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Thin LGADs and thin silicon diodes for applications in radiotherapy

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Low gain avalanche diodes (LGADs) and thin n-on-p silicon diodes, when read out by fast and custom electronics, exhibit characteristics that make them promising candidates for the development of new detectors for clinical applications such as beam commissioning, diagnostics and monitoring, dosimetry, and online treatment delivery verification. Compared to gas ionization chambers, these detectors offer significantly higher sensitivity, enabling the detection of single particles at fluxes of up to 10^8 particles/cm²s—sufficient to cover the entire clinical intensity range of carbon ion therapy and approximately one order of magnitude lower for proton therapy. Various front-end electronics have been developed and characterized for readout configurations, ranging from single channels (pads or strips) to arrays of up to 144 strips. These systems have been applied to single-particle identification for beam monitors in particle therapy, as well as to two-dimensional beam monitoring and dosimetry in ultra-high dose rate and spatially fractionated radiotherapy. This review summarizes the detectors based on LGADs and thin n-on-p silicon diodes developed within the INFN-CSN5 projects MoVeIT, SIG, and FRIDA. Specifically, we present a 2.7×2.7 cm² particle counter for measuring beam fluence and position, a beam energy detector based on the primary particle's time-of-flight, a setup for studying beam time structure at the nanosecond scale, and a system for range verification *via* prompt gamma timing. Current advances in various technologies are reviewed, together with challenges and future perspectives on the application of LGADs and thin silicon diodes in radiotherapy.

KEYWORDS

thin silicon sensors, single-particle sensitivity, LGAD, beam monitoring, particletherapy

1 Introduction

Low gain avalanche diodes (LGADs) are silicon detectors with a specially designed gain layer to provide moderate internal charge multiplication, typically in the range of ~ 5 – $50\times$ (Pellegrini et al., 2014; Paternoster et al., 2017; Gabriele, 2021). When fabricated with thin active thicknesses of approximately 25–60 μm , LGADs exhibit features of interest for particle therapy applications, enabling developments of new detectors for fast beam commissioning, diagnostics and monitoring (Monaco et al., 2023; Villarreal et al., 2023;

Vignati et al., 2023), microdosimetry (Missiaggia et al., 2020), online range verification (Heller et al., 2025; Ranjbar et al., 2025), stopping power measurements (Werner et al., 2024), and medical imaging (Ulrich-Pur et al., 2022). Moreover, thin n-on-p silicon diodes without internal gain have been characterized by our group for single carbon ion discrimination and timing (Data et al., 2024; Montalvan Olivares D. M. et al., 2025), for beam monitoring in ultra-high dose rate (UHRD) scenarios (Vignati et al., 2020a; Medina et al., 2025), and in spatially fractionated radiotherapy (Medina et al., 2024), where the large charge deposition makes further multiplication unnecessary.

The rationale for developing new technologies for beam monitoring in radiotherapy has been extensively discussed in the literature, particularly in the context of enabling high-quality treatments with protons and ions for moving targets, exploiting different dose rates (e.g., FLASH), modifying dose fractionation schemes, and optimizing dose delivery for increasingly personalized therapies (Okpuwe et al., 2024).

In recent years and in the framework of research in medical physics, the INFN-CSN5 MoVeIT, SIG, and FRIDA projects have been comparing the performances of silicon-based detector prototypes with ionization chambers (ICs), which are the gold standard for dosimetry and beam monitoring in clinical scenarios, with the aim of establishing the advantages, limitations, and new possibilities offered by solid-state technology for monitoring beams during treatment delivery. Several sensors have been developed at Fondazione Bruno Kessler (FBK, Trento, Italy). They were characterized first in the laboratory, then with clinical particle beams in the two Italian particle therapy facilities: the Protonterapia in Trento and the National Center for Oncological Hadrontherapy (CNAO, Pavia). It was found that sensitivity, which is typically of the order of thousands of particles for ICs, is reduced to a single ion, demonstrating the capability of discriminating single protons and carbon ions with single crossing time resolutions better than 100 and 30 ps, respectively (Montalvan Olivares D. M. et al., 2025; Vignati et al., 2020b). In addition, the charge collection time can be reduced from hundreds of microseconds, typical of ICs, to less than 2 nanoseconds, thus permitting counting of the number of delivered ions up to clinical rates of 10^8 p/cm²s (Monaco et al., 2023).

