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CONCEPT OF 15 MeV CYCLOTRON FOR MEDICAL ISOTOPES PRODUCTION

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Abstract

The purpose of this article is to show the prospects of cyclotrons with resistive coils and prove that even in such a well-established field there is still room for innovation. The concept of a 15 MeV cyclotron accelerating H^- ions with a current of up to 1 mA is presented. The design features significantly lower weight and power consumption compared to the majority of existing cyclotrons of the same energy.

INTRODUCTION

Cyclotrons are widely used, delivering 10 - 70 MeV proton (mostly) beams for medical isotopes production such as PET, SPECT isotopes and 200 - 250MeV proton beams for hadron therapy. 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 author believes that at least at the low-energy area there is still room for improvements of the resistive-coil machines.

To summarize, 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 also occupy space around the magnet.
- Low magnet field is easier to shim, the isochronizing requirements are lower.

A NEW 15 MeV CYCLOTRON RC3/6

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.

Concept RC3/6

The cyclotron needs to be compact, cheap, reliable and to have a low power consumption. Concept RC3/6 lead 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 Figure 1). The sectors of the magnet are 90˚ 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 128 MHz for magnetic field equal to 1.4 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 and power-efficient.

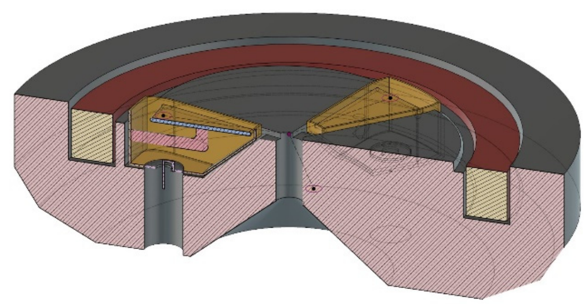

Figure 1: Layout of the 3D computer model of the cyclotron.

Table 1. Parameters of the Cyclotron

Magnet Type	Resistive
Ion source	external
Final energy [MeV]	15
Final radius [mm]	370
Mean Magn. field [T]	1.4
Dimensions (height×diameter) [mm^2]	720 × 1420
Weight [kg]	6500
Hill/Valley field [T]	1.8/0.4
Hill/Valley gap [mm]	25/300
A*Turn number	17 000
Magnet power consumption [kW]	1.5
RF frequency [MHz]	128
Harmonic number	6
Voltage [kV]	20
RF power [kW]	4
Turn number	120
Beam intensity [μA]	Up to 1000
Extraction type	stripping foil

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

The main specific feature of this cyclotron is very low coil current 17000 A·turns. Coil cross-section is 120x100 mm^2, therefore the current density is 17000/120/100 = 1.41 A/mm^2. It is possible to keep this coil even air-cooled. Magnet power consumption is just about 1.5 kW.

If it would be more feasible to use water cooling coil, it is optimal to keep the current density at about 3 A/mm^2 and make the yoke more compact. This would save some money on copper and steel, however increase power consumption.

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 Beam Dynamics Estimations

As the concept is rather unusual, particle tracking has been carried out to confirm the principle.

