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# DEVELOPMENT OF NOVEL NON-DESTRUCTIVE 2D AND 3D BEAM MONITORING DETECTORS AT THE BERN MEDICAL CYCLOTRON*

C. Belver-Aguilar†, T. S. Carzaniga, A. Gsponer, P. Häffner, P. Scampoli[1],
M. Schmid, S. Braccini, Albert Einstein Center for Fundamental Physics (AEC),
Laboratory of High Energy Physics (LHEP), University of Bern, Bern, Switzerland
G. Molinari, TERA Foundation, Novara, Italy
[1]also at Department of Physics "Ettore Pancini", University of Napoli Federico II, Naples, Italy

*Abstract*

The Laboratory for High Energy Physics (LHEP) at the University of Bern is developing novel beam monitoring detectors for the 18 MeV medical cyclotron in operation at the Bern University Hospital (Inselspital). A 2D non-destructive beam monitor — named $\pi^2$ — was developed, based on a thin aluminium foil coated with P47 scintillating material and a camera. It measures the transverse position, shape, and intensity of the beams for several applications, as radiation hardness or radioisotope production studies. This detector allows the processing of data in real time and a reconstruction of the transverse phase space. Based on the $\pi^2$, a first prototype of a 3D beam monitoring detector — named $\pi^3$ — was conceived, constructed, and tested. It is based on the same scintillating foil mounted on a movable support with a miniaturized camera. The $\pi^3$ detector allows for the study of the beam evolution along a beam line, even inside a magnet, and the reconstruction of the beam envelope. In this paper, we report about the design, construction and beam tests performed with these two detectors. Further developments will be also presented and discussed.

## INTRODUCTION

Beam monitoring plays a crucial role in both the commissioning and operation of particle accelerators. For some medical cyclotron applications, like the irradiation of small and expensive solid targets [1], non-destructive beam monitors are essential.

At the Bern medical cyclotron, three different beam monitors have been developed by the LHEP. The first one, named UniBEaM [2], is used to measure the beam transverse profile by means of a moving scintillating fiber. The second one is the $\pi^2$, a detector based on a fixed scintillating foil and a camera, which allows to measure the beam spot in 2D. The third one is the first prototype of an evolution of the $\pi^2$ detector, called $\pi^3$, where both the scintillating foil and the camera are mounted in a moving support to allow assessing the beam evolution along the beam path.

In this paper, the main features and beam tests of the $\pi^2$ and $\pi^3$ beam monitors are reported. Beam tests were performed using the 6 m long Beam Transfer Line (BTL) [3] and the 18 MeV proton beam delivered by the Bern medical cyclotron.

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† carolina.belver@lhep.unibe.ch

## THE $\pi^2$ BEAM MONITOR

The $\pi^2$ hardware, based on a phosphor screen and a camera, is a common design which was already used in some other accelerator facilities, for example at the Korean Institute of Radiological and Medical Sciences [4]. However, the pre-processing and analysis software that has been implemented in our detector represents a step forward in the analysis of the images provided by this type of detectors: it is being developed to perform real-time measurements of beam position, size and current, but also phase space representation and beam emittance measurement, as well as tuning of the BTL magnet currents.

The $\pi^2$ detector, as shown in Fig. 1, consists of a cerium- and terbium-doped yttrium orthosilicate ($Y_2SiO_5$:Ce,Tb) phosphor screen (P47) and a camera, to control the beam position and beam size during a proton irradiation. This detector can monitor beam currents in the range between pA and several µA.

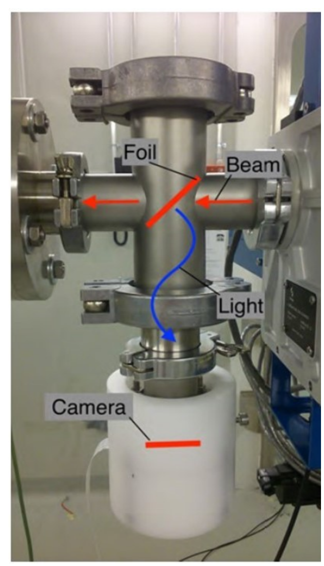


Figure 1: The KF40 four way pipe that supports the $\pi^2$ detector. The positions of the scintillating foil and camera are shown in red.

