DESIGN OF IBA CYCLONE®11 CYCLOTRON MAGNET

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Abstract

The development of a new Cyclone®11 11MeV H^- cyclotron is in progress at IBA. Such machine is designed for the production of radionuclides for nuclear medicine. This cyclotron is based on the existing Cyclone®10 that has been boosted to more than 11 MeV with as minor as possible change to the Cyclone®10 geometry. At first, the magnetic field has been raised by a small reduction of the valley depth. Additionally, the main coil current has been increased. Pole edge milling has been used to obtain the isochronous magnetic field shape. Beam optics in the magnet is excellent. Extraction is ensured by means of stripper foils mounted on carousels located at different azimuths allowing installation up to eight targets and dual beam extraction.

INTRODUCTION

To extend customer choice in the low energy range, IBA is developing the Cyclone®11. It is a fixed energy 11 MeV H^- cyclotron for the production of PET isotopes. The cyclotron magnet is based on the well known Cyclone®10/5 [1,2] with the same yoke dimensions, which is compatible with the IBA self-shielding design [3]. The higher proton energy compared to the 10 MeV machine is beneficial for higher PET isotope production yield.

CYCLOTRON MODEL

The 3D model of the Cyclone®11 cyclotron is based on the Cyclone®10/5 geometry and is shown in figure 1. The movable inserts have been removed and the isochronous magnetic field is obtained by milling one pole edge on each pole. The 90° symmetry has been used for the magnetic field study and 180° symmetry for the extraction study.

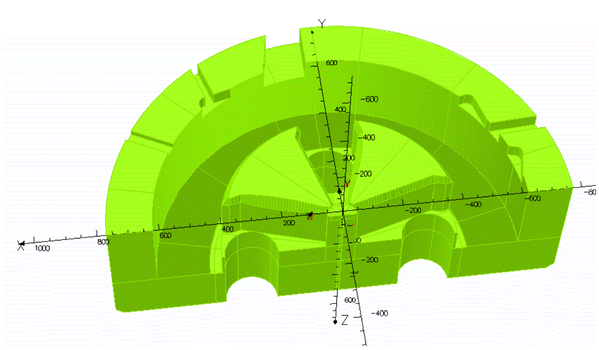

Figure 1: Opera-3D 180° symmetry model of the Cyclone®11 cyclotron.

MAGNETIC FIELD REQUIREMENTS

The magnetic rigidity is proportional to the particle momentum. Therefore, the energy that can be extracted at a given radius in a cyclotron is proportional to the square of the magnetic field. Hence, the relative increase of energy ΔE/E is

$$\Delta E/E = 2\Delta p/p = 2\Delta B/B \qquad (1)$$

According to the Cyclone®10/5 mapping results, the magnetic field should be increased by at least 520 Gauss to be able to extract H^- at 11.0 MeV instead of 10.2 MeV. The magnetic field increase can be provided by a higher main coil current and/or a reduced valley depth. The magnetic field study has been performed using the TOSCA magnetostatic solver of Opera-3D.

Effect of the Main Coil Current

To increase the average magnetic field, the current in the main coil can be increased. The 90° symmetry model without addition of iron in valleys has been simulated for different main coil currents (176 A, 186 A, 196 A). The resulting increase in the magnetic field is shown in figure 2. The average magnetic field gain at the level of the poles is about 160 Gauss per 10 A. The study has also shown that the quality of the iron has very little effect on the field gain.

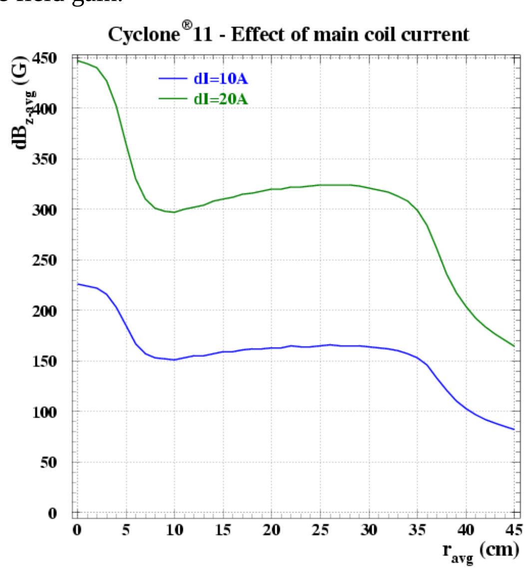

Figure 2: Magnetic field increase as a function of radius for different main coil current increase. The reference map (dI=0 is at IMC=176 A).

