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Test and characterization of multigap resistive plate chambers for the EEE project

E. BOSSINI([1])([2]) on behalf of the EEE COLLABORATION

([1]) *Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi - Roma, Italy*
([2]) *INFN, Sezione di Pisa - Pisa, Italy*

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Summary. — The Extreme Energy Events project is based on the deployment of cosmic-ray telescopes in Italian high schools with the active contribution of students and teachers. Each telescope is made by three Multigap Resistive Plate Chambers readout by strips. With around 50 telescopes already built and others under construction, specific systems to test and characterize the chambers are needed. In this article I will present a flexible and software-configurable solution to perform chamber efficiency studies with a set of scintillators and hardware to automatically scan detector strips to identify electrical issues. Both systems can provide accurate information but at the same time they can be easily operated by students.

1. – Introduction

The detection and study of very high-energy cosmic rays, characterized by an energy above 10^{18} eV, is one of the most interesting and still almost unexplored field of astroparticle physics. This energy is considered a transition point from galactic to extra-galactic cosmic-ray sources and many questions about the exact origin and acceleration mechanism are still waiting an answer. At lower energy satellites are commonly employed to study primary particles before their interaction with the atmosphere, but the low flux ($\sim 1\,\mathrm{km}^{-1}\mathrm{y}^{-1}$ at 10^{18} eV) makes this technique unsuitable due to the small size of the detectors that can be placed in orbit.

The typical experimental technique employed to study this phenomena involves the detection of secondary particles at ground level. Indeed when a primary particle impacts in the high atmosphere it generates a cascade of secondary particles. The secondary particles are almost contained in a disk of few hundred meter thickness and radius dependent on the energy of the primary ones. The disk rotational axis coincides with the primary trajectory. Some of the secondary particles (mainly muons) can reach the ground, distributed in an area with an extension already greater than $1\,\mathrm{km}^2$ at an energy of 10^{18} eV.

2. – The EEE Project

The project "Extreme Energy Events - La scienza nelle scuole" [1] (EEE) is a special experiment of Centro Studi e Ricerche Enrico Fermi (Roma) in collaboration with CERN, INFN and MIUR. The experiment consists in an array of cosmic-ray telescopes, spread all over the Italian territory, covering an area of $\sim 3 \cdot 10^5\,\text{km}^2$. With its extreme area coverage the array can detect showers of large extension. Each station, composed of 3 Multigap Resistive Plate Chambers [2] (MRPCs), has multi-particle tracking capability and can assign a timestamp to the event with a precision better than 80 ns. Stations located in different sites are synchronized through the GPS signal and data are centrally collected at CNAF (Bologna), where single telescope analysis and reconstruction of large showers are performed. The tracking capability is an essential feature of the setup when looking at coincidences among telescopes distant more than 1 km. It is indeed possible to enforce the spurious background rejection requiring that the tracks in both telescopes have almost parallel trajectories. Moreover when only one telescope is hit we can rely only on the tracking information to make some hypotheses on the primary trajectory. Instead when two or more stations are involved the reconstructed trajectories from each site can be combined with the time difference in the timestamps to increase the resolution on the primary direction.

What makes of the EEE project something really special is that the project is carried out with the decisive contribution of students and teachers of Italian high schools, where the stations are hosted. A selected group of students from each school have the unique opportunity to spend one week at the CERN laboratory (Geneva) where, followed by a team of experts, they will build their own chambers. Once completed the chambers are delivered to the school or to the nearest INFN section involved in the experiment as referee of that school. The telescope will then be tested and assembled and will operate with the contribution of all the students. They will perform a daily check on the apparatus and minor operations under the referee supervision. Moreover they can analyze the collected data with the programs provided by the collaboration or, if willing, with their own developed code. Seminars and lectures are given to introduce the experiment and to stimulate students participation. Of course a central control of the whole experiment is also performed by experts [3] but students and teachers represent the field crew providing deep and updated information.

