ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO10

PASSIVE TRANSVERSE BEAM PROFILER FOR REAL-TIME MONITORING FOR FLASH RADIOTHERAPY

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Abstract

Beam monitoring has always been crucial in radiotherapy to ensure precise dose delivery and reliable treatment. Passive real-time beam monitors are particularly advantageous because they provide beam information without influencing the beam itself. Such monitors are especially relevant under extreme beam conditions in newly explored modalities that use ultrahigh dose rates (> 40 Gy/s), such as FLASH radiotherapy, where conventional approaches struggle to measure/monitor beam effectively. The study presents a technique to measure the transverse beam size after exit window/nozzle of an accelerator using an all optical monitor. As the therapeutic beam must inherently traverse the ambient air path from the nozzle to the patient, the monitor passively captures beam-induced fluorescence along its path without affecting the beam. This contribution discusses the device in detail and presents one of the measurements taken on a 10.8 – 28 MeV proton beam at MC40 Cyclotron at University of Birmingham for 1 to 25 nA beam current. The measured beam sizes are consistent with those obtained using EBT-3 radiochromic film. A temporal resolution of 100 ms was achieved at 25 nA, demonstrating the feasibility of real-time beam monitoring.

INTRODUCTION

Beam monitoring in radiotherapy is essential for accelerator control and provides clinicians with feedback to verify that the prescribed dose is being delivered to the correct location. Online beam monitoring devices are typically calibrated against radiochromic films during pre-treatment setup [1], and during treatment they are the only devices providing information on the beam's position, shape, and size. The commonly preferred device, the ionization chamber is often installed at the exit window and exhibit nonlinear responses under extreme conditions, such as those encountered at FLASH dose rates [2]. Thus, although research has contributed to significant advances in beam instrumentation and dosimetry, beam monitoring at FLASH dose rates remains less developed compared to conventional dose rates across electron, proton, and hadron therapies.

Passive monitors measures the beam using the event inherently associated with the beam itself. A charged-particle beam excites neutral atoms or molecules along its trajectory. These excited species release energy through radiative de-excitation (Fluorescence), typically occurring on picosecond to nanosecond timescales, which are much shorter than their thermal transit times. As a result, the emitted photons originate locally along the beam path, allowing the beam position and size to be reconstructed from the fluorescence signal. Since the source of these photons is the neutral medium along the beam trajectory, often absent or intentionally removed in accelerator environments to create high vacuum, fluorescence monitors are not widely adopted in accelerator physics. However, in medical accelerators the therapeutic beam must necessarily travel through ambient air after exiting the window and before reaching the patient. This interaction inevitably generates fluorescence, which can in principle be exploited to passively monitor the beam. Previous attempts have used dark gas-filled tubes with Avalanche Photodiodes (APDs) scanned across the beam to reconstruct profiles [3] and have shown promising results, which can be developed further to improve temporal and spatial resolution.

In this study we demonstrate an all-optical setup capable of capturing the full transverse beam profile in real time, termed the Air Fluorescence Monitor (AFM). We describe the construction of the device and present beam profile measurements for proton beams from the MC40 cyclotron at the University of Birmingham, UK. Results are shown for beam currents ranging from 5 – 25 nA at 20 MeV, with AFM profiles compared against dose distributions obtained from EBT-3 film. The two methods show reasonable agreement within experimental constrains, demonstrating the feasibility of AFM for passive, real-time beam monitoring.

