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A NOVEL AUTOMATIC FOCUSING SYSTEM FOR THE PRODUCTION OF RADIOISOTOPES FOR THERANOSTICS*

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Abstract

A research program on the production of novel radioisotopes for theranostics is ongoing at the 18 MeV Bern medical cyclotron laboratory equipped with a solid target station. Targets are made of rare and expensive isotope enriched materials in form of compressed 6 mm diameter pellets. The irradiation of such a small target is challenging. A specific capsule has been developed made of two aluminium halves kept together by permanent magnets. Since the beam extracted from a medical cyclotron is about 12 mm FWHM, an automatic compact focusing system was conceived and constructed to optimise the irradiation procedure. It is based on a 0.5 m long magnetic system, embedding two quadrupoles and two steering magnets, and a non-destructive beam monitoring detector located in front of the target. The profiles measured by the detector are elaborated by a specific software that, through a feedback optimisation algorithm, acts on the magnets and keeps the beam focused on target. Being about 1 m long, it can be easily installed in any existing medical cyclotron facility. The design of the first prototype together with the results of the first beam tests are presented.

INTRODUCTION

Medical cyclotrons typically produce proton beams of energies between 10-20 MeV. Usually situated in hospitals, they assure the supply of ^{18}F-based radiopharmaceuticals such as fluorodeoxyglucose (FDG) used in nuclear medicine for Positron Emission Tomography (PET). Theranostics is a promising concept foreseeing the combined use of diagnostic (γ or β^+ emitters) and therapeutic (α or β^- emitters) radioisotopes and is presently an active field of research. In contrast to the production of standard radioisotopes with liquid targets, a promising technique to obtain novel theranostic radioisotopes is the use of small (about 5 mm diameter) solid targets [1]. The beam extracted from a cyclotron is usually larger than this kind of target and leads to the production of undesired radioactivity with consequent radiation protection implications and limits the production yield. To enhance the irradiation performance of medical cyclotrons to produce novel radioisotopes for theranostics, the Automatic Focusing System (AFS) [2] was conceived and realised. It consists of a compact electromagnet as well as of a 2D beam profile detector (UniBEaM) [3]. A specifically developed software reads the horizontal and the vertical beam profiles, evaluates them and acts accordingly on the MBL to optimise the beam on target.

MATERIALS AND METHODS

The first prototype of the AFS was tested at the cyclotron laboratory at the Bern University Hospital (Inselspital) [4]. This facility is equipped with an IBA Cyclone 18/18 HC medical cyclotron, a 6 m long Beam Transfer Line (BTL) that conveys the proton beam to a second research bunker with independent access, and an IBA NIRTA Solid Target Station (STS). The Mini Beam Line (MBL) is a 50 cm long combination of two quadrupole and two steering magnets, manufactured by the company D-Pace. The UniBEaM was developed by our group and consists of a 250 µm diameter Ce^{3+} doped quartz scintillating fibre which is moved across the beam pipe by a high-precision motor whose position is measured together with the light signal to obtain the beam profile. A specific two-dimensional UniBEaM was developed for the AFS. To test the functionality of the AFS, a second beam monitor - named π^2 - developed by our group was used. It consists of a Ce^{3+} coated aluminium foil read out by a CCD to measure the two-dimensional profile of the beam on-line. To evaluate the optimisation of the beam profile on target, we introduce an *optimisation parameter* λ, based on user defined *target regions* on both the horizontal and vertical axes. These target regions are intervals along the respective axis and correspond to the size and the position of the target to be irradiated. We then define $\lambda = \lambda_1 \cdot \lambda_2$, where $\lambda_1 = \frac{\mathrm{I_{target}}}{\mathrm{I_{beam}}}$, and $\mathrm{I_{target}}$ and $\mathrm{I_{beam}}$ are the beam intensity inside the target region and the entire beam intensity, respectively. The beam intensity is proportional to the area below the UniBEaM beam profile for currents up to a few µA [3]. λ_1 grows with the relative beam intensity on the target along the given axis. $\lambda_2 = \frac{\sigma}{L}$, where σ is the standard deviation of the portion of the beam profile inside the target region and L the length of the latter. λ_2 grows with the beam homogeneity inside the target region which is an important parameter to avoid target overheating. The optimisation algorithm acts on one of the four coil currents at a time while leaving the other three constant. It proceeds in steps during which the best of three different coil currents

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is retained. In the subsequent step, two new coil currents are probed and compared to the retained current. The setting of these two new currents depends on the outcome of the preceding steps. An example of such an optimisation procedure is shown in Fig. 1, where the downstream quadrupole coil current was changed from 40 A to 48 A.

