EXTRACTION SYSTEM DESIGN FOR THE NEW IBA CYCLOTRON FOR PET RADIOISOTOPE PRODUCTION

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Abstract

At IBA, we have designed, constructed, tested and industrialized an innovative isochronous cyclotron for PET isotope production. The design has been optimized for cost-effectiveness, compactness, ease of maintenance and high performances, with a particular emphasis on its application and market. Multiple target stations can be placed around the vacuum chamber. An innovative extraction method (patent applications pending) has been designed which allows to obtain the same extracted beam sizes and properties on the target window independent of the target number. This is achieved by proper design and shaping of the magnet poles. This magnetic design is discussed together with beam dynamics simulations and beam extraction tests on the first machine.

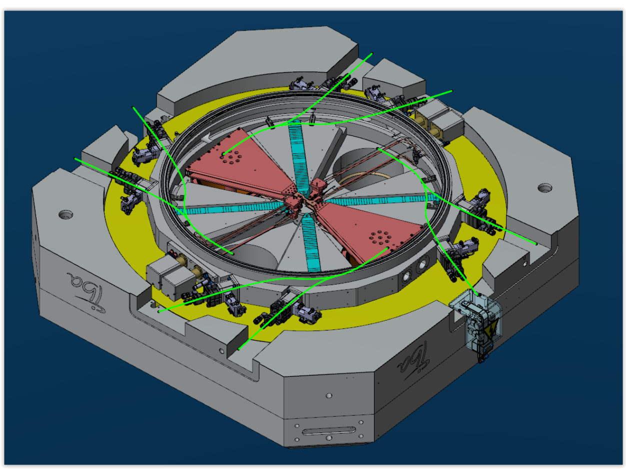

Figure 1: View on the upper half of the CYCLONE® KIUBE. In grey is shown the magnetic iron including the return yoke and the four poles. The pole-inserts (in blue) are used to shim the isochronous field. Further shown is the main coil (yellow), the accelerating structure (red) and the 8 target stations mounted on the vacuum chamber. The extracted orbits are shown in green.

INTRODUCTION

Modern medical radioisotope production cyclotrons often accelerate negatively charged ions such as H^- and/or D^-, because this allows for an easy way of extraction: the beam passes a thin stripper foil which removes the two electrons attached to the ion, resulting in an instantaneous change of sign of the orbit local radius of curvature such that the particles are directed towards the exit of the pole region. The method has several advantages: i) the very simple extraction device, ii) 100% extraction efficiency, iii) the possibility for simultaneous dual beam extraction, iv) the possibility to place several targets around the machine and and v) good beam optics. This technique is also used in the well-known IBA CYCLONE® 18/9 [1]. This cyclotron accelerates H^- to 18 MeV and D^- to 9 MeV. In recent years, the need for D^- has gradually decreased and therefore IBA decided to design the CYCLONE® KIUBE [2,3] as a new PET cyclotron accelerating only H^-. In this new machine we re-visited the extraction design to implement possible improvements. Figure 1 shows a view on the upper half of this new cyclotron.

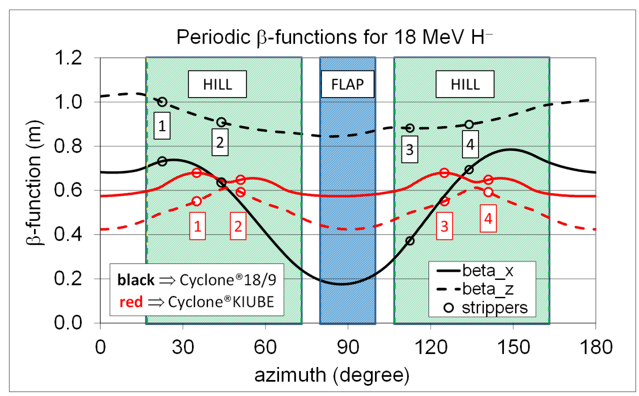

Figure 2: Periodic horizontal (solid) and vertical (dashed) β-functions along the 18 MeV closed orbit. The red curves correspond with the CYCLONE® KIUBE. For comparison, the same curves are given for the CYCLONE® 18/9 [1]

