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03-2-1102-2016/2018

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

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Yakovenko S.L.

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, N.A. Morozov
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.

S.L. Yakovenko, N.G. Shakun

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.

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

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

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

The work was carried out according to the protocol № 4546–2–16/18 on the implementation of joint research work. The protocol was concluded between JINR and INP PAS on October 27, 2015.

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 head of the department of AIC–144 cyclotron gave task to achieve the stable extraction coefficient of proton beam: $K_{ext} = 34\%$.

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.

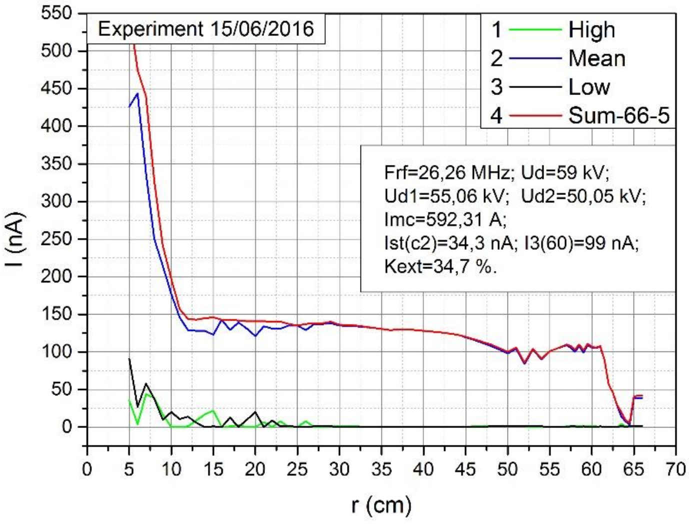


Figure 1: The measured current of proton beam.

Based on automated control system of the AIC–144 cyclotron the Smith–Garren's curve measurements were carried out in 2016. 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.

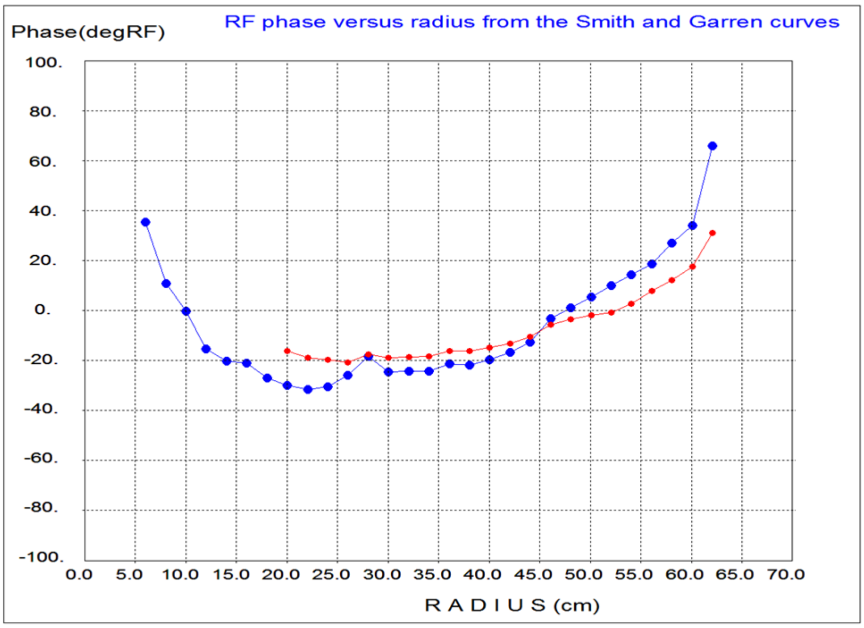


Figure 2: The phase motion. [1) Herve Marie. *"How to use Smith and Garren curves to correct isochronism"*. // Internal report of IBA. December 16, 1993. (Blue curve). 2) R.E. Berg, H.G. Blosser, M.M. Gordon. *"Theoretical and experimental beam studies for the Michigan State University cyclotron"*. //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

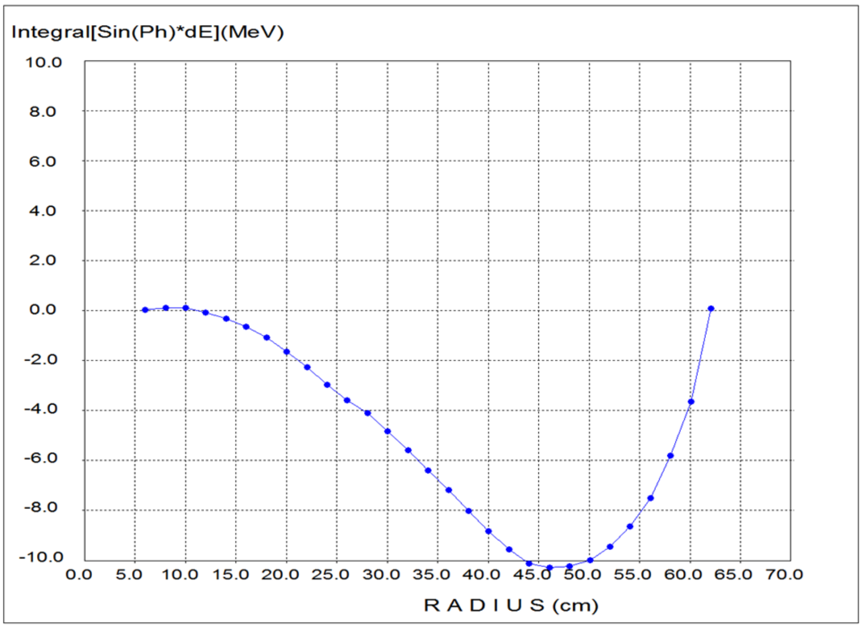


Figure 3: The phase–energy integral.

The value of the phase–energy integral in the radius of throwing beam into the electrostatic deflector: $R = 62\ cm$, is equal to zero. This says about correct formation of the magnetic field of the AIC–144 cyclotron. The correct magnetic field provides the necessary condition for getting the stable maximal value of extraction coefficient of proton beam: $K_{ext} = 34 \pm 1\ \%$.

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.

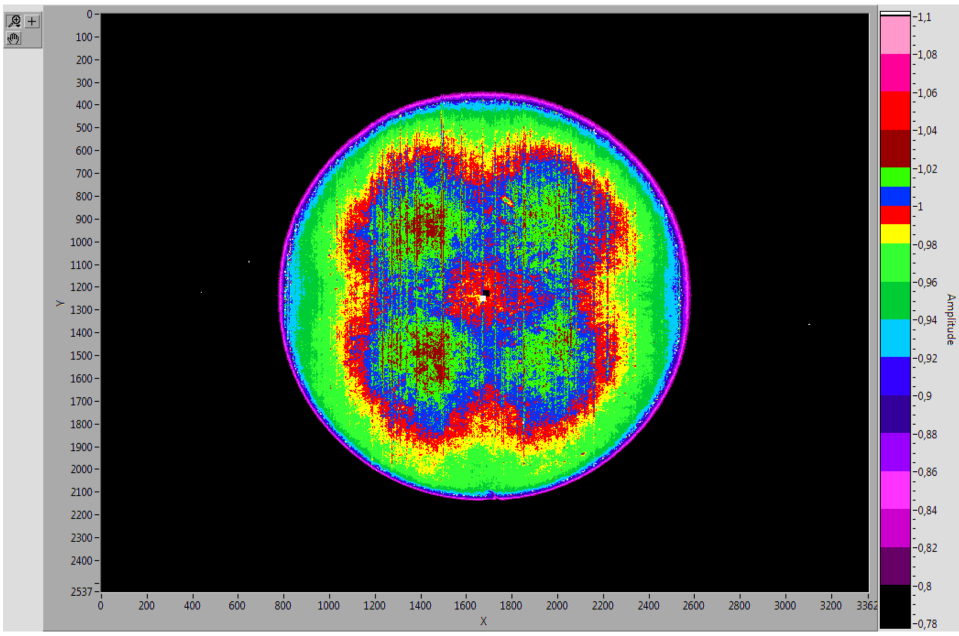


Figure 4: The profile of proton beam by using scintillator. (The collimator: *D=25 mm;* The exposure: *T=40 sec*).

