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AN AUTOMATIC FOCALIZATION SYSTEM FOR ENHANCED RADIOISOTOPE PRODUCTION WITH SOLID TARGETS*

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Abstract

A research program aimed at the production of novel radioisotopes for theranostics is ongoing at the 18 MeV cyclotron laboratory in operation at the Bern University Hospital (Inselspital). A method based on the bombardment of isotope enriched materials in form of compressed 6 mm diameter pellets was developed. To accomplish this challenging goal, accurate knowledge of beam energy, positioning and focusing as well as production cross sections are crucial. Investigations are carried on to assess all these items. In particular, an automatic compact focalization system was conceived and constructed to optimize 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 a fiber detector are elaborated by a feedback optimization algorithm that acts on the magnets and keeps the beam focused on target to enhance the production yield. Following the first successful functional tests, the preliminary results on the production of medical radioisotopes are presented.

INTRODUCTION

Medical cyclotrons for radiosiotope production are nowadays optimized for providing standard radioisotopes as the ^{18}F used in Positron Emisssion Tomography (PET) applications. Theranostics is a novel approach in cancer treatment based on the combined use of diagnostic (γ or β^+ emitters) and therapeutic (α or β^- emitters) radioisotopes. The production of radioisotopes for theranostics is currently a reserach topic. The University of Bern is equipped with an IBA 18/18 HC medical cyclotron for both routine production of radiopharmaceuticals and scientific research. Figure 1 shows a picture of the cyclotron and of its Beam Transfer Line (BTL), which ends in a separate bunker with independent access. Multidisciplinary research activities are carried out at the Bern cyclotron laboratory. These include the study of new radioisotopes for theranostics, radiation hardness, fundamental physics, radiation protection and particle detector physics [1].

Figure 1: The Bern medical cyclotron.

In particular, the production of novel radioisotopes for theranostics is performed by irradiating solid targets in form of 6 mm diameter pellets made of compressed powder [2, 3]. Beams extracted from medical cyclotrons for standard radioisotope production have a typical dimension of the order of 10 mm. Thus, in order to achieve a safe, reliable and optimized production for theranostics, the beam should be focused on target over the whole irradiation. However, the focused beam is very sensitive to any beam instability due, for example, to drifts of the main coil of the cyclotron caused by the temperature increase. To address these scientific requirements, a new Automatic Focalization System (AFS) has been developed. Its operating principle as well as first functional tests carried out on a AFS-prototype installed in the BTL are presented in this work.

MATERIALS AND METHODS

The production of non-conventional radioisotopes at the Bern medical cyclotron is carried out by irradiating solid targets contained in a specifically designed target coin. It is made of two halves, typically made of aluminum, held together by permanent magnets. The overall thickness of the target coin is 2 mm. A picture of the target coin with the permanent magnets and 6 mm diameter pellet is shown in Fig. 2.

A new beam line has been implemented to enhance the performance of the production of new radioisotopes for theranostics (Fig. 3). It is made of a Mini-PET Beamline (MBL), a UniBEaM detector and a IBA Nirta solid target station.

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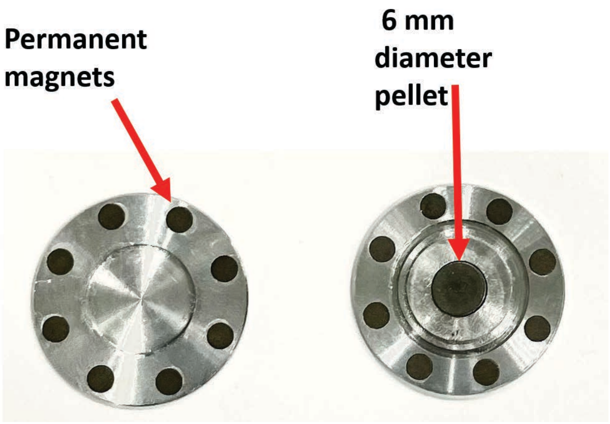

Figure 2: Target coin with permanent magnets and the 6 mm diameter pellet indicated by arrows.

