MAGNET DESIGN OF THE NEW IBA CYCLOTRON FOR PET RADIO-ISOTOPE PRODUCTION

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Abstract

An innovative isochronous cyclotron for PET isotope production has been designed, constructed, tested and industrialized at Ion Beam Applications (IBA) [1]. The design has been optimized for cost-effectiveness, compactness, ease of maintenance and high performance,which are key elements considering its application in the dedicated market. This cyclotron (patent application pending) produces 18 MeV protons and the cyclotron is called the **Cyclone® KIUBE**. Compared to the previous 18 MeV proton and 9 MeV deuteron machine from IBA, the Cyclone®18/9, the gap between the poles has been reduced from 30 mm to 24 mm and the method of pole shimming to obtain an isochronous magnetic field has been reviewed thoroughly. In early 2016, the first prototype Cyclone® KIUBE was successfully commissioned at the IBA factory and the measured proton beam intensity outperformed the Cyclone® 18/9.

MAGNET DESIGN

The magnetic design of the Cyclone® KIUBE was performed with the OPERA-3D code in combination with IBA's in-house beam dynamic codes. One symmetry period of the 4-fold symmetric Cyclone® KIUBE is shown in Fig. 1, where the (lateral) return yoke, the pole, the pole inserts (patent application pending) and sectors are indicated. The Cyclone® KIUBE fits a rectangular cuboid of 1740x1740x860 mm^3. The vertical gap between the pole faces has been reduced by 6 mm in the Cyclone® KIUBE, compared to the Cyclone® 18/9. This minor reduction allows to reduce the total current and power consumption and the overall size and weight of the cyclotron. The pole azimuthal length has been reduced from 55 degrees to 45 degrees. In this way, the valleys become wider and the pumping hole in the valley can be made bigger. It increases the pumping efficiency and improves the vacuum level. As such, beam losses of the H^- ions can be reduced and the transmission efficiency can be increased. The position of the pumping holes is shown in Fig. 2. The vacuum chamber is located between the coil and the outer radius of the pole. The cut corners of the square cyclotron are filled at two opposite locations by the yoke lifting system, whereas the remaining two opposing corners are left free for auxiliary equipment. Two small openings in the lateral return yoke are present for the coil cooling and electrical connections. These holes break the four-fold symmetry of the complete cyclotron, but do not introduce large second harmonic imperfections, as will be shown in Fig. 6. The larger iron volume of the lateral return yoke next to the poles promotes the magnetic flux

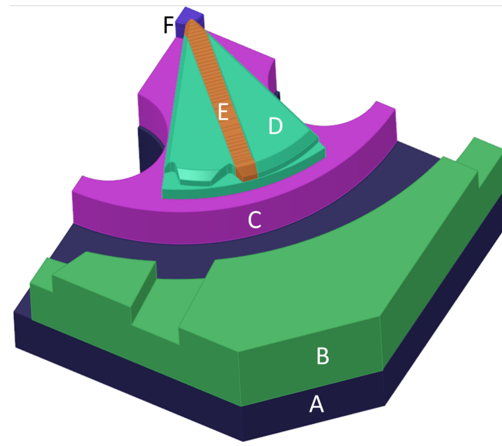

Figure 1: The magnetic circuit, including (A) the return yoke, (B) lateral return yoke, (C) sector, (D) the pole, (E) the pole insert and (F) the central plug.

passage, thereby creating a sufficiently large flutter in the median plane.

A view on the pole is shown in Fig. 3. A "groove" is present in the center of the pole to accomodate the pole insert (see next paragraph). Two stripping extraction systems per pole give the possibility to install 8 targets in the different extraction ports (4) in the lateral return yoke.

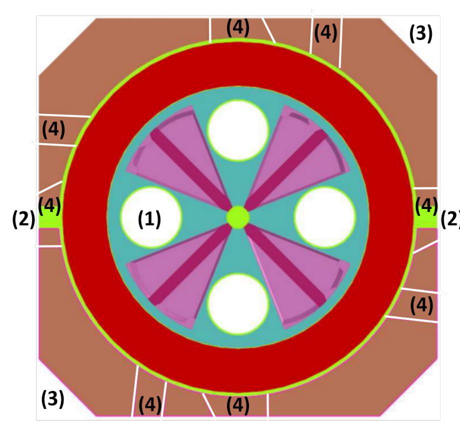

Figure 2: A top view on the Cyclone® KIUBE. 1/ the four pumping holes in the valleys, 2/ the coil electrical and cooling ports, 3/ the yoke lifting system and 4/ the extraction ports.

