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IMPROVEMENT OF THE JINR PHASOTRON AND DESIGN OF CYCLOTRONS FOR FUNDAMENTAL AND APPLIED RESEARCH

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List of Activities

1. **Improvement of the JINR Phasotron and beam channels.**

S.L. Yakovenko, N.G. Shakun

2. **Design and modernization of the cyclotrons for medical purpose.**

G.A. Karamysheva

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

G.D. Shirkov

4. **Development of the cyclotron method for high-current beam acceleration.**

S.B. Vorozhtsov

1. 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:

- 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;
- 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.
- All switching devices were replaced with modern ones in the power supply systems of the beam lines;

- Power schemes for economical and reliable indication systems for Fazotron control panels and racks have been developed and implemented;
- 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.

As a result of the modernization, the energy savings amounted to about 900 kW.

In 2016-2018, 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 Phazotron operating time is 500 hours per year. Mostly for radiobiological research.

2. DESIGN AND MODERNIZATION OF THE CYCLOTRONS FOR MEDICAL PURPOSE.

Important tasks of the topic are the development of methods and codes for designing cyclotron-type accelerators, as well as the application of methods for the development and modification of specific cyclotrons for medical and other applications. Cyclotrons accelerating charged particles to low and medium energies are the main tool for research in the field of atomic nucleus physics and nuclear reactions. At the same time, cyclotrons have proven themselves no less significant for applied applications, in particular in radiation medicine. Low-energy accelerators for producing medical isotopes and cyclotrons with an average energy sufficient for the treatment of cancer patients are widely used.

The design of each accelerator is based on the study of various options for cyclotron systems and optimization of the structure of the installation as a whole. Calculations of beam dynamics require taking into account a wide variety of effects: ion dissociation in an electromagnetic field, beam losses due to charge exchange on the residual gas, space charge effects, depending on the type of cyclotron being developed. To provide all the requirements for accelerators, an integrated approach to the development and design of cyclotrons is necessary, since changing the parameters of one cyclotron system leads to the need to change other systems.

The result of quality development is an accelerator with:

- simple design of the magnet, and other systems;
- low power consumption;
- high beam quality;
- a limited number of adjustable parameters, of the order of 5 (power supply current of the main magnet, RF system voltage, etc.);
- continuous beam (quasicontinuous), which guarantees dose controllability during patient irradiation;
- small size.

It is necessary to adapt calculation methods not only to each accelerator being developed, but also when tuning and optimizing the parameters of operating installations, such as the AIC-144 cyclotron (INP PAS, Poland).

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

The work was carried out according to protocols on the implementation of joint research work. The protocol was concluded between JINR and INP PAS.

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. The task was set to achieve the maximum stable extraction coefficient of proton beam.

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 $K_{ext} = 34 \pm 1\ \%$. The extraction coefficient was stable during three days. The efficiency of proton beam extraction decreased by 5% after replacement of the cathode in the internal ion source. Fig. 1 shows the measured proton beam current as a function of the radius.

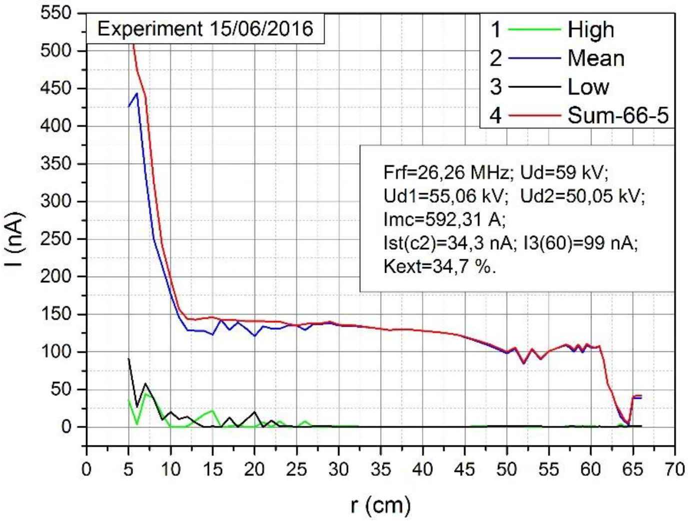

Figure 1: The measured current of proton beam.

Based on automated control system of the AIC–144 cyclotron the Smith–Garren's curve measurements were carried out. The Smith–Garren curve is dependence of integral beam current from current in main coil for certain set of radius values. The Smith–Garren's curves were measured for the main operation mode of the AIC–144 cyclotron. Based on measured data the calculations of proton beam dynamics were performed. The phase motion and the phase–energy integral were calculated. The results of calculations are presented in Fig. 2, 3.

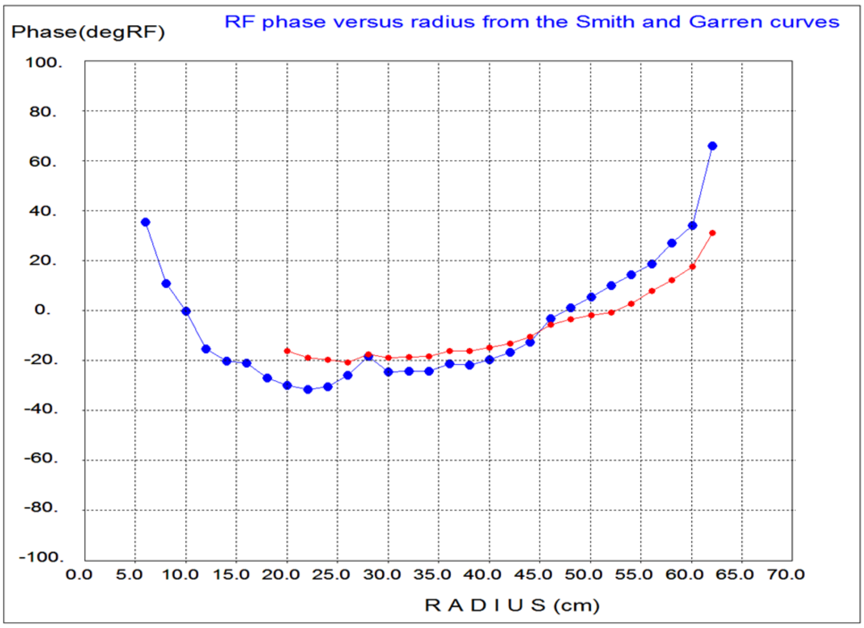

Figure 2: The phase motion. [1) Herve Marie. *"How to use Smith and Garren curves to correct isochronism"*. // Internal report of IBA. December 16, 1993. (Blue curve). 2) R.E. Berg, H.G. Blosser, M.M. Gordon. *"Theoretical and experimental beam studies for the Michigan State University cyclotron"*. // Nuclear Instruments and Methods. No 58 (1968). Pp. 327–341. (Red curve)].

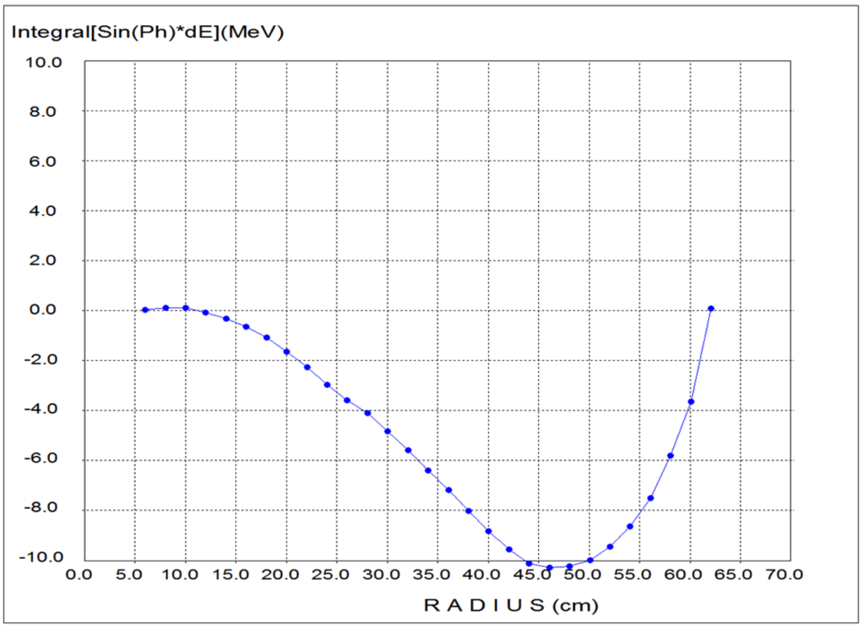

Figure 3: The phase–energy integral.

In 2016 the quality of the beam of extracted protons was tested in the room of proton therapy for the main operation mode of the AIC–144 cyclotron. The results of measurements are presented in Fig. 4, 5.

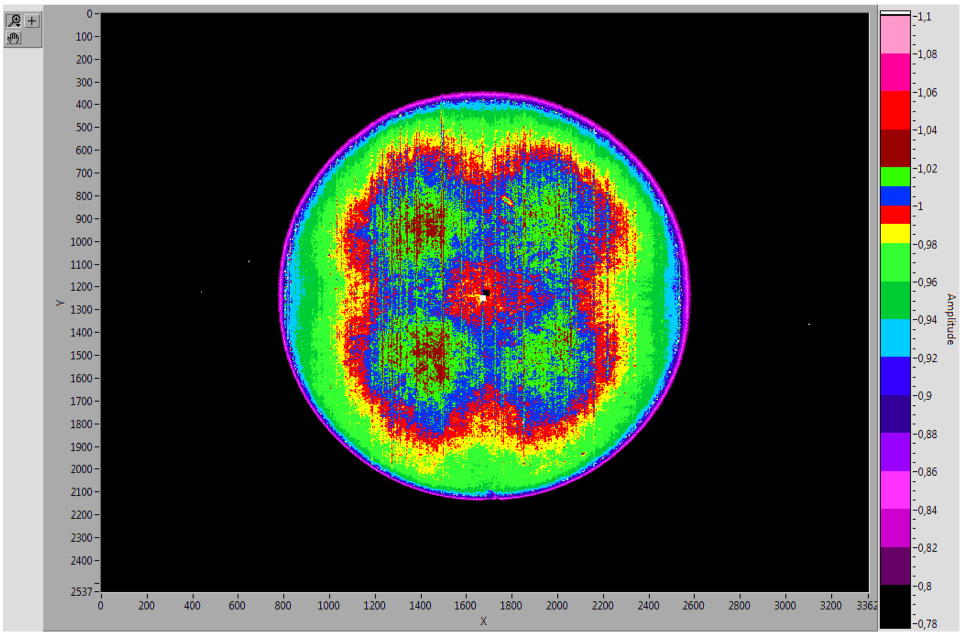

Figure 4: The profile of proton beam by using scintillator. (The collimator: *D=25 mm;* The exposure: *T=40 sec*).

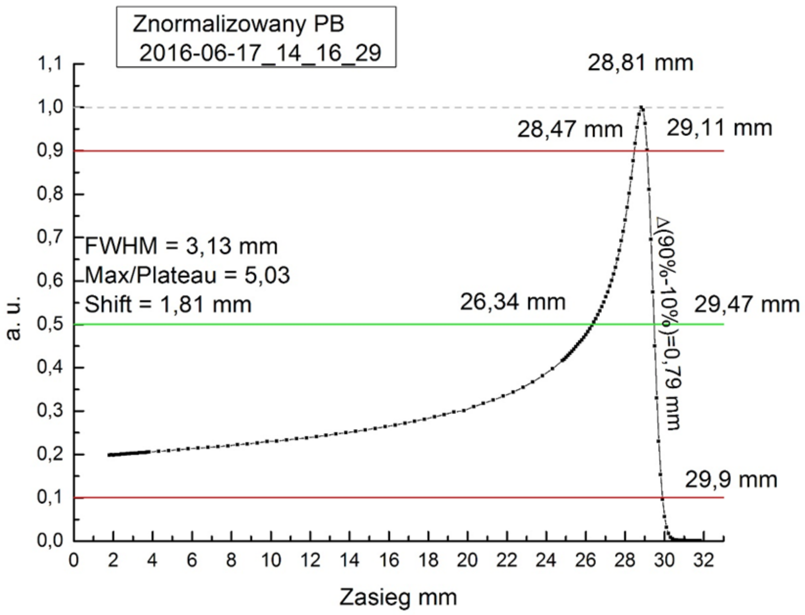

Figure 5: The Bragg peak at run of protons in water.

The Fig. 4 shows that the beam profile has a symmetrical shape. The Fig. 5 shows that 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 Δ*L = 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: $E_k \sim 60 \div 63\ MeV$.

The kinetic energy of protons in 90% of trailing edge of the Bragg peak measured in the room of proton therapy for the beam extracted from the AIC–144 cyclotron was $E_{k,end} \sim 58\ MeV$. The difference between the estimated value of the kinetic energy of protons at the exit of the AIC-144 cyclotron, and the value measured in the room of proton therapy is explained by losses in the glass and the air. The losses were ΔEk~2,7 *MeV*. From these results it is clear that the proton beam extracted from the AIC-144 cyclotron fully fits to demands of the Department of Medical Physics in the Cyclotron Center in Bronowice (Krakow, Poland), where the proton therapy of eye melanoma is carried out.

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 is shown in Figure 6.

