ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS016

A NEW DESIGN OF PET CYCLOTRON

O. Karamyshev†, JINR, Dubna, Russia

Abstract

An innovative approach to a design of cyclotron allows to produce cheaper and more power efficient cyclotrons for medical and industrial application. 15 MeV cyclotron for PET (and other) isotopes production are widely used and in very high demand. In this paper a design of a very compact and cheap to build and to run cyclotron is presented.

INTRODUCTION

Demand for cyclotrons, delivering 10-70 MeV proton (mostly) beams for medical isotopes production such as PET, SPECT isotopes and 200-250MeV proton beams for hadron therapy rapidly is growing. All around the world scientists and engineers are looking into ways to make such cyclotrons more compact, and less costly. The modern trend is to apply superconducting coils to increase magnetic field strength of the cyclotron in order to make the accelerator more compact, and thus reduce the overall cost of the cyclotron setup. Nowadays superconducting cyclotrons and synchrocyclotrons are successfully operating not just for proton therapy (Varian Proscan[1], S2C2 (IBA) [2], Mevion [3]) but also for isotope production (Ionetix [4]). Some of them appeared quite recently, and some work for years and have proved their effectiveness. However, the majority of the cyclotrons still use resistive coils due to it's low cost and reliability.

Here are the reasons why the author believes that cyclotrons with resistive coils are still a good choice for medical applications:

- There are opportunities for optimization, examples are presented further in the paper.
- Compared to superconducting cyclotrons, power consumption and dimensions are not necessarily higher, but in some cases could be lower, as cryocoolers consume power, and occupy space around the magnet.
- Low magnet field is easier to shim, the isochronizing requirements are lower.
- As accelerating system remains resistive, water cooling is required, therefore costly infrastructure of water preparation system can be used also for coil cooling.

A NEW 15 MeV CYCLOTRON

Usually, cyclotrons dedicated for isotope production accelerate H^- ions to get use from extraction by stripping on the foil. Extraction by stripping has about 100% efficiency, low energy H^- ions has only one disadvantage, high vacuum is required. The presented cyclotron is accelerating H^- ions.

† olegka@jinr.ru

Concept

The cyclotron needs to be compact, cheap, reliable and to have a low power consumption. Concept RC3/6 has been published on Cyclotrons 2019 conference, has been modified, magnet field and RF frequency increased, so RF frequency is placed in 144-146 MHz range, which is dedicated for amateur use. This ensures that there should be no issues with legal use of the frequency. This leads us to more efficient design of the cyclotron than typical four-sector accelerator. What is the essence and specific feature of the concept 3/6? The three-sector cyclotron operating at the 6 harmonic mode of acceleration allows to have an effective magnetic system due to wide sectors providing higher mean field and narrow valleys sufficient for placing resonators corresponding to 6th harmonic of acceleration (see Fig. 1). The sectors of the magnet are 90 degrees azimuthal width, and valleys are about 30 degrees. In such case the 6th harmonic mode is optimal for acceleration and the resonance frequency must be 145 MHz for magnetic field equal to 1.55 T.

Such configuration is beneficial for both magnet and RF design, as the magnet, while having necessary average magnet field is being very efficient (has small number of A*turns), high frequency RF system is very compact.

Resistive coils and rather big pole diameter reduce the effort and cost of producing this machine.

