ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-WEA003

DEVELOPMENT OF THE CYCLONE®KEY: HOW INTEROPERABILITY LEADS TO COMPACTNESS*

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Abstract

In 2020, IBA has started the design, construction, tests and industrialization of a new proton cyclotron for the low energy range, the Cyclone® KEY, for PET isotope production (^{18}F, ^{13}N, ^{11}C) for neurology, cardiology or oncology imaging. It is a compact and fully automated isochronous cyclotron accelerating H$^-$ up to 9,2 MeV. Based on the successful design history and return of experience of the Cyclone® KIUBE, the Cyclone® KEY design has been focused on compactness (self-shielding enabled), cost effectiveness and ease of installation, operation, and maintenance. The innovative design consists in the interoperability of the different subsystems: the magnet, the RF system, the vacuum system, the ion source, the stripping extraction, and target changer (with up to three targets). First beam tests results will also be presented.

THE CYCLONE®KEY

The Cyclone® KEY (Fig. 1) is the little brother of the Cyclone® KIUBE [1, 2]. Aiming at the low energy radioisotope production market, it has been designed to be simple to install and operate. Its compact design enables self-shielding operation with the possibility of low activation concrete [3]. All the different subsystems of the cyclotron have been nested in each other to optimize the compactness of the machine. The main parameters of the cyclotron are summarized in Table 1.

Table 1: Cyclone® KEY Design Parameters

Parameter	Value
Accelerated ions	H$^-$
Ion source	Internal PIG
Number of sectors	4
RF frequency	41MHz
RF mode	2
Dee angle	40°
Dee voltage	32kV
Extraction	Stripper (1+5 spares)
Extracted energy	9.2MeV
Cyclotron footprint (L×W×H)	1.5m×1.4m×1.35m

Figure 1: The Cyclone® KEY.

Magnet Design

The magnet inherited the vertical median plane of the Cyclone® 3d [4], which avoids the cost of a yoke lifting system. The magnetic structure, see Fig. 2, takes benefit from the successful design of the Cyclone® KIUBE [2]:

- Vertical gap between pole is 24mm to optimize the coil power consumption.
- The square shape to optimize the presence of iron only where it is needed, i.e. behind the poles.
- Symmetrical yoke penetrations for RF coupler (left), RF tuner and coil connections (right), ion source (bottom) and target (top).
- Pole inserts, in the centre of the pole, milled during magnetic mapping to obtain the isochronous magnetic field.
- The vacuum chamber sits on the sector behind the poles.

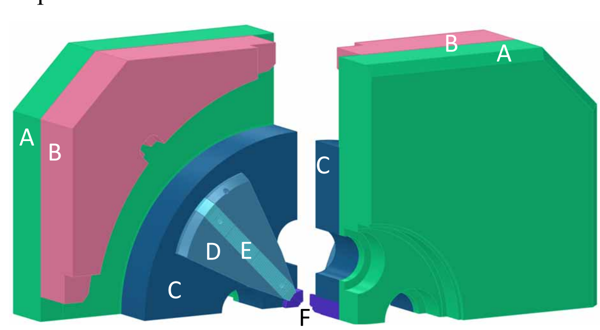

Figure 2: Magnetic circuit, including (A) the return yoke, (B) lateral return yoke, (C) sector, (D) the pole, (E) the pole insert and (F) the central plug.

* Work supported by Pole Mecatech/Biowin/SPW RW - convention 8150: CardiAmmonia.
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Each half of the magnet is milled from a single iron plate which, thanks to precision milling, enables a very low level of harmonic imperfection and better vacuum performances. The valleys are drilled for the vacuum and the RF system at the same time. All magnetic field optimization were computed in Simulia OPERA [5].

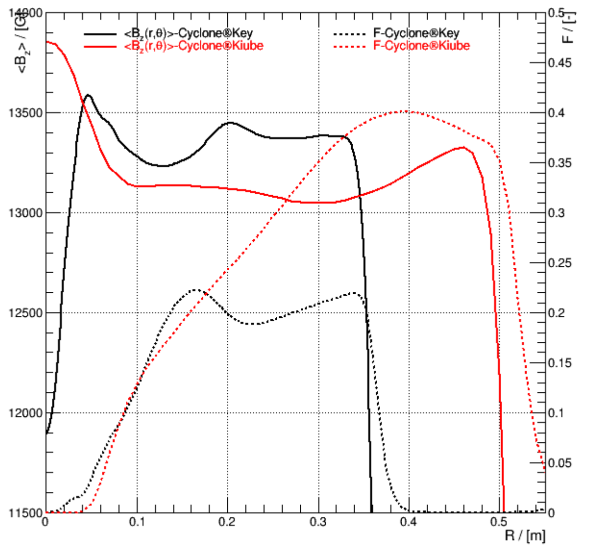

Figure 3: Average magnetic field and flutter in the Cyclone® KEY and in the Cyclone® KIUBE.

