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TECHNICAL NOTE

MEDICAL PHYSICS

Technical note: Measurement of the bunch structure of a clinical proton beam using a SiPM coupled to a plastic scintillator with an optical fiber

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Abstract

Background: Recent proposals of high dose rate plans in protontherapy as well as very short proton bunches may pose problems to current beam monitor systems. There is an increasing demand for real-time proton beam monitoring with high temporal resolution, extended dynamic range and radiation hardness. Plastic scintillators coupled to optical fiber sensors have great potential in this context to become a practical solution towards clinical implementation.
Purpose: In this work, we evaluate the capabilities of a very compact fast plastic scintillator with an optical fiber readout by a SiPM and electronics sensor which has been used to provide information on the time structure at the nanosecond level of a clinical proton beam.
Materials and methods: A $3 \times 3 \times 3$ mm^3 plastic scintillator (EJ-232Q Eljen Technology) coupled to a 3×3 mm^2 SiPM (MicroFJ-SMA-30035, Onsemi) has been characterized with a 70 MeV clinical proton beam accelerated in a Proteus One synchrocyclotron. The signal was read out by a high sampling rate oscilloscope (5 GS/s). By exposing the sensor directly to the proton beam, the time beam profile of individual spots was recorded.
Results: Measurements of detector signal have been obtained with a time sampling period of 0.8 ns. Proton bunch period (16 ns), spot (10 μs) and interspot (1 ms) time structures could be observed in the time profile of the detector signal amplitude. From this, the RF frequency of the accelerator has been extracted, which is found to be 64 MHz.
Conclusions: The proposed system was able to measure the fine time structure of a clinical proton accelerator online and with ns time resolution.

KEYWORDS
fine time structure measurement, FLASH-RT, plastic scintillator fiber optic detector, RF frequency, time resolution

1 | INTRODUCTION

Radiation therapy (RT) has undergone significant technological advances in the last few decades, with proton therapy leading the way for increased dose conformality. New temporal patterns of dose modulation, such as ultra-high dose rate (UHDR) treatments, are emerging as a revolutionary tool to further increase the therapeutic ratio, sparing healthy tissues while maintaining a similar efficacy for tumor control. This has been termed the FLASH effect.[1] The differential biological effect of extreme average dose rates (100 Gy/s) compared to conventional ones (<0.1 Gy/s) aroused a huge interest to monitor the irradiation structure up to the nanosecond level.[2]

Furthermore, it has been shown that the onset of the FLASH effect is deeply influenced by the beam pulse structure (instantaneous dose-rate, dose-per-pulse or the number of pulses) as it modifies the cell's exposure to free radicals.[2–5] Therefore, fast and accurate monitoring of the time structure of the beam is vital for FLASH treatments, which challenges existing solutions. Bunch monitors are also crucial for some range verification techniques in particle therapy that rely on the prompt-gamma ray production within the patient.[6]

Conventional ionization chambers, which are typically used in clinical practice, may exhibit ion recombination effects[7] under FLASH irradiation conditions, which can reach dose rates as high as 10^9 Gy/s[2]. This compromises their use for online monitoring of UHDR treatments,[8] and correction factors need to be considered.[9] To deal with UHDR, the ultra-thin parallel plate ionization chamber (UTIC) has been proposed as an alternative solution.[8] A first prototype has been tested, which does not show ion recombination effects[8] at dose rates up to $2.5{\cdot}10^6$ Gy/s[8]. However, the intrinsic difficulty of fabricating this system and its low availability challenge its use. Recombination effects are less significant with proton beams. In this case, acceptable results have been obtained with commercially available models.[10,11] Recently, other IC-based dosimetry systems, including strip ionization chambers and multigap ionization chambers, have been also successfully proven to perform online FLASH beam monitoring.[12,13] Since recombination effects depend on the temporal structure of the proton beam, further studies are needed to assess the performance of these systems under different pulse structures.

