ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO05

RESEARCH AND DEVELOPMENT OF A RADIATION HARD BEAM PROFILE MONITOR FOR USE IN THE CERN NORTH AREA SECONDARY BEAMLINES

I. Ortega[*,1], H. Danielsson[1], A. Gerbershagen[2], R. Larsen[1,2], M. McLean[1], B. Moser[1], M. Zamkovsky[1]
[1]CERN, Geneva, Switzerland
[2]PARTREC, UMCG, University of Groningen, Groningen, The Netherlands

Abstract

The CERN Beam Instrumentation group is currently investigating a radiation-hard beam profile monitor for the CERN North Area. Our main efforts are now focused on straw tubes, a type of wire chamber detector that offers the advantage of being vacuum-compatible and easily equipped with in/out motorisation. We have launched an extensive testing campaign across several CERN accelerators to demonstrate that straw detectors can cover the same dynamic range as traditional wire chambers, from individual particles up to intensities of around 10^{11} particles per second, and to prove that they can perform reliably with beams of both protons and heavy ions.

INTRODUCTION

Multi-Wire Proportional Chambers (MWPCs) are the most widely used beam profile monitors in the CERN North Area beamlines [1]. However, most of these detectors were commissioned in the early 1970s, at the same time as the North Area itself. Their performance has since been severely degraded by ageing and radiation damage, and they no longer meet the requirements of current physics programs. As part of a major renovation of the North Area, the majority of the beam instrumentation will be consolidated. For beams with intensities below 10^8 particles/s, a scintillating fibre detector, the eXperimental Beam Profile Fibre monitor (XBPF), will replace the old monitors [2]. For higher-intensity beams, up to 10^{11} particles/s, the XBPF lacks sufficient radiation tolerance. A new radiation-hard profile monitor is therefore being researched and developed by the CERN Beam Instrumentation Group. Ideally, the new detector should remain highly compatible with the XBPF to optimise long-term maintenance and resource use.

Detector requirements

The new monitor must satisfy the following requirements: active areas of 10×10 cm^2 and 20×20 cm^2, spatial resolution of a few millimeters, operation over beam intensities from 10^5 to 10^{11} particles/s and momenta between 0.5 and 450 GeV/c, a material budget below $0.3\, x/X_0$, compatibility with both vacuum and air environments, and integration with a motorised in/out system. To ensure long-term operational reliability over several decades, the active component must withstand radiation doses on the order of MGy, while the mechanical structures and local electronics must remain fully functional in radiation environments up to 1 kGy.

To meet these requirements, different detection concepts are being explored. Two approaches have been investigated for the new beam monitor: light-emitting optical fibres and straw tubes. Three types of light-emitting fibres have been studied: quartz rods, crystal capillaries filled with liquid scintillator, and hollow-core fibres filled with scintillating gas. The results for quartz rods and crystal capillaries were presented at IBIC 2023 [3], while the findings on hollow-core fibres—a novel detection technique showing promising results for medical accelerators—are presented at the IBIC 2025 conference [4].

STRAW TUBES

Straw tubes are gaseous detectors widely used for tracking and beam monitoring in particle physics [5–7]. They consist of thin cylindrical tubes, typically a few millimetres in diameter, with a central anode wire held at high voltage and the tube wall acting as the cathode. The tubes are filled with a suitable gas mixture, often based on argon, which provides both ionisation and amplification properties.

When a charged particle traverses the straw, it ionises the gas along its path. The liberated electrons drift towards the anode wire under the influence of the electric field, initiating an avalanche multiplication close to the wire. This process produces a detectable electrical signal proportional to the deposited charge. Thanks to their small diameter and low material budget, straw tubes are able to provide good spatial resolution, fast signal collection, and minimal perturbation of the particle beam. They have also been successfully operated in vacuum, as demonstrated by the NA62 experiment at CERN [6]. Moreover, the modular design of straw tubes enables the construction of monitors that are mechanically compatible with the XBPF, allowing the use of the same vacuum tank and thereby improving efficiency in terms of compatibility and long-term maintenance.

