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Review

Beam monitor detectors for medical applications

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ABSTRACT

Beam monitoring is fundamental for any particle accelerator. In particular, it is a crucial issue in medical applications of particle physics due to the required high precision and reliability. Radioisotope production and cancer radiotherapy require specific beam monitor detectors. In this paper, three recently designed instruments are reviewed. One of them is a newly designed beam monitor detector based on doped silica and optical fibres. It represents a promising solution. This apparatus can be used with various types of beams and for both hadrontherapy and radioisotope production. For this reason, a more detailed description of this multipurpose detector is provided.

1. Introduction

Beam monitoring is essential for any particle accelerator either for commissioning or during regular operation. The precise control of the beam is crucial in medical applications, radioisotope production and cancer radiotherapy in particular.[1] Diagnostic devices are usually installed to obtain information for an optimal control during the whole irradiation process.

In hadrontherapy, tumours are irradiated with millimetre precision and an accurate beam monitoring allows fulfilling the requirements of the treatment plan. Radioisotope production requires an accurate control of the target bombardment for an efficient, safe and reliable production.

The wide spread of medical accelerators boosted the development of precise, robust and reliable instruments for beam monitoring. The beam intensities are different in isotope production and hadrontherapy. In the case of hadrontherapy, proton or carbon ion beams are used with currents of the order of 1 nA. For the production of radioisotopes, the beam intensity is much higher and currents in the range of 10–500 μA are used. Thus, there is a need for both specific detectors and multipurpose instruments.

In the case of hadrontherapy, several detectors have been recently developed.[2–4] Two of them are reviewed in this paper. They are based on sophisticated technologies, which are here only briefly described. Due to their cost, size and complexity, the number of installed devices is often very limited.

For the realization of a multipurpose, robust and relatively cheap instrument, simple but reliable technological solutions have to be employed. At the Laboratory for High Energy Physics of the University of Bern, a prototype based on doped silica and optical fibres has been recently realized and tested.[5]

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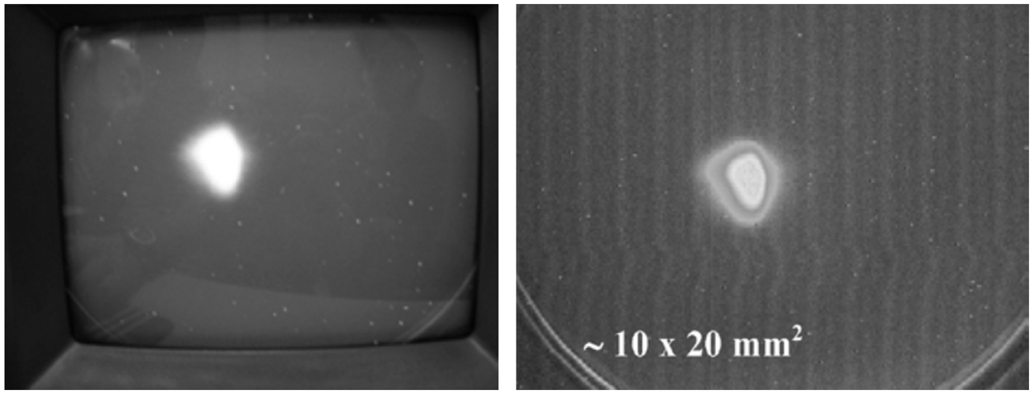

Fig. 1 – Beam profile measured with the beam monitor detector based on secondary electron emission by a thin foil. On the left, the CCD signal on a video monitor is presented. On the right, the signal digitized with a frame grabber is shown.[2]

The aim of this paper is to give a brief overview of current developments in beam monitoring. Three different detectors are reviewed. One of them represents a multipurpose instrument, and for this reason, a more detailed review is provided.

2. Beam monitor detectors for hadrontherapy

2.1. *A real-time beam monitor based on secondary electron emission by a thin foil*

This detector is based on secondary electron emission by an ion beam impinging on a metallic foil. The first prototype of this device has been developed by the TERA Foundation.[2] A thin Al foil is placed in the hadron beam path at 45° with respect to the beam direction. The energy lost by the beam in the foil is transferred to the electrons of the medium. Then, δ-rays are produced together with electrons of the energy below 50 eV that are called secondary electrons (SE). The number of SEs ejected from the foil is proportional to the local beam intensity. The SEs are accelerated to the energy of 20 keV and focused by an electrostatic field towards an imaging device. To measure the two-dimensional profile (Fig. 1) and the intensity of the beam a micro channel plate (MCP) with a phosphor screen have been used. The read-out is provided by a charged coupled device (CCD). In further development, a back-thinned monolithic pixel sensor was used.