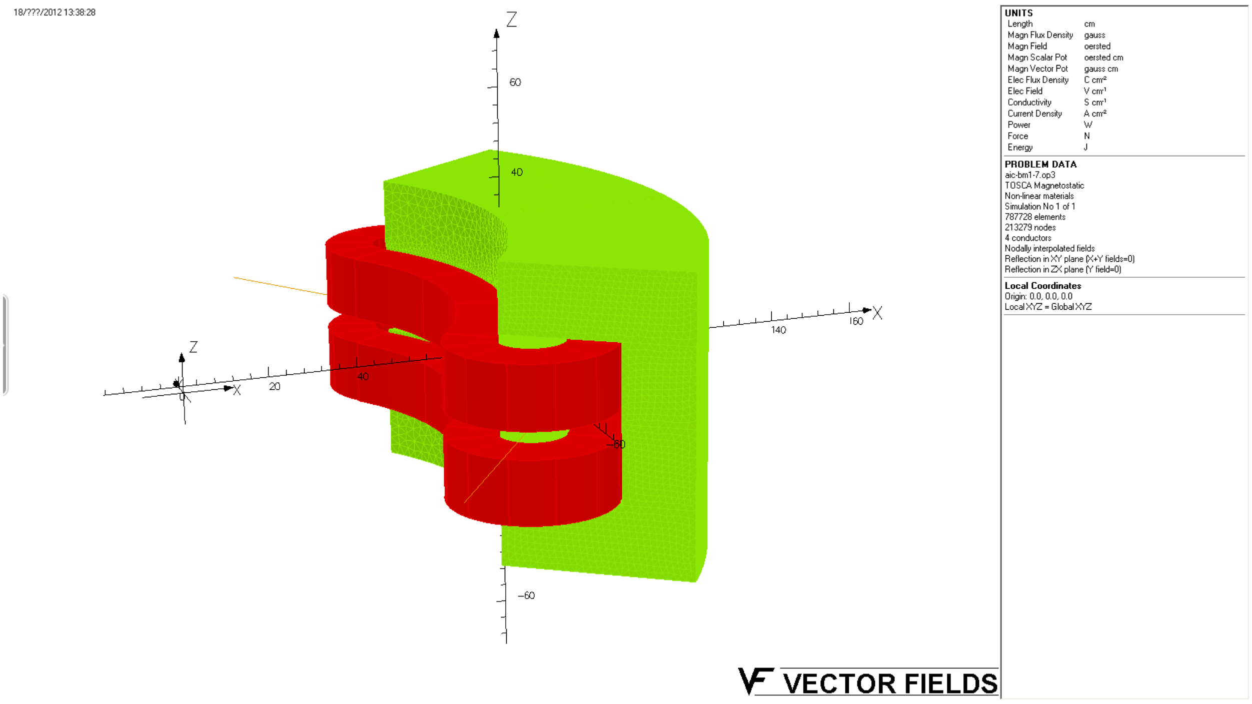

Figure 6: A general view of the new magnet M1

Table 1. Coil parameters of M1

Number of coils	2
Section number in coil	7
Number of turns in the section	22
Total number of turns	22x7x2=308
Conductor	Cu, 8.5x8.5 мм, ø5.3 мм
Length of conductor in one section	38 м
Current (protons 60.5 MeV)	255 A
Voltage	50 V
Power consumption	12.5 kW

Current density	5.1 A/mm^2
Weight of coils	240 kg

Magnet M2 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 in the range of angles of +13 to -24 degrees. The new magnet has a vertical gap of 14 cm, while the vacuum chamber has ferromagnetic covers 2 x 3.5 cm thick, which gives a gap for the beam - 7 cm. The general view of the proposed design of the magnet is shown in Figure 7.

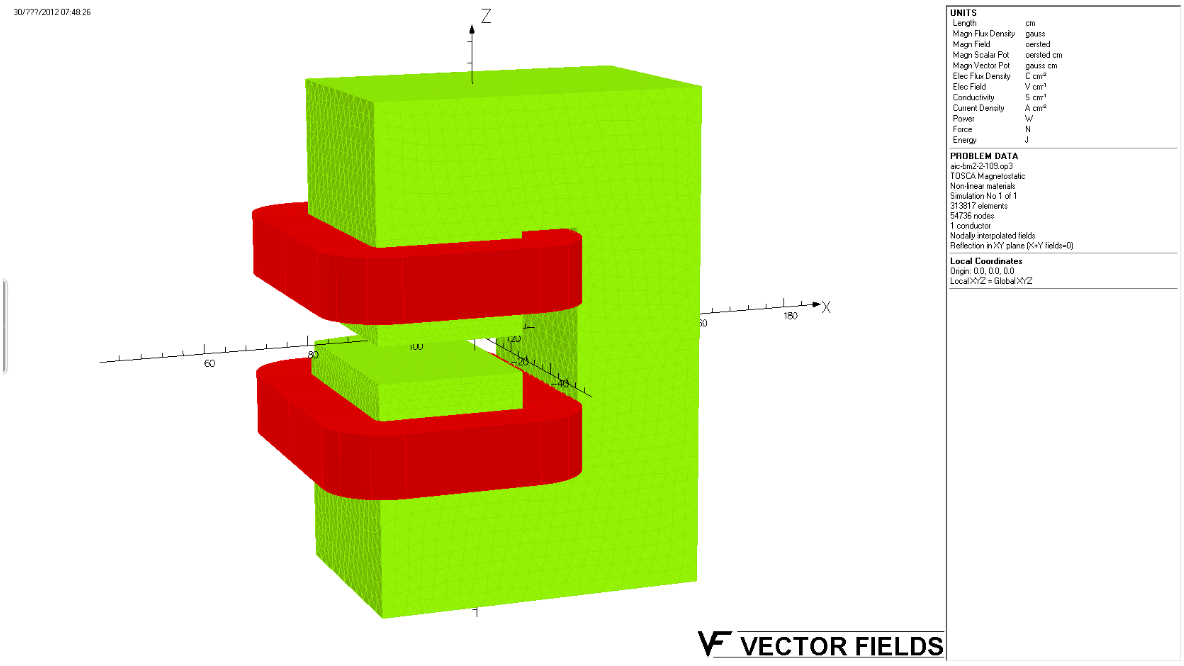

Figure 7: A general view of the new magnet M2

Main results

1. In 2018-2019, 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.

Figure 8: The yoke of the M1 turning magnet. Figure 9: The galettes for the M1 turning magnet.

2. The LNP furnace for baking of galettes was repaired and put into operation. The new furnace power control system was created.
3. New software was created and successfully tested:

- ACS for measuring of Smith-Garren (SG) curves for work with the SC-200 superconducting isochronous cyclotron, which in production stage (IPP CAS, Hefei, China): SG Curves Measurement Program II 2018-2019 (C++). The successful testing of the program was carried out in December 2018 in beam current emulation mode.

- ACS for automated measuring of beam current from three lamellas (Low, Mean, High) of the probe to three KEITHLEY: 6485 pico-ammeters for the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland): Beam Current Measurement Program 2019 (C++).

- A program for recalculation of Smith-Garren (SG) curves into phase motion of accelerated particles in absolute values: SG Curves Recalculation Program 2018-2019 (C++).

4. The magnetic field of the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland) was successfully optimized for the main operating mode of the accelerator (p, Ek = 60,7 MeV) on the base of created software in order to increase the intensity of the current of

Figure 11: The LNP furnace for baking of galettes.

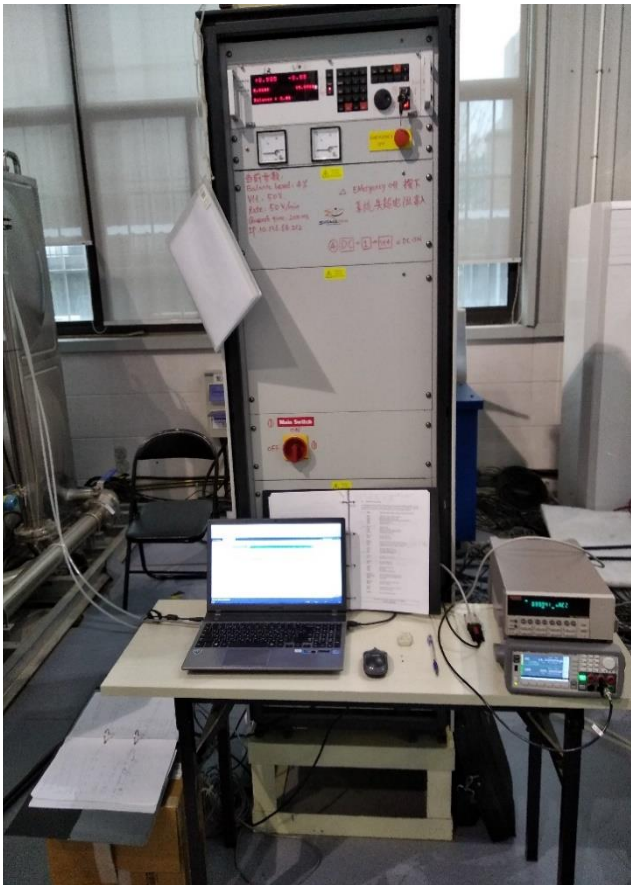

Figure 11: Smith-Garren curves measurement.

the extracted beam without losing of the quality of the extracted beam. The stability of the current of the extracted beam during one hundred seconds was σ<2E-2. The extraction coefficient of the beam was Kext = 30 ± 5 (%). Created and involved software:

- Cyclotron Operator Help's Program Complex 2003-2019 (C++):
  - Cyclotron Operating Mode Calculation Program 2003-2019.
  - Isochronous Field Calculation Program 2003-2019.
  - Free Oscillations Research Program 2003-2019.
  - Phase Motion Research Program 2003-2019.
- Tool Program Complex 2003-2019 (C++):
  - Cubic Spline Interpolation Program 2003-2019.

- Parabolic Interpolation Program 2003-2019.
- Magnetic Field Map Build Program 2003-2019.
- Magnetic Field Map Format Program 2003-2019.

- Equilibrium Orbits Research Program 2012-2019 (C++).
- B1Fi1 Correction Program 2012-2019 (C++).
- SG Curves Measurement Program 2014-2019 (C++).
- SG1-2 Program 2012-2019 (Fortran).
- SG Curves Recalculation Program 2018-2019 (C++).
- Beam Current Measurement Program 2019 (C++).

5. The dynamics of the extracted beams in the beam transportation lines of the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland) was calculated to increase the beam transportation coefficient from the cyclotron exit to the chamber of irradiation of eye melanoma in patients from Ktrans = 80 (%) to Ktrans = 100 (%).

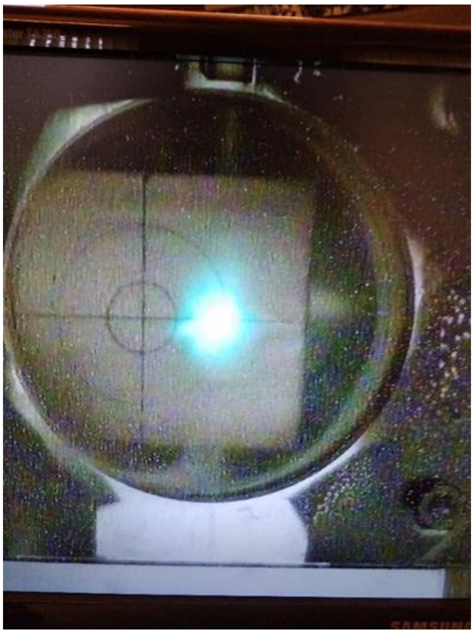

Figure 12 The profile of the extracted beam for the main operating mode of the AIC-144 cyclotron

6. The new GU-94A generator tetrode was purchased at the manufacturing plant in St. Petersburg and sent to Krakow to operate as part of the RF generator of the AIC-144 multipurpose isochronous cyclotron (INP PAS, Krakow, Poland).

The new protocol on cooperation between JINR, LNP and INP PAS (Krakow, Poland): No. 4903-2-20/20 on February 10, 2020 was drawn up. Project: "The revamping and operation of AIC-144 and C-235 cyclotrons for using them in the proton therapy", is financed by the Program of the Plenipotentiary of the Republic of Poland in the JINR.

Figure 13: The GU-94A generator tetrode for the RF generator of the AIC-144 cyclotron (INP PAS, Krakow, Poland).

Publications

1. K. Daniel, K. Gugula, J. Sulikowski, IFJ–PAN, Krakow, Poland. I. Amirkhanov, G. Karamysheva, I. Kiyan, N. Morozov, E. Samsonov, JINR, Dubna, Russia.

„Operation Mode of AIC–144 Multipurpose Isochronous Cyclotron for Eye Melanoma Treatment”, (eng). // PROCEEDINGS OF CYCLOTRONS 2013, Vancouver, Canada, ISBN 978–3–95450–128–Pp.461–463.

http://accelconf.web.cern.ch/AccelConf/CYCLOTRONS2013/papers/fr1pb01.pdf (2014).

2. Amirkhanov I.V., Karamysheva G.A., Kiyan I.N., Sulikowski J.,

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3. I.V. Amirkhanov, I.N. Kiyan, J. Sulikowski. Automated Control System (ACS) for Smith-Garren (SG) Curves Measurement. // E9-2019-46. Preprint of the JINR, Dubna, 2019.

4. I.V. Amirkhanov, I.N. Kiyan, J. Sulikowski. Automated Control System for Smith-Garren Curves Measurement. // ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2020, Vol. 17, No. 1, pp. 57–64. © Pleiades Publishing, Ltd., 2020.

