# HADRON THERAPY RESEARCH AND APPLICATIONS AT JINR

G. Shirkov†, G. Karamysheva, S. Gurskiy, O. Karamyshev, N. Morozov, D. Popov, E. Samsonov, S. Shirkov, G. Trubnikov, JINR, Dubna, Russia

*Abstract*

JINR has the unique experience in cancer treatment with proton beam during about 50 years. In 2005 the collaboration with IBA (Belgium) was established. During these years, the technical design of the first carbon superconducting cyclotron C400 was successfully created, the construction of serial proton cyclotron C235 was significantly improved and the fist modernized cyclotron C235 was assembled, debugged and put in the test operation in Dubna in 2011. This C235 will be used soon in the first Russian medical center with proton therapy in Dimitrovgrad. In 2015 the joint project with ASIPP (Hefei, China) on design and construction of superconducting proton cyclotron SC202 was started. Two copies of SC202 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 replace the Phasotron to continue the proton therapy at JINR.

## PROTON THERAPY IN JINR

The history of proton therapy in JINR began 50 years ago:

- 1967 – the beginning of the research on proton therapy;
- 1968 –1974 – first 84 patients treated with protons;
- 1975 –1986 – upgrading of accelerator and construction of a multi -room Medico -Technical Complex (MTC);
- 1987 -1996 – treating of 40 patients with protons;
- 1999– inauguration of a radiological department of the Dubna hospital;
- Since 2000 - regular treating of patients with tumors seated in the head, neck and thorax.

The modern technique of conformal three-dimensional proton therapy was realized firstly in the JINR Medical-technical accelerator complex which includes the Phasotron, the beam delivery systems and medical cabins.

Now JINR is the leading research centers of proton therapy in Russia. About 100 patients take a course of fractionated treatment in Dubna every year. During last 14 years from the startup of the Dubna radiological department more than 1000 patients were treated with proton beams [1].

The initial operation of the accelerator took place in 1949. In 1979-1984, the synchrocyclotron was converted into azimuthally varying field Phasotron. Now it is heavily depreciated and out of date, so it is important to replace it with the modern accelerator.

## JINR (DUBNA) –IBA (BELGIUM) COLLABORATION

### *Superconducting C400 Cyclotron*

IBA, the world's industrial leader in equipment of the proton therapy centers, in collaboration with JINR has designed the first superconducting carbon C400 cyclotron [2].

Most of the operating parameters (particle energy, magnetic field, RF frequency) of the C400 cyclotron are fixed. Small main field and RF frequency variation are necessary for the switching from one element to another. It is relatively small (6.6 m in diameter) and cost effective.

It offers very good beam intensity control for ultra-fast pencil beam scanning (PBS). But it requires an energy selection system (ESS) in order to vary the beam energy. The efficiency of the ESS for carbon is better than for protons due to lower scattering and straggling of carbon ions in the degrader.

The key parameters of the 400MeV/u superconducting cyclotron are listed in Table 1. The view of the cyclotron is presented in Fig.1.

Table 1. Main Parameters of the C400 Cyclotron

| | |
|---|---|
| **General properties** | |
| accelerated particles | $H_2^+$, $^4He^{2+}$, $^6Li^{3+}$, $^{10}B^{5+}$, $^{12}C^{6+}$ |
| injection energy | 25keV/Z |
| final energy of ions, protons | 400 MeV/u<br>265 MeV/u |
| number of turns | 1700 |
| **Magnetic system** | |
| total weight | 700 t |
| outer diameter | 6.6 m |
| bending limit | K = 1600 |
| **RF system** | |
| number of cavities | 2 |
| operating frequency | 75 MHz, 4$^{th}$ harmonic |

