Characterization of light yield non-proportionality in plastic scintillator-based detectors for satellite cosmic-ray experiments

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Abstract

In the performance studies of plastic scintillator-based instruments for space applications, through dedicated beam test campaigns carried out at CERN SPS, we probed non-proportionality effects within plastic scintillators by inspecting the response of scintillator tiles of different materials and sizes to a beam of ions. The tested tiles were equipped with Silicon Photomultipliers (SiPMs) to detect the scintillation light and their design was optimized for providing charge-tagging capabilities in a vast dynamic range and high charge resolution to both low- and high-Z nuclei.

In this contribution, we present the main results of the characterization of plastic scintillators quenching effects resulting from a wide range of particle energy releases, from minimum ionizing particles (MIPs) to charged nuclei heavier than iron. These effects impact on the charged nuclei identification performances of current and future space-based high-energy cosmic-ray experiments.

Introduction

Scintillators are among the most common detectors employed for characterization and spectroscopy of a wide variety of radiations, with applications ranging from cosmic-ray experiments to nuclear medicine. In satellite experiments, plastic scintillator detectors are a common choice to provide an anti-coincidence shield for gamma-rays and for identifying charged nuclei species. Quenching effects may degrade the scintillation light yield proportionality, inevitably affecting the instrument performance and posing a layer of complexity to its precise calibration.

Non-linearity in scintillators

Quenching effects at high excitation densities can be interpreted following the modified Birks formula proposed in [1]. Birks quenching is commonly considered relevant only for energy deposited by charged particles in a thin region surrounding the particle trajectory (core region), while being negligible for carriers escaping to lower excitation density zones (halo region) located further from the particle path. Accounting for the halo-core interplay, the Birks luminous efficiency L_B can be parametrized as

$$L_B = \frac{1 - f_H}{1 + k_B \frac{dE}{dx}} + f_H \qquad (1)$$

where $dE/dx \propto Z^2$ is the charged particle energy release, f_H is the fraction of carriers escaped to the halo region and k_B represents the Birks quenching parameter.

Several studies on inorganic scintillators proved that additional non-Birks effects can dominate the light yield quenching at low excitation densities [2]. In this work, we found that also in plastic scintillators an additional correction term is necessary to properly model the low excitation density quenching effects. In analogy with [2], we parameterize the correction term as

$$L_{Low} = 1 - \eta \exp\left(-\frac{dE/dx}{(dE/dx)_{Low}}\right) \qquad (2)$$

where η and $(dE/dx)_{Low}$ parameters characterize the strength and excitation density scale of the corrective term.

In this work, we investigated the incidence of the Birks and L_{Low} terms to the quenching effects in plastic scintillators.

Scintillator tiles geometry

In the framework of the R&D and beam test activities for the Plastic Scintillator Detector of the High Energy Cosmic Radiation detection (HERD) facility [3], we tested plastic scintillator tiles with two different geometries, sizes and materials. A BC-404 **Squared Tile (S-Tile)** with 10 cm size and 0.5 cm thickness was equipped with SiPMs:

- ☐ One S14160-3015PS 3x3 mm^2 SiPM with 15 µm cell size;
- ☐ One S14160-1315PS 1.3x1.3 mm^2 SiPM with 15 µm cell size.

An EJ-200 **Trapezoidal Tile (T-Tile)** 40 cm long, 0.5 cm thick, with a trapezoidal section 5 cm wide, was readout with:

- ☐ Four S14160-3050HS 3x3 mm^2 with 50 µm cell size SiPMs;
- ☐ Four S14160-1315PS 1.3x1.3 mm^2 with 15 µm cell size SiPMs.

1.3x1.3 mm^2 SiPMs, tagged as **High-Z**, have low detection efficiency for MIPs but wider Z dynamic range, while 3x3 mm^2 SiPMs, tagged as **Low-Z**, have higher detection efficiency but narrower dynamic range. The employment of SiPMs of both sizes increases the light detection efficiency and the dynamic range for nuclei identification.

Beam test at SPS-H4 (2023)

Ion beam at CERN SPS test beam:

- Derived from a 150 GeV/A primary Pb beam impinging onto a Be target;
- Z ranging from 1 to ~ 60;
- 330 GeV/Z selected beam.

The BETA readout system [4], developed at ICCUB (Institut de Ciènces del Cosmos Universitat de Barcelona), was used to read and digitize the peaking voltage of the SiPMs analog signals.

