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Muon intensity measurements at ISIS RIKEN-RAL Port1 for the FAMU experiment(*)

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Summary. — This contribution reports on the scintillating-fibre hodoscope developed by INFN for the FAMU experiment at RIKEN-RAL (ISIS, UK). The detector, composed of two crossed 32-fiber planes (squared section, 1 mm pitch, 1 mm spacing) read out by SiPMs, measures muon intensity for normalization of muonic hydrogen hyperfine splitting studies aimed at determining the proton Zemach radius. A calibration strategy combining low-rate single-muon data and Geant4/FLUKA simulations established the detector response, yielding a calibration constant to convert total deposited charge into muon rate. Full-rate operations (55 MeV/c muons, 40 Hz spills) produced muon intensity measurements of the order of $\mathcal{O}(10^4)$ μ/s, consistent with expectations. The protocol is proposed as a general method for scintillating-fibre beam monitors.

1. – Introduction

The FAMU (Fisica degli Atomi Muonici) experiment aims to measure the hyperfine splitting (HFS) in the ground state of muonic hydrogen (μp) with high precision, as a

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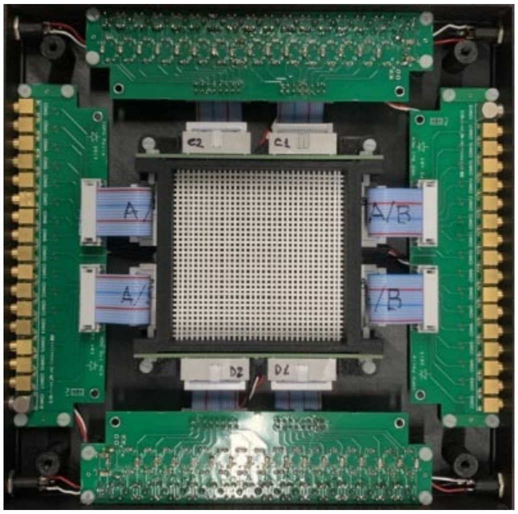

Fig. 1. – The FAMU beam monitor: a central mesh of scintillating fibres, made of two crossed planes of 1 mm squared fibres spaced by 1 mm, is hit by the muon beam. Photons are read out with SiPMs at alternate fibre ends and the signals are then fanned out through MCX connectors.

means to determine the Zemach radius of the proton [1]. Conducted at the RIKEN-RAL muon facility at ISIS (UK) [2], the experiment relies on pulsed low-energy muon beams, requiring accurate and non-invasive real-time monitoring of the incoming muon intensity to normalize the experimental data.

For this purpose, a compact and efficient beam monitor based on scintillating fibres was designed and developed [3], shown in fig. 1. The device, referred to as Hodo-4, consists of two orthogonal planes of 32 plastic scintillating fibres each, read out by silicon photomultipliers (SiPMs). The layout ensures minimal material intrusion into the beam path, preserving beam quality while delivering precise spatial and temporal detection.

A custom calibration method was developed to quantify the monitor's response in terms of deposited charge per muon [4]. This involved operating the beam line under reduced-intensity conditions to isolate single-muon events, and analysing the charge distribution recorded by the SiPMs. Simulation studies using both Geant4 and FLUKA allowed the characterization of energy deposition patterns and track multiplicity within the detector, enabling the derivation of a calibration constant to convert total collected charge into absolute muon intensity.

The system was then operated during full-intensity beam runs (55 MeV/c muons at $\sim$40 Hz repetition), yielding muon intensity measurements on the order of 10^4 muons per second. The method demonstrated robustness and reliability, validating the combined use of experimental data and simulations for beam monitor calibration. The estimation of the accuracy on the measurement of Q_{tot} is discussed here.

2. – Detector Calibration Method

In order to convert the charge measured by the SiPMs into an absolute muon intensity, a dedicated calibration procedure was developed, based on detector simulation and single particle measurements.