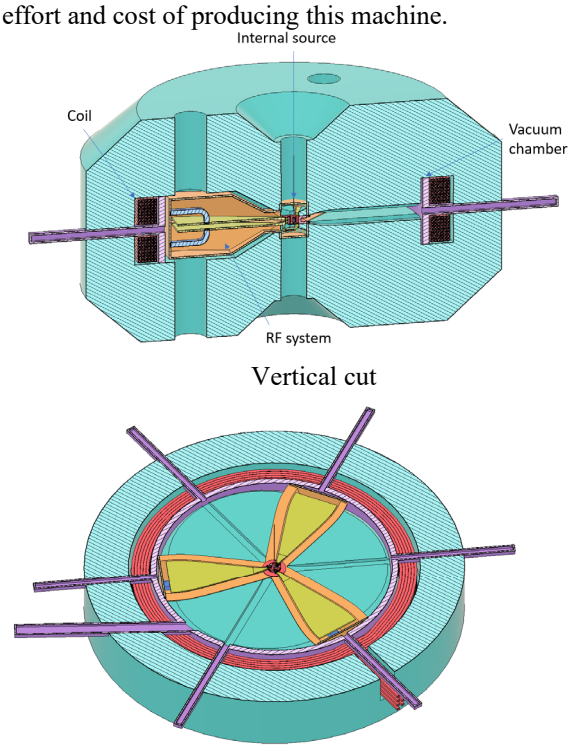

Figure 1: Layout of the 3D computer model of the cyclotron.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS016

Table 1: Parameters of the Cyclotron

Magnet type	Electromagnet with resistive coil
Ion source	Internal/External
Final energy MeV	15
Final radius, mm	360
Mean magn. field, T	1.55
Dimensions (height × diameter), mm^2	750 × 1290
Weight, kg	5500
Hill/Valley field, T	2.1/0.3
Hill/Valley gap, mm	25/210
A*Turn number	27 000
Magnet power consumption, kW	25
RF frequency, MHz	145
Harmonic number	6
Voltage, kV	30-50
RF power, kW	8
Turn number	120
Beam intensity, µA	Up to 1000
Extraction type	stripping foil

The main specific feature of this cyclotron is very low coil current 27000 A*turns (see Table 1.). Coil cross-section is 80x60 mm^2. Each coil has 4 double-pancackes, 12 turns each, the wire is 9.5x9.5mm Luvata 6889 square conductor with 5.5 mm hole. Required water pressure is 4 bar, which will give the water speed over 2 m/s and ensure the temperature rise of 15 degrees.

What makes the magnet of this cyclotron so efficient is low A*turns number in the coil. Such a low value is possible because the magnetic flux inside the magnet remains below the saturation of the Steel 1010 (which is commonly used for cyclotron magnets), so almost all the energy of magnetic field is concentrated between the poles, and the steel is in the mode of an efficient magnet conductor.

Magnetic Field Analysis and Preliminary Particle Dynamics Estimations

Average magnetic field and flutter from CST simulation are presented in Fig. 2.

Magnet flux distribution is shown in Fig. 3. Three wide sector structure of the cyclotron has high 6th and 9th Fourier harmonics in the structure of the magnetic field, which together with the third harmonic lead to a sufficiently large value of the flutter (Fig. 2).

Betatron tunes calculated in equilibrium orbits by CORD [5] code are presented in Fig. 4.

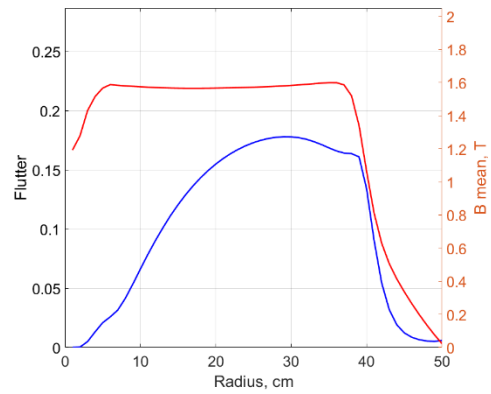

Figure 2: Average magnetic field and flutter along the radius.

