DESIGN OF IBA CYCLONE® 30XP CYCLOTRON MAGNET

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Abstract

IBA is currently developing an evolution of its famous Cyclone® 30 cyclotron. The Cyclone® 30XP cyclotron will be a multi-particle, multiport cyclotron capable of accelerating alpha particles up to 30 MeV (electrostatic extraction), deuteron (D^-) beams between 7.5 and 15 MeV and proton (H^-) beams between 15 and 30 MeV (stripping extraction). The magnet system has been updated with improved versions of IBA Cyclone 18/9 and Cyclone 70 features.

At first, coil dimensions have been updated in order to raise the free space in the median plane to allow mounting a retractable electrostatic deflector system for the extraction of the alpha particle beam. Gradient corrector pole extensions, have been added to ease the alpha beam extraction. Finally, compensation for relativistic effects between H^- (q/m=1/1) and D^-/alpha (q/m=1/2) beams is made by the use of movable iron inserts located in two valleys, as is done in IBA Cyclone® 18/9 cyclotrons.

These modifications could have an adverse effect on the flutter. In addition, the second harmonic induced by the movable iron inserts drives the machine in the $2.\nu_r=2$ resonance close to the extraction. As a consequence, modifications on the pole sectors and chamfers have been made in order to improve the flutter and eliminate harmful resonance up to extracted energies.

After the presentation of the magnet features, some results on beam extraction are also discussed.

INTRODUCTION

IBA, with more than 20 years of experience in building commercial cyclotrons is developing a new version of its first accelerator: the Cyclone® 30XP.

The Cyclone® 30XP will be able to accelerate beams of H^- ions up to 30 MeV, D^- up to 15 MeV and $^4He^{++}$ (α) to 30 MeV. At first glance, it is an extension of the Cyclone® 30 with Cyclone® 18/9 and Cyclone® 70 magnet features [1,2], but a closer look shows it is a bit more complex.

MAGNET FEATURES

As the α-beam will be extracted by means of an electrostatic deflector, the first modification with respect to classical Cyclone 30 was to reduce the height of the coils in order to allow for deflector and deflector movement mechanisms installation.

Then, movable iron inserts have been installed in two valleys out of four to compensate the differential relativistic mass increase between H^- and D^-/α.

Finally, gradient correcting pole-extension have been added in order to ease the extraction of α beam. Such pole extensions are installed on the IBA Cyclone® 70.

Figure 1 shows a schematic of the preliminary design with the added features.

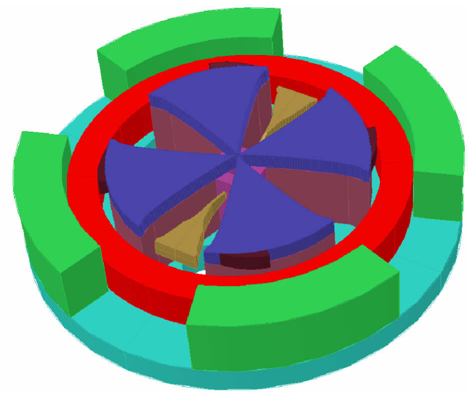

Figure 1: Early structure of the Cyclone® 30XP magnet. One can see the coils (red), poles (in purple), sectors (underneath the poles), movable iron inserts (light brown) and pole extensions (dark purple).

POTENTIALLY HARMFUL RESONANCES

Both the movable iron inserts and the pole extensions have a negative impact on the cyclotron beam optics.

Indeed, the magnetic field change obtained by the movable inserts is as high as 200 Gauss (Figure 2). This implies that the second harmonic of the field changes by the same amount. In addition, the flutter is also reduced when the magnet is in H^- configuration.

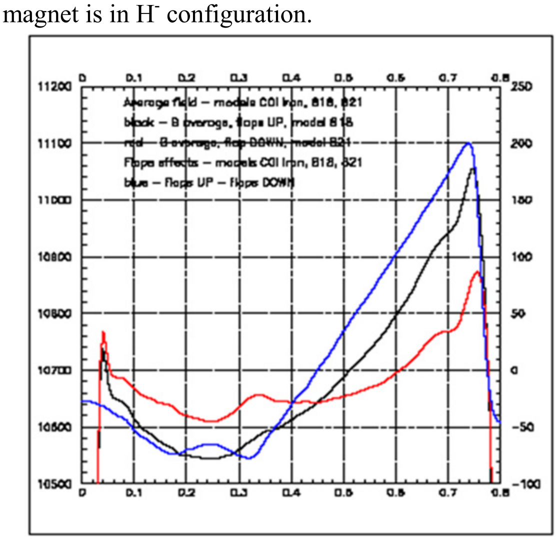

Figure 2: Average field with flaps up (black), down (red) and net effect of the flaps (blue, right scale).

