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The PolarquEEEst mission: Measuring the cosmic ray flux at the North Pole

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Summary. — The PolarquEEEst mission was designed and realised within the Extreme Energy Events (EEE) Project experiment, a strategic project of "Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi", Rome. PolarquEEEst is a campaign to measure the cosmic rays flux at the highest latitudes which took place between July and September 2018. The detector used is made of two scintillator planes coupled to Silicon Photo Multipliers (SiPM); it was installed on the *Nanuq*, a 18 meter sailing boat which, leaving from Iceland, circumnavigated the Svalbard islands (less than 1000 km from the North Pole) and concluded its cruise in Norway. The trip was carried out within the Polarquest project 1928–2018, an expedition to commemorate the unfortunate mission of the airship ITALIA, on the occasion of its 90th anniversary. Other two identical detectors were installed in Norway and Italy, in order to allow a comparative measurement of the cosmic flux over more than 40 degrees of latitude and also to look for possible long-distance correlations. Here we report the details of the detector and the first results.

1. – Introduction

The Polarquest 2018 [1] mission was organized in the occasion of the the 90th anniversary of the airship ITALIA expedition: a 18 meter long sailing boat, the *Nanuq*, sailed from Isafjordur (Iceland) on the 22nd of July, touched Longyearbyen (Svalbard, Norway) and circumnavigated the Svalbard Archipelago reaching a latitude of of $82°07'$, close to the crash point of the ITALIA and ended its voyage on the 4th of September in Tromsø (Norway). The expedition was organized to remember the airship ITALIA and its crew and as for that expedition the *Nanuq* hosted scientific programs, among which the PolarquEEEst experiment, devoted to the measurement of the cosmic ray flux, within the "Extreme Energy Events: Science inside Schools" (EEE) project of the "Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi" (Centro Fermi) in Rome [2].

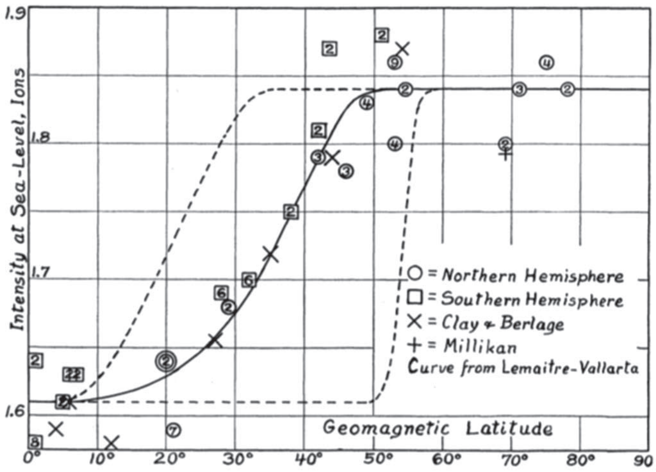

Fig. 7. Intensity *vs.* geomagnetic latitude at sea level, including data of Clay and Millikan.

Fig. 1. – Intensity of cosmic rays *vs.* latitude at sea level as in [3].

PolarquEEEst was designed to study the flux of cosmic rays at latitudes not well covered at sea level; the geomagnetic field induces variation on the cosmic ray flux and, in particular, it is expected to increase with latitude since the decrease of the Earth magnetic field allows also lower energy particles to reach the ground. At a latitude of above 60° another effect, due to the solar wind, is expected to produce a saturation on the increase of the flux. Experimental results were summarized in a compilation, in 1933, by Compton [3]; the data reported were collected using ionization chambers in different measurement campaigns and by different groups and they show the increase of rate with latitude and a flattening above 50°, fig. 1. It is worth stressing that, also during the airship ITALIA expedition toward the North Pole, measurements were performed quite near the sea level using an electroscope, without finding relevant changes within the explored latitudes [4].

Recent results by Solar Ship Survey confirm the flattening of the intensity [5], however, above the arctic circle, few measurements are available and a stronger experimental support is desirable.

