Project

“Development of the Proton Therapy Research Center on the basis of the SC202 superconducting cyclotron”

Theme

1. Introduction

The main goal of the project is development and construction of a dedicated two-room proton therapy center on the basis of the SC202 superconducting cyclotron being jointly developed by JINR and ASIPP (Hefei, China) (http://indico.jinr.ru/conferenceDisplay.py?confId=184).

At the Dzhelepov Laboratory of Nuclear Problems, JINR, the Medico-Technical Complex (MTC) was developed on the basis of the 660-MeV proton accelerator (phasotron), where patients with different tumors are treated using 3D conformal proton beam therapy which allows the dose distribution maximum to be shaped so as to most closely match the shape of the irradiated target. The dose drastically falls off beyond the tumor boundaries, which allows treatment of earlier inaccessible localizations immediately adjacent to a patient’s vital radiosensitive organs.

These investigations began at JINR as far back as 1967. The radiology department of Medico-Sanitary Unit No. 9 opened in December 1999 ensured wider clinical research on hadron therapy of oncological patients with medical beams at JINR. Over the period of 2000 to 2017 proton treatment with the phasotron beams was given to more than 1200 patients with various tumors (including residents of JINR Member States other than Russia).

However, medical uses of the phasotron beams grow low effective for a number of reasons. This accelerator was intended for basic nuclear-physics research, which makes its particle energy about a factor of 3 too high as compared with dedicated proton therapy accelerators. This results in increased power consumption (up to 3 MW), rather sizable personnel (about 50 people), and lower operation reliability. Total annular JINR budget expenditures for phasotron attendance and operation are about €1M.

In addition, deceleration of the proton beam from 660 MeV to 150 MeV (a typical therapy beam energy for treatment of head and neck tumors) is accompanied by a large particle loss, which does not allow a proton beam with the best radiation therapy parameters to be shaped in the treatment room.

Therefore, it seems currently important to construct a new center for medico-biological investigations of interest for almost all JINR Member States on the basis of a new compact dedicated proton accelerator. This simultaneously solves two problems: a decrease in the expenditures for research and production of a proton therapy beam with the best parameters.

Some time ago a similar idea was already considered. It implied placing a compact superconducting accelerator in the DLNP phasotron hall and using the existing beam transport equipment and treatment rooms. However, considering that the phasotron building was constructed about 70 years ago and that requirements of Russian controlling agencies for radiation hazardous installations grow stricter, it seems to be reasonable to construct a dedicated proton therapy center in a new place on the territory of the DLNP technical site.

This center will include two rooms for proton beam therapy: one for treatment using a wide horizontal proton beam and a treatment chair and the other accommodating a gantry system with pencil beam scanning over the target volume and a patient prone positioning system.

The center will be constructed in two stages. At the first stage the room with the fixed horizontal beam and the treatment chair will be equipped. This method is used in MTC treatment room 1 and proved itself to be good over several years of conformal proton beam treatment of head–neck tumors and tumors of other localizations. The equipment of this room can be rather quickly transformed, which allows the break between phasotron-based proton therapy sessions at the MTC to be reduced to a minimum. In this version only the system for shaping and control of the proton therapy beam in the treatment room will be modified.

At the second stage the proton therapy center will be equipped with a gantry capable of scanning the target volume by a narrow proton beam. This method is now considered most promising since it allows more flexible shaping of dose fields and also doing without individual beam-shaping devices (boluses and collimators), which decreases the time of preparation for the course of radiotherapy and the irradiation time.

It is worth noting that development and manufacture of such a sophisticated device as the gantry by the efforts of JINR will take unreasonably long time and require appreciable expenditures. A more practical way is to purchase a commercially produced gantry, e.g., from IBA, with which JINR fruitfully cooperates for a long time. This device has been long and successfully used in several dedicated proton therapy centers all over the world. In this case JINR will only be responsible for producing a proton beam with the parameters appropriate for the correct operation of the gantry and for developing the software for the operation of the entire equipment.

In addition, the building of the center should be designed and constructed with a view to its housing a dedicated medical electron accelerator for the energy of about 6 MeV for concomitant photon–proton therapy and an X-ray and a magnetic resonance tomograph for carrying out the complete cycle of radiotherapy preparation procedures in one place.

It is worth noting that annual expenditures from the JINR budget for operation of this center will be several times lower as compared to the current expenditures for the phasotron operation because of both a significant decrease in the necessary power supply and a substantial reduction of the required maintenance personnel.

Implementation of this project allows the following issues to be solved:

- To stop using the phasotron, which is low effective in its parameters for medico-biological research.
- To create a modern "demonstration" proton therapy center that can be further transformed for practical medicine purposes of JINR Member States.
- In view of recently expanding construction and commissioning of proton therapy centers in Russia and other JINR Member States and considering ample experience of Dubna in this area, it could become a cadre training unit for these centers.

2. Medico-physical and methodological justification

Radiotherapy takes a leading place in modern oncology. Its more than century-old history has demonstrated its stably increasing importance for tumor treatment. Over 70% of tumor patients need radiotherapy in one form or another. Considering this fact and the high rate of radiation oncology development, it can be stated with confidence that the importance of radiotherapy will continue to grow in the foreseeable future.

Improvement of technical means and elaboration of new irradiation methods has become the main direction in development of modern radiotherapy. Today's radiation oncology is impossible without 3D planning and simulation of irradiation, individual beam shaping devices, systems for positioning, immobilization, and position verification of patients, which allow high conformity of radiation therapy.

In addition to improvement of radiation treatment techniques, which is accompanied by optimization of spatial parameters of dose distribution, the search for optimum dose fractioning, i.e., optimization of temporal parameters of irradiation, is of great importance for modern radiotherapy.

Capabilities of traditional types of radiation (photons, electrons) are well studied. However, they are ineffective in a number of tumor patients (10 to 30%, according to different estimations). It is reasonable to treat them using hadron therapy.

Protons, neutrons, and carbon ions are currently used in clinical practice. Spatial dose distribution in proton and carbon ion treatment is much better than in photon and electron treatment. Even modern electron accelerators with multi-lobe collimators do not cancel out this advantage.

In some cases, standard radiotherapy fails to cure a tumor without giving rise to complications. Hadrons are often capable of solving the problem. For example, due to remarkable geometrical characteristics of the dose distribution allowing tumor patients to be cured without complications, protons have become one of the most actively studied sources of hadron radiation.

The idea of using heavy charged particles in radiotherapy was put forward by R. Wilson as far back as 1946, but its implementation became possible only with advent of heavy charged particle accelerators for energies of hundreds of MeV. The first studies of beams of protons and other heavy charged particles for medico-biological applications began in the United States and Sweden in the 1950s. JINR was among the first world centers where these investigations began in 1967.

