Annex 3.

Form of opening (renewal) for Project / Sub-project of LRIP

APPROVED

JINR DIRECTOR

_____________/___________________

"_____" ______________________ **2024.**

PROJECT PROPOSAL FORM

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

1. General information about the project/subproject of a major infrastructure project (hereinafter referred to as LRIP)

1.1. Theme code / LRIP (for extended projects) – *08-2-1127-2016*
The theme code includes the opening date, the end date is not specified, since it is determined by the completion dates of the projects in the theme.

1.2. Project/subproject code LRIP *08-2-1127-1-2024/2027* (for extended projects and subprojects)

1.2. Laboratory

DLNP

1.3. Scientific direction *Accelerators, detectors, R&D, applied research*

1.4. Name of the project/subproject of the IPC

Creation of test benches for testing individual systems of the MSC-230 cyclotron.

1.5. Project/subproject manager(s) of the LRIP

G. A. Karamysheva
S.L.Yakovenko

1.6. Deputy(s) of the head of the project/subproject of the LRIP (scientific director of the project/subproject of the LRIP

2. Scientific case and project organization

2.1. Annotation

To create a medical cyclotron, it is necessary to develop a virtual prototype, on which the main systems are tested and the basic parameters of the accelerator are selected.

A virtual prototype is a computer model of a physical object (in our case, a cyclotron), allowing analysis and testing of both individual systems and the product as a whole. However, virtual prototyping is not enough to produce an effective cyclotron, as some systems require experimental testing on models and prototypes. The most important thing is to optimize and test the ion source and deflector, and a Hall sensor calibration stand is also required to perform commissioning of the MSC-230 cyclotron.

It is advisable to have the following stands in the experimental hall of DLNP NEONU:

1 A test bench of the internal source. Testing of internal source, deflector.

2. Calibration test bench d. Calibration of Hall sensors.

3. Stand for winding coils from HTS tape.

4. Stand for winding copper windings.

5. Cryogenic test bench g for practicing the cooling method.

2.2. Scientific case (aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks)

The relevance of the project, focused on modeling the cyclotron and its systems, is determined primarily by the importance of creating a domestic accelerator for proton therapy using the most modern methods, distinguished by a unique beam intensity, as well as the relevance of medical and biological research that will be conducted in the innovation center.

Medical and biological research at JINR

JINR has many years of experience in fundamental and applied research in radiation biology and medicine. The first radiobiological experiments at JINR using synchrocyclotron proton beams were started in the 1960s. The first sessions of clinical application of proton beams generated by the synchrocyclotron of the JINR DLNP were conducted since 1967. For the first time in Russia, the method of three-dimensional conformal proton radiation therapy was implemented in the MTC of the DLNP. In the period from 2000 to 2019, about 1,300 patients (including non-Russian citizens from JINR member states) with various neoplasms underwent a course of proton radiation therapy using the phasotron beams.

Flash therapy method.

Compared to radiation therapy performed at a conventional dose rate (1–7 Gy/min), Flash irradiation is performed at a dose rate of over 40 Gy/s in less than 0.5 seconds. Healthy tissue is more resistant to Flash irradiation, while the tumor has the same sensitivity as to conventional treatment. The method is of great interest to specialists, since it not only reduces the impact on healthy tissues and reduces the number of treatment procedures, but also allows treating some radioresistant tumors. Currently, research is being actively conducted on proton beams of varying intensity, but the upper limit for beam intensity appropriate for therapy has not been determined. In particular, in Troitsk, at the high-current linear proton accelerator (LA) of the INR RAS, a study is being conducted of the irradiation mode of biological objects at record dose rates for protons of 1 MGy/s, which can be called the “extreme” Flash mode.

It is advisable to start using the new Flash therapy treatment method with the three-dimensional conformal proton beam therapy method, since delivering the required radiation dose at the ultra-high dose rate provided by the Flash method is much more problematic when treating with point scanning.

Pilot studies of the Flash effect were started at JINR back in 2020. For this purpose, a high-intensity proton beam with a uniform cross-section was formed at the phasotron. Two ionization chambers for monitoring the beam intensity and measuring its horizontal and vertical profiles were also designed, manufactured and successfully tested, software was developed for express processing of scanned images from radiochromic films capturing beam profiles. All this made it possible to begin research into the Flash effect during irradiation of both cell cultures and small laboratory animals (mice, rats). At present, work has been completed on studying the cellular survival of the A549 line of human lung carcinoma after proton beam irradiation. Flash mode irradiation turned out to be more sparing for the cells. Therefore, further study of the Flash effect is of great theoretical and practical interest. The use of Flash mode in radiotherapy can minimize damage to healthy tissue and reduce the number of irradiation fractions. However, at present there is no well-developed understanding of the mechanism of action of the Flash effect. Further studies are needed to clarify its radiobiological mechanism. Special attention should also be paid to the development of special equipment and dosimetry tools for conducting experiments in the Flash irradiation mode. These tasks will be taken out into a separate activity within the framework of the theme *08-2-1127-2016*.

