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BEAM DYNAMICS IN A NEW 230 MeV CYCLOTRON

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Abstract

A new cyclotron for proton therapy concept is a compact, but non-superconducting accelerator, that is simple, but cheap. Proposed concept uses 4 sectors with double spiral design and 4 RF cavities operating at harmonic 8, making the central region and extraction a challenging task that needs to be carefully simulated. High injection and extraction efficiency is presented.

INTRODUCTION

The cyclotron project for proton therapy using approach similar to [1] is presented. A detailed description of the proposed project is given in [2] this conference. Center region of the cyclotron is presented in [3] this conference.

Magnet sectors of the cyclotron consist of two parts:

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

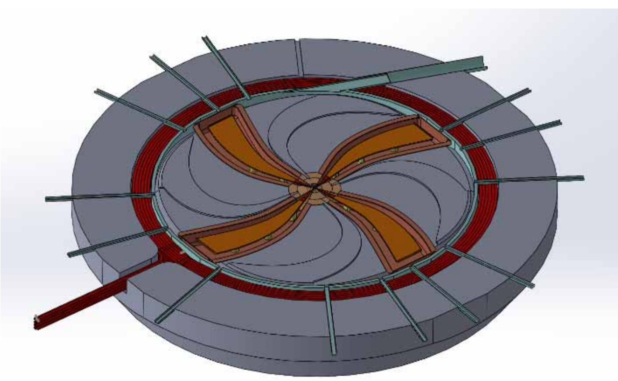

Figure 1: 3D computer model of the cyclotron.

Main parameters of the cyclotron are presented in Table 1.

Table 1: Cyclotron Parameters

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	100 kW (wall losses)
Dimensions	(3850 x 3850 x 2000) mm^3
Beam current	Up to 100 µA

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.

Computer model of the cyclotron (see Fig. 1) was built in CAD and simulated in CST studio.

CODE CORD

CORD code [4] 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. The first part of the code is searching for closed orbits (without acceleration) and calculating the focusing properties of the magnetic field. There are two types of closed orbits: orbits having the same N-fold symmetry as the cyclotron (no imperfections) and orbits obtained in a real field map with errors like low number harmonics.

In CORD we fix the radius r and match p_r and energy T. Initial values for each orbit are independent of other orbits, therefore parallel calculation is possible. A single iteration of the iterative scheme consists of the following 3 stages:

- Calculating the orbit's initial guess values $r(\theta_i)$, $pr(\theta_i)$, $T(r(\theta_i))$, θ_i is the initial angle and θ_f is the final angle.
- Finding $r(\theta_f)$, $pr(\theta_f)$, by solving ODE with MATLAB's ode45 solver, ODEs are simultaneously solved for a large set of radii (multiple orbits).
- New initial values for the next iteration:

$$p_r(\theta_i) \rightarrow p_r^{new}(\theta_i) = \frac{p_r(\theta_f)+p_r(\theta_i)}{2},$$

$$T \rightarrow T^{new} = T\frac{2r(\theta_i)}{r(\theta_i)+r(\theta_f)},$$

$$p^{new} = \sqrt{\frac{T^2}{c^2} + 2Tm}.$$

The number of iterations is constant and can be set to provide the necessary precision.

MAGNET FIELD ANALYSIS

Code CORD can present mean magnetic field and flutter (see Fig. 2), betatron frequencies in a tune operating diagram (see Fig. 3), calculates orbital frequency (see Fig. 4) and the difference between average magnetic field and isochronous one (see Fig. 5).

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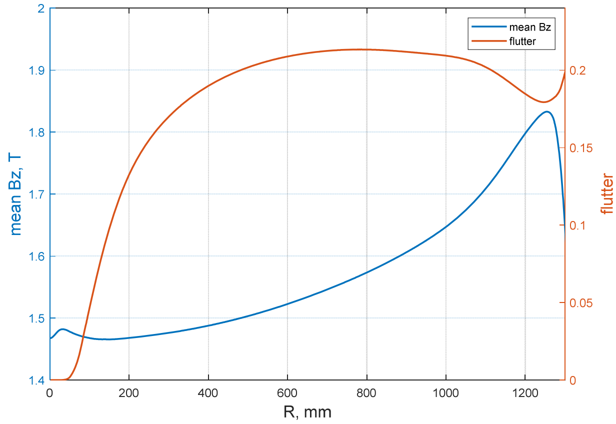

Figure 2: Average magnetic field and flutter along the radius.

