A detector based on silica fibers for ion beam monitoring in a wide current range

2016 JINST 11 P03027

(http://iopscience.iop.org/1748-0221/11/03/P03027)

Published by IOP Publishing for Sissa Medialab

Received: *February 1, 2016*
Accepted: *March 8, 2016*
Published: *March 29, 2016*

2016 JINST 11 P03027

A detector based on silica fibers for ion beam monitoring in a wide current range

M. Auger,[a] S. Braccini,[a,1] T.S. Carzaniga,[a] A. Ereditato,[a] K.P. Nesteruk[a] and P. Scampoli[a,b]

[a] *Albert Einstein Center for Fundamental Physics (AEC),*
Laboratory for High Energy Physics (LHEP), University of Bern,
Sidlerstrasse 5, CH-3012 Bern, Switzerland

[b] *Department of Physics "E. Pancini", University of Napoli Federico II,*
Complesso Universitario di Monte S. Angelo, I-80126, Napoli, Italy

E-mail: `saverio.braccini@lhep.unibe.ch`

Abstract: A detector based on doped silica and optical fibers was developed to monitor the profile of particle accelerator beams of intensity ranging from 1 pA to tens of μA. Scintillation light produced in a fiber moving across the beam is measured, giving information on its position, shape and intensity. The detector was tested with a continuous proton beam at the 18 MeV Bern medical cyclotron used for radioisotope production and multi-disciplinary research. For currents from 1 pA to 20 μA, Ce^{3+} and Sb^{3+} doped silica fibers were used as sensors. Read-out systems based on photodiodes, photomultipliers and solid state photomultipliers were employed. Profiles down to the pA range were measured with this method for the first time. For currents ranging from 1 pA to 3 μA, the integral of the profile was found to be linear with respect to the beam current, which can be measured by this detector with an accuracy of ~1%. The profile was determined with a spatial resolution of 0.25 mm. For currents ranging from 5 μA to 20 μA, thermal effects affect light yield and transmission, causing distortions of the profile and limitations in monitoring capabilities. For currents higher than ~1 μA, non-doped optical fibers for both producing and transporting scintillation light were also successfully employed.

Keywords: Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Instrumentation for particle-beam therapy

---

[1] Corresponding author.

doi:10.1088/1748-0221/11/03/P03027

Contents

1 Introduction

Beam monitoring is essential for commissioning and operating any kind of particle accelerator. The knowledge of the transverse beam profile is very often crucial. For instance, knowing the position and the profile of a particle beam is required in medical applications encompassing hadrontherapy and production of radioisotopes for diagnostics and therapy. Depending on the specific use of the accelerator, different current ranges and locations for beam monitoring devices have to be considered. In particular, proton or carbon ion beams with currents of the order of 1 nA or less are used in hadrontherapy. The precise and continuous control of the position, intensity and shape of such beams is needed during acceleration, transport and extraction to deliver the prescribed dose to the patient. For the production of radioisotopes, proton beams of high intensity, in the range 10–500 μA, are used and the control of target bombardment provides an efficient, safe and reliable production. Some research activities, such as radiobiology, particle detector or materials science developments, require low intensity beams, down to the pA range. Beam profilers are also fundamental tools for beam dynamics studies, as the measurement of the transverse beam emittance, a key parameter to optimize beam transport according to specific needs. A multi-purpose detector suitable for both low (pA) and high (μA) currents would represent an optimal solution to monitor beams in different irradiation conditions. Furthermore, a beam monitor detector should be easy to operate and compact in order to minimize the required space along the beam path.

A beam monitor detector based on doped silica and optical fibers has been conceived and designed at the AEC-LHEP in Bern. The first proof-of-concept prototype was tested with a 2 MeV pulsed beam at an average intensity of 0.8 μA [1]. This beam profiler, named Universal Beam Monitor (UniBEaM), fulfills the requirements of a simple, robust and compact device to be installed along beam transport lines or other critical locations and is suitable to monitor both pulsed and continuous beams. In this paper, we report on further original developments of the UniBEaM detector aimed at exploiting its potential in a wide intensity range from 1 pA to tens of μA. The results of the tests performed for the first time with a continuous beam extracted from the 18 MeV Bern medical cyclotron are presented.

