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NEW DESIGN OF CYCLOTRON FOR PROTON THERAPY

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Abstract

An innovative approach to a design of cyclotron allows to produce cheaper and more power efficient cyclotrons for medical and industrial application is presented. A 230 MeV cyclotron for proton therapy, using this design scheme is presented. The cyclotron is one of the line of cyclotrons from 15 to 230 MeV, that uses same magnet field level and RF frequency and utilises many identical solutions within the line-up to make it cheaper to produce and run. The design suits for FLASH therapy as is it able to produce larger beam current then existing accelerators for proton therapy.

INTRODUCTION

The proposed design follows the same concept, described in the [1]. Currently two types of cyclotrons are successfully operated for proton therapy: IBA C235 [2] and Varian Proscan [3]. More recently developed synchrocyclotrons such as IBA S2C2[4] and Mevion [5] were looking as a superior option in terms of compactness and price before an innovative technique, called FLASH [6] has been discovered, which requires higher beam currents then existing accelerators for proton therapy produce.

In order to achieve high beam current (over 10 micro-Amperes) the cyclotron should have good acceleration rate and low magnetic field to ensure efficient extraction.

In this paper the cyclotron project for proton therapy using similar approach is described. Unlike a 10-70 MeV cyclotrons [7], a 230 MeV proton therapy accelerator requires a 4-sector structure. Acceleration at the 6 harmonic mode is possible when four accelerating cavities operate in push-pull mode, meaning that opposite cavities operate in the same phase, and the other two cavities have to operate with 180deg phase shift. It can be achieved by having a capacitance coupling in the central region.

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, despite its high frequency due to high Q factor. The number of A*turns in this project is 80000 per coil, so coil has rather small cross-section 240*120 mm^2. Compared to the IBA C235 cyclotron with resistive coils, which is widely used in the proton therapy, has the number of A * turns of 250000 per coil and, as a result, its coil dimension is about 500x350mm^2, and as a result the yoke of the magnet is much larger, although the pole diameter is smaller. Minimizing coil cross-section leads to significant reduction of the overall dimensions (see Table 1). As the result, the proposed design requires just 2.7 Tons of copper, which is about 8 times less than for IBA C235 and overall price of copper wire is much cheaper than cryogenics equipment, required for superconducting coil.

Computer model of the cyclotron (see Fig. 1, Fig. 2) was build in CAD and simulated in CST studio [8].

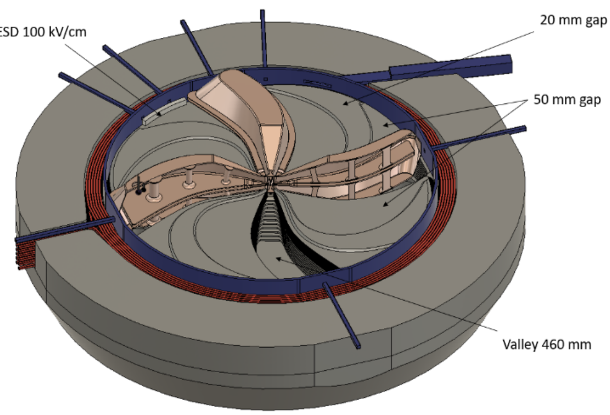

Figure 1: 3D computer model of the cyclotron.

Table 1: Parameters of the Cyclotron

Accelerated particles	protons
Final energy	232 MeV
Ion source	Internal, PIG
Extraction scheme	1 ESD, 2 correctors
Magnet Power Consumption	95 kW
RF power consumption	80 kW (wall losses)
Dimensions	3850x3850x2000 mm^3
Beam current	Up to 100 micro Ampers

MAGNET SYSTEM OF THE CYCLOTRON

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.

Magnet sectors consist of two parts:

1. wide-aperture part with a vertical distance of 50 mm and low helicity
2. small-aperture part with a vertical distance of 25 mm and high helicity.

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

Two Coils consists 6 double pancakes of square 19x19mm^2 hollow conductor (Luvata 8171) with 10 mm in diameter hole. Length of each pancake is 105 meters. Parameters of the magnet are presented in Table 2.

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Table 2: Parameters of the Magnet

Magnet type	Compact, copper coils
Number of sectors	4
Material of magnet	Steel 1010
Sector and Valley gap	20/50 mm, 460 mm
Weight of magnet	130 Ton
Coil type	2x6 double pancakes
Conductor type	19x19 mm^2 Luvata 8171
Cooling pressure, water speed	4 bar, 1.65 m/s
Power consumption,	95 kW

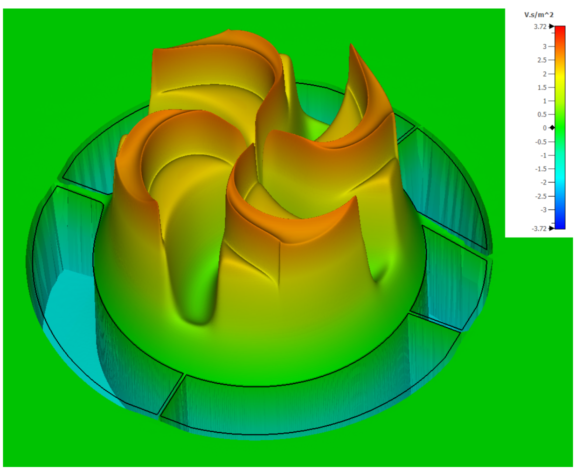

Figure 2: Magnetic field.