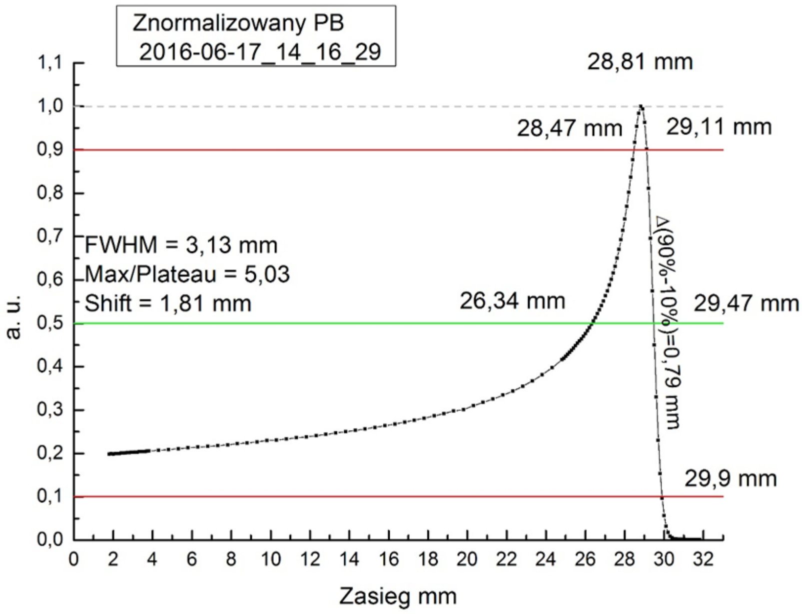


Figure 5: The Bragg peak at run of protons in water.

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

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: $E_k \sim 60 \div 63\ MeV$.

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.

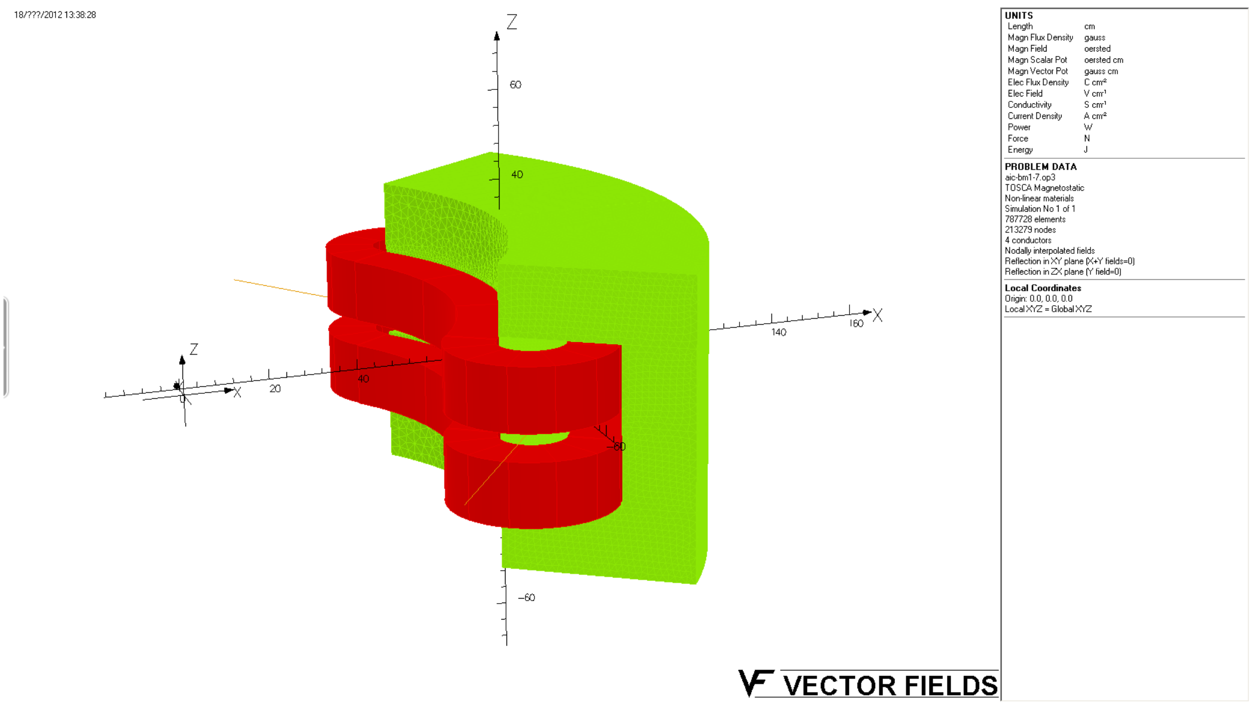


Figure 6: A general view of the new magnet M1

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.

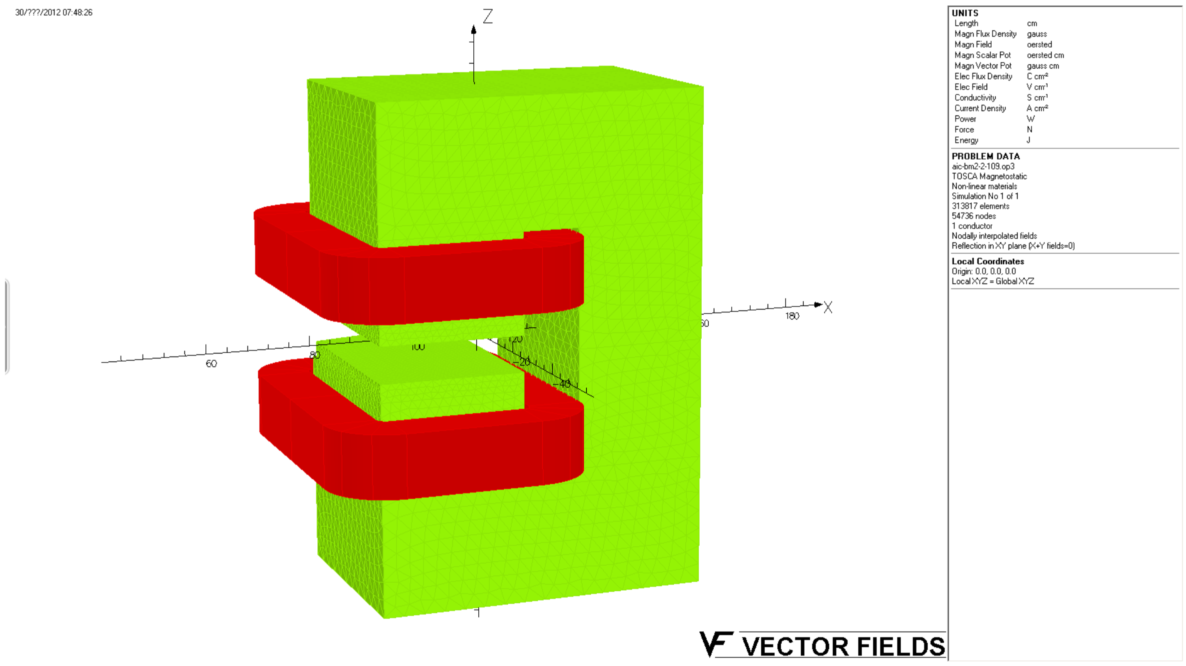


Figure 7: A general view of the new magnet M2

Main results

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).

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.,

"Calculation of Proton Rotation Frequency in Static Equilibrium Orbits at the Isochronous Cyclotron" (rus/eng), // ISSN:1814–5957, eISSN:1814–5973, PEPAN LETTERS, 2015. V.12, No 3(194), pp. 673–677. / ISSN 1547_4771, Physics of Particles and Nuclei Letters, 2015, Vol.12, No. 3, pp. 428–431. © Pleiades Publishing, Ltd., 2015.

