Towards a Direct Measurement of Coherent Radio Reflections from an Electron-Beam Induced Particle Cascade.

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Abstract

The T-576 experiment at the SLAC National Accelerator Laboratory was designed to make the first direct measurement of coherent radio reflections ('radar') off the particle shower produced by an electron beam (>14 GeV/particle; 10^9 electrons per bunch) directed into a high-density polyethylene target [1].

Our preliminary results are obtained using a singular value decomposition (SVD) analysis technique and indicate a signal consistent with a radio reflection at 2.36 sigma significance above background. A detector based on coherent radio reflections may therefore allow lowering the detectable neutrino energy threshold from a few EeV (corresponding to the threshold of currently operating Askaryan radio detectors) to several PeV, where the IceCube experiment runs out of statistics.

Introduction

Cosmic ray (CR) physics offers a wide range of investigations, closely related to gamma, x-ray, radio astronomy, nuclear, and high energy physics. Additionally, the neutrino component of cosmic rays may access a wide range of important open questions in fundamental physics and may be an indicator of Beyond Standard Model physics.

Currently, particle accelerators can achieve energies of $14 \cdot 10^{12}$ eV, while the cosmic rays energy spectrum extends from 10^5 to 10^{20} eV. At ultra-high energies, the cosmic ray and neutrino fluxes drop dramatically, requiring large-scale detectors. Numerically, at an energy of $\sim 10^9$ eV, the CR flux is 1 particle/(m^{2}s), for E$\sim 10^{15}$ eV region, the flux is 1 particle/(m^2-year), and close to maximum energies, at several $\sim 10^{18}$ eV, the flux is 1 particle/(km^{2}year).

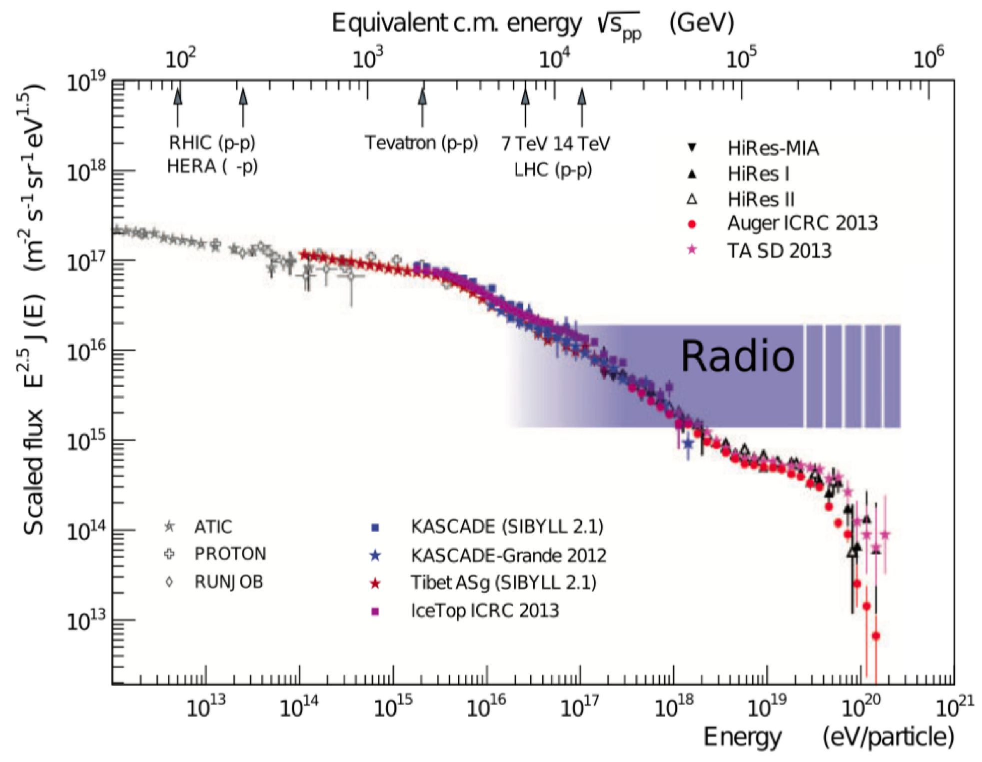

Figure 1: The differential fluxes of all cosmic rays particles (irrespective of Z), measured by various experiments. Figure taken from [4]

Neutrino radio observatories

In the TeV–PeV range, extra-galactic neutrinos are regularly detected by IceCube. At the EeV scale, currently operating neutrino radio detectors (e.g., the ARA, ARIANNA, ANITA experiments) start to be sensitive to cosmogenic neutrinos. These neutrinos, produced by UHE cosmic rays interacting with CMB backgrounds are predicted by the GZK mechanism, but have not been observed yet.