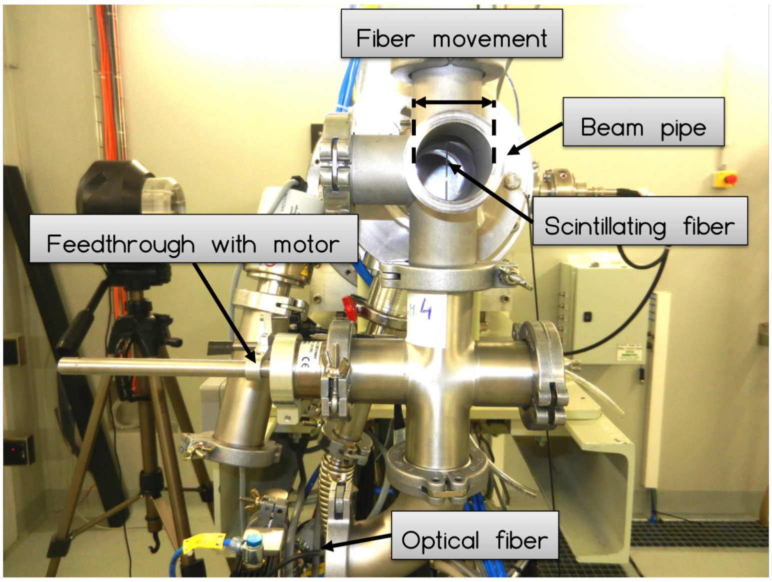

Figure 1. The UniBEaM detector installed on the beam transport line (BTL) at the Bern cyclotron laboratory. The main components and the movement of the fiber are highlighted.

2 Materials and methods

The UniBEaM detector is based on a single doped silica fiber moving transversally across the beam and is shown in figure 1. Charged particles passing through the fiber cause scintillation and yielded light is transported to a photon detector, whose electric signal is then digitized. For a KF-40 beam pipe, an 8 cm long scintillating fiber is coupled to a commercial optical fiber to transfer the optical signal over more than 20 meters with negligible losses. The sensing fiber has a diameter in the range of 200–400 μm, while the diameter of the core of the optical fiber is 400 μm. The coupling between the sensing and the optical fiber is realized by means of two cylindrical aluminum connectors to which the fibers are glued. The one with the scintillating fiber is screwed to the second one, which holds the optical fiber. This solution provides an optimal centering of the connection between the two polished surfaces of the fibers, thus minimizing light losses. Furthermore, the sensing fiber can be easily replaced. To guarantee a good transmission of the signal, optical grease is used for the connection. The fiber is moved by a vacuum tight linear motion feedthrough (Pfeiffer Vacuum DS040A) attached to a spindle drive and a brushless motor (Faulhaber 2232 S 024 BX4 CSD). The motor communication port and data acquisition module are integrated in a Raspberry Pi 2 board and controlled by a dedicated software. A standard beam scan consists of a series of 250 μm motor steps. The step, range and speed of the motion are adjustable. Each step is followed by the measurement of light intensity. The digitized signal from a photodiode or a photomultiplier is plotted online as a function of the position and stored. The fiber being the only sensing device, space along the beam path can be minimized, and several detectors can be put in sequence, as in the case of $x-y$ profile measurements. The interference between the fiber and the beam is minimal and profiles are measured in a non-destructive way and without affecting the operation of the accelerator. Furthermore, all the devices sensitive to radiation damage are located outside the bunker, allowing the use of this detector in presence of intense radiation fields.