EXTRACTION DESIGN

A maximum of 8 targets can be placed around the cyclotron vacuum chamber for isotope production. For the new extraction design we looked for an optical solution such that the beam sizes on these targets i) are more or less independent of the target position and ii) have a more or less circular shape. In the CYCLONE® 18/9 the switch of the isochronous magnetic field shape from D^- to H^-, is done by two movable iron inserts (the flaps), placed in two opposite valleys. In the H^- mode, these flaps are moved close to the median plane and there introduce a considerable 2nd harmonic magnetic field component. This makes that the extracted beam optics towards the targets is quite different for extraction on the pole upstream or the pole downstream of the flap-valley.

The linear beam optics can be conveniently represented with the beta-function Twiss-parameter. The beam size X

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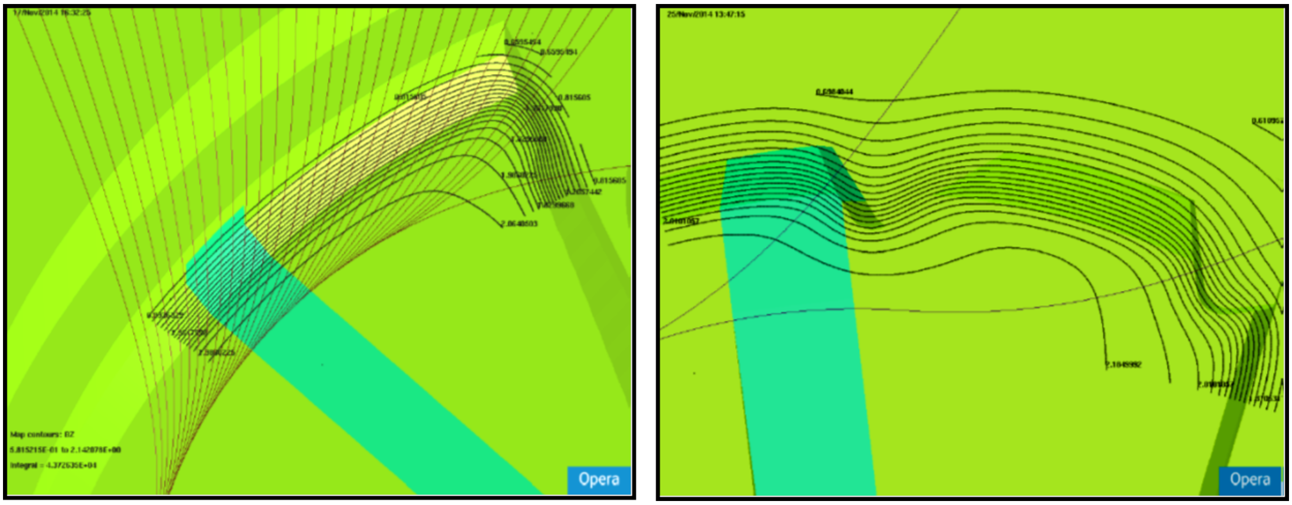

Figure 3: Iso-field lines are shown on top of the OPEAR3D model in the region of the pole radial boundary. Also shown are trajectories of a series of particles extracted at various angular positions of the stripping foil. The left figure shows that there is a rather large angle between the particle direction and the normal vector of the field-lines. This condition leads to a rather large vertical defocusing. The figure on the right shows the modification of the magnetic field pattern due to the iron cuts placed at the pole exit azimuth of the particles. Here the vertical defocusing is much weaker.

(or Z) and the beta-function β_x (or β_z) are related via the beam emittance ϵ_x (or ϵ_z) as $X = \sqrt{\epsilon_x \beta_x}$.