The PolarquEEEst experiment was developed following the same idea of the EEE Project, started in 2004 by A. Zichichi [6]. EEE is a cosmic ray experiment which, at the same time, allows a strong scientific dissemination within high schools. The EEE Project is a network of, nowadays, 59 cosmic muon tracking telescopes made of three large-area ($220 \times 110\,\mathrm{cm}^2$) Multigap Resistive Plate Chambers (MRPC), derived from the Time-Of-Flight detector of the ALICE experiment at CERN LHC [7]. A detailed description of the EEE detectors and their performance can be found in [8]. The total area covered by the network is larger than $3 \times 10^5\,\mathrm{km}^2$, so that it has the largest coverage in the world for such kind of experiments. All data collected are sent in real time to the INFN CNAF computing center for storage and reconstruction. The outreach part envisages the direct involvement of high school students in all the phases of the experiment: from the construction and tests of the MPRCs at CERN, through their installation in schools, till the responsibility to monitor, on a daily base, its performance. Every year, more than a thousand students and teachers participate in the project.

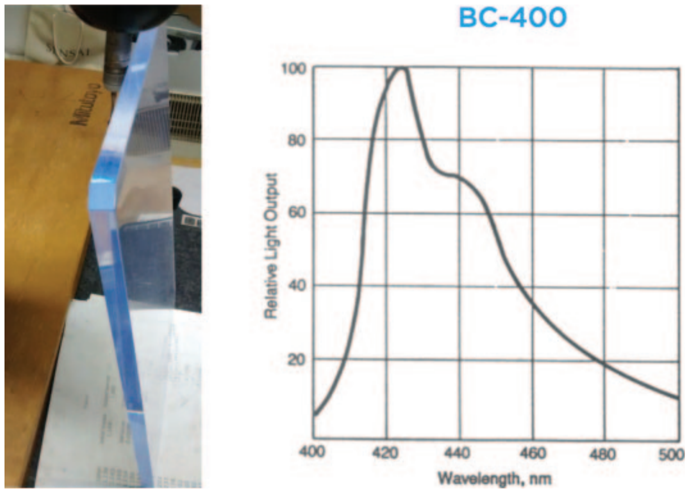

Fig. 2. – Picture of one tile of BC400 (left). Relative light output of BC400 (right).

So, within this line, the PolarquEEEst experiment was carried out involving students form different countries; the students assembled three identical detectors and, beside the one on board of the *Nanuq*, other two detectors were installed in two schools, in Italy and Norway, used as reference also to search for possible long-distance correlations.

In the next section, the PolarquEEEst detector will be extensively described.

2. – PolarquEEEst detector

The PolarquEEEst detector was designed taking into account the constraints in terms of weight, space and power consumption ($< 15\,\mathrm{W}$) for the installation on board of the *Nanuq*. Due to space and weight limits, the choice was to use plastic scintillators as detectors; the final design consists of two planes of plastic scintillator (BC400 Saint Gobain, fig. 2, left) 1 cm thick and 11 cm apart, each divided into four tiles $20 \times 30\,\mathrm{cm}^2$. Figure 2, right, shows the relative light output of BC 400.

Each tile is readout by two $4 \times 4\,\mathrm{mm}^2$ AdvanSid ASD-NUV4S-P-40 SiPMs (fig. 3, left) directly coupled to the scintillator by means of optical grease and placed at two opposite corners (opportunely cut) of the same tile, fig. 2, left. A total of 16 SiPMs are used in the detector. Their main characteristics are reported in table I.

In the final assembly the SiPMs are kept in optical contact to the scintillator using a specifically designed wedge, fig. 3, right.

A light tight box made of DELRIN ® encloses the four tiles constituting a detector plane. The two planes are mounted on supports placed inside another external light tight box of dimensions $560 \times 780 \times 95\,\mathrm{mm}^3$. Figure 4 shows a technical drawing of the detector: on the left, an open view of the light tight box and the scintillator planes; on the right, the final assembly showing also the electronic box. The total weight is about 50 kg.

The mechanical design has been optimized for the final installation inside one of the hatches of the *Nanuq*, named cosmic hatch, as shown both in a technical drawing and in a picture in fig. 5.