† email address: shirkov@jinr.ru

ISBN 978-3-95450-181-6

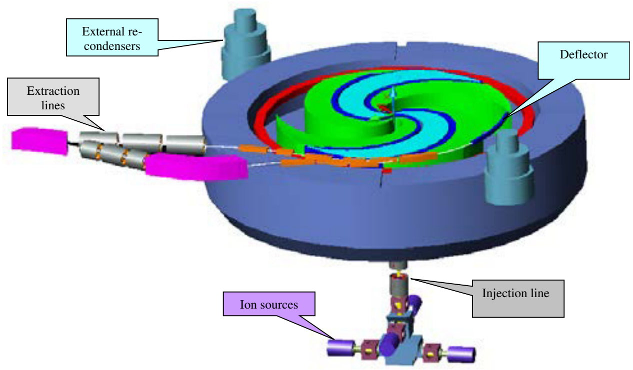


Figure 1: View of the median plane in the C400 superconducting cyclotron.

Three external ion sources are mounted on the switching magnet on the injection line located below the cyclotron. $^{12}C^{6+}$ are produced by a high-performance ECR at current 3 μA, alphas and $H_2^+$ are also produced by a simpler ECR source. All species have a Q/M ratio of 1/2 and all ions are extracted at the same voltage 25 kV, so the small retuning of the frequency and a very small magnetic field change achieved by different excitation of 2 parts in the main coil are needed to switch from $H_2^+$ to alphas or to $^{12}C^{6+}$. We expect that the time to switch species will be no longer than two minutes, like the time needed to retune the beam transport line between different treatment rooms.

Acceleration of the beam will occur at the fourth harmonic of the orbital frequency, i.e. at 75 MHz, and will be obtained through two normal conducting cavities placed in the opposite valleys.

Extraction of protons supposed to be done by means of the stripping foil. Deflector extraction is supposed to be used for the carbon beam. It is possible to extract the carbon beam by means of one electrostatic deflector (located in the valley between the sectors) with a 150 kV/cm field inside.

### *C235-V3 Proton Cyclotron for Dimitrovgrad*

In Russia, construction of several centers of proton and ion therapy within the next few years is planned. The center of proton therapy in Dimitrovgrad will be the first Russian hospital center of the proton therapy, it was approved in 2010. The JINR-IBA collaboration has developed and constructed the C235-V3 proton cyclotron [3] for this center.

This cyclotron is a substantially modified version of the IBA C230 cyclotron (see Fig.2). Its characteristics exceed the series cyclotrons IBA of the previous modifications, already established in eleven hospital oncologic centers of the different countries of world.

JINR specialists examined the reasons for the losses of beam during the process of acceleration, the influence of the radial component of magnetic field in the median plane of accelerator, analyzed the influence of main resonances and carried out the calculations of the beam extraction system.

In Dubna, during 2011-2012 years had been carried out assembling of the cyclotron, shimming magnetic field, optimization of the acceleration modes and testing with the extracted proton beam. Proton transmission from radius 300mm to 1030 mm is 72% without beam cutting diaphragms. This allows reduce irradiation dose of the machine elements in comparison with serial C235 with extraction efficiency is 62%.

For performance assembly and beam tests of C235 V3 the building 5 in JINR was refurbish and adapt. That time connection of electricity, water cooling, ventilation, radiation safety and fire alarm were organized. Building floor reinforcement, vault shielding by concrete blocks, technological pit were prepared.

Figure 2: C235 cyclotron in JINR.

New technologies realized in JINR:

- Special compact (1m size) platform designed and manufactured for mechanical fabrication of the pole edges.
- Special 3D Carl Special 3D Carl Zeiss machine used to measure of the pole edged profile with μm accuracy during shimming of the magnetic field.
- New JINR calibration dipole magnet with field up to 2.9 T used for calibration of the Hall probes.
- The new system of the axial magnetic field measurements was tested.

The cyclotron is delivered to Dimitrovgrad and it's assembling in the hospital is underway now.

The JINR experience and technologies on design and construction of cyclotrons for hadron therapy can be used for creation and development of any accelerators for medicine such as SC202 for proton therapy.