The first dedicated proton therapy center was built and commissioned in a large multipurpose hospital in Loma Linda (USA) in 1990, and after that rapid promotion of this method to the healthcare began in the developed countries.

Since then, dedicated multi-room hospital centers have been actively constructed, each having 3–5 treatment rooms with apparatus for multi-field irradiation of tumors localized in various human body parts using rotatable wide-spectrum beams (gantry). By now, about 60 proton and ion therapy centers have been in operation, and another 30 centers are under construction (https://www.ptcog.ch/index.php/facilities-in-operation).

The Soviet Union's first proton beam with appropriate radio therapeutic parameters was produced at the suggestion of V.P. Dzhelepov at the 680-MeV phasotron of the Laboratory of Nuclear Problems, JINR, in 1967. Clinical investigations began after a series of physico-dosimetric and radiobiological experiments in 1968, being suspended in 1974 because of the conversion of the accelerator and construction of the multi-room Medico-Technical Complex.

After the LNP accelerator was converted to a high-current phasotron, tumor patient treatment sessions resumed. Over the period 1987–1996, 40 patients, mainly with cervical carcinoma, were successfully treated. Then a long interruption in the research came, caused by several factors, the main of which was economic downturn in Russia.

A new impetus was given to this research in December 1999, when a 25-bed radiological ward was opened in Dubna by the efforts of V.P. Dzhelepov. Since 2000, regular runs have been carried out at the MTC to investigate proton therapy efficiency for treatment of tumors located in the head, neck, and other parts of the body. Up to date, over 1200 patients have been given a course of proton therapy using the phasotron beams.

Three-dimensional conformal radiation therapy has been implemented and is now used for treating deep-located tumors with a proton beam, when the dose distribution maximum best coincides with the target shape. This minimizes damage to healthy tissues and organs surrounding the tumor.

Worthy of mention are recently manifested global trends in development and construction of dedicated proton therapy centers. As was already pointed out, successful construction and commissioning of the first such center in Loma Linda initiated rapid growth in the number of these centers constructed in the most industrially developed countries of the world. However, almost all centers had three to five treatment rooms equipped mainly with gantries. At the design and construction stage a knowingly unfeasible center capacity of minimum 2000 and even up to 4000 patients a year was often stated. This policy was dictated by a very high cost of the equipment (over US$100M) and its post-warranty service (7–10%), and these costs have to be justified in any way.

Actually, only the Loma Linda center managed to reach the level of 1000 treated patients a year, but even its capacity has considerably decreased in the past years. All other proton therapy centers are capable of giving at best 500 courses of radiotherapy a year (https://www.ptcog.ch/archive/patient_statistics/Patientstatistics-updateDec2015.pdf), and many of them are in even poorer state.

This frustrating situation stems first of all from the extremely high cost of treatment in these universal multipurpose centers (US$50,000 and more), since the construction of the center must recoup itself and the working expenditures turn out to be very high. Considering the recent sizable progress in technical fit-out of electron accelerators from the world's leading manufacturers, where the cost of treatment is substantially lower at its approximately identical effectiveness in many cases, further advance in the development of proton beam therapy seems rather problematic within this scenario.

Considering this fact, many manufacturers of equipment for proton therapy centers (IBA, Sumitomo, Mevion, etc.) began to offer centers fit out with one accelerator and a single gantry room. The cost of this equipment set together with the building construction cost is substantially lower than the cost of a multi-room complex. At the same time, its capacity may be as high as 300 courses of proton therapy a year, which, as practice shows, meets the demand of practical medicine and makes these centers most competitive.

In this connection, the projected construction of a two-room proton therapy center seems to be best justified from the practical point of view.

3. Main characteristics of the developed and under-development experimental equipment

By the end of 1985, to implement the medico-biological research program, a six-room Medico-Technical Complex had been built at the JINR Laboratory of Nuclear Problems on the basis of its 660-MeV proton accelerator (phasotron).

For a number of reasons, the main efforts were recently concentrated on development of treatment room 1 as the most universal one from the viewpoint of the range of localizations that could be treated. The room was upgraded to meet the requirements of precision 3D conformal proton therapy.

In addition, room 6 is also used in the investigations. It is equipped with a standard Rokus-M gamma therapy apparatus that accommodates a cobalt-60 source for concomitant irradiation, when part of the necessary dose is taken from gamma radiation at a value tolerable for healthy tissues while the tumor core is additional irradiated with protons.

A wide (8cm by 8 cm) decelerated proton beam homogeneous in cross section is extracted into room 1. Its energy ranges from 170 MeV for irradiation of intracranial targets to 220 MeV for irradiation of targets localized in the pelvic region, e.g., prostate cancer. This homogeneous beam is shaped with an individual collimator of Wood’s alloy so that its cross section follows the target projection at the irradiation angle. In addition, the beam is also modified with a shaped decelerator, a bolus, over the path range so that all protons stop at the rear boundary of the target, sparing healthy tissues behind the tumor.

During the session, the patient is fixed in a special positioning chair, which can be easily transformed to a coach for prone positioning.

An X-ray-transparent head fixing device with an individual perforated thermoplastic mask was developed and made for immobilization (fixation) of the patient’s head during pre-treatment computed tomography (CT) for topometric purposes and during subsequent proton treatments.

An X-ray tube is mounted on the beam axis for centering the beam at the target with respect to the most reliable fixed internal bony landmarks. A Konica Minolta Regius-170 digital X-ray system is purchased and used for taking and displaying prompt X-ray verification images of a patient.

Treatment of chest-located targets in the seated position faces planning problems that arise from a considerable difference in positions of internal organs during diagnosis and treatment procedures. To solve the problem, an X-ray computed tomograph for topometry combined with a treatment chair was developed and built.

The main methodological and technological stages of pre-treatment preparation are as follows:

- Immobilization of the region to be irradiated.
- X-ray and magnetic resonance tomographic scanning and inclusion of CT slices in the planning program.
- 3D computer-aided treatment planning.
- Fabrication of individual beam shaping devices—shaped collimators and compensating boluses.
- Implementation and verification of the treatment plan.

As was already pointed out, due to clearly localized range and small side scattering, beams of heavy charged particles allow dose fields with sharp gradients to be formed, making it possible to irradiate tumors immediately adjacent to critical radiosensitive structures and organs of the patient’s body. However, thorough treatment planning is needed for these advantages to be fully used. This requires information on 3D distribution of tissue density in the target location, which can be obtained with X-ray computed tomography (CT).