Cyclotron U-120M, Řež,Czech Republic

Tomas Matlochka

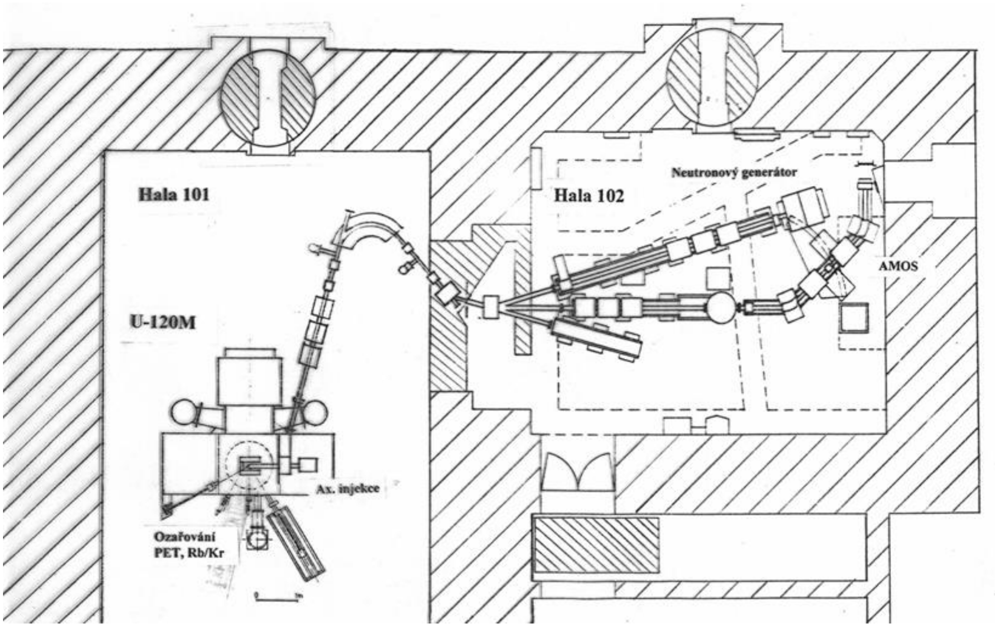


Figure 8: Experimental hall of the U-120M

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

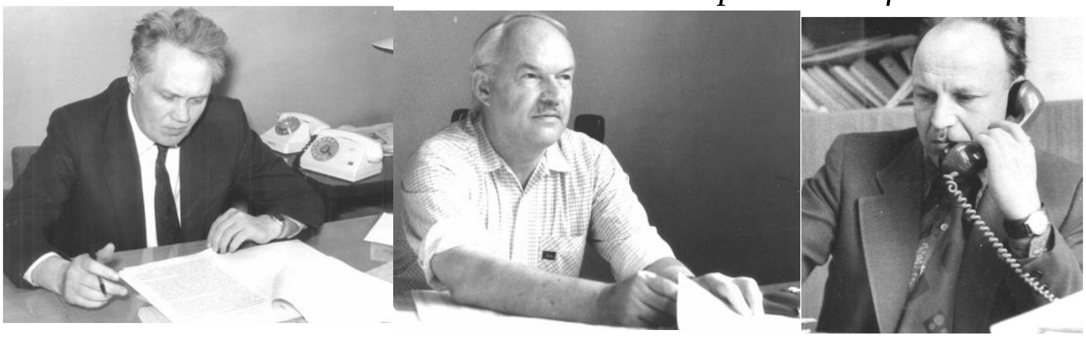


Figure 9: V.P. Dmitrievskij, V.V.Kolga, L.M. Onischenko

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

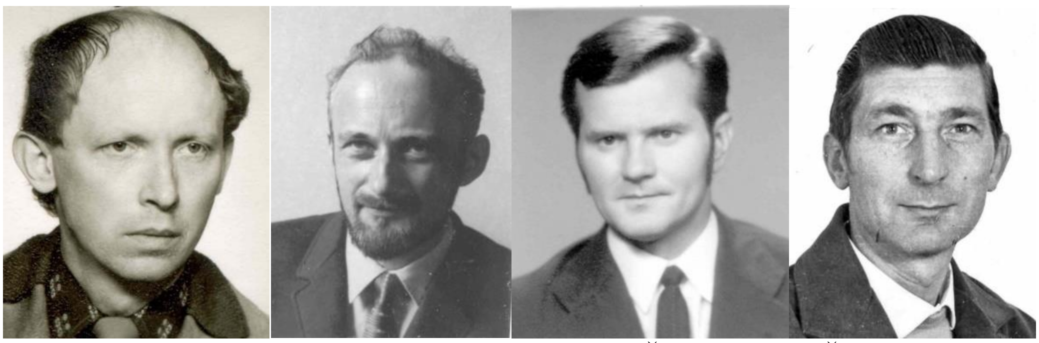


Figure 10: Zdeněk Trejbal, Miloslav Křivánek, Milan Čihák, Josef Šinágl

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

U-120M extraction

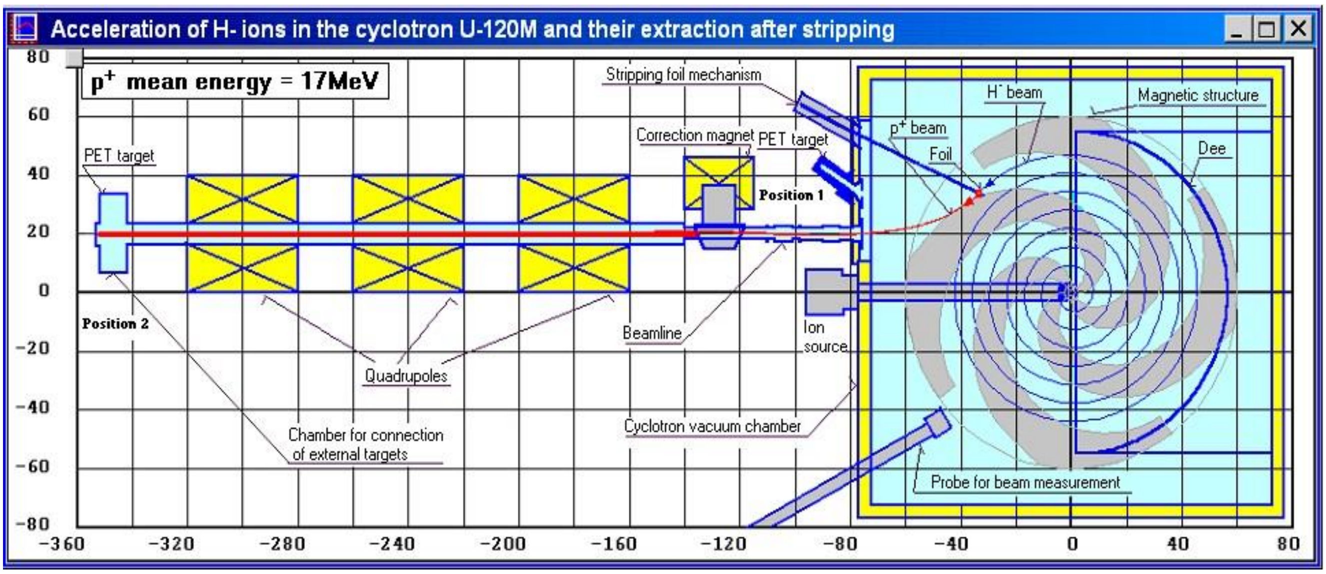


Figure 11: Stripping for negative beams

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 12 and consists of magnetic exciter + three ESD + MC (not shown)