Ion Source and Central Region

The Cyclone® KEY uses the powerful PIG internal ion source of the Cyclone® KIUBE. The vertical gap between the central plug was then constraint to the ion source height. As shown by Fig. 3, the average magnetic field in the centre is quite small compared to the Cyclone® KIUBE. This is mainly due to the smaller gap in the valley which prevents the flux from going into the central plug. To still provide sufficient magnetic field in the centre for the particle to stay isochronous, two iron extensions have been added on the central plug (Fig. 4), but sufficiently far from the ion source to avoid any plasma column deformation. The dee tip geometry has been optimized by beam tracking in AOC [6] to provide good orbit centring, phase acceptance and electric focusing.

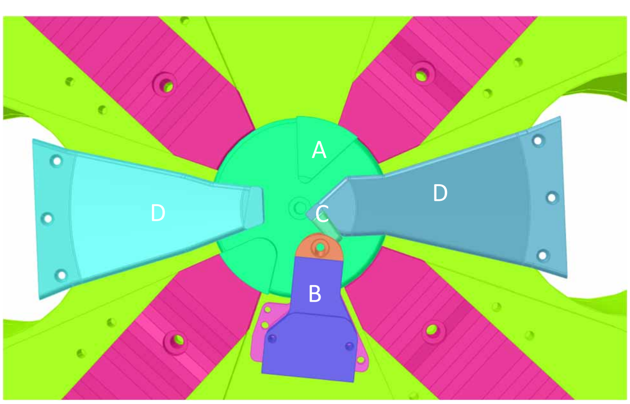

Figure 4: Central region: (A) central plug with iron extensions, (B) Ion source, (C) puller and (D) dee tips.

RF System

The RF system has a perfect cyclotron median plane symmetry and was modelled in Simulia CST studio Suite (Fig. 5) [7]. Such a configuration ensures a better stability in the operation of the cyclotron. Indeed, no RF current is flowing in the iron poles, which are more stable in temperature. No liners are therefore needed on the pole. No voltage occurs neither between the upper and the lower pole, improving the stripper reliability. The geometry and penetration in the iron were optimized for the cavity to resonate at 41 MHz with an effective voltage in the accelerating gap of 32 kV.

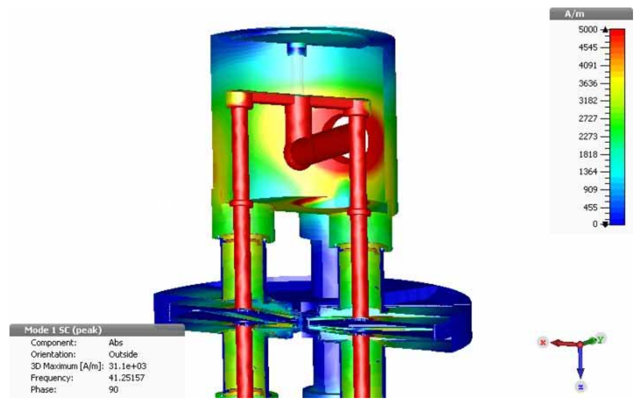

Figure 5: Surface current distribution in the RF cavity.

Vacuum System

Since the beginning of the project, the constraint was to combine the RF system with the vacuum box. The turbomolecular vacuum pump (Pfeiffer HiPace® 2300) is directly connected to the RF cavity which also serves as vacuum chamber that interconnects the four holes in the valley allowing to pump inside the cyclotron. Such configuration also allows for the connection of one or two pumps, depending on the customer's beam requirements. The vacuum system has been modelled in 3D using Molflow+ (Fig. 6) [8]: H_2 gas was emitted from the slit of the ion source. The hole's dimensions in the valleys were optimized for vacuum conductance, RF power and magnetic field. Pressures measured in the model and during beam test were in good agreement.