Detector Design

The concept of the new monitor is based on an array of straw tubes traversed by the beam, allowing reconstruction of the beam profile and position from the signals induced in the individual straws. Figures 1 and 2 show a prototype detector with an active area of 10×10 cm^2. The straws remain under vacuum, while their electrical readout is located outside at atmospheric pressure. Each straw is 35 cm long in order to carry the signal out of the vacuum, achieved through the

* inaki.ortega@cern.ch

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO05

white polyoxymethylene section shown in Fig. 1, which also serves as a vacuum flange. A PCB is mounted on top of this flange to read out the electrical signals from the straws and provide the high voltage. This design can be readily scaled up to an active area of $20 \times 20\,\mathrm{cm}^2$.

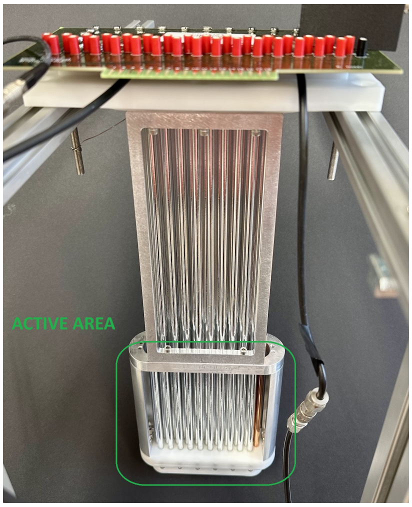

Figure 1: Prototype of a 31-straw monitor with a $10 \times 10\,\mathrm{cm}^2$ active area. The white section serves as the vacuum flange, with the readout PCB mounted on top at atmospheric pressure.

The straws used have a radius of 2.4 mm. Their walls are made of 20 µm-thick Mylar, with an aluminium coating on both the inner and outer surfaces. Each straw contains a 30 µm tungsten wire with a gold coating. A gas mixture of 50 % Ar and 50 % CO_2, maintained at a pressure slightly above atmospheric, was employed, identical to that used in the MWPCs operating in the North Area.

Two types of readout electronics were employed in the study of the straw prototypes: a 5 GHz oscilloscope, used to acquire and record individual particle pulses, and the standard MWPC readout system used in operation. The latter consists of a series of integrators that accumulate the charge per straw over the full duration of the beam extraction, enabling the reconstruction of the beam profile and position.

Detector simulation

The straw detector was simulated using Garfield++ [8] and Magboltz [9], the most widely used simulation toolkits for gaseous detectors. The model describes the interaction of a single straw with incident radiation and allows the study of processes such as ionisation in the gas, charge amplification and transport within the straw, as well as signal formation and transmission. The simulation can be performed for any applied high voltage and gas mixture. At high particle fluxes, the buildup of positive ions leads to a reduction in detector gain, which can result in charge saturation, loss of linearity, and ultimately degraded beam profile reconstruction. This effect was estimated to first order using a numerical code in combination with ionisation parameters from Magboltz. Figure 3 shows the calculated phase space of beam

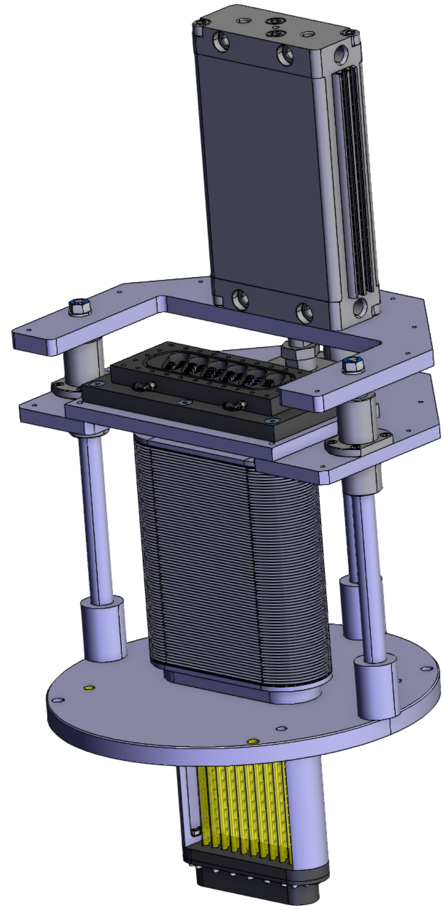

Figure 2: Integration of the straw detector in vacuum, equipped with a pneumatic in/out motorisation system similar to that used for the XBPF beam monitor. The active area of the straws is shown in yellow.

intensity versus detector bias voltage. The y-axis represents the beam intensity in particles per second, while the x-axis corresponds to the applied bias voltage. The yellow region indicates the domain where the detector operates linearly, i.e. without saturation. The red curve indicates the onset of charge saturation, while the blue curve corresponds to a gain of unity, representing the minimum voltage required for charge amplification.