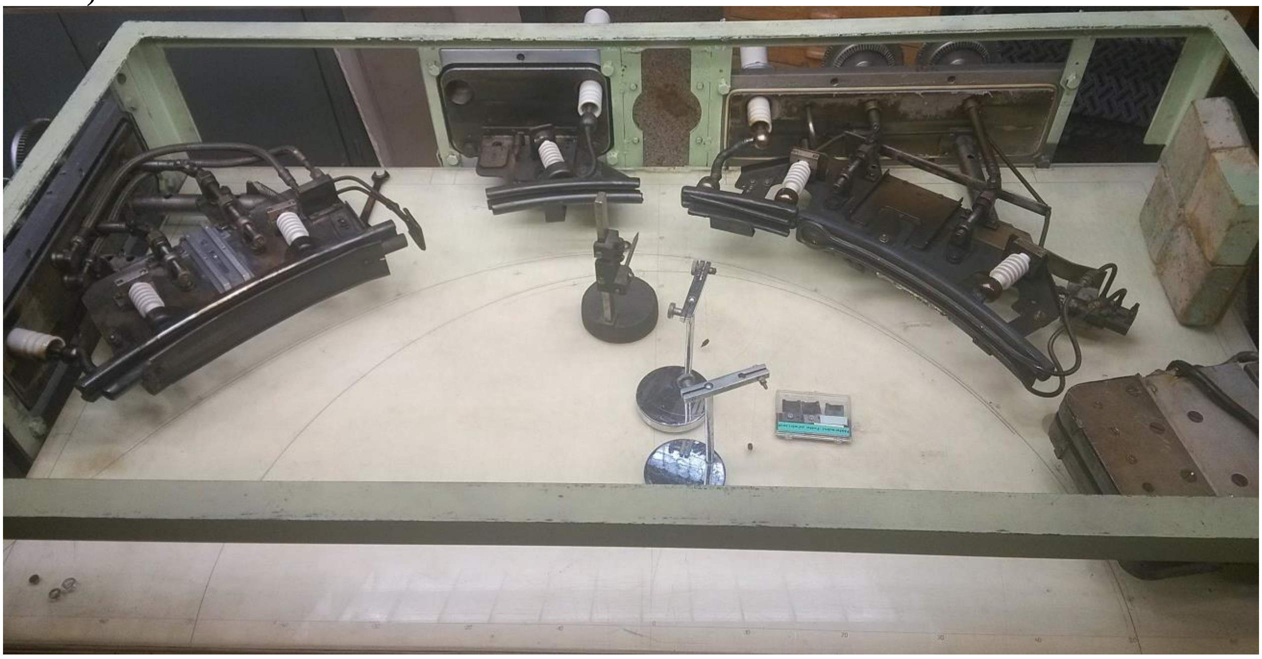


Figure 12: Deflection system for positive particles

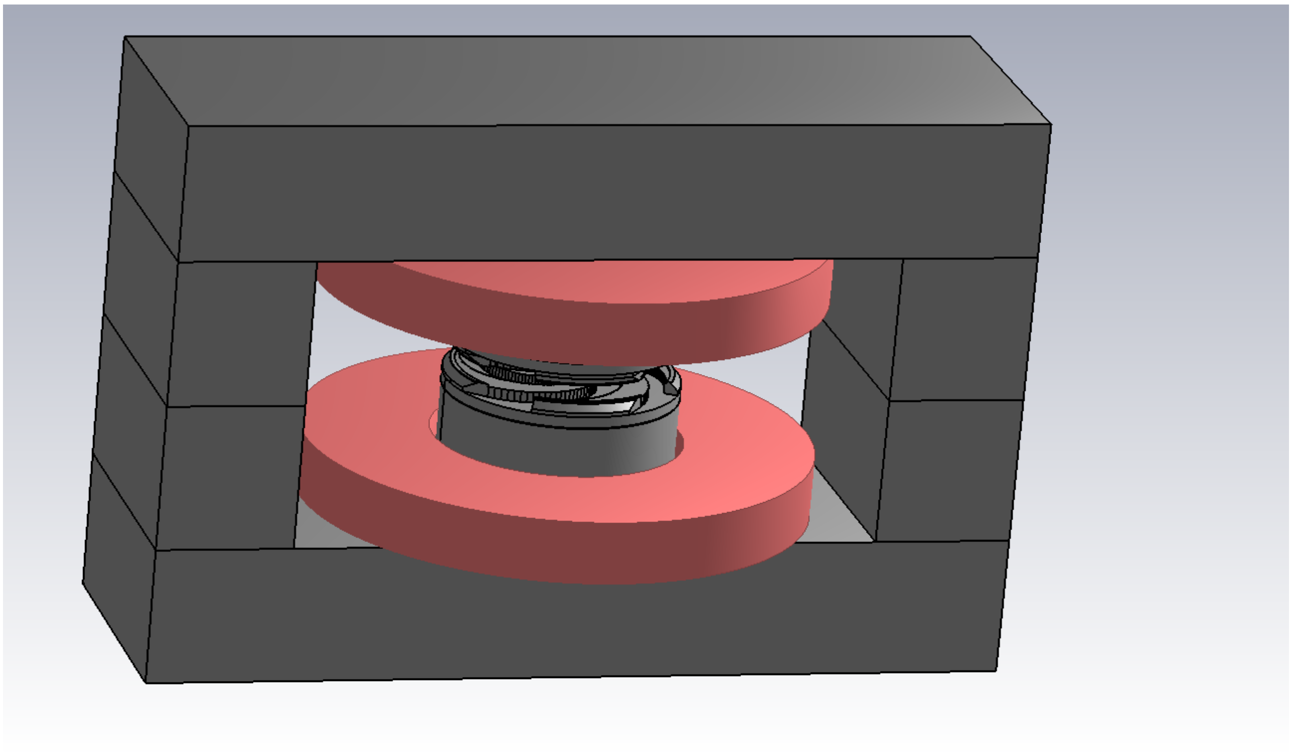


Figure 13: View of the computer model of the magnet

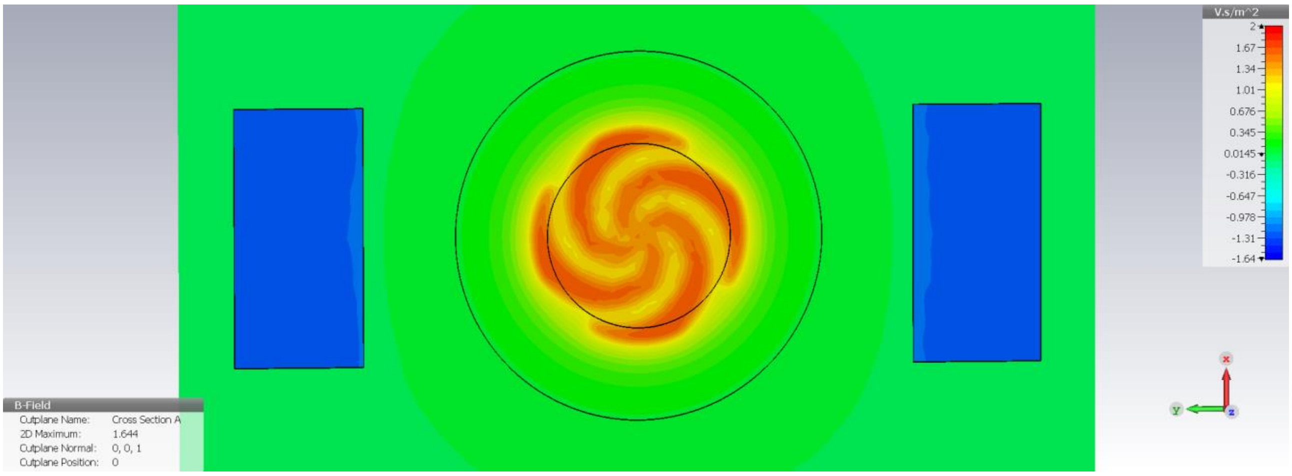


Figure 14: Magnetic field distribution

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. 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 will replace Phasotron in Medico-technical Center JINR Dubna and will be used for further research and development of cancer therapy by protons. Figure 15 shows possible positon of SC202 in the building №1.

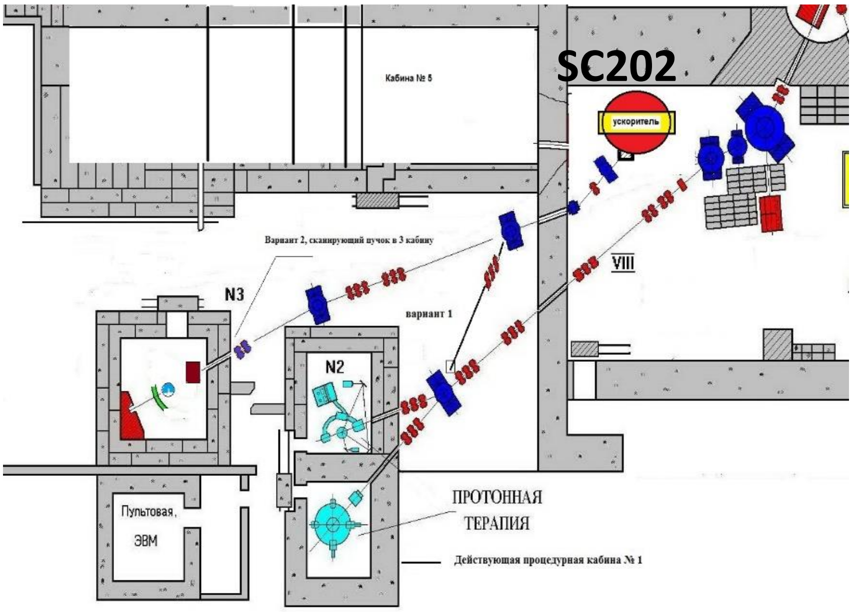


Figure 15: JINR MEDICAL TECHNICAL COMPLEX with future SC202 cyclotron

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 will be in the range of 2.9T/3.6T (center/extraction). Superconducting coils will be 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 will work 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 16). Extraction will be provided by one electrostatic deflector placed in the valley between sector shims.

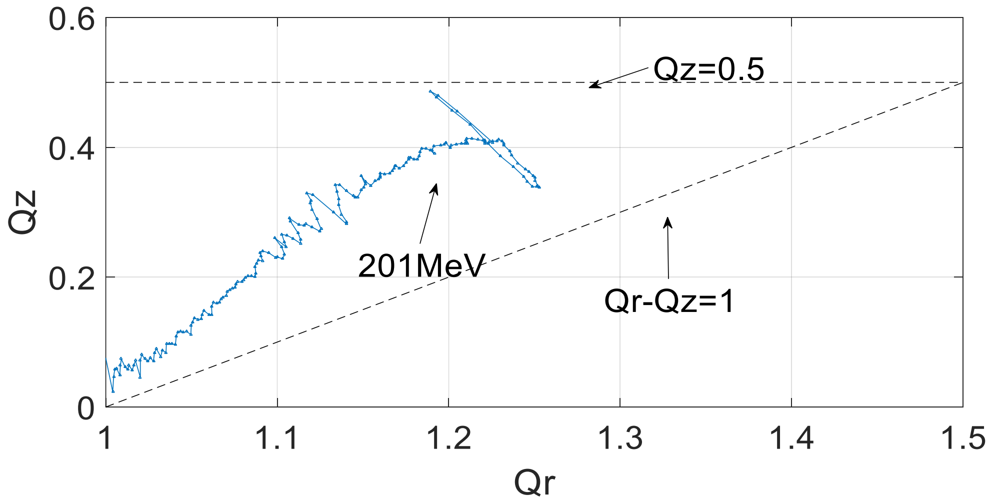


Figure 16: Working diagram.

Designed DLNP SC202 project is approved by the expert commission in the city of Hefei in October 2016. Manufacturing of SC202 systems and elements will be done in 2017. Assembling, tuning and testing SC202 should be finished in 2018.

The results of testing will be used by ASIPP for a serial SC202 manufacturing.

