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BEAM EXTRACTION SIMULATION AND MAGNETIC CHANNELS' DESIGN FOR MSC230 CYCLOTRON

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Abstract

MSC230 is a novate cyclotron for proton (FLASH included) therapy research, designed and developed by JINR. The extraction system of this machine includes only one electrostatic deflector followed by two magnetic correctors. These correctors were designed and included in global model to simulate beam extraction. The peculiarities of the design procedure and the outcome of the simulation is discussed in this paper.

INTRODUCTION

Joint Institute for Nuclear Research (JINR) is working on the design for the new cyclotron for proton therapy: MSC230 – Medical Super Conducting cyclotron of 230 MeV energy [1].

The main idea is to build very reliable and easy in production machine. This allows to maximize extracted beam current to be enough to FLASH therapy.

In order to do that, MSC230 combines advantages of two most successful accelerators in proton therapy – PROSCAN's Varian and IBA's C235. From C235 we took a low magnetic field and the fourth harmonic of acceleration, from Varian we took a superconducting coil, to reduce its weight to ~100 tones, and a constant gap between the sectors along the radius, wide enough to accommodate an electrostatic deflector, and as a result we have four free valleys for placing accelerating cavities connected in center.

JINR International Biomedical Research Center

The final goal of the project is to design and create an international biomedical innovation center at JINR, based on MSC230, for the next purposes:

1. Carrying out fundamental and applied research in the field of radiation biology and medicine, first of all, the FLASH method based on the methods of conformal irradiation from the medical beam of the Medical Technical Complex (MTC DLNP).
2. Training and improving qualifications of specialists in the field of radiation biology and medicine.
3. Creating necessary conditions for the introduction of the latest technologies in the field of proton therapy of oncological diseases into clinical practice.

ABOUT THE EXTRACTION SYSTEM

The extraction system of MSC230 is planned to be done by placing one electrostatic deflector (ESD) followed by two magnetic channels (MC1 and MC2), see Fig. 1. Every element is located under the sectors and surely must take into the account the dimension restriction caused the length of the sector's gap, normal to median plane, is being 50 mm. The azimuthal extent of every element is 40°.

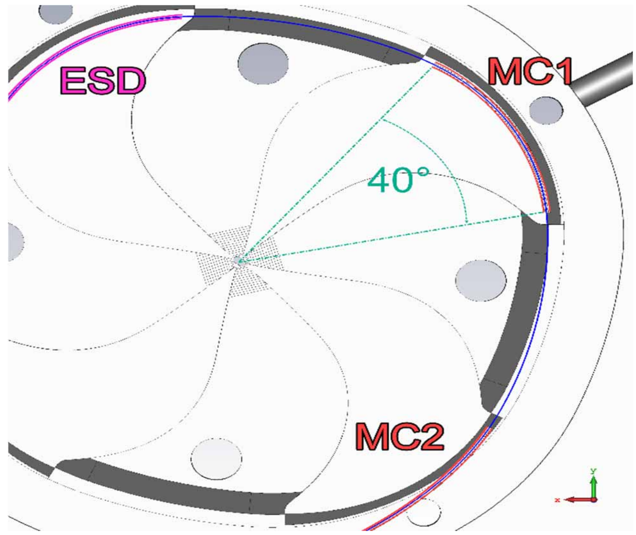

Figure 1: The location of the extraction system elements along beam extraction trajectory (blue curve).

ESD is placed with the idea to catch the beam right after it exits the second accelerating gap. The reliable design of the cyclotron allows to accelerate the beam only in 500 turns which provides the distance between equilibrium orbits of 1.5 mm at the deflector entry. Such design also decreases the requirements for voltage to be quite safe: the eclectic filed strength is only 100 kV/cm at maximum, i.e. the electrode voltage – 50 kV. Due to main beam losses mostly happen on the encounter face of the deflector's septum, septum thickness was chosen 0.1 mm. The aperture of the deflector is 5 mm

The beam, deflected by ESD, enters the first magnetic channel MC1 which continues extraction and decrease horizontal defocusing.

