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A NEW CONCEPT OF CYCLOTRONS FOR MEDICAL APPLICATIONS

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Abstract

Demand for cyclotrons for medical applications is growing rapidly. Cyclotrons delivering proton beams from 15 MeV up to 230 MeV are being used for isotopes production and proton therapy. Author proposes a concept that allows to significantly reduce cost of cyclotrons by making them more compact and power efficient without using superconducting coil. In the proposed design ratio between azimuthal length of sectors and valleys is over 3 to 1, with RF system operating at high frequency and acceleration at harmonic mode of 2 times the number of sectors. Compact size is achieved not by increasing the magnet field level, but by reducing the coil and RF system dimension. Cyclotrons will have 4 sectors and 4 rf cavities operating at harmonic 8 with 1.55 T mean field and accelerating frequency 180 MHz.

MOTIVATION

The production of new cyclotrons for physics research has slowed down since the 1990s (see Fig. 1, the green triangles). At the same time, demand for cyclotrons intended for isotope production and proton therapy is growing. Cyclotrons have a limited lifetime due to irradiation, etc., which means there is a need to replace old cyclotrons with new ones. Cyclotrons are becoming better: more compact, cheaper, more reliable, power efficient.

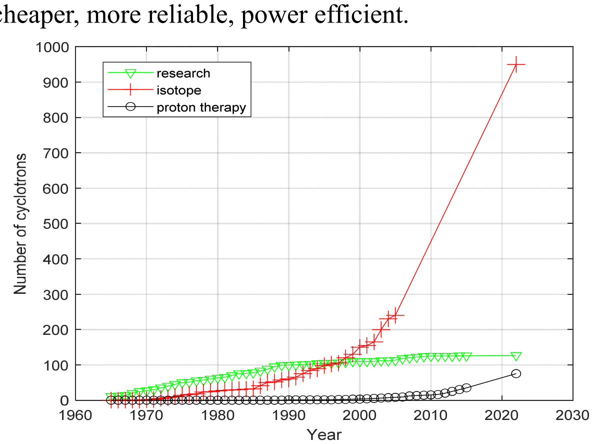

Figure 1: Number of cyclotrons versus years. The green triangles are cyclotrons in operation at research centers, the red crosses the cyclotron for medical radioisotopes production, and the black circles cyclotron for proton therapy [1]. Graphs are updated for year 2020 by data from [2, 3].

THE NEW CONCEPT

The main goal in creating a cyclotron is to make a light and compact design. In past years, the trend has been to increase the magnetic field, thereby decreasing the pole radius (see Fig. 2).

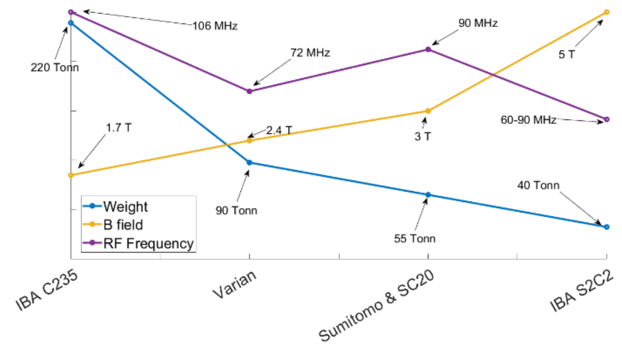

Figure 2: Weight, mean magnetic field and accelerating frequency of the proton therapy cyclotrons.

Superconducting coils is the only way to achieve high B field in cyclotron. Do cyclotrons with superconducting coils are more compact? Yes, the pole diameter is smaller, but cryogenics equipment around cyclotron is huge! Dry magnets with cryocoolers are more compact, but are there power efficient? Cryocoolers consume power 24x7 during operation and more during cooling down. So cyclotrons with superconducting coils have smaller pole diameter but they have the following disadvantages:

- Long time to turn on/off the magnet.
- Long time to cool down.
- Expensive.
- Requires servicing.

Moreover, superconducting cyclotrons do not exist! We only have cyclotrons with superconducting coils. Cyclotron is an accelerator and number one system of any accelerator is an accelerating system, magnet just keeps the beam focused and arrive in time! Superconducting RF systems do not yet work in cyclotrons.

I propose another way to reduce the size of the cyclotron, to make the accelerating RF system and coils more compact by increasing the frequency of the RF system, thereby reducing the valley depth. Reducing the valley depth will result in fewer A coils in the magnet, which will make the coil smaller, which in turn will result in a smaller yoke size. (Fig. 3).

