ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB188

InnovaTron: AN INNOVATIVE INDUSTRIAL HIGH-INTENSITY CYCLOTRON FOR PRODUCTION OF ^{99m}Tc AND OTHER FRONTIER MEDICAL RADIOISOTOPES*

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Abstract

^{99m}Tc is the most used radioisotope in nuclear medicine. It is almost exclusively produced with a few ageing research reactors worldwide. In response to growing concerns about ^{99m}Tc availability and its increasing demand, alternative production routes are being explored. The EU-funded InnovaTron project aims at designing an innovative compact high-intensity self-extracting cyclotron able to deliver proton beams with currents up to 5 mA or more for the direct production of ^{99m}Tc. It could be also used for production of high quantities of other frontier medical radioisotopes. The proton beams exit without using an electrostatic deflector to overcome its current limitations. A prototype cyclotron was built by IBA in 2001. Currents up to 2 mA were extracted from it. However, at higher intensities, the extraction efficiency was not higher than 70-75% and the extracted emittance was rather large. The InnovaTron project will implement new technological solutions in the self-extracting cyclotron to be used for large-scale industrial applications. An overview on the InnovaTron project is here presented together with the first simulation results.

INTRODUCTION

The proof-of-principle of self-extraction was demonstrated by IBA in 2001 by extracting proton currents close to 2 mA from the prototype [1]. Although promising results were obtained, there is still room for improvement. An EU-funded research project, named InnovaTron, is currently ongoing at IBA aimed at improving the concept of self-extraction in low and medium energy cyclotrons. The main goals of the project are to achieve: i) high proton currents up to 5 mA or more, ii) high extraction efficiency (>95%), iii) reasonable quality of the extracted beam. The improved self-extracting cyclotron could find application for the direct production of ^{99m}Tc by means of the nuclear reaction $p + {}^{100}Mo \rightarrow {}^{99m}Tc + 2n$. ^{99m}Tc is used in almost 80% of all diagnostic nuclear medicine procedures worldwide every year [2]. ^{99m}Tc is the decay product of ^{99}Mo. Its supply is regularly at risk since the production of the radioisotope relies on a few ageing research reactors worldwide that produce ^{99}Mo by neutron irradiation of enriched ^{235}U targets [3]. Direct production by cyclotrons would allow a more secure ^{99m}Tc supply and the production would take place in the near environment of hospitals. Cyclotrons are currently used for radioisotope production. However, with the current technology, a dense network of cyclotrons worldwide would be needed to satisfy the global ^{99m}Tc demand, due to small yield of the direct production method compared to fission reactor route. A high-intensity cyclotron technology is needed for a large-scale production of ^{99m}Tc. The high-intensity self-extracting cyclotron is a promising tool for this purpose. Moreover, it could be also used for production of higher quantities of conventional PET and new emerging radioisotopes.

MAIN FEATURES OF THE PROTOTYPE

In the self-extracting cyclotron, proton beams are extracted without any active device. The extraction takes place thanks to a special shaping of the magnetic field in the extraction region and an enhanced turn separation at extraction [4]. The cyclotron has unconventional features with respect to the commercial machines used for radioisotope production: i) the pole gap has a quasi-elliptical shape, decreasing towards larger radii. This allows to create the isochronous field region very close to the radial pole edge; ii) the pole on which the beam is extracted is longer than the other three and a groove is machined in it. The groove is properly shaped in order to act as a "magnetic septum" and to provide optics for the extracted beam; iii) harmonic coils with banana-like shape are placed in the extraction region to create a turn separation at the groove entrance.

A permanent magnet gradient corrector is placed at the groove exit for radial focusing of the extracted beam. A beam separator is placed at the long pole exit to intercept the small fractions of the beam which are not properly extracted. Figure 1 shows the long pole with the groove, the gradient corrector and the beam stop in the prototype.