## JINR (DUBNA)–ASIPP (CHINA) COLLABORATION

### *Superconducting SC202 Cyclotron*

The SC202 superconducting cyclotron for hadron therapy is under development by collaboration of ASIPP (Hefei, China) and JINR [4]. Superconducting cyclotron SC202 will provide acceleration of protons up to 202 MeV with maximum beam current of 1 μA in 2017-2018. We are planning to manufacture in two cyclotrons: one will operate in Hefei cyclotron medical center, the other will replace Phasotron in Medico-technical center to continue the proton therapy research at JINR in the near future.



ISBN 978-3-95450-181-6

The results of simulation of magnetic, accelerating and extraction systems are presented here. The cyclotron is compact and relatively light, the estimate total weight is less than 55 tons and extraction radius is 60 cm only. We have performed simulations of all systems of the SC202 cyclotron and specified the main parameters of the accelerator. Average magnetic field of the cyclotron is up to 3.6 T and the particle revolution frequency is 45.5 MHz. These parameters determine the requirements for the accuracy of all simulation to be unprecedented high.

The Medico-technical complex (MTC) JINR uses proton beam with energy up to 200 MeV specializing mainly on treatment of head localizations. The 200 MeV final energy has been chosen for SC202 cyclotron based on the experience of work of the MTC JINR and statistics for necessary depth of treatment provided by HIMAC (Japan) concerning the treated patients from 1995 to 2001 [5].

The proton beam with energy 200 MeV can irradiate all of the tumor localizations with a maximum depth of 25 cm. SC202 cyclotron will also be used for eye melanoma treatment at energies 60-70 MeV after degrading beam energy. Degrading the 200 MeV energy to 60-70 MeV would provide better beam quality compared to degrading from conventional energy 250 MeV.

SC202 is an isochronous superconducting compact cyclotron. Superconducting coils will be enclosed in cryostat, all other parts are warm. Internal ion source of PIG type will be used. It is a fixed field, fixed RF frequency and fixed 202 MeV extracted energy proton cyclotron. Extraction will be organized with an electrostatic deflector and magnetic channels. For proton acceleration we are planning to use 2 accelerating RF cavities, operating on the 2nd harmonic mode.

## *Magnet System of Cyclotron SC-202*

The design of the SC202 magnetic system is described in details in [6].

Most accurate results of simulations were received in the parametrized model of the magnet (see Fig.3) created in CST studio and COMSOL Multiphysics.

Results of simulations are exporting to MATLAB for analyzing by conventional CYCLOPS-like code and for particle acceleration in 3D fields.

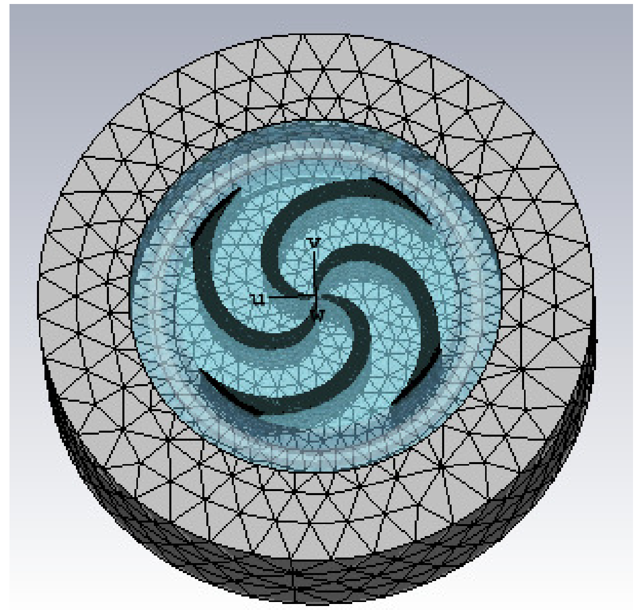


Figure 3: Model of the magnet.