The detector is precise and reliable but relatively large and expensive. It is suitable only for beam lines and, being designed for hadrontherapy, cannot be adopted for higher currents without major modifications. New developments are now pursued by the TERA Foundation and the Laboratory of High Energy Physics of the University of Bern.

2.2. *MATRIX: a pixel ionization chamber for on-line beam monitoring in hadrontherapy*

The MATRIX segmented ionization chamber[3] is made of five successive fibreglass frames, as shown in Fig. 2. It has been developed by the TERA Foundation and the INFN in Turin. The sensitive volume corresponds to the air gap between the cathode and anode foils. The anode foil and the read-out electronics represent the most innovative parts of this instrument.

The detector operates in air and consists of a 21 cm × 21 cm sensitive area divided in 1024 pixels of 6.5 mm × 6.5 mm. The 1024 channels are read out by 8 electronic boards capable of detecting charges down to 100 fC at 5 MHz. Each channel is equipped with a 16-bit digital counter whose output value is proportional to the integrated charge.

Using this detector, it is possible to obtain a two-dimensional map of a clinical beam. It has been successfully tested with a proton beam of 149 MeV at the Loma Linda University Medical Center, the first hospital-based proton therapy centre in the world.

3. A beam monitor detector based on doped silica and optical fibres

Many commonly used particle detectors are based on scintillation. Pure silica and plastic scintillating fibres are used in nuclear and particle physics.[6,7]

Plastic fibres are inappropriate for the monitoring of high current beams due to their low resistance to heat. They can be used in low current regime, e.g. in hadrontherapy. An array of plastic scintillators has been already developed for the Italian National Centre for Hadrontherapy CNAO.[8]

Contrary to plastic fibres, uncoated doped silica fibres have a very good resistance to heat. The resistance of Ce^{3+} doped quartz surfaces up to temperatures of 1300 °C has been reported.[9,10] Moreover, their scintillation properties are well suitable for a read-out with photomultiplier tubes (PMT).

Due to the scintillation properties and resistance to heat of uncoated doped silica fibres, they have been used for the construction of a beam monitor detector developed at the Laboratory for High Energy Physics in Bern.[5] The idea was to develop a universal and cheap detector for the monitoring of beams ranging from fractions of nA to several μA. The scheme of the designed detector is presented in Fig. 3. It is based on a single doped silica fibre moving transversally through the beam. Since uncoated doped silica fibres are very fragile and have a considerable attenuation length (several dB/m), a scintillating sensing fibre of only about 10 cm in length is used. The

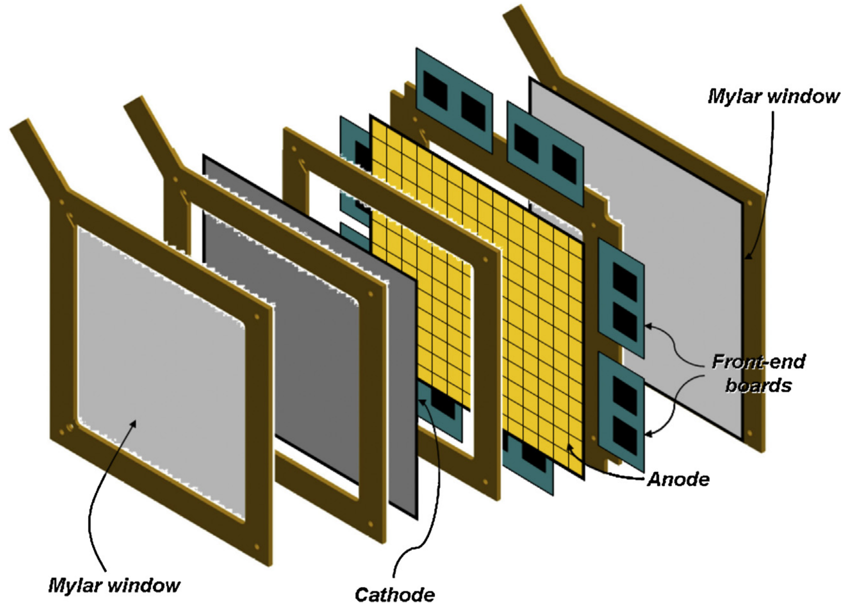

Fig. 2 – Schematic view of the MATRIX pixel ionization chamber.[3]