Expected benefits of the Flash method:

1. Reduced impact on healthy tissues
2. More effective treatment of radioresistant tumors and recurrent diseases
3. Reduced number of cases where carbon ion application is required
4. Reduced number of treatment procedures

With the advent of the new Flash irradiation method, the need for high-current accelerators increased, which led to the development of a new MSC-230 project with a small magnetic field of 1.7 T in the center. The MSC-230 cyclotron project was developed, the main technical solutions of which are based on the experience of successfully operating accelerators (Varian, C-235).

As a result, the cyclotron is capable of providing the highest possible current in this class of accelerators, since in addition to a relatively low field, it has a record acceleration rate with minimal energy consumption of both the magnetic and accelerating systems.

At the D.V. Efremov Institute of Electrophysical Apparatus (NIIEFA), technical design and manufacturing of the main systems of the cyclotron began this year.

Internal source stand. Testing of internal source, deflector.

For successful launch of the MSC-230 cyclotron, testing of individual cyclotron systems on real models and prototypes is required. A number of systems, being expendable materials, will need to be replaced during operation, primarily the ion source and deflector. For some systems, an important task will be optimization, ultimately aimed at increasing the intensity of the beam extracted from the accelerator.

The beam will be extracted from this cyclotron using an electrostatic deflector (ESD) located between the cyclotron sectors.

The voltage at the ESD required for beam extraction is about 90-100 kV/cm. The beam, after passing through the deflector, passes through the accelerating resonator and then exits the cyclotron according to the scheme previously developed for beam extraction from the SC-200 cyclotron.

The thickness of the cyclotron deflector septum is directly related to the amount of losses during beam extraction, it is the amount of losses that imposes a limit on the maximum current of the extracted beam. The minimum thickness of the septum will depend on the material and manufacturing technology. The minimum achievable height of the deflector needs to be checked, which will directly affect the design of the following cyclotron variations.

Testing of ion sources and deflector will create conditions for creating optimal designs and will contribute to improving their characteristics.

Calibration magnet

To form the magnetic field of the cyclotron, it is important to organize an accurate calibration of the Hall sensors in advance on the magnet available in the department in order to provide reliable information obtained during magnetic measurements. The existing calibration magnet requires revision and alteration of the pole in order to increase the magnetic field. A technical project has been prepared and a new pole has been manufactured for the calibration magnet. However, the field will be increased to 3.2 T, it is desirable to have the ability to calibrate to 3.6 T and higher. It is proposed to manufacture a winding from a high-temperature superconductor (HTSC) for the calibration magnet in order to increase the magnetic field, and in the future, for the use of such windings for cyclotrons for the production of isotopes.

The potential of using high-temperature superconductor (HTSC) windings in medical cyclotrons is beyond doubt, since HTSC justifies the use of superconductivity not so much for achieving a high field, but for significant energy savings with ease of maintenance, comparable to the maintenance of magnets with copper windings. The only limitation of HTSC use today is the high price of a second-generation superconductor suitable for manufacturing cyclotron windings.

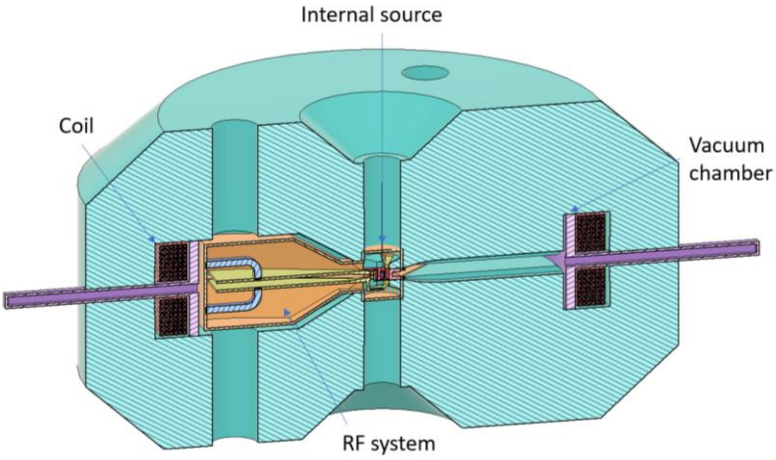
Since windings made of HTSC have not been used in cyclotrons so far, it is proposed to create a test HTSC winding for a calibration magnet, with the aim of increasing the average magnetic field to 3.5 T. JINR FLNP has experience in creating a test magnet made of HTSC tape cooled by a closed-loop cryocooler, intended for a neutron experiment (Chernikov A.N.). HTSC tape 12 mm wide and 0.1 mm thick from SUPERPOWER was used.