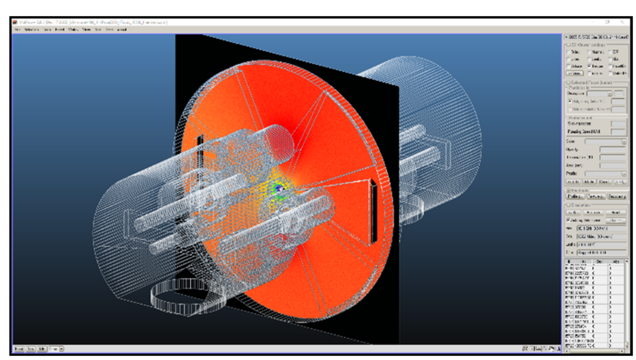

Figure 6: Vacuum model in Molflow+.

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Extraction System and Target Changer

Stripping extraction is the method of choice for such cyclotron. Given the reduced size of the machine, a single exit is only possible, but the return yoke penetrations have been made such that there is sufficient space for a target changer with up to three different targets. A stripper carousel with up to six strippers also allows for improved redundancy and reduced number of cyclotron openings. A rotating pop-up probe and beam collimators (left and right before vacuum chamber) measurements are available as diagnostic tools (Fig. 7). All the mechanical design could fit into the coil gap to limit the impact on the magnet and the self-shielding dimensions. Tracking of the ion beam from the ion source up to the target was performed with AOC [6]. The 1σ beam size at the target level is expected to be around $\sigma_x = 2.1$ mm and $\sigma_y = 1.7$ mm in the target, with an energy of 9.2±0.15 MeV.

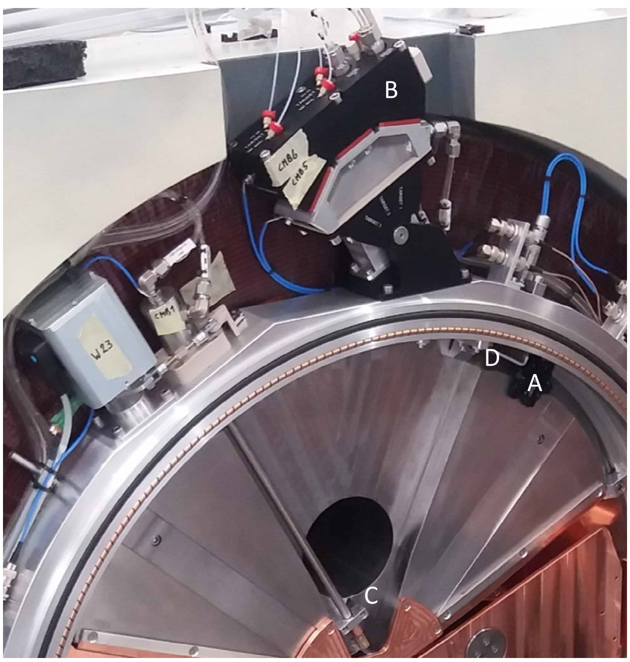

Figure 7: Extraction system and diagnostics: (A) Stripper carousel, (B) target changer, (C) pop-up probe and (D) left/right collimators through the vacuum chamber.

TEST RESULTS

The first machine was completely produced, mapped and first beam test campaign was conducted. Mapping results prove that the harmonic content is very low (<5Gs) and perfectly isochronous (only a few degrees of integrated phase slip). Beam tests with H^+ instead of H^- also confirmed the good isochronism of the machine.

High intensity beam tests with a two turbo molecular pumps configuration demonstrated a constant current of 100 µA on the stripper for 2 hours. The vacuum pressure was also excellent (base: 5.3E-7 mbar, source ON: 1.2E-5 mbar). Beam transmission between pop-up probe and stripper varies between 60-67% depending on the source gas quantity and source current (but still 100 µA on stripper).

CONCLUSION

Following the success of the Cyclone® KIUBE, we have designed, developed, produced, and tested a new powerful cyclotron for the low energy range, the Cyclone® KEY. All the subsystems' imbrications allow for a compact, powerful, and simple operation. The detailed simulation of the different subsystems allows us to have a well born machine. First beam tests have shown promising results and we are waiting for the radioisotope production test at full beam current at customer's site to prove the radioisotope production performances of the machine.

ACKNOWLEDGEMENTS

This work was supported by the Pole MecaTech and Biowin of the SPW RW - convention 8150: CardiAmmonia.

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