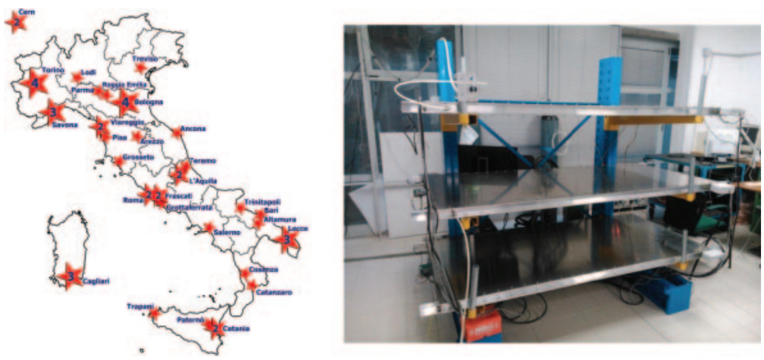

Fig. 1. – Map of currently active stations (left) and picture of one of the station located at the INFN Pisa section for development purposes (right).

At present there are 47 high schools involved and other 3 will join the project this year. The first run of the experiment took place in the first half of 2015 with 35 active and fully functional telescopes. The RUN 2 is currently ongoing with 40 stations and others will be completed during the run. In fig. 1 a map of the currently installed stations is reported together with a picture of the Pisa station, hosted by INFN-Pisa section and used for the development of the electronics hereafter described. As seen from the map the experiment can also rely on clusters of telescopes located in the same city. Coincidences between such stations have already been found [4]. The irregular distribution of sites allows the experiment to span a large angular and temporal acceptance, looking for a possible anomaly in the cosmic-ray distribution in a wide energy range [5], enriching the experimental physics program.

3. – Description of the EEE telescopes

Each telescope is composed of three MRPCs, a gas detector working in avalanche mode, derived from the time of flight (TOF) detector of the ALICE experiment at CERN. Each MRPC is filled with a mixture of $C_2H_2F_4$ (98%) and SF_6 (2%) provided by a gas mixing station. The active volume of the chamber is $\sim 0.82 \times 1.58\,\mathrm{m}^2$, while the external aluminium frame has dimensions of $1 \times 2\,\mathrm{m}^2$. The layout of the chamber on the short side projection can be seen in fig. 2. The sensitive volume is divided in 5 small gaps of 0.3 mm separated by inner glasses of 1.1 mm thickness. The external glasses have their outer surface covered with a resistive paint to form a carbon layer where the high voltage can be applied: the nominal bias voltage is $\sim$ 18 kV. The vetronite with the collecting electrodes is put outside the active area and finally the honeycomb completes the sandwich, giving protection to the internal components.

If we look at the chamber from the top (fig. 3) we can see the collecting strips. The chamber is indeed readout differentially (both top and bottom planes have the readout strips) with 24 + 24 longitudinal copper strips glued to the underlying vetronites.

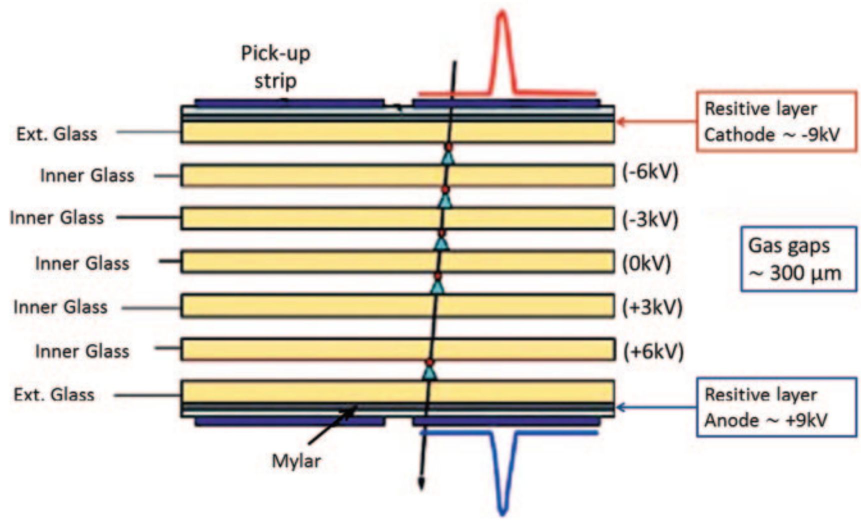

Fig. 2. – Layout of the chamber structure in the x-z plane (perpendicular to the strips direction).