Preparation for the formation of the magnetic field of the MSC-230 cyclotron will not be limited to work on the calibration stand. A program for analyzing the characteristics of the measured magnetic field maps has already been prepared – CORD, which was tested on the previously obtained maps of the C-235 IBA cyclotron, and C-200 (Hefei). Work will continue on preparing shimming plans, as well as on preparing for testing the degree of isochronism of the magnetic field, namely, methods for processing the results of measuring the Smith-Garren curves are being developed.

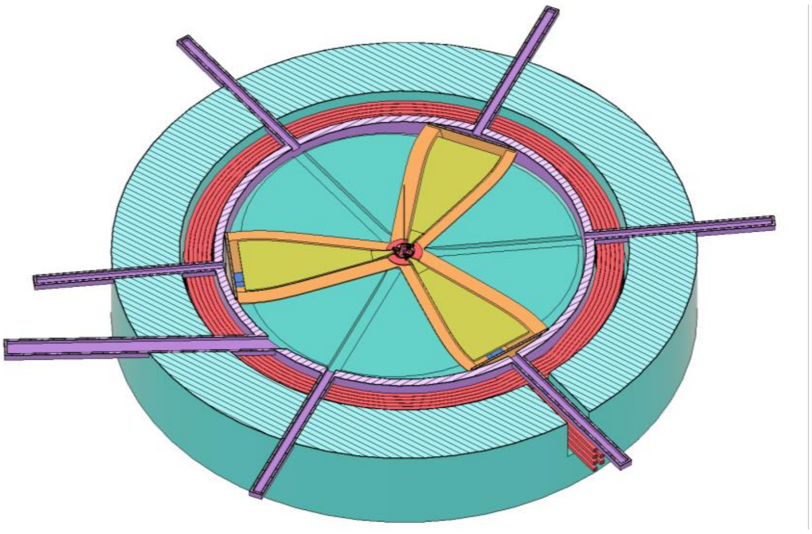
Cyclotron satellite

In addition to treatment, a proton therapy center must also perform diagnostics using PET tomography. An optimal medical cyclotron must have a number of characteristics, such as ease of use, compactness, and energy efficiency. Most of these characteristics are achieved by minimizing the number of ampere-turns required to power the magnet. The size of the coils is reduced, the accelerator becomes more energy efficient and cheaper. Since in this case the cyclotron requires less material to produce the coils, the use of HTSC becomes affordable.

We are working on a cyclotron project for producing isotopes for PET tomography. The NEONU department has interesting developments for creating such a cyclotron. The figure below shows a view of a cyclotron accelerating H^- - ions to an energy of 15 MeV



Vertical section.



Horizontal section.

Figure 1: *View of a 3D computer model of a cyclotron.*

The proposed configuration of the cyclotron with three wide sectors and compact accelerating resonators operating at a high frequency of 145 MHz is advantageous for both the magnet design and the accelerating RF system, since the magnet, providing the necessary average magnetic field, is very efficient (has a small number of ampere-turns - 27,000), and the RF system is highly compact. Resistive coils and a fairly large pole diameter reduce workload and the cost of manufacturing this machine.

Table: Parameters satellite cyclotron .

Magnet type	Electromagnet with resistive winding/HTSC winding
Ion source	Internal / external H
Final energy MeV	15
Output radius , mm	360
Average magnetic field , T	1.55
Dimensions (height × diameter), mm ^{2}	750×1290
Weight , kg	5500
Hill / Valley field , T	2.1/0.3
Hill/Valley clearance , mm	25/210
Number of A* turns	27,000
Magnet power loss , kW	25
RF frequency , MHz	145
Acceleration factor	6
Voltage , kV	30-50
Power loss of resonators , kW	8
Number of revolutions	12 0
Beam intensity , μA	Up to 1000
Conclusion	stripping

Magnetic field analysis and particle dynamics assessment.

The average magnetic field and flutter obtained from the CST simulation are shown in Figure 2. The betatron frequencies calculated at equilibrium orbits are shown in Figure 3.