Another main requirement is complete matching of the irradiated region positions during diagnosis and in each session of fractionated treatment. When targets are localized in the head or neck region, an individual immobilizing mask of perforated thermoplastic is made for each patient to reliably fix his head and neck during tomography scanning and in the treatment chair. For prone irradiation of targets in the pelvic region (e.g., prostate cancer), special vacuum mattresses capable of keeping patient’s body shape for a long time are used, and individual thermoplastic supports are made.

Tomographic scanning is performed with a spiral X-ray tomograph in the prone position with a fixing mask. Up to 200 slices are usually measured at a step of 1 mm. The digital information is then fed into the 3D computer-aided treatment planning system. To determine more accurately the boundaries of the tumor, magnetic resonance tomography, angiography, etc. are additionally performed.

Conformal radiation therapy is impossible without computer-aided radiation simulation. As a result of cooperation with the world's first proton treatment center at Loma Linda (USA), their developed TPN 3D treatment planning system was adapted to the equipment and proton beams of the DLNP phasotron. After a series of dosimetric experiments to verify the dose calculation algorithm, the system became used in clinical practice.

However, this program can in no way be modified to fit new radiation techniques, e.g., dynamic tumor irradiation using a multi-lobe collimator. Therefore, the main components of our own 3D program for computer simulation of conformal proton therapy have been recently developed. The program has already passed dosimetric verification with the heterogeneous Alderson phantom and radiochromic films, and is now under clinical evaluation.

The 3D array of topometric information obtained by computed tomography is fed in the digital form into the treatment planning system. The radiation oncologist delineates the target and the critical structures, e.g., the brain stem, the optic nerve, etc., on each axial slice. In addition, the number of treatment fields and their directions are set. Based on these data, the planning system generates 3D models of the delineated structures.

The Beam's-Eye-View function built into the program and digital reconstructed X-ray photographs are used to determine and delineate the proton beam of particular cross-section shape for each direction, which is shaped in the real treatment session by the individual Wood's alloy collimator.

The dose distribution over the depth and shape of the target is made conformal by calculating and making so-called compensating boluses, decelerators of a complex shape allowing for the heterogeneous structure of patient's tissues and organs on the way of the beam.

The treatment preparation ends with making the calculated individual shaped collimators and boluses at the MTC workshop fit out with specially designed and fabricated technological equipment.

Proton treatment, usually fractionated, is given every day except days-off for 3–7 weeks (so-called acceleration cycle). Each day, before the beginning of the treatment session, the proton therapy beam is extracted into the treatment room and thorough dosimetric measurements are performed. The beam profile, depth dose distribution, and dose rate are measured. Then these parameters are controlled during the treatment of the patients.

Immediately before the treatment, an X-ray photograph of the patient is taken for each irradiation direction using the X-ray tube mounted behind the patient on the beam axis and the digital X-ray detector. In addition, the detector is simultaneously exposed to a low-intensity proton beam. The result is a distinctly seen position of the proton beam with respect to the anatomic skull structures. If this position disagrees within 1 mm with the positon calculated by the planning program, the position of the chair with the patient is corrected with respect to the beam. Immediately after that the proton treatment is performed.

Adequate dosimetric support of proton beam therapy is integral to its "quality assurance". This notion includes both determination of the radiation dose absorbed in the tumor and the healthy tissues and many other aspects related to the shaping of the proton therapy beam, calculation of dose distributions, microdosimetric features of the interaction of the radiation with tissues and cells, etc.

To control the proton therapy beam parameters in real time, a special system was developed, which consisted of plane-parallel and multiwire ionization chambers and allowed horizontal and vertical beam profiles and the dose deposited in the irradiated target to be controlled with a high accuracy and the accelerator to be automatically switched off as soon as the preset dose value is obtained. In addition, a proton beam energy (path) control system based on semiconductor detectors was developed and constructed.

For a few recent years, dosimetric calibration of the MTC Rokus-M gamma therapy apparatus in units of absorbed dose as recommended by the IAEA was carried out together with the scientists of the Radiation Dosimetry Department, Institute of Nuclear Physics (Prague, Czech Republic). A test bench for calibration of clinical dosimeters was developed and constructed. It allows the dosimetric calibration of the proton therapy beam to be kept accurate to 3%, which complies with the international standard.

Linear energy transfer (LET) spectra were measured for the proton beam of the DLNP phasotron. They were used to estimate the relative biological efficiency of the proton beam, which is an important parameter for proton therapy and radiobiological investigations.

Dose distributions beyond the targets irradiated by a proton beam were measured using thermoluminescent dosimeters and track detectors at DLNP and the Proton Therapy Center in Prague. The measured doses were compared with the irradiation doses beyond the proton beams passively shaped at the DLNP phasotron using collimators, additional decelerators, and comb-shaped filters. These investigations are important for estimating the radiation risks for the surrounding healthy tissues.

Errors in the standard proton treatment planning caused by metallic implants in the patient’s body region to be irradiated are studied together with the scientists of the Radiation Dosimetry Department, Institute of Nuclear Physics (Prague, Czech Republic) and the Faculty of Physics, Bucharest University (Magurele, Romania). The investigations are carried out using both simulation methods and experiments with special phantoms.

A method using radiochromic films and the heterogeneous Alderson phantom for verification of all technological stages in preparation and performance of radiation treatment was developed in collaboration with the scientists of the Wielkopolskie Cancer Center (Poznan, Poland).

A mock-up of an automated multilobe collimator with four pairs of plates for the proton beam was developed and built. After the tests of the mock-up and all related technologies it will be a prototype of the full-scale device with 33 pairs of plates needed for implementation of the so-called dynamic method for proton teatment of various neoplasms. This device was granted patent of invention No. 2499621 dated 27.11.2013.

