IL NUOVO CIMENTO **49 C** (2026) 91
DOI 10.1393/ncc/i2026-26091-6

Colloquia: FATA 2025

Timing performance of the Multigap Resistive Plate Chambers for the cosmic ray telescopes of the EEE Project

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received 12 March 2026

Summary. — The Extreme Energy Events (EEE) Project has built since 2004 a GPS-synchronized network of cosmic ray telescopes based on Multigap Resistive Plate Chambers (MRPC), which are distributed over the Italian territory. Most of them are installed within high school institutes and operated by local teams of students and teachers. Various upgrades, also concerned with the use of new eco-friendly gas mixtures have been undertaken, to reduce the impact of the traditional gases with high Global Warming Power. Good tracking, efficiency and timing capabilities of the MRPCs have allowed a variety of physics investigations, accompanied by an intense outreach programme over the last years. After the early cosmic ray and in-beam measurements carried out at CERN at the PS T10 East Hall beam line, the timing performance of the various telescopes has been long investigated by a combined analysis of the results obtained from a large number of individual detectors operated for year-long data taking periods. The overall organization of the EEE project, with special emphasis on the timing aspects of the involved MRPC detectors, will be discussed in this contribution.

1. – Introduction

The Extreme Energy Events (EEE) Project [1] is a peculiar experiment born in 2004 thanks to the collaboration of Centro Fermi (Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi") [2], INFN (Istituto Nazionale di Fisica Nucleare), CERN (European Council for Nuclear Research) and MIUR (the Italian Ministry of Education, University and Research). The experiment aims to study the flux of cosmic rays (CR) and their related phenomena using a sparse, large array of about 60 detectors, installed in Italian high schools, INFN sites and CERN. The network is completed by 3 scintillator-based detectors, called POLA-R, installed at the Svalbard islands. A total of about 80 high schools are involved in the project, with or without an installed telescope. The map of the EEE network is reported in fig. 1. Thanks to the joint venture of the different organizations, and the presence of the array in the whole Italian territory, the project has a dual role:

- *scientific*: the network, thanks to its characteristic, is able to investigate different properties of the CR flux, such as anisotropies in the secondary component [3], dependence on the latitude [4], Forbush events [5], and detection of Extensive Air Showers [6];
- *outreach*: high schools are directly involved in the data taking process, monitoring the telescopes during the coordinated runs, analysing the data acquired with such telescopes, and participating to other related activities.

These aspects, in addition with the unconventional sites where the telescopes are placed, the spatial extension of the network, the large area of the employed detectors, and the long term operations, create a unique project.

Fig. 1. – The map of the EEE network, that shows the location of the involved sites with different symbols: schools with MRPC telescopes, schools that joined the project without hosting a telescope, and a few sites where telescopes are installed inside CERN, INFN or University centres. The inset shows the POLA-R scintillator detectors installed at the Svalbard.

2. – MRPC for the EEE telescope

Considering the physics goals of the experiment, the required characteristics for the detector are:

- easy to find and to work materials, considering that high school students built the chambers of their own telescope;
- a reasonable cost, due to the large number of detectors needed and the scope of the project;
- long term operations;
- efficiency close to 100%;
- ability to reconstruct the direction of the track, hence at least three planes of detector are needed;
- spatial resolution of few centimetres in both the horizontal coordinates for the localization of the hit point on each plane and the extrapolation of the reconstructed tracks;
- good time resolution, of the order of the hundreds of ps, due to the expected time of flight measurements (few ns). Moreover the time resolution should be enough to allow the correlation of signals detected in different devices located at large distance using a GPS device, and to guarantee the discrimination of the accidental background generated by noise signals.

With these requirements, the selected detector was a larger ($\sim$1.5 m^2) and simpler version of the Multigap Resistive Plate Chamber (MRPC) developed for the ALICE TOF detector [7]. A picture of an actual telescope is reported in fig. 2. The telescope consists of 3 planes of chambers of area $\sim 80 \times 160\,\text{cm}^2$ separated by 50 cm. Moreover, each telescope is equipped with stand-alone low voltage power supplies, DC/DC converter for the high voltage, a GPS unit to provide the time stamp and the synchronization of the network, a VME-based data acquisition system, a gas flow system provided by a commercial mixing one, and a weather station. The data collection is centralized: all the raw data are transmitted to the INFN-CNAF data center, where they are reconstructed and stored.