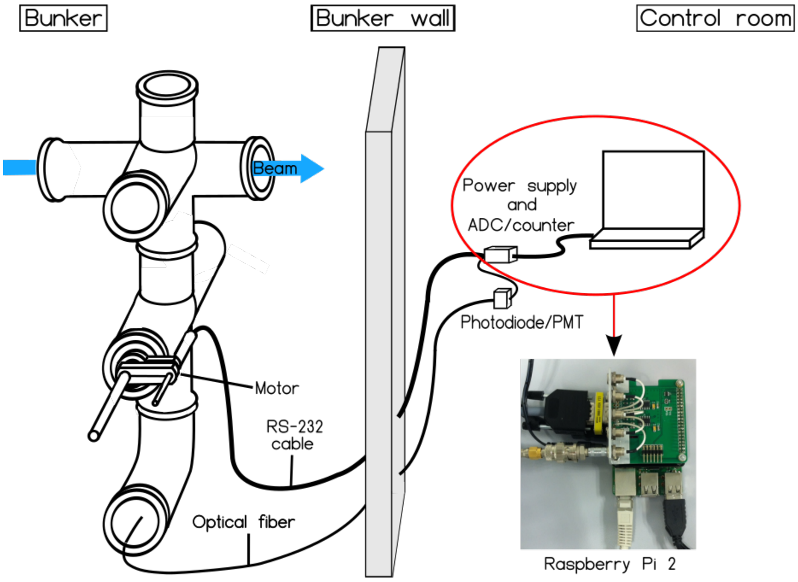

Figure 2. Typical experimental set-up of the UniBEaM detector. All the electronic devices are located in the control room.

Scintillation also occurs in non-doped silica fibers due to the presence of impurities. The feasibility of using an optical fiber for both producing and transmitting scintillation light was studied. This solution leads to a further simplification by avoiding the doped-optical fiber coupling.

Monitoring beams below 1 nA is challenging due to the limited yield of scintillation light. To achieve sensitivity to currents down to the pA range, a specific read-out system was designed. It consists of an ultra low noise single-photon counter (IDQ ID100-MMF100ULN), a NIM discriminator (LeCroy 623B), and a 100 MHz counting rate CAMAC scaler (LeCroy 2551). The single-photon counter is crucial for this operation mode. It is based on a solid state photomultiplier and allows to obtain a time resolution of 40 ps with a maximum counting rate of 20 MHz and a dark count rate of 20 Hz. With this system, the number of counts is recorded at each step of the motor for a duration of the order of 100 ms.

Beam tests with a continuous proton beam were performed at the cyclotron laboratory in operation at the Bern University Hospital (Inselspital), where a medical PET cyclotron is equipped with an external beam transport line (BTL). A detailed description of the Bern cyclotron laboratory can be found in [2]. In order to obtain low current beams, the accelerator was operated according to the procedure described in [3]. The experimental set-up is reported in figures 2 and 3. A Faraday cup for measuring the current is installed after the UniBEaM detector at the end of the BTL.

3 Measurements and results

For the measurements in the pA range, Ce^{3+} doped silica fibers were used due to their good scintillation properties [1, 4] and large light yield. The sensing fiber was moved through the beam and photon counting was performed at each position for 100 ms with the read-out system described above. Beam profiles for beam currents of 1 pA and 50 pA are reported in figure 4. The signal due to the beam is clearly visible with a signal-to-noise ratio of 10 and 320, at 1 pA and 50 pA,

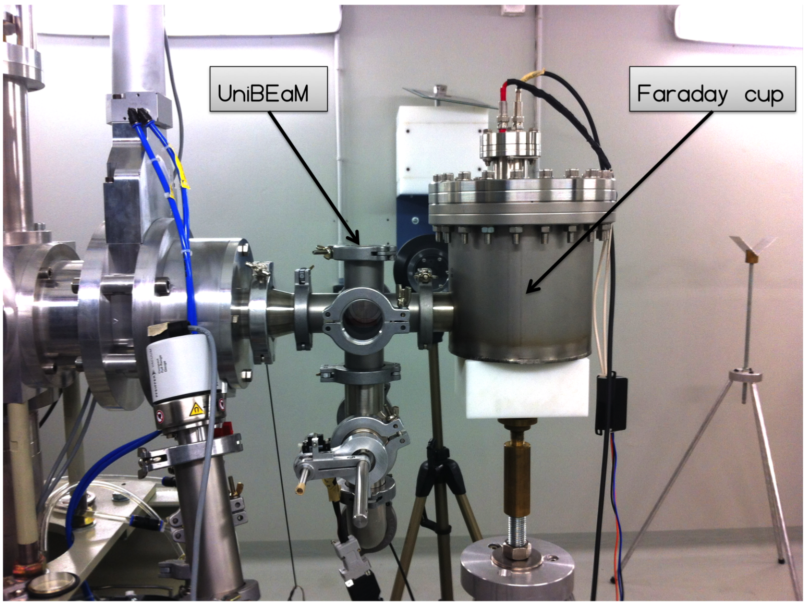

Figure 3. The UniBEaM detector and the Faraday cup installed on the BTL at the Bern cyclotron laboratory.