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Effect of the Valley Depth

A second solution to raise the average magnetic field is to increase the field in the valleys. For that purpose, the valley depth has to be decreased and the effect on the flutter has to be checked. The 90° symmetry model has been simulated for different valley depth with a main coil current of 186 A. dD=0 mm is the Cyclone®10/5 valley depth, dD=-50 mm corresponds to a valley filled with 50 mm of iron and dD=-100 mm a valley filled with 100 mm of iron. The effect of the valley depth on the magnetic field is shown in figure 3. The average magnetic field gain at the level of the poles is about 180 Gauss with 50 mm of iron and 450 Gauss with 100 mm of iron. The effect on the flutter is less than 5% and do not affect the beam stability.

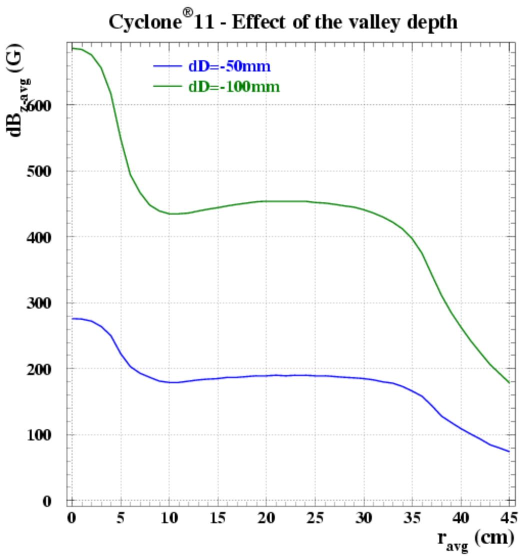

Figure 3: Magnetic field increase as a function of radius for different thicknesses of additional iron.

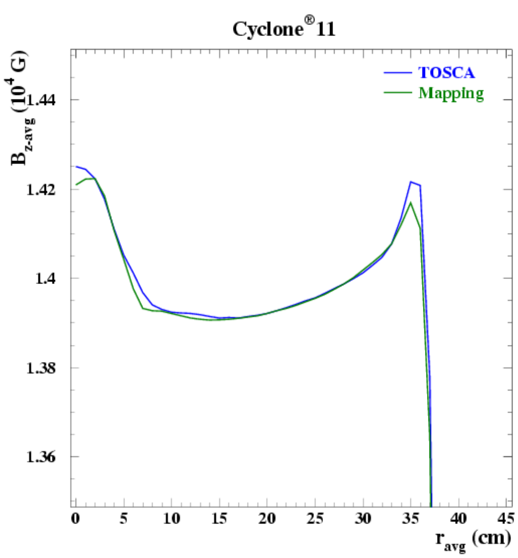

Figure 4: Comparison of the experimental magnetic field profile with the results of the TOSCA analysis.

Adopted Solution

Compared to the Cyclone®10, increasing the main coil current by 15 A and filling the valleys with 100mm of iron should provide an increase in the average magnetic field of about 690 Gauss which roughly correspond to an extracted energy of about 11.3 MeV. Both modifications were applied for the new cyclotron. The magnet has been made and has already been mapped. The TOSCA magnetic field at 185 A with the valley filled with 100 mm of iron is compared to the isochronous experimental map of Cyclone®11 on figure 4. The agreement is very good.

ISOCHRONISM

Isochronism of the cyclotron is obtained by milling one edge per pole. The BH curve used for the TOSCA analysis is directly provided by the iron supplier. It can be seen on figure 5 that the magnetic fields are isochronous with the (second harmonic mode) RF frequency of 42.877 MHz. The vertical and horizontal betatron frequencies are plotted on figure 6.

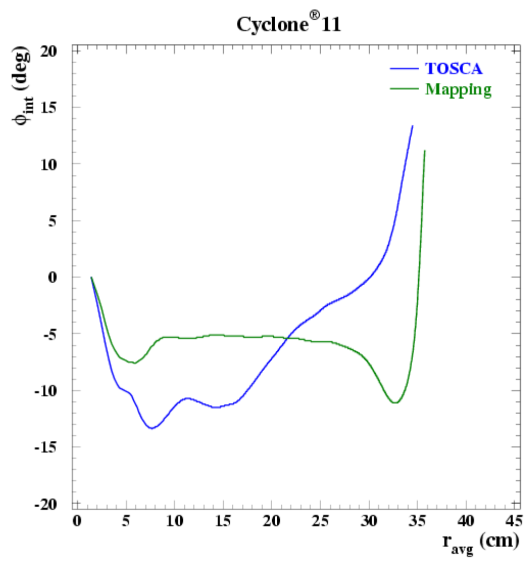

Figure 5: Experimental and simulated integrated phase shifts for the Cyclone®11.