Other detectors used in particle therapy and UHDR dosimetry include radiochromic films[14] or alanine and thermoluminescence detectors.[15,16] Although all of them are dose-rate independent, do not provide online information of the treatment. As an alternative, diamond detectors have been proposed to perform dosimetry in this area.[17] Despite their favorable features, the detector response at these dose per pulse conditions is still under investigation.[18,19]

Scintillators display unique features for UHDR measurements, including excellent temporal resolution (<<ns), dose and dose-rate linearity as well as high radiation hardness.[20,21] Moreover, they can be implemented in a great variety of geometries and in several dimensions.[22,23] Some previous work has been done with singular sensors capable of ultra-fast beam diagnosis in real time. However, most of them rely on an indirect measurement of the beam, which is based on the scattered photons,[20] prompt gamma rays[6] or neutrons.[24]

Due to their composition, organic plastic scintillators are by nature water-equivalent, energy-independent (down to of kV)[25] and can be placed along the proton beam path. Traditionally, plastic scintillators are coupled to PMTs for beam monitoring measurements.[26,27] However, SiPMs are more compact and have an easily tunable dynamic range, while displaying similar capabilities. Both the plastic scintillator and the SiPM can be coupled by means of optical fibers. This allows us to perform measurements in the control room, outside the treatment bunker, thereby preventing radiation damage to electronics. In addition, for clinical proton beams, the contribution of Cherenkov radiation to the measured signal can be neglected and the signal will be solely due to scintillation light.[28,29]

The use of scintillating fibers for online dosimetry has been previously reported in different RT modalities.[30–32] They exhibit several advantages over common commercial devices, such as small size, ruggedness, ease of use or high dynamic range. Not only do they produce scintillation light, but also they guide the produced optical photons with negligible self-absorption. The registered signal is directly proportional to the energy lost in the fiber, thus providing a direct measurement of the beam, without the need of relying on secondary radiation detection.

Recently, some experimental work has been done in the field of online FLASH-RT dosimetry with electrons[33,34] and protons.[35–37] Rahman et al.[38] used a 2D dosimetry system composed of a CMOS camera and a scintillation matrix to solve pencil beam scanning (PBS) protons with a temporal resolution of 10 ms. Another study by Kanouta et al.[36] improved this time resolution. Spot and transition durations in a PBS proton FLASH treatment were measured using four fiber-coupled inorganic scintillators. More recently, they have shown the feasibility of this system to perform time-resolved in-vivo dosimetry.[37] However, in both studies, the authors were limited by the sampling rate of the readout method, 50 kHz, corresponding to 20 μs. Casolaro et al.[35] have also reported on a small detector system with similar configuration as the one proposed in this work. In that case, the system was tested with proton FLASH beams and using several fast photosensors, including SiPMs and PMTs, but the minimum time resolution achieved was 100 ns.

In our work, we have evaluated the timing capabilities of a novel plastic scintillator fiber optic detector coupled to a SiPM and read out by an ultrafast data acquisition system (DAQ). The main design requirements for the clinical application of this prototype are direct exposure to the proton beam, compact size, ease of use, radiation hardness, while keeping superior (better than a few ns) time resolution and a dynamic range spanning from normal dose rate to UHDR conditions. The experiment consisted in the irradiation of the small plastic scintillator with a 70 MeV proton beam and subsequent analysis

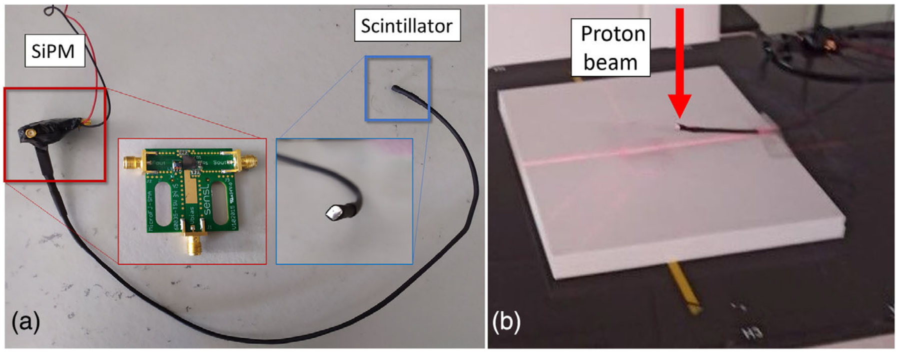

FIGURE 1 (a) Detector system used in the measurements: the plastic scintillator is coupled to a 3 × 3 mm^2 SiPM via an optical fiber. (b) Position of the detector and beam direction during the irradiations.

of the individual pulses with subnanosecond sampling. This allowed us to determine the RF frequency and the particle bunch structure of the clinical accelerator.