respectively. The profiles were measured with a spatial resolution of 0.25 mm, corresponding to one step of the motor.

The beam profile — the beam width in particular — can be precisely evaluated provided that the fiber response is linear with respect to the local beam intensity. To study this issue, beam profiles were collected for different currents in the pA range and the corresponding integrals calculated. The beam current was measured by the Faraday cup connected to a high-precision electrometer (Keysight B2985A). A good linearity of the response was found, as shown in figure 5. This allows to use the UniBEaM detector to measure the beam current with an accuracy of ∼ 1%. The system used for these measurements was developed for the pA range and saturates for currents exceeding about 100 nA.

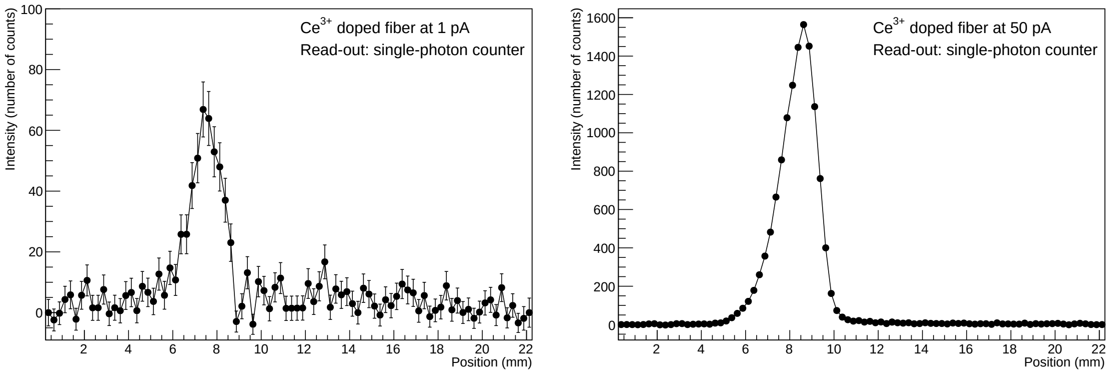

Figure 4. Profiles of a 1 pA beam (left) and a 50 pA beam (right).

2016 JINST 11 P03027

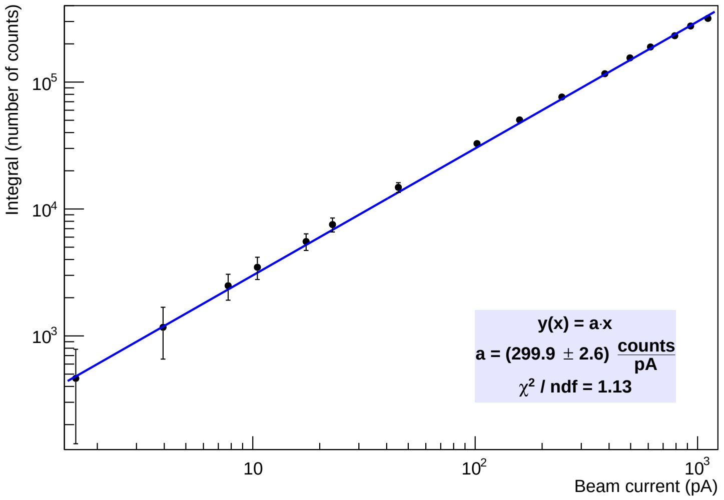

Figure 5. Integral of the beam profile as a function of beam current in the pA range. The parameters of the linear fit are reported in the inset.

