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A new RPCs generation for astroparticle physics

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The Resistive Plate Chambers (RPCs) can be extensively used in Cosmic Ray Physics and Gamma-Ray Astronomy. Indeed, the ARGO-YBJ detector, a 7000 m^2 full coverage RPC carpet, was operated at YangBaJing (Tibet, 4300 m asl) with very low maintenance and excellent performance for more than a decade. It provided: high efficiency detection of low energy showers, down to 100 GeV, by means of the dense read-out sampling; wide energy range investigated, 100 GeV – 10 PeV, by means of the combined digital/charge read-outs; good energy and angular resolutions with unprecedented details in the shower core region.

The RPC-based flare hunter we propose is therefore based on the experience of the ARGO-YBJ experiment. A new RPC generation dedicated to cosmic ray experiments is in preparation, the main differences from ARGO-YBJ being the avalanche mode operation instead of streamer and the gas closed loop that strongly reduces the fresh gas consumption.

This contribution shows experimental results on several new generation prototypes that were built in view of a test experiment to be performed in the South hemisphere. The experiment can be carried out either as standalone or by installing the RPC layer on top of a water Cherenkov detector. The purpose of this hybrid detector would be to combine the RPC capability of imaging the shower front, down to few keV/hit, with the Cherenkov capability of integrating all signals produced by the shower in several radiation lengths of water. In both cases the RPCs would strongly increase the sensitivity to the observation of flaring phenomena like GRBs or AGNs below the TeV.

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1. Introduction

The observation of transient emissions starting from the prompt phase of the high energy (>GeV) emission is crucial in a multi-messenger study of the Universe.

With increasing energy the photon emission can be studied in a statistically significant way only with ground-based detectors measuring the different components of Extensive Air Showers (EAS). The classical approach is to detect, with suitable telescopes, the Cherenkov radiation produced in atmosphere by secondary charged particles in air showers. Another possibility is to sample the charged particles at ground with arrays of detectors.

The main features of arrays are the large field of view (FoV) (≈2 sr) and continuous operation, which make them the ideal detector to search for transient sources such as GRBs. Indeed, transients are unpredictable events both in time and location, therefore detectors able to continuously survey the sky are needed.

While arrays are less sensitive than imaging atmospheric Cherenkov telescopes (IACTs), their nearly 100% duty-cycle allows to observe the prompt phase of GRBs, and other transients, nearly in all the overhead sky. On the contrary, the FoV of IACTs is very small, limited to a few degrees, therefore they can react to alerts but cannot scan continuously the sky searching for the transients thus losing the prompt phase of the emissions.

From an experimental point of view, the sampling of secondary particles at ground can be realized with two different experimental approaches ([1])

1. Particle Counting. A measurement is carried out with thin ($\ll$1 radiation length) counters providing a signal proportional to the number of charged particles (as an example, with plastic scintillators or RPCs). The typical detection threshold is in the keV range. ARGO-YBJ or the KM2A array of LHAASO are examples of Particle Counting detectors.

2. Calorimetry. A signal proportional to the total incident energy of electromagnetic particles is collected by a thick (many radiation lengths) detector. An example is a detector constituted by many radiation lengths of water to exploit the Cherenkov emission of secondary shower particles. HAWC or the WCDA ponds of LHAASO are examples of these detectors.

The energy threshold in gamma-ray astronomy of these detectors is very different. Generating 1 photoelectron (pe) on a 8-inch PMT, requires an electromagnetic particle of about 100 MeV energy. Therefore, an EAS secondary electromagnetic particle with a typical energy of 10 MeV yields on average 0.1 pe on the PMT, and the corresponding detection efficiency is extremely modest. The number of photoelectrons generated by multiple secondaries is a sum of each and it could reach a large value when the number of secondaries is high, e.g. when the detector is near a shower core.

Very low energy (<500 GeV) showers, however, do not show a well-defined core. Moreover, secondary particles have a very low energy (≈MeV) and are dispersed on a wide area. As an example at the ARGO-YBJ altitude (4300 m asl, 606 g/cm^2), a 0.1 (0.5) TeV gamma-induced shower produces on average about 10 (100) secondary electrons and 70 (700) photons with energy above 1 MeV. About 20 (40)% of these electrons (photons) have an energy greater than 100 MeV [2]. As a consequence, showers induced by 0.5 TeV are hardly detected by PMT, thus the energy threshold of water Cherenkov detectors is of order of 0.7-1 TeV.