The sole purpose of MC2 is to suppress horizontal defocusing, for the beam to fit the required aperture.

MAGNETIC CHANNELS' REQUIREMENTS

The basic requirements for the channels are the following (see Table 1), which should be delivered along the intervals of the beam trajectory into the magnetic field shown in the Fig. 2.

Table 1: The Requirements for the Magnetic Channels

Channel	Aperture [mm]	Gradient [Gs/mm]	B_z shift [Gs]
MC1	10	100	-600
MC2	10	170	0

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We set the following tolerances for the requirements: one needs to meet gradient requirements within 12 mm aperture on median plane, keeping gradient deviation in 10%, for the external field of the average value (Fig. 2, grey lines). A channel, fitting these tolerances, is expected to be able to execute its function correctly.

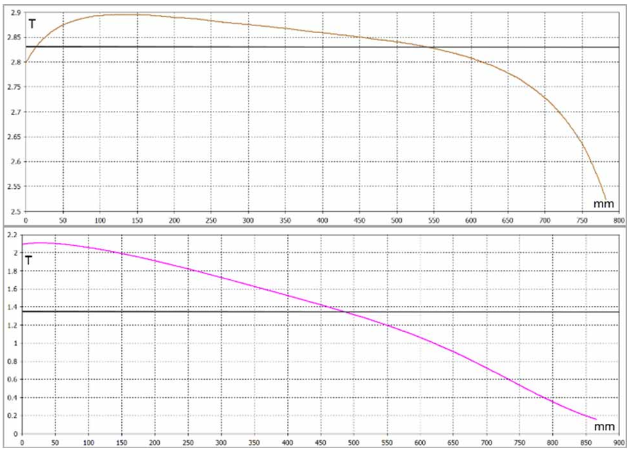

Figure 2: The vertical component of the magnetic field (B_z) along trajectory intervals for MC1 (top) and MC2 (bottom). Grey line is an averaged value.

Finally, the last pursue is to make channels more compact, that provides several benefits at once. Small mass reduces the effect of magnetic field distortions in the area of circulating beam, as well it reduces magnetic forces applied on the channel, reducing the size and complexity of the mount. And obviously, small dimensions of the channel make its displacement adjustment easier in several ways, also leaving room for other cyclotron devices.

DESIGN PROCEDURE PECULIARITIES

The design and simulation of magnetic channels were performed in CST studio suite.

Initial Design Stage

The initial design was done in the parametric model which simulates 2D cross section magnetic channels normal to the beam trajectory.

The major part of this search for the design is the variation of the form of the channel cross section in order to achieve the magnetic field alteration which is close to the requirements as much as possible. CST studio helps to automate this process and immensely reduce time spent on this procedure, due to the following two features. The first CST allows to parameterize the value of almost every initial variable of the model you build, in our case the dimensions (form) of the channel. The second – is easy way to process the results, in our case: to evaluate field on desired curve (or area), then to calculate the gradient on that curve, to give the integral deviation from required once (according to the chosen functional space metric), as the single scalar value outcome. This turns the model simulation into a scalar function from the parameters as arguments. The only thing is needed – is to enforce the convergence below desired tolerance by finding minimum of that function, which could be made manually, using Parametric Sweep dialog, or, in some cases, automatically by using Optimizer.

Full Magnet 3D Simulation

Once the initial design, that fits the requirements of 2D model, was found, the channels were inserted into 3D model of cyclotron magnet in order to perform the following actions. The first – is to check whether they fit the requirements all along the trajectory. If they failed to fit, then it could be corrected: 1) by going back and perform better initial design, 2) by varying parameters (e.g. thickness) or adding elements along trajectory. After that being done, one could conduct the extraction part of the beam dynamics simulation into full 3D magnetic field map to assess the quality of the channels.

THE RESULTS

Designed Channels' Overview

The initial design procedure was enough to create the following channels, using only 2D-like simulation. They have rather small dimensions and there for weight which makes them easy to place, easy to move, easy to hold. Nevertheless, the channels' aperture is relatively big, which results in good beam channeling and small collision beam losses.