The schematic layout of the EEE MRPC is reported in fig. 3. Each MRPC is made of a 6 gas gap system of 300 μm, obtained stacking glass sheets. The voltage is applied only on the external sheets, while the ones inside are left floating. The cathode and anode are made of two glasses (160 cm $\times$ 85 cm, 1.9 mm thick) treated with a resistive coat paint, obtaining a surface resistivity of 5–20 M$\Omega/\Box$. In the space between the electrodes, the gas gaps are created using 5 intermediate glass sheets (158 cm $\times$ 82 cm, 1.1 mm thick), separated by fishing lines. On the outer glasses, a Mylar foil (175 cm $\times$ 86 cm) is stretched on a vetronite panel of equal area, in order to insulate the readout strips from the electrodes. Such readout strips are made using 24 copper strips (180 cm $\times$ 2.5 cm, spaced by 7 mm). At the two edges of the chambers, two FEA (Front End Acquisition) boards are mounted in order to read the signals from the readout strips. Two rigid honeycomb panels (180 cm $\times$ 90 cm) are used in order to ensure a good mechanical stability. Finally, all the structure is enclosed in a gas-tight aluminium box (220 cm $\times$ 110 cm of external dimension, 192 cm $\times$ 92 cm inside), with the gas inlets

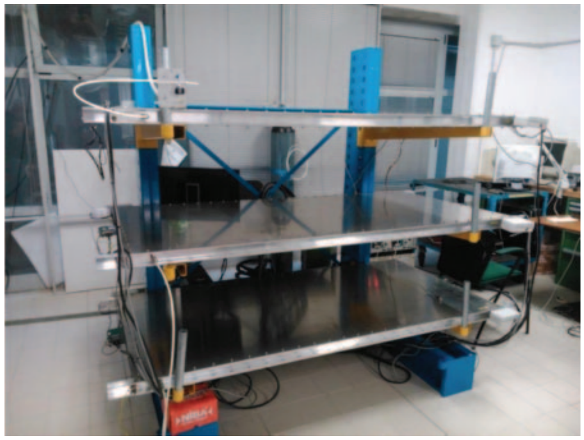

Fig. 2. – One of the EEE telescopes, with three MRPC chambers.

and outlets, and the high voltage connectors located at the end of the long side, while the FEA boards are located on the short sides. Up until 2021 chambers where filled with a gas mixture of a 98%/2% of R134a ($C_2F_4H_2$) and SF_6 at a continuos flux of 2 l/h, while the current operations are carried out using a new ecological gas mixture made of 50% HFO (C_3H_2F4) and 50% helium fluxed at 1 l/h [8-10].

3. – Timing performance under beam

Considering the peculiarity of the construction materials and techniques, one of the first steps of the project was to verify the chamber performances under beam: such tests were performed in 2006 at the CERN PS (Proton Syncrotron) accelerator [11]. The experimental apparatus consisted of two pairs of crossed scintillators of different area ($1 \times 1\,\mathrm{cm}^2$ and $2 \times 2\,\mathrm{cm}^2$) to provide the trigger, a $5 \times 5\,\mathrm{cm}^2$ scintillator to ensure that the beam passed through the MRPC under test, two scintillator bars ($2 \times 2 \times 10\,\mathrm{cm}^3$) orthogonal to each other, coupled with four photomultipliers at the end of the bars, to obtain a precise time reference. The chambers were fluxed with the standard mixture with a flux of 5 l/h. During the data acquisition, the beam was centred in the middle of the strip, in order to ensure the stability of the system. To avoid dependence of the signal from the position of the hit, the signals from both ends of the strip are collected

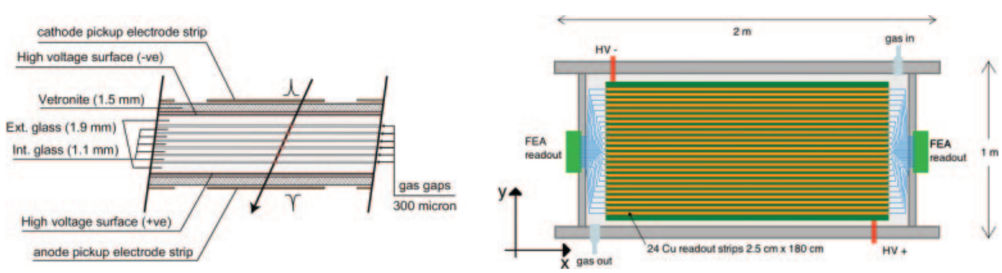

Fig. 3. – Schematic description of the MRPC of the EEE experiment.