At present, the engineering design of SC202 project has been completed, each subsystem of the Hefei cyclotron is in production or experimental verification. The cryogenic electrical 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. For the moment, the RF generator and the low level control system are manufactured. The low power test of the accelerating cavity model is completed. RF cavities will be manufactured in the nearest future. Design and manufacture of subsystems of SC202 are performing in accordance with the project schedule. There is some delay in cryostat and superconducting coils production.

Figure 17: View of the cyclotron.

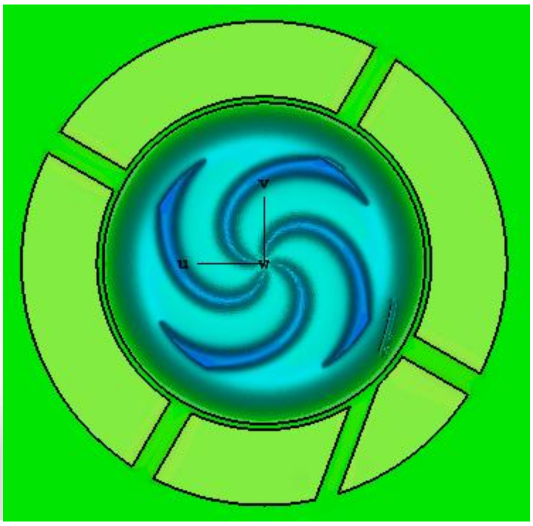
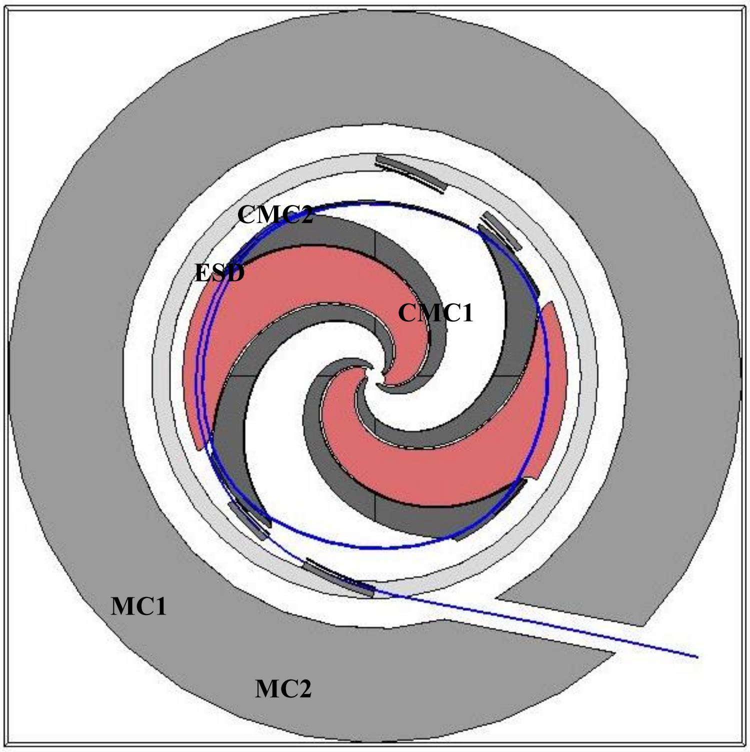


Figure 18: Magnetic field calculated in CST Studio

Project of the cyclotron SC202 (Dubna) is not finished. Cyclotron SC202 (Dubna) will use extraction schema which differ substantially from one used for the cyclotron for Hefei medical center.

The particles from SC202 (Dubna) cyclotron will be extracted with one ESD electrostatic deflector, two magnetic channels MC1 and MC2 (Figure 19). Cyclotron SC202 (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 20). 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.



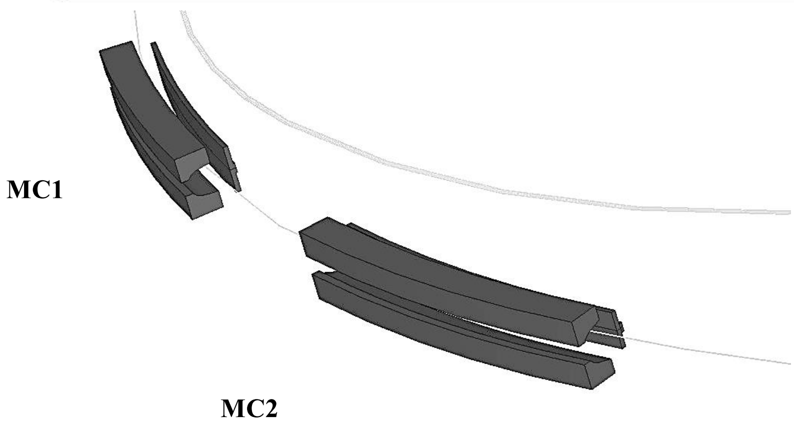


Figure 19: View of the half of the cyclotron with the extraction system. Blue line is trajectory of the particle. Elements of the extraction schema: ESD – electrostatic deflector, MC1, MC2 – passive magnetic channels, CMC1, CMC2 – compensation magnetic channels.

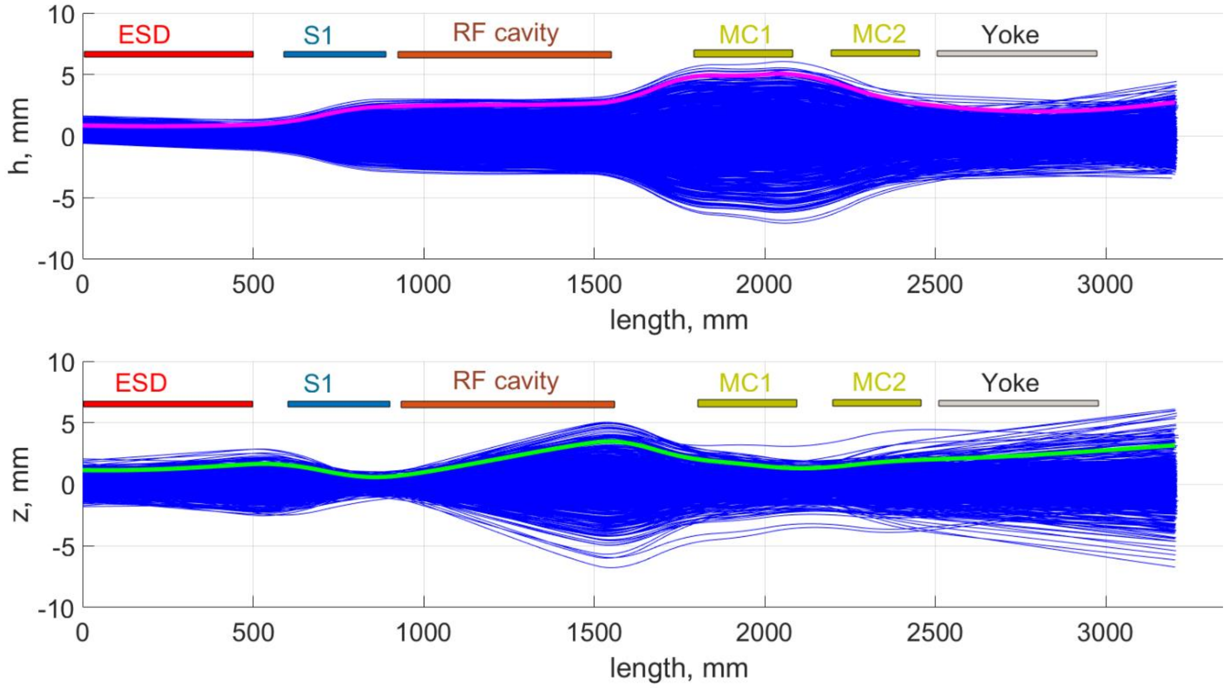


Figure 20: Horizontal and vertical motion of the beam during extraction, thick lines - 2σ envelopes

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.

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 21). 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.

