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# Design and performance of the FIT scintillating-fiber tracker

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Tracking detectors based on scintillating fibers, read out with silicon photomultipliers (SiPMs), have emerged as a competitive alternative to silicon strip detectors in high-energy and astroparticle physics. The scintillating-fiber tracker (FIT), proposed for the upcoming High-Energy Cosmic-Radiation Detection (HERD) facility, consists of several tracking planes of fiber mats stacked along two orthogonal coordinates. FIT is designed to reconstruct the trajectory of traversing charged particles, measure their absolute charge, and enhance the photon conversion into electron-positron pairs. A prototype detector, named MiniFIT, has been produced and extensively tested in various beam-test campaigns at CERN. In this work, we will discuss the development of the FIT detector, as well as design and performance of MiniFIT.

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## 1. Introduction

Over the last 15 years, space-borne experiments such as AMS-02 and DAMPE have been critical to our understanding of the universe and astrophysical phenomena [1, 2]. Each experiment has pursued the work achieved by its predecessors, steadily advancing our ability to study cosmic rays. However, many questions remain open, such as the acceleration and propagation mechanisms of cosmic rays and the governing mechanisms of high-energy astrophysical sources such as supernova remnants, pulsars, magnetars and active galactic nuclei. Moreover, the fundamental nature of dark matter and dark energy continues to be a central subject of inquiry.

In order to push the boundaries of our understanding, we must extend the limits of our technology. Today's detectors have brought us to an unprecedented level of energies, but unraveling the remaining mysteries requires access to even higher energies. Future experiments such as HERD will require detectors with larger acceptance, while still satisfying the strong constraints imposed by space-borne missions [3]. Next generation space-borne experiments will demand large-area trackers offering higher resolution, faster readout, compactness, low power consumption, and cost-effectiveness—all while maintaining the mechanical stability necessary to survive launch conditions. Developing such detectors is not just an engineering challenge — it is the key to moving forward in astrophysics.

This contribution will present the development of the scintillating-fiber tracker FIT specifically designed for such experiments and the preliminary performance of its scaled-down version MiniFIT, in both position resolution and charge measurement.

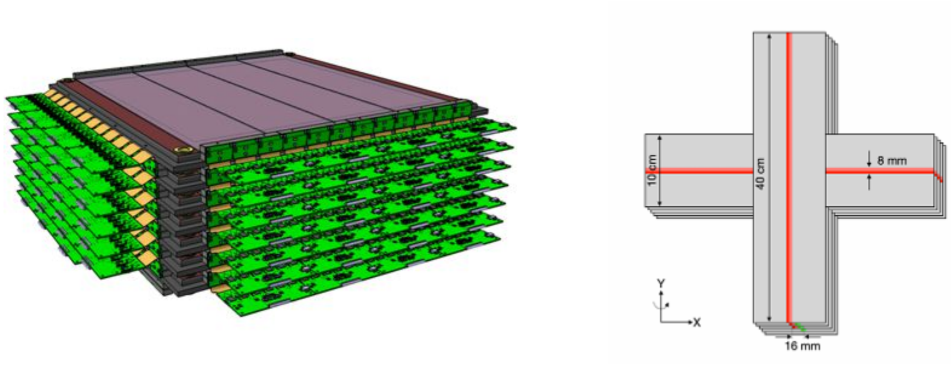
## 2. The scintillating-fiber tracker (FIT)