To reach the single-particle regime, the beam transport system was intentionally detuned by modifying quadrupole settings and magnetic fields. This reduced the effective transmission of the beam line, enabling the observation of isolated muons with minimal pile-up. A coincidence requirement between the two fibre planes within a 50 ns time window was applied to select single-muon events.

The charge spectra recorded by each SiPM channel were analysed to extract the average signal amplitude for a single muon interacting with two fibres, Q_μ. Due to the geometry of the detector, muons may cross one or two adjacent fibres. To account for this, the hit multiplicity distribution was studied using detailed Geant4 and FLUKA simulations, which provided the fractions of events depositing energy in one fibre ($W_1 = 24.9(4)\%$) and two fibres ($W_2 = 49.61(9)\%$), along with the energy deposition ratio $\eta = E_2/E_1 = 2.11(5)$.

These values were used to derive a calibration constant that relates the total collected charge Q_{tot} to the number of muons delivered per second [4]:

$$\varphi\,[\mu/\mathrm{s}] = \frac{r}{W_2 + W_1/\eta} \cdot \frac{Q_{\text{tot}}}{Q_\mu}$$

where φ is the muon intensity, and r is the average repetition rate of the pulsed beam (40 Hz).

This approach effectively allows the monitor to be calibrated without an external reference detector, relying solely on low-rate beam data and validated simulation models.

3. – Charge Stability and Beam Fluctuations

To evaluate the stability and reliability of the monitor response, the distribution of the total collected charge Q_{tot} over repeated beam spills has been studied in comparison with the total number of detected characteristic X-rays measured with the FAMU detectors over 8 consecutive events (to enhance statistics and cancel out the event-by-event oscillations). The latter variable is a clear marker of the number of muons entering the experiment target.

Figure 2 summarizes the behaviour of the system at different levels of event integration. The upper panel shows the correlation between Q_{tot} and the X-ray count when considering a single spill (*i.e.*, one event). The distribution exhibits significant spread, forming no clear linearity, and the histogram of Q_{tot} displays a relative width of approximately 3.8%. The unclear correlation reflects the effect of detector resolution and low statistics rather than intrinsic spill-to-spill variation in the muon beam intensity.

The middle panel shows the same distributions, but after averaging over 10^3 consecutive spills (roughly corresponding to 25 seconds). The Q_{tot} *vs.* X-ray count plot exhibits a proportionality, with strongly reduced spread, while the histogram of Q_{tot} narrows to a width of $\sim$1.8%. This confirms that the integrated charge is stably proportional to the number of muons, and that statistical fluctuations decrease as expected under averaging.

The lower panel quantifies this behaviour more generally, showing the relative standard deviation (RMS/$\langle Q_{\text{tot}} \rangle$) of the collected charge as a function of the number of events averaged. An initial decrease in fluctuation is observed, consistent with statistical averaging, followed by a plateau at $\sim$1.8% for $N \gtrsim 10^3$. This residual spread reflects the physical intensity fluctuations of the muon beam at the source, and represents the ultimate resolution limit of muon intensity normalization using this method. Importantly, it demonstrates the monitor's ability to track beam variations with high fidelity.