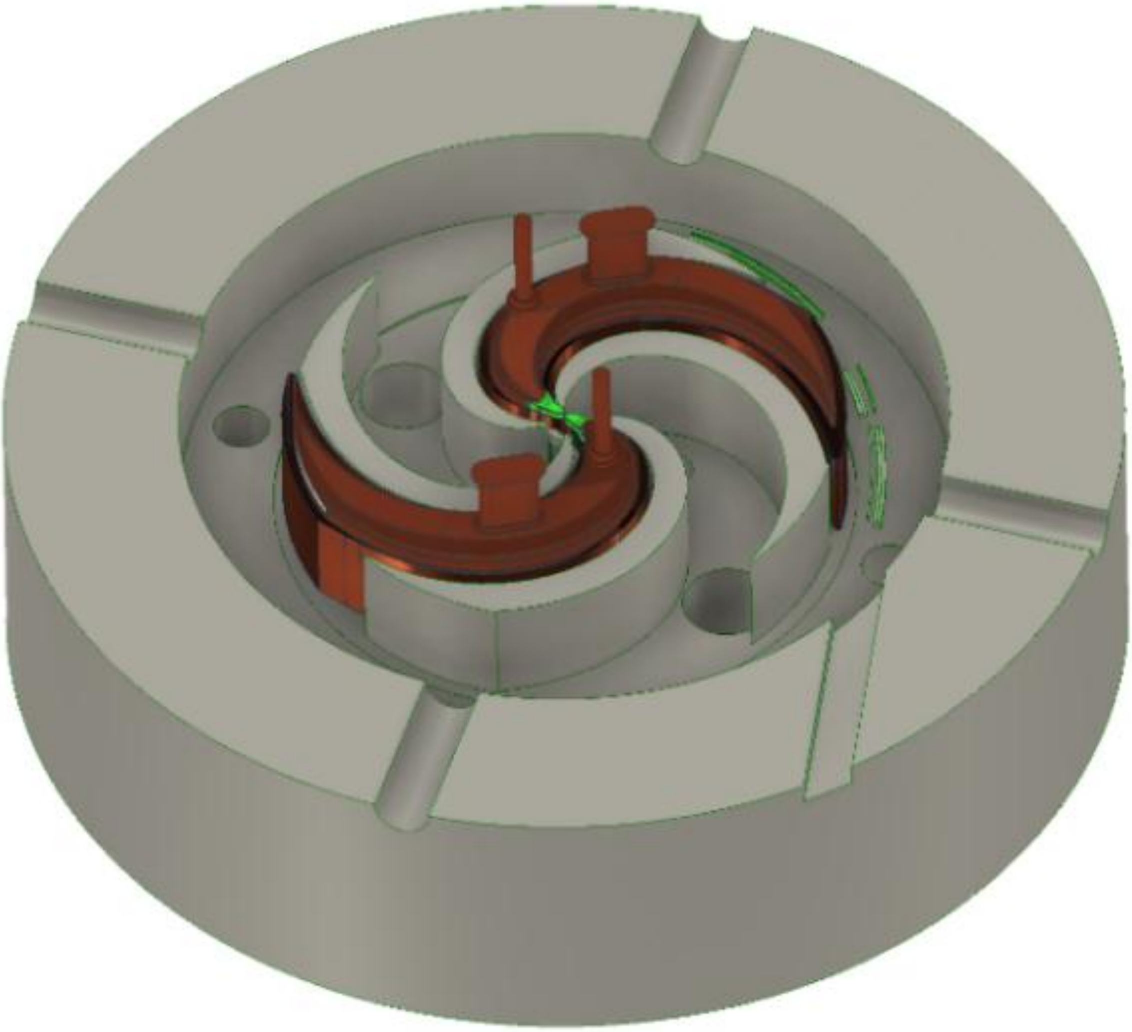
The invention made it possible to maximally fast and accurately form any desired aperture of the proton beam and use various irradiation techniques for applying the maximum absorbed dose to the tumor while minimizing irradiation of healthy tissues, i.e., providing the ultimate treatment conformity.

In addition, the proposed multilobe collimator allows reducing the treatment session time, dose absorbed by the personnel due to induced radioactivity of the collimator, and labor input and cost as compared with the use of individual collimators.

4. Projected investigations and methodological developments

4.1. Superconducting cyclotron SC202

In 2015 the joint project JINR (Dubna, Russia) - ASIPP (Hefei, China) on design and construction of superconducting proton cyclotron SC202 was started. Two variants of SC202 cyclotron shall be produced, according to the Collaboration Agreement between JINR and ASIPP. One will be used for proton therapy in Hefei and the second one will be used to replace the Phasotron in the research and treatment program on proton therapy at JINR.



Layout of the cyclotron 3D computer model.

MAGNET DESIGN

The SC202 magnet design was based on the main cyclotron design characteristics:

- Compact design;
- Fixed energy, fixed field and fixed RF frequency;
- Superconducting coils enclosed in cryostat, all other parts are warm;
- Injection by PIG ion source;
- Extraction with an electrostatic deflector and passive magnetic channels.
- Bending limit W=200 MeV;
- Deep-valley concept with RF cavities placed in the valleys;
- Acceleration up to ~5-7 mm from pole edge ⇒ to facilitate extraction;

Main parameters of the magnet:

- Sector angular width 22-33 degrees (from center to extraction);

- Small sectors vertical gap near beam extraction -9mm;
- Pole radius = 61 cm;
- Outer diameter = 250 cm;
- Height = 170 cm;
- Hill field = 4.75 Tesla, valley field = 3 Tesla;
- A*turn (1 coil) 725 000;
- Weight is about 55 tons.

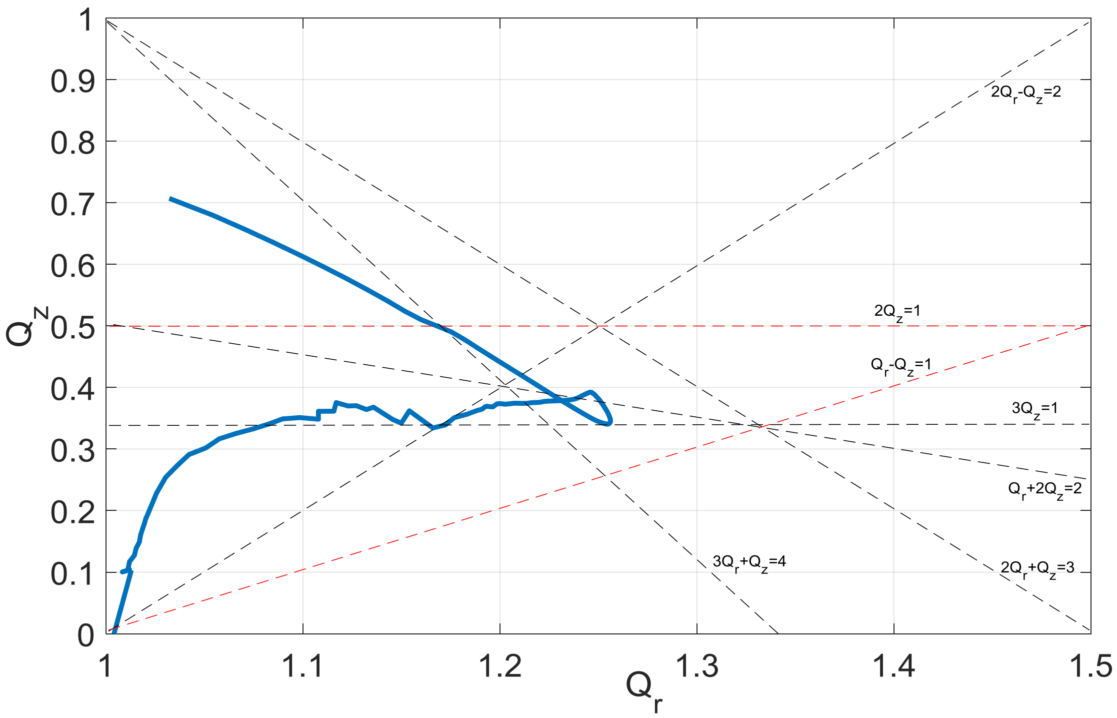
CST studio was used for the SC202 magnetic system design. During the magnet simulations the following design goals were achieved:

Isochronous field in whole accelerating range;

Keep last orbit close to pole edge 5-7 mm;

Keep the stray field at an acceptable level;

Avoid dangerous resonances (see Fig. 3).