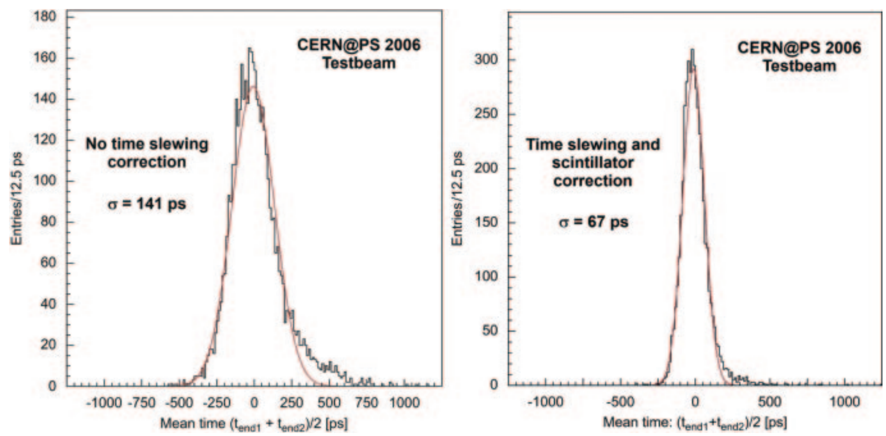

Fig. 4. – Mean time distribution for the MRPC of the EEE project, obtained during the 2006 PS testbeam, before (left) and after (right) applying the time slewing correction [11].

and their mean time, $(t_{end1} + t_{end2})/2$, is studied. The obtained time distribution is reported in the left panel of fig. 4. Such distribution shows a tail on the right: the cause of this effect is the impedance of the readout card. In fact, during the data taking, the readout cards matched with the ALICE-TOF MRPC were used. These cards had an impedance of 50 Ω, while the strips of the EEE MRPC chamber have an impedance of about 100 Ω: this mismatch creates a reflected signal. Moreover, such distribution is not corrected for the time slewing, due to the use of constant fraction discriminators. After applying such correction the obtained mean time distribution is reported in the right panel of fig. 4. The time resolution of the chamber is then calculated fitting such distribution with a Gaussian function, and subtracting quadratically from the width the value of 30 ps, that is the effect of the jitter of the scintillators used as time reference. The obtained time resolution is about 67 ps, in excellent agreement with the requirements for the experiment.

4. – Timing performance with cosmic rays

After the preliminary tests under beam on prototype chambers, the full construction and installation of the network was carried out. Then, it was possible to perform a systematic analysis on all the network's telescopes, in order to understand the time resolution of the chambers during the normal operations. This study, reported in detail in ref. [12], has been conducted using the data collected during the Run 3 (November 2016–May 2017), with a total of 33 telescopes, all equipped with dedicated boards which distribute a common clock to the TDCs, in order to avoid any time drift. In this case, the information of the upper and lower chambers of the telescope are used to evaluate the performance of the middle one, and this value is then compared with the one measured experimentally. The time residual is defined as

$$\Delta t = \frac{t_{top} + t_{bot}}{2} - t_{mid}, \tag{1}$$

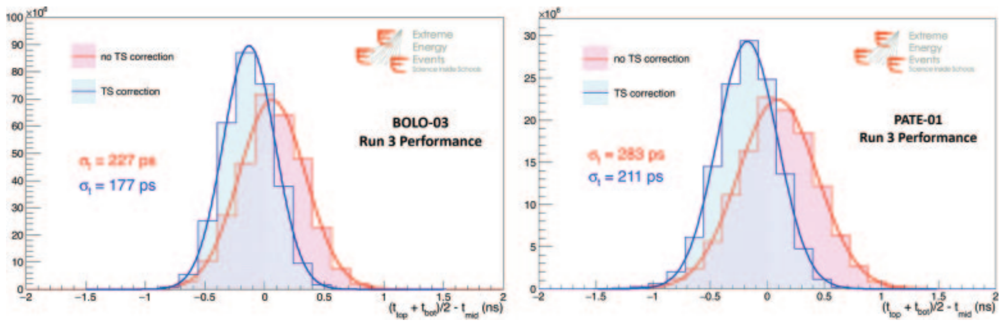

Fig. 5. – Time distributions for the BOLO-03 (left) and PATE-01 (right) telescopes, before (red) and after (blue) applying the time slewing correction [12].