Isochronism of the average field was achieved by decreasing of the sector width correspondently to orbital frequencies in closed orbits. Azimuthal width of sector against radius which provide isochronous field shown in Fig. 4. Orbital frequency of the final average field (Fig. 5.) is presented in Fig. 6. From Fig. 6 one can estimate that difference between mean field and isochronous is about 3-4 Gauss in accelerating region.

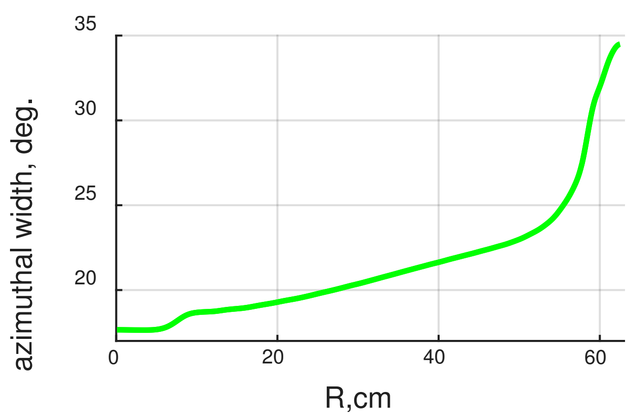


Figure 4: Azimuthal width of sector.

ISBN 978-3-95450-181-6

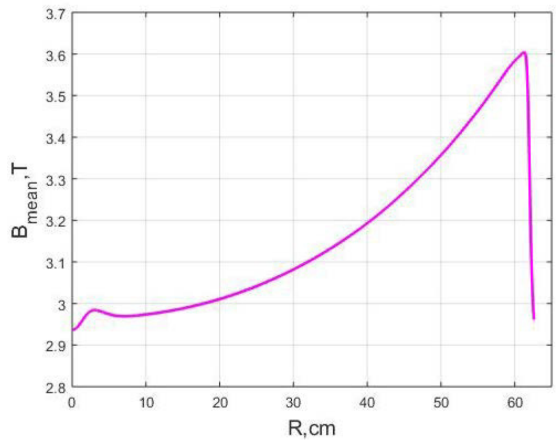


Figure 5: Average magnetic field along the radius.

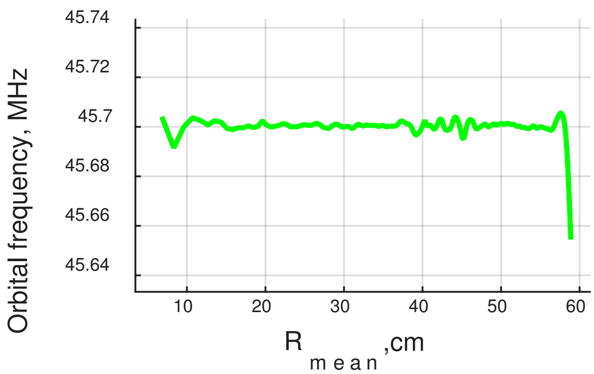


Figure 6: Orbital frequency against mean radius.

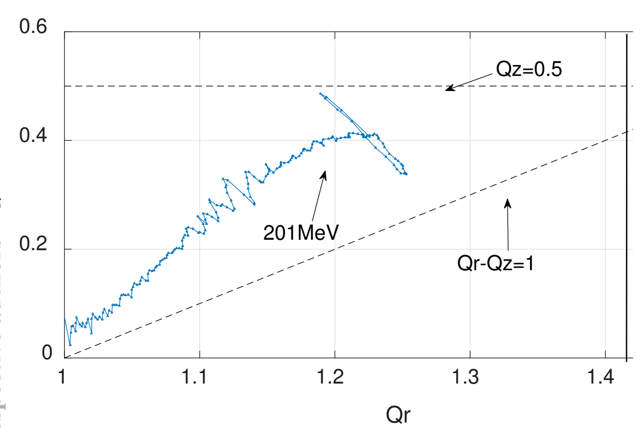


Figure 7: Working diagram in SC202.

CYCLOPS-like code was used to calculate the betatron tunes. Working diagram is presented in Fig. 7.