On the contrary, Resistive Plate Chambers (RPCs) are able of imaging the shower front down to few keV/hit. Note that 1 cm scintillator requires a threshold energy of 1.5 MeV not keV! Therefore, RPCs and provide the ideal detector for a flaring hunter.

RPCs, a widely used detector in Particle Physics, has been extensively used also in Cosmic Ray Physics and Gamma-Ray Astronomy. Indeed, the ARGO-YBJ detector, a 7000 m^2 full coverage RPC carpet, was operated at YangBaJing (Tibet, 4300 m asl) with very low maintenance and excellent performance for more than a decade [3].

ARGO-YBJ is constituted by a central carpet of RPCs with a high granularity of the read-out. Each RPC is read by 80 external strips of 6.75×61.80 cm^2 (the spatial pixels), logically organized in 10 independent pads of 55.6×61.8 cm^2 which represent the time pixels of the detector ([4]). The readout of 18,360 pads and 146,880 strips is the experimental output of the detector.

Because of the small pixel size, the detector is able to record events with a particle density exceeding 0.04 particles m^{-2}, keeping good linearity up to a core density of about 15 particles m^{-2}. This high granularity allows a complete and detailed three-dimensional reconstruction of the front of air showers starting from an energy threshold of $\approx$100 GeV.

The median energy of the first multiplicity bin (20-40 fired pads on the carpet) for photons with a Crab-like energy spectrum is $\sim$300 GeV ([5]), with a $\approx$50% efficiency in the detection of 100 GeV gamma-induced showers. The granularity of the read-out at centimeter level and a noise of accidental coincidences of 380 Hz/pad, half due to local radioactivity, allowed to sample events with with multiplicity threshold of only 20 fired pads, out of 15,000 pads, with a noise-free topological-based trigger logic.

Therefore, RPCs provided: high efficiency detection of low energy showers, down to tens of GeV range, by means of the high granularity of the read-out sampling; very wide covered energy range, up to 10 PeV, by means of the combined digital/charge read-outs; good energy and angular resolutions with unprecedented details in the shower core region.

A RPC-based flare hunter can be therefore based on the experience of the ARGO-YBJ experiment.

In this contribution a proposal for a RPC-based GRB hunter made by a wide field of view shower array instrumented with a full coverage core made by RPCs is introduced.

Such a detector could constitute the core detector in new proposals such as SWGO [6] to have a very low energy threshold.

2. New generation RPCs

The type of RPC detector foreseen for this proposal test is similar to the well tested ARGO-YBJ chambers, with a few differences suggested by the evolution of the detector in the last 15 years:

- operation in avalanche mode instead of streamer;
- thinner electrode plates: 1.2 mm instead of 2 mm;
- new front-end electronics, adequate to the avalanche mode operation.

Each chamber consists of a gas volume (or gas gap) sandwiched between two readout-support panels, with the front-end electronics located along the chamber edge, on the panel external surfaces.

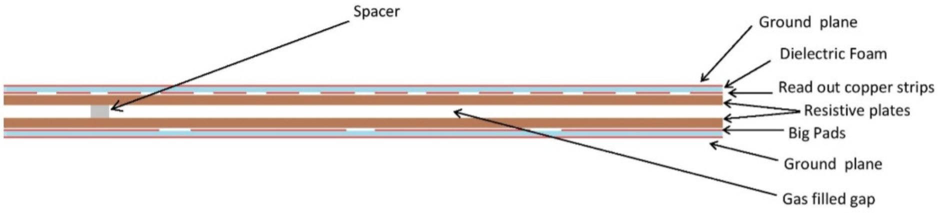

Figure 1: RPC layout.