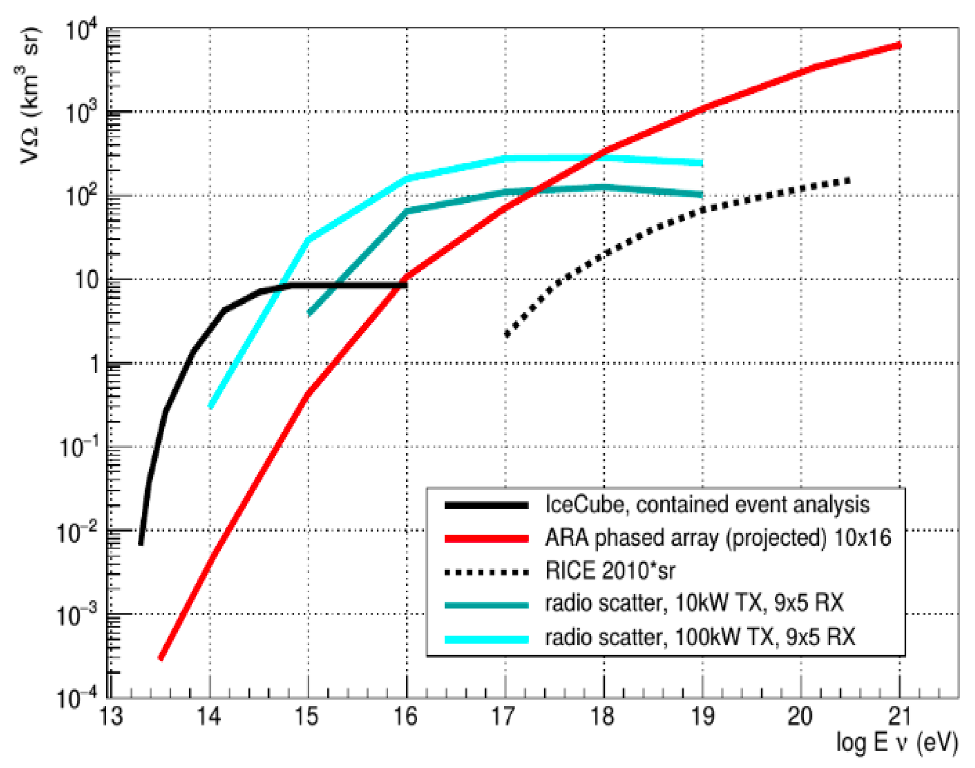

Figure 2: Calculated target effective volume for UHE neutrino detectors. The radar technique has the best projected sensitivity in the 10^{15}–10^{18} eV range. Figure taken from [3].

The existence of radio emission produced by particle showers was first predicted by G. Askaryan in the 1960's. Currently, there are a number of experiments based on this effect. Superluminal showers resulting from primary cosmic ray collisions with a dense dielectric target (such as ice) emit a cone of coherent radiation in the radio range of the electromagnetic spectrum. The strength of the EM far field is proportional to the initial CR particle energy; due to the long radio attenuation length of ice, the radio signal is an excellent probe for the detection of cosmogenic neutrinos at ultra-high energies.

Coherent radio reflection ('radar')

As the particle shower passes through the medium, it creates an ionization wake plasma for a short period of time. Depending on the initial particle energy, the ionization process may become dense enough to reflect at radio wavelengths. Over-dense scattering is defined by the condition that the sounding frequency has to be below the plasma frequency $\nu_{obs} < \nu_{plasma}$ [2]. The reflected signal strength depends on the transmitter power and the position of the source. Thus, by broadcasting a powerful enough radio signal, it is possible to detect reflected wavelengths from a low-energy neutrino in a radio-quiet area.