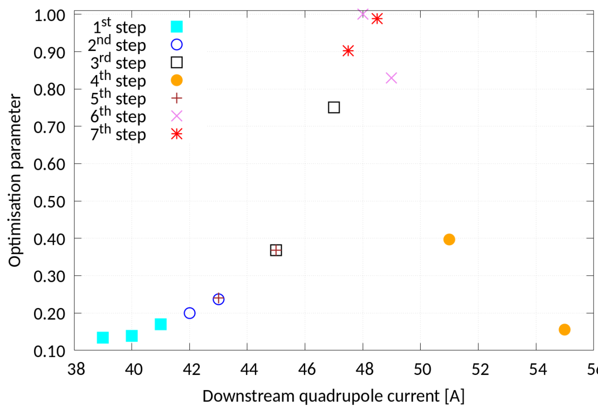

Figure 1: Optimisation procedure of the MBL downstream quadrupole coil.

The beam profiles are measured about 30 cm upstream of the actual target position and are modified according to calculations aimed at estimating the beam profile on target. The first calculation determines the scaling factor f due to the beam convergence or divergence. It is defined as:

$$f = \frac{\sigma_{target}}{\sigma_{UB}} = \sqrt{L^2 \cdot \frac{\gamma_{UB}}{\beta_{UB}} - 2 \cdot L \cdot \frac{\alpha_{UB}}{\beta_{UB}} + 1}, \quad (1)$$

where σ_{target} and σ_{UB} are the beam profile standard deviations at the position of the target and of the UniBEaM, and L is the distance between them. The Twiss parameters α_{UB}, β_{UB}, γ_{UB} are estimated by a beam transport formalism as a function of the two quadrupole coil currents at the position of the UniBEaM. The second calculation evaluates the displacement of the beam profile and can be derived from the Lorentz force equation:

$$\Delta x = \frac{q(\int B(l)dl)c}{\sqrt{E_{kin}^2 + 2E_{kin}mc^2}} \cdot L, \quad (2)$$

where q is the proton electric charge and $\int B(l)dl$ the MBL magnetic dipole field strength integrated along the beam axis. E_{kin} is the kinetic energy and m the mass of the particle and c the speed of light. Both calculations are performed by the optimisation algorithm for both axes in the transverse plane.

FIRST TESTS

The first tests of the AFS prototype were performed using the BTL since access to the beam area was mandatory. A typical set-up is shown in Fig. 2, where the beam spot on target was monitored by the π^2 detector.

The capacity of the AFS to predict the beam profiles on target was verified with a second beam profile detector installed

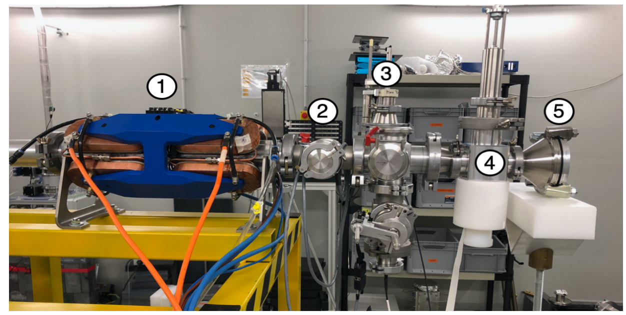

Figure 2: Experimental test of the AFS. 1: MBL, 2: drift space, 3: 2D UniBEaM detector, 4: π^2 detector, 5: beam dump.

at the target position. As shown in Fig. 3, excellent agreement was found between calculated and measured beam profiles.

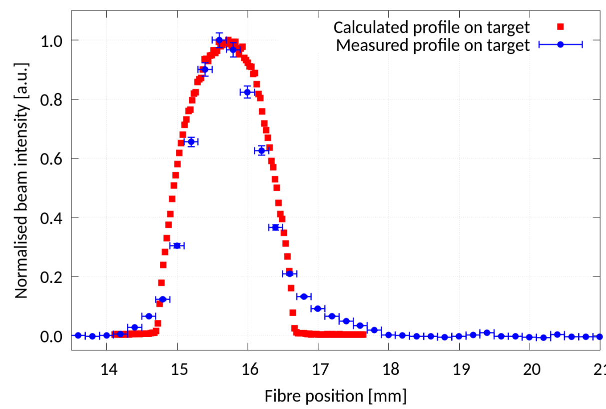

Figure 3: Comparison between calculated (red) and measured (blue) beam profiles on target.

A second test aimed at focusing a broad beam using the AFS optimisation procedure. For this purpose, a π^2 detector was installed at target position. Figures 4 and 5 show two images taken with the π^2 detector before and after the optimisation. They demonstrate the optimal focusing capability of the system.

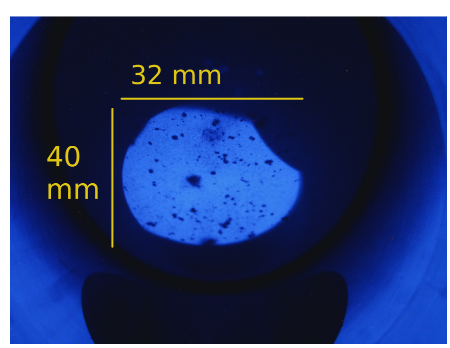

Figure 4: Beam before AFS optimisation.