It should be emphasised that achieving a dynamic range spanning six orders of magnitude in beam intensity constitutes a particularly demanding requirement for a particle detector. Straw tubes, however, offer a distinct advantage in this respect, as their gain can be tuned by adjusting the applied bias voltage. As illustrated in Fig. 3, such tuning allows charge saturation inside the straw to be avoided, thereby providing the flexibility to adapt the detector response to different beam intensities. In principle, straw tubes could thus be operated at intensities up to 10^{12}. To investigate this experimentally, beam tests were carried out in several CERN accelerators.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO05

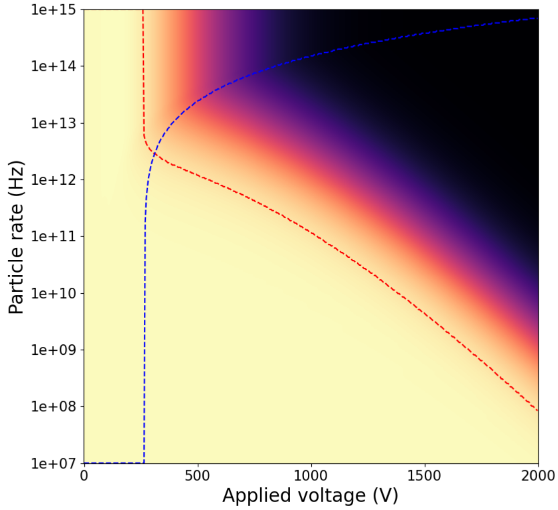

Figure 3: Simulated linearity of a straw as a function of beam intensity and applied bias voltage. The yellow region indicates the domain where the detector response remains linear. The red curve marks the onset of charge saturation, while the blue curve corresponds to a gain of unity, representing the minimum voltage required for charge amplification.

BEAM TESTS OF STRAW TUBE PROTOTYPES

To test the predicted behaviour of the straw detector at different beam intensities and operating voltages, beam tests were carried out at several CERN facilities:

- East and North beam test areas [1]: provide up to 10^7 particles/s in an unbunched, slowly extracted spill over 4.8 s. These beams allowed tests of single-particle detection and comparison of straw performance with MWPCs.
- IRRAD facility [10]: delivers high-intensity beams of 10^{10} and 10^{11} particles/s, slowly extracted over 400 ms several times per minute. Doses of several MGy can be accumulated within days, also enabling studies of material radiation hardness.
- HiRadMat facility [11]: provides bunched beams directly extracted from the CERN SPS, with intensities ranging from 10^{10} and 10^{12} particles per pulse.

RESULTS

The beam tests provided a valuable mean to validate the theoretical model and simulation of the straw detector. Different regions of the gain space shown in Fig. 3 were successfully tested up to a beam intensity of 8×10^{11} particles/s without loss of linearity. These tests were performed in 2025, and part of the data analysis is still ongoing. For instance, the HiRadMat dataset has proven challenging to analyse due to noise originating from an unknown source of electromagnetic interference. A subset of the IRRAD data is presented in Fig. 4, showing good linearity of the straw. Figure 5 presents a comparison of beam profiles measured with a MWPC and with the straw prototype, demonstrating that the straws can achieve the same spatial resolution as the MWPC when using the same readout. The fit to the straw data was performed with an algorithm that corrects for the circular geometry of the straws.

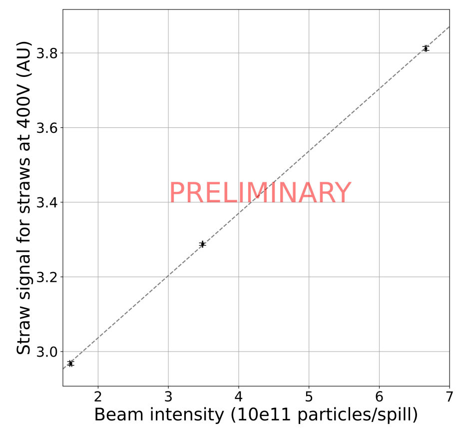

Figure 4: Beam intensity scan performed at IRRAD, illustrating the linearity of the straw in the high-intensity regime.