LGADs' excellent timing resolution enabling precise tracking and energy measurement of individual proton have been also exploited by Kramberger (2023) and Ulrich-Pur et al. (2022) for advanced particle imaging techniques such as proton computed tomography (pCT).

Most recently, colleagues from Kraków presented the application of LGADs to real-time proton beam monitoring at the TREDI 2025 Conference, demonstrating their ability to resolve the fine temporal structure of cyclotron beams and operate effectively at high instantaneous dose rates (Bellora et al., 2025).

In addition, the large electric field (>10 kV/cm) of small thickness (50 μ m) limits the effects of charge volume recombination at ultra-high dose rates (>40 Gy/s average dose-rate) foreseen in the challenging FLASH dose delivery modalities. The spatial resolution and rate capability of sensors segmented into strips integrated with multichannel readout chips could meet the requirements of 100 μ m of spatial resolution for beam monitoring

applications in spatially fractionated radiotherapy (Medina et al., 2024).

Different technologies, such as micropattern gas detectors, have also been explored to overcome the intrinsic limits of current beam monitors for particle therapy (Cong et al., 2025; Bortfeldt et al., 2022).

In the following, we review our main achievement with thin LGADs and thin silicon diodes for applications in radiotherapy.

2 Fundamental principles and key technological advances of LGADs

Moderate internal gain in LGADs is provided by a highly doped multiplication layer. Ionizing radiation deposits energy in the active bulk, generating electron-hole pairs that, while drifting through the multiplication layer, undergo controlled impact ionization, resulting in charge multiplication. This mechanism enables the fabrication of thinner active regions (~ 25 – 60 μ m) which allow for excellent time resolution (~ 30 ps) at moderate bias voltage (typically 200–300 V) while preserving good signal-to-noise ratios (Pellegrini et al., 2014; Paternoster et al., 2017; Gabriele, 2021; Sadrozinski et al., 2016).

A thin active thickness significantly improves both timing performance and radiation hardness thanks to reduced depletion volume (Ferrero et al., 2019). Studies have investigated the optimization of active substrate thickness, gain implant (Siviero et al., 2022; Sola et al., 2024), and sensor-periphery-enabled LGADs to withstand fluences $>10^{15}$ n_{eq}/cm², making them suitable for high-luminosity LHC (HL-LHC) environments (Crocì et al., 2023). Such radiation tolerance enables operation without loss in performance up to fluences of approximately 10^{15} protons/cm² for use in particle therapy at a wide energy range. Considering 10^8 – 10^{10} delivered protons per fraction (Vignati et al., 2020c), LGADs should survive roughly 10^5 delivery fractions before needing replacement.

Better doping profiles and simulations guarantee a uniform gain layer and thus uniform signal response across the active area. Moreover, to reduce perturbations to the incident beam in applications such as online monitoring or telescope-based time-of-flight measurements, silicon sensors can be thinned from ~ 600 μ m to 120 μ m, approaching nominal active thickness while remaining mechanically manageable.

LGAD developments, such as AC-LGADs and trench-isolated LGADs (TI-LGADs), are improving spatial resolution and fill-factor. AC-LGADs, also called “resistive silicon detectors” (RSD)—as prototyped in the “RSD” and “4DSHARE” CSN5 projects—exploit a capacitive readout, enabling fine spatial resolution and a 100% fill-factor spreading signal across multiple readout pads (Tornago et al., 2021; Arcidiacono et al., 2023). RSDs allow for a low-power front-end readout, reduced number of readout channels, and reduced material budget for beam position measurements compared with, for example, two layers for horizontal and vertical standard LGAD segmented into strips. Instead of using standard p-stop/p-spray isolation between pads or pixels, TI-LGADs use etched and doped trenches (deep physical cuts into silicon) which prevent electrical cross-talk and charge sharing between neighboring pixels (Giacomini and Platte, 2023).