References:

[1] G. Tarle, S.P. Ahlen and B.G. Cartwright, Cosmic ray isotope abundances from chromium to nickel, Astrophys. J. 230 (1979) 607.
[2] W.W. Moses et al., The Origins of Scintillator Non-Proportionality, IEEE Trans. Nucl. Sci. 59 (2012) 2038
[3] D.Serini et al.,, Nuclei identification performances studies of the Plastic Scintillator Detector (PSD) for the future HERD space mission, 38th International Cosmic Ray Conference (ICRC2023)
[4] A. Comerma, D. Gascon, S. Gomez, and A. Sanmukh, HERD-FiBre TrackEr ReadouT Asic (BETA) Specifications Document, 2019

High excitation density quenching in the S-Tile

The ADC counts distribution of the S-Tile High-Z SiPM at the SPS beam test is shown in Figure 1. Via a Multi-Gaussian fit, the individual peaks were associated to the ion charge numbers Z and the Birks quenching effects in high excitation density conditions were evaluated. Figure 2 shows the peaks mean values, in ADC counts, as a function of Z^2, up to $Z = 24$.

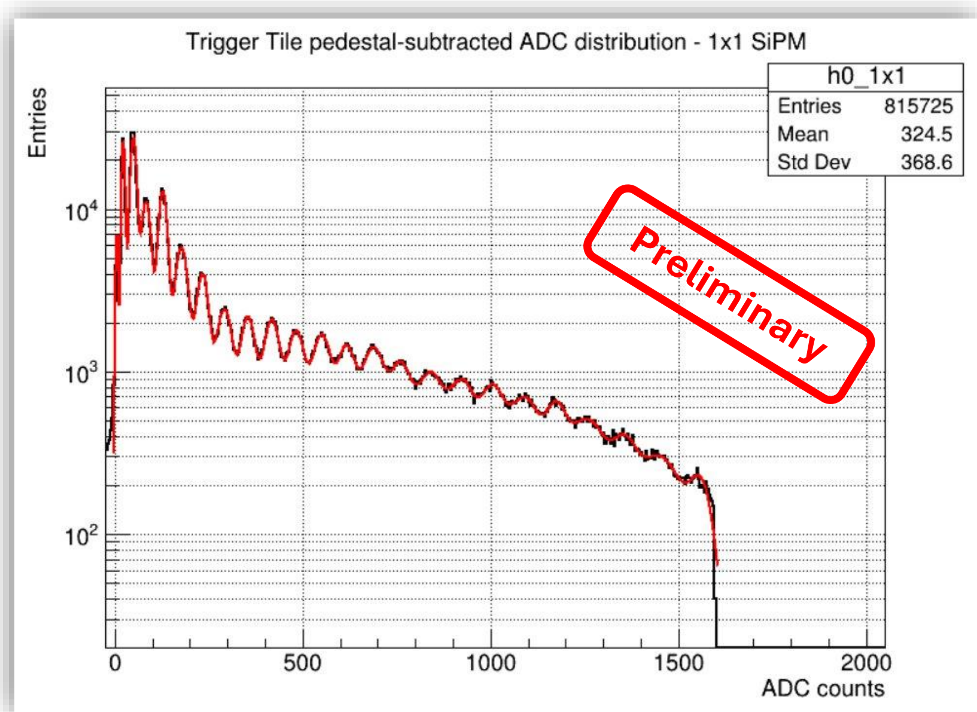

Figure 1. ADC counts spectrum of the High-Z SiPM with Multi-Gaussian fit (in red).

