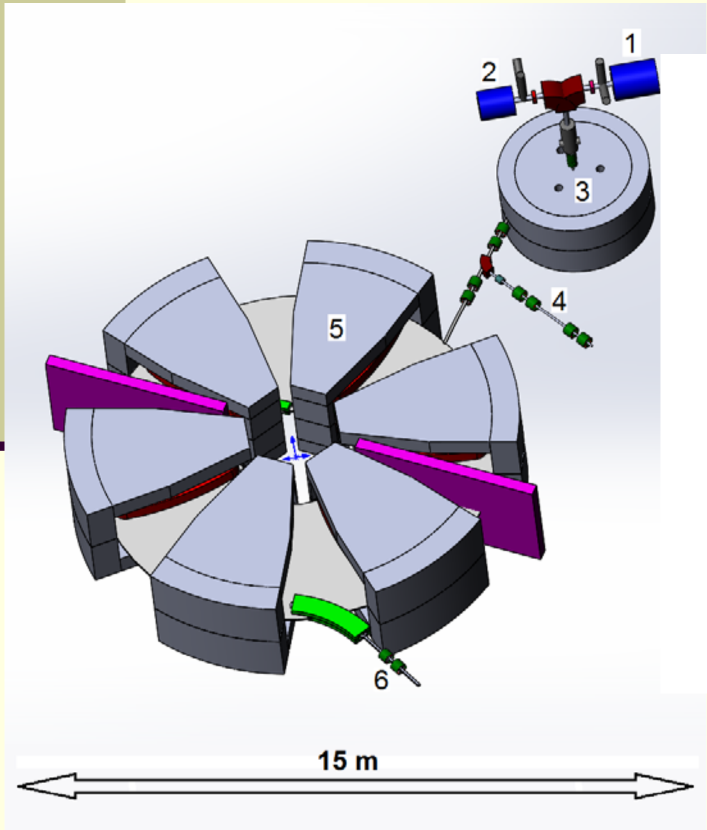
Development of the cyclotron method for high-current beam acceleration

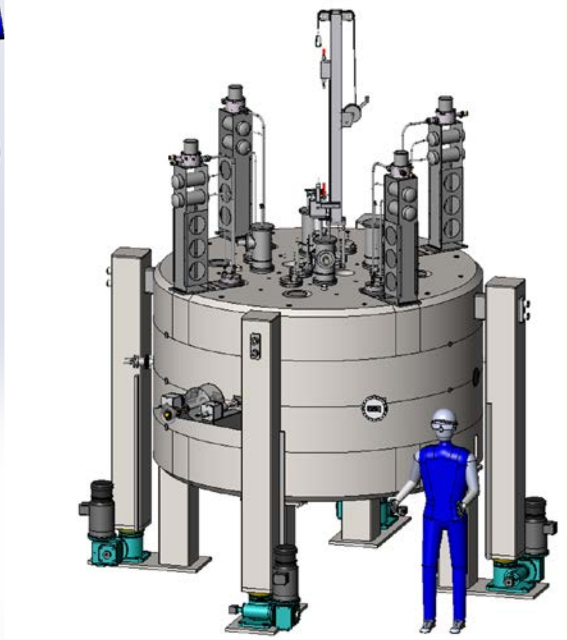
S.B.Vorozhtsov, V.L. Smirnov

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!





May 2018

2015-2018 годах опубликовано около 50 печатных работ,

в том числе 20 в рецензируемых журналах

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*
  - etc

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

Этапы работы

- Совершенствование фазотрона и трактов его пучков.
- Разработка циклотронов для медицинских применений.
- Разработка и изготовление сверхпроводящего циклотрона для протонной терапии совместно с ИФП (Хефей, КНР).
- Развитие физико-технических методов и программ для разработки перспективных ускорителей циклотронного типа.

Список участников и организаций

Страна или организация	Город	Институт или лаборатория
Польша	Краков	ИЯФ ПАН
Чехия	Ржеж	ИЯИ
Узбекистан	Ташкент	ИЯФ АН РУз
Китай	Хэфэй	ИФП
Бельгия	Лувен-ла-Нев	IBA
Япония	Чибо	NIRS
США	Лансинг	IONETIX

Ожидаемые результаты по завершении темы

- Устойчивая работа Фазотрона, модернизация систем электропитания трактов пучков Фазотрона.
- Запуск специализированного сверхпроводящего изохронного циклотрона SC202 для протонной терапии.
- Создание методик и программ для проектирования ускорителей циклотронного типа. Применение разработок в проектах ускорителей.

Полная сметная стоимость темы

№№ п/п	Наименование работ	Полная стоимость	Расходы в год (тыс. долл. США)		
			1-й год	2-й год	3-й год…
1.	Совершенствование фазотрона и трактов его пучков	**630**	**210**	**210**	**210**
2.	Разработка циклотронов для медицинских применений.	**60**	**20**	**20**	**20**
	ВСЕГО	**690**	**230**	**230**	**230**

Другие источники финансирования

Программа Полномочного Представителя Правительства Республики Польша 15, 000 тыс.дол.

От ОИЯИ участвует около 40 научных сотрудников и инженеров, в основном сотрудников отделов НЭОНУ, НХП “ОФ”.

- Основные участники работ:
  Ворожцов С.Б.,Галкин Р.В., Гурский С.В., Доля С.Н., Заплатин Н.Л., Казакова Г.Г., Карамышев О.В., Киян И.Н., Лепкина О.Е., Ломакина О.В, Морозов Н.А.,Петров Д.С., Попов Д.В., Малинин В.А., Поляков Ю.А., Романов В.М., Самсонов Е.В., Смирнов В.Л., Сыресин Е.М., Чеснов А.Ф., Шакун Н.Г, Ширков С.Г., Яковенко С.Л.
- Из них моложе 35 лет – 10 человек.

Thank you for your attention