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Design and assembly of an XY-type beam current monitor for cyclotron accelerators

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A R T I C L E I N F O

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A B S T R A C T

A water-cooled XY-type beam current monitor was designed, manufactured and assembled in a cyclotron accelerator beam transport line. Tests were performed, demonstrating that apparatus is an instrument of great assistance in proton beam position. The XY-type beam current monitor has been widely used in liquid target irradiations, employing irradiation system which were originally designed for irradiations on 18 MeV cyclotron accelerator (Cyclone 18, IBA) only, however, with this apparatus, the target may be exchanged between the 30 MeV (Cyclone 30, IBA) and 18 MeV cyclotrons.

1. Introduction

On August 28, 1998 a new Cyclone 30 cyclotron, manufactured in Belgium by Ion Beam Applications, started operating in Nuclear and Energy Research Institute (IPEN), located in São Paulo, Brazil. This machine can accelerate negative ions ($^{-}$H), with kinetic energy in a range from 15 up to 30 MeV, and the beam current can achieve up to 300 μA (Ion Beam Applications, 1994; Jogen and Ryckewaert, 1988). There are two external beam transport lines assembled on opposite sides, in such way that the proton beam is driven to targets placed in two separated irradiation rooms, as shown in Fig. 1. Since then, Cyclone 30 has been used in routine production, as irradiation of solid, liquid and gaseous targets, such as ^{18}F-FDG (2-[^{18}F]fluoro-2-deoxy-D-glucose), ^{67}Ga, ^{201}Tl and ^{123}I.

In liquid and gaseous targets irradiation room, at the end of the beam transport line, there is a switching magnet that allows irradiation in five different positions (Conard et al., 1990; Van der Linden et al., 1990).

Due to the length of the beam transport lines (6 m long), the beam focusing is done by quadrupole magnetic lenses, and steering coils are used for vertical/horizontal positioning. Often, the targets have a circular-shaped beam collimator, whose diameter does not exceed 10 mm, so it is important that the proton beam passes through the collimator with small losses before reaching the target. For this reason, an XY-type beam current monitor was designed and constructed, to allow the cyclotron operator to adjust the beam position, before passing through the collimator in order to reach the target with maximum efficiency.

In 2008, another cyclotron was installed on the premises of the Nuclear and Energy Research Institute, a Cyclone 18/9 also built by Ion Beam Applications. This new cyclotron can accelerate negative ions ($^{-}$H), at fixed 18 MeV energy, and proton beam current up to 100 μA. It has eight beam output ports, which can irradiate up two of them simultaneously (Conard et al., 1990; Ion Beam Applications, 2003). In each of these exit ports, there are beam gates, which isolate the cyclotron vacuum chamber from the targets. These targets were developed particularly for use in Cyclone 18/9 cyclotrons only, however, with design and construction of the XY-type beam current monitor, these targets can be irradiated in both Cyclone 30 and Cyclone 18/9, which has provided a benefit for IPEN, because the ^{18}F-FDG productions will not be stopped even if one of the two cyclotrons is in maintenance.

2. Materials and methods

2.1. The XY-type beam current monitor

There are several techniques for beam profile monitoring of electrically charged particles, which have been used with success in several research centers and cyclotron radioisotope production facilities

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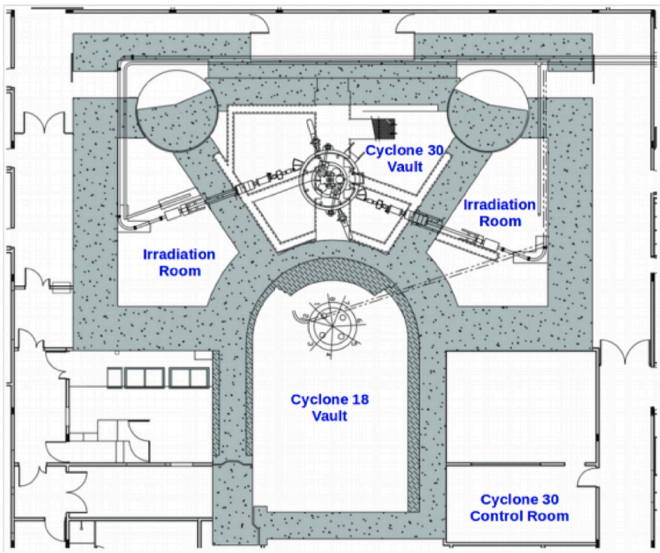

Fig. 1. Cyclone 30 vault and irradiation rooms.