The detector layout is reported in Fig. 1. The gas volume is a 2 mm gap between two resistive electrode plates each 1.2 mm thick (instead of 2 mm as in ARGO-YBJ). These electrodes are made of high-pressure laminate (HPL) based on phenolic resin, as in ARGO-YBJ. The gas volume is sandwiched between the read out panels, which detect the signals generated inside the gas gap. The top one, see Fig. 1, is equipped with strips of size 6×37 cm^2, with the front-end electronics located at the end of the strip along the chamber edges, as shown in Fig. 2. Each electronics channel consists of an amplifier followed by a discriminator, which supplies a fixed amplitude output signal suitable for timing purposes. The front-end electronics is embodied inside the detector Faraday cage, as for ARGO-YBJ. This strip panel provides the "digital" read out which gives the number of hits of the shower and saturates when the shower hit density approaches or exceeds the number of strips per unit area. In order to measure the hit density at the core of energetic showers, the chamber is also equipped with the “analog” ("charge") read out, which is provided by the bottom panel in Fig. 2. This consists of 4 "big pads", working as large capacitances integrating the charge induced by all hits falling in the pad. The amplitude reached by this analog signal allows to measure the shower hit density up to about 2×10^4 m^{-2} in the streamer working mode and about 5×10^5 m^{-2} in avalanche mode as foreseen for this proposal.

3. A RPC-based flaring hunter

We propose a flaring-hunter made by a full coverage core detector, located at 5000 m asl, constituted by (see Fig. 3)([7])

(a) a 150×150 m^2 RPC full coverage carpet, with a 0.5 mm lead layer on top mainly to improve the angular resolution at the threshold;

(b) a dense muon detector below the carpet constituted by a water Cherenkov pond buried under 2.5 m of soil to improve the rejection of the background due to charged cosmic rays.

Adequate photon statistics above 50 TeV, to study Ultra-High Energy (UHE) gamma emissions, can be eventually provided by an array of plastic scintillators (or water tanks) and muon detectors in a 30 m grid around the core detector covering a total area of 1 km^2 at least.

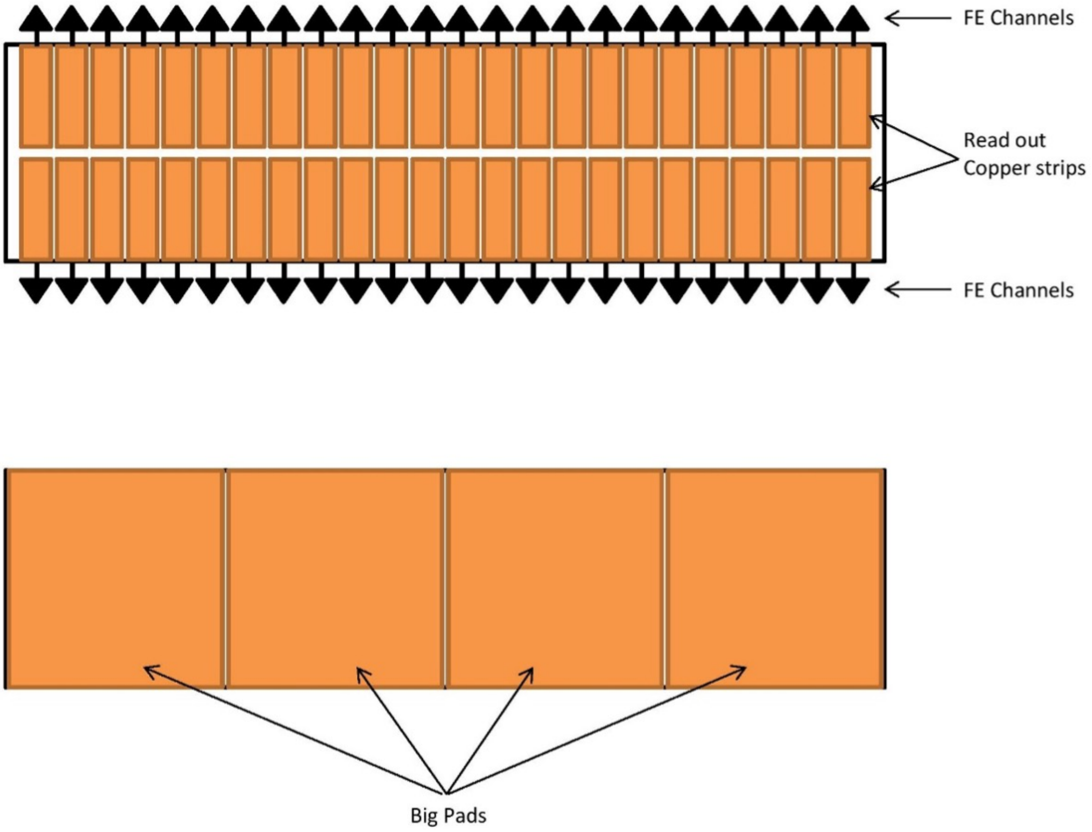

Figure 2: The structures of the two read-out panels.