The dimensions of the yoke were chosen to restrict the magnetic stray field in the range of 100G just outside accelerator, providing full saturation of the iron poles and yoke. Average magnetic field and flutter from CST simulation are presented in Fig. 3. Figure 4 demonstrates accurate isochronism of the magnetic field of the model.

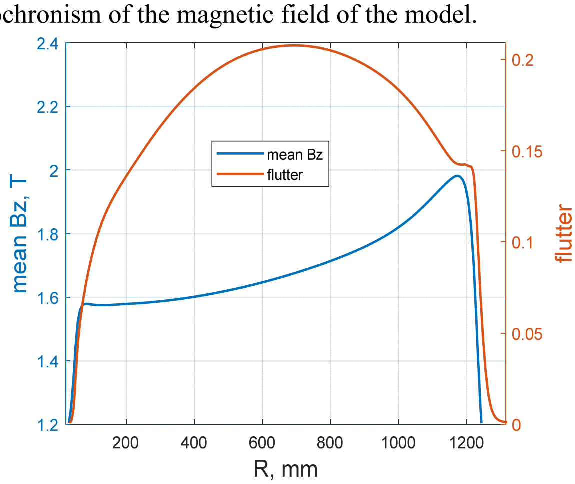

Figure 3: Average magnetic field and flutter along the radius.

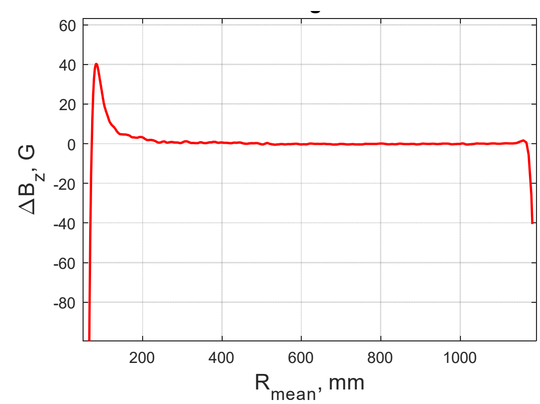

Figure 4: Difference between average and isochronous field.

Tune diagram was calculated (see Fig. 5) by code CORD (Closed ORbit Dynamics) code [9].

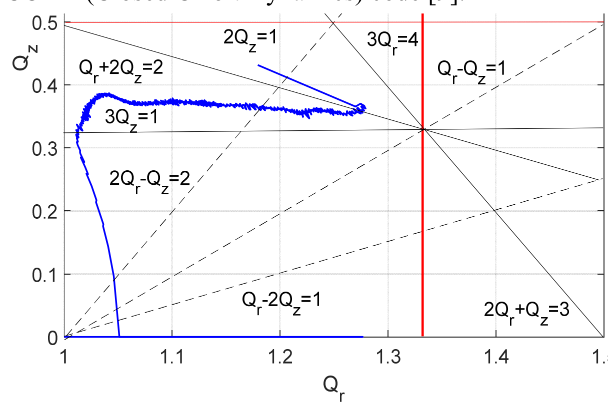

Figure 5: Working diagram.

ACCELERATING SYSTEM DESIGN

To accelerate protons, it is planned to use 4 accelerating RF cavities located in the valleys of the magnet and operating in 6th harmonic mode.

The characteristic parameters of the half-wavelength coaxial resonant cavity with three stems have been obtained from simulation in CST studio. The RF cavity solution for the cyclotron can be seen in Fig. 1. Azimuthal extension of the cavity (between middles of the gaps) against radius is presented in Fig. 6.

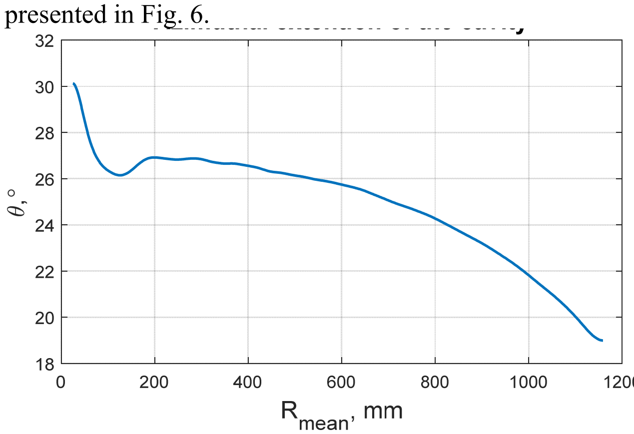

Figure 6: Azimuthal extension of the cavity (between middles of accelerating gaps).

