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# SLAC T-510: Radio emission from particle cascades in the presence of a magnetic field

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**Abstract.** Cosmic ray induced particle cascades radiate in radio frequencies in the Earth's atmosphere. Geomagnetic and Askaryan emission provide an effective way to detect ultra-high energy cosmic rays. The SLAC T-510 experiment was the first to measure magnetically induced radiation from particle cascades in a controlled laboratory setting. An electron beam incident upon a dense dielectric target produced a particle cascade in the presence of a variable magnetic field. Antennas covering a band of 30-3000 MHz sampled RF emission in vertical and horizontal polarizations. Results from T-510 are compared to particle-level RF-emission simulations which are critical for reconstructing the energy and composition of detected ultra-high energy cosmic ray air showers. We discuss the experimental set up, the data processing, the systematic errors and the main results of the experiment, which we found in a good agreement with the simulations.

## 1 Introduction

Radio emission from extensive air showers is a promising way to probe the properties of high energy cosmic rays [1]. Two mechanisms describe radio emission from particle cascades inside a dielectric in a magnetic field. Askaryan radiation was hypothesized in 1962 [2]. It is due to a charge excess in the cascade that builds up from Compton scattering, positron absorption, and other processes. It is linearly polarized in the direction radial to the cascade axis. Askaryan radiation has been measured in previous SLAC experiments with cascades developing in silica sand, rock salt, and ice targets [3] [4] [5]. In the presence of a magnetic field a magnetically induced component of radiation also develops. The charges in the shower form a transverse current due to the Lorentz force. This radiation is polarized in the $\mathbf{v} \times \mathbf{B}$ direction. Magnetically induced radiation is particularly useful for detecting cosmic rays whose cascades develop in the Earth's magnetic field. The detected signal is a sum of both types of radiation. The radio emission from a cosmic ray air shower has to be compared to simulations in order to be interpreted. In particular, the endpoint [6] and ZHS [7] formalisms track individual particles in the cascade and calculate the radiation from each track segment, which is then summed up at the point of an observer. Since there are systematic uncertainties in the hadronic interaction models and the primary mass of a detected cosmic ray is unknown, the only way to directly compare radio emission from a particle cascade to simulations is through a controlled beam experiment. The SLAC T-510 experiment was designed to provide the first measurements of magnetically induced radiation in a controlled laboratory setting and to compare experimental data to simulations [9].

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## 2 Experimental Design

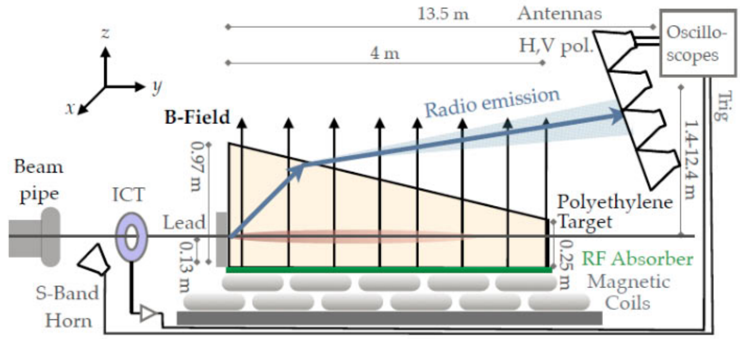


**Figure 1.** Schematic of the SLAC T-510 experiment [9].

The SLAC T-510 experiment used a target of high density polyethylene ($\rho = 0.97$ g/cm$^3$). Electron bunches of 4.35 and 4.55 GeV cascaded in the target, creating a total cascade charge equivalent to a $4 \times 10^{18}$ eV cosmic ray air shower. Fifteen coils underneath the target provided a variable magnetic field between ±970 Gauss. The top edge of the target was sloped at 9.8° to allow the radiation in the target to escape. In order to make the experiment applicable to cosmic ray air shower detection and to see the effects of both emission mechanisms at a comparable amplitude in one experiment, the ratio of magnetically induced radiation to Askaryan radiation was designed to be roughly 1. Askaryan radiation scales with the shower length (which goes as $1/\rho$) and is weighted by the charge asymmetry. Magnetically induced radiation scales with the shower length as well as the drift velocity of the charges, which goes as the magnetic field strength divided by the dielectric density. In total, the ratio of magnetically induced radiation to Askaryan radiation is $B/\rho$. In an air shower the magnetic field is on the order of 0.5 Gauss and the density of air is $1.225 \times 10^{-3}$ g/cm$^3$ at shower max. These values were scaled to 970 Gauss and 0.97 g/cm$^3$.

A variable height antenna array consisted of four dually polarized antennas. The experiment was designed so that Askaryan radiation would be detected in only the vertical polarization and magnetic induced radiation would be detected in only the horizontal polarization. Both radiations could then be measured simultaneously and independently. A schematic of the experiment is shown in Figure 1. The antenna array covered distances of 1.4 to 12.4 meters above the beam line and was sensitive to radiation between 300 and 3000 MHz, and results in the 200-1200 MHz range are discussed in the following sections. This frequency band is comparable to 10 - 60 MHz when scaled to air shower frequencies.

## 3 Results

Data was taken across the Cherenkov cone in both horizontal and vertical polarizations and at magnetic field strengths ranging from -970 to 970 Gauss. The left panel of figure 2 shows the peak voltage from the detected signal plotted against the antenna height above the beam. Vertically polarized emission (in red) remains at the same amplitude regardless of magnetic field strength. Horizontally polarized emission (in blue) is only seen in the presence of a magnetic field. The shape of the Cherenkov cone is clear, and the signal strength peaks at the expected position of the cone, based on the target geometry. The right panel of figure 2 shows the narrowing of the Cherenkov cone with increasing frequency band. The yellow line indicates a band of 300-600 MHz, red 600-900 MHz, and blue 900-1200 MHz.