(Hendriks et al., 2013; Hornstra and Simanton, 1969; Hyman and Jankowski, 1973; Simanton et al., 1969; Tsang et al., 2008). The beam current monitor presented in this work is quite simple in design. It is composed by water-cooled "four-fingers", mounted in a single block, as shown in Fig. 2. The material used is 6063 or 6061 aluminum alloy, and the electrical insulator discs are made of PEEK (PoliEter-Etil-Ketone) (Fink, 2014). This block is mounted in a DIN100 standard high vacuum valve (beam gate), in one of the five ports of the switching magnet, in the liquid and gaseous irradiation room. On the opposite side, an aluminum plate is mounted, where the Cyclone 18/9 beam gate is fixed (Fig. 3). This way, the Cyclone 18/9 targets can be mounted and irradiated in Cyclone 30 cyclotron.

The DIN100 flange (Fig. 2), which is also water-cooled, connects the XY-type beam current monitor to the cyclotron's beam gate, has a conical-shaped primary collimation aperture with the largest aperture measuring 30 mm and the smallest 15 mm. After passing through this first collimation, the beam must cross the region where the 4-fingers are mounted, whose cross section is a square with sides measuring 10 × 10 mm. Next, the beam reaches the target collimator (Fig. 5), also in a cone shape with a larger opening measuring 40 mm and the smaller one, more internal and closer to the target, measuring 10 mm. The main objective of XY-type beam current monitor is to intercept a small fraction of the beam in a continuous measurement, to establish a spatial profile of the beam (in transverse directions - XY) to provide the best performance to parameters as target pressure, target temperature and production yield when hit the target.

2.2. Electrical instrumentation

The electronic instrumentation, used to monitor the spatial beam profile, is composed of a data acquisition unit (hardware), which is directly connected to the XY-type beam current monitor, and a data processing unit (software), which converts the analog signals into digital ones. The nominal values of currents on each finger are shown on the computer screen of the control room, so that, the cyclotron operator can make the necessary spatial positioning of the beam on the target.

2.3. Hardware

The beam monitoring technique used in this work is based on the interception of the proton beam, by means of cooled aluminum collectors (fingers or sectors), and the measurement of the induced electric current (by secondary electrons), produced in the finger or sector (Williamson et al., 1966).

Fig. 4 shows a diagram, where is represented the connections among the XY-type beam current monitor, the target and the acquisition unit. The electrical signals from each finger are connected with 50 Ω coaxial cables to the data acquisition unit, located in the cyclotron control room, 50 m away.

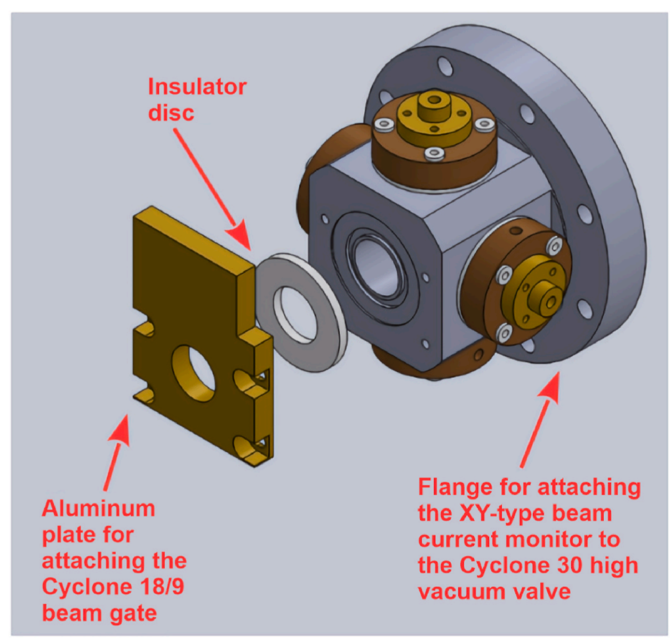

Fig. 3. Aluminum plate for attaching the Cyclone 18/9 beam gate and flange for attaching Cyclone 30 high vacuum valve.