Cyclotron U-120M, Řež,Czech Republic

Tomas Matlochka

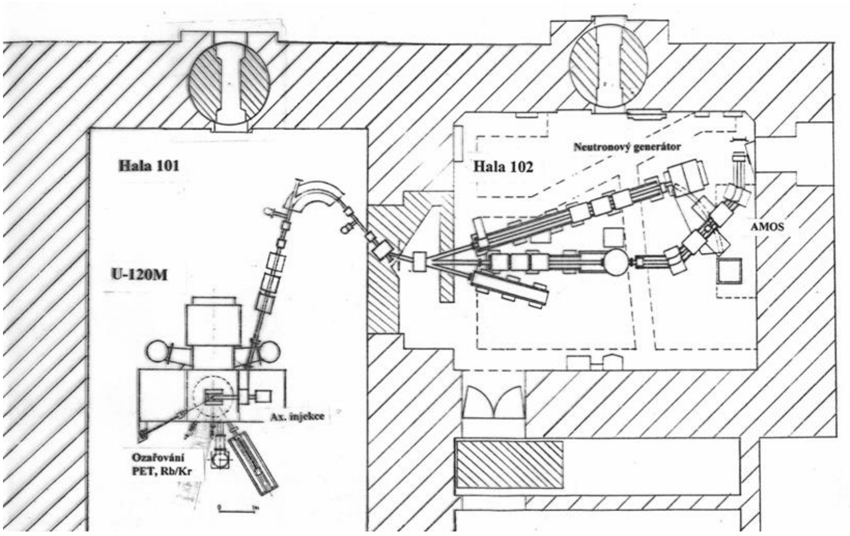

Figure 14: Experimental hall of the U-120M

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

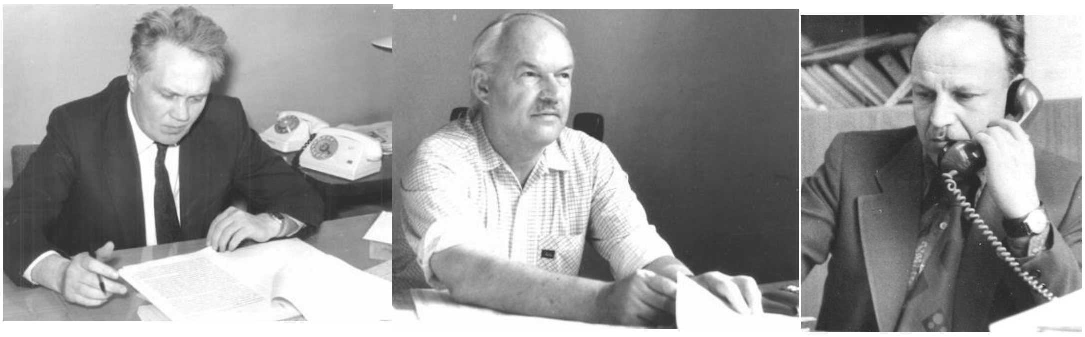

Figure 15: V.P. Dmitrievskij, V.V.Kolga, L.M. Onischenko

Participants on realization of the U-120M in Dubna in years 1971-1977:

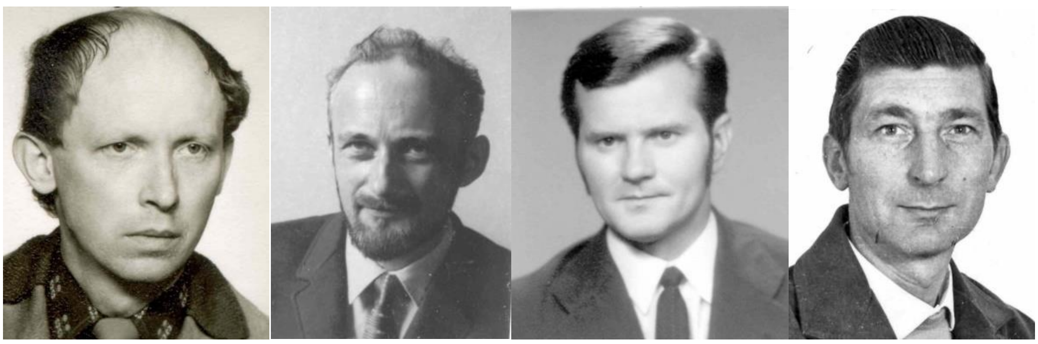

Figure 16: Zdeněk Trejbal, Miloslav Křivánek, Milan Čihák, Josef Šinágl

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

U-120M extraction

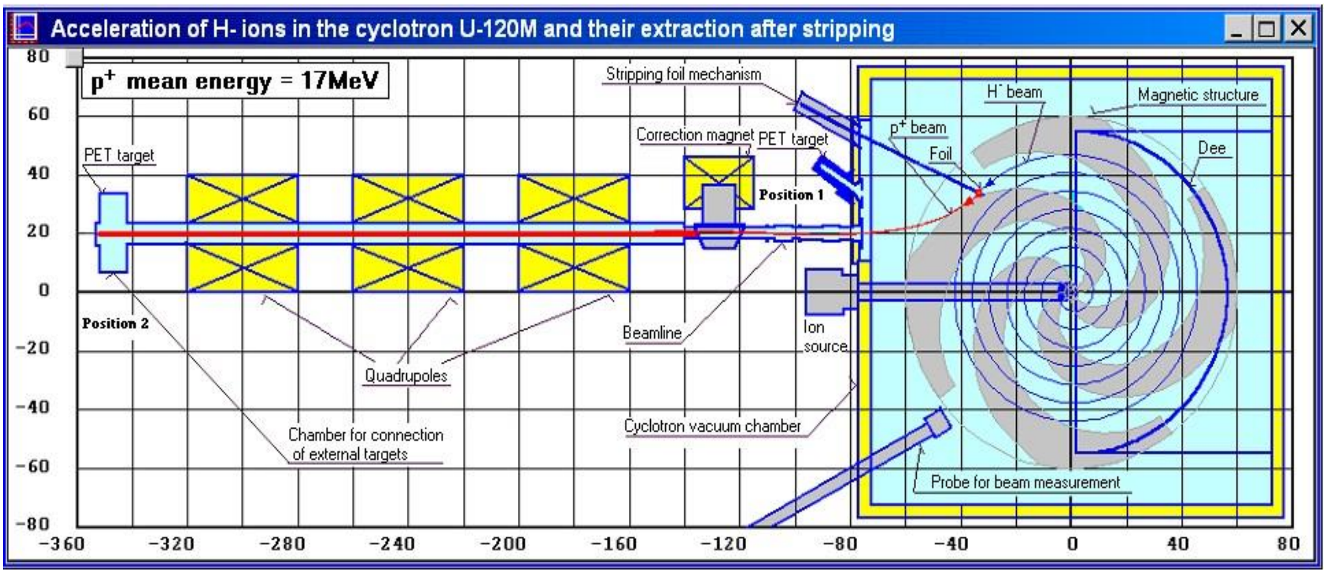

Figure 17: Stripping for negative beams

Stripping extraction works well. Extraction for positive ion extraction: 4He 40 MeV, Protons 23 MeV has low efficiency, only 2 – 4 %

Extraction system is presented in Figure 18 and consists of magnetic exciter + three ESD + MC (not shown)

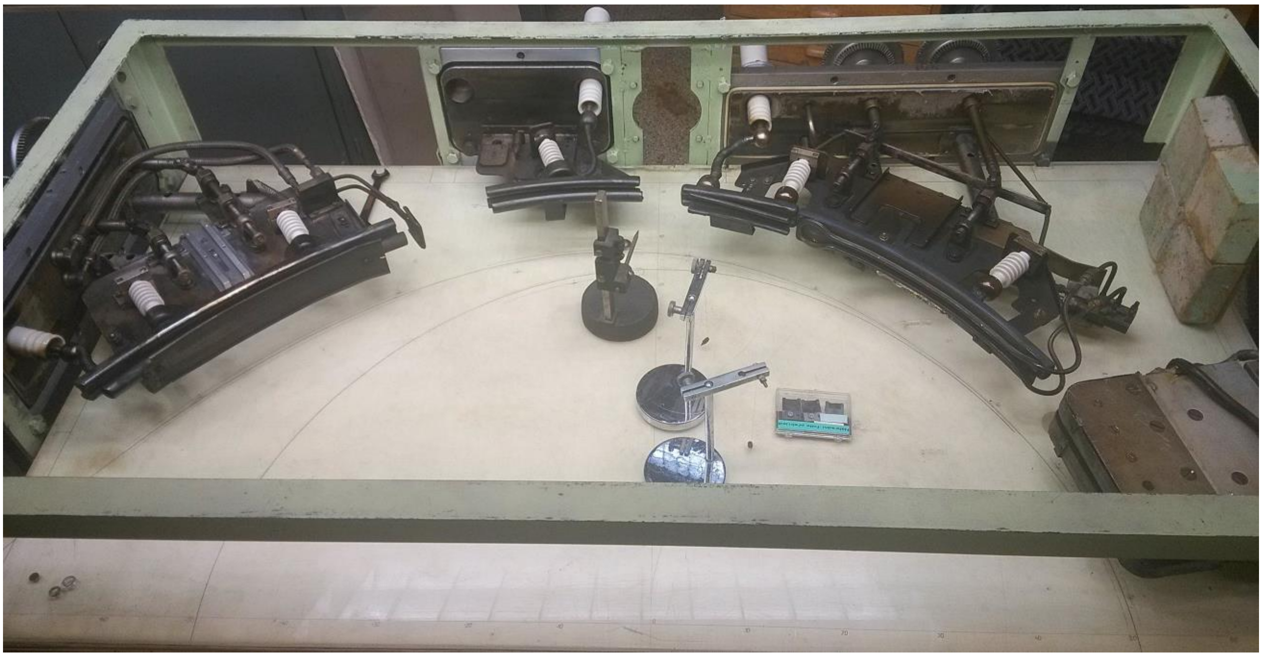

Figure 18: Deflection system for positive particles

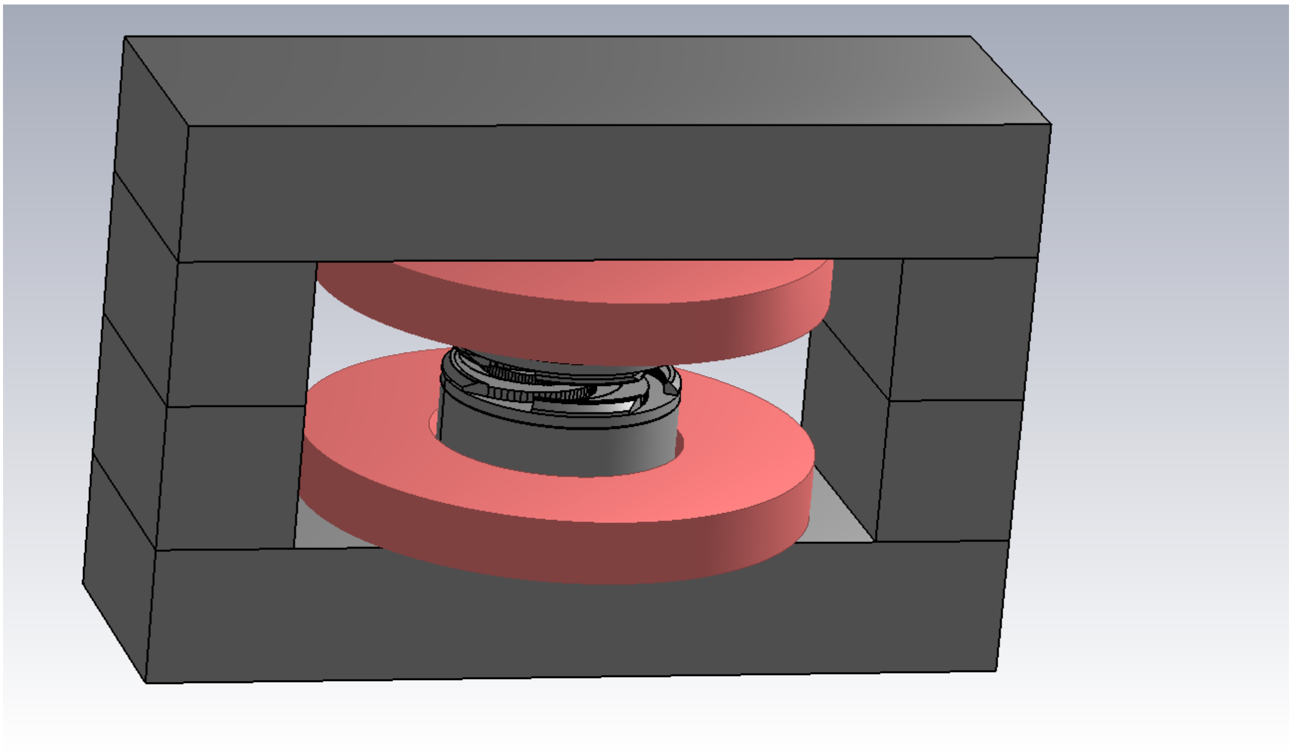

Figure 19: View of the computer model of the magnet

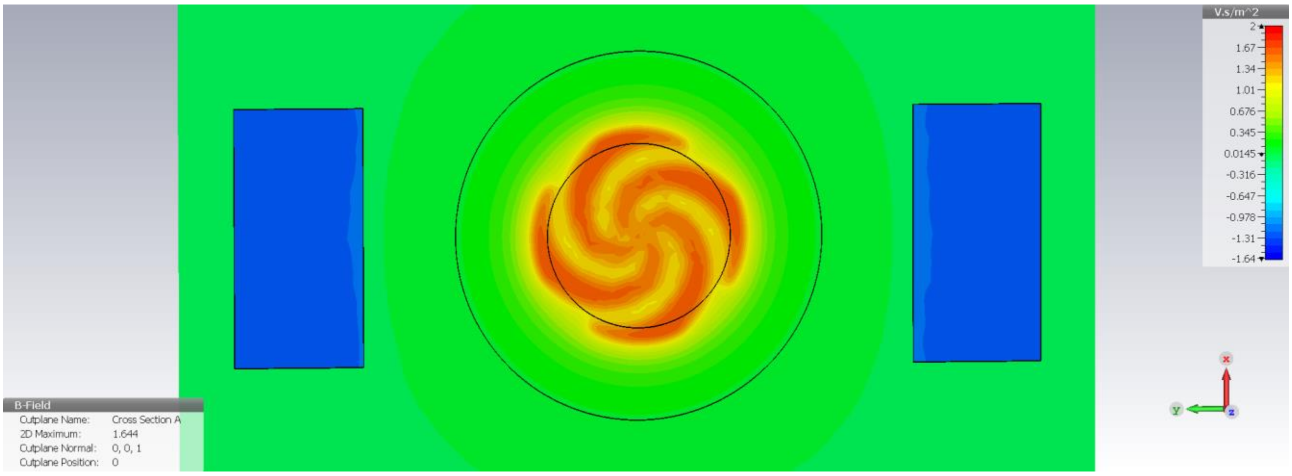

Figure 20: Magnetic field distribution

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.