The scintillating screen is placed at the center of a KF40 four way pipe with a tilt angle of 45° with respect to the beam path. It has a diameter of 20 mm, and consists of a 0.8 µm aluminum foil coated with a 1 µm layer of P47. An optimal heat dissipation is achieved by gluing the thin

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aluminum foil onto an aluminum support with SikaPower 1548 glue. A remotely controlled pneumatic system is used for inserting and extracting the phosphor screen from the beam path during beam operations [5].

The camera used for this detector is a Raspberry Pi Camera Module V2 [6], which is equipped with a 8 megapixel CMOS sensor [7]. It is placed inside a cylinder made of polyoxymethylene (POM) for neutron shielding, as shown in Fig. 1. The size of the camera is 4.6 mm (diagonal). The camera can capture images with a resolution of 3280 × 2464 pixels. It can also record videos with a resolution of 1920 × 1080 pixels and a maximum frame rate of 90 FPS.

### *The $\pi^2$ software*

A Python program has been developed for image preprocessing and data analysis. The integrated software allows for monitoring on-line several beam parameters. The main functions are:

**Real-time view of the 2D beam spot** This mode is very useful when tuning the beam, and has the possibility of streaming the camera output over the network. A computer connected to the LAN receives the video stream with a latency of about 2–3 seconds.

**Evaluation of beam position, beam size and beam current** The analysis software allows for the correction of the perspective of the captured image due to the tilted position of the scintillating foil with respect to the beam. It also converts pixels to mm. Furthermore, a brightness value, between 0 and 255, is assigned to each image pixel to assess the total intensity, which is then normalized to the camera gain and exposure time in order to determine the beam current. In particular, the range of beam currents at which a linear response of the $\pi^2$ can be expected was studied at the BTL of the Bern cyclotron. Results are shown in Fig. 2, where a good linearity was found from ~ 500 nA to ~ 2 µA. A Graphical User Interface (GUI), shown in Fig. 3, has been developed to measure beam position, beam size and beam current in real-time. It allows to start a live view, capture and show an image by setting an automatic or manual exposure time, and show the Gaussian fit of the projections in both the horizontal and vertical plane. A measurement of the total and normalized intensities, as well as the mean and FWHM of both fits are also shown.

**Tuning of the BTL magnet currents with the $\pi^2$** When performing experiments at the BTL, setting up the 4 quadrupole currents is usually very time consuming. In order to ease the tuning of the BTL optics, a machine learning library of Python (scikit-learn) has been used to train a multi-output linear regression model providing the optics configuration required for a given beam width in both the horizontal and vertical planes. The beam transport matrix through a drift space is used to predict the optics configuration at any point along the BTL. This first model has been

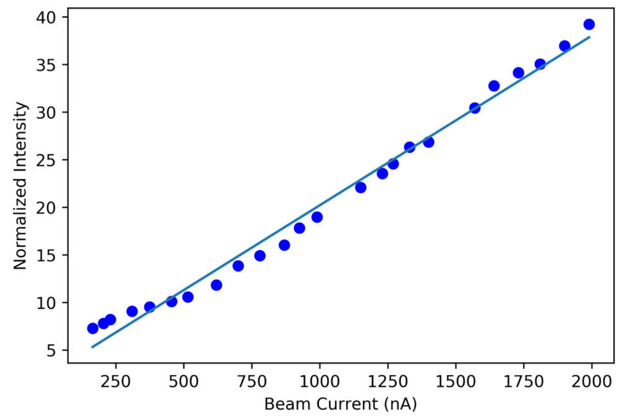


Figure 2: Normalized intensity measured with the $\pi^2$ as a function of the beam current.

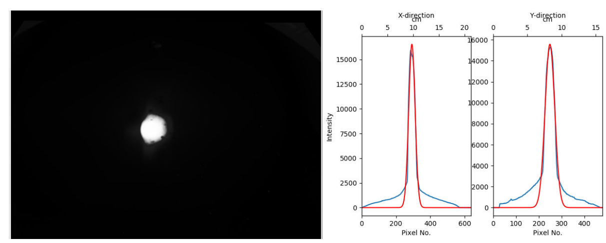


Figure 3: Screenshot of the $\pi^2$ GUI, showing the 2D beam cross-section (left) and the projections in both the horizontal and vertical planes (right).

tested for beam sigmas between 2 mm and 10 mm, with promising results.

**Phase space reconstruction** A study on the reconstruction of the transverse beam phase space based on the projections of the 2D beam spot is ongoing. The tomography method is used in the software. Phase space tomography is based on the reconstruction of the transverse phase space in each plane by using several projections at different angles. The quadrupole scan method is used for taking beam projections at different rotation angles, and the filtered back projection technique reconstructs back the phase space.