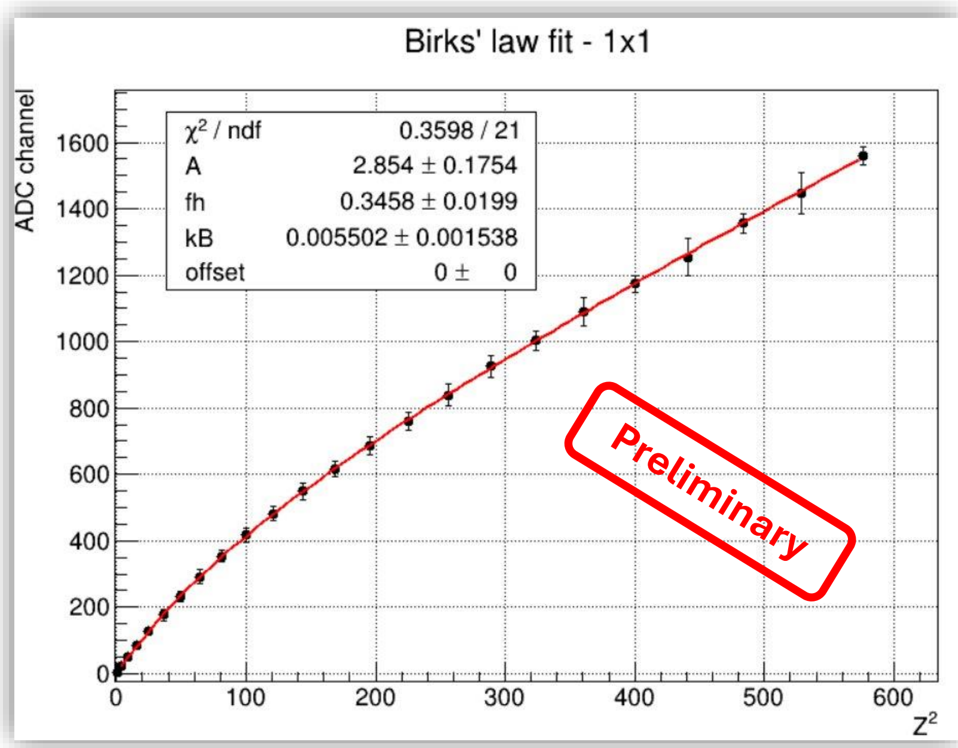

Figure 2. S-Tile High-Z SiPM ADC peaks from Multi-Gaussian fit as a function of Z^2. Fit function curve (3) is represented in red.

The trend was fitted with the function

$$\frac{dL}{dx} = AZ^2 L_B \qquad (3)$$

where A is a normalization constant and L_B accounts for Birks effects (Eq. 1). We derived a best-fit value of $f_H = (35 \pm 2)\%$ and constrain k_B to $(5.5 \pm 1.5) \times 10^{-3}$ cm MeV^{-1}.

The S-Tile shows high-resolution (up to $1-5\%$) nuclear identification capabilities and Eq. (3) provides a precise calibration of its response over a wide Z dynamic range.

Low excitation density quenching in the T-Tile

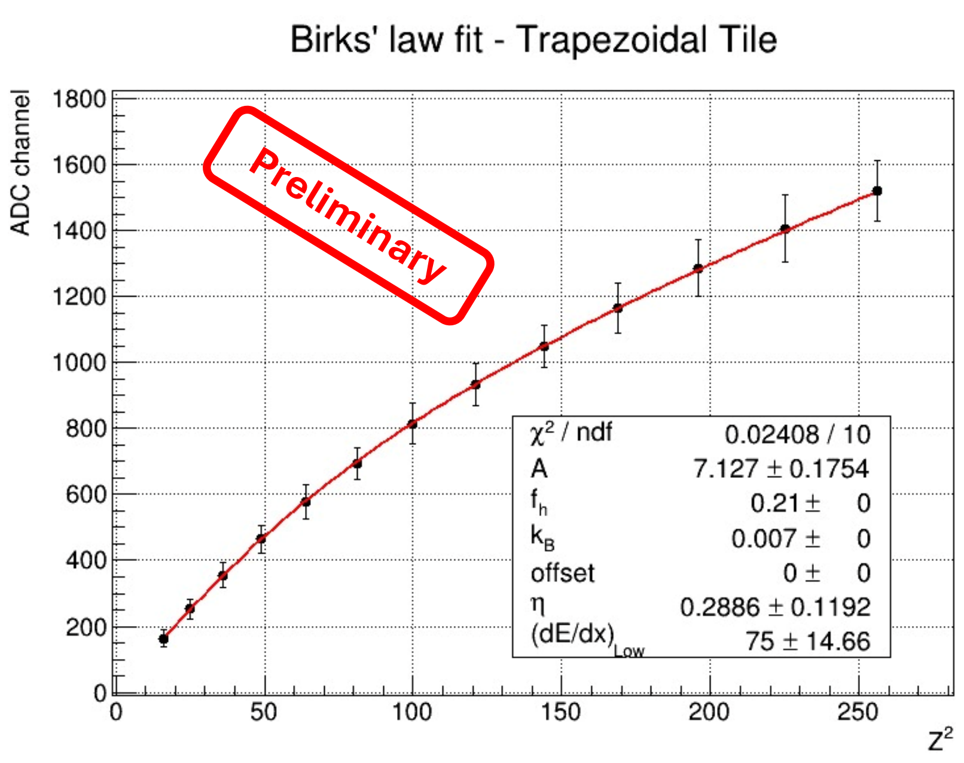

Figure 3. T-Tile Low-Z SiPMs mean values from Gaussian fit as a function of Z^2. Fit function curve (4) is represented in red.