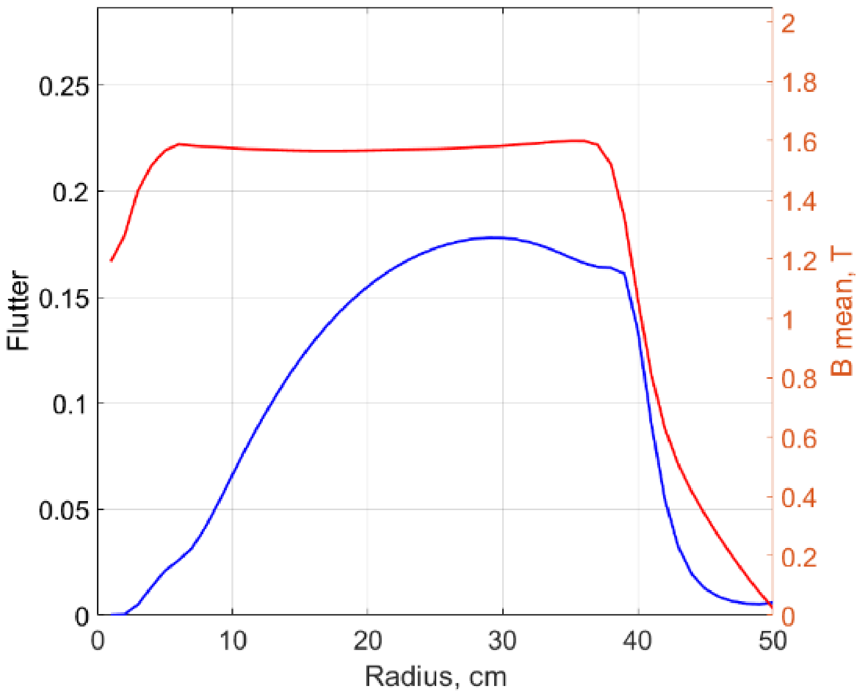


Figure 2: Average magnetic field and flutter as a function of radius.

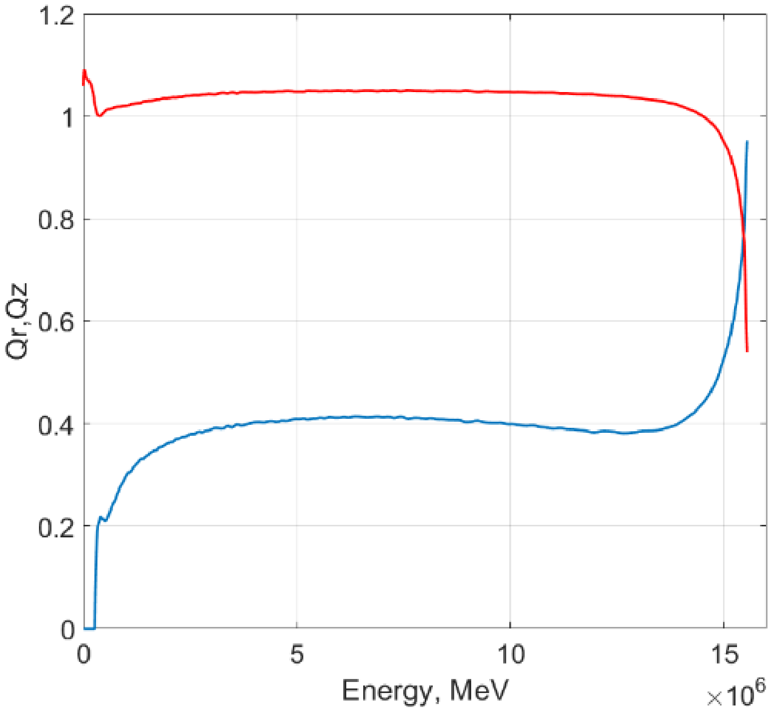
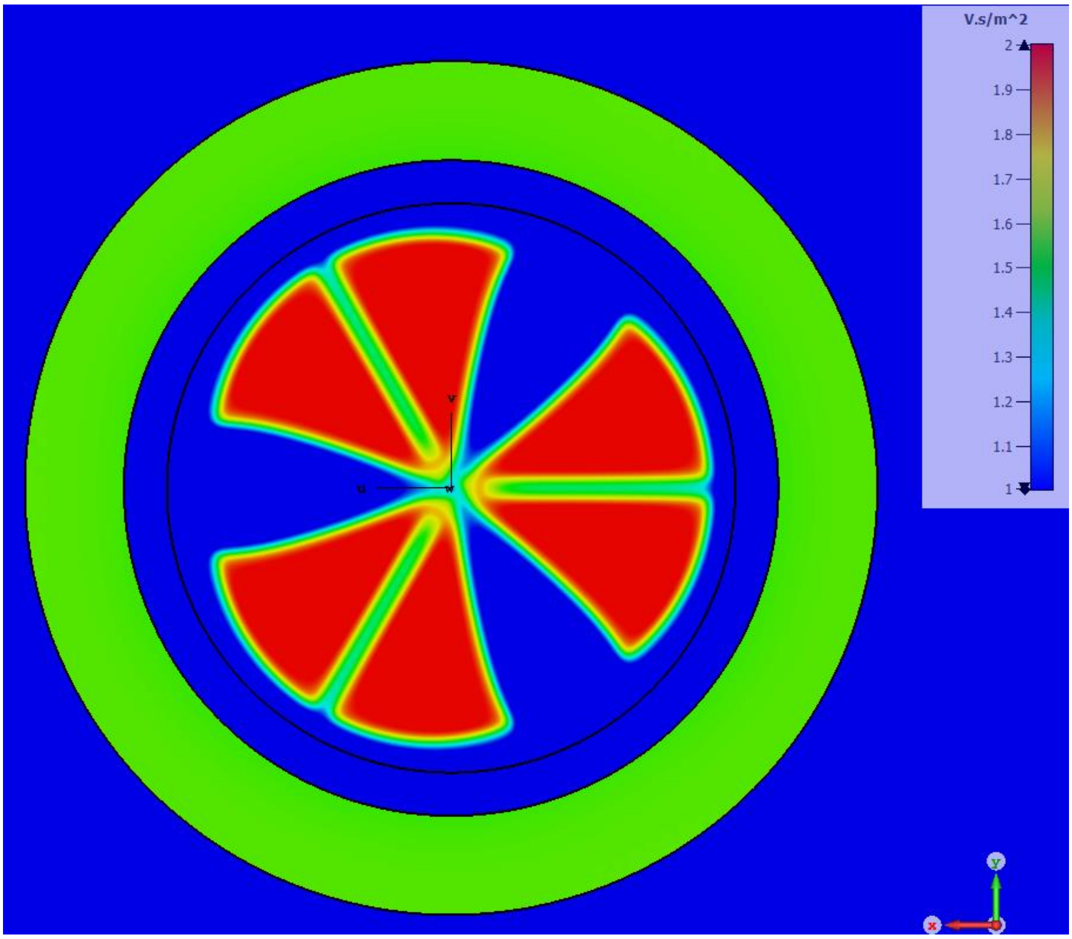