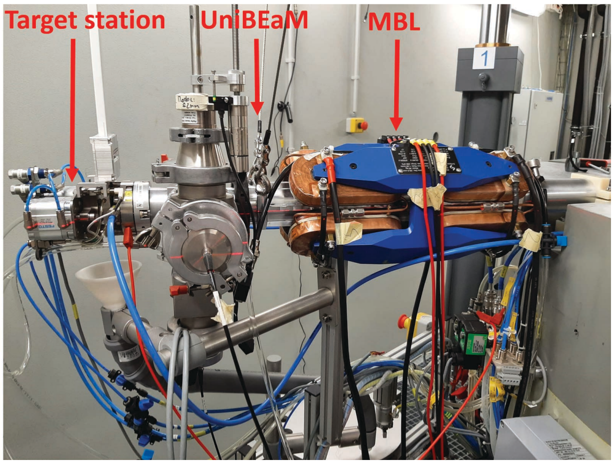

Figure 3: Beam line for the production of novel radioisotopes for theranostics at the Bern medical cyclotron.

The MBL is a 50 cm long structure with two quadrupole and two steerering magnets produced by the company D-Pace. The UniBEaM is a two-dimensional beam profiler based on scintillation optical fibers, developed by our group [4]. Specifically, two 250 µm diameter Ce^{3+} doped quartz scintillation fibers are moved across the beam pipe by two high-precision motors; the beam profile is determined by measuring the light intensity and the corresponding fiber position. The MBL focuses the beam on the target and beam profiles are measured by the UniBEaM. The new Automatic Focalization System (AFS) features a specific software which adjusts the MBL currents on the basis of the feedback provided by the UniBEaM detector. A schematic of the AFS main elements is shown in Fig. 4.

In detail, the operating principle of the AFS control system is the following:

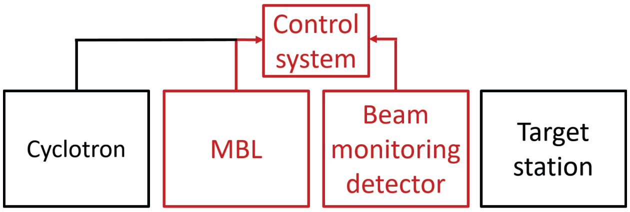

Figure 4: Schematic of the elements of the cyclotron for non-conventional radioisotope production. The part in red refers to the Automatic Focalisation system.

1. UniBEaM X and Y profiles are recorded and optimization parameters are defined as functions of the centroid and FWHM for each profile.
2. The optimization parameters are compared to those of the target region (i.e. the position of the pellet in the target station).
3. The MBL currents are varied and new optimization parameters are compared to those of the previous profile.
4. The automated procedure ends when the difference between the optimization parameters of two consecutive beam profiles is less than a defined tolerance.

A different detector was also used as beam monitor for the AFS. In particular, the π^2 detector, a yttrium orthosilicate coated aluminium foil read out by a CCD camera, has been used to assess the focusing capabilities of the new system. This detector was recently developed by our group [5]. The AFS has to withstand harsh conditions with irradiations of several hours and beam currents up to 30 µA.

RESULTS

The beam profiles measured by the UniBEaM are used by the Automatic Focalization System (AFS) to adjust the MBL currents and finally focus the beam on the target. However, the position of the UniBEaM is 30 cm far from that of the target. Thus, the beam profile on the target is evaluated starting from the measured UniBEaM profiles throughout beam dynamics calculations [6]. In particular, the scaling factor f for the beam divergence is defined as follows:

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

where σ_{target} and σ_{UB} are the beam profile standard deviations at the position of the target and of the UniBEaM, L is the distance between the target and the UniBEaM. The Twiss parameters α_{UB}, β_{UB}, γ_{UB} are defined as a function of the two quadrupole currents at the position of the UniBEaM.

The displacement of the beam profile is derived from the Lorentz force equation as follows:

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

where m and q are the proton mass and elementary charge, $\int B(l)dl$ is the integral of the magnetic field along the beam axis, E_{kin} is the kinetic energy and c the speed of light. These calculations are performed by the optimization algorithm for the horizontal and vertical measured UniBEaM profiles to obtain the beam profile on the target. In order to verify the correctness of this evaluation, we measured the beam profile on the target with a second UniBEaM. The results, shown in Fig. 5, report an excellent agreement between the measured and calculated beam profiles.