2 | MATERIALS AND METHODS

2.1 | Clinical facility

The experiment was carried out at the Quironsalud protontherapy center (Madrid, Spain). The facility is equipped with an IBA Proteus-ONE system,[39] consisting of a compact synchrocyclotron (S2C2) with a RF frequency in the 60–90 MHz range.[40] The single-room proton therapy system delivers protons with energies up to 230 MeV with a pulse repetition rate and width of 1000 μs and 10 μs, respectively.[41]

2.2 | The detector system

The measurements were performed using an in-house design, depicted in Figure 1a. A 3 × 3 mm^2 SiPM (MicroFJ-SMA-30035, Onsemi, formerly SensL)[42] was coupled to a 3 × 3 × 3 mm^3 fast plastic scintillator (Eljen Technology EJ-232Q) quenched with 0.5% of benzophenone.[43] The quencher renders the scintillator must faster, with rise and decay times of 110 ps and 700 ps, respectively,[44] at the expense of a reduced light yield. Both elements were coupled using an assembly of ten optical fibers with a diameter of 0.8 mm each and a length of 63 cm. To improve the optical coupling and fix the entire detector assembly, a layer of Norland Optical Adhesive 61 (NOA-61) was applied between the optical fibers and the SiPM and the plastic. Finally, a standard black heat-shrinkable tubing was used to cover the optical fiber and to protect the SiPM from external light.

The SiPMs were biased with a programmable voltage supply (Tenma 72–2550) at 28 V (22°C) which warrants that the detector was not saturated during the irradiations. The SiPM was mounted in a PCB board providing separate fast and slow signals, also from Onsemi (MicroFJ-SMA-30035-GEVB).[45] Both output signals from the SiPMs processing board were acquired by an 8-bit digital scope with a bandwidth of 350 MHz (Picoscope 6403D) and a sampling rate of up to 5 Gs/s. The time resolution of this assembly was tested with the fast timing setup in our laboratory[46] using 511-keV photons from a Na-22 source in gamma-gamma coincidence, considering Compton and photopeak regions. It was found to be less than 715 ps, limited mainly by the small scintillation light produced by the individual gamma photon in the plastic scintillator (Table 1). These values are in good agreement with coincidence resolving times of SiPMs coupled to plastic scintillators reported in other works,[44,46] and we conclude that they are very well suited for the proposed measurements.

TABLE 1 Time resolution (FWHM) for different SiPM[42,47] +optical coupler+plastic scintillator measured from coincidences for 511 keV gamma photons from a ^{22}Na source, using the methodology described in a previous work.[48]

SiPM	Fiber	Length (cm)	Time resolution (ps)
S13360-3075CS	Plastic coupled directly		58 (10)
MicroFJ-SMA-30035	Plastic coupled directly		128 (4)
S13360-3075CS	Set of fibers	60	638 (5)
MicroFJ-SMA-30035	Set of fibers	60	715 (5)
S13360-3075CS	Solid	10	176 (4)
S13360-3075CS	Solid	60	329 (5)

Note: Contribution from the PMT+LaBR detector has been subtracted from the total coincidence resolving time.

