33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Search for Microwave Signals from Air Showers with the Electron Light Source at Telescope Array

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Abstract: The Electron Light Source (ELS) is a linear accelerator to produce bunches of 40 MeV electrons that are used to calibrate the fluorescence telescopes of Telescope Array (TA). The beam is shot vertically up into the air and resembles an air shower of $10^{16.5}$ eV. A measurement campaign has been started to search for microwave emission from air showers by placing GHz antennas at close distance to the ELS beam. Initial measurements were done with a parabolic reflector of 2.3 m diameter and receivers in the C band. The experimental setup and results from the first measurements will be shown.

Keywords: Molecular bremsstrahlung, microwave emission, extensive air showers.

1 Introduction

Extensive air showers produce different types of radiation in the Earth's atmosphere. The radiation of high-energy particles of the shower disk due to Cherenkov and geomagnetic effects covers a wide range of wavelengths. Furthermore, the short-lived electron-ion plasma in the air, produced through ionization processes by high-energy shower particles, is a source of radiation in different wavelength bands.

Cherenkov radiation is typically measured at optical, and in particular UV, wavelengths, at which the radiation of the individual particles adds up incoherently. Detection of Cherenkov radiation in the UV wavelength band is one of the efficient methods of measuring showers in the energy range below and around the knee in the cosmic ray spectrum (see, for example, [1, 2]). The Cherenkov signal is strongly amplified in the VHF radio band since the wavelength becomes then comparable to the size of the shower disk and the signals of individual particles add up coherently. In the radio frequency range this process of coherent emission is known as Askaryan effect[1] [3, 4]. The deflection of the charged particles of the shower disk in the Earth's magnetic field lead to particle acceleration and charge separation, causing emission of synchrotron-like radiation [5]. This type of coherent radiation process is nowadays referred to as geomagnetic radiation [6, 7].

The relevant radiation processes related to the ionization and excitation of the air molecules by the shower particles include the well-known fluorescence light production by molecular nitrogen (UV wavelengths) and also emission in IR. The former is the workhorse of shower detection at the highest cosmic ray energies, see, for example, [8, 9, 10]. While these processes involve the ionized nuclei, also the low-energy electrons knocked out of the air molecules due to ionization are expected to emit radio waves. Recently Gorham et al. [11] pointed out that these electrons are expected to emit molecular bremsstrahlung. Given that high-energy particles of a shower produce a thin, non-moving plasma of charged and neutral particles behind the shower front, ionization electrons are expected to elastically scatter off the abundant neutral molecules in air and emit bremsstrahlung. Estimates show that this type of radiation is expected to have a flat spectrum in the GHz range reaching up to THz frequencies [12].

For completeness we also want to mention radar reflection off the ionization trail or disk of the ionization electrons [13, 14]. In this case a beam of radio waves is scattered by the short-lived plasma produced by a shower. Although this process is known already for many years no unambiguous detection of the radar signal of an air shower has been achieved until now.

As suggested by Gorham et al. [11], measuring molecular bremsstrahlung with microwave radio antennas could be a very efficient way to study air showers at the highest energies.

- First of all, the radiation is expected to be unpolarized and emitted isotropically with an intensity proportional to the number of produced ionization electrons, and hence would provide a calorimetric signal.

- Secondly, microwave radiation of frequencies up to a few GHz propagates virtually without absorption through the atmosphere. Also the variation of atmospheric conditions such as humidity, temperature or clouds have negligible impact on the absorption.

1. In fact, the signals of shower electrons and positrons would cancel each other if there was not a $20-30\%$ excess of electrons in the shower disk

- Thirdly the background radiation of anthropogenic and natural origin is very small, reaching the level of the cosmic microwave background radiation under ideal conditions. With several frequency bands being protected from being used except for satellite TV transmission, the number and intensity of transient sources is small.

- Last but not least, thanks to satellite TV a large variety of commercially produced receivers, amplifiers and antennas of high quality are readily available and can be used for experiments.

It should be noted, however, that the intensity of incoherently produced molecular bremsstrahlung is very low and probably not detectable with the current technology. On the other hand it can be expected that attachment and absorption processes determining the plasma evolution can lead to a skewed energy distribution that in turn gives origin to partially coherent, and hence amplified, microwave emission.