3 RESEARCH AND DEVELOPMENT OF THE SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY FOR IPP CAS, HEFEI, CHINA.

According to the agreement between the Institute of Plasma Physics (IPP) of the Chinese Academy of Sciences in Hefei (China) and Joint Institute for Nuclear Research, Dubna, (Russia), the project of a superconducting isochronous cyclotron for proton therapy SC202 is developed at JINR [1]. The cyclotron will provide acceleration of protons up to 200 MeV with maximum beam current of 1 μA. We plan to manufacture in China two cyclotrons: one will operate in Hefei cyclotron medical center the other we plan to replace Phasotron in Medico-technical Center JINR Dubna and will be used for further research and development of cancer therapy by protons. Figure 21 shows possible positon of SC202 in the building №1.

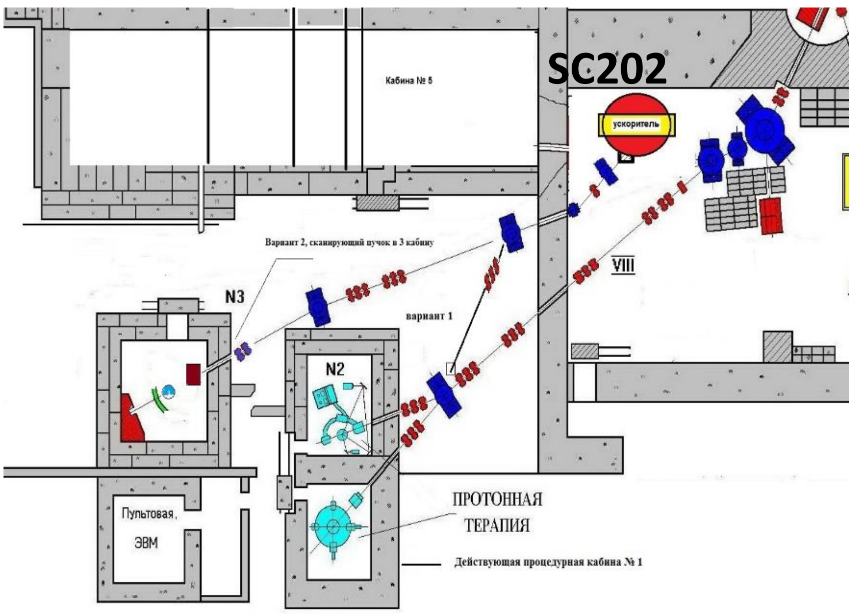

Figure 21: JINR MEDICAL TECHNICAL COMPLEX with future SC202 cyclotron

Now we have finished physical design of the SC202 cyclotron. We have performed simulations of all systems of the SC202 cyclotron, specified parameters of the accelerator and simulated beam dynamics from ion source to exit from the cyclotron.

SC202 is an isochronous superconducting compact cyclotron with four-fold symmetry and spiral sectors. Diameter of cyclotron is 2.5 m it’s weight is about 55 tons. Mean magnetic field is in the range of 2.9T/3.6T (center/extraction). Superconducting coils are enclosed in cryostat, all other parts are warm. It is a fixed field, fixed RF frequency and fixed ~200 MeV extracted energy proton cyclotron. Internal ion source of PIG type will be used. Two half wave RF cavities, placed in opposite valleys and connected in the centre will be used for beam acceleration. Accelerating system works on the 2nd harmonic on approximately 91 MHz. Much effort has been done to avoid the most dangerous resonances during acceleration (see working diagram in Figure 22). Extraction will be provided by one electrostatic deflector placed in the valley between sector shims.

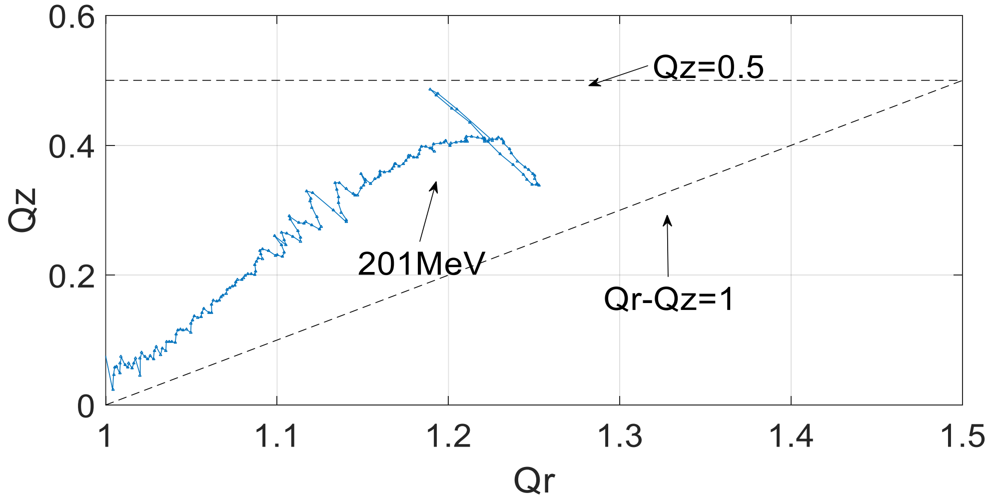

Figure 22: Working diagram.

Designed DLNP SC200 project is approved by the expert commission in the city of Hefei in October 2016. Manufacturing of SC200 systems and elements was begun in 2017.

At present, the engineering design of SC202 has been completed, each subsystem of the Hefei cyclotron is manufactured and in experimental verification. The cryogenic properties of the superconducting magnet coils are tested successfully, the test results meet the design requirements, the superconducting magnet is manufactured. The PIG ion source has been designed and manufactured. The low power test of the accelerating cavities is completed. Assembling, tuning and testing SC202 are not finished. There is a delay in the shimming of the magnetic field of the cyclotron associated with some delay in cryostat and superconducting coils production and prolonged quarantine in China due to coronavirus pandemic.

Figure 23: View of the cyclotron.

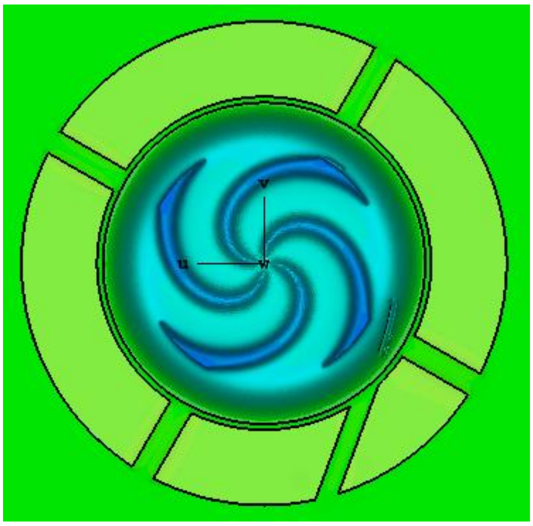

Figure 24: Magnetic field calculated in CST Studio

A modification of the SC200 cyclotron (Dubna) was developed using an extraction schema which differ substantially from one used for the cyclotron for Hefei medical center.

The particles from SC200 (Dubna) cyclotron will be extracted with one ESD electrostatic deflector, two magnetic channels MC1 and MC2 (Figure 25). Cyclotron SC200 (Dubna) extraction system will be supplied by compensation channels CM1 and CM2 in order to avoid first harmonic of magnetic field which can induce resonances $2Q_z=1$ and Q_r-$Q_z=1$.

Proposed extraction scheme allows efficient extraction of the beam from an isochronous superconducting cyclotron with a minimal increase in the transverse beam envelopes (Figure 26). Losses of the beam will be determined mainly by thickness of the septum electrode of the deflector and will not be less than 15 % for 0.1mm septum. This scheme of extraction is suitable for cyclotron with standard for proton therapy energy 230-250 MeV either.

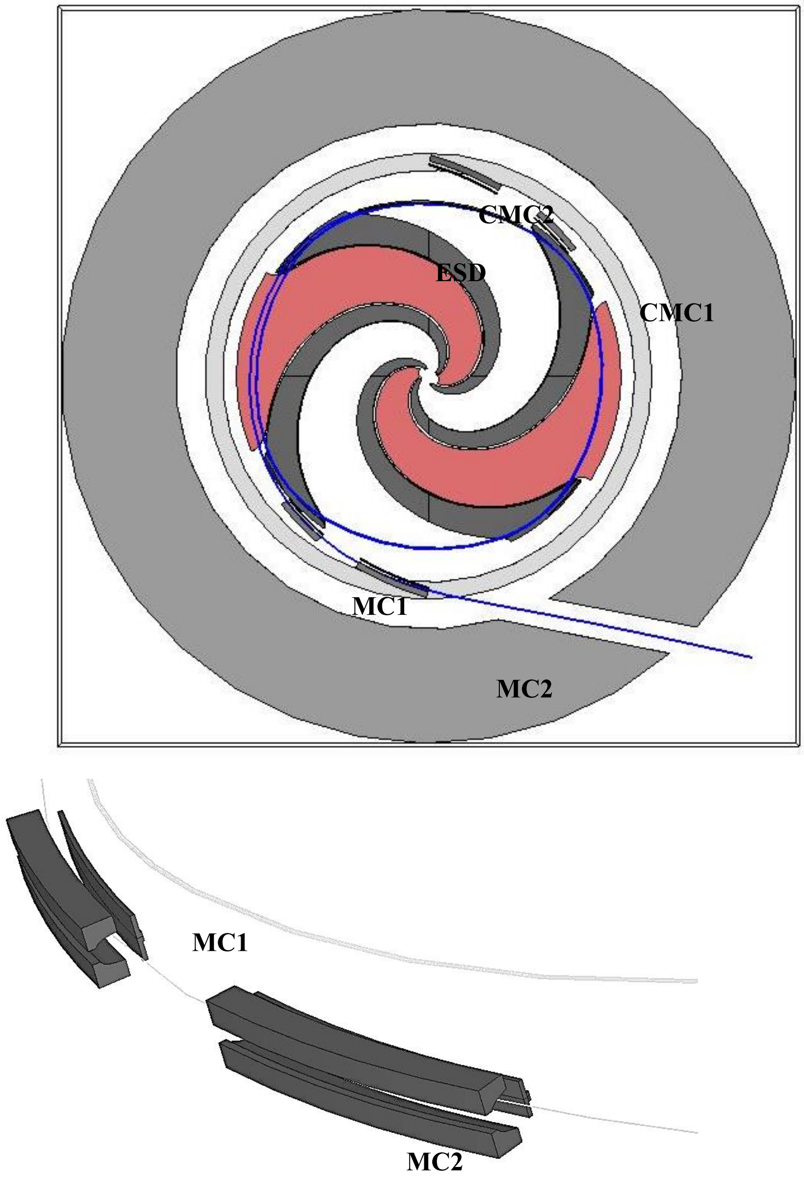

Figure 25: View of the half of the cyclotron with the extraction system. Blue line is trajectory of the particle. Elements of the extraction schema: ESD – electrostatic deflector, MC1, MC2 – passive magnetic channels, CMC1, CMC2 – compensation magnetic channels.

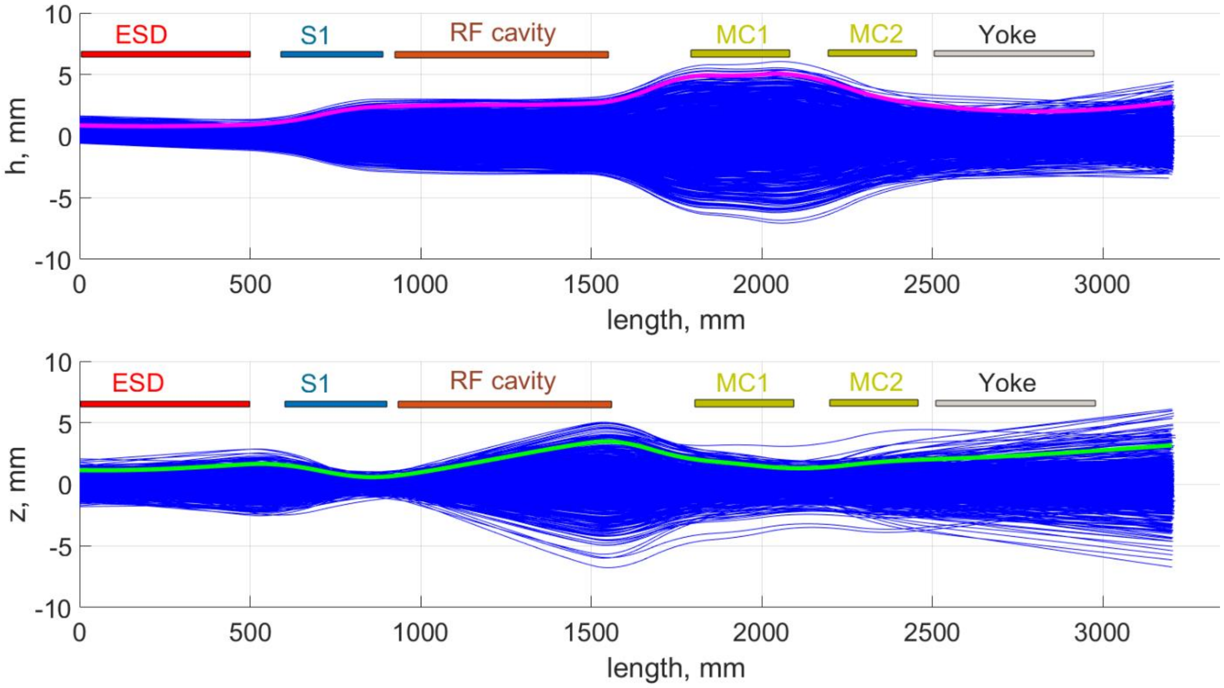

Figure 26: Horizontal and vertical motion of the beam during extraction, thick lines - 2σ envelopes

Techniques and algorithms for accurate analyzes of the electromagnetic field were developed for the R&D of the SC202 cyclotron for proton therapy, which is under production by collaboration between DLNP JINR (Dubna, Russia) and ASIPP (Hefei, China).

Using a 2D field map in the median plane for beam dynamics simulations is a traditional method which is used in cyclotron physics in commissioning stage during shimming of the magnet field.