Beam profile measurements in the nA range were performed with both Sb^{3+} [1, 5] and Ce^{3+} [1, 4] doped fibers. Two different read-out devices were used: a photodetector based on a silicon photodiode (Thorlabs SV2-FC) and a photomultiplier tube (PMT — Hamamatsu H8443). These two systems are less sophisticated and less expensive than that used for the pA range. The wavelength spectrum of Sb^{3+} doped fibers presents two peaks at 695 nm and 755 nm, thus matching the responsivity of both detectors. The photodiode provides sufficient gain to measure beam profiles for currents exceeding 20 nA, while a PMT is used at lower currents. Since the wavelength spectrum of Ce^{3+} doped fibers peaks at 490 nm, the responsivity of the silicon photodiode (0.25 A/W at 490 nm) is too low to measure scintillation light. Therefore, only the photomultiplier tube is used with Ce^{3+} doped fibers. As examples, beam profiles obtained at 5 nA with a Ce^{3+} doped fiber and at 100 nA with an Sb^{3+} doped fiber are presented in figure 6. The signal due to the beam is clearly visible with a signal-to-noise ratio of 100 and 170 at 5 nA and 100 nA, respectively. Also with this system, a good linearity of the response was found for currents up to 3 μA, as reported in figure 7.

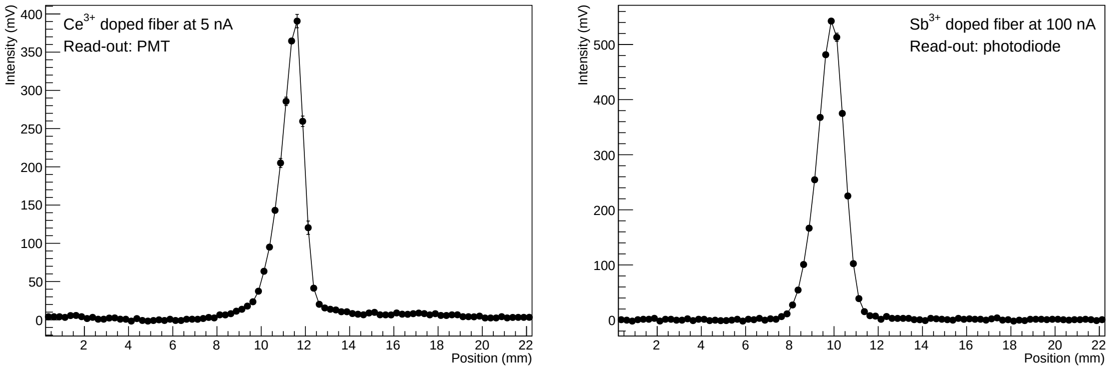

Figure 6. Profiles of a 5 nA beam (left) and a 100 nA beam (right) measured with Ce^{3+} and Sb^{3+} doped silica fibers.

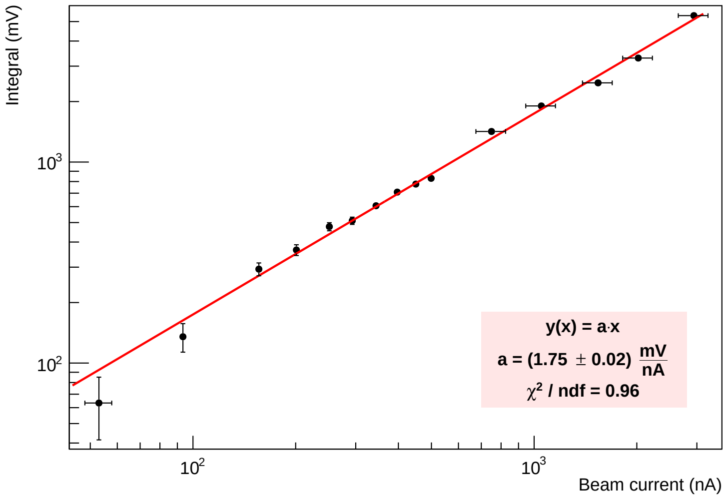

Figure 7. Integral of the beam profile as a function of beam current in the nA and μA range for an Sb^{3+} doped fiber. The parameters of the linear fit are reported in the inset.