We are going to use 2 RF cavities operating on 2nd harmonic mode, each 50 degrees in azimuthal length, the acceleration is going to be relatively week on each turn. That is why, avoiding resonances is crucial for the design of the SC202 cyclotron.

Many efforts have been done to avoid the most dangerous resonances during acceleration Qr-Qz=1 and 2Qz=1. One can see that the first resonance is avoided completely while the second one is close at the end of acceleration.

### *RF System*

Two RF cavities, connected in the center will be working on the 2nd harmonic on approximately 91.4 MHz.

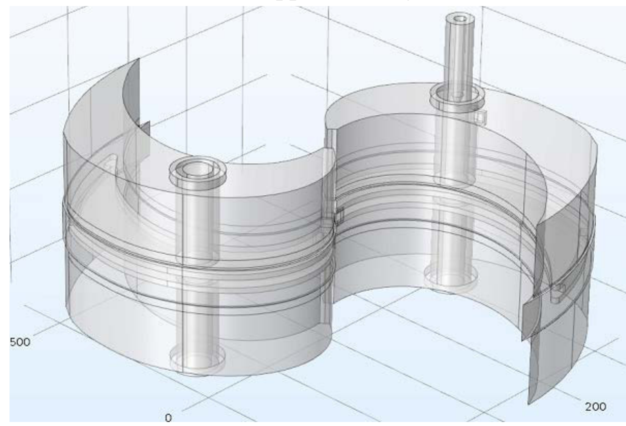

Figure 8: Overview of 3D model of RF system.

From the beam dynamics point of view the choice of 2nd harmonic is not the best solution, as the acceleration rate will be lower compared to 4th harmonic which seems like a natural choice for a cyclotron with 4 sector structure. However, operating on 182.8 MHz would raise problems with the extraction of particles from the ion source and the generators on 182.8 MHz are not widely available as compared to 91.4 MHz ones. As we avoid all critical resonances and extraction scheme does not require high acceleration rate we are able to use just 2 cavities on the 2nd harmonic. Computer simulations of the cavity was performed (see model in Fig. 8) Suitable accelerating frequency and voltage along radius (Fig. 9) were achieved. Accelerating system is described more detailed in report [7].

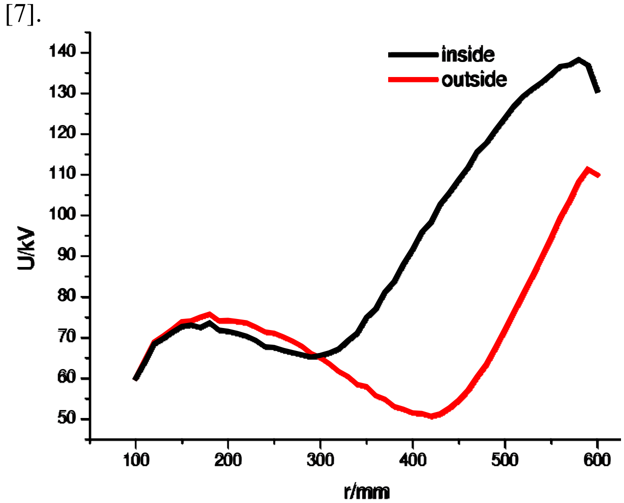


Figure 9: Mean acceleration voltage along radius.

### *Central Region Studies*

Internal PIG proton source will be used in our cyclotron, so our simulations start from the inside of the source. We have built a 3D model of the source and the central region. In order to increase the efficiency of the extraction of the



ISBN 978-3-95450-181-6

protons from the source the first accelerating gap between the tip of the RF dee and the source should be kept as small as possible. However, sparking must be prevented, so we need to provide safe distance in both vertical and horizontal directions. The compact size of the accelerator is the major challenge in the design of the central region.

It was chosen to use 60 kV in the central region, and in this case, the major problem was to bypass the source on the first turn. In order to do so, we had to shape the dee tips in the center in such way to provide optimal acceleration rate.