Figure 3: Betatron oscillation frequencies.



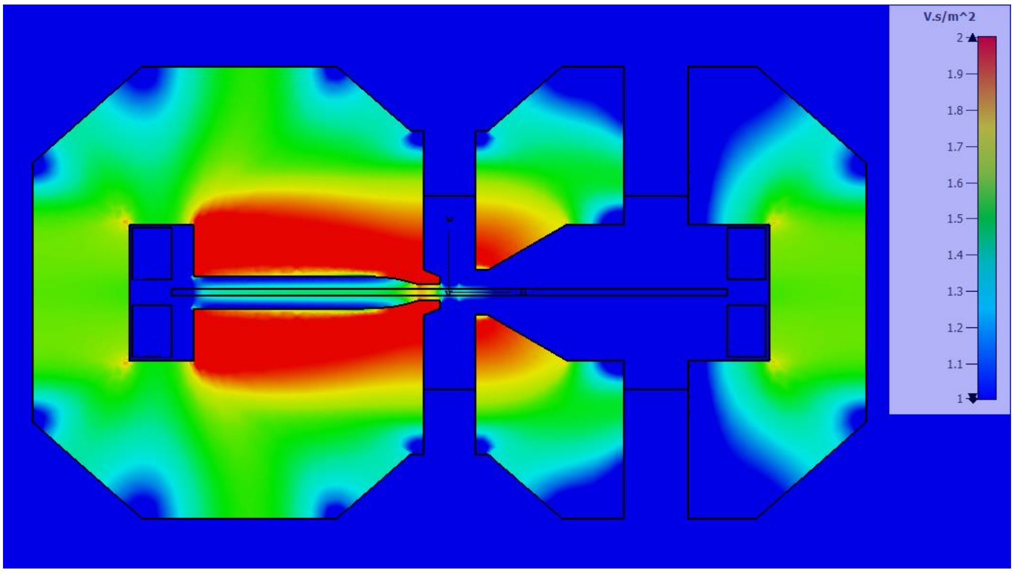


Figure 4: Distribution of magnetic flux density in the median plane (top), inside the magnet yoke (bottom).

The magnetic flux density distribution is shown in Figure 4. The cyclotron structure of three wide sectors has high 6th and 9th Fourier harmonics in the magnetic field structure, which together with the third harmonic lead to a fairly large flutter value (Figure 2).

Since the concept is quite unusual, particle motion simulations were performed for proof-of-work. The beam was accelerated in 3D magnetic field maps and 3D RF electric field maps with initial betatron oscillation amplitudes of up to 5 mm. The total number of revolutions to reach the design energy of 15 MeV at an accelerating voltage of 20 kV was 125. There were no particle losses at any radius.

Accelerating system and central region

Geometrical model of a two-gap delta resonator placed inside the valley of the RC 3/6 cyclotron magnetic system, simulated in CST STUDIO SUITE is shown in Figure 5. The design acceleration frequency and the voltage required for acceleration along the radius were calculated. Both resonators operate in phase and are galvanically connected in the central region.