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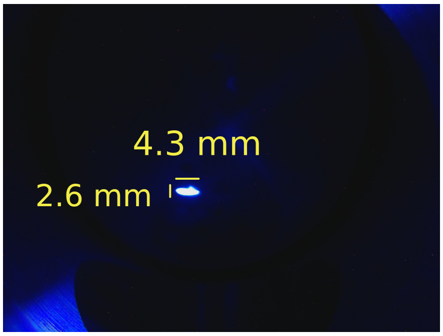

Figure 5: Beam after AFS optimisation.

To test the capability of beam recentring after an external perturbation, the BTL was used to modify the beam parameters at the entrance of the AFS. Afterwards, the AFS optimisation procedure was performed to restore the initial beam centring. A second beam profile detector, installed at target position, was used to monitor the full procedure. As an example, the horizontal beam profiles of such a test are shown in Fig. 6. The agreement in beam centring between initial and rectified beam is excellent.

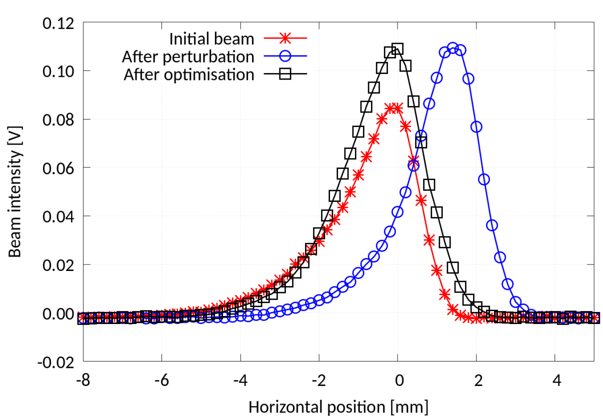

Figure 6: Beam profile before and after a perturbation provoked by the BTL magnets, as well as after the AFS optimisation.

In a final test, the increase of the radioisotope production yield was assessed by irradiating two natural Zn pellets (mass (90 ± 10)µg). One pellet was irradiated while the MBL was turned off, the other with an AFS-optimised beam spot. One of the pellets can be seen in Fig. 7, inserted in a specific capsule developed by our group [1]. The capsule was put into a target station at the end of the BTL which holds it in place during the irradiation and allows to read-out the proton current on the pellet.

The characteristic γ lines of the ^{66}Ga and ^{67}Ga produced during the irradiation were analysed using a High Purity Germanium Detector (HPGe). The gain factor in production yield was determined to be (22 ± 4), which is in agreement with the measured increase of the integrated current on the pellet. It should be noted that these results arise from two

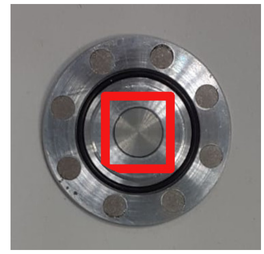

Figure 7: One of the two natural Zn pellets inside the capsule.

extreme cases, i.e. a very broad beam and a very focused beam, so that the precise gain factor at the STS exit port is still a matter of research. However, the yield was considerably increased due to the AFS optimisation of the beam spot.

CONCLUSIONS AND OUTLOOK

To enhance the production capability of radioisotopes for theranostics using solid targets, a novel system for automatic beam focusing and positioning was developed and successfully tested using the Beam Transfer Line of the Bern medical cyclotron. Its compactness (about 1 m including the target) allows its installation in all existing medical cyclotron facilities. This device can also be adapted to applications outside the field of medical physics and to any ion accelerator facility. Following the successful results described in this paper, this new system was recently integrated with the Solid Target Station and further developments are presently ongoing.

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REFERENCES

[1] S. Braccini, C. Belver-Aguilar, T. S. Carzaniga, G. Dellepiane, P. Haeffner, and P. Scampoli, "Novel Irradiation Methods for Theranostic Radioisotope Production With Solid Targets at the Bern Medical Cyclotron", in *Proc. 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19)*, Cape Town, South Africa, Sep. 2019, pp. 127–131. doi:10.18429/JACoW-CYCLOTRONS2019-TUA02

[2] P. D. Häffner *et al.*, "An Active Irradiation System with Automatic Beam Positioning and Focusing for a Medical Cyclotron", *Appl. Sci.*, vol. 11, no. 6, p. 2452, 2021. doi:10.3390/app11062452

[3] M. Auger *et al.*, "A detector based on silica fibers for ion beam monitoring in a wide current range", *J. Instrum.*, vol. 11, p. 03027, 2016. doi:10.1088/1748-0221/11/03/p03027

[4] S. Braccini *et al.*, "The new bern PET cyclotron, its research beam line, and the development of an innovative beam monitor detector", in *AIP Conf. Proc.*, vol. 1525, pp. 144-150, 2013. doi:10.1063/1.4802308