OPTICAL SETUP

Figure 1 shows the optical setup of the AFM: an imaging assembly consisting of a lens system to create an image of the beam traveling through air, a microchannel-based image intensifier, and a digital camera. The lens system is an apochromatic triplet with a 40 mm aperture having 80 % transmission across the 300 to 700 nm spectral range. This range covers the dominant fluorescence emission lines expected from air [4]. With a design focal length of 160 mm, the objective lens is positioned 320 mm from the beam axis achieve a magnification of –1 on the photocathode of the image intensifier. The beam image is projected onto the input of a Proxikit PKS 2581 TZ-V image intensifier. The image intensifier has a 25 mm diameter UV-enhanced S20 photocathode at the input that provides relatively high quantum efficiency up to 650 nm while maintaining a low dark count rate. The signal is then amplified by a double-stacked

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chevron microchannel plate (MCP) electron multiplier with a typical gain of 10^6 , before being converted back to light on a P43 phosphor screen supported by clear glass at the exit. The image intensifier preserves a 1:1 magnification, ensuring that the spatial fidelity of the beam image is maintained. The phosphor screen is imaged using a Basler acA1920-40gm CMOS camera equipped with a Sony IMX249 sensor (11.25 mm × 7.03 mm active area, 1920 × 1200 resolution). The internal optics of the camera were selected to achieve a 25:11 imaging ratio, enabling the full 25 mm diameter of the intensifier output to be mapped along the long edge of the sensor.

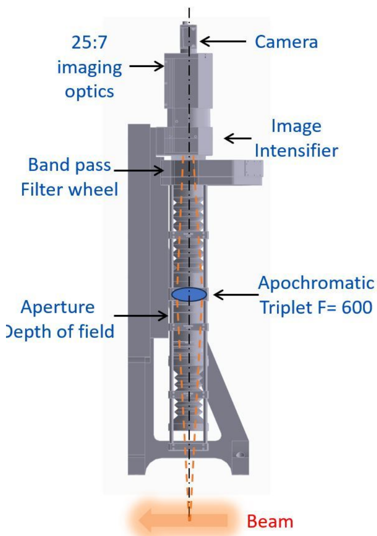

Figure 1: Schematic of the Air Fluorescence Monitor (AFM).

The optical setup is calibrated with a reference scale, which yields an effective resolution of 53.47 pixels/mm accounting small deviations of the alignment. The resulting measurement window spans 35.91 mm along the beam and 22.44 mm across it, corresponding to a photon collection solid angle of 0.01229 sr. This calibration is used to translate beam sizes recorded on the sensor into absolute length scale. The configuration of the optical setup provides the AFM with high sensitivity to low fluorescence yield while preserving spatial resolution across the beam of up to ~22 mm wide.

EXPERIMENT SETUP

The optical system was assembled with opto-mechanical mounts rigidly secured to aluminum frame and installed on top of a stainless-steel chamber positioned along the beamline as shown in Fig. 2. The chamber was a standard DN-160 CF 6-way vacuum vessel repurposed for this experiment. It was aligned such that the proton beam passed along the chamber axis, while the optical axis of the imaging setup was oriented perpendicularly, viewing the beam from above. The chamber was kept open to atmosphere in order to collect fluorescence emission generated in air. To minimize background light, the internal chamber walls were coated with graphite aerosol paint (black), and all experiments were performed in a dark room. Under these conditions, the measured background signal was reduced to the level of thermal noise at maximum detector sensitivity in the absence of the ion beam.

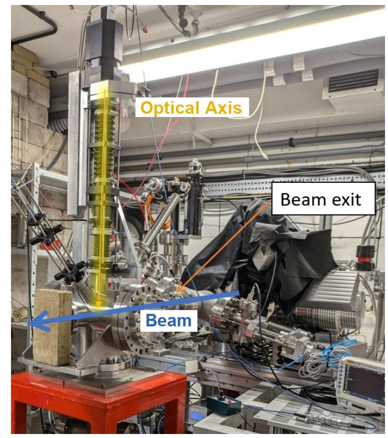

Figure 2: Experiment setup of AFM installed on the beamline of the MC-40 cyclotron.

The measurements were carried out for multiple sets of beam currents at three different beam energies of 10.8 , 16 , 20 MeV. The measurement point of AFM is defined by the intersection of the optical axis with the beam path and lies 160 mm downstream of the accelerator exit window. The exit window is a 0.25 mm thick titanium foil with Advance Marcus Ionization chamber installed on it to monitor the beam current. The beam profile was also recorded using an EBT-3 radiochromic film installed 160 mm after the measurement point of the AFM. Limited control from accelerator and scattering at the exit window can introduce an angular diversion resulting is slight variation of beam sizes as measured by AFM and EBT-3 film spaced 160 mm apart, which could not be avoided.