The scintillating-fiber tracker (FIT) was designed around the HERD experiment [4]. As a large-acceptance space-borne experiment, HERD requires a large-area tracker meeting its constraints. FIT was thus designed to reconstruct the trajectory of traversing particles as well as offer a redundant measurement of the absolute value of the particle's electric charge ($|Z|$) [5]. FIT also facilitates the conversion of low-energy gamma rays into pairs of electrons and positrons and enables their track reconstruction. FIT is a highly modular detector, optimized to be compact yet precise, requiring low-power and low budget, adapted for space applications. Its basic unit is the FIT module (Fig. 1). A module includes a scintillating-fiber mat and a front-end board, housing three linear arrays with 128 silicon photomultipliers (SiPMs) each. A tracking layer is composed of two perpendicular layers (X and Y), each made of modules glued next to each other. The two layers are attached to each side of a support tray. The latter is a mechanical structure made of two sheets of carbon fiber reinforced polymer (CFRP) enclosing a core of aluminum honeycomb. A FIT sector consists of 7 tracking layers, a number optimized to provide the best trade-off between high-precision measurement and compactness, facilitating its integration into a multi-detector experiment. The mat is made of six layers of scintillating fibers, manufactured by Kuraray (type SCSF-78MJ). They have a round cross section with an average diameter of 250 µm. The mat has a width of 97.8 mm and matches three Hamamatsu S13552-10 SiPM arrays, each containing 128 SiPMs. Each SiPM has 3749 pixels with a pitch of 10 µm. Every SiPM array is mounted on a small printed circuit board (PCB), which is screwed to the end piece of the fiber mat. The three PCBs are connected to the main body of the front-end board through individual flexible cables. To offer bias-voltage correction based on temperature, a PT100 thermal sensor is mounted on the backside of the SiPM's PCB. A custom-made ASIC, named BETA-64 [6], has been developed for the FIT readout. It features a 15-bit high dynamic range (avoiding saturation even for more than 3800 fired pixels), a dual-path architecture with automatic gain switching, slow digital control via I2C, and a power consumption below 1 mW per channel. The BETA-64 further ensures a wide dynamic range, enabling accurate charge measurement up to $|Z| = 26$.

**Figure 1:** The FIT module.

## 3. MiniFIT

MiniFIT is a small-scale version of a FIT sector. It was designed to evaluate the tracking and charge measurement capabilities of the FIT detector as well as the new BETA ASICs developed for the HERD experiment. MiniFIT consists of 7 tracking-planes, capable of 7 independent measurements of the position and 14 measurements of the absolute value of the charge of the traversing particle. Each plane contains 4-X and 4-Y FIT modules, with a fiber mat length of about 40 cm.




**(a)** Schematic view of MiniFIT.

**(b)** Layout of MiniFIT during the beam-test.

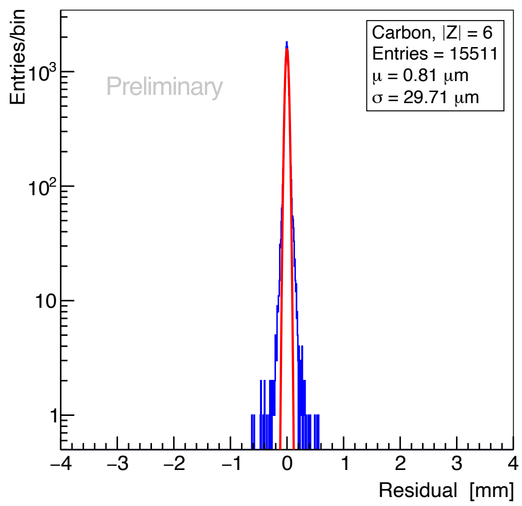
**Figure 2**

## 4. Performance evaluation of MiniFIT

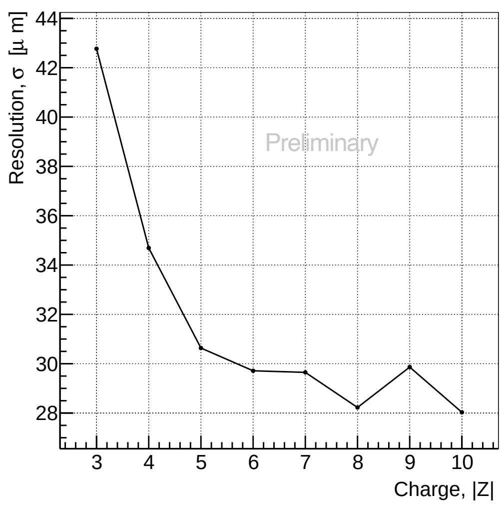
In November 2024, MiniFIT was tested at the CERN SPS with a fragmentation ion beam, created with a beam of lead nuclei hitting a 40 mm thick beryllium target. Over 4 tracking-planes, four X-modules and four Y-modules were read out using a preliminary version of the ASIC, providing 16 channels per chip, named BETA-16 [7]. The detector's layout during the beam-test is shown in Fig. 2b.