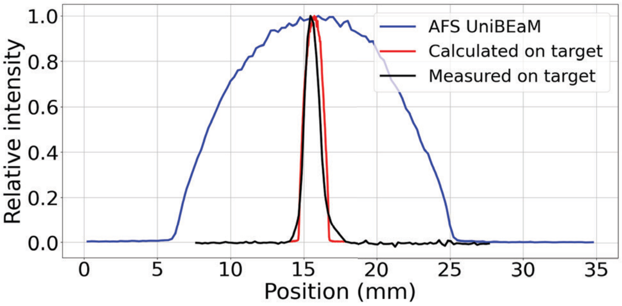

Figure 5: Beam profile measured by the AFS-UniBEaM (blue); calculated (red) and measured (black) beam profiles on the target position.

AFS focusing capabilities have been proved by comparing the beam spot of a focused (after the AFS) and unfocused (before the AFS) beam measured with the π^2 detector placed at the target position. Images of Fig. 6 demonstrate that the AFS is capable to focus the beam on a target region of 4×3 mm^2, which is less than the surface of the pellet (6 mm diameter).

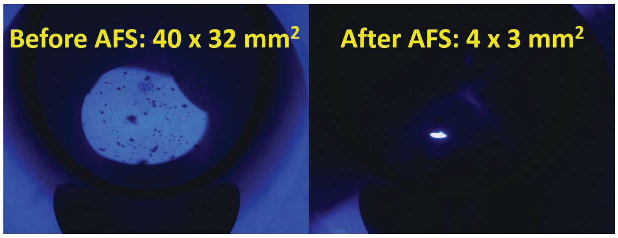

Figure 6: Beam spot before (left) and after (right) the optimization procedure.

To assess the capabilities of the new AFS in recovering the beam after a beam instability, we produced a slight perturbation of the beam by acting on the external magnetic steerers; thus, we ran the AFS. The results, reported in Fig. 7, show that the AFS is able to put back the beam in position following a 1.3 mm horizontal beam shift. Similar results have been obtained after a beam shift on the vertical axis. Finally we tested the enhancement of the AFS performance by irradiating two natural zinc targets, one with a flat beam and the other with an AFS optimized beam. For these two extreme cases, we found a gain factor in the produced ^{68}Ga and ^{67}Ga specific activities of about 20 [6].

CONCLUSIONS AND OUTLOOK

A new beam line has been implemented at the Bern medical cyclotron aimed to establish a reliable procedure for the irradiation of solid targets in view of the production of theranostics radioisotopes. A beam monitoring detector provides a fast feedback for the control system which automatically adjusts the currents of the quadrupoles and steerers to focus and position the beam on target. We successfully tested the AFS with the UniBEaM, a beam profiler based on scintillation optical fibers, and the π^2 detector, a beam monitor based on a scintillation foil and a CCD camera. In particular, we observed that the AFS is able to focus the beam on a surface smaller than that of the pellet of material for the production of theranostics radioisotopes as well as to automatically recover the optimized condition following an external perturbation. Being less than 1 meter, the compactness is a crucial aspect allowing the installation in facilities with limited space including the cyclotrons for radioisotope production. Follwing the tests with the BTL, the AFS was installed directly on the cyclotron and tests and optimization are ongoing.

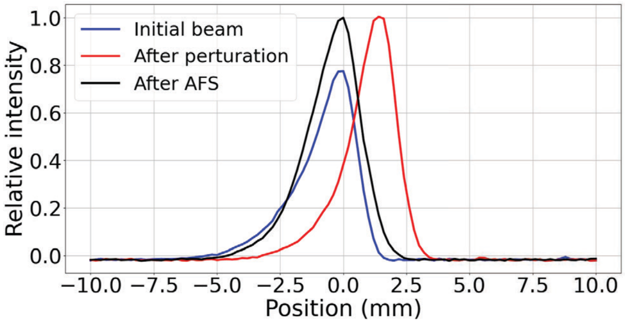

Figure 7: Automatic Foclisation Capabilities in recovering the beam after a perturbation on the focused beam.

ACKNOWLEDGEMENTS

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