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Main parameters of accelerating system are presented in Table 3. The choice of 6th harmonic was done to minimize azimuthal extension of the cavity. RF cavities will work in push-pull mode on approximately 145 MHz frequency. The frequency distance between push-pull mode and push-push mode is about 160 kHz. This is sufficient for avoiding unwanted excitation of the push-push mode.

Table 3: Accelerating System Parameters

RF Frequency	145 MHz
Cavity type	Half-Wave
Stem number	6 per cavity
Harmonic number	6
Number of RF cavities	4
Power losses	80 kW
Q-factor	10300
Voltage center/extraction	30/110 kV
Accelerating gap center/extraction	5/35 mm
Number of turns	600

Suitable accelerating frequency and voltage along radius were achieved. The calculation results of acceleration voltage are presented in Fig. 7. The value of the accelerating voltage was obtained by integrating the electric field in the median plane of the resonant cavity along the arc of a circle for each gap separately.

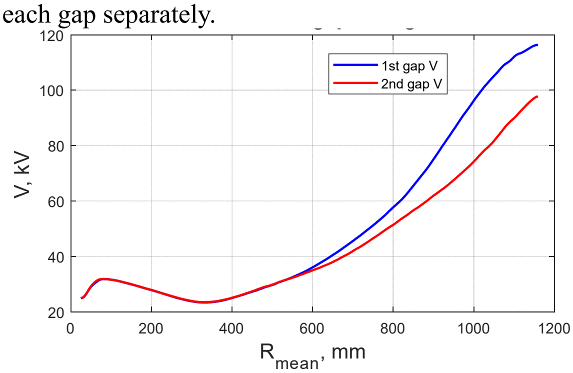

Figure 7: Accelerating voltage along radius.

The phase motion in the cyclotron calculated via the analysis of equilibrium orbits is shown in Fig. 8.

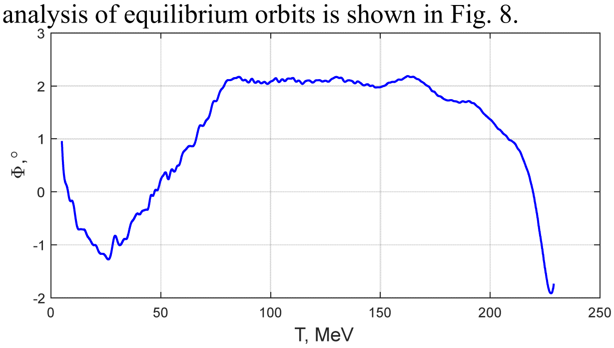

Figure 8: Integral phase shift along the radius. Positive phase corresponds to the lagging particle

The phase motion of an equilibrium particle reflects the number of turns that the particle has passed in the accelerator. In our calculations with SC230 magnetic and RF electric field maps, the equilibrium particle reaches a final energy of 230 MeV in less than 600 turns. Figure 9 shows the orbit separation distance and the number of turns as functions of radius.

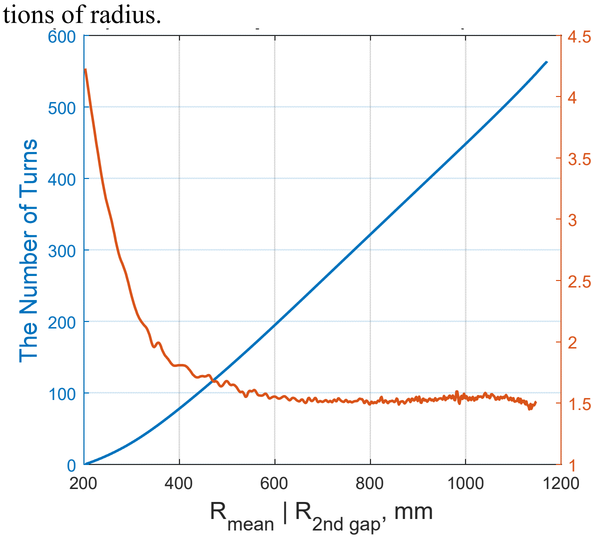

Figure 9: Number of turns (blue dashed line) and orbit separation distance (red solid line) in the cyclotron along the radius.

Ray tracing was done to ensure that there were no resonance effects and to simulate beam extraction. The beam extraction will be performed with 1 electrostatic deflector and 2 passive focusing magnetic channels located between the sectors. The value of electric field in deflector will not exceed 100 kV/cm.

Power losses

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8 * 10^7$ $1/(\Omega m)$. The quality factor was about 10300 and power losses of all cavities were: for storage energy 1 joule voltage in the center/extraction 30-110 kV, thermal losses are 80 kW.

CONCLUSION

The optimization possibilities of the design of cyclotrons with resistive coils are not exhausted. The main advantage of the proposed cyclotron design is its low power consumption and reasonable size. Such conception can be used for cyclotron with HTC coils, the main disadvantage of which is big price, so minimisation of coil dimensions makes price acceptable.

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