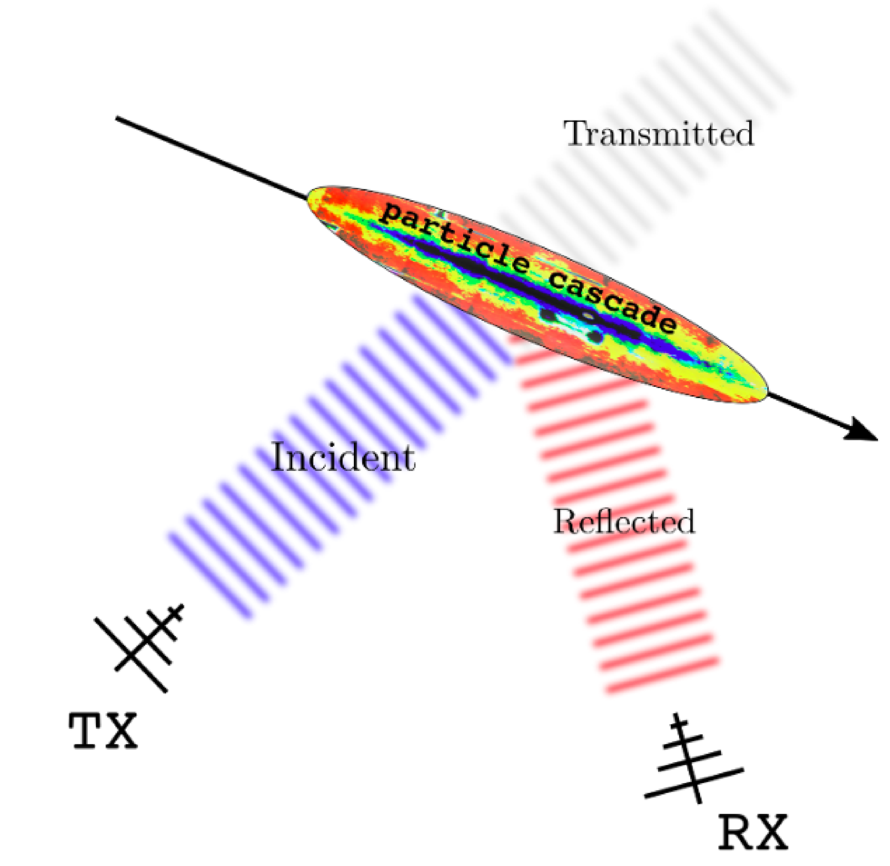

Figure 3: Schematic representation of the radio reflection from a particle cascade.

The fact that we can control the power of the broadcast signal increases the sensitive volume in comparison with other radio neutrino detectors. It follows that the method based on coherent radio reflection technique may allow lowering the energy threshold from EeV to several PeV, covering the currently existing gap in sensitivity.

T576 experiment

The t576 experiment at SLAC End Station A facility was designed to make the first measurement of a coherent radio reflection signal from the particle cascade produced by O(10-14 GeV) electron beams (10^9 particles per bunch) directed into a polyethylene target. This beam is approximately equivalent to the shower produced by an EeV energy neutrino interacting in cold Antarctic ice. The principal scheme of the experimental set up and the DAQ system is shown in the Fig.[4]. A typical Beam ON TX ON t576 event is presented on Fig.[6].

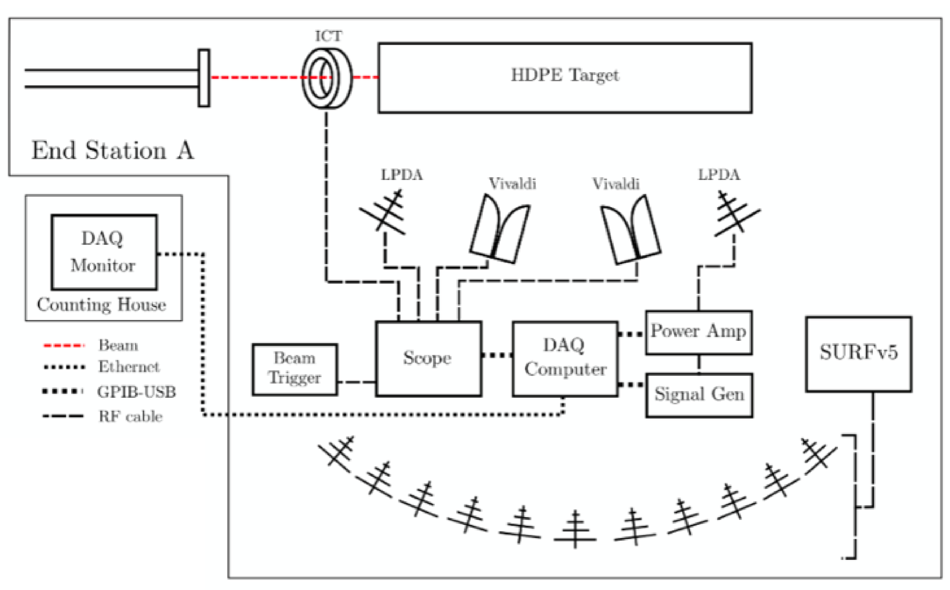

Figure 4: Experimental setup from Run 2.