EXTRACTION

Proton extraction is performed by stripper foils mounted on a carrousel (figure 7) with the same design as the Cyclone®18/9 carrousel with a fork length of only 25 mm. The fork length is 5 mm shorter than the one of the Cyclone®10 which allows for extraction of higher energy orbits. Each carrousel can accommodate two stripper foils to reduce the number of cyclotron openings. There are eight carrousels located at eight different azimuths.

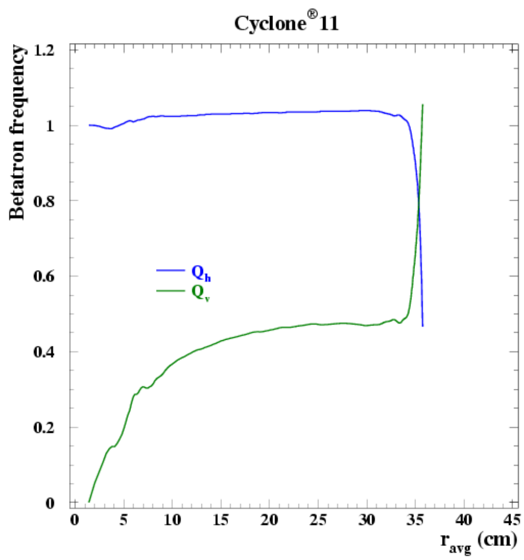

Figure 6: Horizontal and vertical betatron oscillation frequencies as a function of average orbit radius for the experimental map of the Cyclone®11.

The extraction study has been performed on the two first ports, the other being symmetric. As the experimental magnetic field measurement can be performed only up to a radius of 45cm, we extend the experimental map with the TOSCA map for radii from 46cm to 100cm. The particles are tracked in that map for different energies. It has been found that with the Cyclone®11 extraction system, the extracted beam has an energy of 11.5MeV (figure 8). Note that compared to the Cyclone®10/5, the position and direction of the exit ports in the vacuum chamber have been adapted to the new extracted orbits.

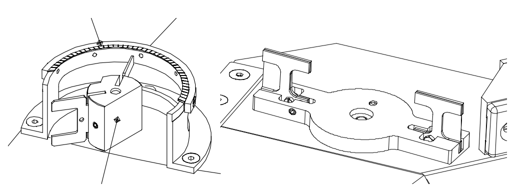

Figure 7: Carrousel for extraction: Cyclone®10/5 design (left); Cyclone®18/9 design used for Cyclone®11 (right).

PRESENT STATUS

The iterative procedure to obtain the isochronous magnetic field in Cyclone®11 was successfully finished in the mechanical workshop of IBA subcontractor. The installation of other subsystems of the cyclotron in the assembly hall of IBA is nearly completed and initial beam tests will follow.

CONCLUSIONS

Calculation results of the Cyclone®11 are in very good agreement with the experimental data. Compared to the Cyclone®10 (with movable inserts removed), increasing the current up to 185 A and filling the valley with 10 cm of iron allows to increase the energy above 11 MeV.

The experimental map of magnetic field shows that we manage to get the Cyclone®11 isochronous and the extracted energy can be expected to be close to 11.5 MeV.

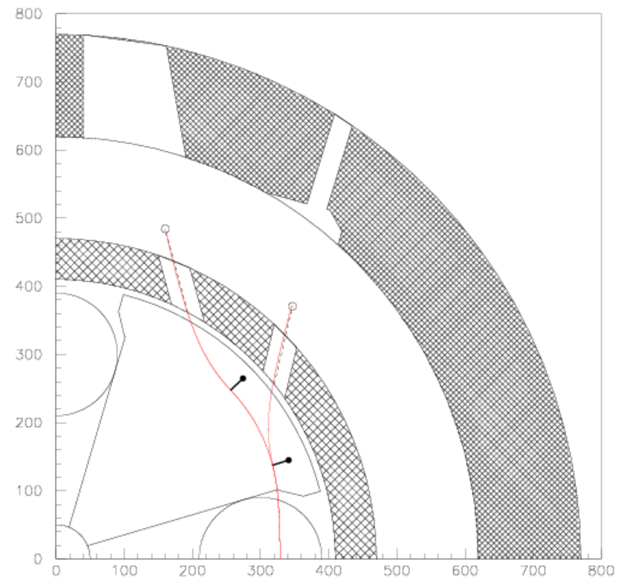

Figure 8: Particle track at the extraction in the experimental map of the Cyclone®11.

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