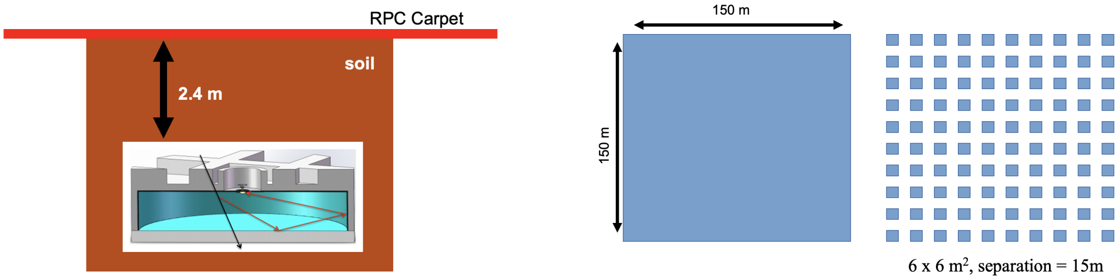

Figure 3: Left Panel: Layout of the GRB hunter. Right Panel: Layouts of 2 different muon detectors under the RPC carpet.

Results of preliminary calculations are shown in the following ([7]). The effective area for showers produced by primary photons and protons are shown in the Left Panel of Fig. 4 as a function of the median energy for different bins of strips multiplicity.

As you can see from the figure, we have $A_{eff} \sim 3\times10^3$ m^2 at 100 GeV and $A_{eff} \sim 10^6$ m^2 at 100 TeV. The energy distributions are shown in the Right Panel of Fig. 4 for 4 different strip multiplicities. The peak energy of the first bin is about 100 GeV. The energy resolution is about 50% at the threshold.

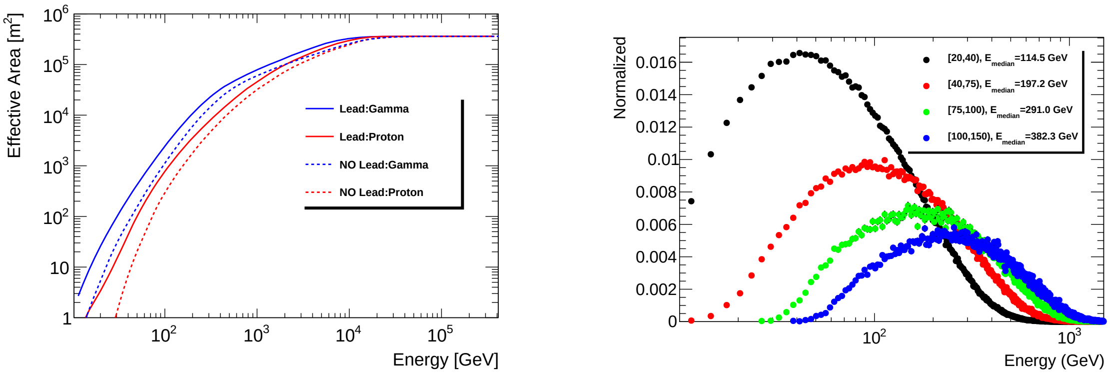

Figure 4: Left Panel: Effective areas for photon- and proton-induced showers as a function of the primary energy. Right Panel: Energy distributions of photon-induced showers for 4 different strip multiplicities measured by the RPC carpet ([7]).

3.1 Sensitivity to a Crab-like gamma source

In Fig. 5 the sensitivity of the central detector, located at 5000 m asl ([7]), is compared to that of LHAASO at 4400 m asl ([9, 10]) and SWGO at 5000 m asl ([6]).

As you can see, a smaller full coverage detector instrumented with RPCs has a sensitivity comparable with much larger arrays like LHAASO or SWGO and can constitute the central core detector of a powerful GRB hunter.