The TX antenna connected to the pulse generator broadcasts signal over a wide frequency range. Reflected signals were measured by a set of RX antennas at different angles and distances from the target. Analysis of Run 1 data (May 2018) showed evidence for a signal-region excess at 2.36 sigma over a null hypothesis. More data were collected during Run 2 (October 2018), which will improve the statistical significance of the previous result and verify the expected R_{tx}^2 rather than R_{rx}^2 dependence and frequency scaling of the observed signals.

Analysis

The main challenge of this experiment is to extract the signal from the much larger background. The two strongest background sources were observed to be room reflections and a strong radio signal from the beam/target interaction ('beam splash'). Fig.[5] shows an example of signals caused by beam splash recorded by one of the t576 antenna, and comprises sudden appearance, transition radiation, Askaryan radiation, and their reflections.

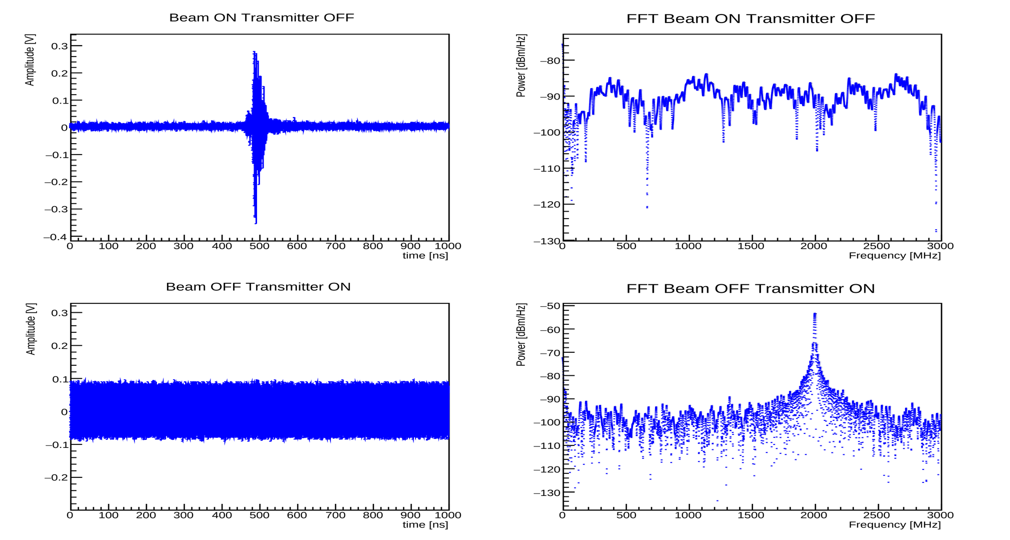

Figure 5: . Example of Beam-only event and transmitter-only events with their FFT spectra.

The SVD analysis technique decomposes the signal into a basis of patterns. In order to extract the radar signal, a null dataset was prepared. The carrier-only (TX ON / Beam OFF) and beam-only (TX OFF/ Beam ON) events are summed to produce a sample which imitates real data in phase and amplitude. After carrier subtractions both real and "null" datasets were decomposed and the most and the least prominent modes were removed, because they correspond to beam splash and uncorrelated noise modes.