Codes for beam dynamics simulations were upgraded by new algorithms for calculations of the magnetic field components outside the median plane. Scripts for producing 3D magnetic field maps from 2D map received from magnetic field measurements were written.

The biggest problem of these calculations is that the derivatives of magnetic field on median plane is taken using field map, which already contains error. Special mathematical algorithms were developed in order to obtain smooth and realistic derivatives of the magnetic field on the median plane (see Figure 27). Such results were obtained by combining fitting of the field map by spline surface together with smoothing algorithms.

Created 3D field maps can be used for beam dynamic simulations for investigation the resonance crossing.

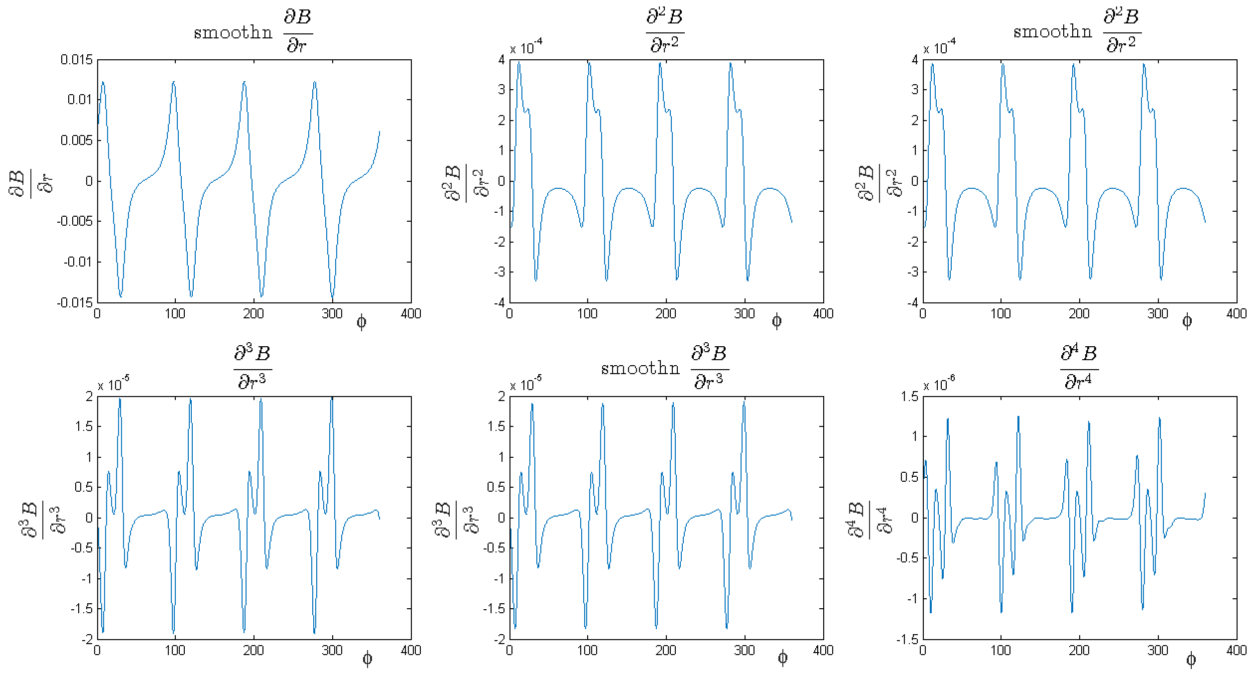

Figure 27: Derivatives taken with smoothing algorithms.

High accuracy and high efficiency of simulations will help on commissioning stage during shimming of the magnet.

JINR PROJECTS OF CYCLOTRON FOR PROTON THERAPY

The production of the cyclotron SC200 faced a lot of engineering challenges which are mainly aroused due to high magnetic field of the accelerator.

Recent developments of superconducting cyclotrons for proton therapy, such as SC200, Pronova [2], Sumitomo 230MeV [3] share similar parameters that define the structure of the cyclotron. All projects are four-sector cyclotrons with ~3T central field. Such parameters were chosen in pursuit of compact dimensions. None of those cyclotrons are yet in operation.

Therefore, it was decided to rethink some design decisions after careful analysis of SC200, other projects and operating cyclotrons for proton therapy.

There are two most successful accelerators in the proton therapy: Varian Proscan [4], design proposal by H.Blosser et al in 1993, and C235 (IBA Belgian) [5]. Both cyclotrons have much smaller central field, 2.4 and 1.7 Tesla.

First of all we increased the pole of the cyclotron in order to decrease mean magnetic field to about 1.5 T in the center. Corresponding RF frequency for this value of the magnetic field is about 90 MHz at 4^{th} harmonics operation mode.

As the cyclotron will have a relatively small magnet field, it is possible to use both superconducting and resistive coil. Both solutions have their pros and cons.

SC-230 cyclotron (superconducting coils)

The physical design of the compact superconducting cyclotron SC230 (91.5 MHz) has been developed. This cyclotron can produce a proton beam with an energy of 230 MeV for therapy and biomedical research. Here we remind its parameters (see Table 1).

Table 1: Parameters of the cyclotron SC230

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

Simulations were performed in CST studio [7] in the parametrized model of the magnet (see Figure 28) created in Autodesk Fusion 360.

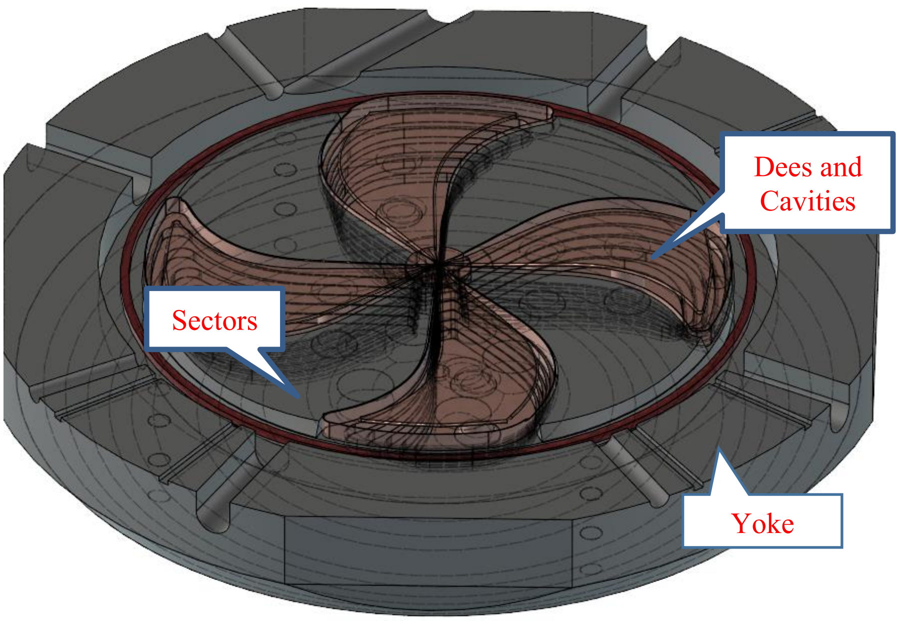

Figure 28: Layout of the cyclotron's 3D computer model (magnet and accelerating system).

The dimensions of the yoke (see Figure 29) were chosen to restrict the magnetic stray field in the range of 200-300G just outside accelerator, providing full saturation of the iron poles and yoke. Average magnetic field and flutter from CST simulation are presented in Figure 30.

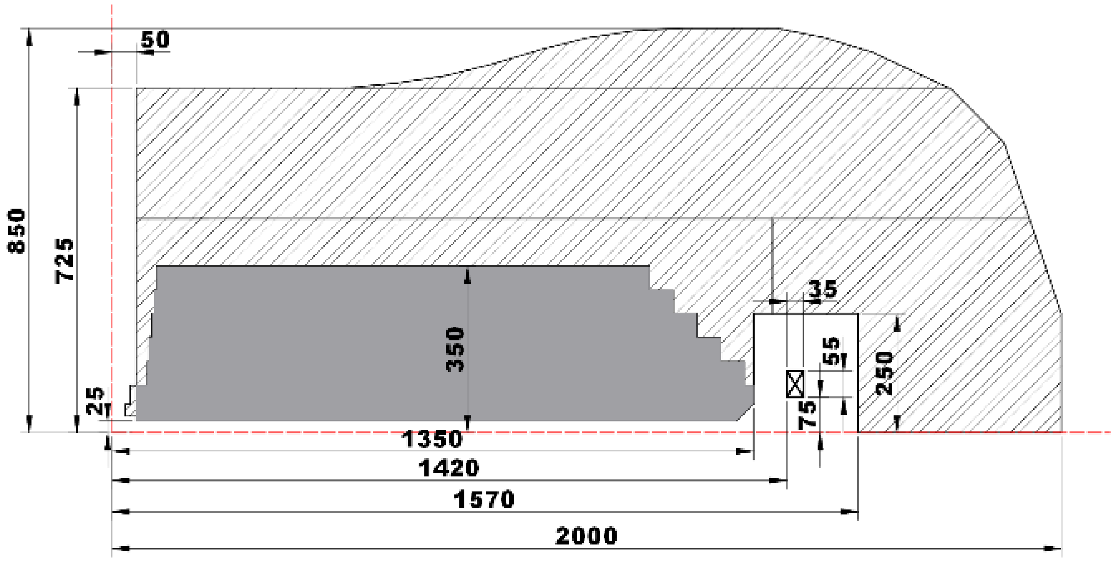

Figure 29: SC230 magnet yoke and SC coil general dimensions

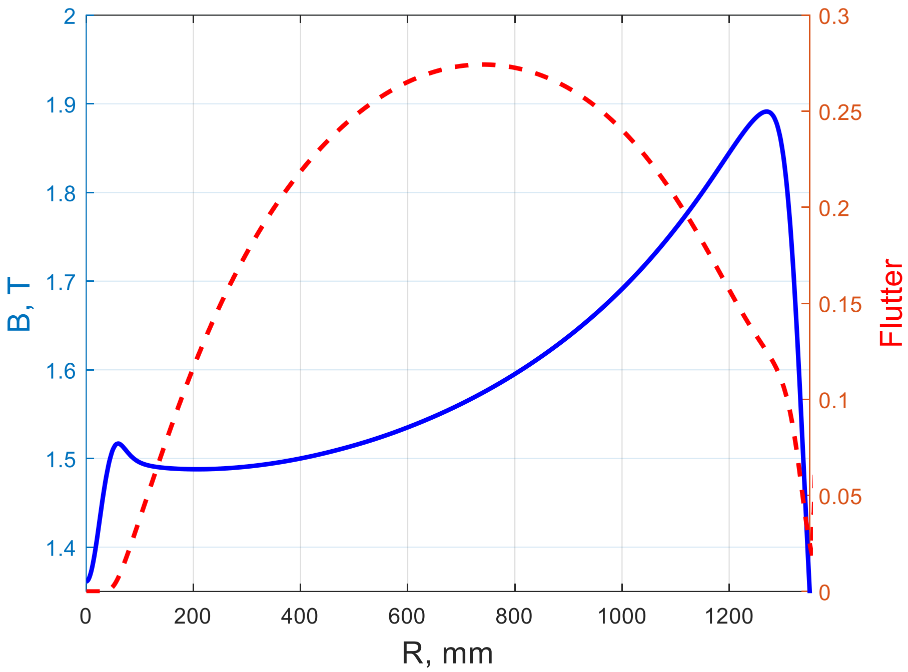

Figure 30: Average magnetic field and flutter along the radius.

Betatron tunes calculated with CYCLOPS-like code are presented in Figure 31.

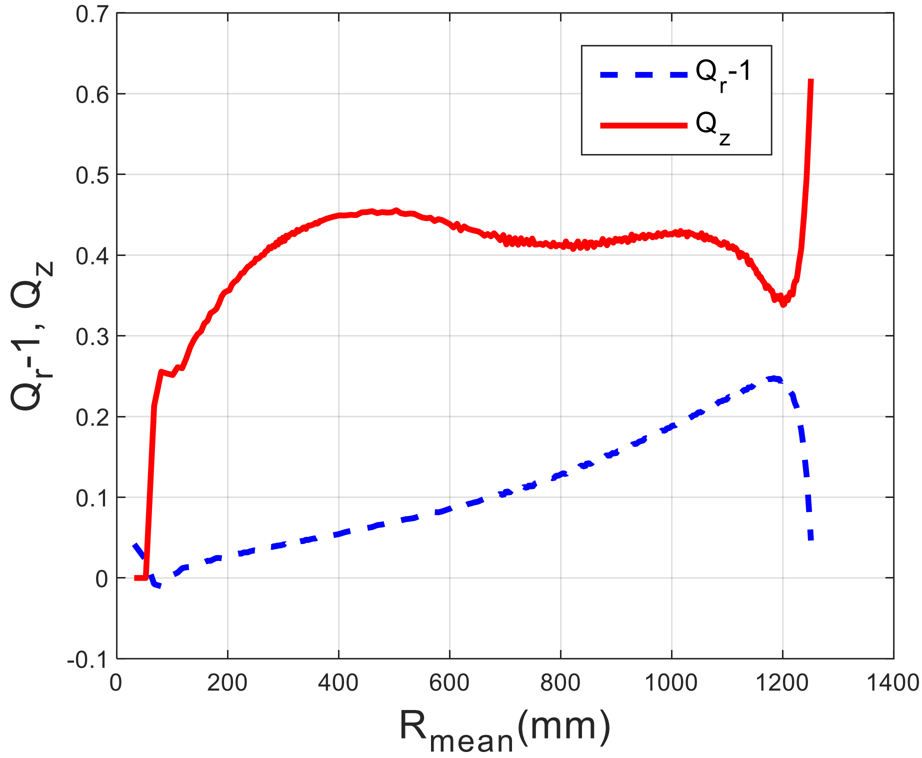

Figure 31: Vertical and radial betatron tunes in SC230.