### 4.1 Position resolution

The resolution of the position measurements of MiniFIT is separately computed along X and Y using the inner modules, $x_2$ and $y_2$ respectively, since they have the smallest track extrapolation error. For each axis, a 3-point linear fit is computed using the measured position on the three other modules to estimate the traversing particle's track (either $x_0$, $x_1$ and $x_3$ or $y_0$, $y_1$ and $y_3$). We then define the residual as the difference between the projected hit position ($x_{\text{fit}}$) and the measured position ($x_{\text{hit}}$). The residual distribution is fitted with a Gaussian function and the resolution is defined as the standard deviation of the Gaussian function. Fig. 3a shows the distribution of track-hit residuals for the module $y_2$ for Carbon nuclei. The position resolution of MiniFIT using 4 x-y tracking planes is $< 30$ µm. Subsequently, the position resolution was computed in function of the charge of the traversing particle. Fig. 3b shows the position resolution obtained for charges with $|Z| > 2$ up to $|Z| = 10$. It can be seen that the position resolution decreases for higher charges, reaching 28 µm for particles with charge $|Z| = 8$ and $|Z| = 10$.




**(a)** Distribution of the position residuals for reconstructed Carbon nuclei tracks ($|Z| = 6$) in the $y_2$ layer.




**(b)** Position resolution of MiniFIT as a function of the charge of the traversing particle in the $y_2$ layer.

**Figure 3**

### 4.2 Charge measurement

With the BETA-16 ASIC, MiniFIT is able to resolve nuclei with charges up to $|Z| = 12$. Fig. 4 shows the square root of the mean integral of the reconstructed clusters on the X-layers plotted against that on the Y-layers. The different nuclei are identified as they are sorted according to their charge. Fig. 5 shows the charge distribution of the reconstructed nuclei (beam composition) fitted with a multi-Gaussian function. The linearity between the square root of the measured signal and the particle charge is shown in Fig. 6. A slight saturation can be observed above $|Z| = 11$. This effect is expected to be corrected by accounting for both scintillator and SiPM saturation.

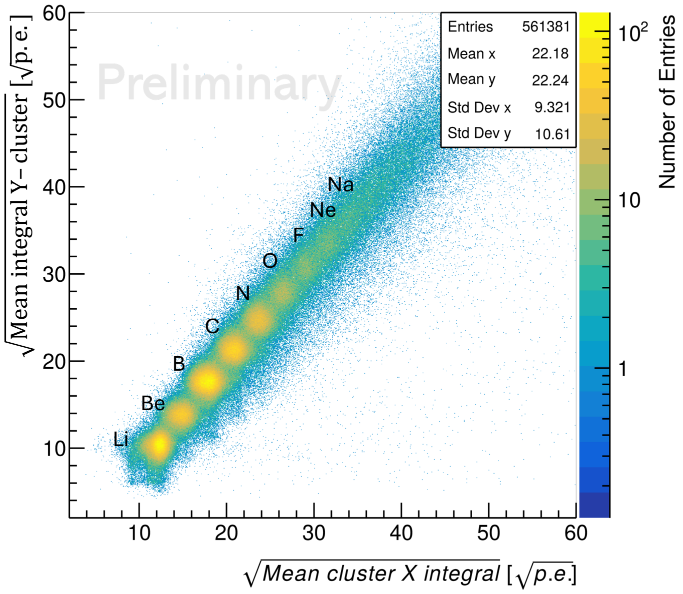



**Figure 4:** Square root of the mean integral of reconstructed clusters on the Y-layers plotted against the corresponding value of reconstructed clusters on the X-layers.