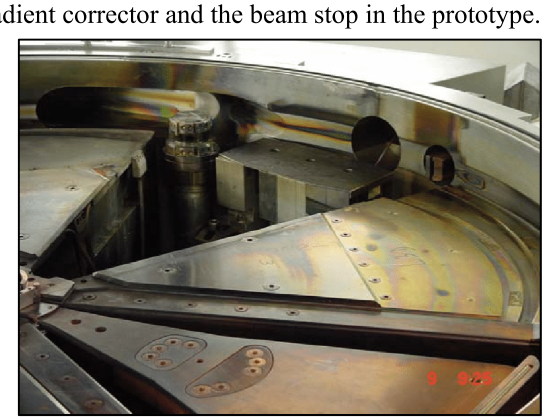

Figure 1: The groove in the long pole, the gradient corrector and the beam separator in the prototype.

* Work supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 886190.
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INNOVATRON PROJECT

Several improvements of the prototype design are foreseen in the InnovaTron project: i) the cyclotron has fully 2-fold symmetry and two internal PIG sources. This allows the acceleration of two beams simultaneously and their extraction from two opposite exit ports. In this way it is possible to increase the radioisotope production yield by irradiating two targets at the same time. Alternatively, the second ion source can be used as a backup by increasing the cyclotron reliability; ii) the radially varying quasi-elliptical pole gap is constant along off-centered circles that approximate the equilibrium orbits. This allows to have a steeper transition from the internal stable orbit towards the non-stable extracted orbit with a consequent increase of the extraction efficiency; ii) the groove in the longer pole is replaced by a plateau (step-like shape) in order to improve the optics for the extracted beam and therefore to enhance the beam quality; iii) the required turn separation at the extraction is created by an off-centring of the ion sources and no longer by harmonic coils; iv) beam collimation is performed in the cyclotron centre to lower undesired beam losses on the beam separators. The main cyclotron design parameters are present in Table 1.

Table 1: Cyclotron Main Design Parameters

Cyclotron Type	Compact Isochronous
Particle	Proton
Injection	2 internal PIG sources
Extraction radius/Energy	52 cm; 14 MeV
Rotational symmetry	2-fold (quasi 4)
B_{ave} and B_{max}	1.15 T; 1.9 T
Quasi-elliptical gap	16 mm < g < 40 mm
Minimum gap at extr.	18 mm
Radius of short/long pole	54 cm; 57 cm
Number of dees/angle	2; 36°
RF frequency; mode	69.1 MHz; h = 4
Dee-voltage	55 kV

SIMULATION STRATEGIES

The approach used to reach the overall goal of the project consists in an iterative process of optimization of the cyclotron subsystems and of the full integrated cyclotron design, using Finite Element (FE) modelling tools, such as OPERA [5], as well as precise 3D beam tracking in the simulated cyclotron electric and magnetic fields. The 3D beam dynamics studies are performing with AOC, the advanced code developed at IBA [6]. Specific tasks mutually connected are currently ongoing: i) 3D FE modelling and optimization of the magnet, gradient corrector and central region; ii) development of the 3D beam tracking model; iii) study of turn separation at extraction. Parametrized tools to generate FE models of the cyclotron components have been developed as well as high-level script for automated optimization of cyclotron settings by 3D beam tracking from injection up to extraction, aiming for the highest possible extraction efficiency.

MAGNET FEATURES

Figure 2 (a) shows the 3D FE design of the cyclotron iron together with the gradient corrector and beam separator. The 3D FE design of the long pole is present in Fig. 2 (b). The plateau in the long pole creates a sharp dip of the magnetic field in the extraction path of about 0.3 T (see Fig. 2 (c)). Particles arriving at the entrance of the plateau experience a lower magnetic field. Consequently, the curvature radius of the orbits increases, and the particles are directed out of the accelerating area. After the sharp dip, the field does not rise again close to the initial value as in the prototype. This lowers the magnetic sextupole component in the extraction path with consequent improvement of the extracted beam quality. As it is shown in Fig. 2 (b), local cut in the long sector (A) and pole (B) are optimized to reduce second harmonic field errors in the acceleration area.