where t_{top}, t_{bot}, and t_{mid} are, respectively, the time measured in the top, bottom and middle chambers. The width of the Δt distribution is proportional to the time resolution of the chambers: assuming similar performances for the three chambers, the single chamber has a time resolution equal to

$$\sigma_t = \frac{\sigma_{\Delta t}}{\sqrt{3/2}}. \tag{2}$$

Figure 5 shows an example of the time distributions for two telescopes located in Bologna (BOLO-03) and釣ternò (PATE-01), respectively. Also in this case, the correction for the time slewing is applied. The distributions show a displacement of the mean values from zero: this shift, due to missing calibrations, does not directly influence the measurement of the time resolution. Considering all the different telescopes, the obtained time resolution ranges between 140 and 380 ps: these different values can be explained by missing optimization of the detector working point, possible inhomogeneities in the MRPC constructions, and possible not optimal calibration for the strips. Among these causes, the first one is the most likely, since the construction process was well standardized. It is also possible to evaluate the average resolution of the network, looking at the time resolution distribution for all the telescopes: such distribution is reported in fig. 6. The distribution is fitted with a Gaussian function, obtaining an average time resolution of $\sigma_t = 238 \pm 40\,\text{ps}$. If we compare this value with the one obtained during the test beam, reported in the previous paragraph, it is higher: the difference is easily understandable, since during the normal data taking the same controlled conditions (focused, monochromatic, collinear beam monitored with a complex setup of detectors) present during the test beam are not achieved. Nevertheless, the time resolution is fully compatible with the experiment requirements.

5. – Timing performance with new eco-mixtures

Recent EU regulations have set the upper limit for the Global Warming Potential (GWP)([1]) for gas-operated devices to 150, in order to reduce the greenhouse emissions. If we consider the standard mixture used by the EEE telescopes, it has a GWP of

([1]) The GWP measures the effect of greenhouse gas normalized to the one of CO_2.

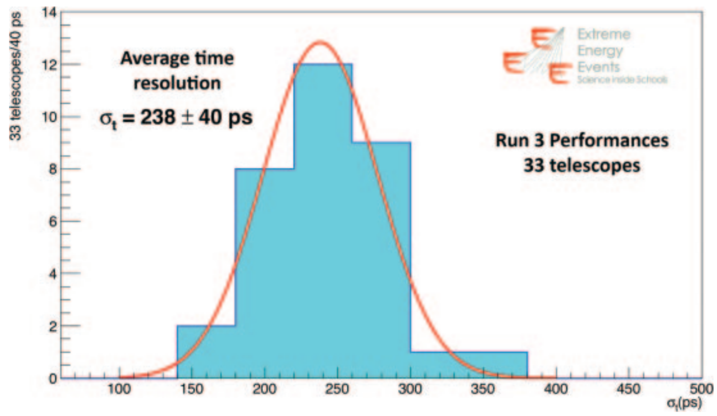

Fig. 6. – Time resolution distribution measured with the 33 telescopes of the EEE network during the Run 3 [12].

$\sim$2030. Even if the standard mixture is still suitable for scientific purposes, the EEE Collaboration has decided to reduce their greenhouse emission, replacing the gas employed in their detectors, switching to a more ecological alternative. To do so, an extensive campaign of R&D was carried out during the COVID-19 stop, when the telescopes were turned off due to unavailability of the contribution of high school students. The main requisites of the new mixture were:

- a lower GWP with respect to the standard mixture;
- only non flammable, non toxic gas allowed, due to the peculiarities of the installation sites;
- only binary fluxes, due to the limitation on the gas apparatus of the telescopes;
- ability to ensure the operations with a maximum bias voltage of 20 kV;
- FEE (Front End Electronic) ability to handle the signal generated with the new mixture;
- detector's performance not having a negative impact on the physics programme;
- cost comparable with the old one.

The new mixture used is composed by HFO (C_3H_2F4, GWP $= 6$) and helium (GWP < 1). The R&D programme was carried out exploring different relative percentage on the new eco-mixture, in order to understand the efficiency of the chambers and the timing resolution. During the tests, reported in detail in ref. [9], only the middle chamber has been fluxed with the new eco-mixture with a 1 l/h flux, while the top and bottom chambers were fluxed with the standard mixture. The tests were conducted using the REND-01 telescope, applying for each explored setup the voltage that ensures a 95% efficiency. After applying a strip-by-strip time calibration, in order to correct possible time offset generated by the setup, the time residuals have been calculated. The obtained distributions for the different gas setup are reported in fig. 7. With respect to the studies performed with the standard mixture, reported in the previous paragraph, the resolution