POLE INSERTS

The pole inserts in the Cyclone® KIUBE are the novel approach to the traditional pole edge milling (used in the Cyclone®18/9) during the magnetic mapping of the

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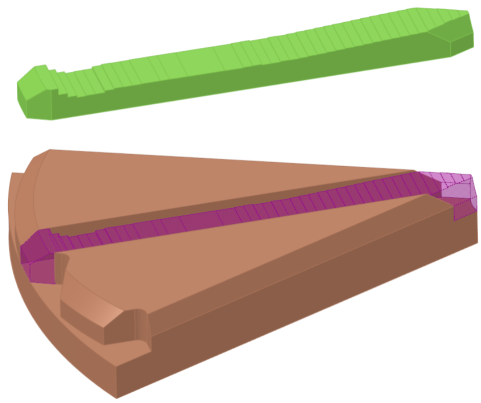

Figure 3: A view on the Cyclone® KIUBE pole. A groove is present in the middle of the pole to accomodate the pole insert. The pole insert is shown as well, where the milling profile on the face closest to the median plane is visible. The azimuthal length of the pole is 45 degrees and gradient corrector cuts on the pole outer border are present to facilitate the extraction from the cyclotron (see [2]).

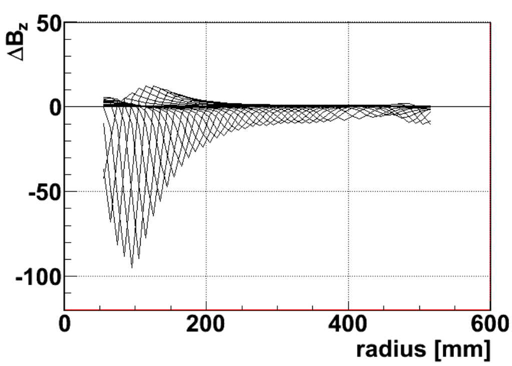

Figure 4: The effect on the average field of iron milling on the pole insert. These curves correspond to 24 identical cuts of 10 mm radial width and 5 mm depth on different radial positions.

cyclotron to obtain an isochronous magnetic field. As can be seen in Fig. 3, a large "groove" is present in the pole, which extents from the center tip of the pole to the outer edge. Inside these grooves, the pole inserts are mounted. This new design and milling method was optimized in collaboration with the machining subcontractor in order to achieve the optimum cost and time effectiveness. At the same time, the new milling method reduces possible harmonic errors due to small machining errors on the four identical pole inserts. The final shape of the pole insert is presented in Fig. 3 without the necessary holes to fix it to the pole. As seen in Fig. 3, each pole has a large, deep groove for the pole insert and two gradient corrector cuts (patent application pending) on the outer pole edge to improve the beam extraction optics [2]. The outer pole edge (patent application pending) is made of two steps to optimize the magnetic flux flow close to the extraction radius. The first step, touching the sector, has its outer edge that follows the sector geometry. The second chamfered step, close to the median plane, has its outer edge similar to the last turn trajectory.

In the prototype, the initial pole insert filled the groove

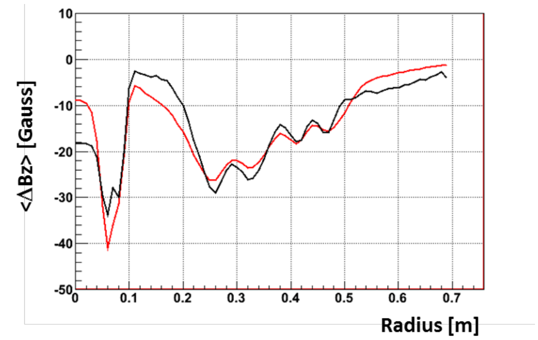

Figure 5: Comparison of a calculated and measured magnetic effect after milling of the pole insert.

up to the pole surface. Detailed OPERA3D calculations were made to assess the magnetic effect of the pole insert milling. The effect of removing a 10 mm long and a 5 mm deep triangular piece of iron was evaluated at several radial positions on the pole insert. The change in average field on each radius was evaluated and a so-called "shimming matrix" was constructed. Typical profiles are shown in Fig. 4. Figure 5 shows a comparison of a simulated milling effect (on the average field) and the measured magnetic effect (the difference of the average magnetic field in a magnetic map before and after the milling). The shimming matrix changes with the cutting depth and has been recomputed for the final profile of the pole insert. For the next cyclotrons, the initial profile of the pole insert is close to the prototype final profile and the shimming matrix corresponding to the final profile is used to reduce milling iterations.

MAPPING RESULTS

Figure 6 compares the first and second harmonics in the Cyclone® KIUBE and the Cyclone® 18/9. The first harmonic is much lower than in the Cyclone® 18/9, most probably due to the more symmetric milling of the pole inserts, compared to the shimming of the pole edges in the Cyclone® 18/9. The high harmonic 2 in the Cyclone® 18/9 is due to the presence of movable pole inserts in the two opposing free valleys for the acceleration of 9 MeV deuterons, which are not present in the Cyclone® KIUBE.

The tune diagram of the Cyclone® KIUBE is shown in Fig. 7. The potentially destructive resonances near $2\nu_z$=1 and ν_r=$2\nu_z$ are rapidly crossed near 4 MeV due to the large energy gain per turn. From tracking calculations in the in-house particle tracking code AOC [3] and from experimental measurements on the Cyclone® KIUBE prototype, no important beam losses have been observed near 4 MeV.