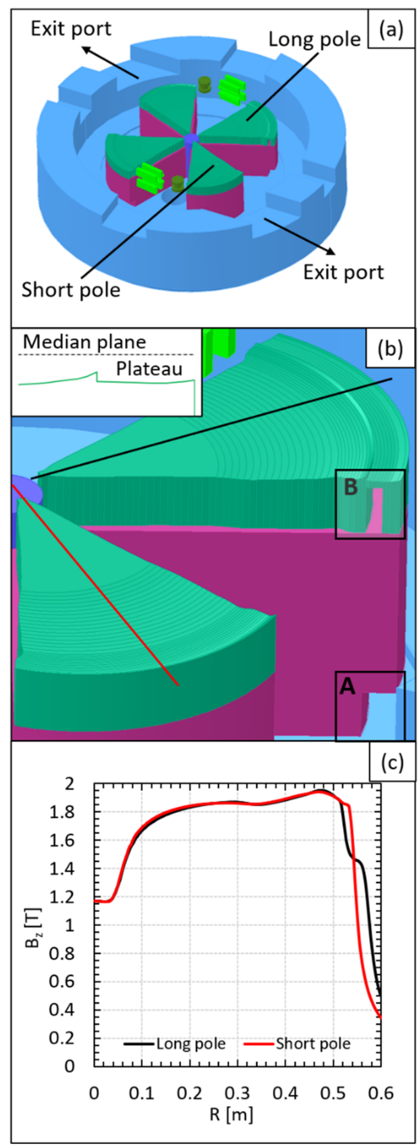

Figure 2: (a) 3D FE model of the cyclotron iron; (b) 3D design of the long pole; (c) Magnetic field along a line that bisects the long and short poles, as shown in (b).

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Figure 3 shows a schematic vertical cross section of the gradient corrector and the shape of the produced field. The gradient corrector is composed of four blocks of permanent magnets (Sm2Co17) with the indicated polarity in the figure. At inner radii, two small blocks are placed to reduce the perturbing magnetic field in the acceleration area.

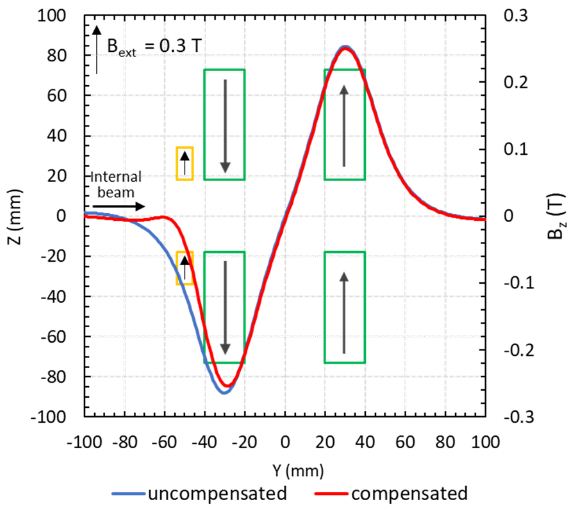

Figure 3: Schematic cross section of the gradient corrector. The shape of the produced magnetic field is also showed together with the two small compensating blocks.

CENTRAL REGION DESIGN AND EXTRACTION EFFICIENCY

A large turn separation at the entrance of the extraction plateau is needed to maximize the extraction efficiency.

Several methods are currently under study to achieve this goal: i) acceleration of a well-centered beam and use of first harmonic coils at extraction; ii) acceleration of a well-centered beam and use of first harmonic coils close to the cyclotron centre; iii) off-centering of the ion sources (first harmonics coils not used). The last method is the most challenging but at the same time the most attractive because first harmonic coils cannot be used for dual beam extraction. In all the cases under study the extraction efficiency strongly depends on the central region design.

Centered Ion Sources and Harmonic Coils

A well-centered beam is accelerated up to extraction with small orbit centering errors (≤ 1 mm) in a large RF-phase acceptance. Figure 4 (a) shows the simulated well-centered beam accelerated in the central region. Turn separation at extraction is obtained by harmonic coils that add a first harmonic component to the main field and create a coherent beam oscillation at the plateau entrance. The shape of the harmonic coils coincides with the equilibrium orbit profile in the hill. Due to the slightly different profile of the equilibrium orbit in the long and short pole, two different couples of harmonic coils are used. Figure 5 shows one of the harmonic coils used in the prototype.