2.3 | Experimental methods

Throughout each irradiation, the detector was placed on the surface of the treatment couch perpendicular to the beam direction, as shown in Figure 1b. The irradiations

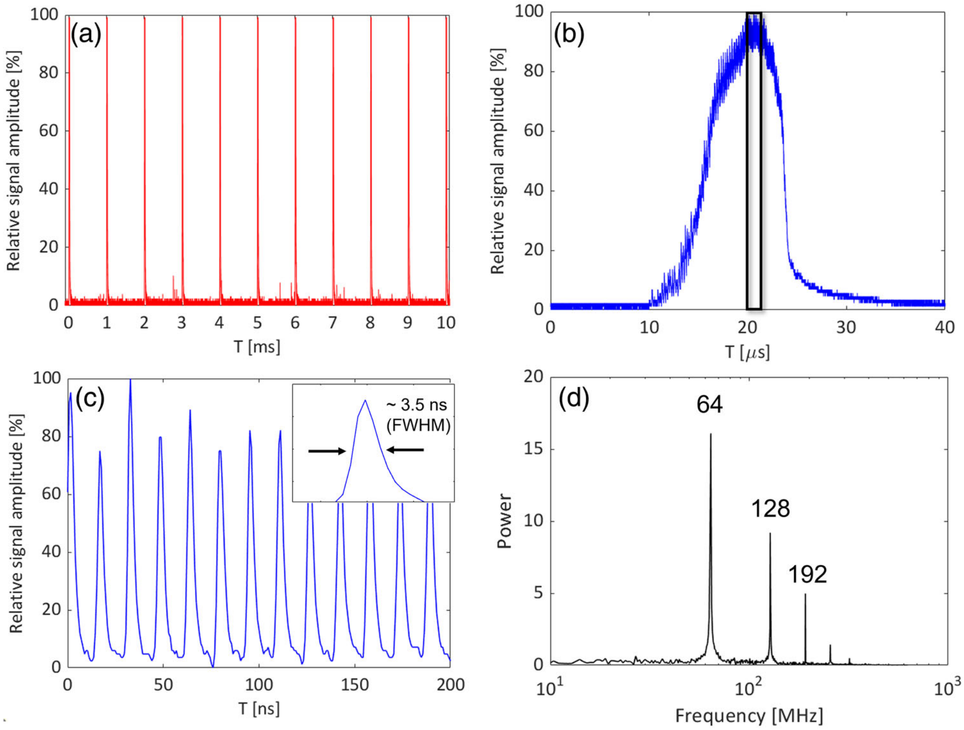

FIGURE 2 (a) Signal intensity as a function of time for a sequence of 10 spots delivered at 1 kHz. (b) Individual measurement of a single pulse. (c) 200 ns zoom of the fast output in the planar region of one pulse, indicated in Figure 2b. The signal shows a clear repetition pattern with spikes every 16 ns. The FWHM of the proton bunch is of the order of 3.5 ns. (d) FFT frequency spectra of the accelerator RF signal, which reveals an operating frequency of 64 MHz.

were made at the isocenter plane of a 70-MeV proton beam (8 mm^2 sigma spot size) with the beam current set to 8.98 nA.

Time measurements of the beam were performed with two different recording lengths. First, the beam signal was acquired for seven seconds with a sampling rate of 4.76 MS/s (210 ns in between samples), which was enough to resolve the 10 μs macropulses delivered at 1 kHz repetition rate. To resolve the time structure of these 10 μs proton pulses, the sampling rate was increased to 1.25 GS/s (0.8 ns). This high sampling rate allowed us to overcome the limitations reported in previous studies, consequently increasing the time resolution.[36,37]

The frequency spectrum of each pulse was obtained using the Fast Fourier Transform (FFT) spectrum analyzer tool available in MATLAB (R2021b). The analysis included a total of 2048 samples, with the sampling period set to the sampling interval of 0.8 ns.

3 RESULTS AND DISCUSSION

Figure 2a illustrates the characteristic pulse structure of the Proteus One accelerator in a 10-ms region taken from the first measurement, acquired during seven seconds. The 1 ms period has been extracted from it and corresponds to the expected 1 kHz pulse repetition rate of the accelerator.[40] This serves as a verification of the measurement procedures and time calibrations of the setup. This time structure was repeated during the full irradiation.

Figure 2b shows an individual acquisition of one micropulse. Each pulse has a characteristic width of 10 μs and ripples are observed due to the accelerator RF system. Figure 2c presents a 200 ns zoom over the intermediate region indicated in Figure 2b, corresponding to the fast signal. A clear repetition pattern with visible spikes can be observed. Examination of this region yields a micro-bunch period of 16 ns and a bunch width of about 3.5 ns FWHM.