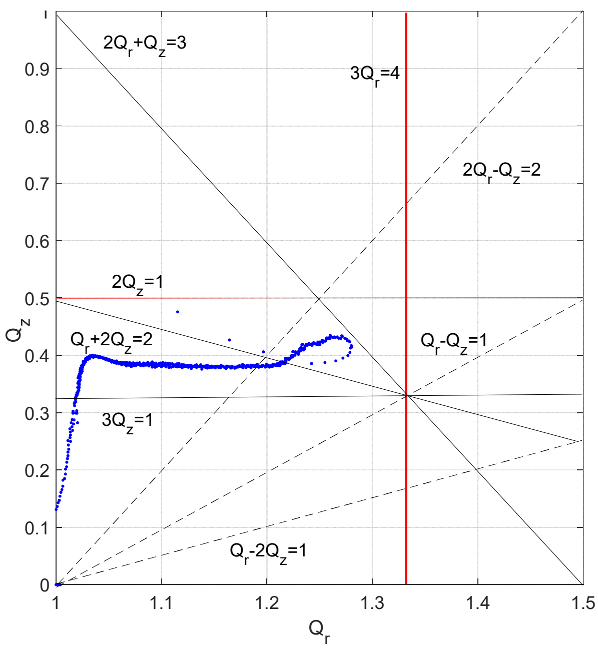

Figure 3: Tune diagram.

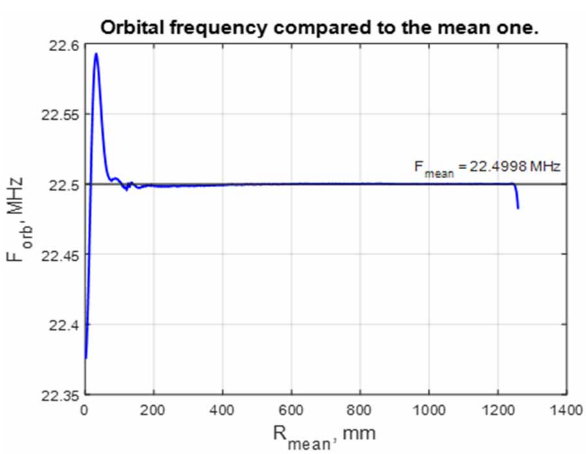

Figure 4: Orbital frequency against radius.

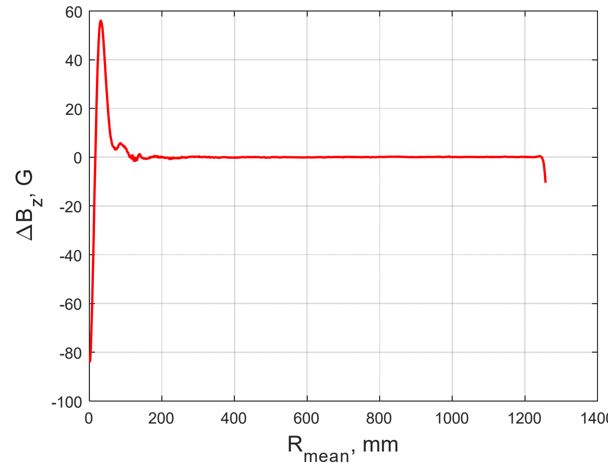

Figure 5: Difference between average magnetic field and isochronous one.

ACCELERATING FIELD ANALYSIS

We calculate effective azimuthal extent of the cavities (see Fig. 6), defined as the angular distance between the maxima of the electric field distribution in the median plane for the entire range of radii. Code CORD defines the voltage across the accelerating gaps as the integral of the electric field strength along the arc of a circle passing through the gap (see Fig. 7). The integral phase slip is presented in Fig. 8. Number of turns and orbit radial step against the radius (Fig. 9) were also calculated by CORD code. Table 2 shows the accelerating parameters of the accelerator.

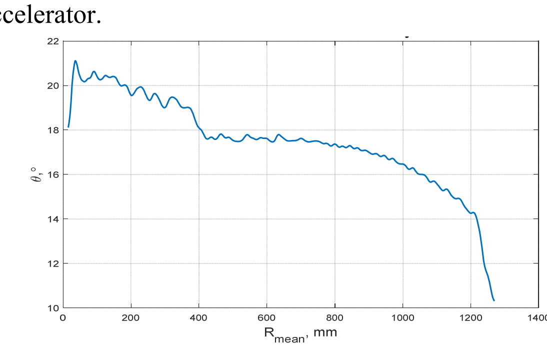

Figure 6: Azimuthal extent of the cavities against radius.

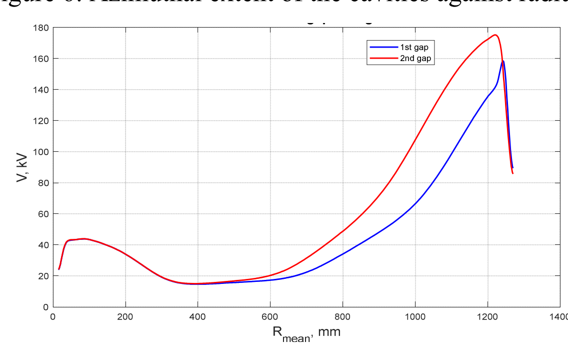

Figure 7: Voltage distribution along radius.