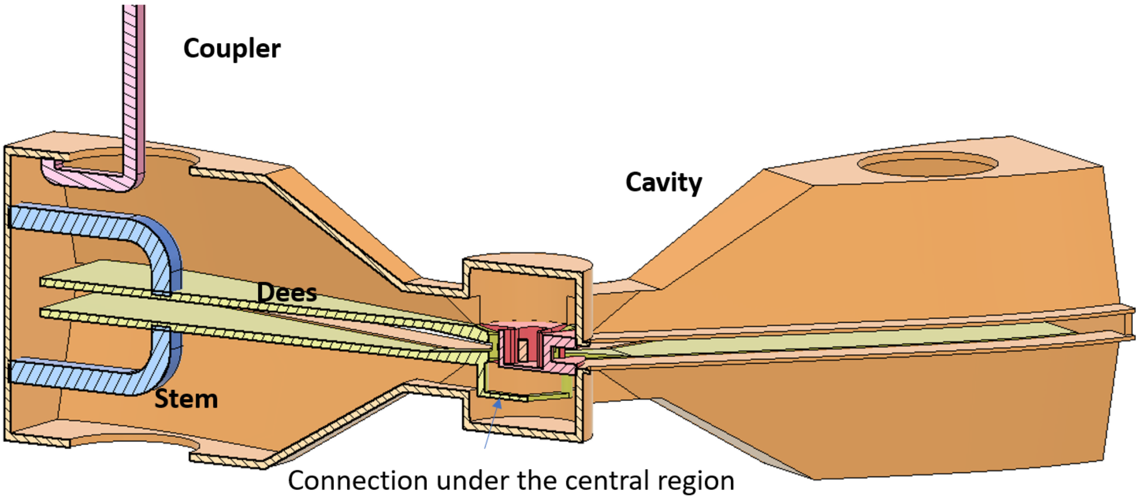
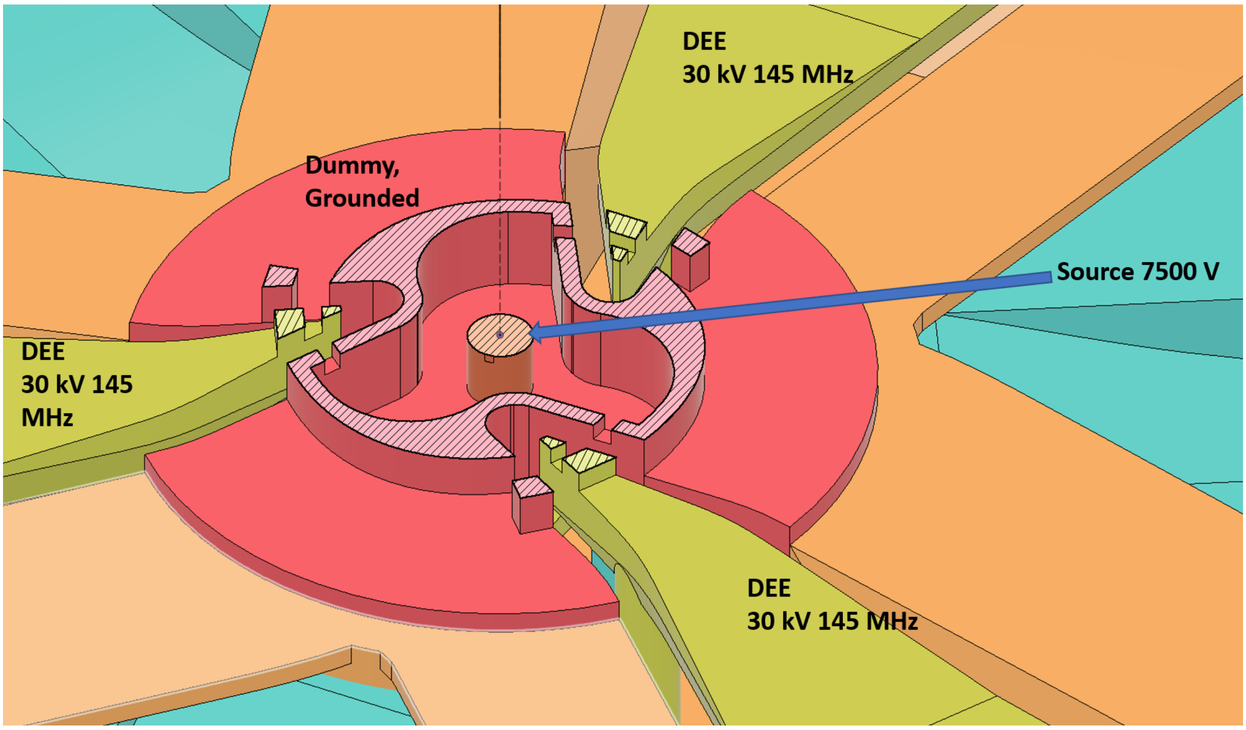


Figure 5: View of the RF resonator.

An active tuning system for compensating for the detuning due to temperature changes during HF heating can be implemented by a capacitive tuner from the radial direction. Calculation shows that the frequency of the model is about 145 MHz. For an accelerating voltage of 30 kV, the calculated losses are about 8 kW.