Figure 8 shows the integrated phase slip as a function of the average equilibrium orbit radius in the prototype Cyclone® KIUBE and confirms the quality of the isochronous magnetic field after the final pole insert milling.

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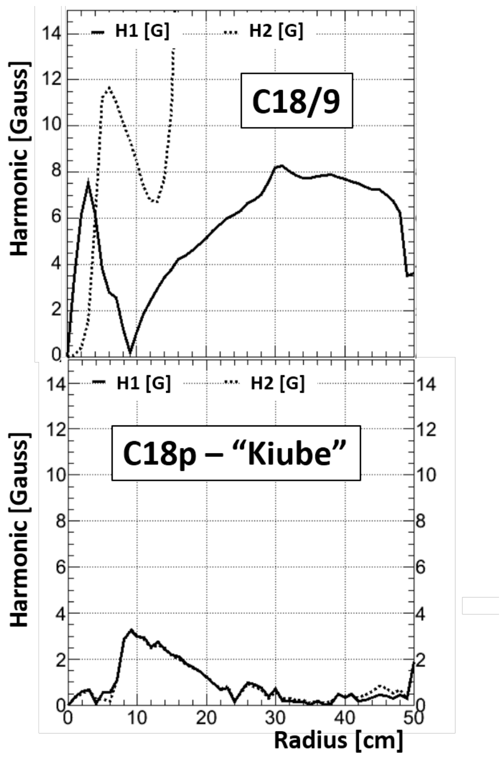

Figure 6: The 1st and 2nd harmonics in the measured magnetic map: (top) in the Cyclone® 18/9 and (bottom) in the Cyclone® KIUBE. The large harmonic 2 in the Cyclone® 18/9 is due to the presence of movable iron inserts in the valleys.

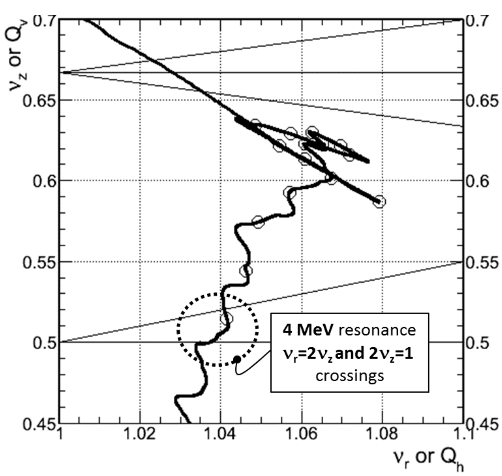

Figure 7: Tune diagram of the Cyclone® KIUBE.

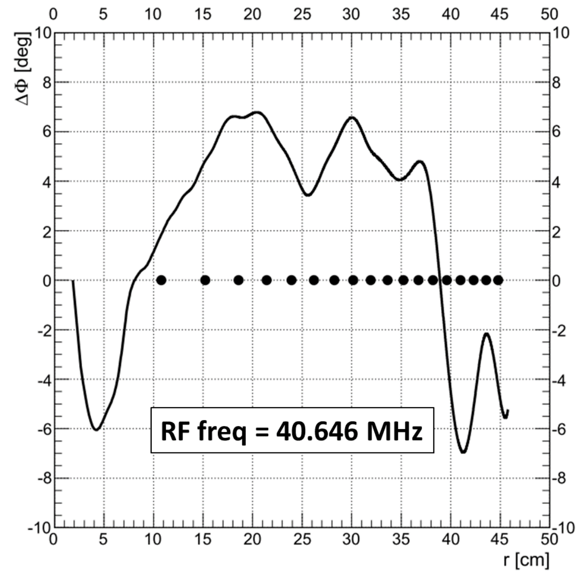

Figure 8: The integrated phase slip as a function of the average equilibrium orbit radius in the prototype Cyclone® KIUBE

CONCLUSION

The prototype of the Cyclone® KIUBE has been successfully commissioned at the IBA factory. The new IBA Cyclone® KIUBE outperforms the classical IBA Cyclone® 18/9 in terms of all important parameters (beam intensity, size, weight, pumping speed, beam transmission, extraction efficiency, power consumption) confirming the correct design of the cyclotron magnet and other cyclotron subsystems.

REFERENCES

[1] B. Nactergal *et al.*, "Development of a New IBA Cyclotron for PET production", presented at Cyclotrons'16, Zurich, Switzerland, Sep. 2016, paper TUD03, this conference.

[2] W. Kleeven *et al.*, "Extraction System Design for the New IBA Cyclotron for PET Radioisotope Production", presented at Cyclotrons'16, Zurich, Switzerland, Sep. 2016, paper TUP03, this conference.

[3] W. Kleeven *et al.*, "AOC, A Beam Dynamics Design Code for Medical and Industrial Accelerators at IBA", in *Proc. IPAC'16*, paper TUPOY002.

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