Tune diagram.

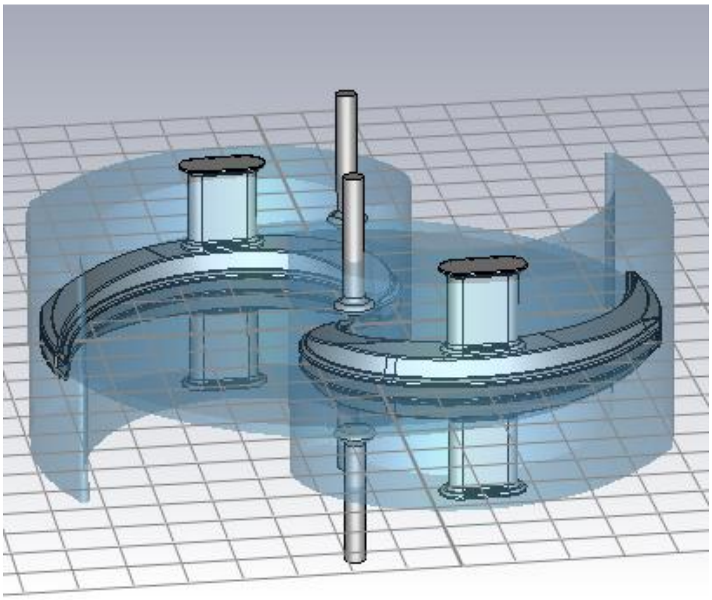
During the magnetic field mapping and shimming procedure, it will be possible to use the next correction elements:

- Central field shaping by changing the position and shape of the central plug.
- Magnetic field shaping by changing the azimuth width of the sectors.
- Magnetic field correction at the extraction region may be done by the sectors gap cut.

RF CAVITY DESIGN

For proton acceleration, we are planning to use 2 accelerating RF cavities, operating on the 2nd harmonic mode.

The characteristic parameters of the half-wavelength coaxial resonant cavity have been accomplished based on simulation.



View of the cavity model.

Voltage in the center is about 55 kV corresponds stored energy 1 Joule in both cavities
Main results of the RF cavity simulation:
Frequency 91.7 MHz
Power losses for two RF cavities are about 93 kW. Quality factor is about 6 000.

BEAM DYNAMICS SIMULATIONS.

For all beam dynamics simulations 3D electric field maps from RF cavity simulations and 3D magnet field maps from magnet simulations were used.

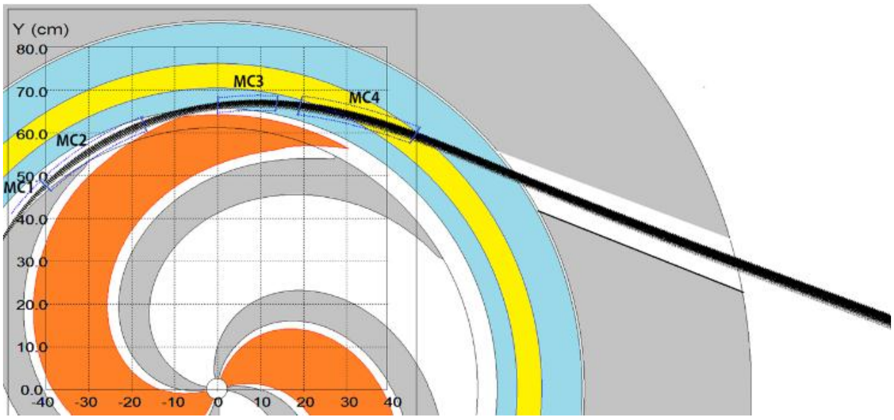
Center region.

Internal PIG proton source will be used in our cyclotron. Vertical focusing in the very center is provided for lagging particles by electric accelerating field for the radius up to 5 cm, after this radius magnetic focusing induced by bump occurs.

The beam has been accelerated with amplitudes of betatron oscillations up to 3 mm. There were no losses of particles in any radius after center region. There were no influence of any resonance. Acceleration was successful from ion source up to 201 MeV. It takes from about 900-1000 turns depend on field map in different models and frequency and voltage of accelerating field.

Extraction simulation

Extraction will be organized with an electrostatic deflector and 4 magnetic channels (see Figs. 9,10). The beam is extracted applying electric field 150 kV/cm in deflector. Maximum attainable extraction efficiency ~60% is achieved if amplitude of vertical oscillations does not exceed 2 mm and septum has constant thickness 0.1 mm.



Extraction system on plan view

The engineering design of SC202_Hefei project has been completed, each subsystem is in production or experimental verification. At present, the superconducting magnet is being manufacturing, and the cryogenic electrical properties of the superconducting magnet are tested successfully, the test results meet the design requirements. The PIG ion source has been designed and assembled. The model of the RF cavity converts the RF power to the desired high frequency electric field to accelerate the particle. For the moment, the RF source and the low level control system are being processed and manufactured, and the low power test of the RF cavity is completed. The test results verify the correctness of the design, RF cavity will be manufactured in the nearest future. Design and manufacture of subsystems of SC202_Hefei are performing in accordance with the project schedule.

SC202_Dubna project differs from Hefei version in extraction system design and will be finished in 2018 year. Manufacture of magnet system of the SC202_Dubna cyclotron will be started in 2018.

4.2. Horizontal-beam treatment room

According to the project, this room will be equipped at the first stage of its implementation. Almost all equipment necessary for proton treatment sessions can be obtained by transforming the MTC room 1 equipment: the treatment chair for patient fixation and adjustment, laser and X-ray localizers, image processing system for digital X-ray images of Minolta Konica Regius-170 X-ray detectors, clinical dosimeters, etc. To resume proton treatment sessions, this equipment will have to be dismounted from the MTC treatment room and appropriately mounted in the treatment room of the projected center, which can take 5 to 6 months.