The front-end electronics is based on a custom-made board, developed in collaboration with Politecnico di Torino and is shown in fig. 6. Each board serves two SiPMs so a total

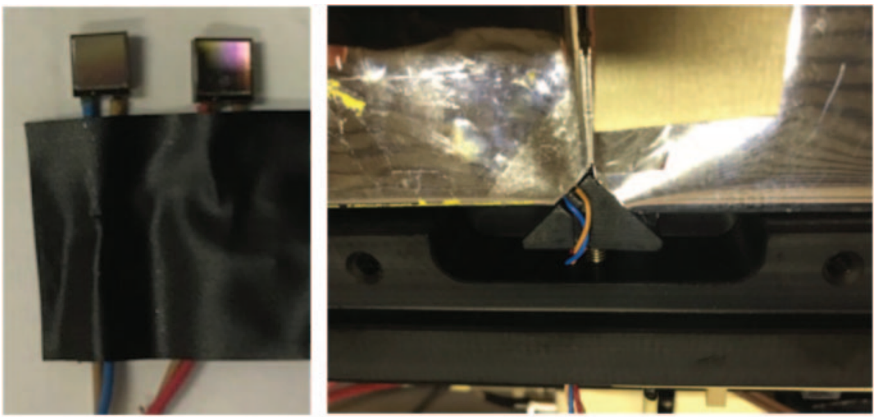

Fig. 3. – Picure of two $4 \times 4\,\mathrm{mm}^2$ SiPMs (left). Final assembly of the SiPMs kept in contact to the scintillators by means of a dedicated wedge (right).

TABLE I. – *Main features of the chosen Advansid SIPMs.*

Parameter	ASD-NUV4S-P-40
Active area	$4 \times 4\,\mathrm{mm}^2$
Number of cells	49340
Cell size	$40 \times 40\,\mu\mathrm{m}^2$

of 8 FE boards are needed for the detector. The FE boards mount DAC used to set V_{BIAS} and the discrimination threshold (V_{Thr}) for each SiPM.

Signals overcoming the V_{Thr} are digitalized in $LVDS$ standard and charge information of the signals are encoded for the duration of the $LVDS$ signals (Time Over Threshold (TOT)). The SiPMs and the front-end boards are hosted inside the detector light tight box. The power to the front-end boards, DAC communication and the signals coming from the detectors travel on a twisted flat cable. The total consumption is 2.5 W. Figure 7 shows a picture of the whole detector assembled with marks indicating the position of

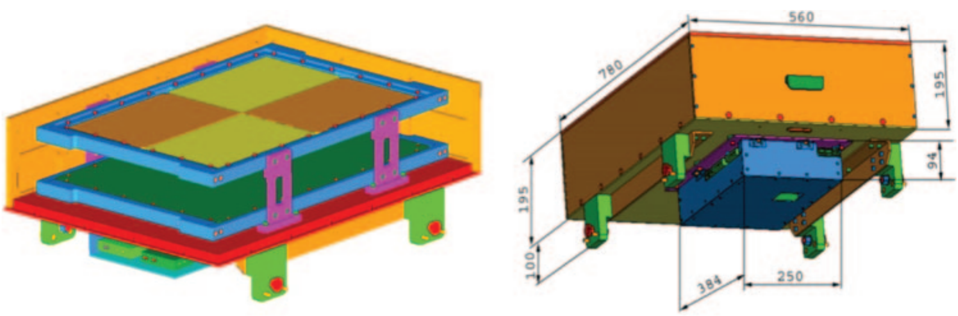

Fig. 4. – Technical drawing of the PolarquEEEst detector. See text for details.

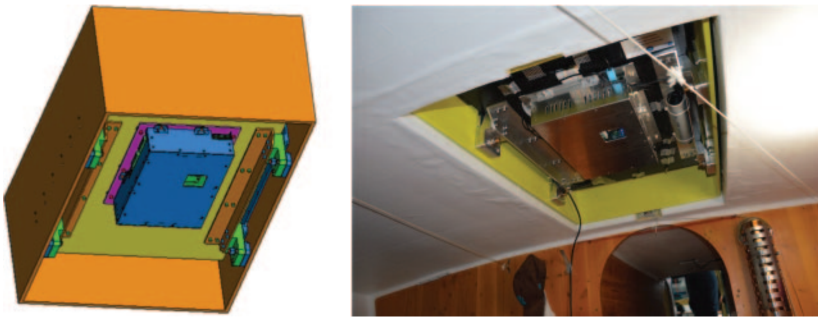

Fig. 5. – Technical drawing (left) and picture of the PolarquEEEst detector installation inside *Nanuq*.

the SiPMs, also FE boards are visible.