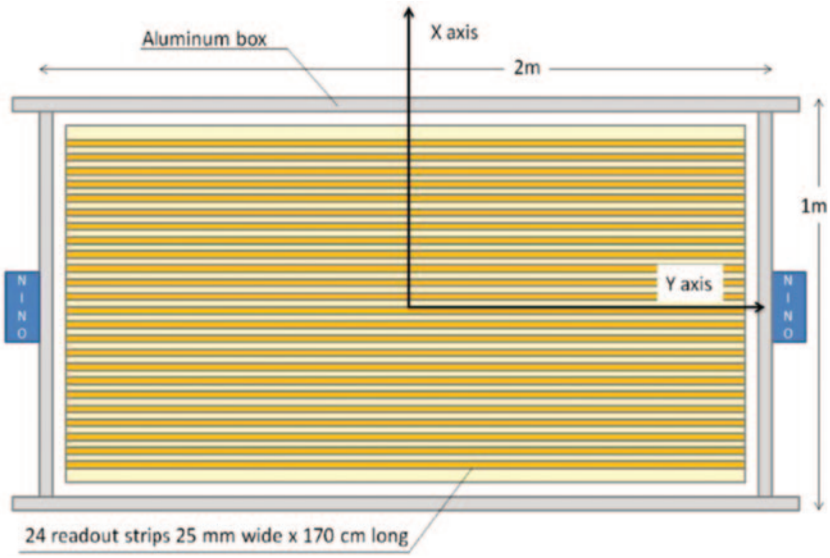

Fig. 3. – Top view of the chamber with the front-end electronics placed at both ends.

When a charged particle passes through the active area, ionizing the gas, independent electronic avalanches start inside each gap, inducing a signal on a readout strip. The signal travels towards both detector ends where the strip is connected to the front-end electronics with a leakage-proof interface board. The front-end electronics, based on the NINO chip [6], performs a differential discrimination and digitization of the strip signal. The output is an LVDS signal for each strip which encodes the total charge information in the signal width, so that time walk effects can be off-line corrected. Moreover the front-end generates a local trigger signal, that corresponds to the logic "OR" of all the strips. The data acquisition is triggered when all the 6 front-end cards (3 chambers, 2 front-end cards each) produce a simultaneous local trigger signal.

The NINO signals from each side are thus sent to the DAQ electronics, equipped with the High-Precision Time to Digital Converter [7] (HPTDC, developed at CERN), able to measure both rising and falling edges with a bin size of $\sim$100 ps. A hit, or impact point, is defined when signals from both sides of a strip are collected. The impact point is reconstructed from the strip number (x-coordinate) and from the difference in the time of arrival of the signal at the two edges (y-coordinate). The high time resolution of the HPTDC allows us to achieve a resolution of ~ 1 cm in both coordinates.

The timing information is also used to measure the particles Time Of Flight (TOF) so that a measure of the particle speed is possible. This feature has already been used for didactical purposes, involving undergraduate students to measure the muon life-time. They can search among the collected events for a down-going particle (the cosmic muon, which can stop in the bottom chamber or in the floor), followed by an up-going particle (the decaying electron) within a defined time window. Cuts on the particles trajectories and velocities can then be placed at will. Much work is ongoing to perform detector calibration and improve the precision on the TOF measurement.

The detector setup is completed by the GPS receiver, a remote voltage-current controller, where students can read and report in an online logbook all the values (remote desktop is also possible in case of necessity) and a weather station. The weather station is used to perform detector calibration with atmospheric pressure and temperature. Variation of the muons flux can be measured with high sensitivity and effect related to astrophysical events, like the *Forbush decrease* [8], measured.

4. – Test and characterization

The large number of chambers (already over 150 units) requires tools for characterization and testing. Chambers efficiency has to be measured periodically to have a reliable control over the system. Moreover it can happen that some chambers have a malfunction and a diagnostic setup is needed. Each referee has some freedom in the choice of the hardware to use for the telescopes of competence. In this article we will describe some procedures and systems developed for the Tuscany area, but similar setups are used by the rest of the collaboration. Our goal was to involve students and teachers also in those operation, developing a compact and user-friendly instrumentation. The idea is to extend their experience to the commissioning and debugging stages of the experiment, completing their overview of a real physics experiment.