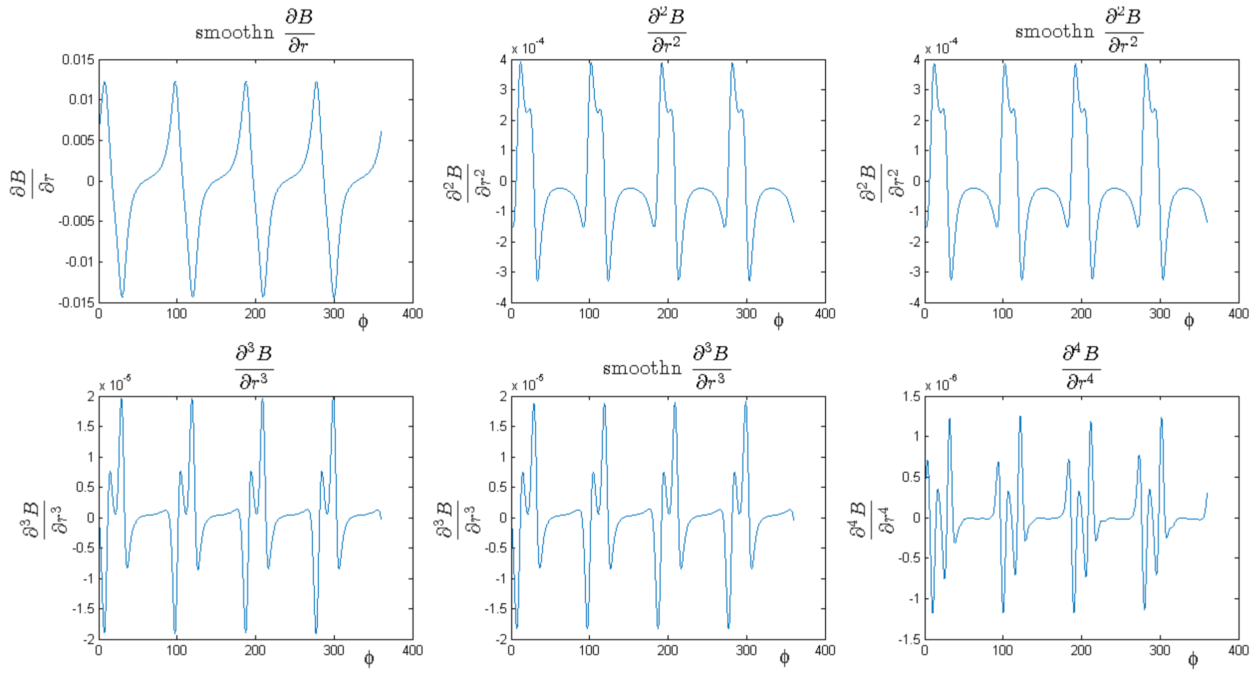


Figure 21: Derivatives taken with smoothing algorithms.

- Codes for beam dynamics simulations were upgraded by new algorithms for calculations of the magnetic field outside the median plane.
- Scripts for producing the 3D magnetic field maps in CST studio and 3D electric and magnetic field maps from RF cavity simulations and for reading them into the Matlab workspace were written.
- Several programs for deriving 3D field map from 2D field map were coded, their efficiency and errors assessed and compared.

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

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2. IPAC’16, the Seventh International Particle Accelerator Conference, Pohang Accelerator Laboratory, Korea, *RESEARCH AND DEVELOPMENT OF A COMPACT SUPERCONDUCTING CYCLOTRON SC200 FOR PROTON THERAPY*, S.V. Gurskiy, G.A. Karamysheva, O.V. Karamyshev, S.A. Kostromin, N.A. Morozov, E.V. Samsonov, G.D. Shirkov, Y. Bi, Y. Song, K. Ding, G. Chen,, 2016 .
3. IPAC’16, the Seventh International Particle Accelerator Conference, Pohang Accelerator Laboratory, Korea, *RESEARCH AND DEVELOPMENT OF A COMPACT SUPERCONDUCTING CYCLOTRON SC200 FOR PROTON THERAPY*, S.V. Gurskiy, G.A.

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7. 21st International Conference on Cyclotrons and their Applications, Zürich, Switzerland, Computer Modelling of Magnet for SC202 Superconducting Cyclotron, G.Karamysheva, O.Karamyshev, N.Morozov, E.Samsonov, G.Shirkov.
8. 21st International Conference on Cyclotrons and their Applications, Zürich, Switzerland, S. Gurskiy, COMPACT SUPERCONDUCTING CYCLOTRON SC200 FOR PROTON THERAPY, G.Karamysheva, O.Karamyshev, N.Morozov, D.Popov, E.Samsonov, G.Shirkov, S.Shirkov.

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

S.B.Vorozhtsov, V.L. Smirnov

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

Ionetix Corporation, with the great contributions from the JINR participants, completed the conceptual and technical design for the machine. Tesla Corporation that was responsible for design, building, and test the cyclotron cryostat has analyzed the magnet for forces and thermodynamics. Also, Tesla has got through the engineering to get a buildable magnet, the making engineering changes to the rods, extraction elements, etc to try and find a simpler commercially viable system with like characteristics followed (general engineering design). The detailed design (transformation of the Ionetix model level designs to detailed procurable components), the procurement, fabrication, assembly, and commissioning will follow. Ionetix will continue to provide technical support in this project with the JINR participants still involved.

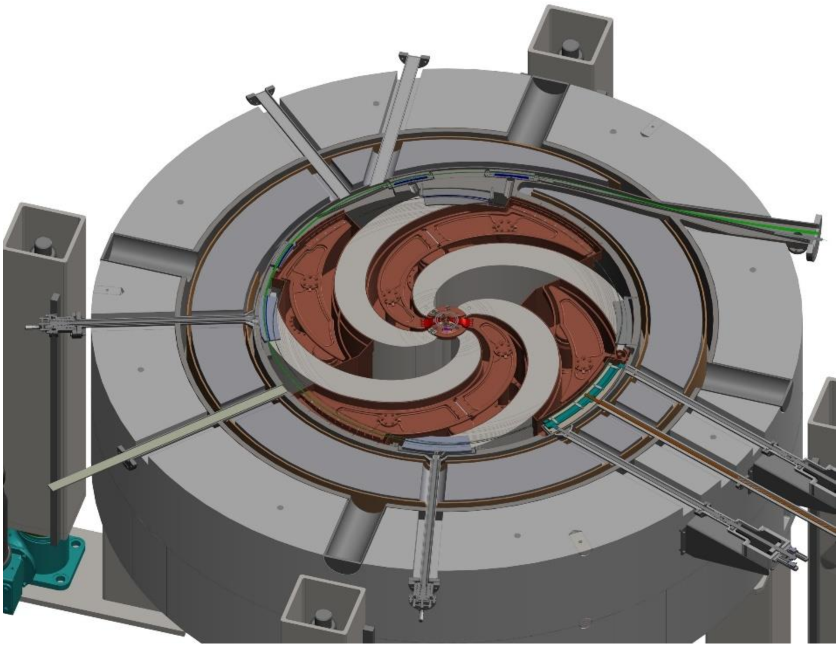

Figure 22: Midplane layout

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 22).

Pronova is leading the current project to procure, fabricate, assemble, and eventual commissioning of the K230 superconducting cyclotron, with continuing scientific, mechanical engineering and other technical support from Ionetix and JINR.

Tesla Corporation, UK, is responsible for engineering, building, and testing the K230 cyclotron cryostat and superconducting coil.

Construction Schedule [*]:

Aug 2017 – Pronova has finalized the contract with Tesla to start building the cryostat.

Sept 2017 - Tesla officially started to build the k230 magnet.

Гни * X. Wu. Private Communication. Aug.2017.

Dec 2017 – The original plan [†] was to have the K230 magnet operational but about 6-months delay in machine construction would probably take place.

Late 2018 - The current plan is to have the whole K230 cyclotron together.

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

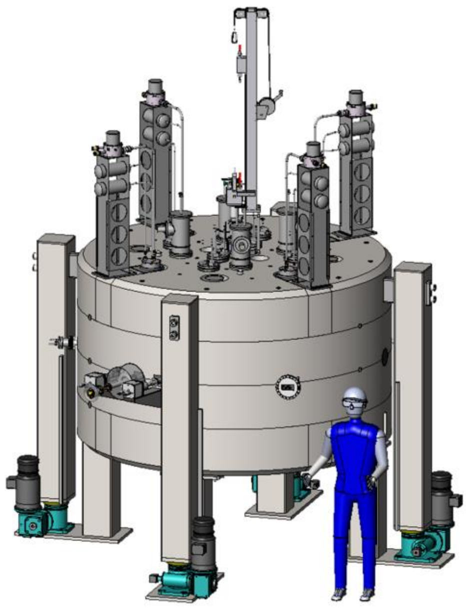

Figure 23: Pronova K230 superconducting cyclotron.

Ionetix ION-12SC cyclotron

5 cyclotrons of this type already have been fabricated and were at various stages of readiness. The Ion-12SC T1 at University of Michigan, MI, has passed FDA validation test run. It is a very important milestone. The machine has to run 6 runs per day for three consecutive days to demonstrate its performance. It was already used to scan the 1st patient in March 2017.

The 2nd Ion-12SC cyclotron has been delivered to next customer and commissioned. Ion-12SC 1st magnetic harmonic problems did not appear in T1 and T3. And the beam commissioning went well.

Tesla Corporation changed some manufacture procedure internally afterwards, and the following systems started having issues in T4 and T5. We are working with Tesla to identify the problems, and all magnets will be mapped before leaving Telsa from now on.

The tuning the beam for T5 cyclotron at the Ionetix was performed successfully. The viewer probe (just to have general ideas of the beam position, see Figure 24Figure 25 and the beam current probe (to give more accurate information, see Figure 25) were used in the beam tests. SNOP code was applied to find a case matching what was observed in the beam tests. This certainly helped to understand the problems and deal with them eventually.

