Characteristics and performance of the Multigap Resistive Plate Chambers of the EEE experiment

F. Coccetti, a,b,c L. Baldini, a,d,e R. Baldini Ferroli, a,f G. Batignani, a,d,e M. Battaglieri, a,g,h S. Boi, a,i,j E. Bossini, a, E. Coccia, a,d F. Carnesecchi, b,c L. Cifarelli, a,d,e M. Garbini, a,c M. Schioppa, f,g,h l. Cicalò, a L. Cifarelli, a,l,m E. Coccia, a,d A. Corvaglia, a,i M. De Angeli, a,i,j M. De Pasquale, p,q F. Fabbri, a,f D. Falchieri, m L. Galante, a,r,s M. Garbinì, a,m G. Gemme, h I. Gnesi, a,t S. Grazzi, a, D. Hatzifotiadou, a,k,m P. La Rocca, a,u,v Z. Liu, w L. Lombardo, x G. Mandaglio, a,u,y G. Maron, e M.N. Mazziotta, e A. Mulliri, i,j R. Nania, a,m F. Noferini, a,m F. Nozzoli, a,c F. Palmonari, a,d M. Panareo, p,q M. P. Panetta, a,o R. Paoletti, f, o c M. Parvis, x C. Pellegrino, a,z L. Perasso, a,h O. Pinazza, a,m C. Pinto, a,u,v S. Pisano, a,f F. Riggio, a,u,v G. Righini, a c. Ripoli, p,q M. Rizzi, e G. Sartorelli, a,f,m E. Scapparone, a,m M. Schioppa, f,g,h A. Scribano, a,c M. Selvi, a,m G. Serri, a,i,j S Squarcia, h,ae M. Taiuti, h,ae G. Terreni, a,d A. Trifirò, a,u,y M. Trimarchi, a,u,y C. Vistoli, z L. Votano, a,n M.C.S. Williams, a A. Zichich a,i,m and R. Zuyeuski a

Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Roma, Italy
Dipartimento Interateneo di Fisica, Università di Bari, Bari, Italy
INFN Sezione di Bari, Bari, Italy
INFN Sezione di Pisa, Pisa, Italy
INFN Laboratori Nazionali di Frascati, Frascati (RM), Italy
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.
INFN Sezione di Genova, Genova, Italy
Dipartimento di Fisica, Università di Cagliari, Cagliari, Italy
INFN Sezione di Cagliari, Cagliari, Italy
CERN, Geneva, Switzerland
Dipartimento di Fisica, Università di Bologna, Bologna, Italy
INFN Sezione di Bologna, Bologna, Italy
Gran Sasso Science Institute, Italy

Corresponding author.
The Extreme Energy Events (EEE) experiment, dedicated to the study of secondary cosmic rays, is arguably the largest detector system in the world implemented by Multigap Resistive Plate Chambers. The EEE network consists of 60 telescopes distributed over all the Italian territory; each telescope is made of three MRPCs and allows to reconstruct the trajectory of cosmic muons with high efficiency and optimal angular resolution. A distinctive feature of the EEE network is that almost all telescopes are housed in High Schools and managed by groups of students and teachers, who previously took care of their construction at CERN. This peculiarity is a big plus for the experiment, which combines the scientific relevance of its objectives with effective outreach activities. The unconventional location of the detectors, mainly in standard classrooms of school buildings, with heterogeneous maintenance conditions and without controlled temperature and dedicated power lines, is a unique test field to verify the robustness, the low aging characteristics and the long-lasting performance of MRPC technology for particle monitoring and timing. Finally, it is reported how the spatial resolution, efficiency, tracking capability and stability of these chambers behave in time.

**KEYWORDS:** Performance of High Energy Physics Detectors; Resistive-plate chambers; Particle tracking detectors; Timing detectors

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1 Introduction

The Extreme Energy Events (EEE) experiment [1] is a project of the *Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”* [2], in collaboration with the Istituto Nazionale di Fisica Nucleare (INFN), CERN and the Italian Ministry of Education, University and Research (MIUR). It is conceived to study cosmic rays and related phenomena, through a synchronous sparse network of around 60 tracking detectors located throughout the Italian territory and at CERN. The network covers over 10 degrees of latitude and 11 degrees of longitude and is enlarged regularly, since a few new stations are built every year at CERN.

The EEE telescopes form a sparse network in which each location is at distances between 15 meters and several kilometers from another nearby. Each station, which is called an “EEE telescope”, consists of three Multigap Resistive Plate Chambers (MRPCs in the following). MRPCs used in EEE are a version, dedicated to cosmic rays, of the detector type successfully used for the Time Of Flight (TOF) systems of many high-energy physics experiments at colliders. The total active area covered by the EEE telescopes is about 75 m$^2$; but, since for each telescope three MRPCs are used, the area that would be covered by the EEE MRPCs, if placed close together, would be about 230 m$^2$, which makes EEE the system with the largest surface of MRPCs in the world. For comparison, the total surface of the MRPCs of the ALICE TOF system is approximately 144 m$^2$ [3].