4˙1. *Electric tester*. – One of the issues more often encountered is related to noisy channels or to internal cabling. We thus developed a setup to perform an electrical test of all the strips automatically, without the need for a signal generator and oscilloscope. The setup is based on a Terasic development board (DE2 [9]), hosting an Altera FPGA Cyclon II with a custom firmware and a 16X2 LCD screen. The 2 on-board expansion connectors (J1 and J2) are connected to the chamber interface card on each side (see fig. 4) by means of passive adapters. A square digital signal is generated inside the FPGA and sequentially pulsed on each strip through J1. The signal is expected to travel along the strip and come back to the FPGA through connector J2. On its path it passes through the C-R circuit of the interface board (used to decouple the strip from the front-end chip), and thus we receive back a double-delta signal, still easy to handle in FPGA. The firmware is designed to work also with single components of the chamber, like internal stand-alone cables. The type of test can be selected with the on-board buttons and instructions and test results are displayed on the LCD screen. There is no need to have an external PC connected or any other electronic equipment, thus making it a very compact and "plug and play" system.

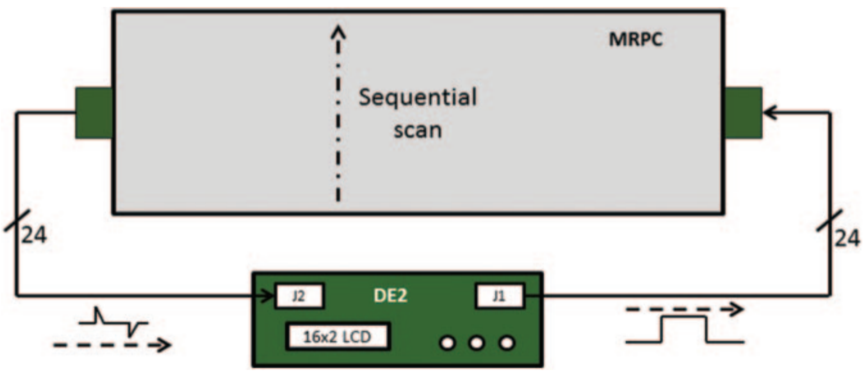

Fig. 4. – Scheme of the setup for the electric test.

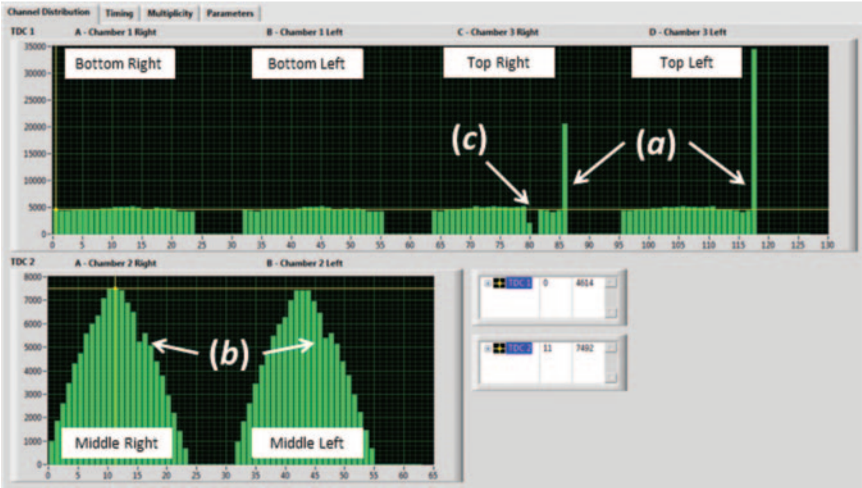

Fig. 5. – Occupancy distribution for the three chambers, with the issues highlighted.

If any issue is found during the automatic scan the system generates an error list that contains strip by strip error information:

- *Short*, when the signal is back not only from the strip under test. It can also be a hint of crosstalk.
- *Not connected*, when we have no signal back.
- *Shift*, when signal is back on any other line except the one pulsed.

Testing a full set of chambers requires less than 5 minutes, and can be done by everyone.