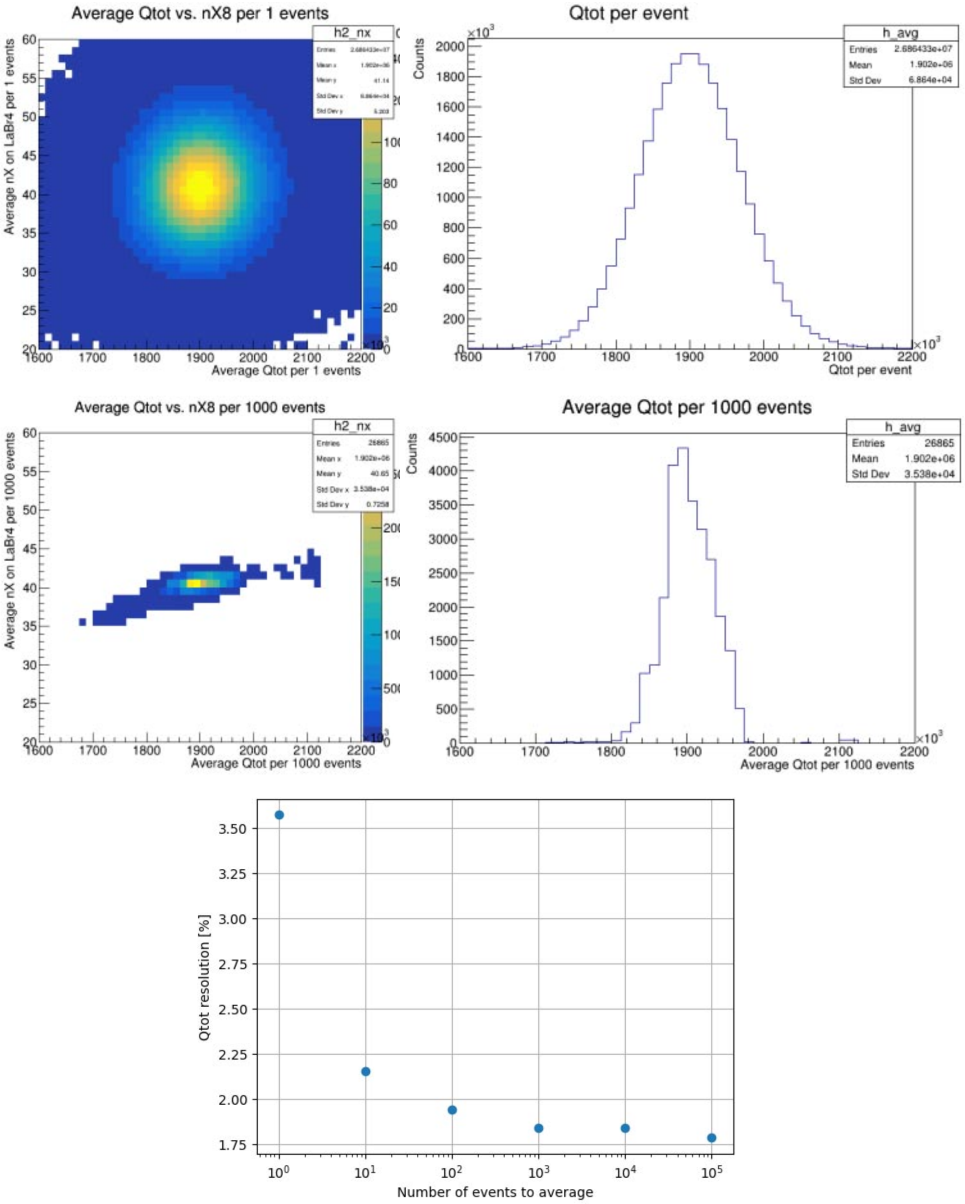

Fig. 2. – Upper and middle panels: proportionality of the number of X-rays in 8 consecutive events and the value of Q_{tot}, for one event and by averaging on 1000 events, respectively, and related histogram of Q_{tot}. Lower panel: measured width of the Q_{tot} distribution as a function of the number of averaged events.

4. – Results

Following calibration, the beam monitor is deployed in standard operating conditions during the FAMU experimental runs, using pulsed muon beams with a momentum of 55 MeV/*c* and a spill repetition rate of 40 Hz.

Charge distributions are accumulated over each spill, and the total integrated charge per spill is converted into muon beam intensity using the previously determined calibration constant. The measured intensities are of the order of 10^4 muons per second, consistent with expectations. The detector demonstrated excellent linearity, stability, and reproducibility across various run configurations.

No significant degradation in SiPM performance or detector efficiency was observed throughout the data-taking campaign. The compact and low-material design of the hodoscope ensured minimal interference with the beam profile and allowed for continuous online monitoring without affecting the experiment.

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