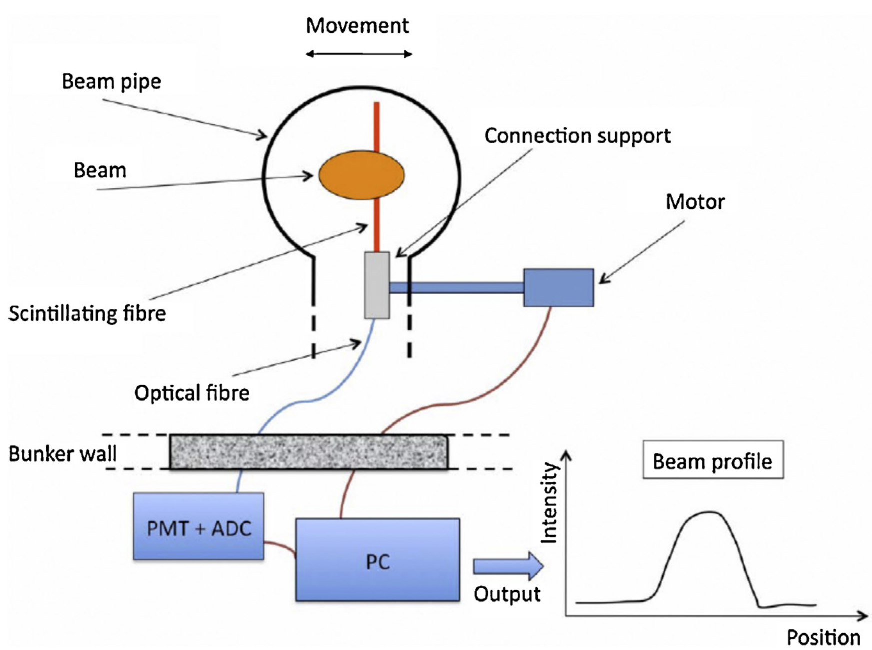

Fig. 3 – General scheme of a beam monitor detector based on a single moving scintillating doped silica fibre coupled to an optical fibre.[5]

sensing fibre is coupled to a commercial optical fibre to transport a signal. Thanks to this solution, a read-out device can be located far away from the detector. The sensor moves in the plane transversal to the beam and a signal is sent to a read-out device (PMT or a diode). A peak sensing ADC (analog-to-digital converter) is used to obtain the beam profile.

In the first prototype detector the movement was manual and the position of the sensor was adjusted using calibrated blocks. A new device equipped with a step motor and dedicated software is under development at the new cyclotron laboratory in Bern.[11]

For the first beam tests, a 2 MeV radio frequency quadrupole (RFQ) linac was used. It produces a H^- beam with spills at a repetition rate in the range 10–150 Hz. The peak current and the beam pulse width can be adjusted in the range of 1–5 mA and 1–25 μs, respectively. The detector installed on the RFQ accelerator is shown in Fig. 4. The sensing fibre was mechanically put in contact with the optical fibre inside a V-groove connection. The light losses with such a coupling were estimated to be of 20–50%.

The position of the sensing fibre was changed in the range of 0–26 mm with a 1 mm step. To obtain the beam profile, a PMT

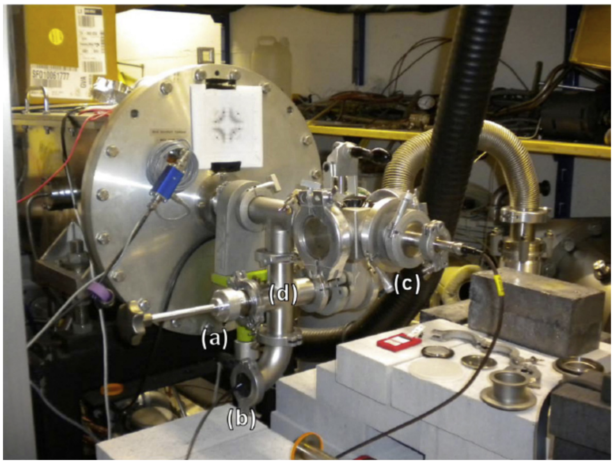

Fig. 4 – The first prototype detector installed on the RFQ accelerator. The linear motion (a) and the optical fibre feedthrough (b) are visible together with the Faraday cup (c) used for measuring the total intensity of each spill. The V-groove connection between the sensing and optical fibres is realized inside the cross joint (d).[5]