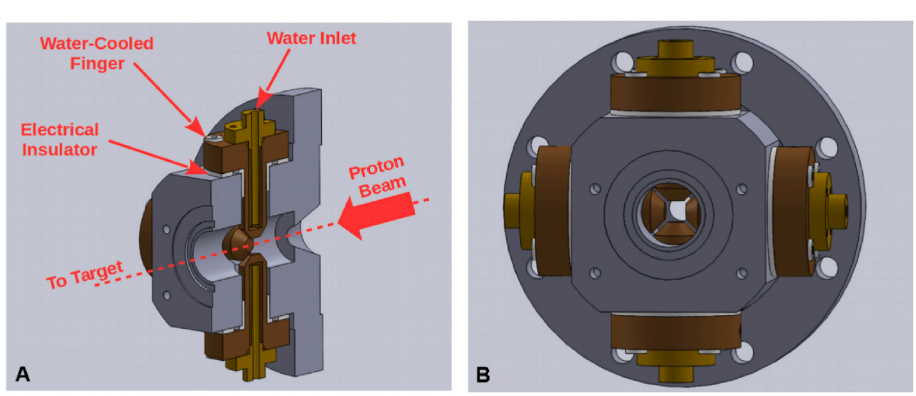

Fig. 2. (A) Cut-out of the current monitor aluminum body; (B) Fully assembled XY-type beam current monitor.

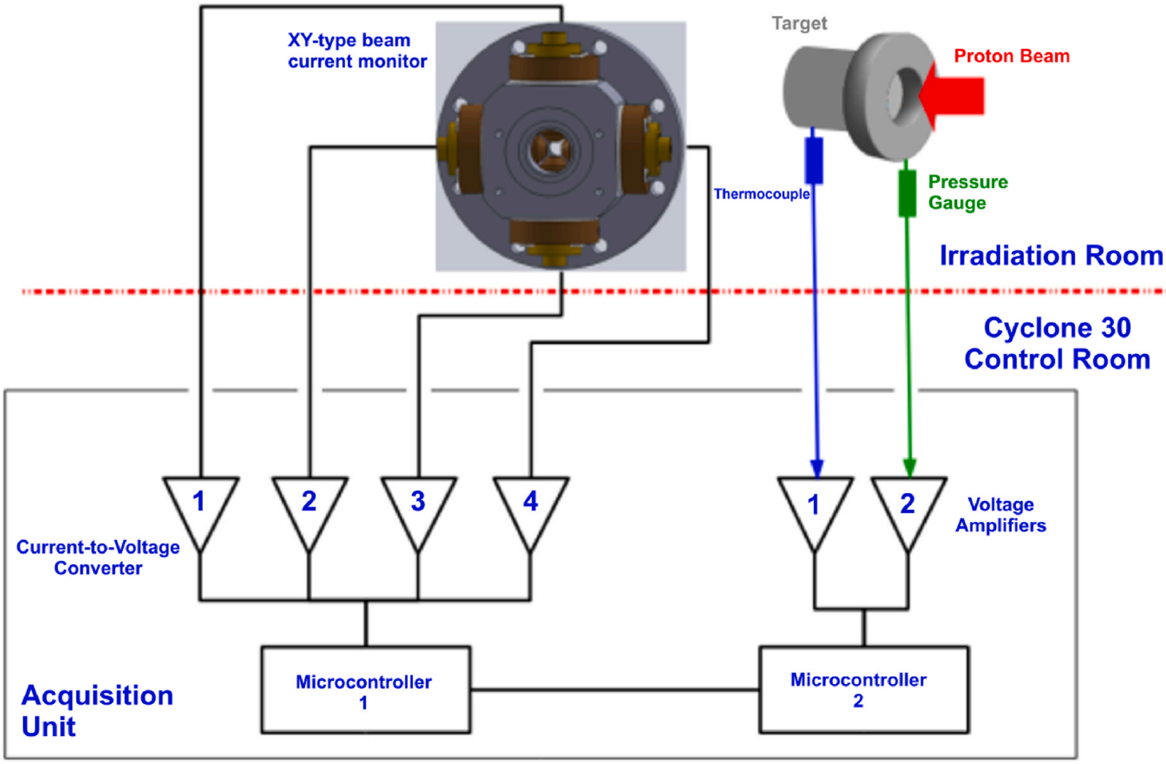

Fig. 4. Electronic instrumentation used in XY-type beam current monitor.