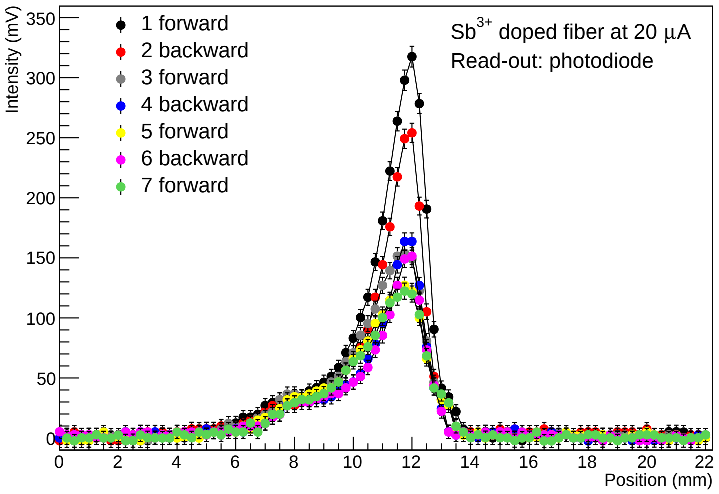

Figure 8. Seven consecutive acquisitions of the beam profile at a current intensity of 20 μA.

In this range, the UniBEaM detector can be used to measure the beam current with an accuracy of ~ 1%. The position of the maximum and the beam width are determined with a precision of 0.25 mm, corresponding to one motor step. Equivalent results were found for both Sb^{3+} and Ce^{3+} doped fibers.

The linear response of the sensing fiber was lost for currents exceeding a few μA due to thermal effects. Changes in the emission and transmission properties of the fiber lead to distortions of the beam profile, thus limiting the performance of UniBEaM. However, these effects can be reduced by decreasing the time to pass through the beam. The maximum power delivered to the fiber is reached when it passes through the center of the beam. For the measurements reported in this paper, the maximum power per beam current was estimated to be about 0.05 W/μA for beams of about 5 mm diameter. Distortion effects on the signal are clearly visible in figure 8, where seven successive profiles measured at a beam current of 20 μA using an Sb^{3+} sensing fiber are reported. The time of one beam scan is about 3 seconds. These data are in agreement with our previous measurements on the decrease of the light output due to temperature [1]. The maximum of the signal is found to decrease significantly during the first three scans. The signal decrease is less pronounced for the following scans due to the stabilization of the conditions of the fiber. The scintillating properties of the sensing fiber can be recovered by keeping the fiber outside the beam for about five minutes. These effects produce distortions of the profile and an accurate estimate of the beam width is compromised.

However, in some applications, such as radioisotope production, the knowledge of the beam position and an approximate estimation of the beam size are enough to optimize the irradiation. Furthermore, asymmetries of the beam profile can be measured. As an example, the left-sided tail of the profile due to stripping extraction in the cyclotron is visible in figure 8. In fact, not all of the H^- ions reach the stripper at the same turn, which results in a slightly higher energy for the protons stripped at larger radii and a slightly different exit angle. Different bending occurs in the quadrupoles of the BTL for off-axis proton beams and, for some settings as in the case of figure 8, the distributions due to particles with different energies do not overlap, giving the tail in the profile.

For currents in the μA range, the UniBEaM based on a non-doped optical fiber, as described in section 2, was tested for the first time. The minimum observable current is found to be about 1 μA when a photodiode is used as a read-out device. However, this minimum current depends on the particular kind of fiber, since the amount of impurities causing scintillation is not known. For instance, differences were found for the same type of commercial fibers coming from different production batches. A profile measured at a beam intensity of 1 μA is shown in figure 9. Also in this case, the tail due to stripping extraction in the cyclotron is clearly visible. As discussed above, the linearity with respect to the beam current does not hold in this current range. However, this simpler solution is proven to be suitable to monitor beams in the μA range with the same limitations as in the case of doped silica fibers.