The first use of the tester was made in the Grosseto site. In fig. 5 the strip occupancy obtained by students with the standard EEE analysis suite is reported. The occupancy on top and bottom chambers are expected to be flat, while the middle chamber should have a bell shape due to the geometrical acceptance of the telescope. For each strip both sides (left and right) are reported separately. Three issues appear in the distribution. In chamber 3 one strip is noisy (marked as a) and a couple seems to be not fully efficient (c), an inefficiency appears also in chamber 2 (b). The tester output recognized that issue a was related to a bad internal cabling (shifting) and b was a problem of crosstalk. No error was found regarding c, which means that the problem was down-stream in the acquisition (NINO or TDC). The test was thus able to disentangle and identify the problems related to the chamber from the one in the acquisition chain, allowing a precise intervention on the telescope.

4·2. *Characterization.* – For efficiency studies we make use of a set of scintillators coupled to PMTs. In the basic configuration two scintillators (with an active area of $\sim 20 \times 60\,\mathrm{cm}^2$) are employed, whose signals are used to generate a trigger that can be fed directly to system DAQ (fig. 6). The efficiency is determined by the ratio between the events with at least one reconstructed hit in the chamber and the total acquired events. The small dimension of the scintillators allows to scan the chamber active area to search for efficiency variation. If desired we can require that the hit position is inside the area covered by the scintillators.

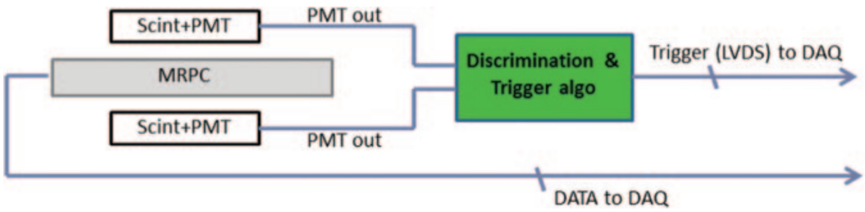

Fig. 6. – Scheme of the setup to measure detector efficiency.

The standard electronics employed for this purpose (crate, NIM modules and so on) is not a good choice if you need to go around schools spread all over the Tuscany area. We wanted something easy to transport and with a quick setup. With this idea we developed a custom board (see fig. 7) with enough flexibility to be employed also in other applications. The board accepts up to 8 PMT analog inputs and performs signal discrimination. The channels are grouped 2 by 2 and for each group it is possible to set a threshold with an on-board Digital to Analog (DAC) converter. The DAC can be remotely controlled. The discriminated signals enter in the FPGA when their rates are measured and the trigger algorithm performed. With a PC is possible to read the rates and to change the trigger pattern at will. The output is finally produced as LVDS, ready to be used in any application.

Again, the final goal is to allow the students to perform the measure. As a first step we tested the system with the undergraduate students of the physics department, that use the Pisa site for laboratories activities. They work with the data of the telescope performing calibration and cosmic-ray studies and one of their main activities is to find the working point of all MRPCs of the telescope. In fig. 8 we make use of our setup to measure the detection efficiency of one MRPC as a function of the applied high voltage.

The same setup was used in the work described in [10]. An auxiliary telescope was created with the same DAQ of the main telescope. This second DAQ was triggered by

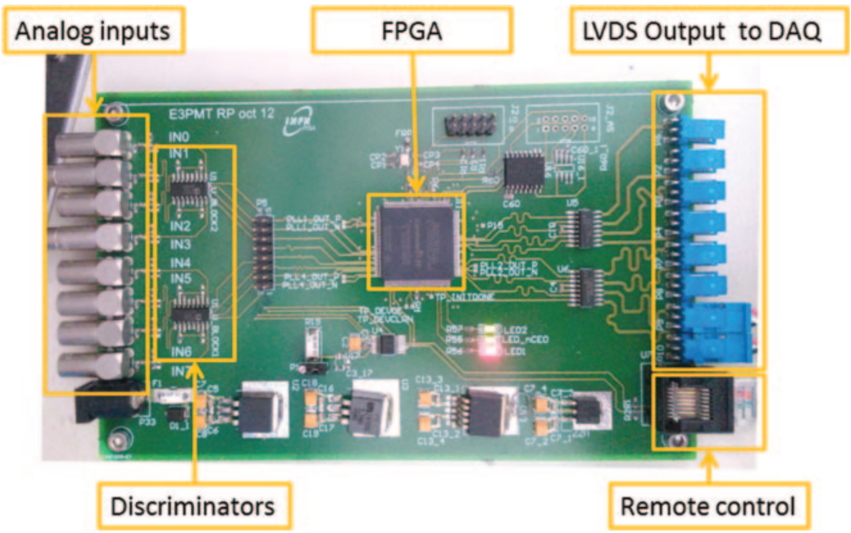

Fig. 7. – Picture of the scintillator board.