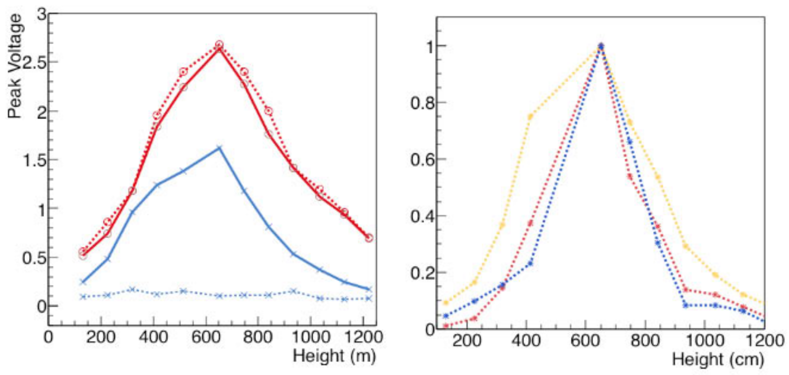


**Figure 2.** Left: Peak amplitude of the signal at different antenna positions. Vertically polarized emission is in red and horizontally polarized emission is in blue. Solid lines represent data taken with full strength magnetic field and dashed with no magnetic field. Right: Normalized Cherenkov cones for different frequency bands. In yellow is 300-600 MHz, red is 600-900 MHz, and blue is 900-1200 MHz.

The left panel of Figure 3 shows the linearity of the magnetically induced emission with the magnetic field strength. The signal polarity is expected to change with the sign of magnetic field, indicating that the transverse velocity changes direction with magnetic field. The right panel of Figure 3 shows horizontally polarized signals at ±240 G, ±480 G, ±720 G, and ±970 G, with negative magnetic field runs in green and positive in blue. The shape of the signal remains the same and only the polarity changes.

The comparison of T-510 data with simulations is ciritically important and is discussed in [8].

## 4 Systematic Uncertainties

For the T-510 data to be compared to simulations, the systematic uncertainties in the experiment must be well understood. Quantities used in simulation include cascade energy and charge, detector and target geometry, and magnetic field strength and distribution. The charge bunch that generated the electromagnetic cascade in the target was measured with an integrating current transformer to have a mean charge of 131 pC with 3% variation. The height of the antenna array was measured with laser distance meter to an accuracy of 0.01 cm. The measurement was made relative to a target on the array, for a total uncertainty of 5 cm. The accuracy of the angular geometry of the array was estimated to be known to within 3°. The magnetic field was measured at beam height in a 5 cm × 5 cm grid to 3.64 G precision and was also monitored during the runs at a single point. The RMS of the single point measurement was 72 G, giving a total of 7.4% uncertainty.

The limiting uncertainty was the reflection of the signal off the bottom of the target. A radio frequency absorbing mat was placed under the target during the experiment, but the characteristics of the mat below 1000 MHz are not well known. The direct reflection of the signal is separated from the main signal by less than 1 ns, and cannot be separated in time. Ideas for handling the reflection include doing another run optimized to understand the reflection, or including the reflection in simulations (see [8]). In a follow up experiment, a mat with well known characteristics could be included, or the geometry of the target could be redesigned so that the reflection was separated in time from the main

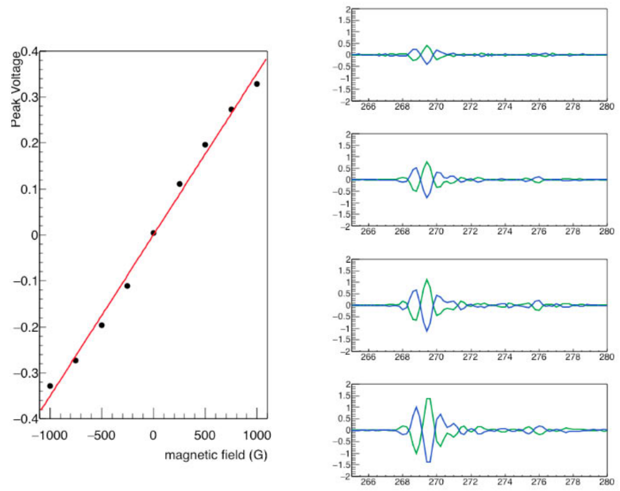


**Figure 3.** Left: Peak amplitude of the horizontally polarized signal normalized by the vertically polarized signal. Right: Voltage waveform at ±240 G, ±480 G, ±720 G, and ±970 G magnetic fields.

signal. A mirror could also be placed at the bottom of the target so that the reflection has a coefficient of 1. The reflection coefficient could also be measured independently of a second run and subtracted from the T-510 data.

## 5 Summary

The T-510 experiment provides the first data for radio emission from an electromagnetic cascade developing in the presence of a magnetic field in a controlled laboratory experiment. The radiation shows a distinct Cherenkov cone that narrows with increasing frequency. The magnitude of the magnetically induced radiation increases linearly with magnetic field strength while the Askaryan signal remains the same. The frequency range of detected emission in this experiment is relevant to current cosmic ray experiments. Other than the reflection, the systematic uncertainties are well understood. Comparison of T-510 data to simulations will lower the uncertainty in the interpretation of detected radio emission from cosmic ray air showers.

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