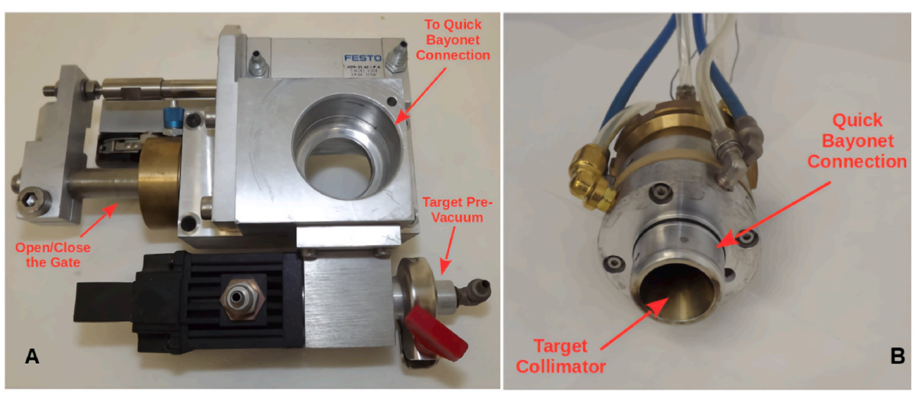

Fig. 5. (A) Cyclone 18/9 standard beam gate; (B) Cyclone 18/9 ^{18}O-enriched water target, used in the XY-type beam current monitor tests.

In the data acquisition unit, current-to-voltage converters convert the induced electric currents from the sectors into voltages (0–5 V). These signals are sent to the analog inputs of the PIC micro-controllers (Microchip Technology Inc, 1999; Silva Junior, 1997), which convert the signals into 10-bit digital data. These, in turn, are sent via serial RS-232-C interface (Capelli, 2000) to a personal computer, where they are recorded and displayed in real time on the computer screen, so that the cyclotron operator can monitor and make the necessary corrections. As the usual target current, for ^{18}F production, is between 50 and 60 μA, the current expected in each finger must remain between 0 and 5 μA, the amplification method adopted avoids the lost of signal, and ensures the accuracy, considering the distance of 50 m from the acquisition unit.

2.4. Software

All operations performed by the micro-controllers (acquisition, analogue-digital conversion, serial communication, etc.), are established via ASSEMBLER programmed routines and recorded in their EEPROM data memories.

An application developed in MS Visual Basic 6.0®, allows the cyclotron operator to monitor, in real time, on the personal computer screen, the behavior of the spatial beam profile, during the entire irradiation time, namely, the value of the beam current in each one of the sectors, by reading the data from the respective micro-controller buffers, with a data refresh interval of 0.5 s (Microsoft Corporation, 1998).

The program also allows storing the values obtained in the data acquisition in a file (.mdb -MS Access®) for future analysis (Microsoft Corporation, 2003). This data is recorded every 2 s. A record routine allows data to also be displayed in the form of a chart versus time.

2.5. Irradiation tests

For the XY-type beam current monitor tests, a medium volume (3 mL) ^{18}O-enriched water target was used, and several irradiations were made, modifying the beam spatial profile, so that, it was possible to verify the current readings in each water-cooled finger (Da Costa, 2014).