Accelerating system design

RF cavities are located at the valleys of the magnet, the geometry of the RF cavity is restricted by the size of spiral sectors. For proton acceleration, we are planning to use 4 accelerating RF cavities, operating on the 4th harmonic mode. All four RF cavities will be connected in the center and will be working on approximately 91.5 MHz frequency. Cavities can be equipped with an inductive coupling loop and will be adjusted by capacitance trimmers like in SC200 [8].

Computer model

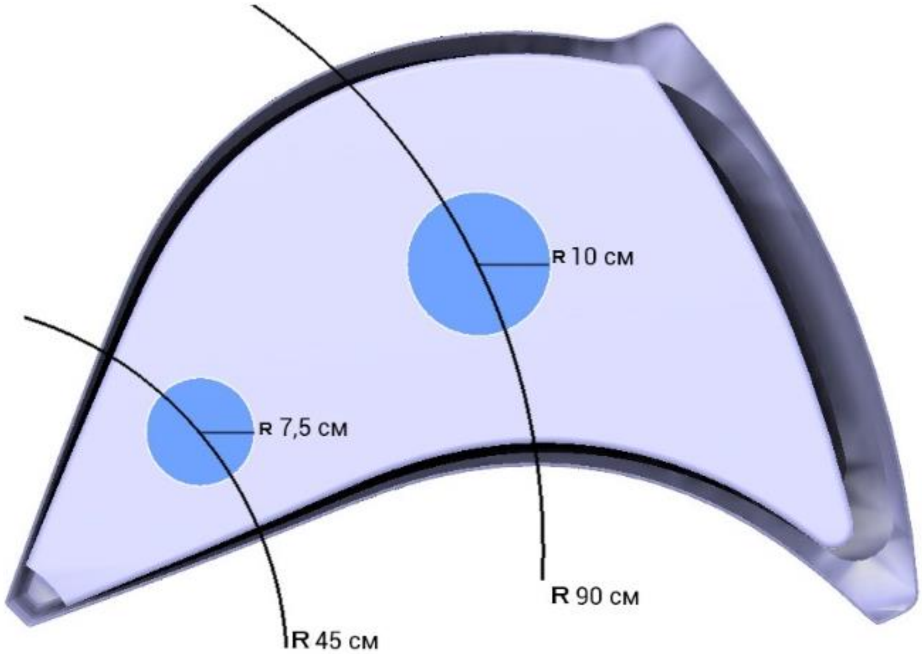

Figure 32: View of the model of the cavity.

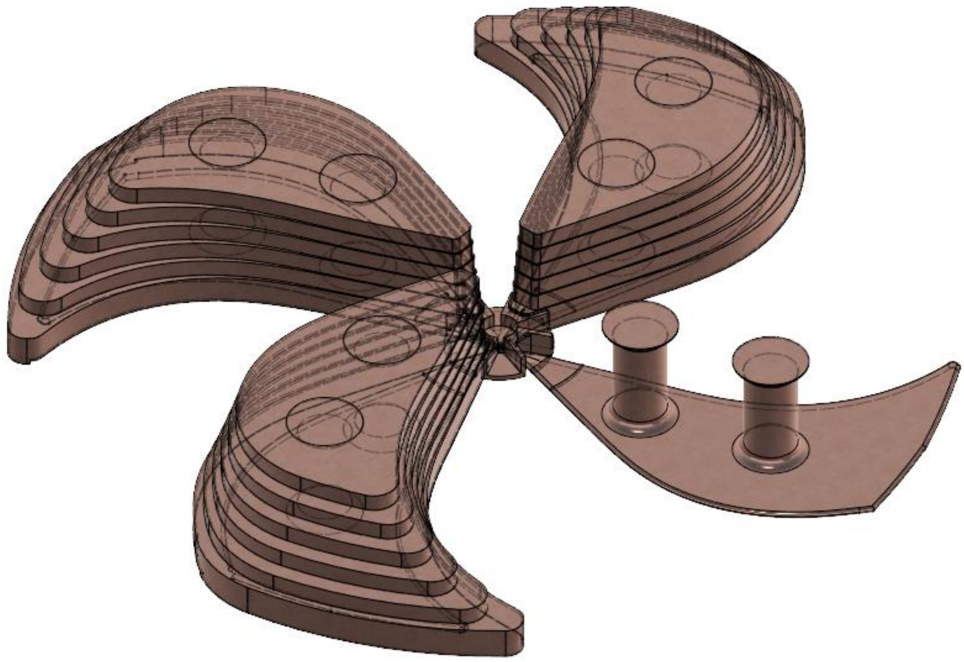

Figure 33: Overview of 3D model of RF system.

The characteristic parameters of the half-wavelength coaxial resonant cavity with two stems have been obtained from simulation. The RF cavity resonator solution for the SC230 cyclotron can be seen in Figure 32.

Azimuthal extension of the cavity (between middles of accelerating gaps) is about 40 degrees.

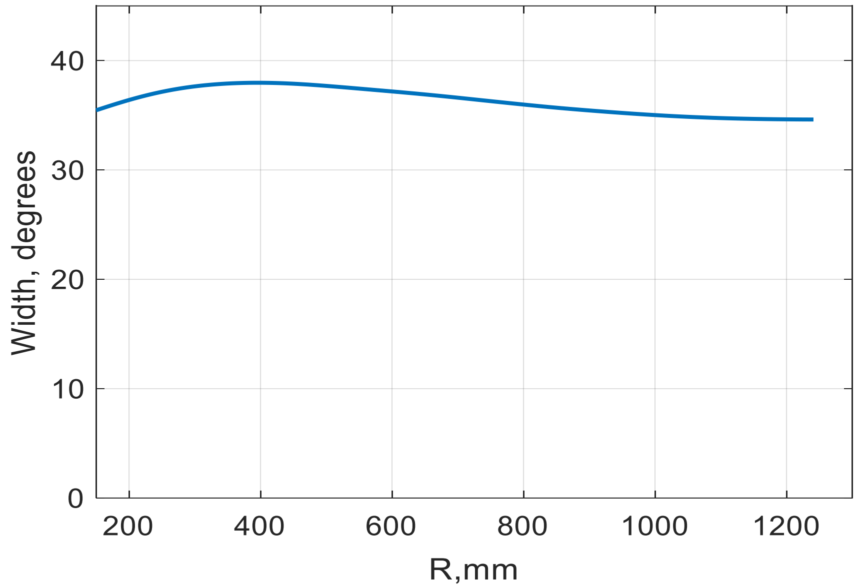

Figure 34: Azimuthal extension of the cavity

As the beam will be accelerated in the fourth harmonic mode we believe that the RF magnetic field will not have noticeable effect on the beam.

Suitable accelerating frequency and voltage along radius were achieved (see Figure 35).

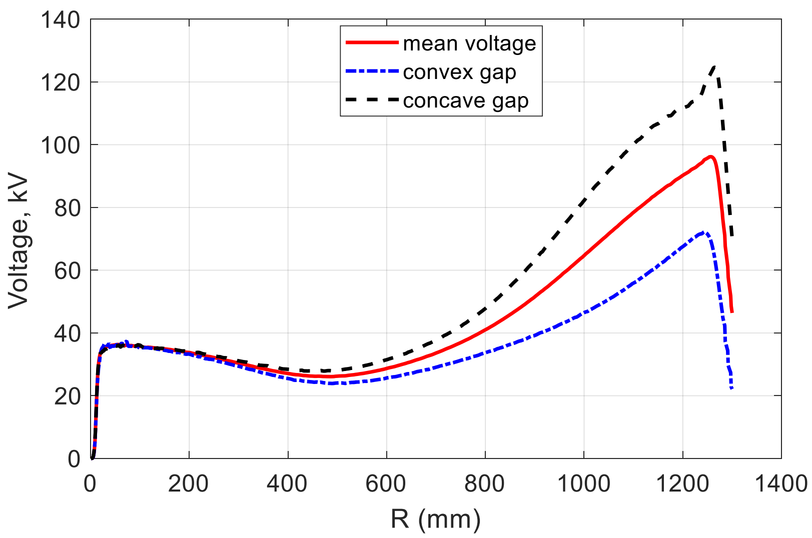

Figure 35: Accelerating voltage along radius.

Power losses.

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8 * 10^7$ 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.

Overall power and cooling requirements of the RF system are rather small.

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.

A cyclotron for proton therapy RC240.

Magnet system

We simulate a cyclotron similar to the SC230 cyclotron, but with some changes optimizing the accelerator design with resistive coils (RC, copper) and water cooling.

Relying on modern computing capabilities it is possible to design a cyclotron with resistive coils with sizes smaller than the leader of the proton therapy market C235 (IBA).

Table 2. Parameters of the cyclotron RC240

Magnet type	resistive
Ion source	PIG
Final energy, MeV	240
Pole radius, mm	1350
Mean magnetic field (center), T	1.45
Dimensions (height×diameter), m	1.62 × 3.95
Weight, tonnes	140
Hill/Valley field, T	1.8/0.4
Hill/Valley gap, mm	15/700
A*Turn number	120 000
Magnet power consumption, kW	140
RF frequency, MHz	89
Harmonic number	4
Number of RF cavities	2
Voltage center/extraction, kV	50-110

RF power, kW	50
Turn number	800
Beam intensity, μA	1.0
Extraction type	ESD

To have more compact design of the cyclotron with resistive coil the vertical gap between sectors needs to be as small as possible. In the proposed design the gap between the sectors is 15 mm, which resulted in a low current value in the coil, and the weight of the magnet was about 140 tonnes. It is important that the gap between sectors is constant, compared to IBA C235 design with elliptic gap, that decreases towards the extraction down to 9mm. It is much easier and cheaper to manufacture and easier to control during installation. The diameter of RC240 is below 4 m, in order to simplify the logistics of the magnet. It is important for the cyclotron that needs to be delivered to the hospitals in different location to be fairly simple for the transportation. Therefore, each element of yoke is below 30 tonnes.

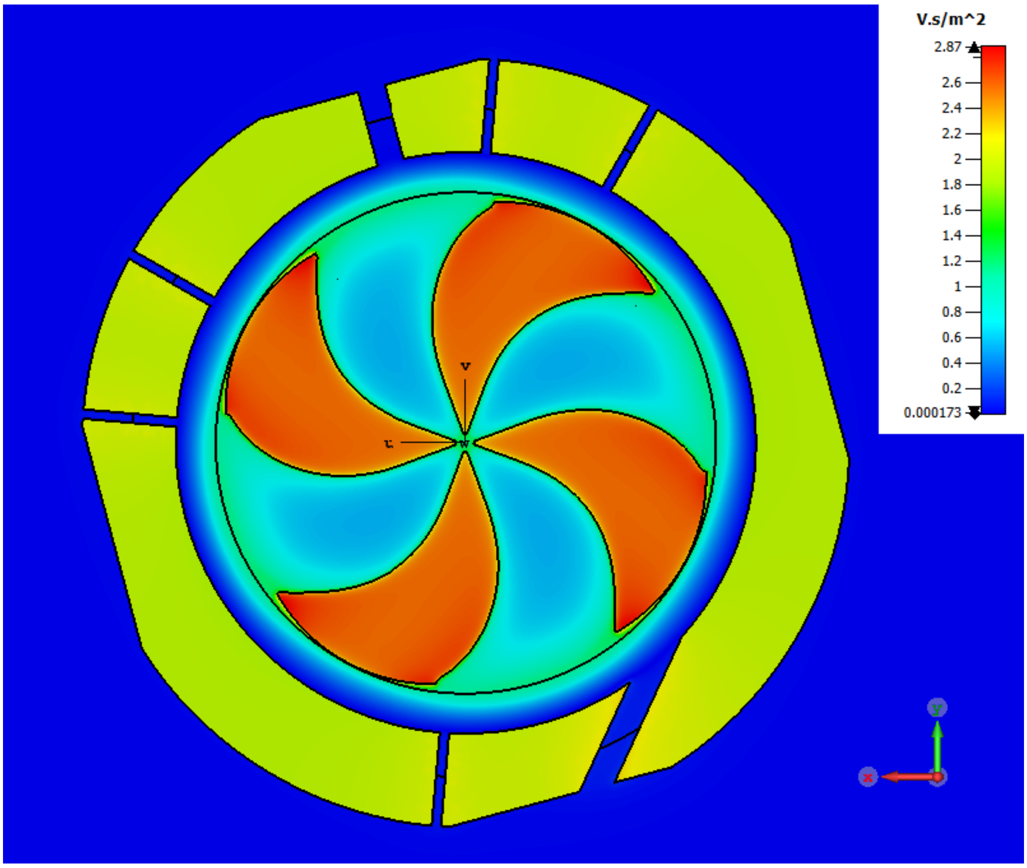

Figure 36: Magnet flux through median plane.

The number of A*Turn is 120000 and therefore it's power consumption is rather small 140 kW. Average magnetic field and flutter from CST simulation are presented in Figure 37.

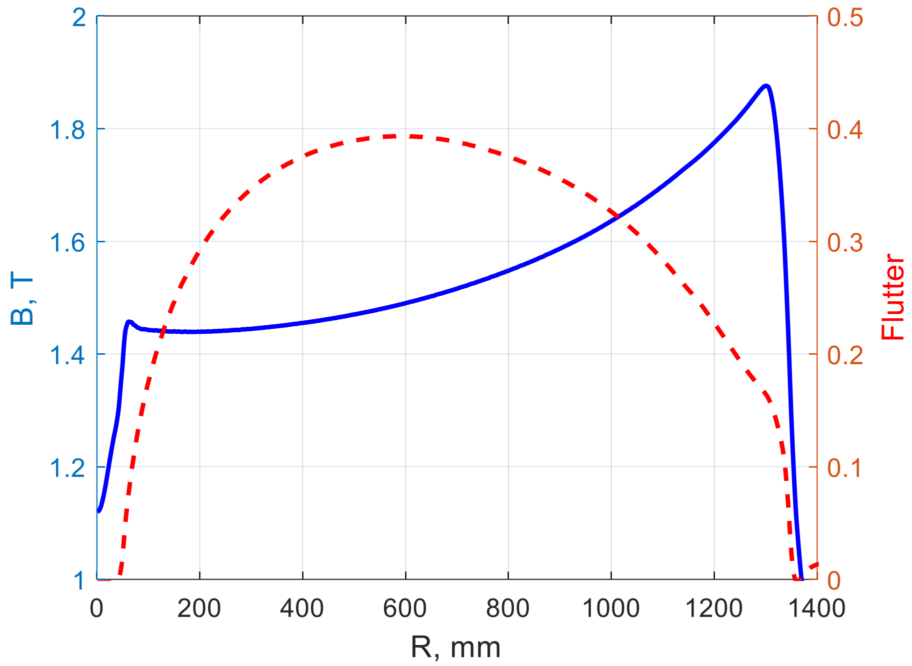

Figure 37: Average magnetic field and flutter along the radius.