The pole extensions further reduce the flutter by diverting part of the pole's magnetic flux. One can choose to have one, two or four pole extensions, trying to find a compromise between minimal field reduction or minimal impact on first and second harmonics.

Out first Cyclone® 30XP model had two movable iron inserts and four-fold symmetric poles and pole extensions. After isochronisation for the various particles, it has been found that the betatron oscillations of the H^- beam locked on the $2Q_r=2$ resonance. This effect is shown on Figure 3 and 4 and needs to be corrected to avoid high beam losses and high energy spread of the extracted beam.

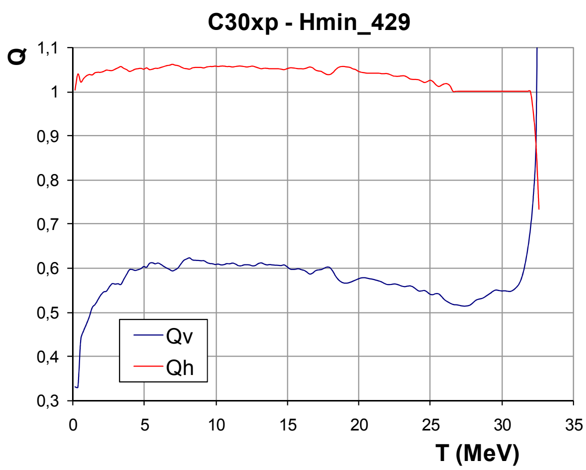

Figure 3: Locking on the 2Qr=2 resonance for H- on early Cyclone 30xp models (flat plateau on the red curve).

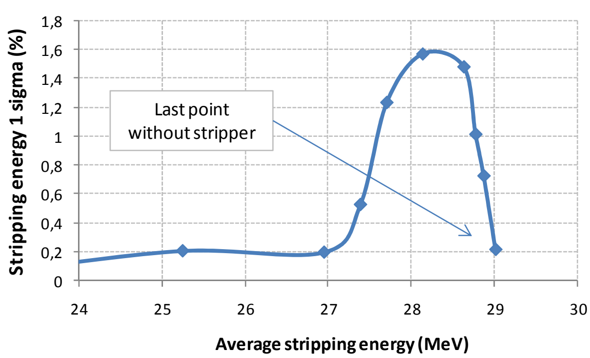

Figure 4: Effect of the 2Qr=2 resonance on the H- beam.

INCREASING THE FLUTTER AND AVOIDING HARMONICS

The flutter has been increased by reducing the azimuthal extension of the poles. This implies an increase in the number of ampere-turns in the Cyclone® 30XP with respect to the classical Cyclone® 30. This increase has been limited by keeping the sectors as they were and chamfering the pole outer radius (Fig. 5). It has also been decided to have only two pole extensions to limit their impact on the flutter.

To avoid resonance problems, the first and second harmonic imperfections from the magnetic field are corrected by an iterative process. This procedure has already been used during the development of IBA's Cyclone® 14 cyclotron [3].

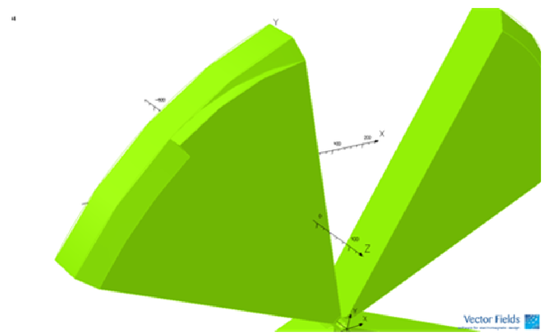

Figure 5: Chamfers on the outer radius of the pole.

Correction of the first harmonic requires the milling of δ_1 and δ_2 corrections, computed as:

$$\delta_1 = \left(\frac{\sin(\alpha_2 - \varphi_1)}{\sin(\alpha_2 - \alpha_1)} \right) \cdot \frac{\pi H_1}{B_h - B_v}$$

$$\delta_2 = \left(\frac{\sin(\varphi_1 - \alpha_1)}{\sin(\alpha_2 - \alpha_1)} \right) \cdot \frac{\pi H_1}{B_h - B_v}$$

Where: H_1 - amplitude of the first harmonic imper-fection error; φ_1 - azimuth or phase angle of the first harmonic imperfection error; α_1 and α_2 - azimuthal positions of two pole edges closest and around the azimuth of the first harmonic φ_1; B_h and B_v - the magnetic field in the hills and in the valleys of the cyclotron.

These equations assume a hard edge approximation of the magnetic field and the corrections should be applied on the two pole edges located around the azimuth of the first harmonic.