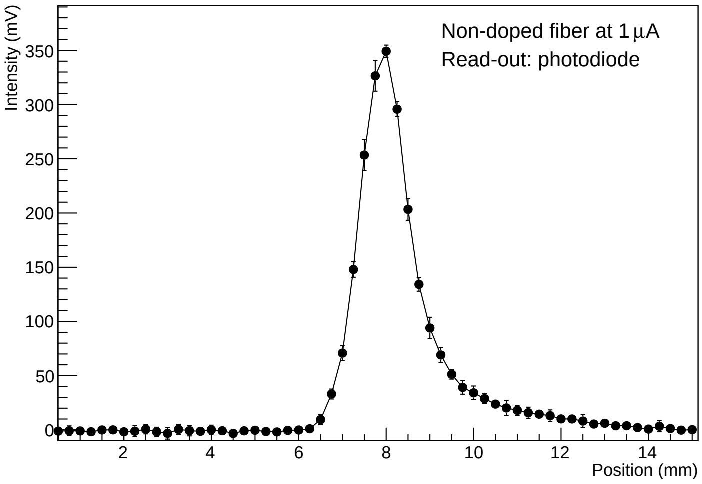

Figure 9. Beam profile recorded at 1 μA with a non-doped silica fiber.

4 Conclusions and outlook

The UniBEaM detector was developed as a compact and wide intensity range ion beam monitoring system. It was tested for the first time with a continuous proton beam at the Bern medical PET cyclotron. Beam profiles were measured for currents from 1 pA to 20 μA. Profiles down to the pA range were measured with this method for the first time. Fiber response is found to be linear with respect to beam intensity in the range from 1 pA to 3 μA, allowing for profile and intensity measurements. At higher currents, the linearity is lost due to thermal effects. Although the beam profiles are distorted in the 5–20 μA range, this system still provides information on beam position and width, useful for specific applications such as the production of medical radioisotopes. For currents in the μA range, a non-doped silica fiber was successfully used as a sensor.

Further developments and optimizations are on-going. The UniBEaM detector is employed in several research activities at the Bern cyclotron laboratory, as the assessment of radiation hardness of electronic components or the study of the transverse beam emittance [6]. Read-out systems based on single-photon counting and optical attenuators for currents exceeding 100 nA are currently under study. This solution could potentially lead to a read-out device able to cover the full intensity range from pA to tens of μA. Developments aimed at extending the intensity range above 20 μA are being pursued. Furthermore, the industrialization of the UniBEaM detector is on-going in collaboration with the Canadian company D-PACE [7].

Acknowledgments

We acknowledge contributions from LHEP engineering and technical staff. We are indebted to Valerio Romano and Jonas Scheuner from the Institute of Applied Physics (IAP) of the University of Bern and to Anna Vedda and Norberto Chiodini of the University of Milano-Bicocca for the useful discussions and for providing us with some fibers. We thank ID Quantique SA (Switzerland) and D-PACE Inc. (Canada) for their collaboration.

References

[1] S. Braccini et al., *A beam monitor detector based on doped silica and optical fibres*, 2012 *JINST* **7** T02001.

[2] S. Braccini et al., *The new Bern cyclotron laboratory for radioisotope production and research*, in *Proceedings of IPAC2011*, San Sebastian Spain (2011), THPS080, pg. 3618, http://jacow.org;
S. Braccini, *The new Bern PET cyclotron, its research beam line, and the development of an innovative beam monitor detector*, *AIP Conf. Proc.* **1525** (2013) 144.

[3] M. Auger et al., *Low current performance of the Bern medical cyclotron down to the pA range*, *Meas. Sci. Technol.* **26** (2015) 094006.

[4] N. Chiodini et al., *Ce-doped SiO2 optical fibers for remote radiation sensing and measurement*, *Proc. SPIE* **7316** (2009) 731616.

[5] M. Neff et al., *Broadband fluorescence of Sb^{3+}-doped silica fibres*, *Opt. Mater.* **33** (2010) 1.

[6] K.P. Nesteruk et al., *Study of the transverse beam emittance of the Bern medical cyclotron*, in *Proceedings of IBIC2015*, Melbourne Australia (2015), MOPB041.

[7] www.d-pace.com.