The RC240 needs 2 times less A-turns in the coils compared to IBA C235, so we are able to use a much smaller coil cross-section. The RC240 coil is only 272x170 mm^2, and IBA C235 coil is about 600x500mm^2. So even having much smaller field and bigger sectors radius, thanks to much smaller coil the overall size and weight of the RC240 is much smaller and it consumes less power.

Results of simulations of the magnetic field were exported to Matlab to be analysed with CYCLOPS-like code. Orbital frequency shows rather good isochronism of the field (see Figure 38).

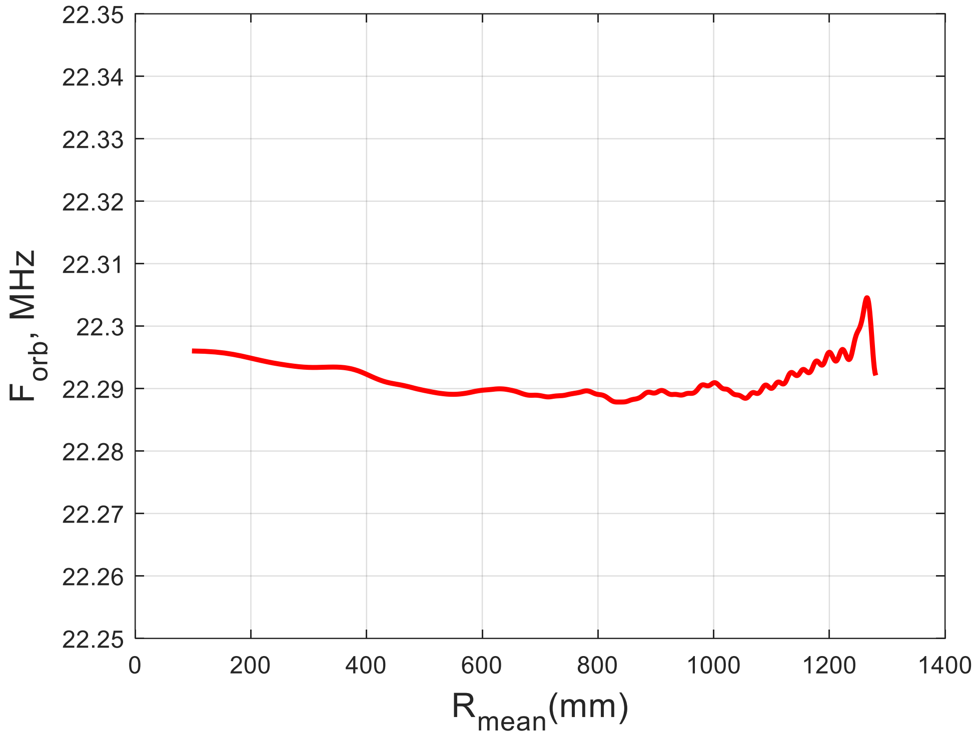

Figure 38: Orbital frequency.

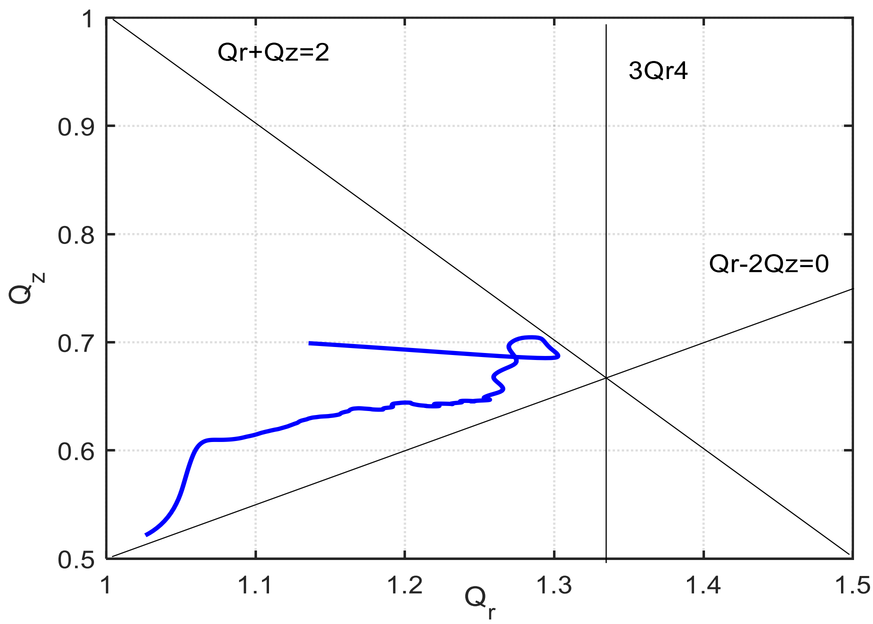

Figure 39: Working diagram.

Figure 39 shows that working point does not cross dangerous resonances. This cyclotron has different path of the working point. In both IBA C235 and Varian as well as in projects with 3 T magnetic field (SC200, Sumitomo and Pronova) Q_z (vertical tune) stays below 0.5. In case of the RC240 the flutter is too high, so we immediately "jump" over Qz=0.5 and stay over the Qr=2Qz resonance. Particle tracking in realistic 3D electric and magnetic fields have been performed in order to prove that such unconventional path is indeed ok.

Accelerating system

Two RF cavities are located at the opposite valleys of the magnet. Accelerating RF cavities will operate at 89 MHz (acceleration on the 4th harmonic mode). Space in the valley is enough to place cavities with azimuth extension about 40 degrees.

The characteristic parameters of the half-wavelength coaxial resonant cavity with two stems have been obtained from simulation in CST studio. Quality factor of the cavity is about 14000.

RF cavities will be connected in the center, can be equipped with an inductive coupling loop and will be adjusted by capacitance trimmers.

Extraction from this cyclotron will be performed by ESD placed in empty valley. The ESD voltage, required for extraction is about 100 kV/cm.

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

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

Conclusion

We chose a low level of the magnetic field in the cyclotron and found out that dimensions of the cyclotron can be reasonable. Low magnetic field will provide efficient extraction with electrostatic deflector. The superconducting option is lighter, consumes less power, has bigger gap between poles, however superconducting coil is more expensive to build and to run. Both options are great candidates for JINR to be used for medical research program.

Both projects have conservative and well-established solutions. The concept of a cyclotron with a low field level was published [9] and presented at accelerator conferences [10, 11]. 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).

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4. DEVELOPMENT OF THE CYCLOTRON METHOD FOR HIGH-CURRENT BEAM ACCELERATION

Construction stage simulations for ProNova K230 superconducting cyclotron for proton therapy.

The scientific project of a 230 MeV compact superconducting isochronous cyclotron for proton therapy was completed in collaboration between Ionetix Corporation (Lansing, USA) and Joint Institute for Nuclear Research (Dubna, Russia) [1]. The cyclotron is designed and will be manufactured by Pronova Solutions, LLC with advanced functions [2], [3] compared to existing machines of this class. In particular, the weight of the K230 cyclotron is less than 60 tons, which allows it to be transported on the road. Extensive physical and engineering calculations were performed during the design process to meet the technical specifications required by Pronova. The process of scientific design includes iterative scientific optimization of input, extraction, and analysis of a magnet using three-dimensional beam dynamics, followed by extensive engineering analysis, optimization, and certification of the resulting systems. Detailed design and construction of the K230 cyclotron is currently underway at Pronova Solutions, LLC.

The K230 cyclotron consists of: a superconducting magnet with a warm vacuum chamber, an internal source of low power ions with a cold cathode, a central region, high-frequency resonators and an extraction system using one electrostatic deflector and five passive magnetic channels (Figure 40) To accurately evaluate the performance of the machine and quantify the beam loss during the design process, detailed modern beam simulations were performed using the SNOP and Z3cyclone codes using three-dimensional magnetic and electric fields created by the Tosca \ Opera3D code.

Construction Schedule :

The K230 project schedule required the magnet to be completed before 2019, but there was obviously some delay.

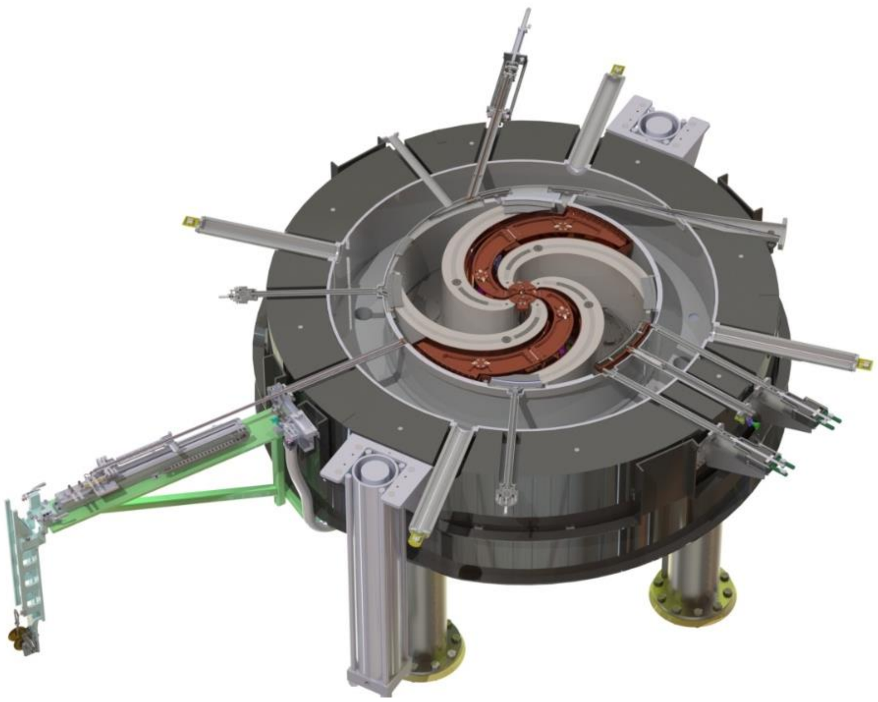

Figure 40: Midplane layout

The physics and mechanical design for all subsystems, including superconducting magnet, beam chamber, internal ion source, RF resonators, and extraction system are completed and ready for manufacture (Figure 40).

The current JINR activity in this direction includes, among other things, computer simulations on manufacture and assembly tolerances for a superconducting cyclotron [4].

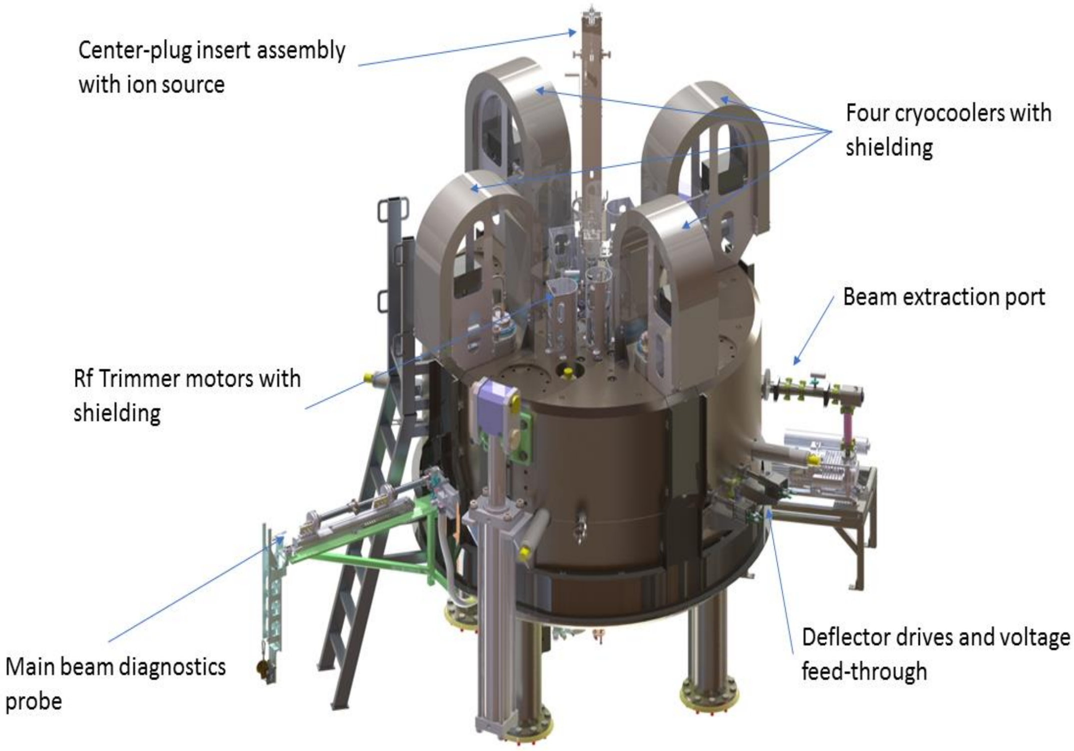

Figure 41: Pronova K230 superconducting cyclotron.

Work on the production of the cyclotron continues.

Ionetix Ion-12SC Superconducting Cyclotron for Production of Medical Isotopes

In collaboration with Ionetix Corporation some activity in support of the already operational ION-12SC machine and preparation of new design proposals for small cyclotrons for medical or industrial applications continued.