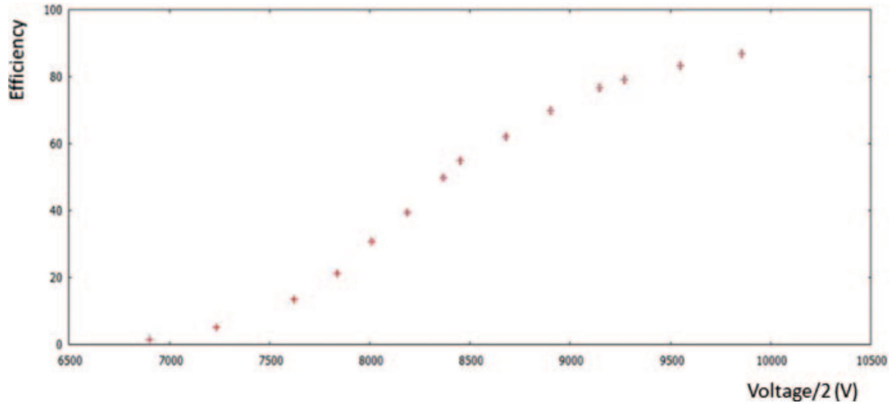

Fig. 8. – Efficiency of one chamber w.r.t. applied high voltage. The total voltage is twice the value (see fig. 2).

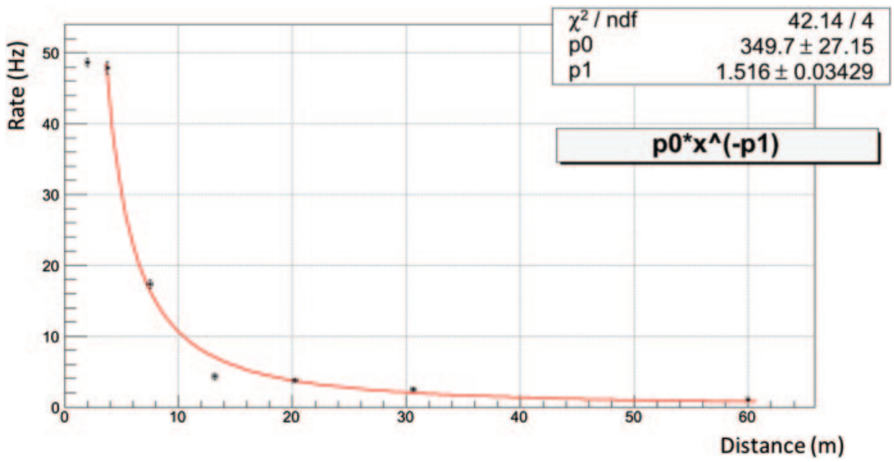

Fig. 9. – Cosmic-ray showers rate *vs.* telescopes relative distance. Detector and acquisition efficiency have been considered constant and thus such corrections are not applied.

the scintillators setup described above, but no MRPC was connected, which means that no tracking information was generated but only the event timestamp from the GPS. The system was mounted on a moving cart with the aim to measure the decoherence curve of the coincidence rate between the main telescope and the auxiliary one (fig. 9). This is also a way to test the GPS synchronization and resolution.

5. – Conclusion

The EEE experiment really brings the science in school. The project is a real physics experiment, producing results and publications. At the same time it is carried out with the students and teachers contribution, and the detectors are located inside high schools. The number of MRPCs already built is over 150, and others are under construction. These chambers have to be tested and their efficiency must be periodically evaluated.

We have presented some tools and setups developed for the Tuscany area. Our goal was to make them as compact and user-friendly as possible. Our solutions have already been successfully used and tested by undergraduate students in the Pisa site and employed in schools by INFN researchers. Other upgrades will be done in the next future and the final setup will be used directly by students and teachers under our supervision.

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