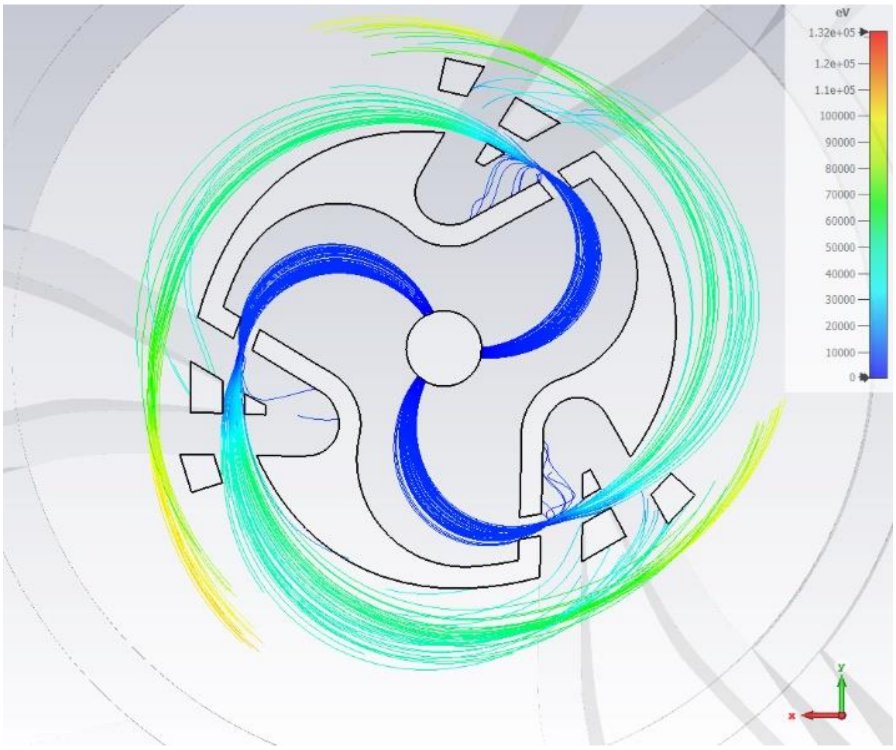


Figure 6: top: view of the central area; bottom: particle trajectories in the central region.

Of course, the high frequency of the RF system can potentially lead to poor particle capture in the first acceleration gap. But this problem can be solved if the particles enter the first acceleration gap with some energy, due to which they pass through the first gap much faster.

The particles start from the PIG source, which is under voltage of 7500 V, accelerate to the "bowl" (red part in Fig. 6 top) and arrive at the first gap with energy of 7.5 keV. Another advantage of such a central region is that one ion source placed in the center can deliver a beam to each slit simultaneously, due to the symmetry of such a central region.

The particle motion on the first turn is shown in Fig. 6 bottom. This approach to designing the central region can be used to achieve high beam currents. Other internal source configurations are being studied at NEONU and will be tested at the ion source facility.

The 15 MeV RC3/6 cyclotron is just an example, the RC3/6 concept of a three-sector cyclotron operating in the 6th acceleration mode will be an effective solution for acceleration to higher energies. Development of cyclotrons for the production of alpha-emitting isotopes such as At-211 and up to a cyclotron for accelerating H^{-} at 70 MeV is promising. The limitation for accelerating H^{-} is an energy of about 70 MeV, since further acceleration will lead to magnetic dissipation of H^{-} ions and will require a decrease in the magnetic field, which will make the cyclotron large and therefore expensive.

A similar approach is also possible for higher energy proton cyclotrons, such as 230 MeV [OK6] for proton therapy.

Application of artificial intelligence in cyclotron design.

Designing and optimizing cyclotrons requires a large number of calculations of both individual cyclotron systems and particle beam dynamics during acceleration, with careful consideration of many interdependent parameters. The application of AI in cyclotron design and operation is already yielding significant results, helping to speed up the development process, improve control, and increase the reliability of these complex systems. Artificial intelligence methods have the potential to revolutionize the design and optimization of cyclotrons. With the help of AI, researchers can simplify the design, consider a wider range of options, and improve the overall performance of the devices.

Nearest plans and prospects

1. **Continue training models for magnetic field isochronization**
    - Continuing to work with models to achieve isochronism in magnetic fields is a key step in improving the performance of cyclotrons. This requires strengthening data processing approaches, optimizing the architecture of the models used, and introducing new parameters for training based on the data obtained.
2. **Using information in optimizing the MSC-230 RF resonator for training models**
    - The data obtained from the RF cavity optimization can be used to create more accurate models that can predict cavity behavior for other types of cyclotrons. Building and training on this data can help create more effective predictive models that can be used in the design of new accelerators.
3. **Training of parameterized models for magnetic channel calculations**
    - Parameterized models have already been used for magnetic channel calculations. New training should be conducted using the latest data to check how effectively these models can adapt to new conditions and optimize channel performance.
4. **Development of approaches for applying AI in ion source control**
    - AI approaches to ion source control can significantly improve the system's efficiency. We plan to explore the possibilities of using machine learning algorithms to control ion source parameters in real time, as well as conduct bench tests. Correct control of the ion source in a proton therapy accelerator is a very important task, especially for the implementation of the Flash method.
5. **Testing and generating ideas for creating an optimal cyclotron**
    - This stage will allow us to explore different configurations, evaluate their effectiveness and identify the best solutions to improve the accelerator’s performance.