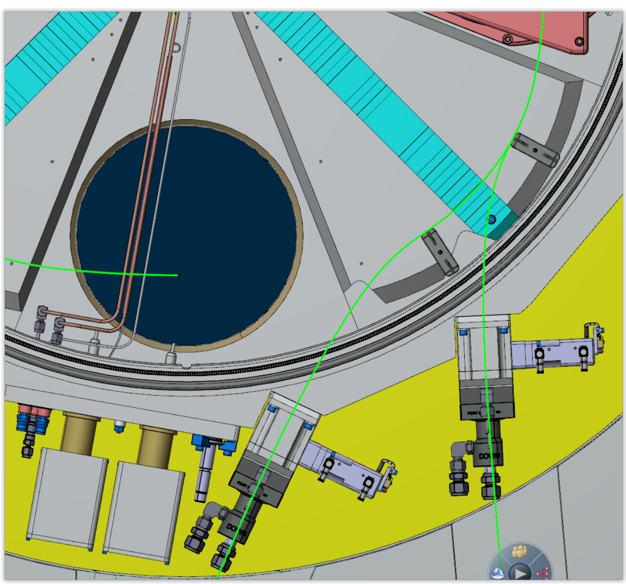

Figure 4: The radial pole contour is (a part of) an off-centred circle which closely follows the shape of the closed orbits near extraction. The pole cuts are shown and also the stripper-carousels and the extracted orbits (in green) hitting the isotope production targets.

The periodic β-function is calculated along the closed orbit and has the same n-fold symmetry. Figure 2 shows the horizontal and vertical periodic β-functions on the 18 MeV closed orbit in both the CYCLONE® 18/9 (symmetry n=2) and the CYCLONE® KIUBE (symmetry n=4), as calculated with the IBA in-house tracking code AOC [4]. Also the position of the stripper foils is shown. For the CYCLONE® 18/9 the horizontal β-function shows a strong variation (with about a factor 4) along the azimuth making that the optical conditions at the four stripping foil positions are substantially different. This results in substantial different beam sizes on the targets. For the CYCLONE® KIUBE this variation is much weaker. Furthermore (due to the 4-fold symmetry) the conditions from one pole to the next remain the same. It is also seen that the vertical focusing in the CYCLONE® KIUBE is substantially stronger.

In the CYCLONE® KIUBE the radial contour of the pole is a circle which is off-centred from the cyclotron geometrical centre. This circular contour very closely follows the shape of the 18 MeV equilibrium orbit. This can be seen more clearly in Figure 4. In this way, the distances from the stripper to the radial pole edge and from the stripper to the target become almost independent of the angular position of the stripper and thus also guarantees close to equal beam-spots on the target.

When the particles cross the radial pole edge, they may experience a strong vertical defocusing due to the rather large angle between the beam direction and the normal vector on the pole-contour. This then results in a largely asymmetric beam spot on the target window and thus corresponding larger losses on the circular target collimator. In order to reduce this asymmetry, a local cut has been made in the iron of the pole at the crossing angle with the beam. This can be seen in Figure 4. The modification of the iso-magnetic field lines is illustrated in Figure 3. It is seen that the extracted orbits are more perpendicular to the iso-field lines.

OPTIMIZATION AND SIMULATIONS

The geometry of the pole-cuts have been optimized in Opera3D and by particle tracking with AOC. Figure 5 shows the horizontal and vertical beta-functions along the path of

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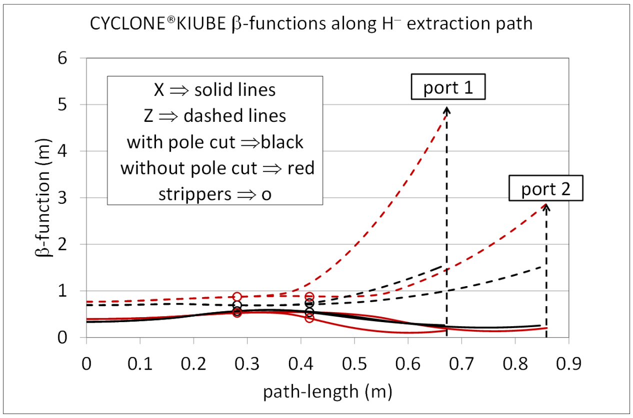

Figure 5: Horizontal (solid) and vertical (dashed) β-functions along the path of the extracted orbits. A comparison is made to show the effect of the pole cuts. Stripper positions are also shown.

the extracted orbits from the middle of the upstream valley up to the target window. Results are shown for both targets. The final pole-cut configuration is compared with a configuration without pole cut. The effect of the pole cut is clearly seen by the substantial decrease of β_z on the target window for both extraction ports.