RESULTS

Figure 3 shows a raw image of a 20 MeV proton beam at 25 nA, recorded with 100 ms integration time. The image orientation reflects the projection of the beam onto a plane above the beam path. The image was acquired at 90 % image intensifier gain, corresponding to a photon multiplication factor of approximately 10^5. The absolute intensity corresponds to the total fluorescence yield across the full spectral sensitivity range of the photocathode, integrated along the line of sight of the imaging system.

Each image was processed to remove saturated pixels before defining a region of interest (ROI) where the signal-to-noise ratio was maximum. The ROI, shown as a red box in Fig. 3, corresponds to a 10 mm segment along the beam axis and 22.44 mm transverse to it. The pixel intensities within the ROI were averaged longitudinally and plotted as a function of transverse position using the pixel-to-mm

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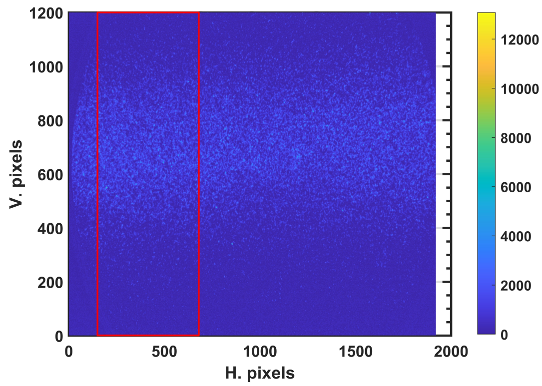

Figure 3: Raw image of the proton beam in air, captured by the AFM imaging system.

conversion estimated during calibration (53.47 pixels/mm). The resulting beam profile, together with a Gaussian fit, is shown in Fig. 4. The full width half maximum (FWHM) of the fit is used to represent the transverse size of the beam measured by the AFM, which is 7.42 mm.

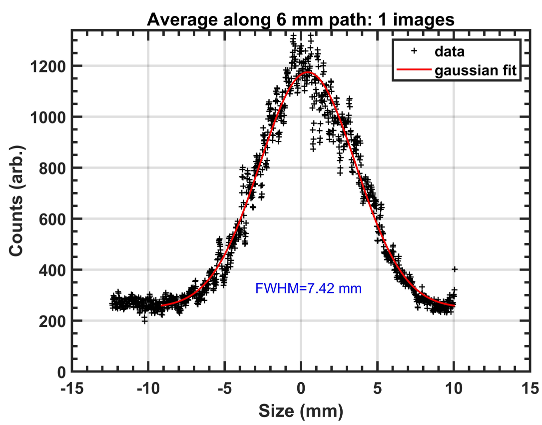

Figure 4: Transverse beam profile extracted from the AFM image in Fig. 3. A Gaussian fit is overlaid to estimate the beam width.

For comparison, beam profiles were also measured using EBT-3 radiochromic film under the same condition. The irradiated film was scanned in transmission mode with an Epson 11000XL scanner. EBT-3 films record dose as a function of change in optical density (OD) induced by irradiation. The OD of the irradiated film was estimated with reference to the OD of an unirradiated region of the film [5], for the red channel of the scanned 16-bit RGB image. This increase in OD was converted to dose values using a rational function from the calibration.

The calibration curve of rational function was generated using a separate set of slightly thinner EBT-3 films irradiated with known doses, following the standard method [6] and manufacturer's instructions . The measured OD values were fitted with a rational function, which was then applied to convert intensity profiles into dose. The calibration films indicated that the effective dose response was approximately 62 % of the measured intensity. i.e. the dose profiles were 62 % of the intensity profiles. This correction was applied to the film used to measure beam profile for comparison with AFM measurements.