Using the event-per-event S-Tile **charge tags** [3], the T-Tile ADC spectra at fixed Z were fitted with Gaussian functions [4]. The High-Z ADC spectra were used to estimate the Birks parameters for EJ-200, $f_H = (21 \pm 2)\%$ and $k_B = (7 \pm 5) \times 10^{-3}$ cm MeV^{-1}. A significant difference in the f_H parameters for the two scintillators can be highlighted.

The trend of the ADC peak values for the T-Tile Low-Z SiPMs as a function of Z^2 is well fitted with the function:

$$\frac{dL}{dx} = AZ^2 L_B L_{Low} \qquad (4)$$

The contribution of the L_{Low} term (2) for low-Z particles energy releases is displayed in Figure 4. The black points represent the $(dL/dx)/(AZ^2)$ data derived from Figure 3, whereas the lines represent the contributions of the Birks and L_{Low} terms to the $L_B L_{Low}$ product. In low excitation density conditions, a proper calibration of plastic scintillator response requires accounting for both the Birks and L_{Low} terms.

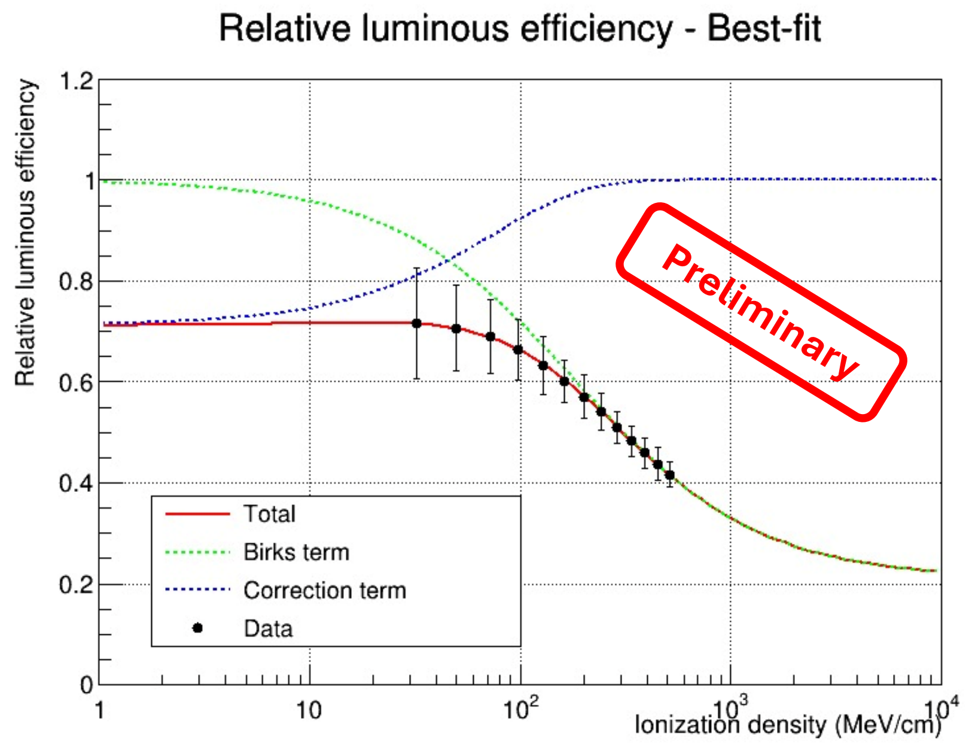

Figure 4. Birks L_B and L_{Low} contribution to the relative luminous efficiency. The terms are estimated with the best-fit values in Figure 3.

Conclusions

We probed low and high excitation density quenching effects in plastic scintillators by exposing BC404 and EJ200 tiles to ions in beam test campaigns conducted at CERN SPS. Our measurement is sensitive to discriminate a difference in the Birks parameters of the two scintillators and to estimate the contributions of the Birks and L_{Low} effects to the scintillation light yield quenching, whose characterization is essential for a proper interpretation of the response of scintillator-based detectors.

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