## THE $\pi^3$ BEAM MONITOR

The $\pi^3$ beam monitor is based on a scintillating foil mounted on a moving support together with a miniaturized camera, which allows to reconstruct the beam distribution along the beam path, providing either an online video or a graphical reconstruction of the beam envelope. At the Bern medical cyclotron, the $\pi^3$ first prototype has been used to characterize the beam inside the PET-Mini Beamline (MBL) [8]. The MBL consists of a movable ensemble of one quadrupole doublet and two embedded steering magnets, mounted on a beamline of ~ 1 m long. This compact instrument will be used to irradiate solid targets and produce non-standard radioisotopes for medical and nuclear physics using a solid target.

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The main components of the $\pi^3$ detector are shown in Fig. 4. The scintillating foil is placed in one of the edges of the movable support. As in the case of the $\pi^2$, it consists of an aluminium foil coated with P47 and a camera. The camera used for this first prototype is a KKMoon 5 mm 2 m Mini Digital USB Endoscope Inspection Camera, with a diameter of 5 mm. The resolution of this camera is 640×480 pixels and it can record videos at 8 frames/second. The USB port of the camera is connected via a vacuum feedthrough to a Raspberry Pi computer, which is used for data acquisition. A pulley system is used to pull the cable of the miniaturized camera when it moves backwards along the MBL.

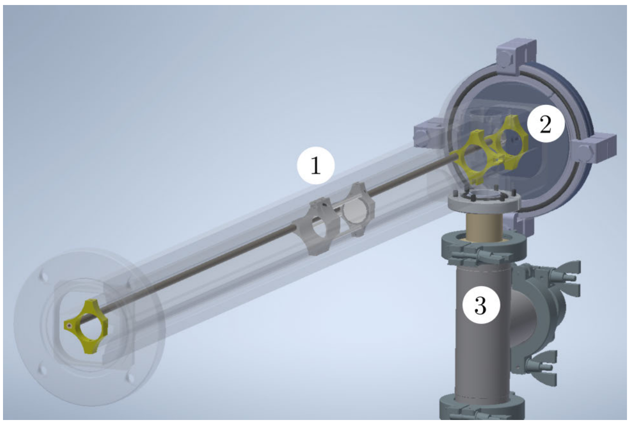

Figure 4: 3D view of the $\pi^3$ detector mounted inside of the MBL beampipe. The moving support (1), the motor (2) and the tube for the pulley system (3) are visible.

The movable support featuring the scintillating foil and the camera is connected to a long endless screw located all along the beam pipe of the MBL. This screw is linked to a stepper motor, which moves the support 1 mm per revolution and can perform very small steps down to 1/100 rotation. A thermal gap filler pad has been used between the camera and the support to allow heat conduction and prevent image degradation due to overheating of the camera.

### *The $\pi^3$ software*

During a measurement, the support is moved for a given distance and the camera view is recorded at the same time. Images can be analyzed by the $\pi^3$ software after pre-processing is applied, including a perspective correction and the application of a circular mask to cut off parts of the image which are not on the sensitive area of the scintillating screen, therefore reducing image noise. The goal of the analysis program, written in Python, is to fit a Gaussian distribution to all the individual images to reconstruct the beam shape at each acquired position inside the MBL. This Gaussian distribution describes the beam by means of the beam center and the covariance matrix. From the diagonal of the covariance matrix, the standard deviation $\sigma$ in both the horizontal and vertical planes can be calculated, which are directly connected to the $\beta$-function commonly used in beam dynamics.

### *First Beam Tests*

The $\pi^3$ prototype was installed in the BTL of the Bern cyclotron. The $\pi^2$ detector was also used to study the beam before entering to the MBL, as it shown in Fig. 5.

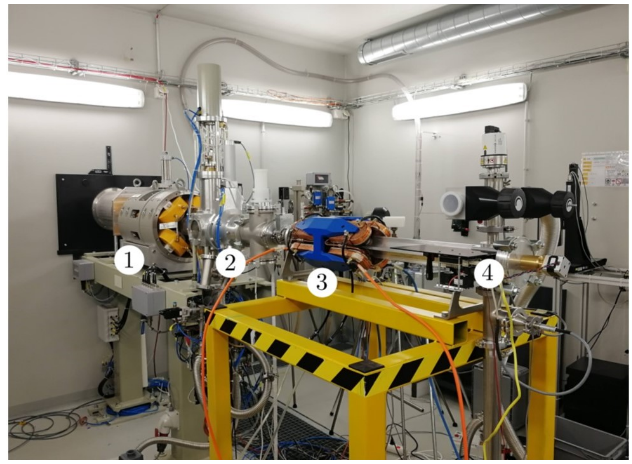

Figure 5: The setup for beam tests of the $\pi^3$ detector at the BTL of the Bern medical cyclotron: (1) one of the two BTL quadrupole doublets, (2) the $\pi^2$ detector, (3) the integrated magnets of the MBL, and (4) the controller and motor of the $\pi^3$ detector are visible.