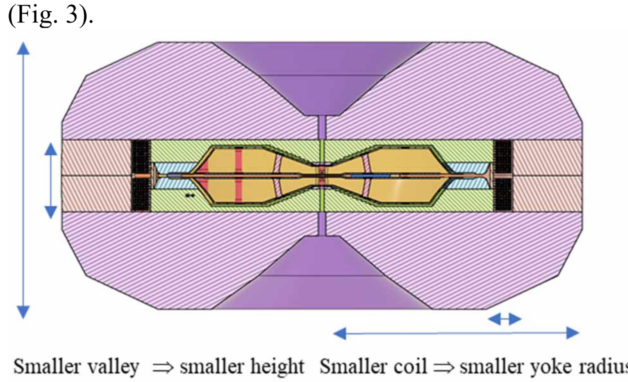

Figure 3: Dimensions of the cyclotron.

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So, in order to reduce the size of the cyclotron, the frequency of the accelerating system can be increased, but how much? If we look at frequency allocation chart [4] we will find out that the highest frequency in medical cyclotrons is 106.8 MHz, used by IBA C235 [5] is also the end of the lane dedicated for FM Radio, but between 108 and 136 MHz there are frequencies dedicated for aeronautical navigation, therefore it is not suitable for cyclotron. So the frequency for RF system in cyclotron can be 145 MHz, which is dedicated for amateur use or between 174 and 216 MHz.

VIRTUAL PROTOTYPING

A single parametrized model of the cyclotron, that integrates every major system of accelerator is developed in CAD (Solidworks). Individual systems are sent to CST studio to simulate in the corresponding modules. If changes are applied to one of the system, other system automatically adjusted and re simulated.

The "flagship" cyclotron accelerates protons to 230 MeV, magnet has 4 sectors, acceleration on 8th harmonic, accelerating frequency is 180 MHz. Smaller energy models are going to be derived from the big cyclotron.

Main magnet parameters are presented in Table 1.

Table 1: Magnet Parameters

Magnet Type	Compact, Copper Coils
Number of sectors	4
Material of magnet	Steel 1010
Sector and Valley gap	20/50 mm, 320 mm
Weight of magnet	130 Ton
Coil type	2x4 double pancakes
Nominal current/ total A-turn	1224A / 57kA-turns
Conductor type	15x25mm^2
Cooling pressure, water speed	4 bar, 1.95 m/s
Power consumption	80 kW
Water temperature rise	15 degrees

Magnetic Field CST Simulation

In order to minimize the A-turns number the design of the magnet is following the rule: maximize the amount of steel inside the cyclotron. Another important feature applied in cyclotron magnet design – so called "double sector".

"Double sector" consists of two parts (see Fig. 4):

1. wide-aperture part with a vertical distance of 50 mm and low helicity.
2. small-aperture part with a vertical distance of 20 mm and high helicity.

This structure makes it possible, firstly, to place the deflector between the sectors in the wide-aperture part, while retaining all the valleys for placing the RF cavities, and, secondly, to ensure isochronous growth and vertical focusing mainly due to the small-aperture part of the sector.

An increase in the azimuthal width of the small aperture part of the sector with a radius increases the magnetic field flutter (see Figs. 5 and 6), and a large helicity angle of the small aperture part of the sector (see Fig. 7) provides the necessary vertical focusing.

To ensure the growth of the mean field in the extraction zone, we also set the shape of the chamfer of the sector edge not around a circle centered at the geometric center of the cyclotron, but along the shape of the trajectory of the accelerated particles, which differs from the circle the more, the higher the flutter of the magnetic field.

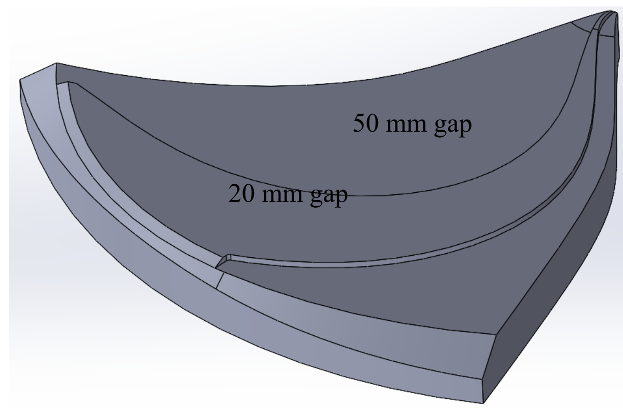

Figure 4: Double gap sector, double spiral, chamfered along beam trajectory.