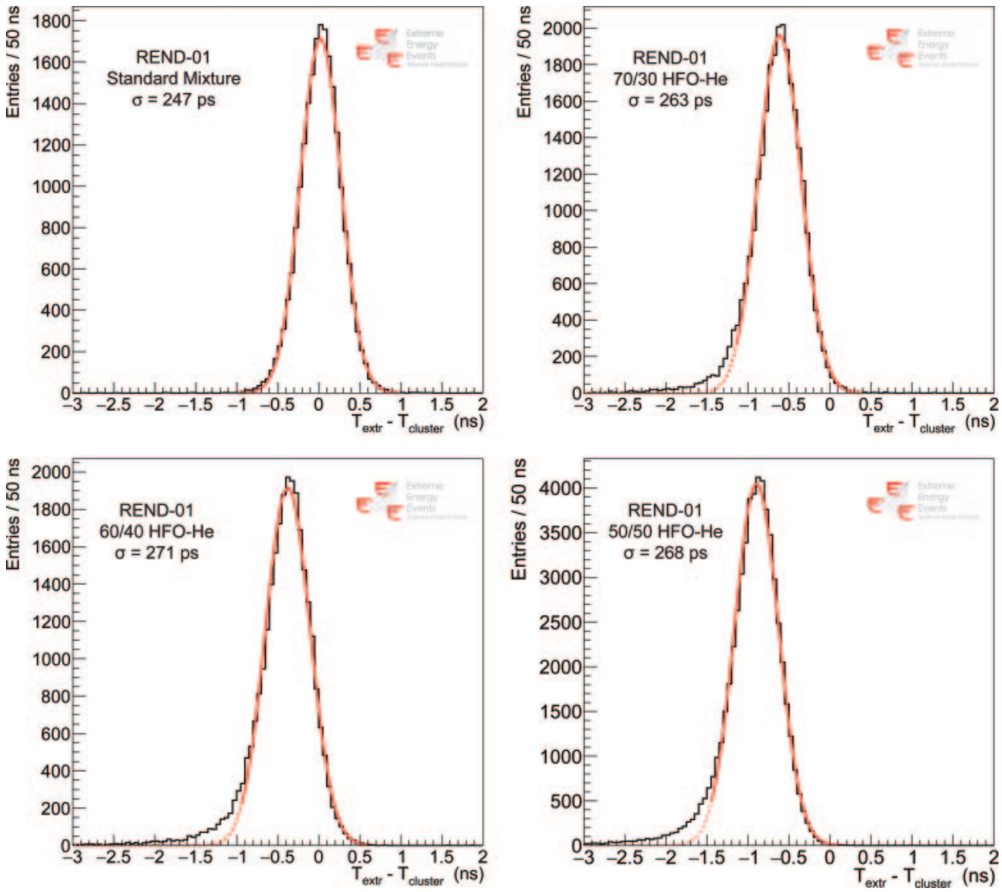

Fig. 7. – Distribution of time residuals for the chamber under test using the standard mixture (top left), and the 70/30 (top right), 60/40 (bottom left) and 50/50 (bottom right) ratios for the new eco-mixture [9].

of the single chamber cannot be calculated using eq. (2), since the assumption of similar performances for the three chambers is not valid any more. Nevertheless, comparing the evolution of the time residual distributions as a function of the different mixture ratios, it is possible to identify the most performing one. In the new eco-mixture, unlike the standard one, a tail on the left of the distribution is present. Moreover, a slightly larger time residual is observed. The obtained values are reported in table I. The increased values suggest a lower time precision of the chambers, that can be due to different drift speed, different Townsend coefficient, larger spread in signal total charge, etc. Further offline studies can improve the detector performance, but the current results are still within the requirement needed for the EEE Collaboration physical goals.

6. – Conclusions

The EEE network, with its large covered area, its overall detector surface and long-living network of detectors, is certainly a peculiar experiment for cosmic ray measure-

Table I. – *Time residual distribution widths for the different gas mixtures.*

Mixture	Time residual distribution width (ps)
Standard	247
70/30	263
60/40	271
50/50	268

ments. Moreover, the direct involvement of high schools students creates a unique project, not only from a scientific point of view, but also as an outreach activity. The technology of the MRPC has been validated during the years, and the time resolution has been evaluated using measurements under beam, with cosmic rays, and after the ecological transition of the network. In all the cases, the time resolution, of the order of 200 ps, remains within the requirement of the EEE Collaboration.

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