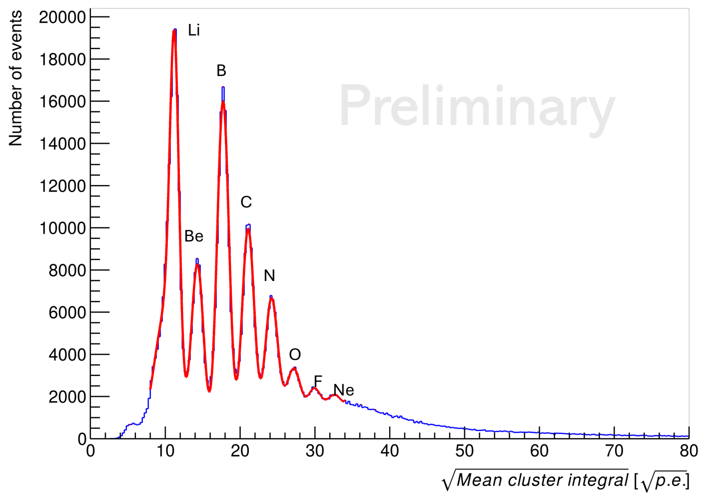



**Figure 5:** Mean cluster integral distribution with a multi-Gaussian fit.

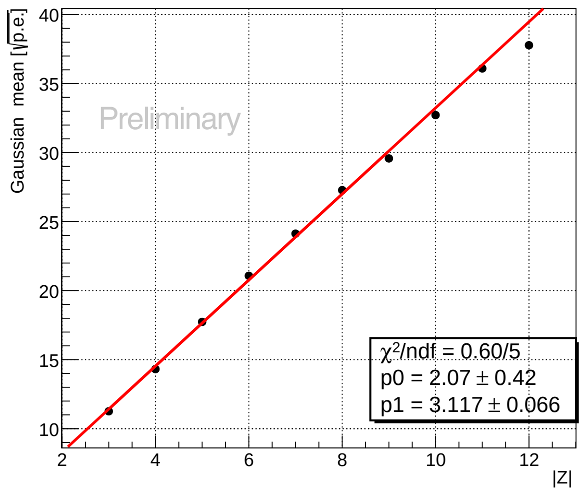



**Figure 6:** Linearity between the square root of the measured signal and the particle charge.

## 5. Conclusion

Cosmic rays have been the subject of extensive experimental study for decades, since they provide a unique natural probe of their astrophysical accelerators, of the interstellar medium through which they propagate, and even of fundamental physics, including dark matter and high-energy interactions beyond the capabilities of terrestrial laboratories. FIT is a highly modular scintillating-fiber tracker developed for space applications specifically designed for the study of cosmic rays. Its objectives include the reconstruction of particle trajectories and absolute value of the particle's electric charge ($|Z|$), the enhancement of the conversion of low-energy gamma rays and the reconstruction of the tracks of the electrons and positrons produced. To demonstrate the tracking and charge measurement capabilities of FIT, a scaled-down version was designed, called MiniFIT. Preliminary results indicate that the spatial resolution improves with nuclear charge, ranging from 43 μm for Lithium nuclei (|Z| = 3) down to 28 μm for Neon nuclei. A precise charge identification and strong linearity was also found during the charge measurement up to charge $|Z| = 10$, with a slight saturation observed for charge $|Z| \geq 11$. Recent results thus show exceptional preliminary position resolution as well as precise charge measurement, making FIT the ideal tracker for multi-detector experiments. In the next beam-test campaigns, we aim at testing MiniFIT with updated test boards hosting new BETA-64 ASICs and using the 7 tracking layers, further improving the position resolution and resolving nuclei up to higher charges.

## 6. Acknowledgments

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