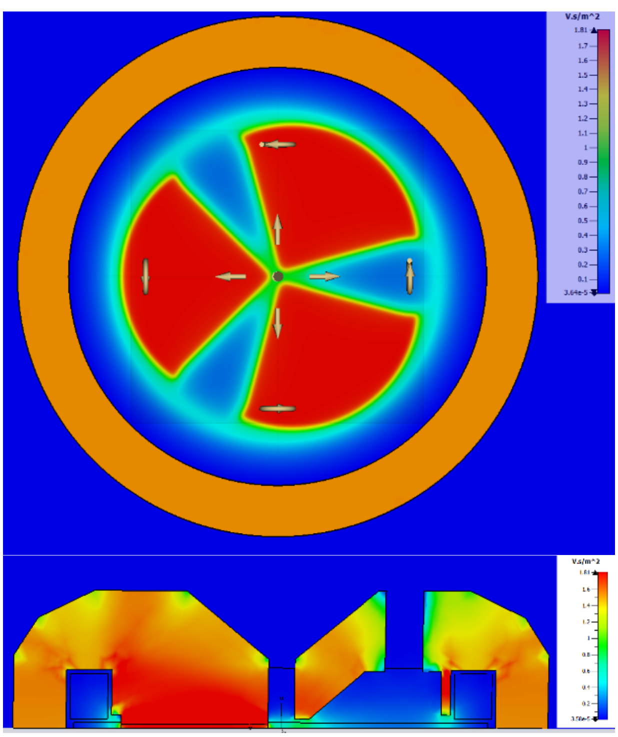

Figure 2: Magnet flux distribution through median plane (up), inside the yoke of the magnet (down).

Average magnetic field and flutter from CST simulation (Figure 2) are presented in Figure 3.

It can be seen from Figure 4 that the 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 (Figure 3).

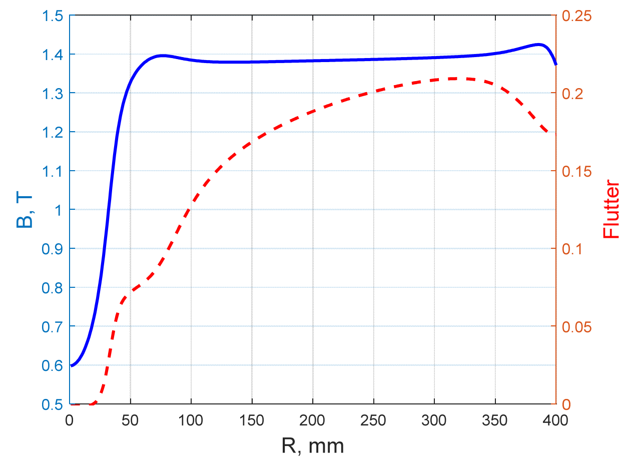

Figure 3: Average magnetic field and flutter along the radius.

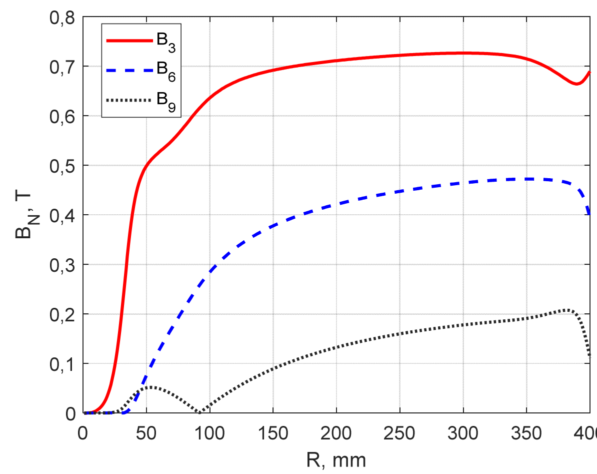

Figure 4: Fourier harmonics of the cyclotron magnetic field.

It can be seen from Figure 4 that the 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 (Figure 3).

Orbital frequency and betatron tunes calculated in equilibrium orbits by CYCLOPS-like code are presented in Figure 5 and Figure 6 correspondently.

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 mm (see Figure 7). Total number of turns with 20 kV accelerating voltage was equal 120. There were no losses of particles in any radius.

The beam is injected from the external CUSP ion source, using usual electrostatic spiral inflector or magnetostatic inflector. Accurate 3D model of the inflector and the central region is not finished yet but it is clear that center region should not cause any troubles.