The FFT frequency spectra resulting from the analysis of 2048 consecutive samples (~1.6 μs) in this region is shown in Figure 2d. The analysis reveals a main peak component at 64 MHz followed by other minor peaks with decreasing intensities resulting from the contribution of higher harmonics. FFT analysis of the set of 32 individual pulse measurements demonstrates the same characteristic frequency. This value is in the nominal RF range of the S2C2/Proteus ONE accelerator, which is between 60 and 90 MHz.[40]

Proton beam diagnosis systems based on scintillation dosimeters have been evaluated in silico[22] and experimentally[49] in several dimensions, also reporting nanosecond timing resolutions. New detector prototypes with a similar configuration have also been developed in the field of FLASH-RT with proton beams, and tests are ongoing in several clinical facilities. Previous systems have achieved sub-millisecond[36,37] or sub-microsend[35] temporal resolutions. In the current work, we have improved this value by including a high bandwidth and sampling rate digitizer and the signal was readout with a sub-nanosecond (0.8 ns) frame rate.

Although we report on a proof-of-concept experiment, the system can be readily implemented for online clinical monitoring, especially for small-field and multipoint dosimetry, which are typically used in FLASH-RT. To ensure the clinical observation of the FLASH effect, its reproducibility and translation, beam parameters must be thoroughly measured in vivo. A recent work performed by Ahsraf et al.[50] using a point scintillator detector has demonstrated this possibility in a murine model, by measuring the number of pulses and the dose per pulse. Moreover, if the exit dose is measured, the procedure becomes minimally invasive.

Thanks to the mechanical flexibility of the components employed in the current study, 2D and 3D monitoring of the beam can be also readily implemented to achieve spatial average dose-rate. This involves the use of several probes[36] covering the radiation field or the use of a scintillator matrix.[38] Spatial distribution measurements are especially relevant for larger fields, such as those achieved with spot scanning techniques, where contributions from remote spots with lower dose rates might affect the FLASH response.

4 | CONCLUSION

In this work, we have shown the feasibility of a plastic scintillator detector coupled to an optical fiber to build a nanosecond time-resolved proton monitor. The RF structure of a clinical accelerator has been measured in an individual proton pulse-by-pulse basis, with a system time resolution of 0.8 ns, leveling other proton bunch monitors based on plastic scintillators and better than similar available detection systems proposed in FLASH-RT. The signal has been FFT analyzed, and the resulting frequency is in the range of the nominal values of the accelerator. The system has an adaptable dynamic range, with gain easily controlled in a very large range, to avoid saturation even with very high dose rates. Thus, it is very well suited to perform FLASH-RT online monitoring with superior time resolution.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to disclose.

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REFERENCES

1. Favaudon V, Caplier L, Monceau V, et al. Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice. *Sci Transl Med*. 2014;6(245):245ra293. https://doi.org/10.1126/scitranslmed.3008973
2. Friedl AA, Prise KM, Butterworth KT, Montay-Gruel P, Favaudon V. Radiobiology of the FLASH effect. In: *Medical Physics*. Vol 49, John Wiley and Sons Ltd; 2022:1993-2013. https://doi.org/10.1002/mp.15184
3. Labarbe R, Hotoiu L, Barbier J, Favaudon V. A physicochemical model of reaction kinetics supports peroxyl radical recombination as the main determinant of the FLASH effect. *Radiother Oncol*. 2020;153:303-310. https://doi.org/10.1016/j.radonc.2020.06.001
4. Jansen J, Beyreuther E, García-Calderón D, et al. Changes in Radical Levels as a Cause for the FLASH effect: impact of beam structure parameters at ultra-high dose rates on oxygen depletion in water. *Radiother Oncol*. 2022;175:193-196. Published online August 2022:S0167814022042451. https://doi.org/10.1016/j.radonc.2022.08.024
5. Espinosa-Rodriguez A, Sanchez-Parcerisa D, Ibáñez P, et al. Radical production with pulsed beams: understanding the transition to FLASH. *Int J Mol Sci*. 2022;23(21):13484. https://doi.org/10.3390/ijms232113484
6. Magalhaes Martins P, Dal Bello R, Seimetz M, Hermann G, Kihm T, Seco J. A single-particle trigger for time-of-flight measurements in prompt-gamma imaging. *Front Phys*. 2020;8:169. https://doi.org/10.3389/fphy.2020.00169
7. Kaiser FJ, Bassler N, Tölli H, Jäkel O. Initial recombination in the track of heavy charged particles: numerical solution for air filled ionization chambers. *Acta Oncol*. 2012;51(3):368-375. https://doi.org/10.3109/0284186X.2011.626452
8. Gómez F, Gonzalez-Castaño DM, Fernández NG, et al. Development of an ultra-thin parallel plate ionization chamber for