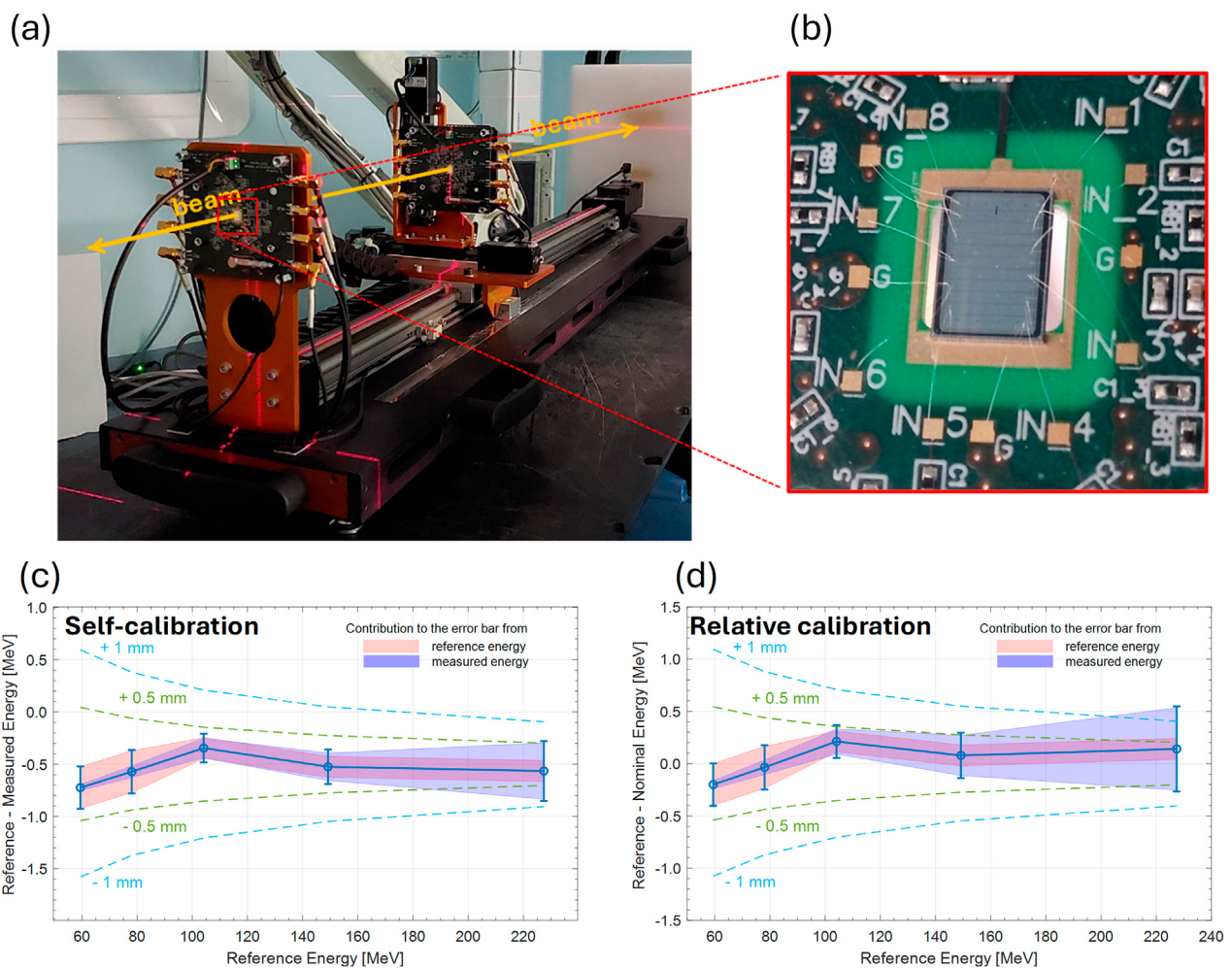


FIGURE 1

(a) Final beam energy detector (results not published) built with two strip-segmented sensors shown in (b) From (6): deviations between reference and measured energies for five beam energies at clinical intensity and at the largest flight distance (97 cm), with (c) self-calibration and (d) relative calibration, both with the proof-of-concept setup. The blue and red shaded regions represent, respectively, the errors on the measured and reference energies, while the error bars correspond to the uncertainty on the difference. The dotted lines show the corresponding deviations in the water range within 1 and 0.5 mm. Figures (c,d) reproduced from Vignati et al. (2023) under the CC BY 4.0 licence.