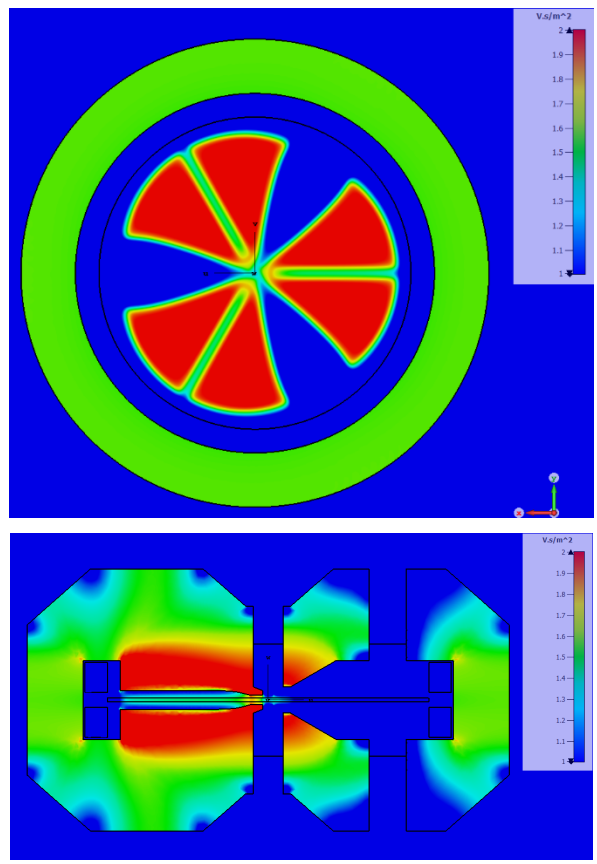

Figure 3: Magnet flux distribution through median plane (up), inside the yoke of the magnet (down).

As the concept is rather unusual, particle tracking has been carried out to confirm the principle. Isochronism of the model is good enough for beam dynamics simulation. The beam has been accelerated in the 3D magnetic and 3D RF electric field maps with initial amplitudes of betatron oscillations up to 5. Acceleration takes about 120 turns beginning from energy 1 MeV to 15 MeV. Total number of turns with 20 kV accelerating voltage was equal 125 turns. There were no losses of particles in any radius.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS016

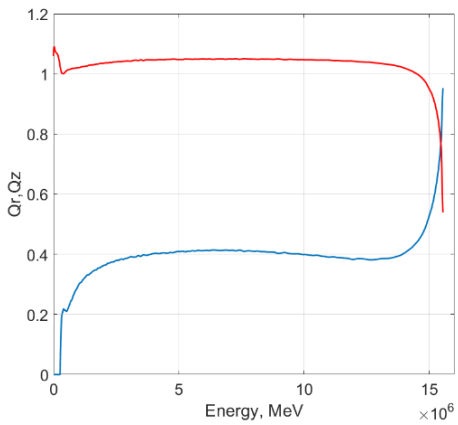

Figure 4: Betatron frequencies.

Accelerating System and Central Region

Geometric model of the double gap delta cavity housed inside the valley of the magnetic system of the cyclotron RC3/6 simulated in the CST STUDIO SUITE is presented in Fig. 5. Suitable accelerating frequency and voltage along radius were achieved. All 3 cavities will be powered independently with a coupling loop. It is not possible to have galvanic connection in the center region. All coupling loops can be connected to the coaxial power line, going in 100 mm hole through the yoke from the top of the cyclotron. All cavities operated in the same phase. Top/bottom Dees should be connected via contact fingers at the extraction end.

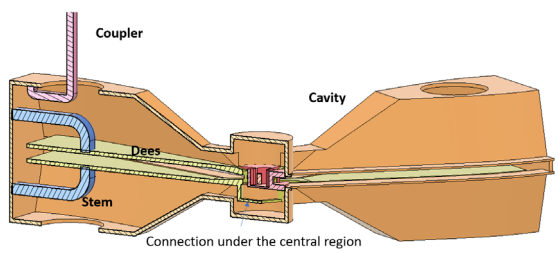

Figure 5: RF overview.

The active tuning system must be designed to bring the cavities on the frequency initially to compensate detuning for temperature variations due to RF heating and can be realized by capacitance tuner from radial direction. Simulations show that the frequency is about 145 MHz.

For accelerating voltage 30 kV, calculated losses are about 8 kW.

Of course, high frequency of RF system can potentially lead to poor capture of particles in the first accelerating gap. But this problem can be solved if in the first accelerating gap particles will arrive with some energy, thus travel through first gap much quicker.

Particles start from the PIG source, which is placed under 7500 V and accelerate to the "Cup" (red part on Fig. 6) and arrive to the first gap with 7.5 keV energy. Also, the advantage of such central region is that one ion source placed in the middle can deliver beam in each gap simultaneously, due to the symmetry of such central region.