The system for the proton beam shaping and parameter control will have to be seriously modified, since the characteristics of the beam injected into the treatment room are completely different from those of the current phasotron beam, and these characteristics must most favorable for radiotherapy.

The proposed scheme of the therapy beam shaping in the treatment room is shown in Fig. 1. A standard two-scatterer technique is used, which allows lower beam losses during beam shaping as compared with the one-scatterer scheme. The maximum beam diameter in the irradiation region will be 150 mm at the cross-section homogeneity no worse than 2.5%. This size is, on the one hand, sufficient for irradiating most head–neck tumors and, on the other hand, ultimate for changing individual collimators in treatment sessions without mechanizing the process.

Fig. 1. Scheme of the treatment beam shaping in the treatment room.

In addition, considering a relatively low energy of protons at the SC202 exit (about 200 MeV), it was decided to do without the system for beam energy selection at the entrance to the room. Characteristics of the proton beam with this energy (transverse and distal dose decay gradients) fully meet the requirements imposed on this treatment room, which considerably simplifies the beam shaping and control system.

4.3. Gantry treatment room

As was pointed out above, the gantry system, which allows the proton beam to be rotated around the patient immobilized and fixed in the cradle, is a very complicated structural element. Its development will require a lot of investments and time. In this connection, the most efficient solution seems to purchase the system, now almost a commercial product, from the IBA, the largest manufacturer and supplier of dedicated equipment for proton therapy centers.

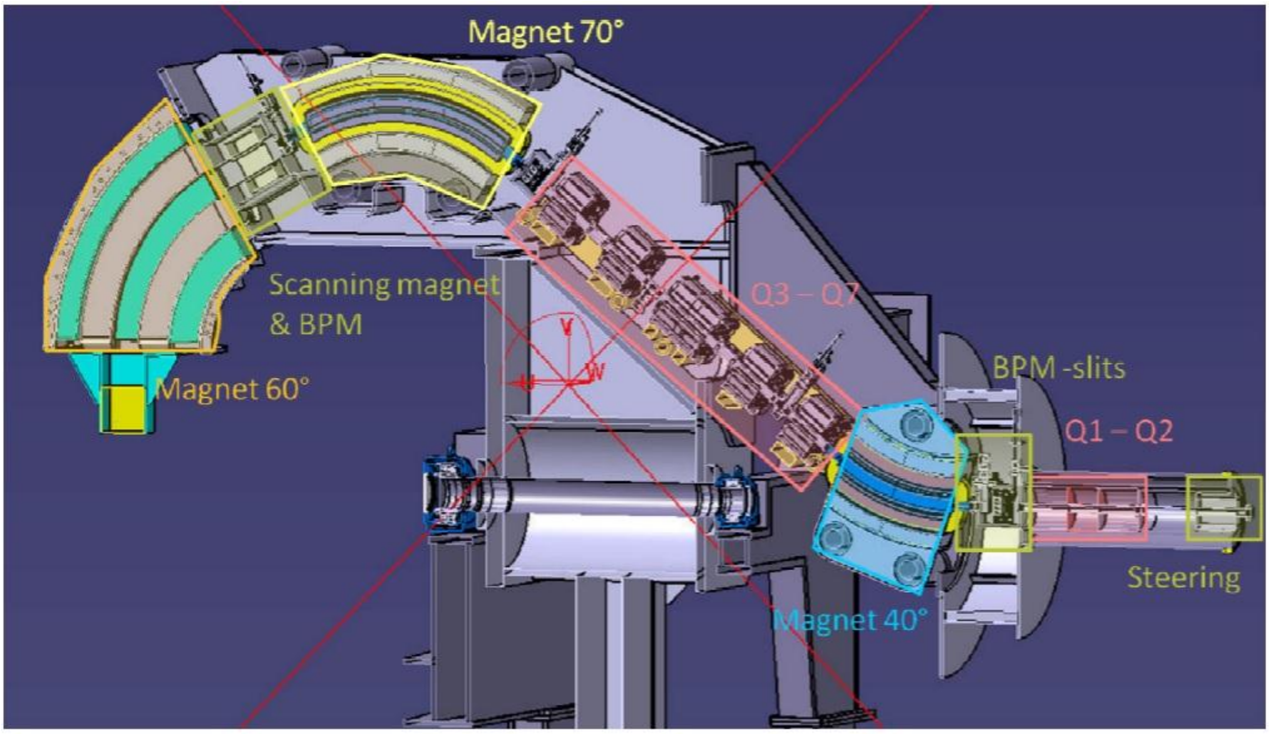


Fig. 2. Internal structure of the IBA single-room Proteus ONE gantry system.

Figure 2 shows the internal structure of the IBA Proteus ONE single-room gantry system for a proton therapy center. This gantry allows dynamic irradiation of deeply localized targets in a human body by the technique of pencil beam scanning over the target volume. This technique allows more flexible shaping of dose fields without using individual beam-shaping devices (boluses and collimators), which decreases the period of preparation for the course of radiation therapy and the treatment time.

Apart from the gantry itself, it will be necessary to purchase a system for prone positioning and fixation of the patient and some other auxiliary equipment.

In this scenario, the JINR specialists will be responsible for shaping a proton beam with the parameters needed for correct gantry operation and developing software for the entire equipment of the complex.

5. Location of the proton therapy complex

The DLNP Design Office has developed the concept of situating the Proton Therapy Research Center in a two-storied building (Fig. 3, 4). The first floor accommodates scientific equipment and rooms for patients, and on the second floor there are rooms for the personnel and technical maintenance rooms (Figs. 4, 5).