Both TI-LGADs and AC-LGADs were not used in the studies presented here, as they were still under development during the same period. However, TI-LGADs, thanks to their higher fill factor, are expected to significantly improve the efficiency of future online beam fluence, profile monitors, and other detectors operating at clinical beam rates. Conversely, the AC-LGAD architecture appears more suitable for applications at sub-clinical rates, such as proton and ion imaging or selected radiobiological experiments, where precise spatial resolution is prioritized over rate capability.

3 Fast-beam energy detector for commissioning, quality assurance, and online energy check

Using a pair of thin LGADs segmented in 11 strips, each with a sensitive area of 2.2 mm^2 (strip length 4 mm, width 0.550 mm, and

pitch 0.591 mm) and a precise mechanical system to position them at adjustable separations 30–95 cm along the beam path with 5 μm accuracy, a beam energy detector based on time-of-flight measurements was developed (Figure 1a). The published results (Vignati et al., 2023; Vignati et al., 2020b) were performed with a simpler telescope as proof of concept and have been summarized in the following and in Figures 1c,d.

Measurements were performed at CNAO using five proton beam energies covering the entire clinical energy range (60–230 MeV), delivered at the maximum beam intensity and with four sensor separations (7, 37, 67, and 97 cm). In all measurements, a clear peak in the time difference distribution was observed. A model, which accounts for the energy loss in the sensors and the air, was developed, carefully benchmarked against a Monte Carlo simulation, and used to determine the beam energy at the isocenter from the measurements. Additionally, two calibration methods—relative and self-

calibration—were developed to determine the sensor distances and the time offset between readout channels with 0.25 μm and 1.5 ps precision, respectively (Vignati et al., 2023). The relative method relies on reference beam energies from the facility and a χ^2 minimization to extract both quantities. It is simpler but is limited by the accuracy of the external references. The self-calibration, instead, exploits the known displacements of the second sensor to obtain the same parameters, reducing systematic uncertainties and improving precision by approximately a factor of 2, at the cost of requiring measurements at multiple positions. It is independent and more accurate but is experimentally more demanding.

The energies determined with the calibrated system were compared to the nominal values of CNAO and for two distances between sensors (67 and 97 cm). Both the deviations from the nominal values and the statistical errors on the measured quantities were of few hundreds of keV, indicating a sensitivity to the corresponding range in water less than the clinical tolerance of 1 mm. Furthermore, these results were achieved in a few seconds of irradiation, with an effective acquisition time of 0.4‰ of the irradiation time.

The results of this test demonstrated that LGAD sensors can measure the energy of a clinical proton beam within a few milliseconds, achieving high accuracy (± 500 keV—Figures 1c,d) with minimal perturbation to the beam.

However, challenges remain in enabling the full clinical application of this method, specifically in expanding the transverse sensitive area and reducing the acquisition system's dead time. Addressing these issues would significantly increase system complexity but also enhance its clinical impact.

The single crossing time resolution was also measured using the strips and front-end board shown in Figure 1b. The results were 75 ps at the minimum proton energy (60 MeV, corresponding to approximately 5 MIPs) and 115 ps at the maximum energy (230 MeV, corresponding to approximately 2 MIPs) [ref. 17]. The observed degradation in time resolution compared to the one-MIP case is consistent with the expected screening effect and the influence of Landau fluctuations.

4 Particle counter for online fluence and position control of clinical beams

A strip LGAD-based proton counter was developed and characterized within the Modeling and Verification for Ion beam Treatment planning (MoVe-IT) CSN5-Call project. It features a 45- μm active thickness LGAD with an active area of 2.7×2.7 cm^2 to cover the entire ion beam, segmented into 146 strips (114 μm width, 26214 μm length, 180 μm pitch)—chosen as a compromise between the number of readout channels and the need to reduce the pile-up effect. The gain layer was optimized for proton beams in clinical energy range (60–250 MeV corresponding to 2–5 MIPs). This sensor aimed to measure fluences by counting hits up to 10^8 p/cm²s. The latter rate is useful for radiobiological experiments with protons while the average rate used for treatments ranges from 10^9 to 10^{11} p/cm²s. The layout of the sensors was designed in collaboration with FBK, and 14 wafers were produced in 2020.

4.1 LGAD sensor laboratory characterization

The sensors were characterized in the laboratory using picosecond lasers to investigate their static electrical behavior, dynamic properties, and strip active area. Paternoster et al. (2017) demonstrated that the wafer dicing process did not affect the yield production, and the overall MoVe-IT-2020 sensor production was of very high quality. Approximately the width of the inter-strip dead region, the measured value was 80.8 μm —22% greater than the distance of the gain layers—and was found to decrease by 3%, thus increasing the laser intensity.