The main idea is to get as close as possible to gradient requirements (Table 1) on the blue line, establishing B_z shift requirements in beam center, see Fig. 3. This resulted in the following channel profile design, enforcing required tolerance of 10% for MC1 and even twice less tolerance of 5% for MC2. MC1 and MC2 are made of steel 1010 and have a mass of 325 g and 525 g respectively.

The maximal error from required gradient in beam aperture zone for MC1 and MC2 is 40% and 23% respectively, which might seem big, but in fact, such deviation only occurs at the beam aperture border and affects very small portion of particles, where us for most of the particles the deviation is less than 15% and 10% respectively.

The magnetic field in MC2 almost comes down to a zero closer to the channel's end, as shown in bottom plot of Fig. 2. It was the reason for us to investigate and to mention here the possibility of the replacement of the last half of MC2 with a channel made of permendur vanadium, which provides better magnetic qualities keeping the same size [2, 3]. We will leave this procedure as additional adjustment option, since the beam dynamics simulation proved designed channels to be sufficient for the extraction.

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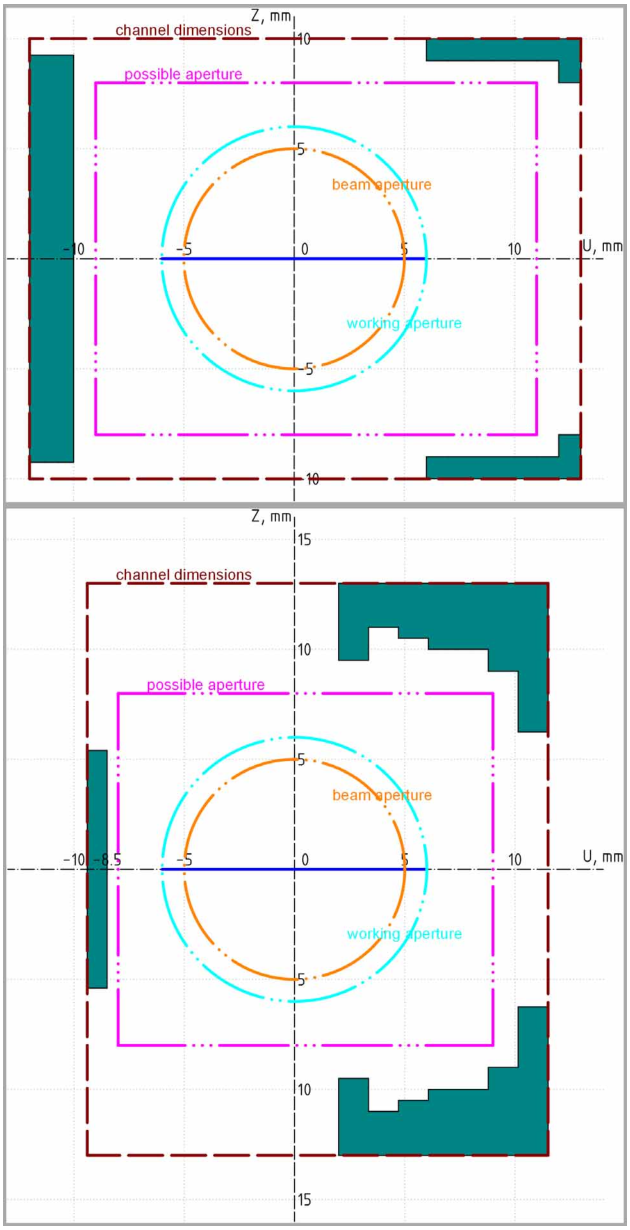

Figure 3: Axial cross section of MC1 (top) and MC2 (bottom), centered on the beam center. Blue line – the result line for 2D simulation.

Extraction Beam Dynamics

The tracing of beam though the extraction system was performed in 3D magnetic field maps which were calculated taking into account the magnetic channels and the compensating channels. The simulated computer model with correctors is shown in Fig. 4. The beam tracing, displayed on this figure, could be seen visually which helps to control the beam passing inside the cyclotron structure. The particle traces of the extracted beam are also presented in Fig. 5.