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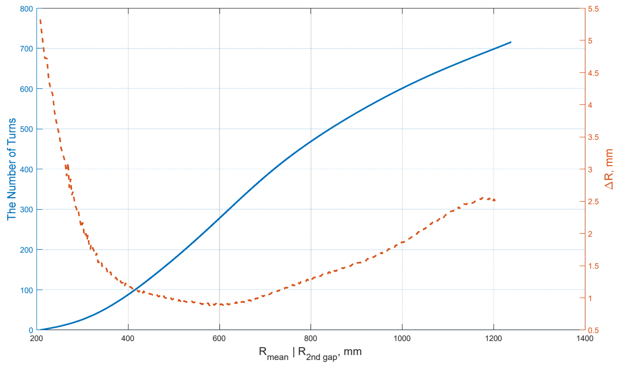

Figure 8: Number of turns (blue solid line) and orbit separation distance (red dash line) in the cyclotron along the radius.

Table 2: Accelerating System Parameters

Frequency [MHz]	180
Harmonic number	8
Q-factor	11000
Voltage center/extraction [kV]	30/160

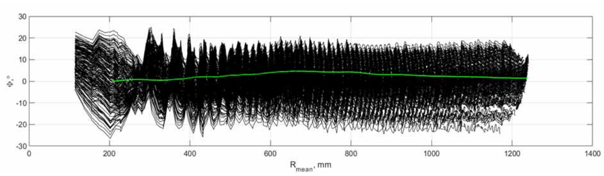

Figure 9: Integral phase slip along the radius. Positive phase corresponds to the lagging particle. Black lines – phase motion of the beam from particle tracking, green line – CORD.

EXTRACTION SYSTEM

The beam extraction for this machine can be carried out by means of 1 electrostatic deflector (ESD), located between the sectors, and 2 passive focusing magnetic channels (MC1 and MC2). We restricted electric field in deflector by the value of 90 kV/cm.

The beam, after being pulled with the deflector, passes through the accelerating RF-cavities and magnetic channels. Passive magnetic channels are located inside sector's gap.

MATLAB allows the import of 3D CAD models, which makes it possible to draw beam trajectories against the background of a full cyclotron model. The beam tracing, displayed on the Fig. 10, could be seen visually the beam passing inside the cyclotron structure which helps to control the process of acceleration and extraction.

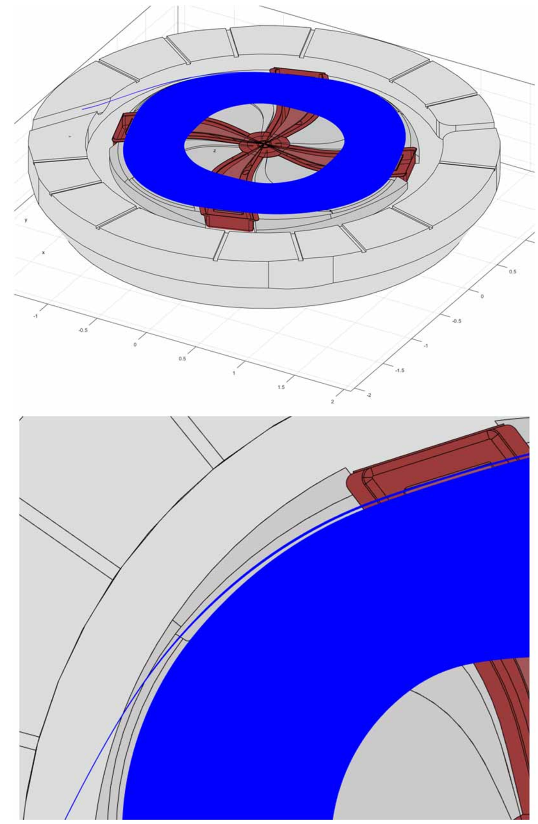

Figure 10: The beam tracing in the cyclotron structure.

CONCLUSION

The main feature of the proposed designs is the small number of A*turns of the coils. Together with the energy-efficient acceleration system, this determines low power consumption of the project. Such a coil has small dimensions, so the accelerator has acceptable dimensions, despite the large pole diameter. A small copper coil is economically attractive. Beam dynamics simulations revealed no problems with particle acceleration and extraction.

REFERENCES

[1] O. Karamyshev, "New Design of Cyclotron for Proton Therapy", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2973-2976. doi:10.18429/JACoW-IPAC2022-THPOMS015

[2] O. Karamyshev, "A new concept of cyclotrons for medical application", presented at Cyclotrons'22, Beijing, China, Dec. 2022, paper THBO01, this conference.

[3] O. Karamyshev, "High power central region with internal ion source", presented at Cyclotrons'22, Beijing, China, Dec. 2022, paper WEPO004, this conference.

[4] O. Karamyshev *et al.*, "Cord (Closed Orbit Dynamics): A New Field Map Evaluation Tool for Cyclotron Particle Dynamics" *Phys. Part. Nucl. Lett.*, vol. 18, no. 4, pp. 481–487, Aug. 2021. doi:10.1134/S1547477121040117