Particle motion on the first turn is presented on Fig. 7.

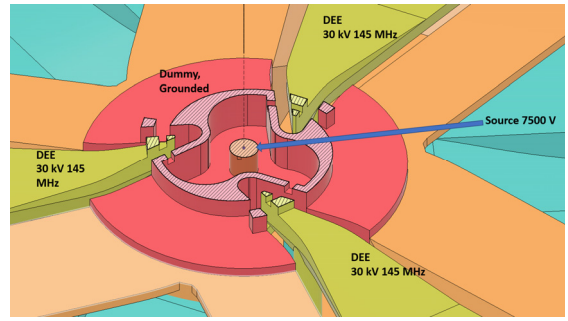

Figure 6: Overview of the central region.

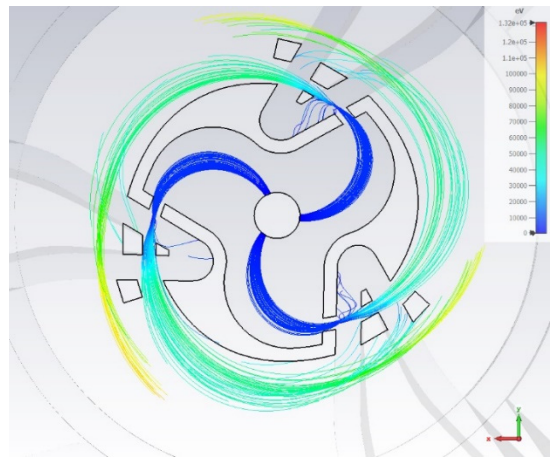

Figure 7: particle trajectories in the central region.

Such approach to central region design can be used to achieve high beam currents.

Vacuum

Vacuum chamber wall 30 mm width between the end of the sectors and coil. The rest of the vacuum chamber is the magnet itself. Vacuum seals in the RF/vacuum pump holes. Three holes from the bottom will be used for vacuum pumping.

Expected pressure in the cyclotron is 2÷5 10^{-7} Torr, by using three turbo-molecular pumps, pumping through 100 mm holes placed at the distance 0.5 m away from median plane.

The limitation for H^- acceleration is the energy of about 70 MeV, as further acceleration would result in magnetic dissipation of H^- ions, and require reduction of magnetic field, making the cyclotron big, and therefore expensive. The 15 MeV cyclotron RC3/6 is just an example, the concept RC3/6 can work at least up to 70 MeV.

CONCLUSION

The concept RC3/6 of a three-sector cyclotron operating in 6th harmonic mode will be an effective solution for accelerating to higher energies. The author will continue to develop this concept and design different cyclotrons for the alpha-emitting isotopes production, such as At-211 and up to the 70MeV H^- cyclotron.

Also, similar approach is possible for proton cyclotrons of a higher energies, such as 230 MeV [6] for proton therapy.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS016

REFERENCES

[1] J. Schippers, R. Dölling, J. Duppich, *et al.*, "The SC cyclotron and beam lines of PSI's new proton therapy facility PROSCAN", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 261, p. 773, 2007.

[2] J. G. M. Kleeven *et al.*, "The IBA Superconducting Synchrocyclotron Project S2C2", in *Proc. Cyclotrons'13*, Vancouver, Canada, Sep. 2013, paper MO4PB02, pp. 115-119.

[3] http://www.mevion.com/products/mevion-s250-proton-therapy-system

[4] X. Wu *et al.*, "Recent Progress in R&D for Ionetix Ion-12SC Superconducting Cyclotron for Production of Medical Isotopes", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3568-3570. doi:10.18429/JACoW-IPAC2019-THPMP052

[5] O. Karamyshev *et al.*, CORD (Closed ORbit Dynamics): A New Field Map Evaluation Tool for Cyclotron Particle Dynamics, ISSN 1547-4771, *Phys. Part. Nucl. Lett.*, 2021, vol. 18, no. 4, pp. 481–487. doi:10.1134/S1547477121040117

[6] O. Karamyshev, "New Design of Cyclotron for Proton Therapy", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper THPOMS015, this conference.