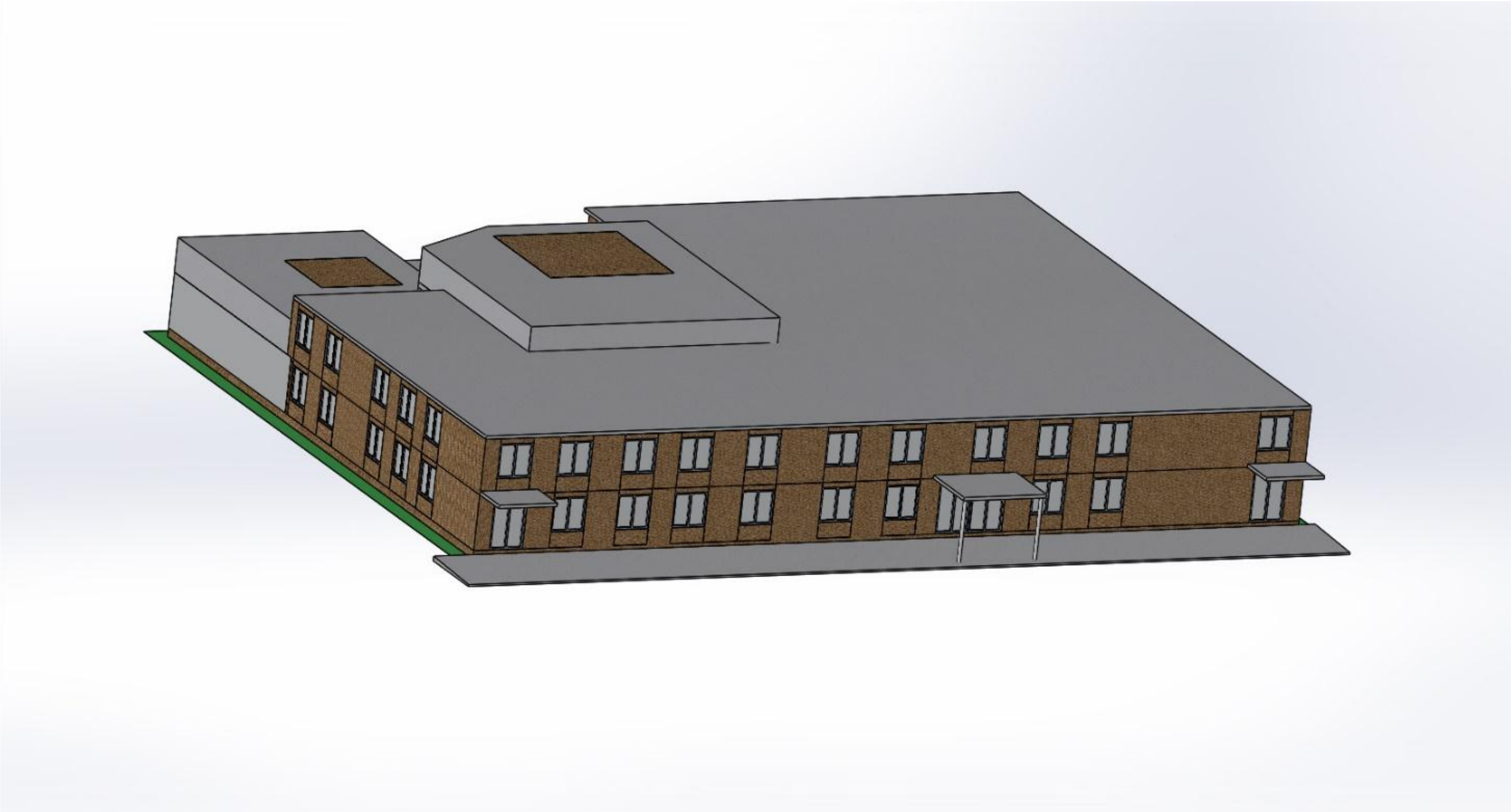


Fig. 3. Artist’s view of the Proton Therapy Research Center.

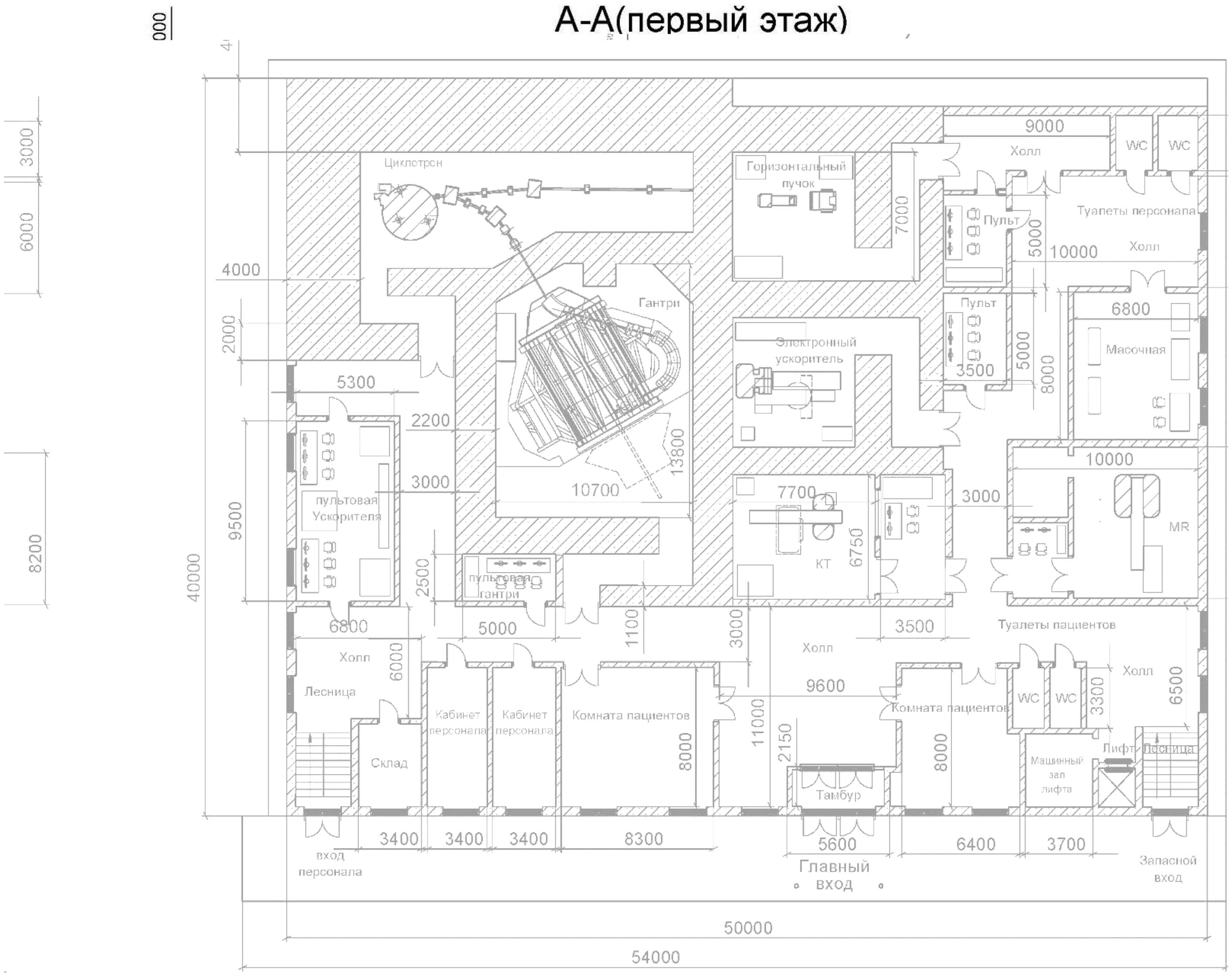


Fig. 4. First floor plan.