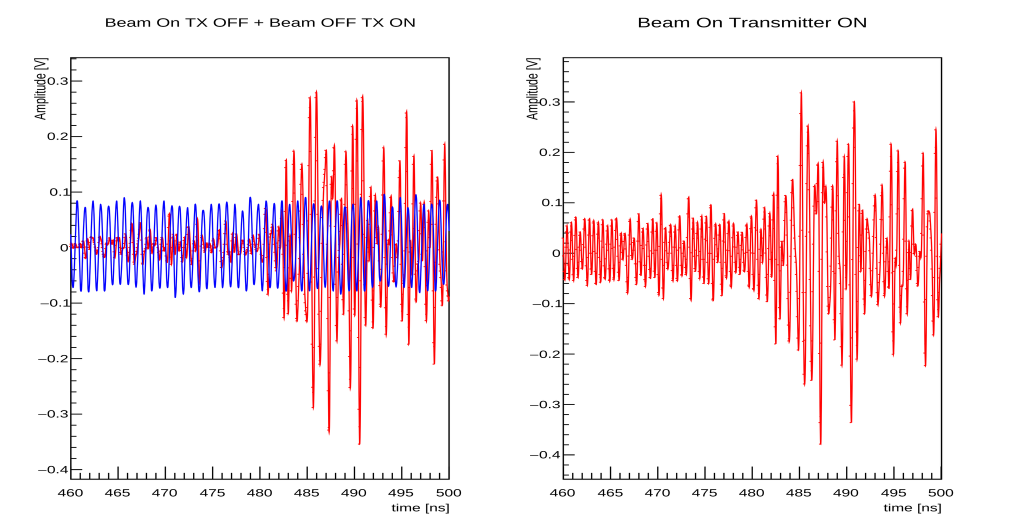

Figure 6: Example of "null" and real events.

The time-vs-frequency plot of remained signals presented on the Fig.[7], which shows an excess in signal region with 2.36 sigma confidence level.

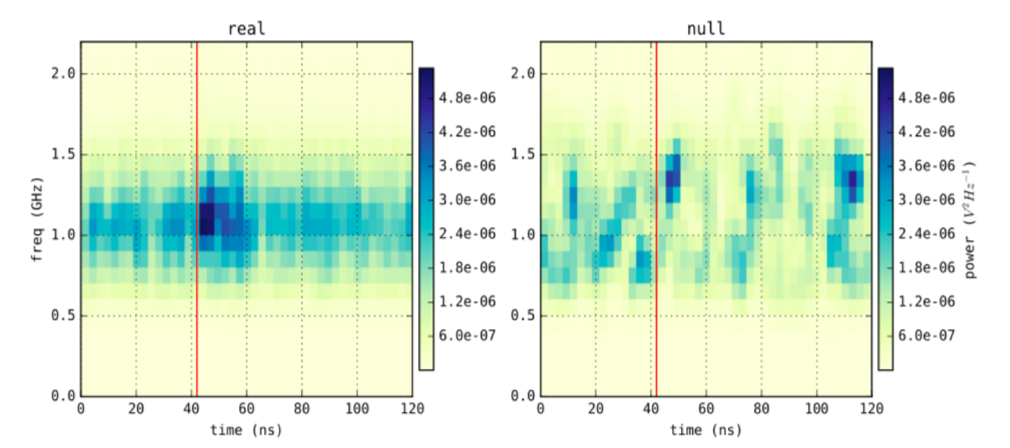

Figure 7: Run 1 analysis results, showing the excess signal after svd decomposition and removal of the most significant patterns (corresponding to background).

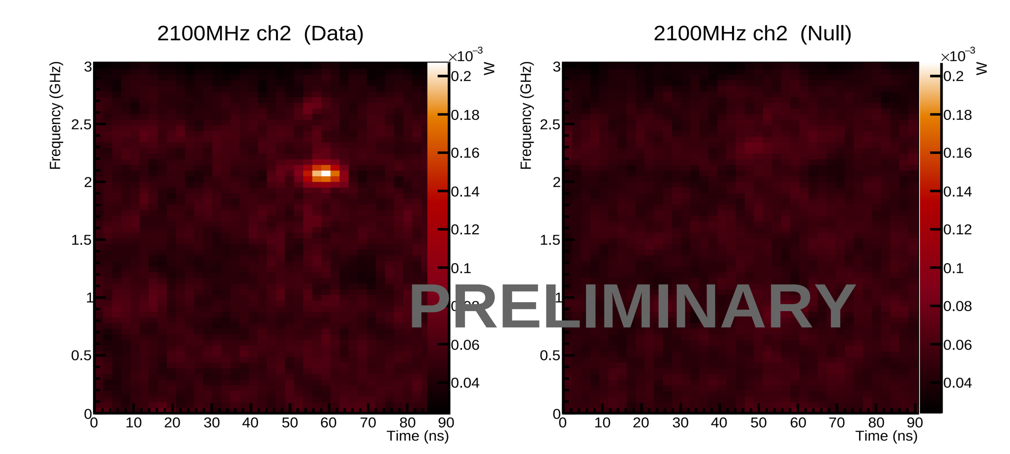

Figure 8: Preliminary Run 2 analysis results, showing the excesses signal in Hpol using an improved SVD-based analysis technique (to be detailed in a forthcoming publication.)

Conclusions

Experimental searches for coherent radio reflections from particle cascade are presented. New experimental techniques based on radar may cover the sensitive gap in neutrino detection from 10^{15} to 10^{18} eV. An in-ice experiment at the South Pole is planned for December 2019. Data analysis of Run 2 data is ongoing.

References

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