The first tests were devoted to study the performance of the detector considering different optics configurations: (1) disabling the MBL, which is equivalent to move the $\pi^3$ detector along a drift space, (2) when a focalized beam enters the MBL, and (3) when a flat beam enters the MBL. In case (3), the two quadrupoles of the MBL are used to focalize the beam at the end of the line. The results are shown in Fig. 6.

The $\pi^3$ beam monitor has been able to measure the evolution of the beam width along the MBL, for a length of 660 mm, in several magnet configurations. For the first configuration (Fig. 6, left), the beam was focused by the BTL magnets, whereas the MBL magnets were disabled. In this configuration, the foil and the camera were moved along a drift space, and the sigma increase in both planes as expected from the transport matrix along a drift space. In the second case (Fig. 6, center), the beam is focused at the MBL entrance by the BTL magnets and refocused by the MBL magnets. In this case, the sigma inside the MBL shows the effect of the MBL quadrupoles, both with a current of 40 A. The net effect of the two quadrupoles is a small focusing of the beam in the vertical plane, as compared with the drift space, whereas in the horizontal plane it remains the same. In the third case, when a flat (not focalized) beam enters the MBL, the MBL magnets are able to slightly reduce the beam sigma in both planes, when the first quadrupole is disabled and the second one has a current of 75 A.

## CONCLUSIONS AND OUTLOOK

Two types of beam monitoring detectors have been developed at the LHEP, both using a scintillating foil and a

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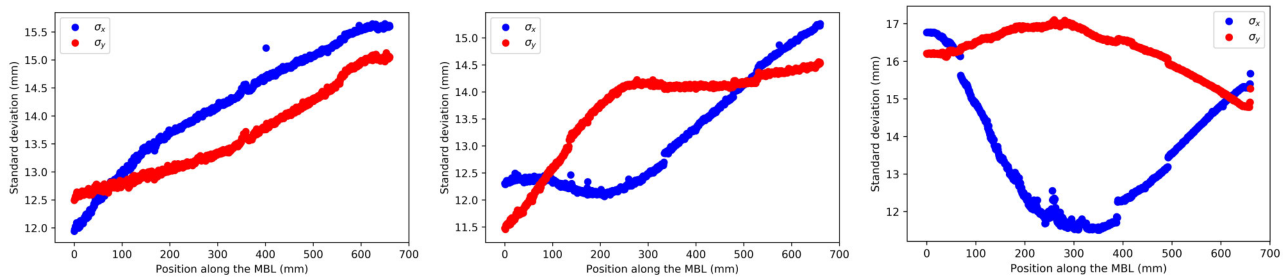


Figure 6: The sigma of the beam measured in both horizontal (red) and vertical (blue) planes, along the MBL length, for three different BTL and MBL magnet configuration: (1) when considering the MBL as a drift space (left), when focusing with the BTL and re-focusing with the MBL magnets (center), and when a flat beam enters the MBL (right).

camera to image the beam cross-section and measure beam position, size and current. The first detector, named $\pi^2$, is already used in a daily basis at the BTL of the Bern medical cyclotron. It is used to control the beam in experiments where beam currents from about hundred nA to a few µA are required. A complete Python software and a GUI have been developed for this detector, allowing additional features such as the tuning of the BTL magnet currents on-line and reconstruction of the transverse phase space. The second detector, named $\pi^3$, is a first prototype that has been tested with the BTL. The main differences between the $\pi^2$ and the $\pi^3$ detectors are the movable support of the $\pi^3$, which holds together the scintillating foil and the camera, and allowed to study the beam evolution along the MBL, and the location of the camera outside and inside the vacuum chamber, respectively. The results of the first beam tests show that the $\pi^3$ monitor can successfully be used to study and understand the effects of the optics of a beam line on an ion beam. Further developments of these two detectors are ongoing.

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