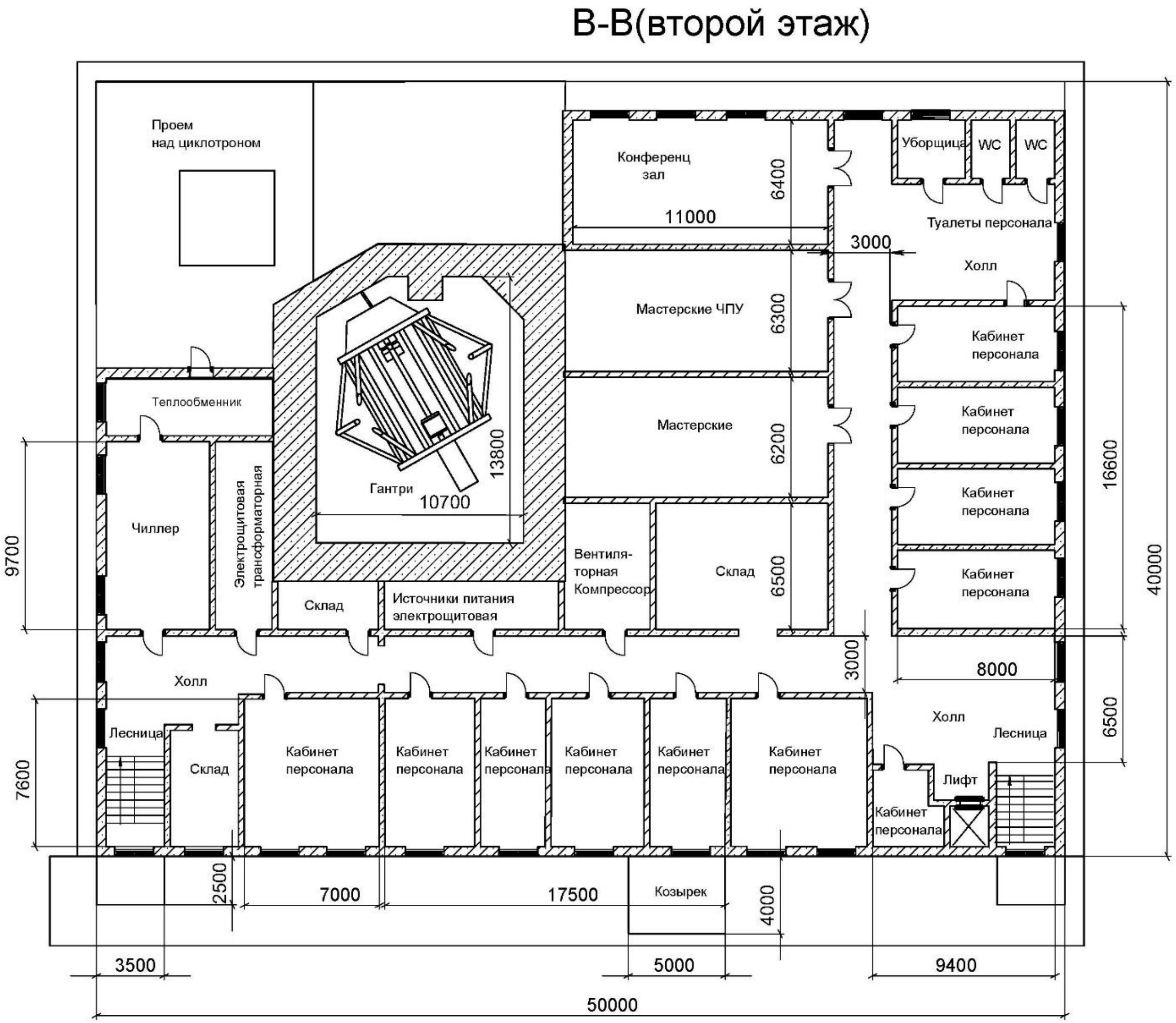


Fig. 5. Second floor plan.

SCHEDULE

for the project “Development of the Proton Therapy Center on the basis of the SC202 superconducting cyclotron”

2019

1. Design of the building for the future center.
2. Design of the beam extraction system, accelerator control system, and accelerating and vacuum systems of the accelerator.
3. Development of the beam shaping and parameter control system for the fixed-beam room.
4. Design of the system for transporting the beam to the treatment rooms.
5. Beginning of the development of the software for the gantry room.
6. Commissioning of the SC202_Hefei, completion of the SC202_Dubna project, and manufacture of the magnetic system for the SC202_Dubna (in Hefei).

2020

1. Beginning of the construction of the building for the center.
2. Manufacture of the beam extraction system, accelerator control system, and accelerating and vacuum systems of the accelerator.
3. Manufacture of the beam transport system elements.
4. Manufacture of the beam shaping and parameter control system for the fixed-beam room.
5. Continuation of the software development for the gantry room.
6. Assembly and shimming of the magnetic system for the SC202_Dubna (in Hefei).

2021

1. Completion of the construction of the building for the center.
2. Transfer of the equipment from MTC treatment room 1 to the new fixed-beam room.
3. Mounting of the equipment for the beam shaping and parameter control system in the fixed-beam room. Commissioning work in the fixed-beam room.
4. Obtaining of approvals.
5. Renewal of proton therapy sessions in the treatment room of the new center.
6. Continuation of the software development for the gantry room.
7. Assembly and commissioning of the SC202_Dubna cyclotron.

Form 26

Proposed schedule and necessary resources
for the implementation of the project
“Development of the Proton Therapy Center on the basis of the SC202 superconducting cyclotron”

Facility units and systems, resources, funding sources	Cost of units (thous. USD); resource requirements	Proposed distribution of funding and resources		
		1st year	2nd year	3rd year
1. Design and construction of the building	10000	500	5000	4500
2. Development and fabrication of beam shaping and parameter control systems	60	10	50	0
3. Development and fabrication of accelerator systems	1000	200	500	300
4. Mounting of equipment and commissioning of accelerator	600	100	200	300
5. Mounting of equipment and commissioning work in fixed-beam room	50	0	0	50
6. Gantry with equipment				
7. Electron accelerator				
8. CT	5000	0	0	5000
9. MRT	2000	2000	0	0
10. Dosimetric equipment	300	0	0	300
11. Equipment for making proton	650	0	0	650
beam shaping devices in	25	0	25	0
treatment room				
	100	0	0	100
Expenditures from budget	**19785**	**2810**	**5775**	**11200**
<u>Required resources (norm-hours)</u>				
DLNP Design Office	4000	1000	2000	1000
DLNP Workshop	4000	1000	2000	1000

Project leaders