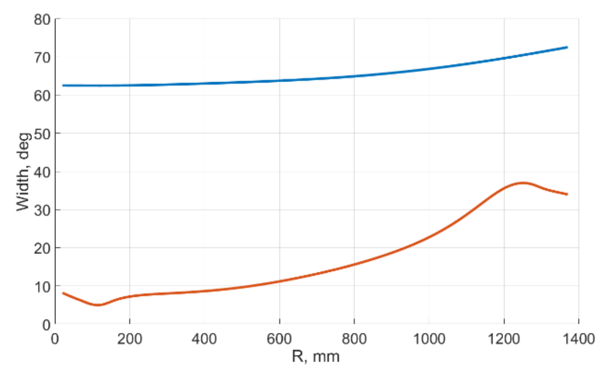

Figure 5: Azimuthal width sector.

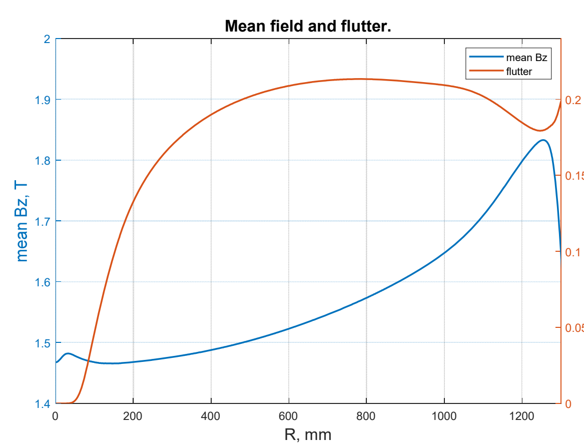

Figure 6: Mean field and flutter.

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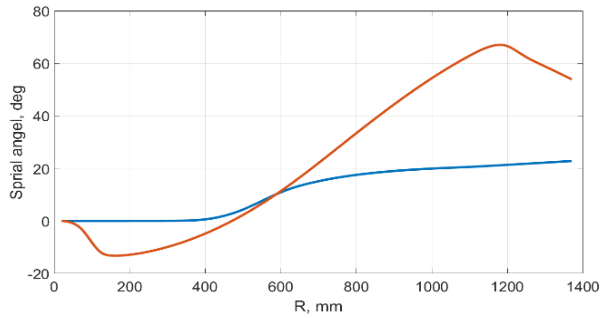

Figure 7: Spiral angle of the sector.

Accelerating System

To accelerate protons, it is planned to use 4 double gap delta RF cavities with 3 stems (see Table 2, Fig. 8) located in the valleys of the magnet (8th harmonic acceleration mode).

Table 2: Acceleration System Parameters

Parameter	Value
Frequency, MHz	180
Harmonic number	8
Q-factor	11000
Voltage center/extraction, kV	30/160
Power loss	30-50 kW total

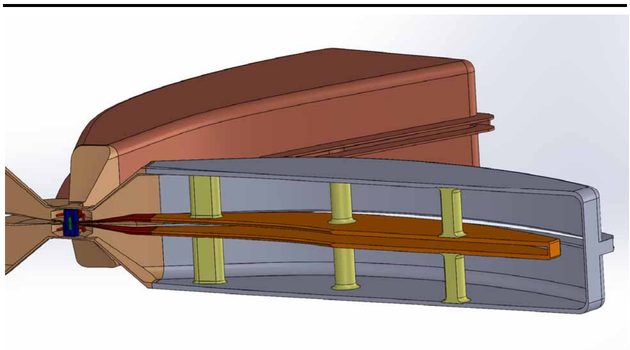
Figure 8: View of the accelerating system.

Accelerating voltage and azimuthal extension of the cavities along radius were calculated and presented in Ref. [6].

Particle Dynamics

The particle dynamics studies were carried out using magnetic and electric field maps obtained by simulating the corresponding systems in the CST studio. CORD code was used for estimation of the field characteristics. CORD is providing particle dynamics analysis based on a combination of magnetic field map analysis with electric field map analysis [6, 7].

Center Region

Capturing the beam from the ion source into the acceleration at high frequency of the accelerating field is an issue. If the particles from the ion source start with zero energy, only a few (or zero?) particles can be captured at 180 MHz, but even a small initial velocity of 5 keV allows the beam to be captured with a phase expansion up to 15 deg. External injection, of course, is the obvious solution for such a cyclotron, but there is an alternative to increase the capture efficiency from internal ion source. Efficient center region for this cyclotron is described in detail in Ref. [8].

Particles start from the PIG source, which is placed under 6600 V and accelerate to the “Ninja star” housing (zero potential) and arrive to the first gap at 6.6 keV energy.

Most challenging part of the central region design was to leave enough space for connection of all 4 dees, leave big enough hole for the ion source at 6600V and have B field with “bump” distribution to provide vertical focusing (Figs. 9 and 10).