† V. Derenchuk et al. Application of Superconducting Technology for Proton Therapy. NAPAC2016 – Proceedings, Chicago, IL, USA, October 9-14, 2016.

‡ V. Smirnov, S. Vorozhtsov, Z. Neville, G. Blosser, X. Wu, and J. Vincent. Computer Simulations on Manufacture and Assembly Tolerances for a Superconducting Cyclotron. DLNP Seminar on “Problems of charged particles accelerators”, June 8, 2017.

In August 2017 a new cyclotron T7 mapped field in the mid-plane after shimming was done at Tesla. The 1st harmonic has been reduced to ~ 13 gauss at R=90 mm. T7 has been shipped to Ionetix at the beginning of the September. Once it got cooled down, it was mapped again at Ionetix before doing the beam testing.

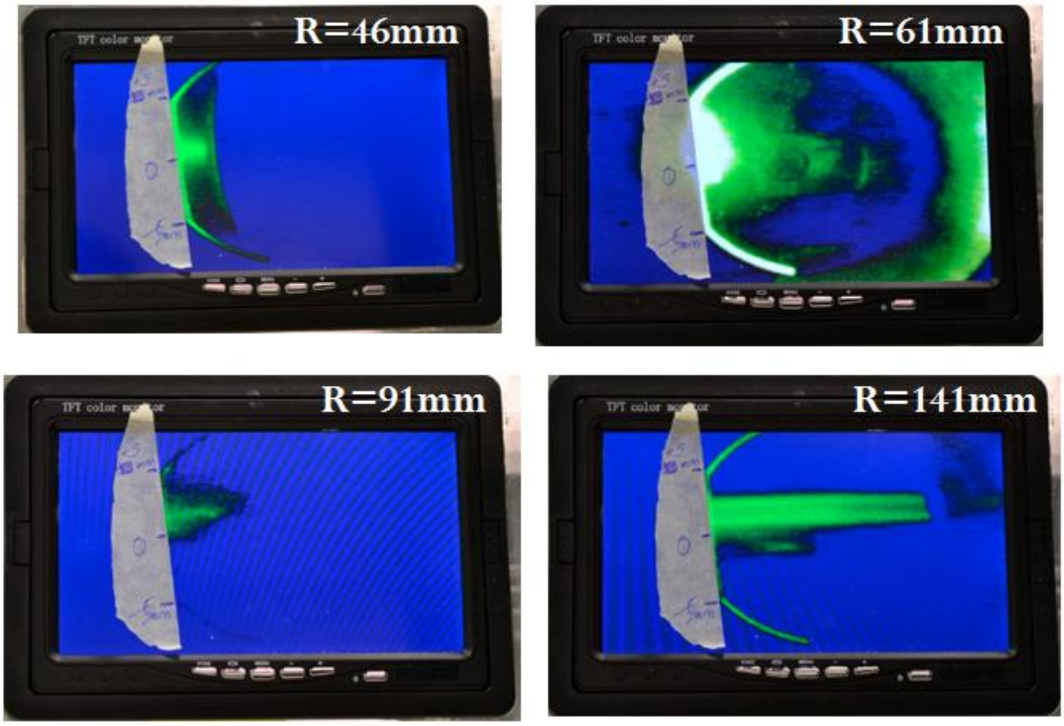

Figure 24: ION-12SC beam viewer probe reading.

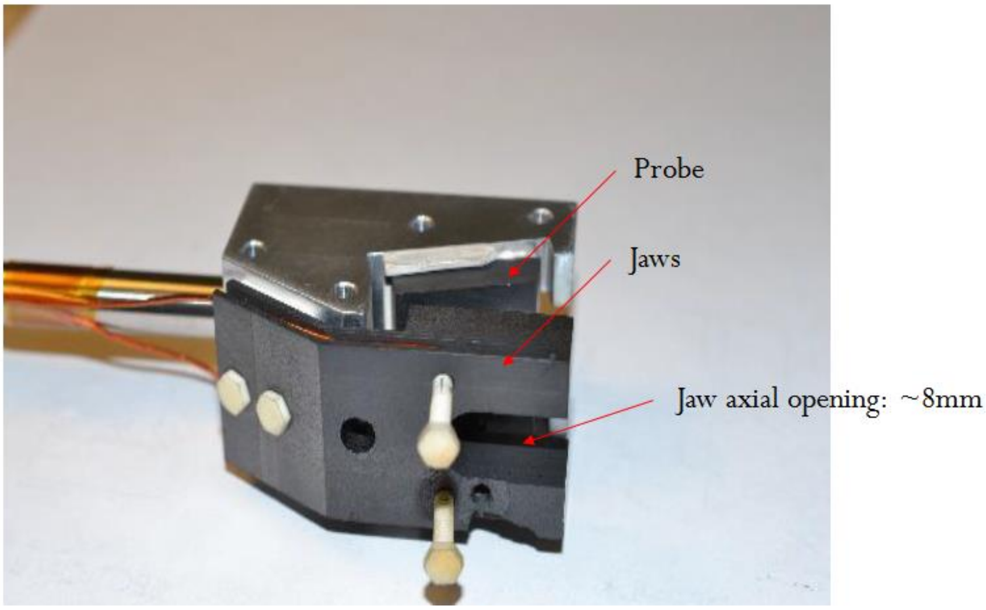

Figure 25: ION-12SC beam current probe

Below Figure 26 and Figure 27 give impression of the cyclotron general appearance.

Figure 26: Accelerator in hospital.

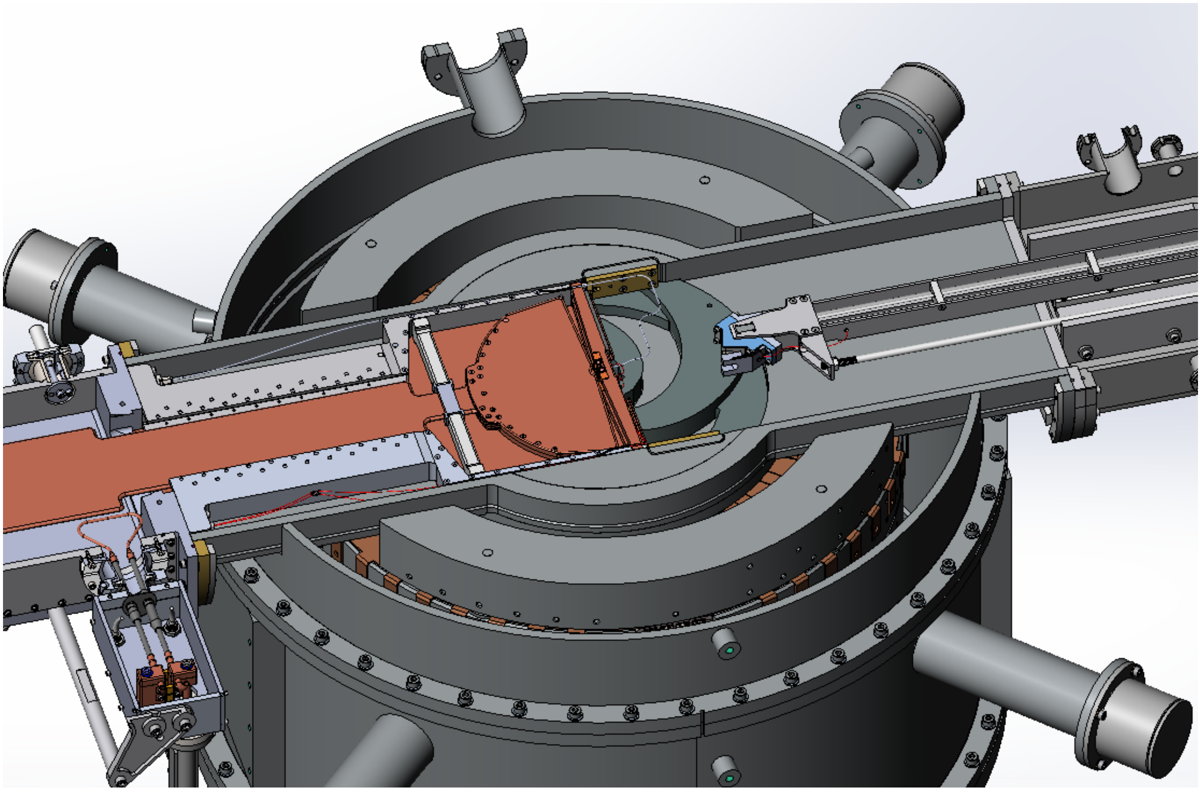

Figure 27: Accelerating system

A Cyclotron Complex for Carbon Ions Acceleration

An accelerating complex for hadron therapy is proposed. Facility consists of two superconducting cyclotrons and is aimed to produce beams of $^{12}C^{6+}$ ions with energy of 400 MeV/u (Figure 28). Accelerator-injector is a compact 70 MeV/u cyclotron (Figure 29). Main machine is a separated sector cyclotron consisting of six magnets. Basic features of the main cyclotron are high magnetic field, compact size, and feasible design of the accelerator systems. The advantages of the dual cyclotron design are typical of cyclotron-based solutions. The initial design studies show that it is technically feasible with acceptable beam dynamics in both machines. The accelerator complex having a relatively compact size of ~15 m can be an alternative to synchrotrons for the same applications [§].