4.2 LGAD sensor characterizations with clinical proton beams

Performance as proton counters was investigated, for practical reasons, using a smaller LGAD sensor with an area of 15×5 mm^2 segmented into 20 strips (150 μm width, 216 μm pitch, 2 mm^2 active area) and 55 μm of active thickness. The sensor was characterized at CNAO and at the Protonterapia of Trento, with proton beams provided by a synchrotron and a cyclotron, respectively. Signals from single-beam particles were discriminated against a threshold and counted. The number of proton pulses for fixed energies and different particle fluxes was compared with the charge collected by a compact ionization chamber to infer the input particle rates. In Pellegrini et al. (2014), Monaco et al. demonstrated that the counting inefficiency due to the overlap of nearby signals was less than 1% up to particle rates in one strip of 1 MHz, corresponding to a mean fluence rate on the strip of approximately 5×10^7 p/(cm²s). In order to extend the maximum counting rate by one order of magnitude, a count-loss correction algorithm based on the logic combination of signals from two neighboring strips was developed and implemented on the FPGAs used for data acquisition.

4.3 Multi-channel front-end board for a 2.7×2.7 cm^2 particle counter

An ESA-ABACUS front-end board was developed to house six ABACUS chips (Fausti et al., 2021) in order to read out the 144 central strips of the 2.7×2.7 cm^2 sensor, wire-bonded to the chip input channels. The ABACUS chip allows the detection of signal pulses in a wide charge range (4–150 fC), accounting for the large energy loss fluctuations in thin sensors by clinical protons and carbon ion beams in the energy ranges of 60–230 MeV and 115–400 MeV/u, respectively.

On-board and on-chip digital-to-analog converters were used to set the threshold channel by the channel to discriminate particle signals from noise. The output digital low voltage differential signals (LVDS) I/O are read out by three FPGA boards. Details on the ESA_ABACUS features and laboratory characterization are described in Data et al. (2025).

4.3.1 Noise and counting efficiency

Among the most significant results, noise was found to be fairly independent of the input charge. For one chip, the distribution of the noise standard deviation was approximately 0.89 mV, corresponding to an equivalent noise charge (ENC) of 4,090 electrons, with a dispersion of 0.35 mV (ENC 1680 electrons). The signal-to-noise ratio (SNR) was