A distinctive feature of the EEE network is that the telescopes are housed in High Schools and managed by groups of students and teachers, who previously took care of their construction at CERN. This peculiarity is a big plus for the experiment, which combines the scientific relevance of its objectives with effective outreach activities. The unconventional location of the detectors, mainly in standard classrooms of school buildings, with heterogeneous maintenance conditions and without controlled temperature and dedicated power lines, is a test field to verify the robustness, the aging characteristics and the long-lasting performance of MRPC technology.

In EEE data collection is centralized, and raw data are transmitted from all EEE Telescopes to the INFN-CNAF data center, where they are reconstructed and stored. The current analyses concern more than 100 billion candidate muon reconstructed tracks.
The EEE experiment achieved interesting scientific results in several fields of Cosmic Ray physics, for instance: observation of Forbush decreases [4], study of muon decay into up-going events [5], detection of Extensive Air Showers (EAS) [6], search for long distance correlations between EAS [7], study of possible cosmic muon anisotropy at sub-TeV scale [8]. At the moment, researches are focused also on: long time-scale building structure stabilities, strategies to reduce the global warming impact of the gas used in the EEE MRPCs, and a detailed GEANT-GEMC simulation framework for the EEE telescopes. These latter topics are detailed in the proceedings of the RPC 2020 Conference (see [9–11] for more details).

2 MRPCs and the EEE telescopes

EEE telescopes use specially designed MRPCs to achieve: efficiency close to 90%, adequate time resolution, long term stability, reliable localization and synchronization capabilities combined with easy assembly procedures and affordable production costs.

![Figure 1. Cross section of one of the EEE Telescope’s MRPC.](image)

The structure of the detector, shown in figure 1, is described in detail in previous articles by the EEE collaboration [12, 13].

In the EEE telescopes, the trigger logic consists of a six-fold coincidence of the OR signals from the front-end cards reading the MRPCs, corresponding to a triple coincidence of both ends of each chamber. Recently, a new VME custom made trigger module was designed, constituting one of the most interesting features of the new EEE telescopes [14]. In fact, in order to simplify the readout electronics architecture of the EEE telescopes, the new board was conceived to also integrate in a double Eurocard board both the mentioned trigger logic and a GPS receiver, used for time stamping purposes. The GPS receiver is the ICM SMT 360™ unit, mounted on a carrier board in an open PCB assembly without enclosure, specifically conceived to be integrated in host systems. This receiver can operate with GNSS signals from GPS, GLONASS, Galileo, or Beidou satellite constellations. The GPS unit allows to synchronize the telescopes of the EEE network with a precision around 10 ns. Moreover, this new combo Trigger/GPS card is fully compatible with the DAQ system already in use in the experiment, so that no new software was to be developed. The new cards also offer additional features, such as a remotely programmable trigger logic, counters to monitor the chambers counting rates and the distribution of a precise clock to synchronize the two TDC modules used for reading the chambers of each EEE telescope. The Amphenol connectors and cables, used in the old trigger cards, were substituted with Nugent-Robinson ones, less expensive and easier to use.
As most RPCs used in high energy physics experiments, also the EEE chambers are filled with a mixture of R134a (C₂F₅H₂) and 2% SF₆, at a continuous flow and atmospheric pressure. In the EEE telescopes, the gas flow is provided by a commercial mixing system and fills the chambers in a daisy chain, with the exhaust connected to the outside. The telescopes were operated with a gas flow of 2 l/h. Lately, the use of the above mentioned gases, which are optimal from the point of view of the performance achieved, has become a drawback, since they are characterized by a Global Warming Power (GWP) higher than allowed by the European Community regulations in industrial applications.

To reduce the gas consumption in the detectors, a special procedure has been implemented in order to seal as much as possible all the chambers. The sealing level reached was checked by means of a series of leak tests, described in detail, with the relative results, in [10]. The underlaying idea of this procedure is to apply the pressure drop technique, namely inject a known quantity of air and measure the subsequent pressure drop after the chamber inlets and outlets have been sealed. Although these measures are based on a simple principle, high precision in measuring pressure drop and temperature is necessary to correctly size the leak rate; for this purpose, a differential manometer with an accuracy better than 0.01 mbar and thermistors to monitor possible temperature changes in the room are used. If a leak is found, it must be localized, and then sealed with silicone. Then, the procedure must be repeated until the measured leak is reduced to be below 1 l/h. At present, this operation was successfully completed for about half of the EEE telescopes. The ultimate goal is to reduce the flow of gas from 2 l/h to 1 l/h in all the EEE network, implying that the GWP gas emission would be reduced in half.