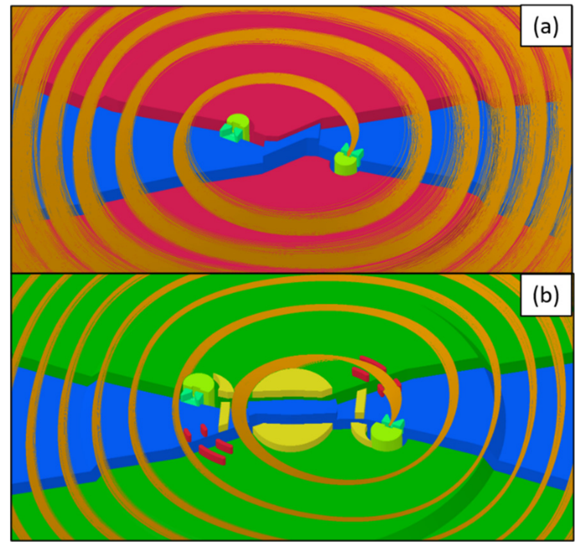

Figure 4: (a) A simulated well-centered beam in the 3D cyclotron central region model; (b) A simulated beam with a large orbit centering error in the 3D cyclotron central region model with the off-centered ion sources.

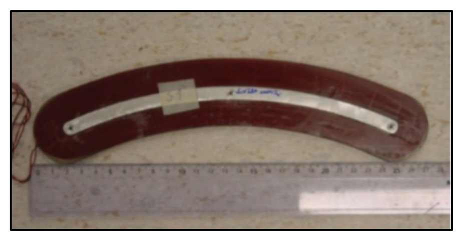

Figure 5: Harmonic coil in the prototype.

Off-centered Ion Sources

A coherent horizontal betatron beam oscillation is created in the cyclotron centre and it propagates up to extraction. The most important optimization parameters are the position (r, θ) of the ion sources and the angle of the first gap. The orbit centering error of the beam centroid is quite large (≈ 15 mm). As shown in Fig. 4 (b), the beam in the first turn passes between the ion sources. Collimators in the central region remove parts of the beam that would be lost on the beam separators at the extraction. In the simulations, the second ion source has been also used as a beam collimator.

CONCLUSION

The project aims at improving the concept of self-extraction in low and medium energy cyclotrons to be used for production of medical isotopes. Specific tasks mutually connected are currently ongoing to achieve the overall goal of the project. The most challenging goal is to have an enhanced turn separation at the extraction to maximize the extraction efficiency. Several methods are currently under study for this purpose; the most attractive being the use of off-centered ion sources. It would allow the simultaneous extraction of two beams.

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REFERENCES

[1] W. Kleeven *et al.*, "The IBA self-extracting cyclotron project", in *Proc. Nukleonika*, Warsaw, Poland, Sep. 2002, pp. S59-S67.

[2] R. Alberto and H. Braband, "SPECT/PET Imaging with Technetium, Gallium, Copper, and Other Metallic Radionuclides", *Comprehensive inorganic chemistry II: from elements to applications*, vol. 3, pp. 785–817, 2013. doi:10.1016/B978-0-08-097774-4.00331-4

[3] A. Boschi, L. Uccelli, and P. Martini, "A picture of modern Tc-99m radiopharmaceuticals: production, chemistry and applications in molecular imaging", *Appl. Sci.*, vol. 9, p. 2526, 2019. doi:10.3390/app9122526

[4] W. Kleeven *et al.*, "The self-extracting cyclotron", in *Proc. CYC'01*, East Lansing, Michigan, USA, May 2001, paper L-1, pp. 69–73.

[5] OPERA, https://www.3ds.com/

[6] W. Kleeven *et al.*, "AOC, A Beam Dynamics Design Code for Medical and Industrial Accelerators at IBA", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 1902–1904. doi:10.18429/JACoW-IPAC2016-TUPOY002