dosimetry in FLASH radiotherapy. *Med Phys*. 2022;49(7):4705-4714. Published online 2022. https://doi.org/10.1002/mp.15668
9. Leite AMM, Cavallone M, Ronga MG, et al. Ion recombination correction factors and detector comparison in a very-high dose rate proton scanning beam. *Phys Med*. 2023;106:102518. https://doi.org/10.1016/j.ejmp.2022.102518
10. Lee E, Lourenço AM, Speth J, et al. Ultrahigh dose rate pencil beam scanning proton dosimetry using ion chambers and a calorimeter in support of first in-human FLASH clinical trial. *Med Phys*. 2022;49(9):6171-6182. https://doi.org/10.1002/mp.15844
11. Diffenderfer ES, Verginadis II, Kim MM, et al. Design, implementation, and in vivo validation of a novel proton FLASH radiation therapy system. *Int J Radiat Oncol*. 2020;106(2):440-448. https://doi.org/10.1016/j.ijrobp.2019.10.049
12. Yang Y, Shi C, Chen C, et al. A 2D strip ionization chamber array with high spatiotemporal resolution for proton pencil beam scanning FLASH radiotherapy. *Med Phys*. 2022;49(8):5464-5475. https://doi.org/10.1002/mp.15706
13. Giordanengo S, Guarachi LF, Braccini S, et al. Fluence beam monitor for high-intensity particle beams based on a multi-gap ionization chamber and a method for ion recombination correction. *Appl Sci*. 2022;12(23):12160. https://doi.org/10.3390/app122312160
14. Sanchez-Parcerisa D, Sanz-Garciá I, Ibánez P, et al. Radiochromic film dosimetry for protons up to 10 MeV with EBT2, EBT3 and unlaminated EBT3 films. *Phys Med Biol*. 2021;66(11):115006. https://doi.org/10.1088/1361-6560/abfc8d
15. Ashraf MR, Rahman M, Zhang R, et al. Dosimetry for FLASH radiotherapy: a review of tools and the role of radioluminescence and Cherenkov emission. *Front Phys*. 2020;8:32. https://doi.org/10.3389/fphy.2020.00328
16. Esplen N, Mendonca MS, Bazalova-Carter M. Physics and biology of ultrahigh dose-rate (FLASH) radiotherapy: a topical review. *Phys Med Biol*. 2020;65(23):23TR03. https://doi.org/10.1088/1361-6560/abaa28
17. Berdermann E, Blasche K, Moritz P, Stelzer H, Voss B. The use of CVD-diamond for heavy-ion detection. *Diam Relat Mater*. 2001;10(9-10):1770-1777. https://doi.org/10.1016/S0925-9635(01)00443-5
18. Marinelli M, Felici G, Galante F, et al. Design, realization, and characterization of a novel diamond detector prototype for FLASH radiotherapy dosimetry. *Med Phys*. 2022;49(3):1902-1910. https://doi.org/10.1002/mp.15473
19. Kranzer R, Schüller A, Bourgouin A, et al. Response of diamond detectors in ultra-high dose-per-pulse electron beams for dosimetry at FLASH radiotherapy. *Phys Med Biol*. 2022;67(7):075002. https://doi.org/10.1088/1361-6560/ac594e
20. Sanchez-Tembleque V, Sanchez-Parcerisa D, Valladolid-Onecha V, Fraile LM, Udias JM. Simultaneous measurement of the spectral and temporal properties of a LINAC pulse from outside the treatment room. *Radiat Phys Chem*. 2019;158:1-5. https://doi.org/10.1016/j.radphyschem.2019.01.002
21. Liao S, Erasmus R, Jivan H, Pelwan C, Peters G, Sideras-Haddad E. A comparative study of the radiation hardness of plastic scintillators for the upgrade of the Tile Calorimeter of the ATLAS detector. *J Phys Conf Ser*. 2015;645:012021. https://doi.org/10.1088/1742-6596/645/1/012021
22. Iakovenko V, Jaffray DA. Development of photonic detector system for ultra-fast beam diagnostics in proton radiotherapy: the proof of concept. In: *Journal of Physics: Conference Series*. Vol 2167. IOP Publishing Ltd; 2022. https://doi.org/10.1088/1742-6596/2167/1/012030
23. Beddar S. 3D dosimetry for proton therapy. In: *Journal of Physics: Conference Series*. Vol 1305. Institute of Physics Publishing; 2019. https://doi.org/10.1088/1742-6596/1305/1/012038
24. Charyyev S, Liu R, Yang X, et al. Measurement of the time structure of FLASH beams using prompt gamma rays and secondary neutrons as surrogates. *arXiv preprint arXiv:2209.01178*, 2022.