First experiments searching for molecular bremsstrahlung have been inconclusive [11, 15]. While the first beam experiments indicated a strong microwave signal, later measurements with an electron beam of lower energy could not confirm an emission at such a high level.

There are a number of limitations inherent to beam experiments that make it difficult to measure molecular bremsstrahlung from a plasma under conditions similar to those found in air showers. First of all the effective volume in which the plasma can be created by a beam of accelerated particles is very limited, and also the energy as well as the lateral distributions of the shower particles do not resemble those of extensive air showers. Also the background radiation in accelerator laboratories is typically very high and correlated with the beam activity (for example, transition radiation produced when the beam enters the measurement chamber). In addition, the high intensity of Askaryan and beamstrahlung produced inside the measurement chamber makes it difficult to disentangle a possible signal due to molecular bremsstrahlung from these radiation sources.

In this work we will report on a different type of beam experiment that overcomes many of the aforementioned limitations. Using the electromagnetic showers produced by the Electron Light Source (ELS) [16, 17], a linear accelerator installed at the site of Telescope Array (TA) for calibrating the TA fluorescence telescopes, we have searched for radiation stemming from molecular bremsstrahlung. Pointing an antenna at the air showers produced by the ELS allows us measure the microwave signal that is scattered in backward direction. As there are no installations above the ELS, any possible emission in the forward hemisphere cannot be reflected backward (one of the backgrounds classical beam experiments have to cope with), in particular we do not expect to see any signal due to the Askaryan, geomagnetic, and Cherenkov effects. Except for possible RFI from the linear accelerator itself this is a background-free experiment. Here we will focus on measurements in the C band, see [18] for searches at higher frequencies.

2 Setup for GHz measurements

We have used a fully metallic parabolic reflector of 2.35 m diameter and 0.92 m focal length with different types of C band (3.4 – 4.2 GHz) receivers in the focal point of the reflector. The linearly polarized receivers were commercial low-noise blocks (LNBs) that contain, in addition to the receiver itself, a mixer and low-noise amplifier. The point spread function (emission pattern) of the antenna has been verified at the site of measurement with a sun transit.

A DAQ system similar to that of the CROME [19] experiment allowed us to measure the time-dependent power of the receiver output with a time constant of about 4 ns. A trigger signal delivered by the ELS has been used to read out the signal of the receiver over a wide time window before and after the trigger. Based on the known time delays between the trigger signal and the different steps of accelerating and releasing electrons in the ELS the time of shower production has been estimated. RFI from the linear accelerator produced in the early part of the acceleration process provided a cross-check of the relative timing.

The antenna has been pointed to different heights in the air showers produced with the ELS. The exact pointing of the antenna relative the the beam of the ELS was difficult to determine, making a scan in horizontal direction necessary. Typically between 100 and 500 shots of the ELS have been observed for a given geometrical configuration and averaged over afterwards. To estimate the background from the accelerator an extended data set was taken in which the accelerated electrons were directed to a beam dump and not released into the air.

2.1 The Electron Light Source (ELS)

The ELS [16, 17] is a linear accelerator located about 100 m from the fluorescence building Black Rock Mesa of the TA experiment. It's primary purpose is the end-to-end calibration of the TA fluorescence telescopes by producing an air shower of known parameters in the field of view of two telescopes. Releasing about 10^9 electrons of 40 MeV per shot a shower of $10^{16.5}$ eV is produced that, viewed at this short distance, resembles an air shower of more than 10^{18} eV at typical observation distances. Electrons are accelerated with a rate of about 1 Hz and the energy and total charge per bunch can be controlled to high precision ($\sim 4\,\%$).

The different components of the ELS are shown in Fig. 1. An electron source produces electrons with 100 keV kinetic energy. These are grouped into bunches and accelerated by the main accelerator to 40 MeV and, after passing a bending magnet, released vertically upward into the air. Different ways of operating the ELS are possible, including one mode in which the electrons are stopped in a beam dump.

The ELS and the corresponding cooling and power units are surrounded by a metallic fence for safety, limiting the minimum distance between an external antenna and the beam exit hatch to ~ 15 m.

Lead blocks of 50 mm thickness are used to shield the horizontal beam line and the bending magnet. In addition concrete blocks are placed around the beam line for radiation shielding and safety. Thanks to these shielding measures and the installation of the ELS in a 40-ft overseas container the electrical parts of the accelerator are well shielded and almost no RFI could be measured at 90° to the beam axis.