A box containing all the electronics needed for power, readout and data acquisition completes the setup. The box is placed below the light tight box, see fig. 4, right. In particular, it hosts the trigger and readout board, a board designed by the electronic group of the Bologna INFN unit. It processes the $LVDS$ signals coming from the SiPMs, form the trigger and provides time of the signals and TOT to the data acquisition which is performed by a RaspBerry PI device. As a trigger is formed, a GPS module generates the time stamp of the event allowing time studies of the events (correlation between different detectors and with atmospheric data). The trigger board is equipped with an Altera Cyclotrone 5 FPGA and can measure time of events using two different systems; indeed it is possible to use the FPGA as TDC, but it is also possible to use HPTDC mounted on dedicate mezzanine. In this way, the time measurements are redundant and guaranteed also with different granularities. The electronics is completed by different sensors to measure pressure, temperature and also monitor the movement of the detector (by means of gyroscopes and accelerometers). The DAQ is based on python and provide data from the detector and sensors for offline analysis.

Three twin detectors were assembled at CERN by 23 students coming from high schools in Italy, Norway and Switzerland, similarly to all other EEE detectors. The three detectors, named POLA-01, POLA-02 and POLA-03, were tested for a month at CERN. In July, POLA-02 and POLA-03 were then installed in two high schools in Nesodden (Norway) and Bra (Italy) respectively, under the control and monitoring of the students. POLA-01 was shipped to Isafjordur and mounted on *Nanuq*.

3. – Detector calibration at CERN

Before installation, in the final experimental sites, the POLA-01/02/03 detectors were tested at CERN, inside Building 29, using cosmic rays. Figure 8 shows a picture of the detectors ready to be tested at CERN after their assembly.

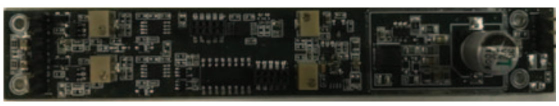

Fig. 6. – Picture of the front-end board serving two SiPMs of the PolarquEEEst detector.

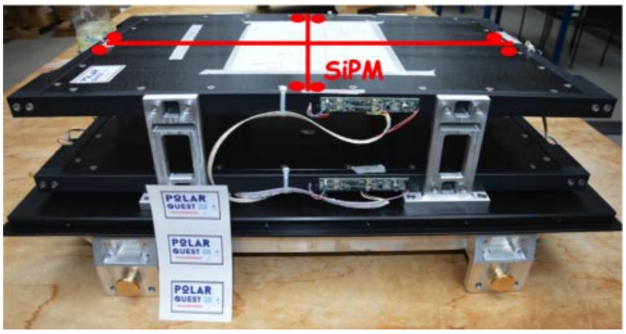

Fig. 7. – Picture of the PolarquEEEst detector.

First of all, the total power consumption was checked to be inside the design and the limits imposed by operation on board of *Nanuq*. A total power consumption of 12.5 W was measured, lower than the limit of 15 W.

After the first functionality tests, measurements were performed to equalize the SiPMs response and to optimize the software codes (both DAQ and sensors readout). Figure 9 shows the distribution of the TOT for each channel of the detectors after the calibration obtained using cosmic rays; the V_{Thr} and the V_{BIAS} of all the SiPMs have been tuned in order to obtain equal gain.

At CERN there are two EEE MRPC telescopes separated by a distance of about 20 m that detect about 120 coincidences/h. We checked the functionality of the PolarquEEEst detectors searching for coincidences between them and the EEE telescopes. Figure 10 shows schematically the position of all the detectors at CERN and their distances (left); in the same figure, on the right, the time difference distribution between one of the EEE telescopes and POLA-01 is reported, and the peak of events in coincidence, *i.e.*, muons belonging to the same shower, is clearly visible.

The tests and calibrations lasted for about one month after which the three detectors where shipped to their final destinations for the PolarquEEEst mission.

4. – Data collection and preliminary results

As already reported the Polarquest 2018 started on the 22nd of July when the *Nanuq* sailed from Isafjordur (Iceland) and finished on the 4th of September in Tromsø (Norway). During the expedition all the telescopes acquired data in almost continuous and stable

Fig. 8. – Picture of the PolarquEEEst detectors at CERN.