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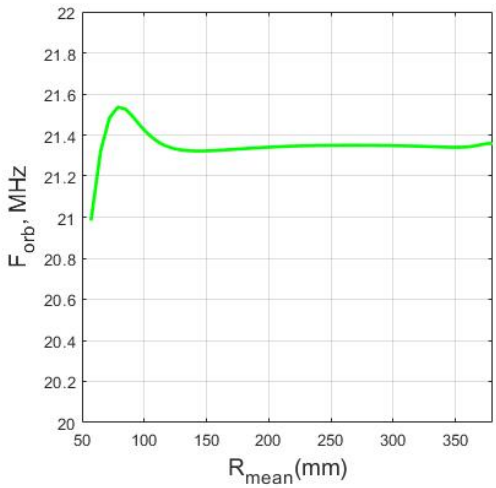

Figure 5: Orbital frequency.

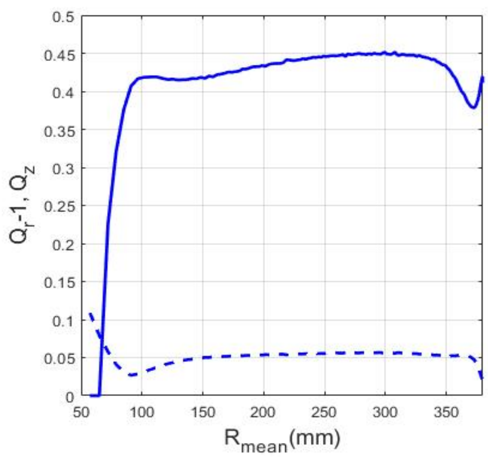

Figure 6: Betatron frequencies.

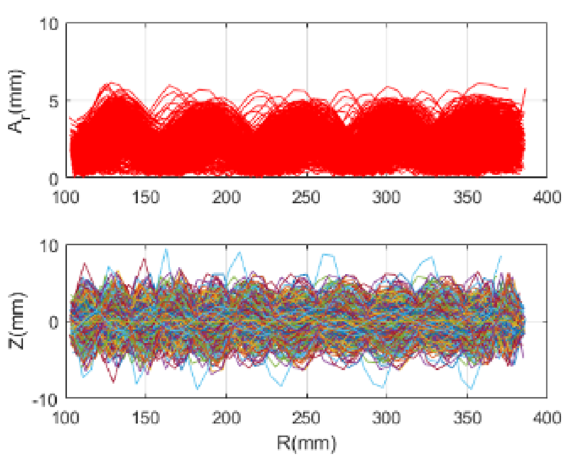

Figure 7: Amplitudes of radial oscillations and vertical motion of the beam during acceleration.

Accelerating System

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 Figure 8. 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, because of a spiral inflector. 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.

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 128 MHz.

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8\text{x}10^7$ 1/(Ωm). The quality factor was about 5500 and power losses of the model were:

For accelerating voltage 20 kV, calculated losses in one cavity are about 1.3 kW.

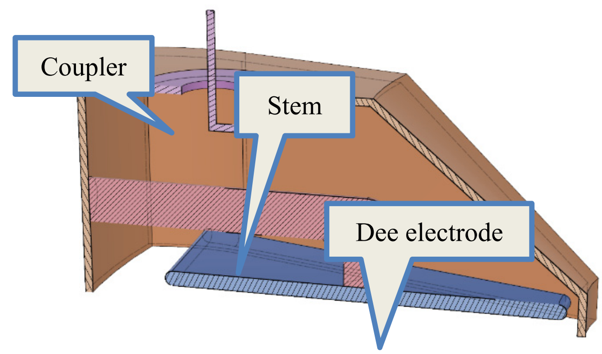

Figure 8: RF cavity overview (one fourth).

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 to 5 $\text{x}10^{-7}$ 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 optimization possibilities of the design of cyclotrons with resistive coils are not exhausted.

The design of the RC3/6 is quite unusual. The main advantage of the RC3/6 cyclotron is its low power consumption and small size. Dimensions are even smaller than those of the superconducting ION-12SC cyclotron [4].

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

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develop this concept and design different cyclotrons for the alpha-emitting isotopes production, such as ^{211}At and up to the 70 MeV H$^-$ cyclotron.

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

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