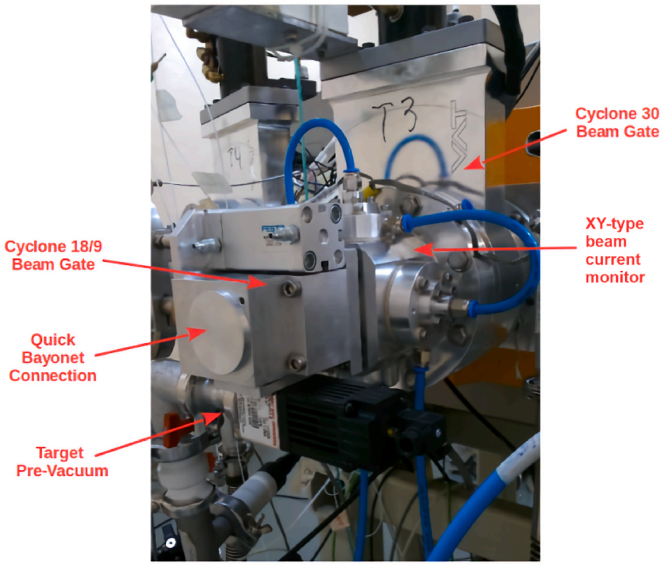

Fig. 6. XY-type beam current monitor assembled on Cyclone 30 beam gate.

Fig. 5 shows the Cyclone 18/9 beam gate, used in this assembly, and the ^{18}O-enriched water target used in the current monitor tests, and Fig. 6 shows the XY-type beam current monitor and Cyclone 18/9 standard beam gate assembly mounted to the Cyclone 30 switching magnet output port, in the liquid and gaseous irradiation room.

3. Results and discussion

In liquid targets, the volume is not completely filled, there is an empty region above the liquid surface, which, when hit by the beam, causes a growth in the target pressure greater than when the beam reaches only the liquid region, due to this, the operator searches for a beam profile in order to avoid this empty region.

During the XY-type beam current monitor irradiation tests, the proton beam was purposely moved horizontally (x-direction), both to the left and to the right, and in the same way, in the vertical direction (y-direction), up and down. Plots of the current readings on the four water-cooled fingers were made in real time, to verify the equipment operation as shown in Figs. 7 and 8. These figures show the application main screen during a typical irradiation for ^{18}F-FDG production. In these screens, four main fields can be highlighted: a front view of the current monitor (upper left corner), where the four "cooled fingers", with their respective beam current values can be seen; chart of beam currents as a function of time (top right), and target and collimator beam current chart (bottom right), target pressure and water cooling temperature values (in the bottom left).

Other relevant parameters, which are also monitored by the data acquisition system, are the current in the beam collimator, the total current integrated into the target, the temperature of the water cooling and the pressure inside the target. The values of these parameters are shown on the current monitor main screen and also assist the cyclotron operator during irradiation. If the beam profile matches the description above, however the temperature and/or pressure are too high, this may cause damage to the system. Before this occurs, the cyclotron operator must intercept the proton beam to prevent the leakage of radioactive material or the cyclotron vacuum loss.

As absolute measurements are not strictly required, thermal beam loading studies were not carried out and the effect of secondary electron emission from the fingers was neglected.

Fig. 2 shows the cooling channels quite close to the intercepting tips of each finger, the channels are chilled by low conductivity water, the monitoring of water resistivity may indicate changes in electrical current conduction and the necessity of calibration with the data acquisition system, however, cyclotron accelerators have a unique water resistivity meter usually to the whole accelerator systems, and a exclusive water resistivity meter to the 4-fingers should be used to the calibration.

The tests performed with the current monitor as well as the data acquisition and processing units were done during routine ^{18}F-FDG productions. The behavior of the components was monitored throughout the production time and the parameters observed were visualized by the cyclotron operator and recorded in register files.

4. Conclusions

It was designed, manufactured and assembled an XY-type beam current monitor. The apparatus was mounted at the end of a cyclotron beam transport line.