The design study has been carried out to show that a coupled superconducting cyclotron complex is a serious candidate for a light-ion medical facility. The cyclotron complex is more compact than the synchrotron and simpler to operate. The cyclotron elements specified in the current design are realistically achievable

[§] V. Smirnov and S. Vorozhtsov. Feasibility Study of a Cyclotron Complex for Hadron Therapy. Intended for publication in NIMA. October, 2017.

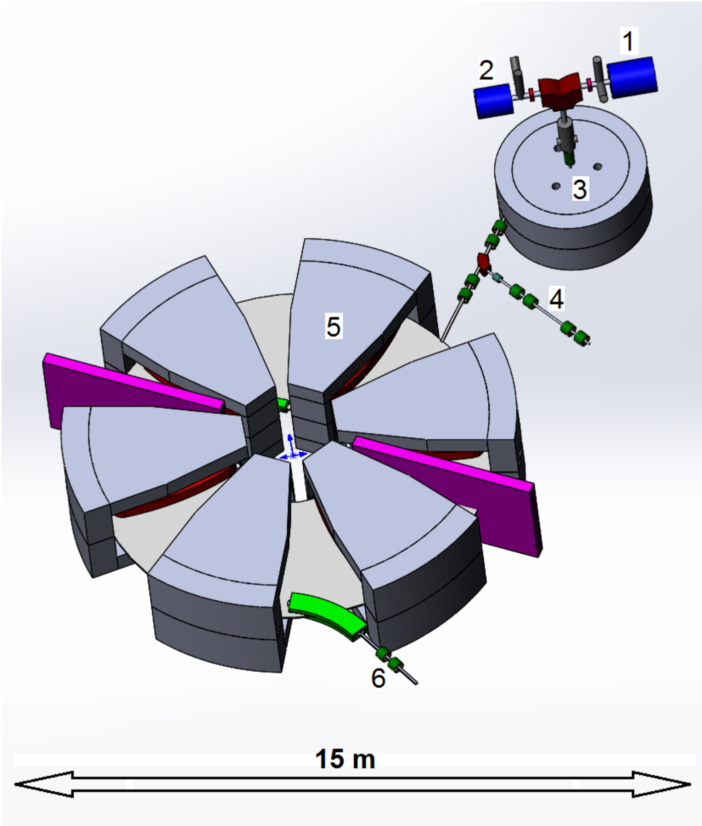

Figure 28: Acceleration complex including the cyclotron-injector and the booster: 1 – $^{12}C^{6+}$ ECR, 2 – H_2^+ ECR, 3 – cyclotron-injector, 4 – medium energy beam transport line (proton and carbon 70 MeV/u), 5 – main cyclotron, 6 – heavy energy beam transport line (carbon 400 MeV/u).

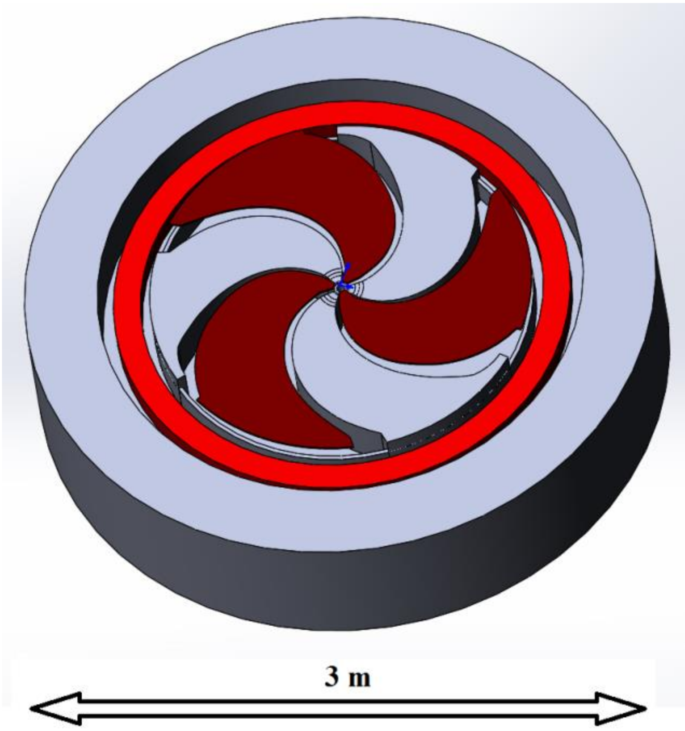

Figure 29: Cyclotron-injector

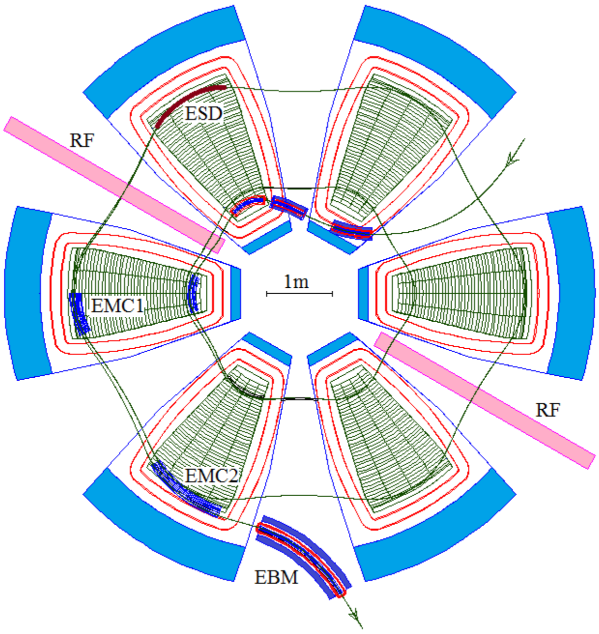

Figure 30: Extraction system of the main cyclotron: ESD – electrostatic deflector, EMC1, EMC2 – extraction magnetic channels, EBM – extraction bending magnet.)

Energy Upgrade and Beam Transmission Efficiencies for RIKEN K-70 AVF Cyclotron

The central region of the RIKEN AVF cyclotron was modified in order to increase the beam energy of protons and M/Q = 2 ions, and acceleration tests were performed. In order to increase the beam energies to meet the demands from users for nuclear physics and radioisotope production, the modification of the central region of the cyclotron was designed [5] and was executed (Figure 31). In the tracking simulations, the injection acceptance in the modified central region was not very different from that for the existing structure. In the acceleration tests, we successfully increased the beam energy of protons from 14 MeV to 30 MeV. On the other hand, the transmission efficiencies in the H = 2 operations were lower than those before the modification. Hereafter, we will analyze the results of the acceleration tests and review the structure of the central region.

Figure 31: Photograph of the RF shields around the inflector.

Publications

1. Modern compact accelerators of cyclotron type for medical applications V. L. Smirnov and S.B. Vorozhtsov, ISSN 1063-7796, Physics of Particles and Nuclei, 2016, Vol. 47, No. 5, pp. 863–883. © Pleiades Publishing, Ltd., 2016.
2. 21st International Conference on Cyclotrons and their Applications, Paul Scherrer Institute, PSI, and the Swiss Federal Institute of Technology, ETH, ETH Zürich, Switzerland. The Ionetix ION-12SC Compact Superconducting Cyclotron for Production of Medical Isotopes, John J Vincent, Gabe Fawley Blosser, Gary Steven Horner, Xiaoyu Wu, Victor Smirnov, Sergey Vorozhtsov, 2016.
3. 12th European Conference on Accelerators in Applied Research and Technology (ECAART12), Jyväskylä, 3–8 July 2016, University of Jyväskylä; 3–8 July 2016, Finland Approach for Realization of High Intensity Cyclotron Beam, Masao Nakao, Satoru Hojo, Ken Katagiri, Akinori Sugiura, Takashi Wakui, Akira Noda, Nobuyuki Miyahara, Koji Noda, Victor L. Smirnov, Sergey B. Vorozhtsov, Akira Goto, 2016.
4. 21st International Conference on Cyclotrons and their Applications, Paul Scherrer Institute, PSI, and the Swiss Federal Institute of Technology, ETH, ETH Zürich, Switzerland. A Coupled Cyclotron Solution for Carbon Ions Acceleration, Victor Smirnov, Sergey Vorozhtsov, 2016.
5. S. B. Vorozhtsov, V. Smirnov, and A. Goto., "Modification of the central region in the RIKEN AVF cyclotron for acceleration at the H=1 RF harmonic," in *Proc. Cyclotrons'10*, Sept. 2010, pp. 138–140.