To reconstruct the tracks, a linear fit to the hits found in the three chambers is performed and the corresponding $\chi^2$ is calculated. All possible combinations are used and ordered by their $\chi^2$. The track candidates are defined by iteratively selecting the lowest $\chi^2$ and removing the corresponding hits, continuing up to the point when the whole set of available hits has been assigned to a track. Finally, a set of tracks with no hits in common is defined and transferred to the output file. For the measurements presented in this study, the track selection requires $\chi^2 < 5$ and the rejection of events with more than one track.

### 3 Performance

#### 3.1 Time and spatial resolution

For the correct operation of the EEE network, was of paramount importance to check that the performance of the EEE telescopes is not affected by such a relevant reduction in the gas flow described in the previous section. Therefore, data taken in the last quarter of 2019 and the first quarter of 2020 were used to compute time and spatial resolution, using, for this analysis, only the subset of the network of EEE telescopes for which the gas flow was actually reduced from 2 l/h to 1 l/h by means of the MRPC chamber sealing procedure briefly described above. These new results were compared with those obtained in previous years [12], with the gas flow in the telescopes of 2 l/h, and demonstrated that the change in the gas flow has not caused any deterioration in performance.

In particular, time and spatial resolution of the middle chambers of the EEE telescopes were measured using the information from the hits registered for the same track in the “top”, “middle” and
“bottom” chambers. The width of the distributions of Δs were used, where Δs = (s\text{top} + s\text{bot})/2 - s\text{mid}, and s\text{top}, s\text{mid}, s\text{bot} are the time and spatial values for hits in top, middle and bottom chambers, and s represents t (the time information), x (the spatial coordinate along the readout strips), or y (the spatial coordinate transverse to the readout strips) respectively.

Figure 2 shows the comparison of the time resolution between the EEE chambers taking data at 1 l/h and the same chambers taking data at 2 l/h in 2017. In both cases, similar results are obtained, \( \sigma_T(1 \text{l/h}) = 237 \pm 67 \text{ ps} \) and \( \sigma_T(2 \text{l/h}) = 238 \pm 39 \text{ ps} \), meaning that the sealing procedure of the telescopes allows a 50% reduction in the gas flow, keeping the time resolution unchanged.

![Figure 2](image)

**Figure 2.** Left: time resolution extracted from data taken in the last quarter of 2019 and first quarter of 2020 for 22 telescopes, fed with a gas flow of 1 l/h. Right: time resolution extracted from data taken in RUN 3 (2017) for 33 telescopes, fed with a gas flow of 2 l/h. The average time resolution is computed by a gaussian fit for both plots.

A similar analysis was performed for spatial resolution. Figure 3 shows the longitudinal and spatial resolutions, whose values resulted to be: \( \sigma_x(1 \text{l/h}) = 1.4 \pm 0.1 \text{ cm} \), for the telescopes operated with a gas flow of 1 l/h and \( \sigma_x(2 \text{l/h}) = 1.48 \pm 0.04 \text{ cm} \) for the telescopes operated with gas flow of 2 l/h. The analogous plots shown in figure 4 refer to the transverse spatial resolution, where was measured to be \( \sigma_y(1 \text{l/h}) = 0.92 \pm 0.05 \text{ cm} \) and \( \sigma_y(2 \text{l/h}) = 0.92 \pm 0.01 \text{ cm} \). Comparing the spatial

![Figure 3](image)

**Figure 3.** Left: distribution of the longitudinal spatial resolution (along the x coordinate) extracted from data taken in the last quarter of 2019 and first quarter of 2020 for 25 telescopes, fed with a gas flow of 1 l/h. Right: distribution of the longitudinal spatial resolution extracted from data taken in RUN 3 (2017) and RUN 2 (2016) for 46 telescopes, fed with a gas flow of 2 l/h. The average spatial resolution is computed by a gaussian for both plots.
resolution distributions in both gas flow conditions, it is demonstrated that the upgraded telescopes can be operated at half the gas flow, keeping performance unchanged.

3.2 Efficiency

The efficiency curves as a function of the applied voltage are measured both at CERN, immediately after the construction of the chambers, and after the installation of the telescopes in schools. Typically these curves are obtained using scintillator detectors as an external trigger and with additional electronics. In this work we introduced a different method, where the efficiency is measured during data taking, using a slightly modified version of the reconstruction code. To make this procedure work, the trigger logic has to be modified from the standard 3-chamber trigger to a double chamber coincidence, excluding the chamber under test from the trigger [12]. The two chambers in the trigger are therefore used for event selection and tracking. Once a track has been defined, the procedure checks whether there is a hit on the chamber under test within a 7 cm distance from the calculated position. An HV scan of the chamber is performed, collecting around 150000 events in 10 minutes steps. Pressure and temperature were also measured during data collection and their variations, although often negligible, were taken into account in the results. This method was applied to the middle chamber in the EEE telescopes, and the respective results are shown in figure 5. The average efficiency of the telescope network is about 93%, compatible with EEE requirements and with results of the beam test in [13].