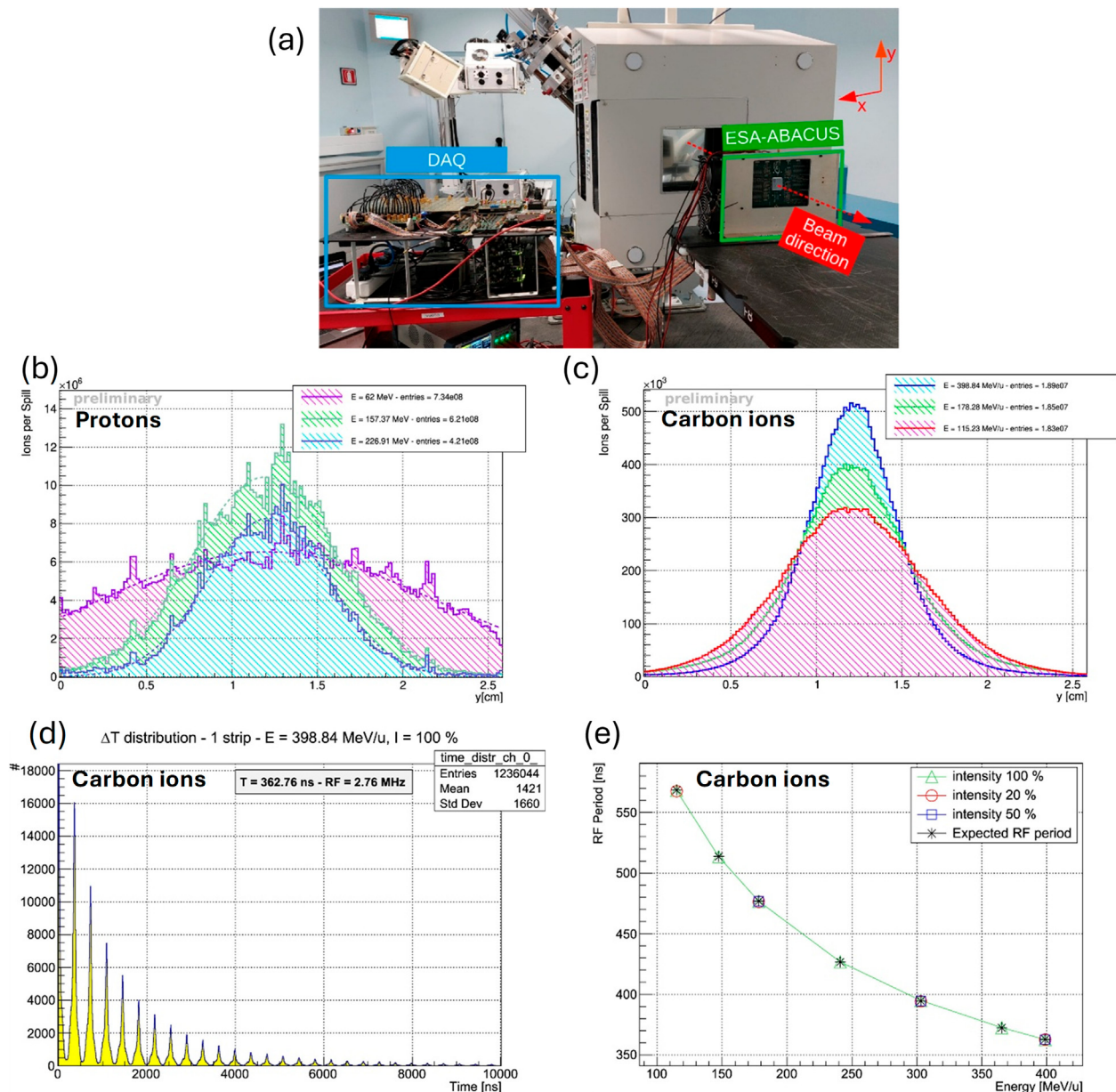


FIGURE 2

From Data et al. (2024). (a) Experimental set-up with ESA-ABACUS board in treatment room at CNAO. (b) Projections on the axis perpendicular to the strips of one spill for three proton energies: 62 (red), 157 (green), 227 (blue) MeV. (c) Projections of one spill for three carbon ions energies: 115 (red), 178 (green), 399 (blue) MeV/u. (d) Distribution of time interval between carbon ion intensities 100%, 50%, and 20% (green triangles, blue squares, and red circles, respectively) compared with expected values (black stars). Figures reproduced from Data et al. (2025) under the CC BY 4.0 licence.

found to increase with the input charge, as expected, with values of 30–38 dB, depending on the channel.

Counting efficiency as a function of the pulse frequency up to 200 MHz and input charges between 9.0 and 37.0 fC was found to equal 100% up to 143 MHz, indicating that the dead time of the channel was smaller than 7 ns.

A preliminary beam test at CNAO (Figure 2a) with clinical protons showed good separation between signal and noise in the LGAD strip and very short signals (<2 ns), which allow for counting protons up to 10^8 p/cm²s by selecting a proper threshold strip by strip. In addition, the beam projections along the axis perpendicular to the strips of proton

beams were measured with the ESA-ABACUS for three different energies in the clinical energy range (Figure 2b), resulting in distributions with FWHM between 0.8 and 2.2 cm, compatible with reported results (Filipev et al., 2024; Mirandola et al., 2015).

4.4 Thin silicon diodes for primary carbon ions counting and timing

In parallel, a n-on-p diode sensor with the same 2.7×2.7 cm² area as the LGAD, segmented in 146 strips (26214 μ m length,