The Adler Institute for Advanced Imaging and the Ionetix Corporation are pleased to report that construction and installation of the new revolutionary small footprint superconducting cyclotron, ION-12SC are now complete, see Figure 42. This exciting new technology will produce the gold standard radiopharmaceutical, Ammonia N-13 for Cardiac PET imaging.

Karel D. Kovnat PhD, of Adler Imaging welcomes the Ionetix ION-12SC cyclotron.

Figure 42: Ion-12SC superconducting cyclotron at the Adler Institute for Advanced Imaging

The Ion-12SC is a sub-compact, 12.5 MeV proton superconducting isochronous cyclotron for commercial medical isotope production recently developed at Ionetix Corporation [5,6,7,8]. The machine features a patented cold steel and cryogen-free conduction cooling magnet, a low power internal cold-cathode PIG ion source, and an internal liquid target. It was initially designed to produce N-13 ammonia for dose on-demand cardiology applications but can also be used to produce F-18, Ga-68 and other medical isotopes widely used in Positron Emission Tomography (PET). The 1st engineering prototype was completed and commissioned in September 2015, and four additional units have been completed since. The first two units have been installed and operated at the University of Michigan and MIT. R&D efforts in physics and engineering have continued to improve machine performance, stability and reliability. These improvements include: 1) Water cooling added to the dummy dee to limit the operating temperature of the ion source to improve lifetime and performance, 2) Magnetic field maps, obtained with a Hall probe based mapper, were used to accurately measure the isochronism and provide information needed to compensate for any unwanted 1st harmonics and

3) Feedback based control methods applied to regulate the beam intensity on target by adjusting the ion source cathode current.

The C1 unit installed at the University of Michigan Medical School early this year treated ~100 patients/month with N-13 ammonia. The machines are now capable of routinely producing > 21 doses/day with > 99% availability. The Ionetix manufacturing facility is capable of producing up to 30 machines per year.

Figure 43: Ion-12SC unit C1 at the University of Michigan Medical School.

A set of operational Ion-12SC machines has been produced by the Ionetix manufacturing facility. The obtained beam intensity on the target is well within reach of the design goal. R&D efforts in physics and engineering to improve the machine performance, stability and reliability required extensive computer simulations including analysis of the measured magnetic fields and beam dynamics modeling. This activity allowed predicting some of the beam loss mechanisms and then determining methods to mitigate them by tailoring the magnetic field to increase the beam intensity on the production target.

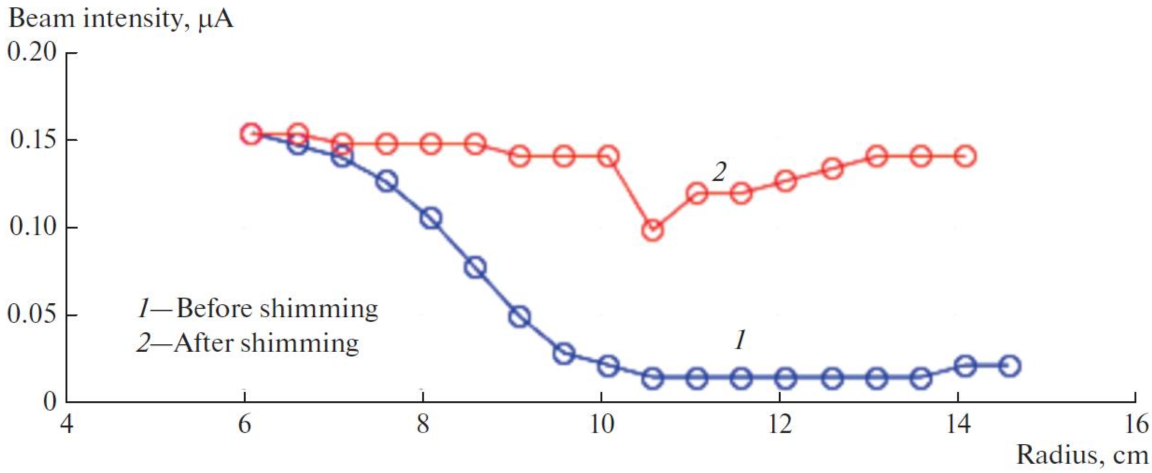

Figure 44: Measured beam intensity before and after correction of the first harmonics.

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LINAC-200 JINR LINEAR ELECTRON ACCELERATOR.

The methods and codes for the development of cyclotron-type accelerators developed in the department are successfully used not only for the design of cyclotrons but also, for example, were used to commission the LINAC-200 electronic linear accelerator (DLNP JINR) [1-5]. It is assumed that the accelerator will make it possible to conduct methodological studies of elementary particle detectors created at DLNP and other laboratories on test electron beams with energies from 20 MeV to 200 MeV in a wide range of beam intensities. In the future, the electron energy can be increased to 2 GeV. A gun and four accelerator stations out of thirteen were mounted, which already makes it possible to accelerate electrons to an energy of 200 MeV. After repairs in the 118th building, the linear accelerator will be put into operation and test beams of electrons with the necessary auxiliary equipment will be arranged on it. This is expected to happen during 2020.

Figure 45: LINAC-200 linear electron accelerator after the first stage of repair in the 118th DLNP building

The subject of initial consideration is the design of the electron beam transport line from section 2, where the beam energy is 60-70 MeV. The task is to deviate the beam from the main line of the accelerator, lead away from it and direct it to the target along an axis parallel to the linear accelerator. It is necessary to ensure the functioning of the line in two main operating modes, differing in the cross section of the beam spot on the target: 0.5 × 0.5 mm2 and 100 × 100 mm2. The line may consist of magnetic rotary dipoles and magnetic quadrupoles. It is necessary to have free space in front of the target for installing collimators that limit the transverse dimensions of the beam.

The beam parameters at the exit from accelerator section 2: beam energy 60-70 MeV (60 MeV is used in the calculations), geometric transverse emittances 0.2 π mm mrad, energy spread ± 200 keV, peak beam current 25 mA.

The lines consist of two 35-degree rotary dipoles and two quadrupoles. The outer diameter of the ion guide increases from 30 to 240 mm. The line length, measured from the entrance to the first rotational magnet to the target, increases from 4.1 m for 60-70 MeV to 5.9 m for 200 MeV (Figure 46).

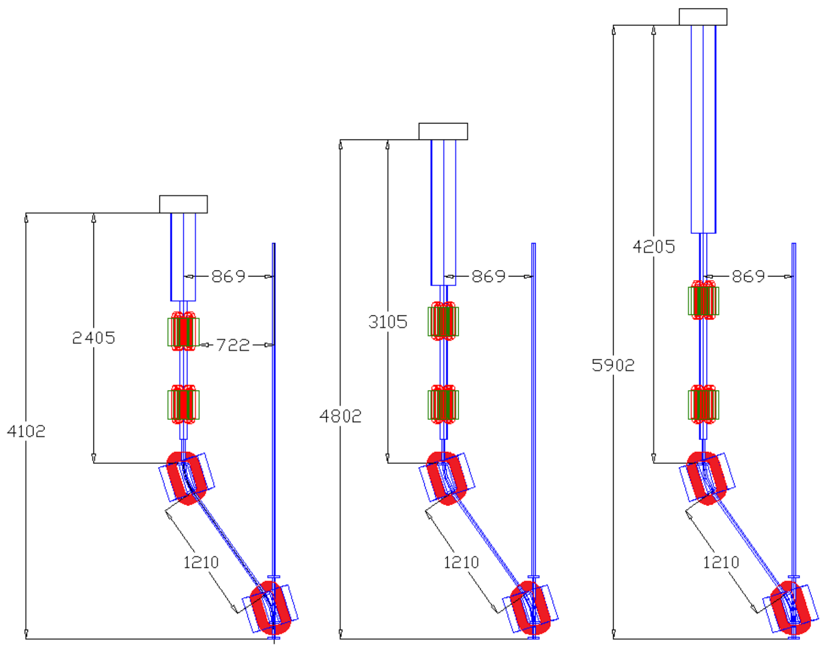

Figure 46: Beam line for 60, 120 и 200 MeV

Next, three-dimensional calculations of the beam dynamics were carried out using the fields of the designed dipoles and quadrupoles, which showed that in the modes with a small finite beam size for all three lines, the beam spot size can be ~ 2.5 × 2.5 mm^2 or ~ 4.0 × 0.6 mm^2. The transition from one beam size to another is due to a small change in the fields of quadrupoles. There is no way to reduce the horizontal size of the beam (i.e. get something like ~ 0.6 × 4.0 mm2). Thus, to obtain a small beam diameter (~ 0.5 × 0.5 mm2), it is apparently necessary to use a horizontal collimator. In the mode of operation with a large final beam size, the beam spot size is not less than 100 × 160 mm2. For the 60 MeV line, the size can be further increased by increasing the field of quadrupoles. For the lines of 120 and 200 MeV, the quadrupole fields (8 T/m) are close to the maximum possible. If it is possible to obtain large fields, then, accordingly, there will be a larger beam size. The vertical size always exceeds the horizontal, therefore, to align the transverse dimensions, you must use a vertical collimator. At a beam size of ~ 200 mm, particle losses begin on the aperture of the ion guide near the location of the target. Therefore, if you think about a beam size exceeding 200 mm (for a 60 MeV line), then you need to increase the diameter of the pipe.

The resistive dipole magnets type DIA will be a part of LINAC-200 facility at JINR. The dipoles are made of solid iron yokes and of water-cooled coils wound from hollow copper conductor. They have a full mechanical aperture of 32 mm and an iron length of 340 mm. Figure 47 shows a computer-generated view of the dipole magnet type DIA. The Technical Specification defines the requirements for the design, fabrication, testing, measurements and shipment of DIA magnets for the JINR.

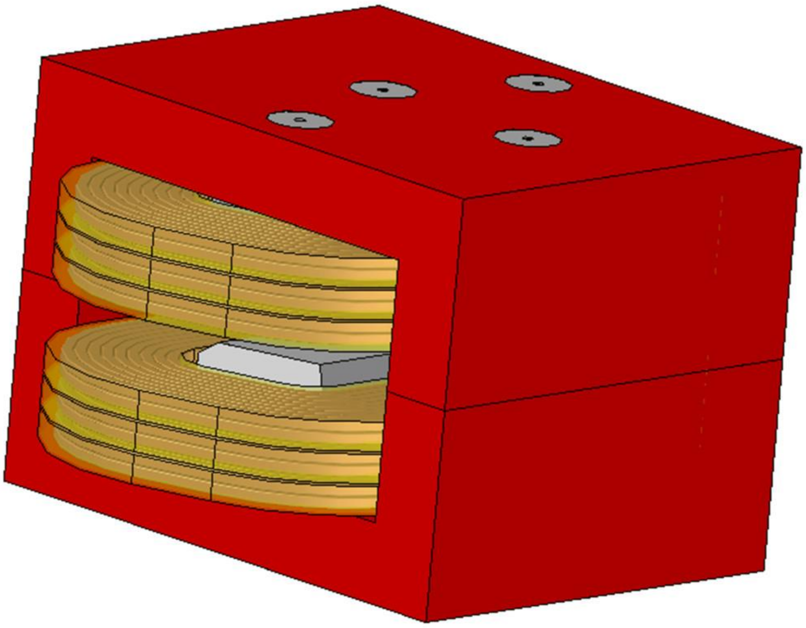

Figure 47: DIA magnet

The resistive quadrupole magnets type QA will be a part of LINAC-200 facility at JINR. The quadrupoles are made of solid iron yokes and of water-cooled coils wound from hollow copper conductor. They have an inscribed diameter of 72 mm and an iron length of 270 mm.

Figure 48 shows a computer-generated view of the quadrupole magnet type QA.

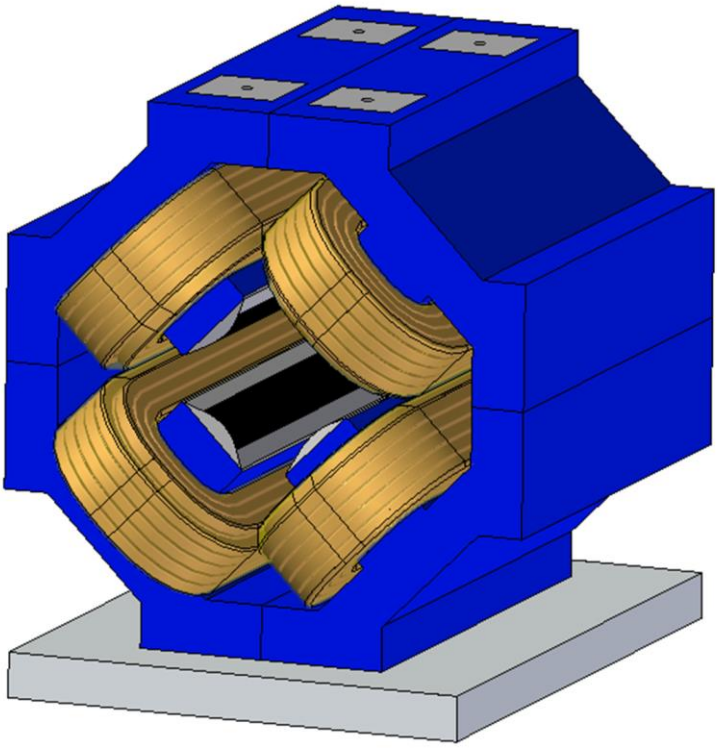

Figure 48: QA magnet

The research and development work on the installation of LINAC-200 in the DLNP JINR will be continued under the new project.

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КРАТКИЙ ССВУ – АНАЛИЗ

The world-known beam dynamics calculation codes have been developed at NEONU DLNP, which are used in the design of various cyclotron-type accelerators, both in Russia and in a number of countries of the world. The team of the project includes 2 Doctors of Sciences, 8 Candidates of Sciences (5 of them are younger than 35 years old) and 5 young specialists working on candidate dissertations. For 2016-2020, the department's employees published under the theme 03-2-1102-2016/2020 about 25 articles in refereed journals; more than 50 reports were made at international and Russian scientific conferences and meetings. One patent for invention No. 2702140 is filed.