3.3 Long term stability

In order to monitor the status of the telescopes, a special Data Quality Monitor has been set up, accessible to all project participants. It is indeed difficult to achieve long-term stability for the EEE detectors, since many unexpected events can occur in schools. For this reason, the EEE collaboration continuously tries to improve the quality of the components that characterize the telescopes. On the DQM website [16], several types of plots are available for all telescopes, reporting the most significant quantities in near real time. In particular, are constantly monitored: the average tracks
Figure 5. **Left:** efficiency vs. applied HV (corrected for standard $p$ and $T$) of the middle MRPC of 9 EEE telescopes. The red arrow indicates the usual value chosen as working point. **Right:** distribution of the efficiency obtained at the plateau (corrected for standard $p$ and $T$) of the middle MRPC for 31 EEE telescopes. The efficiency value for each telescope in the plot was obtained at the work point and it is the average efficiency over the middle chamber active area. An efficiency better than 90% is reached by 77% of the network.

$\chi^2$, the raw acquisition rate, the multiplicity (number of hits per MRPC per triggered event, within a 500 ns window), the percentage of raw events where at least one-track candidate has been found, the Time of Flight of the tracks between top and bottom chambers and the rate of events with at least one candidate track. No relevant effects related to ageing have been noticed for the monitored quantities in all these years, although many of the telescopes are located in the most varied environments.

With more than 10 years deployed in site, MRPC based telescopes are showing a stable performance, as it is demonstrated by the measures taken. The track rate per day and the fraction of raw events with at least one candidate track per day for two EEE Telescopes (BOLO-01 and LAQU-01) are shown in figure 6, with data collected since 2015. Both detectors were built in 2004, therefore they are more than 15 years old. BOLO-01 is located in the building of the INFN Division of Bologna, and LAQU-01 is hosted in L’Aquila in the High School “Liceo Scientifico A. Bafile”. LAQU-01 did not take data in the 2017/2018 school year. **Right:** fraction of raw events with at least one candidate track, per day, for each of the same two EEE Telescopes. The detectors are turned off when schools are closed in summer and other times of the year.

Figure 6. **Left:** track rate per day of two EEE Telescopes since 2015. BOLO-01 is located in the building of the INFN Division of Bologna, and LAQU-01 is hosted in L’Aquila in the High School “Liceo Scientifico A. Bafile”. LAQU-01 did not take data in the 2017/2018 school year. **Right:** fraction of raw events with at least one candidate track, per day, for each of the same two EEE Telescopes. The detectors are turned off when schools are closed in summer and other times of the year.
Division of Bologna, and LAQU-01 is hosted in L’Aquila in the High School “Liceo Scientifico A. Bafile”. In the 2017/2018 school year this detector did not take part in the coordinated acquisition because it had to be moved to a different classroom in the same school. Data acquisition takes place in coordinated Runs, between all telescopes, during the school year, which exclude summers and other periods when schools are closed; for this reason, the plots are discontinuous.

4 Conclusions and outlook

The Extreme Energy Events experiment, dedicated to the study of secondary cosmic rays, is the largest detector system in the world implemented by Multigap Resistive Plate Chambers, which placed close together would cover an area of 230 m$^2$.

The characteristics of the telescopes were analyzed after the gas flow was reduced from 2 l/h to 1 l/h, with the prospect of halving consumption for the entire EEE network, and it was verified that there was no drop in performance. In fact, the new performance of the telescopes is in accordance with the EEE experiment requirements in terms of efficiency ($\sim 93\%$), time resolution ($237 \pm 67$ ps), longitudinal spatial resolution ($1.4 \pm 0.1$ cm) and transverse spatial resolution ($0.92 \pm 0.04$ cm). At the same time, a gas recirculation system is under study and will be implemented in the near future, to further reduce operating costs. Furthermore, all this adds up to studies on new gas mixtures to reduce the global warming impact that are in progress at CERN.

Right now, two important partnerships are being formed to obtain even more reliable results and distribute costs. First, the collaboration with Istituto Nazionale di Fisica Nucleare (INFN) will be strengthened to share Telescope maintenance and development, data analysis and outreach. Second, a collaboration with the Istituto Nazionale di Ricerca Metrologica (INRIM) has been recently set up, to further improve the performance of the synchronization across the EEE Network. In the coming years, more MRPCs will be built at CERN and more telescopes will be installed in schools; this will increase the coverage of the EEE network and the collected statistics, thus increasing the reach of the ongoing studies of this experiment.

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