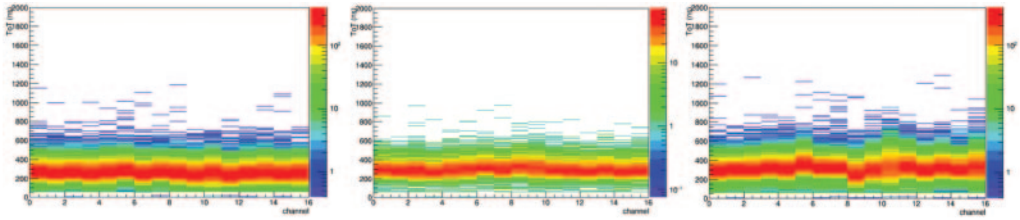

Fig. 9. – TOT distribution of the 16 SiPMs of POLA-01 (left) POLA-02 (middle) ad POLA-03 (right).

way thanks to the robustness of the designed system. Moreover, it was possible to quickly react to problems thanks to the monitoring system used based on the one used in the EEE experiment. The telescopes installed in high schools, POLA-02/03, continuously transmitted data to the EEE computing center at CNAF (Bologna) where data are automatically processed and analyzed to produce data quality monitor plots; this permits an almost on line check of the operation of the detector. POLA-01 during the expedition from Iceland to Norway had no stable Internet connection so the data acquired were analyzed on board and summary plots were sent as soon as a connection was possible. The *Nanuq* sailed for about 3500 NM and acquired data almost continuously for about 980 hours with a duty cycle of $\sim$91%; POLA-02/03 had a duty cycle at the level of 100%. In total more than 100×10^6 tracks per detector were collected.

Figure 11 shows the uncorrected rate of events acquired by the three detectors during the whole expedition. Local effects due for example to atmospheric conditions affect these rates. Moreover the POLA-03 detector installed inside the school in Italy suffers a greater absorption effect due to the building than the POLA-01/02 detectors that had less material on top.

Some offline corrections can be applied using data coming from the sensors installed in the detectors. The effect of the atmospheric pressure can be evaluated and used to correct data. Figure 12 shows the correlation between the rate and the measured pressure: as expected the increase of pressure produces a reduction of the rate since the pressure reflects the amount of air on top the detector. The trend is fitted with an exponential law and the barometric coefficient is determined as the slope coefficient.

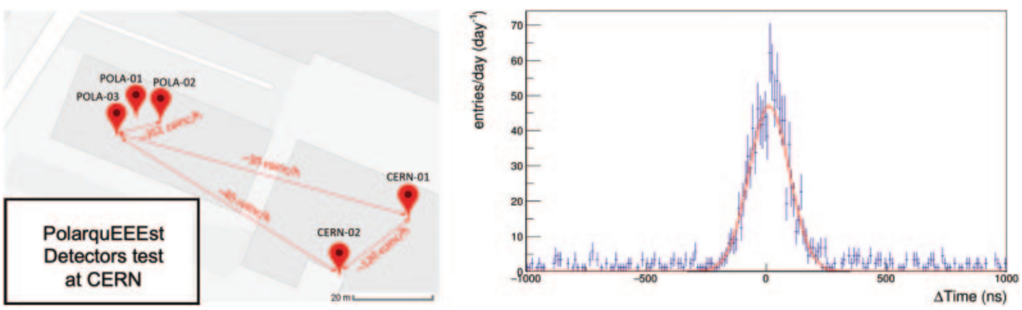

Fig. 10. – Schematic view of the position of the EEE telescopes and the PolarquEEEst detectors at CERN (left) and distribution of time difference between events in one of the EEE telescopes and POLA-01.

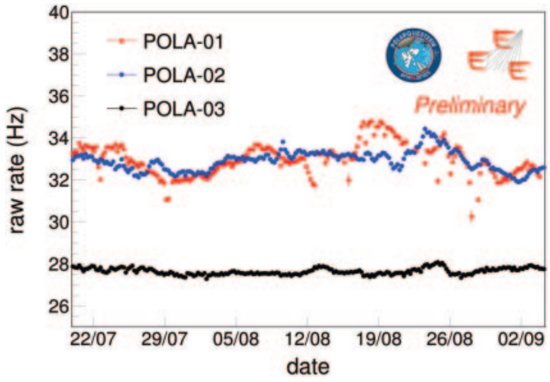

Fig. 11. – Uncorrected rate of the POLA-01/02/03 detectors as measured during the expedition.

The measured values of the barometric coefficient for the three detectors are:

- POLA-01: -0.00217 ± 0.00002;
- POLA-02: -0.00203 ± 0.00002;
- POLA-03: -0.001471 ± 0.000002.