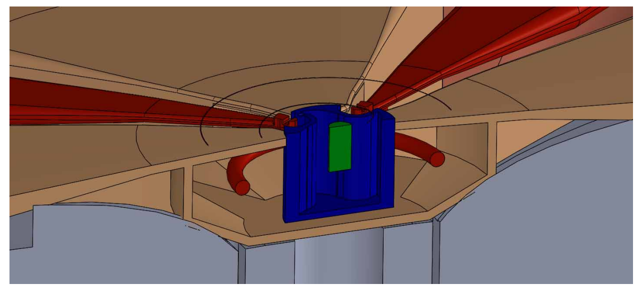
Figure 9: Center region design.

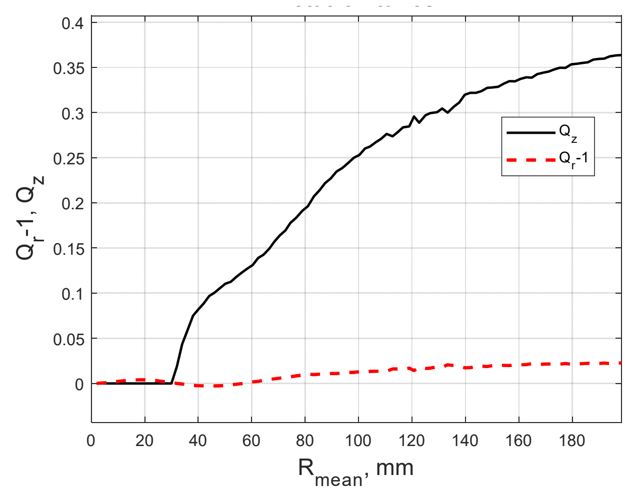

Figure 10: Betatron tunes in the center region.

Advantages of the proposed scheme of central region:

- At least 4 times higher current, as 4 bunches captured at the same time.
- Much higher capture in each 1st gap due to initial acceleration. In this case phase range increases from 0 to 15 deg RF.
- Only protons arrive to the RF puller, resulting in less erosion of RF parts.
- The ion source is separated from the rest of the chamber by a "Ninja star" housing, which provides an improved vacuum in the cyclotron. An additional pump can be used to pump gas from the inside of the “Ninja star”.
- Only safe voltage is used. Smallest gap is 3.0 mm, voltage on RF puller is 25 kV, so electric field strength is just 83 kV/cm at frequency 180 MHz.

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Of course, 8th harmonic mode of acceleration is not an ideal option for truly high power cyclotron, however such design of the center region if used with 4th harmonic acceleration, especially with even higher voltage on the source can lead to 10 mA currents and higher.

Extraction

The beam extraction for this machine will be carried out by means of 1 electrostatic deflector (ESD), located between the sectors, and passive focusing magnetic channel (Fig. 11) [6]. The electric field strength in the deflector is 80 kV/cm.

This extraction scheme is presented as a proof-of-concept, author is currently analyzing alternative schemes.

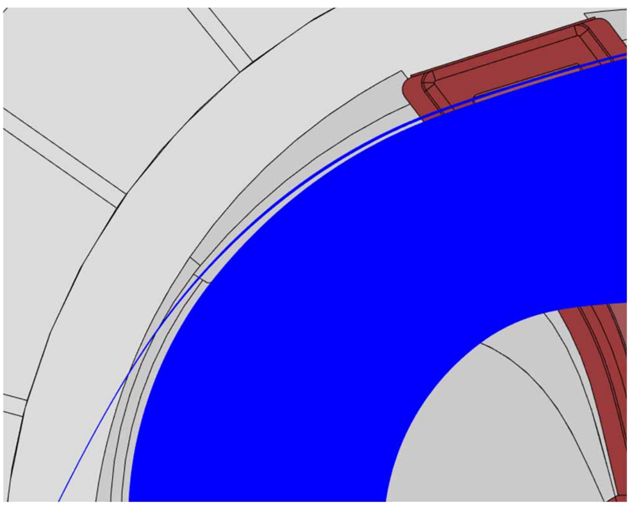

Figure 11: Beam extraction.

CONCLUSION

New concept of cyclotrons for medical application has been developed.

The advantages of the concept are:

- Compact but non-superconducting design, thus cheaper.
- All cyclotrons in the line from 15 to 230 MeV will share the same RF frequency, making many parts identical for different models.
- The design is simple and robust, no extreme solutions, moderate currents, power, voltages on deflector etc.

The new concept opens up the possibility of using HTS. HTS does not work well (requires low temperatures) in a magnetic field. In proposed design the magnetic field in the coil is low (about 1.5 T), which means it is possible to use high-temperature superconductor at temperatures >70 K, which will significantly reduce the power consumption and cost of cryogenic equipment.

Looking for partnership to advance from virtual prototyping to real prototypes!

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