2.3. Estimated completion date

2026-2027

2.4. Participating JINR laboratories

BLTP, LIT, FLNP, VBLHE

2.4. 1. MICC resource requirements

Computing resources	**Distribution by years**				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Tapes					
Tier 1 (CPU core hours)					
Tier 2 (CPU core hours)					
SC Govorun (CPU core hours) - CPU - GPU					
Clouds (CPU cores)					

2.5. Participating countries, scientific and educational organizations

Organization	**Country**	**City**	**Participants**	**Agreement type**
ASIPP	**China**	**Hefei**	**Yun Tao Song** **Chen Gen**	**Cooperation**

2.6. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

3. Personnel provision
3.1. Personnel requirements during the first year of implementation

№№ n/a	**Category of personnel**	**JINR staff, amount of FTE**	**JINR Associated Personnel, amount of FTE**
1.	research scientists	1 1	0
2.	engineers	6	
3.	specialists	~~5~~	
4.	office workers	~~2~~	
5.	technicians	~~1~~	
	Total :	**30**	**0**

3.2. Manpower

3.2.1. JINR staff

№№ n/a	Category of personnel	Full name	Division	Position	Amount of FTE
1.	research scientists	O.V.Karamyshev I.N. Kiyan A.F. Chesnov S.N. Dolya S.V. Gursky T.V.Karamysheva I.D.Lyapin V.A.Malinin D.V. Popov G.M.Skripka S.G. Shirkov M.S. Novikov A.N.Chernikov	DLNP DLNP DLNP DLNP MLIT DLNP DLNP DLNP DLNP DLNP DLNP VBLHEP FLNP		1 1 1 1 1 1 1 1 1 1 0.5 0.2 0.3
2.	engineers	S.B. Fedorenko R.V.Galkin V.A.Gerasimov A.L.Gonshior O.E.Lepkina O.V.Lomakina D.A.Malysh I.M.Palnikov D.S.Petrov V.M.Romanov A.A. Sinitsa A. I. Vlasov	DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP		1 1 1 1 1 1 1 1 1 0.5 1 1
3.	specialists	I.V. Evseeva L.D. Sedov D.A.Malish	DLNP DLNP DLNP		1 0.5
4.	technicians	D.V.Rogozin	DLNP		1
	Total :				**25**

3.2.2. JINR associated personnel

№№ n/a	Category of personnel	Partner organization	Amount of FTE
1.	research scientists		
2.	engineers		
3.	specialists		
4.	technicians		
	Total :		

4. Financing

4.1 Total estimated cost of the project/LRIP subproject

The total cost estimate of the project (for the whole period, excluding salary).
The details are given in a separate table below.

4.2 Extra funding sources

Expected funding from partners/customers – a total estimate.
500000$

Project (LRIP subproject) Leader __________/___________/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: _________
Date of decision of the laboratory's STC: _________ document number: _________

Year of the project (LRIP subproject) start: ________________

(for extended projects) – Project start year: _______

Proposed schedule and resource request for the Project / LRIP subproject

Expenditures, resources, funding sources			**Cost (thousands of US dollars)/ Resource requirements**	**Cost/Resources, distribution by years**				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation	40	20	20			
		Materials	90		90			
		Equipment, Third-party company services	200	100	100			
		Commissioning						
		R&D contracts with other research organizations						
		Software purchasing	10	5	5			
		Design/construction						
		Service costs (*planned in case of direct project affiliation)*						
Resources required	**Standard hours**	Resources						
		– the amount of FTE,						
		– accelerator/installation,						
		– reactor,…						

Sources of funding	**JINR Budget**	JINR budget *(budget items)*	340	170	170			
	Extra fudning (supplementary estimates)	Contributions by partners Funds under contracts with customers Other sources of funding						

Project (LRIP subproject) Leader__________/_________________/

Laboratory Economist __________/_________________/

APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT

TITLE OF THE PROJECT/LRIP SUBPROJECT

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/LRIP SUBPROJECT CODE

THEME / LRIP CODE

NAME OF THE PROJECT/ LRIP SUBPROJECT LEADER

AGREED

JINR VICE-DIRECTOR	____________ SIGNATURE	__________ NAME	__________ DATE
CHIEF SCIENTIFIC SECRETARY	____________ SIGNATURE	__________ NAME	__________ DATE
CHIEF ENGINEER	____________ SIGNATURE	__________ NAME	__________ DATE
LABORATORY DIRECTOR	____________ SIGNATURE	__________ NAME	__________ DATE
CHIEF LABORATORY ENGINEER	____________ SIGNATURE	__________ NAME	__________ DATE
LABORATORY SCIENTIFIC SECRETARY THEME / LRIP LEADER	____________ SIGNATURE	__________ NAME	________ DATE
PROJECT / LRIP SUBPROJECT LEADER	___________ SIGNATURE	__________ NAME	__________ DATE

APPROVED BY THE PAC	____________ SIGNATURE	__________ NAME	__________ DATE