The real-time visualization, of the beam spatial profile, allowed the cyclotron operators a better control on the positioning of the proton beam, in the region of the target, under the liquid surface, maintaining the target pressure within the security parameters. Beam current measurements, on the collimator and target, allowed the optimization of the

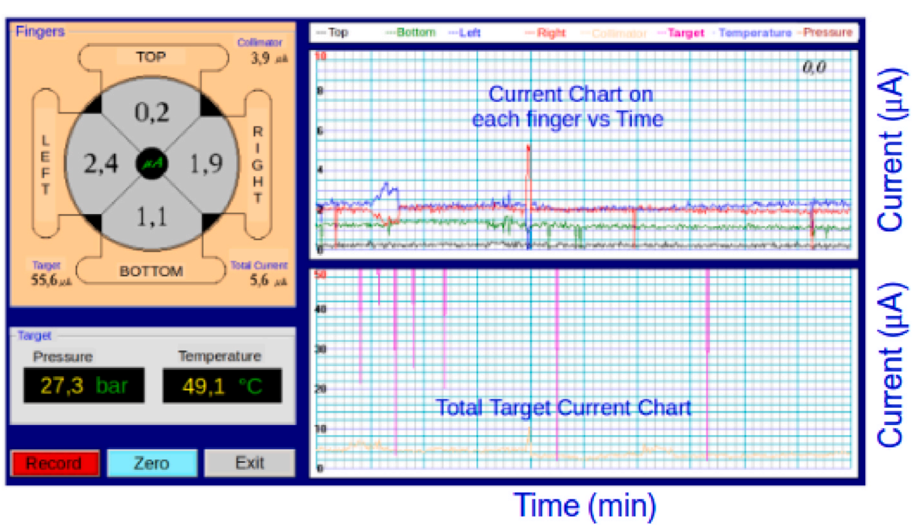

Fig. 7. XY-type beam current monitor screen during typical ^{18}F-FDG production, with scattering beam profile in the X-direction and slightly displaced vertically to bottom.

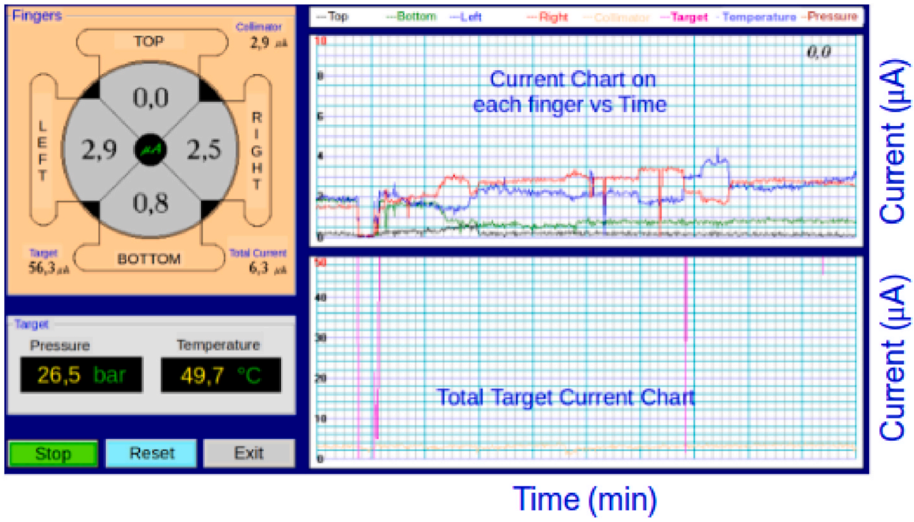

Fig. 8. XY-type beam current monitor screen during typical ^{18}F-FDG production, with scattering beam profile in the X-direction and vertically focused.

target/collimator current ratio in a shorter time.

Nowadays, the XY-type beam current monitor has been used in several liquid target irradiations. In the future, will be designed and assembled a beam spatial monitoring system, composed of a double set of monitors, similar to the one described in this paper, mounted axially and spaced 50 cm apart. The objective is to improve the beam profile in gas target irradiation, as these are longer than those used in liquid target irradiations.

CRediT authorship contribution statement

Henrique Barcellos: de Oliveira, Writing – original draft, Visualization, Investigation, Conceptualization. **Hylton Matsuda:** Software, Resources, Methodology, Investigation. **André L. Lapolli:** Software, Investigation. **Luiz Carlos do A. Sumyia:** Resources, Investigation. **Fernando de C. Junqueira:** Visualization, Methodology. **Osvaldo L. da Costa:** Writing – review & editing, Visualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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