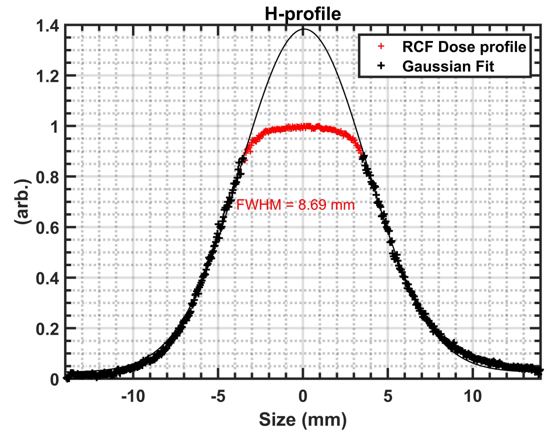

Figure 5: Dose profile of the beam measured using EBT-3 film.

The normalized dose profile obtained from the EBT-3 film is shown in Fig. 5. The flat-top region indicates saturation of the film and does not represent the true dose distribution; therefore, it was excluded from the Gaussian fit used to estimate the beam size in terms of FWHM, which was found to be 8.69 mm. A comparison shows that the FWHM measured by the AFM agrees within 15 % of the value obtained from the EBT-3 dose profile.

CONCLUSION

We have demonstrated a passive technique for beam size measurement using the fluorescence emission from a beam travelling through air. The method was implemented using a bespoke device, the Air Fluorescence Monitor (AFM), and tested with 20 MeV proton beams at various beam currents. The beam size measured by the AFM was found to be within 15 % of that obtained with the dose profile measurement of the EBT-3 radiochromic film following standard methods. The observed deviation can be attributed to the different measurement positions, with the AFM located 160 mm and the film 320 mm downstream of the accelerator exit window. The results demonstrate the AFM's capability to capture transverse beam profiles passively with integration times up to 100 ms (for a 25 nA beam at 20 MeV). These findings highlight the strong potential of the AFM for real-time beam monitoring in radiotherapy, at conventional and high dose rates.

ACKNOWLEDGEMENTS

The research was funded by STFC Grants ST/W002159/1 and ST/X002632/1, the HL-LHC-UK phase II project ST/T001925/1 funded by STFC, STFC Cockcroft core grant ST/V001612/1, and the Faculty Impact Fund, University of Liverpool. We thank Hao Zhang for his support to assemble the optical setup.

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REFERENCES

[1] T. Kojima, H. Sunaga, H. Takizawa, H. Hanaya, and H. Tachibana, "3–45 MeV/u ion beam dosimetry using thin film dosimeters", *Int. J. Radiat. Phys. Chem.*, vol. 68, no. 6, pp. 975–980, Dec. 2003. doi:10.1016/j.radphyschem.2003.02.001

[2] K. Petersson *et al.*, "High dose-per-pulse electron beam dosimetry — A model to correct for the ion recombination in the Advanced Markus ionization chamber", *Biol. Med. Phys. Biomed. Eng.*, vol. 44, no. 3, pp. 1157–1167, Feb. 2017. doi:10.1002/mp.12111

[3] A. Trigilio *et al.*, "The FlashDC project: Development of a beam monitor for FLASH radiotherapy", *Nucl. Instrum. Methods Phys. Res. A*, vol. 1041, p. 167334, Oct. 2022. doi:10.1016/j.nima.2022.167334

[4] M. Ave *et al.*, "Measurement of the pressure dependence of air fluorescence emission induced by electrons", *Astropart. Phys.*, vol. 28, no. 1, pp. 41–57, Sep. 2007. doi:10.1016/j.astropartphys.2007.04.006

[5] K. M. Holm, E. G. Yukihara, M. F. Ahmed, S. Greilich, and O. Jäkel, "Triple channel analysis of Gafchromic EBT3 irradiated with clinical carbon-ion beams", *Physica Med.*, vol. 87, pp. 123–130, Jul. 2021. doi:10.1016/j.ejmp.2021.06.009

[6] GAFchromic EBT-3 film, www.gafchromic.com