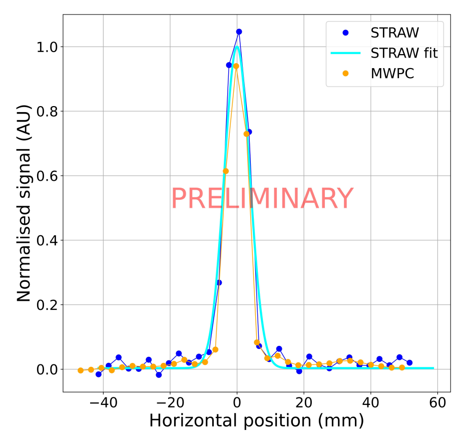

Figure 5: Comparison of beam profiles measured with the MWPC and the straw prototype at an intensity of 10^6 particles per spill.

CONCLUSION

Several straw prototypes were tested under a wide range of beam conditions to evaluate this technology for a future radiation-hard beam profile monitor. Preliminary analysis of the collected data confirms that the detector response can cover the required beam intensities. Ongoing analysis will determine whether its radiation hardness meets the specifications. A forthcoming test of the $10 \times 10\ \mathrm{cm}^2$ prototype with ion beams later this year will also asses whether the straw technology can be applied to this type of beam.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO05

REFERENCES

[1] D. Banerjee *et al.*, "The North Experimental Area at the CERN Super Proton Synchrotron", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2021-0015, Jul. 2021. `https://cds.cern.ch/record/2774716`

[2] I. Ortega Ruiz *et al.*, "The XBPF, a new multipurpose scintillating fibre monitor for the measurement of secondary beams at CERN", *Nucl. Instrum. Methods Phys. Res. A*, vol. 951, p. 162996, Jan. 2020. `doi:10.1016/j.nima.2019.162996`

[3] E. Buchanan *et al.*, "Radiation Hard Beam Profile Monitors for the North Experimental Beamlines CERN", in *Proc. IBIC'23*, Saskatoon, Canada, Sep. 2023, pp. 321–325. `doi:10.18429/JACoW-IBIC2023-WE3C03`

[4] R. Larsen *et al.* "Novel hollow core optical fibre-based radiation sensing technique for medical applications and extreme environments", presented at IBIC'25, Liverpool, UK, Sep. 2025, paper TUPMO14, this conference.

[5] B. Mindur, "ATLAS Transition Radiation Tracker (TRT): Straw tubes for tracking and particle identification at the Large Hadron Collider", *Nucl. Instrum. Methods Phys. Res. A*, vol. 845, pp. 257–261, Feb. 2017. `doi:10.1016/j.nima.2016.04.026`

[6] A. Sergi, "NA62 Spectrometer: A Low Mass Straw Tracker", *Physics Procedia*, vol. 37, pp. 530–534, 2012. `doi:10.1016/j.phpro.2012.03.713`

[7] W. Erni *et al.*, "Technical design report for the $\overline{P}$ANDA (AntiProton Annihilations at Darmstadt) Straw Tube Tracker: Strong interaction studies with antiprotons", *Eur. Phys. J. A*, vol. 49, no. 2, Feb. 2013. `doi:10.1140/epja/i2013-13025-8`

[8] *Garfied++, a toolkit for the simulation of particle detectors based on ionisation in gases and semiconductors*, `https://garfieldpp.web.cern.ch/`

[9] S. F. Biagi, "Monte Carlo simulation of electron drift and diffusion in counting gases under the influence of electric and magnetic fields", *Nucl. Instrum. Methods Phys. Res. A*, vol. 421, no. 1–2, pp. 234–240, Jan. 1999. `doi:10.1016/s0168-9002(98)01233-9`

[10] PS-IRRAD facility, CERN, `https://ps-irrad.web.cern.ch/ps-irrad/`

[11] HiRadMat facility, CERN, `https://hiradmat.web.cern.ch/`