180 μm pitch) without dead regions and gain, was optimized for counting and timing the carbon ion beams at clinical energy and rate ranges (115–400 MeV/u, 10^7 C/cm²s) for its use as real-time beam monitor with tracking capabilities—see the next section and [Data et al. \(2024\)](#). It aims to be part of the next generation of beam delivery systems for future nozzle-providing ion pencil-beam scanning and to be suitable for integration in future compact ion gantries. The counting and crossing time measurements of primary ions have been a research goal of the Superconducting Ion Gantry (SIG) CSN5 project. Thin (20–60 μm thick) silicon sensors segmented into 4×0.59 mm² strips and different pads with areas between 0.03 and 2.33 mm² were characterized with carbon ions at CNAO, showing fast ($\sim$ ns) response times and well-defined signals easily distinguished from noise. The large signal-to-noise ratio allows the discrimination of individual carbon ions in a therapeutic beam to achieving a single-hit temporal resolution lower than 30 ps ([Montalvan Olivares D. M. et al., 2025](#)). Furthermore, potential issues such as charge sharing, which can lead to counting inefficiencies, were found to be negligible.

The 146-strip-segmented diode sensor was tested with carbon ions at CNAO, reading the strips by means of the ESA-ABACUS. Beam projections were measured at different energies ([Figure 2c](#)) showing compatibility with Gafchromic films, and a counting efficiency larger than 90% was found ([Data et al., 2024](#)).

5 Primary particles' time of arrival measurements and applications

To explore the possibility and limitations of integrating the single particle crossing time measurement into the silicon-based beam monitor described in the previous section, the use of the PicoTDC evaluation board developed at CERN ([Altruda et al., 2023](#)) was investigated. It features a 64-channel time-to-digital converter (TDC) with a 3 ps bin size and a dynamic range of 205 μs . It can operate in streaming mode to acquire all the input events or in trigger mode, in which only events occurring in a specific time window are stored. A window with programmable width is open back in time, depending on the set latency, whenever a trigger signal arrives. The DAQ of the PicoTDC is based on a Virtex7 FPGA board with dedicated firmware developed at CERN.

One channel of one ABACUS chip was connected to the PicoTDC to measure the delay between the ABACUS output and the input pulse from a pulse generator. The pulse frequency was set to a value lower than 143 MHz, so that ABACUS counting efficiency was 100% and the delay distribution was obtained. The results showed a strong dependence on the delay from the input charge for measurements performed, setting a fixed threshold in ABACUS. This effect, due to time walk, could induce systematic uncertainties when timing measurements at different beam energies are compared; thus, the threshold must be changed energy by energy. The time resolution of the system composed by ABACUS and PicoTDC was given by the delay distribution standard deviation and was found to be approximately 100 ps.

5.1 Beam time structure

The ESABACUS-PicoTDC integrated setup ([Figure 2a](#)) was tested at CNAO with carbon ion beams at seven energies and three different fluences. Time-of-arrival measurements with the PicoTDC were acquired in triggered mode at 50 kHz within a 20 μs window, thus implying no deadtime.

[Figure 2d](#) reports the distribution of time interval between consecutive carbon ions in one strip for energy 398.84 MeV/u and [Figure 2e](#) shows the radio-frequency period measured for different carbon ion energies and intensities together with the expected values. The measured period is independent of the intensity, and results are compatible with the expected values for all energies at a significance level of 5% (ZGauss $\sim$ 0.3) ([Data et al., 2024](#)). A recent paper was published with similar measurements performed at MedAustron using a high frequency silicon carbide readout ([Knopf et al., 2026](#)).

5.2 Prompt gamma timing

Among the interesting applications of the primary particles' time before entering the patient's body, and thus in the nozzle, it is worth mentioning the prompt gamma timing (PGT) technique for range verification. PGT relies on secondary prompt photons produced during the interaction of the beam with patient tissue ([Golnik et al., 2014](#)) and more specifically on their times of flight, exploiting for start time in a synchrotron facility the single particle's crossing signal measured with thin LGAD for protons ([Monaco et al., 2023](#); [Vignati et al., 2020b](#)) and thin silicon sensors for carbon ions ([Montalvan Olivares D. M. et al., 2025](#)).

The preliminary PGT distributions obtained at the Italian Center of Oncological Hadrontherapy (CNAO) in Pavia (IT) with protons on homogeneous phantoms are encouraging, as the system was able to estimate the stopping power within 2% of the theoretical value ([Werner et al., 2024](#)).

Further extensive research is ongoing on the experimental data to evaluate the PGT statistical fluctuations for the available configurations and quantitatively assess the detected PGT differences ([Schellhammer et al., 2022](#)).