The main reason is the full coverage layout of the muon detector allowing to efficiently reject charged cosmic ray background in the TeV range and to have a background-free regime starting from about 50 TeV. We remind that in LHAASO the large area muon detector consists in a sparse array (coverage $\approx 4.4 \times 10^{-2}$) with an energy threshold of about 10 TeV. In addition, the full coverage of the RPC carpet allows an energy threshold of ≈100 GeV as demonstrated by ARGO-YBJ. The effect of a shower array located around the central carpet is not included yet in this calculation.

4. Conclusions

The observation of transient emissions starting from the prompt phase of the high energy emission is crucial in a multi-messenger study of the Universe. Based on the experience of the ARGO-YBJ experiment we introduced the proposal of a RPC-based GRB hunter made by a wide field of view shower array instrumented with a 150×150 m^2 full coverage central carpet made by RPCs. RPCs provide the ideal detector to observe flaring emissions of high energy photons, even in the prompt phase, starting from the GeV energy range. A new RPC generation dedicated to cosmic ray experiments is in preparation, the main differences from ARGO-YBJ being the avalanche mode operation instead of streamer and the gas closed loop that strongly reduces the fresh gas consumption. Preliminary calculations show that below the TeV the sensitivity of such a detector is comparable or even better than much larger LHAASO or SWGO experiments.

Such a detector could constitute the core detector in new proposals such as SWGO to have a very low energy threshold.

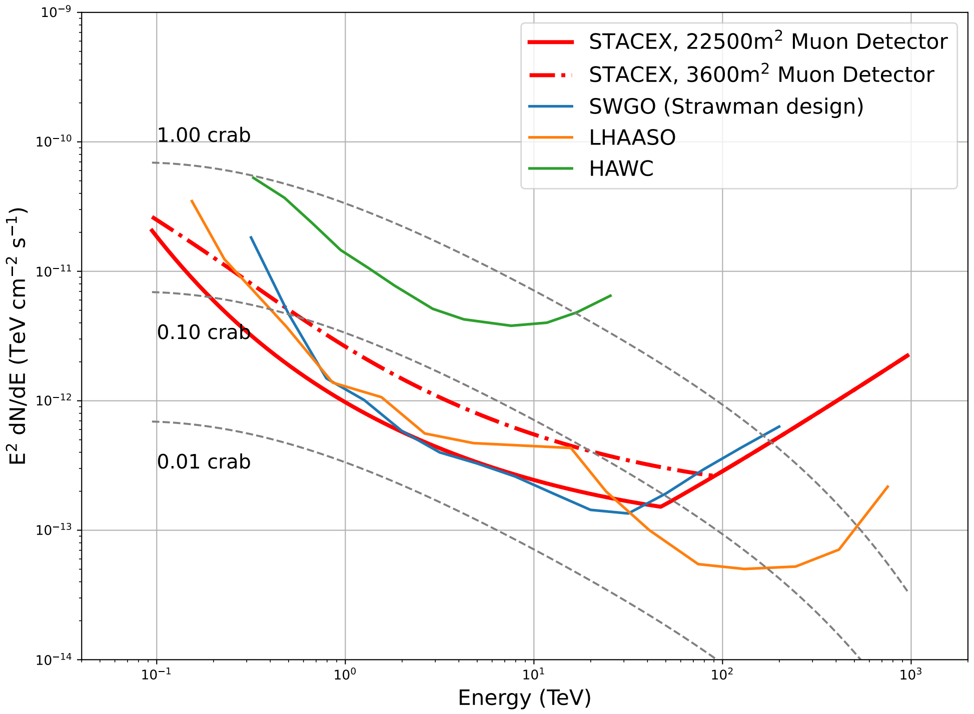

Figure 5: Differential sensitivity of STACEX central detector in 1 year compared to HAWC (22,500 m^2 at 4100 m asl) (Abeysekara [8]), LHAASO (1.3 km^2 at 4400 m asl) ([9, 10]) and SWGO (220,000 m^2 at 5000 m asl) ([6]). The calculations refer to the 2 different muon detector layouts discussed in the text. The effect of a shower array located around the central carpet is not included yet in the calculation ([7]).

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