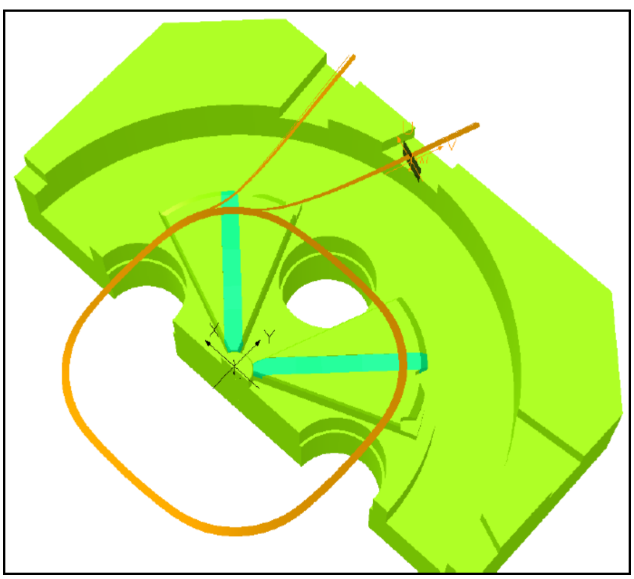

Figure 6: Trajectories are numerically integrated with the IBA in-house tracking code AOC [4] and imported into the finite element model of the CYCLONE®KIUBE magnet as developed in OPERA3D [5]. Two stripper foils placed on one pole extract the beam towards the corresponding targets. The beam spot and phase space is analysed on a patch, placed at the target entrance window.

In order to validate these results also in the non-linear condition, we tracked in AOC a beam of 1000 particles with an RF phase width of 40° and initial transverse emittances of 50 π mm-mrad from 1 MeV in the cyclotron center through the stripper foils and up to the target windows. Figure 6 shows an import of the last few turns of the computed beam into the Opera model. Then an intersecting patch is placed at the target window in order to see the beam cross-section. The result is shown in Figure 7. Here the configuration with and without pole-cuts are compared for both exit ports. It confirms that indeed a substantially better (more symmetric) beam spot is obtained on the targets.

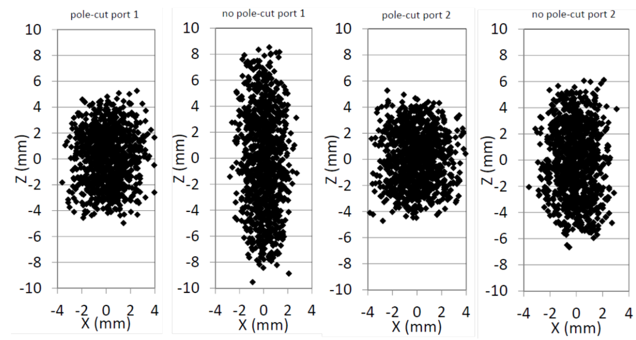

Figure 7: The beam spot on the target windows as simulated with AOC. It is seen that a more symmetric (round) shape is obtained due to the pole cuts and also that both extraction ports are almost of same shape.

CONCLUSION

The prototype of the CYCLONE®KIUBE has been successfully commissioned at the IBA-sites in Louvain-La-Neuve and is currently being installed on the customer site. The performance of the machine well exceeds the CYCLONE®18/9 in terms of beam transmission between the ion source and the stripper foils, the extraction efficiency between the strippers and the targets and also in terms of the 18-F production yields. The extraction efficiency (defined as the ratio between target current and target + collimator current) is for all 8 target positions, between 90 and 95% for a collimator diameter of 9 mm.

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