For the second harmonic, similar equations are used, but the milling of $\delta_1(\alpha_1)$ and $\delta_2(\alpha_2)$ should be applied on the four pole edges located close and around the phase of the second harmonic and on the opposite pole $\delta_1(\alpha_1 + 180^\circ)$ and $\delta_2(\alpha_2 + 180^\circ)$:

$$\delta_1(\alpha_1) = \delta_1(\alpha_1 + 180^\circ) = \left(\frac{\sin 2(\alpha_2 - \varphi_2)}{\sin 2(\alpha_2 - \alpha_1)} \right) \cdot \frac{\pi}{2} \cdot \frac{H_2}{B_h - B_v}$$

$$\delta_2(\alpha_2) = \delta_2(\alpha_2 + 180^\circ) = \left(\frac{\sin 2(\varphi_2 - \alpha_1)}{\sin 2(\alpha_2 - \alpha_1)} \right) \cdot \frac{\pi}{2} \cdot \frac{H_2}{B_h - B_v}$$

Applying this method at each radius for both the first and second harmonics significantly reduced the level of harmful harmonics. For instance, the second harmonic generated by the flaps can be reduced down to less than 10 Gauss for a given particle species. With such method, resonances can be pushed towards higher radii: energies of 31.2 MeV and 31 MeV are obtained for α and H^- acceleration, respectively, before the resonance appears.

EXTRACTION

Extraction studies for each beam of the Cyclone® 30XP are part of the magnetic design as they can affect the field harmonics and have a significant impact on the machine design.

The position of the stripper mechanisms have been determined by tracking H^- and D^- particles in the isochronous field. Particles are started on the equilibrium orbit. It has been found that the existing Cyclone 30 yoke allowed for the extraction towards the "internal" switching magnet (right part of Figure 6), but that it had to be modified for extraction to an "external" switching magnet in order to allow for vacuum chamber installation.

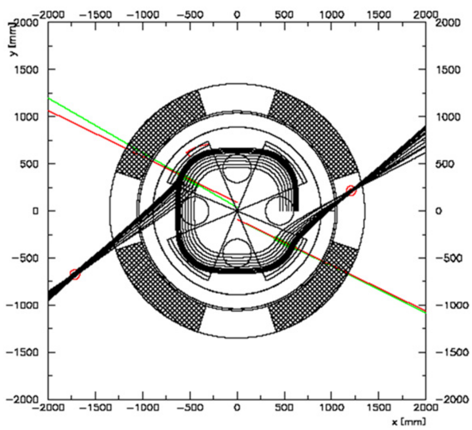

Figure 6: Equilibrium orbits and extracted trajectories for H- and protons respectively.

The position, length and shape of the electrostatic deflector have also been optimized by particle tracking. It has been found that, despite pole extensions, smooth extraction of the α-beam requires strong focusing before exiting the cyclotron yoke. A permanent magnet quadrupole doublet has been designed for this purpose. Figure 7 shows the position of that quadrupole doublet and the extracted α-beam.

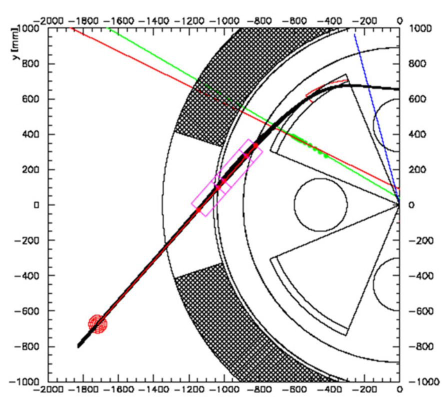

Figure 7: Trajectories for extracted alpha beam.

FINAL DESIGN AND CONCLUSIONS

The modification of the Cyclone 30 towards the Cyclone® 30XP was not as straightforward as was expected but thanks to previous experience with IBA's Cyclone® 30 and 70, important pitfalls have indeed been detected early in the design process. Several modifications have been made to the first design, leading to the geometry pictured below.

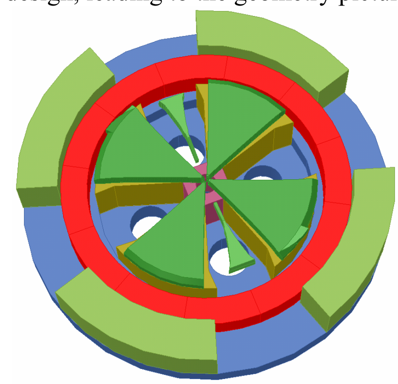

Figure 8: Final Cyclone® 30XP model.

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[1] Y. Jongen et al., "IBA C70 cyclotron development", proc. of the 18th international conference on cyclotrons and their applications, pp 54-56, 2007.

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[3] W. Kleeven et al., "The self-extracting cyclotron", proc. of the 16th international conference on cyclotrons and their applications, pp 69-73, 2001.