Beam dynamics provided pretty good results holding the beam within the aperture of 10 mm (Fig. 5). The calculated horizontal emittance at the accelerator's exit is about 8π mm·mrad, whereas the vertical one is about 2π mm·mrad.

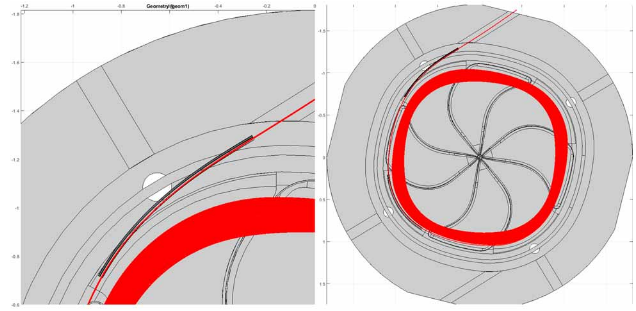

Figure 4: Beam dynamics simulation for the extraction interval conducted in full 3D field, above the cyclotron structure.

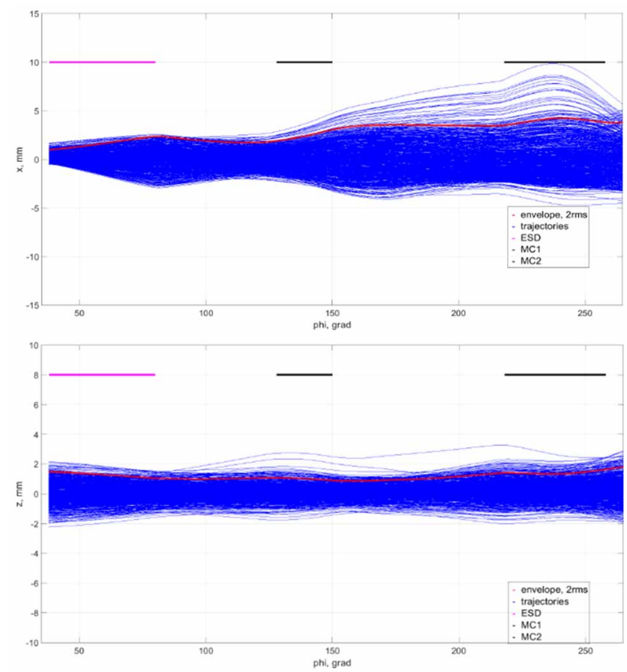

Figure 5: Radial motion (top) and vertical motion (bottom) of the particles through the extraction system.

FINAL WORDS

Created Channels

The MCs' design has been done within rather small tolerances for the requirements, during the initial 2D design stage. As the result, being inserted into full magnet 3D model, the channels immediately produced the magnetic field alteration that managed to perform the desired extraction through beam dynamics simulation. Also, the channels have rather small weight and dimensions which simplifies the mounting and the adjustment. Permendur vanadium option was taking into account in case of unforeseen complications.

CST Studio for Channel Design

The capabilities of CST EM Studio for magnetic channels design were thoroughly investigated. Despite the studio provides only 3D simulation for channels problem, in 3D we've managed to create parametric model for 2D channel axial cross section in external (main) magnetic

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field. The model was also supplied with Post Processing module that evaluates required values after every solver run. Special model geometry allows differentiate the field alteration with an error less than 0.5 Gs, consuming only 2 seconds. As se result, the search for the right channel profile has been done within dozens of minutes.

FUTURE PLANS

Developing Automation Application

The most important outcome for cyclotron design is that, during this job, there were automated several significant design steps. Combined with acquired experience, it is planned to create special application for magnetic channels design. For a start, we are planning to create CST module (macros most probably). When it's completed we will write MATLAB code to orchestrate the action of other modules of other simulation packages (COMSOL [4], Tosca, Maxwell, FEMM, etc...) which will be added in future. This code will join other MATLAB codes (e.g. CORD [5]) to become a part of integrated platform for cyclotron virtual prototyping.

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