Another parameter that affects the data of the POLA-01 is related to the orientation of the detector while sailing. It was measured using the information of the accelerometer installed: the projection of the acceleration along the local z-coordinate is the cosine of the zenithal angle (θ). For values of the cosine ($g_z/|g| = \cos\theta$) lower than 1 the rate is expected to decrease because the distribution of secondary muons has a maximum at $\theta = 0$. Figure 12, right, shows the rate as a function $g_z/|g| = \cos\theta$; the points have been fitted and the result has been used to correct the data of the POLA-01 detector.

The effect of the corrections to the rate is reported in fig. 13 together with the data coming from the OULU neutron monitor [9] in Finland (scaled by a factor 0.3).

Comparing figs. 11 and 13, it is clear that after corrections the rate measured by POLA-01/02 are in nice agreement and all the single detector fluctuations, due to local

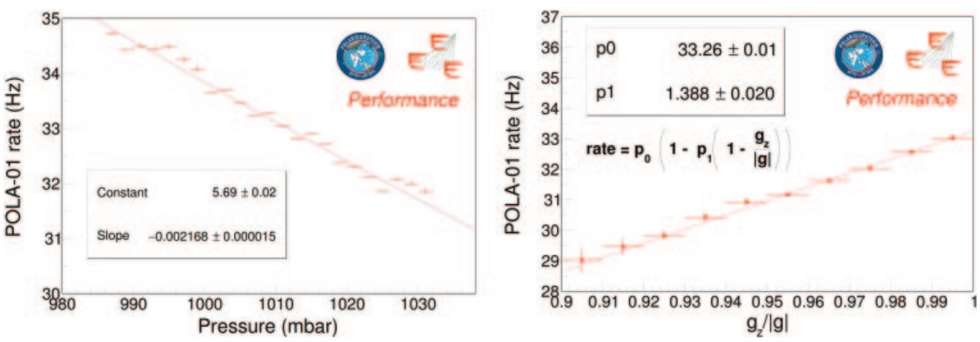

Fig. 12. – POLA-01 rate as a function of atmospheric pressure (left). POLA-01 rate as a function detector orientation with respect to the vertical (right).

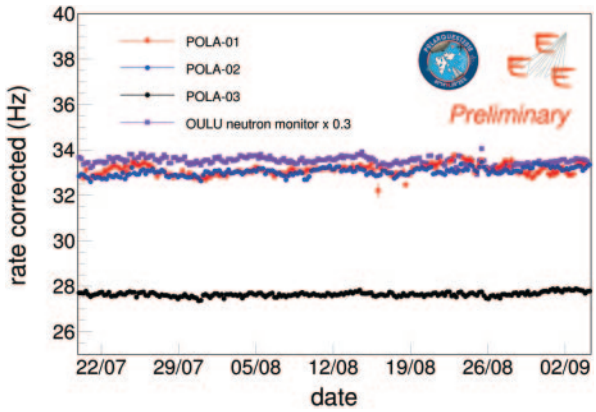

Fig. 13. – POLA-01/02/03 corrected rate compared to the corrected rate measured by the OULU neutron monitor in Finland.

conditions, have been cancelled. Moreover the PolarquEEEst detectors shows the same stability of the neutron monitor.

These are preliminary results and after the PolarquEEEst expedition the POLA-01 detector has been delivered in various sites at different latitudes in Italy to continue the data collection for rate *vs.* latitude studies.

5. – Conclusions

During the summer of 2018, the Polarquest 2018 mission has been organized to commemorate the the 90th anniversary of the airship ITALIA expedition; the high-tech boat *Nanuq* sailed from Iceland circumnavigated the Svalbard Archipelago reaching a latitude of $82°07'$ close to the crash point of the ITALIA and ended its voyage on the 4th of September in Tromsø (Norway) hosting several scientific programs. The PolarquEEEst experiment measured the cosmic ray flux using a specially designed detector up to latitudes poorly studied. The experiment took place within the "Extreme Energy Events: Science inside Schools" (EEE) project of the "Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi" (Centro Fermi) in Rome [2]; three identical detectors were built by teams of students and were located at three different latitudes to simultaneously measure the cosmic radiation. The detectors operated almost continuously for 45 days, collecting about 100×10^6 tracks per detector. The first results here reported regard the rate measured by the telescopes; after corrections due to local effects they show good agreement. The forthcoming analysis of the data acquired from one of the detector, POLA-01, at different sites in Italy will be used to study the rate as a function of the latitude.

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