25. Archambault L, Arsenault J, Gingras L, Beddar AS, Roy R, Beaulieu L. Plastic scintillation dosimetry: optimal selection of scintillating fibers and scintillators. *Med Phys*. 2005;32(7):2271-2278. https://doi.org/10.1118/1.1943807
26. Beddar AS, Mackie TR, Attix FH. Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations. *Phys Med Biol*. 1992;37(10):1883-1900. https://doi.org/10.1088/0031-9155/37/10/006
27. Beddar AS, Mackie TR, Attix FH. Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements. *Phys Med Biol*. 1992;37(10):1901-1913. https://doi.org/10.1088/0031-9155/37/10/007
28. Wootton L, Holmes C, Sahoo N, Beddar S. Passively scattered proton beam entrance dosimetry with a plastic scintillation detector. *Phys Med Biol*. 2015;60(3):1185-1198. https://doi.org/10.1088/0031-9155/60/3/1185
29. Darafsheh A, Taleei R, Kassaee A, Finlay JC. The visible signal responsible for proton therapy dosimetry using bare optical fibers is not Čerenkov radiation: Čerenkov radiation is not responsible for proton dosimetry. *Med Phys*. 2016;43(11):5973-5980. https://doi.org/10.1118/1.4964453
30. Archer J, Madden L, Li E, Wilkinson D, Rosenfeld A. 2D photon dosimetry with a scintillation fibre optic dosimeter. *Radiat Phys Chem*. 2020;166:108490. https://doi.org/10.1016/j.radphyschem.2019.108490
31. Ding L, Wu Q, Wang Q, Li Y, Perks RM, Zhao L. Advances on inorganic scintillator-based optic fiber dosimeters. *EJNMMI Phys*. 2020;7(1):1-23. https://doi.org/10.1186/s40658-020-00327-6
32. Yang Y, Yang CP, Xin J, et al. Performance of a plastic scintillation fiber dosimeter based on different photoelectric devices. *Nucl Sci Tech*. 2021;32(11):120. https://doi.org/10.1007/s41365-021-00965-0
33. Jeong DH, Lee M, Lim H, et al. Optical filter-embedded fiber-optic radiation sensor for ultra-high dose rate electron beam dosimetry. *Sensors*. 2021;21(17):5840. https://doi.org/10.3390/s21175840
34. Poirier Y, Xu J, Mossahebi S, Therriault-Proulx F, Sawant A. Technical note: characterization and practical applications of a novel plastic scintillator for online dosimetry for an ultrahigh dose rate (FLASH). *Med Phys*. 2022;49(07):4682-4692.
35. Casolaro P, Braccini S. An innovative detection system based on plastic scintillators, optical fibers, and fast photosensors for dosimetry in FLASH radiotherapy PROOF (PRecision dOsimetry in FLASH radiotherapy with Optical Fibers) View project Optorad View project. Published online 2022. doi: 10.13140/RG.2.2.27532.18567
36. Kanouta E, Johansen JG, Kertzscher G, Sitarz MK, Sørensen BS, Poulsen PR. Time structure of pencil beam scanning proton FLASH beams measured with scintillator detectors and compared with log files. *Med Phys*. 2022;49(3):1932-1943. https://doi.org/10.1002/mp.15486
37. Kanouta E, Poulsen PR, Kertzscher G, Sitarz MK, Sørensen BS, Johansen JG. Time-resolved dose rate measurements in pencil beam scanning proton FLASH therapy with a fiber-coupled scintillator detector system. *Med Phys*. 2022. Published online December 29, 2022:mp.16156. https://doi.org/10.1002/mp.16156
38. Rahman M, Brůža P, Langen KM, et al. Characterization of a new scintillation imaging system for proton pencil beam dose rate measurements. *Phys Med Biol*. 2020;65(16):165014. https://doi.org/10.1088/1361-6560/ab9452
39. Pidikiti R, Patel BC, Maynard MR, et al. Commissioning of the world's first compact pencil-beam scanning proton therapy system. *J Appl Clin Med Phys*. 2018;19(1):94-105. https://doi.org/10.1002/acm2.12225
40. Henrotin S, Abs M, Forton E, et al. COMMISSIONING AND TESTING OF THE FIRST IBA S2C2. 2016.
41. Mazal A, Vera Sanchez JA, Sanchez-Parcerisa D, et al. Biological and mechanical synergies to deal with proton therapy pitfalls:

minibeams, FLASH, Arcs, and Gantryless rooms. *Front Oncol*. 2021;10:6. https://doi.org/10.3389/fonc.2020.613669
42. J-SERIES SIPM: Silicon Photomultiplier Sensors, J-Series (SiPM). Accessed January 18, 2023. https://www.onsemi.com/pdf/datasheet/microj-series-d.pdf
43. EJ-232, EJ-232Q - Fast Timing Plastic Scintillator - Eljen Technology. Accessed January 18, 2023. https://eljentechnology.com/products/plastic-scintillators/ej-232-ej-232q
44. Wen X, Hayward JP. Time resolution measurements of EJ-232Q with single- and dual-sided readouts. *IEEE Trans Nucl Sci*. 2020;67(9):2081-2088. https://doi.org/10.1109/TNS.2020.3010469
45. MICROFJ-SMA-30035-GEVB. Accessed January 18, 2023. https://www.onsemi.com/design/tools-software/evaluation-board/microfj-sma-30035-gevb
46. Benito J, Garcia-Diez M, Sanchez-Tembleque V, Fraile LM, Udias JM. Performance study of plastic scintillators coupled to SiPM for fast-timing measurements. In: *2021 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*. IEEE; 2021:1-3. https://doi.org/10.1109/NSS/MIC44867.2021.9875794
47. S13360-3075CS. Accessed January 18, 2023. https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf
48. Sanchez-Tembleque V, Vedia V, Fraile LM, Ritt S, Udias JM. Optimizing time-pickup algorithms in radiation detectors with a genetic algorithm. *Nucl Instrum Methods Phys Res Sect Accel Spectrometers Detect Assoc Equip*. 2019;927:54-62. https://doi.org/10.1016/j.nima.2019.02.017
49. Kim SH, Lee JW, Jung WS, Ahn JK, Jung MH, Kim YJ. Three-dimensional measurement of a proton beam profile at KOMAC with a scintillating fiber detector. *Nucl Instrum Methods Phys Res Sect Accel Spectrometers Detect Assoc Equip*. 2022;1034:166832. https://doi.org/10.1016/j.nima.2022.166832
50. Ashraf MR, Rahman M, Cao X, et al. Individual pulse monitoring and dose control system for pre-clinical implementation of FLASH-RT. *Phys Med Biol*. 2022;67(9):095003. https://doi.org/10.1088/1361-6560/ac5f6f

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