6 Silicon-based beam monitors and dosimeters for ultra-high dose rate (UHDR) and spatially fractionated radiotherapy (SFRT)

Because of the recombination effects affecting traditional ionization chambers, new or adapted technologies are being studied for beam monitoring and dosimetry in UHDR scenarios. Within the FRIDA INFN project, thin segmented silicon pad sensors (30 and 45 μm active thicknesses; 0.25–2 mm² active area) demonstrated a linear response up to $\sim$ 10 Gy/pulse with 9 and 10 MeV UHDR electron beams at the CPFR facility in Pisa and with the modified LINAC Elekta available at the INFN and UniTO Physics Department, ([Deut et al., 2024](#)). Tests are being performed on UHDR proton beams. Moving from pads to 2D configurations could overcome the increase of dose and stray radiation produced in UHDR scanning measurement techniques and meet the requirements for beam monitoring applications in spatially fractionated

radiotherapy. The 146-strip diode sensor allows us to achieve a spatial resolution of 180 μm , corresponding to the pitch between strips. The sensor was integrated with the multichannel readout chip TERA09 and was successfully tested to measure the profile of seven 10 MeV-electron mini-beams, each characterized by FWHM of 1 mm and separated from each other by 3 mm (Medina et al., 2024). The same setup was characterized with 62–226 MeV proton beams at conventional rates, obtaining beam profiles having a FWHM between 0.6 and 2.2 cm, compatible with measurements performed with Gafchromic films (Medina et al., 2024).

7 Discussion and conclusion

Two full detectors based on different LGAD and n-on-p diodes read out by custom front-end boards were developed in the framework of the INFN-CSN5 MoVeIT, SIG, and FRIDA projects (2016–2025). Large area silicon sensors ($2.7 \times 2.7 \text{ cm}^2$) segmented into 146 strips and a dedicated ASIC called ABACUS were developed to build a detector able to count beam particles over the full transverse profile of the clinical ion pencil beams. The overall goal is to provide a transparent beam monitor which measures beam fluence with single particle sensitivity, beam position and profile with resolutions comparable to radiochromic films, and tens of picoseconds time resolution useful for advanced beam delivery techniques up to clinical rates.

Smaller sensors (11 strips, 2 mm^2 each) and a custom analog read-out were employed to develop a different detector for time-of-flight measurement to quickly measure online the beam energy with a few hundreds of keV accuracy.

Moreover, the timing capability was exploited to prove the feasibility of a full 4D tracking system for ion beams at clinical intensities, developing multi-channel readout systems based on fast time-to-digital converters as the picoTDC board from CERN. The latter allowed us to perform measurements of the CNAO beam time structure at the nanosecond level as well as accurate measurements of prompt gamma timing (PGT) with a clinical beam from a synchrotron. A PGT system is a promising method for *in vivo* particle range verification, providing the particles' range within the patients through its correlation with the distribution of the time difference of the primary particles and the emitted photon times.

The applicability to beam monitoring at FLASH dose rates was verified with electron beams, showing good signal linearity up to 10 Gy delivered in 4- μs pulses.

These findings suggest that thin LGADs and thin segmented silicon detectors are a promising technology for developing devices for monitoring therapeutic beams at both conventional and high dose rates, with the additional benefit of allowing for single proton and carbon ion sensitivity at the current clinical beam fluences. Such a demanding feature will increase the beam's delivery flexibility and contribute to applications such as ion and proton radiography and computed tomography (Ulrich-Pur et al., 2022; Johnson, 2024).

However, for clinical applications, the primary challenge remains the development of a detector with a sensitive area of $30 \times 30 \text{ cm}^2$, as required for online beam monitors to fully cover the treatment field using pencil beam scanning delivery. Among the most promising alternatives to the current state-of-the-art ionization chambers are micropattern gas detectors, which have also been under active development for several years [20, 21].

Author contributions

FM: Writing – original draft, Writing – review and editing. ED: Writing – review and editing. AV: Writing – review and editing. MD: Writing – review and editing. MC: Writing – review and editing. MF: Writing – review and editing. VF: Writing – review and editing. EF: Writing – review and editing. VM: Writing – review and editing. DM: Writing – review and editing. FP: Writing – review and editing. MP: Writing – review and editing. VS: Writing – review and editing. RS: Writing – review and editing. SG: Writing – review and editing. Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer PŠ declared a past collaboration with the author MC.

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