We have used our 3D model of the RF system and the magnet in order to simulate the particle trajectories in the central region. It is clear that focusing and the energy gain using are good enough. However, it is very important to keep in mind that the final design will be strongly affected by the changes in magnet model, when we will get the measured BH curve of the steel, that will be used in the SC202 magnet.

### *Extraction*

Simulations show that the extraction can be provided by deflector with electric field 150 kV/cm and focusing magnetic channels (see Fig. 10).

Extraction efficiency has been estimated for different changes of the septum thickness along its length and for different values of the beam radial oscillations during acceleration.

Maximum attainable extraction efficiency ~75% is achieved if amplitude of radial oscillations does not exceed 2 mm and septum has constant thickness 0.1 mm.

The collimator will be used to match the beam parameters with requirements imposed by a transport system.

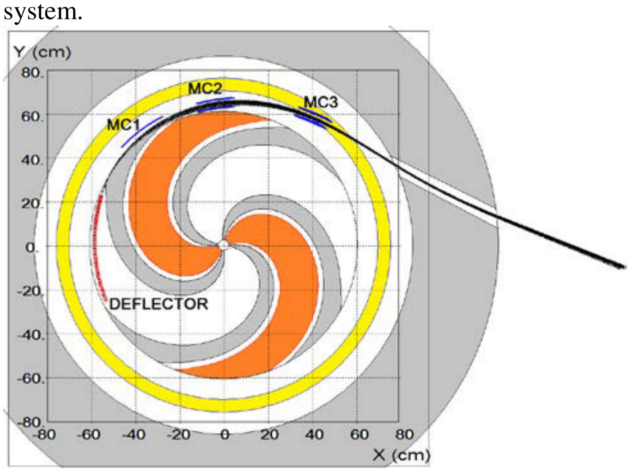


Figure 10: Plan view of the cyclotron with extracted beam.

Both copies of the SC202 will be manufactured in China, JINR and ASIPP will perform together the assembly, field measurements and shimming, RF ion source and beam tests of the both cyclotrons. Works on cyclotron for Dubna can be performed partially in JINR engineering center for the assembling and testing of the medical accelerator equipment.

## CONCLUSION

JINR experience in proton therapy and cyclotron design is very important for the development of the new compact superconducting accelerator SC202 for proton therapy. The technical design of the cyclotron should be finished in 2016. The systems and components for SC202 will be manufactured by Institute of Plasma Physics in 2017 and assembling in China should be completed by the end of 2018.

## REFERENCIES

[1] E.M. Syresin et al., Project of the demonstration center of proton therapy at DLNP JINR, Physics of Particles and Nuclei Letters, July 2015, Volume 12, Issue 4, pp 628–636.

[2] Y. Jongen et al. Compact Superconducting Cyclotron C400 for Hadron Therapy // Nuclear Instruments and Methods in Physics Research Section A. 2012. V. 624, Issue 1. pp. 47–53.

[3] G.A. Karamysheva, O.V. Karamyshev, S.A. Kostromin, N.A. Morozov, et al., Beam dynamics in a C253-V3 cyclotron for proton therapy, Technical Physics 57 (1), pp 106-112, 2012.

[4] G.A. Karamysheva, et al., Compact Superconducting Cyclotron SC200 for Proton Therapy, International Conference on Cyclotrons and Their Applications 2016.

[5] Yasuo Hirao, Results from HIMAC and other Therapy Facilities in Japan, International Conference on Cyclotrons and Their Applications 2001, AIP Conference Proceedings; 2001, Vol. 600 Issue 1, p 8.

[6] Morozov N.A. et al., Computer Modelling of Magnet for SC202 Superconducting Cyclotron, International Conference on Cyclotrons and Their Applications 2016.

[7] Gen Chen et al., Preliminary Design of RF System for SC202 Superconducting Cyclotron, International Conference on Cyclotrons and Their Applications 2016.



ISBN 978-3-95450-181-6