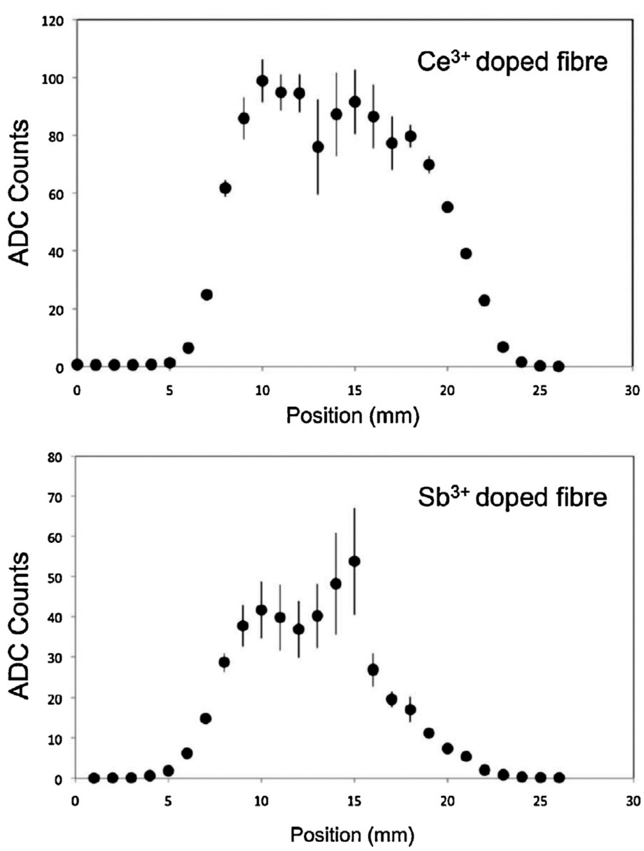

Fig. 5 – Beam profiles measured with the Ce^{3+} (top) and Sb^{3+} (bottom) doped silica fibre moved in steps of 1 mm through the beam. The double structure of the beam is a known effect of the accelerator. The error bars correspond to the RMS of the pulse height distributions and are mainly due to beam intensity fluctuations. The two profiles have been measured with different set-ups of the accelerator.[5]

was used for the read-out. For each position of the sensor, the average of the pulse height distribution has been calculated and the average value in the absence of the beam (pedestal) subtracted. The uncertainties correspond to the RMS (root mean square) of the ADC output distributions. The measurements were taken with Ce^{3+} and Sb^{3+} doped silica fibres. The total charge hitting the sensing fibre was estimated to be 2.7 μC with a total corresponding delivered dose on the volume of the fibre of 560 kGy. The results for cerium and antimony doped fibres are shown in Fig. 5 (top) and (bottom), respectively. The more detailed description of the performed measurements can be found in Ref. 5.

Further measurements with a fully automated system have already been successfully performed at the new Bern 18 MeV cyclotron laboratory for radioisotope production and research. The publication of the results is expected soon.

4. Conclusions

The two specific solutions developed for hadrontherapy and reviewed in this paper are a detector based on secondary electron emission by a thin foil and a segmented ionization chamber. They are both suitable for low currents (nA range). The advantage of the former is that the detector may be installed in beam lines. The latter is conceived to monitor the two-dimensional clinical beam profile in front of the patient.

In the field of radioisotope production, an innovative detector based on doped silica and optical fibres is proposed by the University of Bern. It is simple, robust and allows measuring the profile of the beam with times of the order of a few seconds. The effects due to radiation damage are minimal. This detector is versatile and can be used for beams in the range 1 nA–few μA. For this reason, it represents a multipurpose device.

Conflict of interest

None declared.

Financial disclosure

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