2.2 DAQ for microwave measurement

Depending on the number of LNB channels in the measurement, one or two modules (4 channels each) of the well-tested CROME DAQ [19] were used for data taking. The layout of the DAQ is shown schematically in Fig. 2.

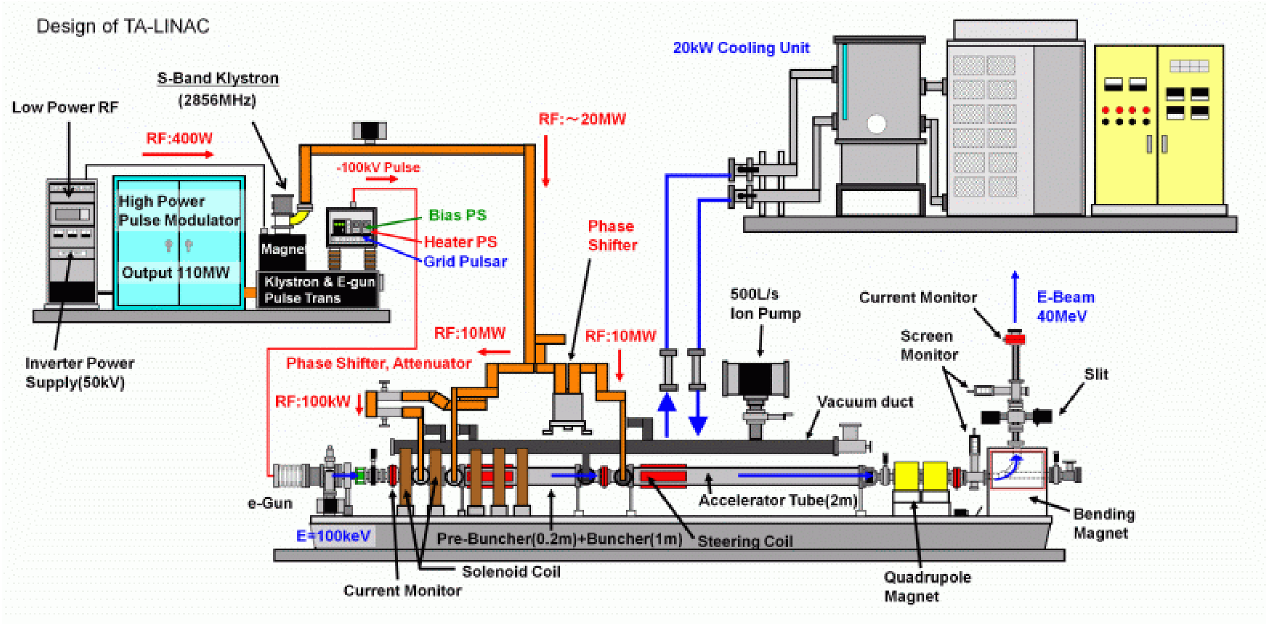

Figure 1: Illustration of the different components of the ELS [16, 17]. The ELS consists of a high power RF system, an electron source, accelerator tubes and a 20 kW cooling power unit. The 40 MeV electron beam is bent by a magnet and released vertically upward.

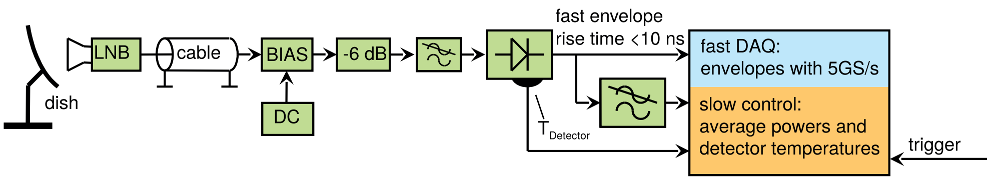

Figure 2: Electronics of DAQ chain. The LNB is a commercial receiver unit optimized for the C band and contains a mixer and low-noise amplifier. A bias tee is used to supply the LNBs with power. The external trigger signal is supplied by the ELS.

The signals from the LNBs were filtered to suppress the frequencies corresponding to 4.0 – 4.2 GHz before mixing to suppress RFI from airplane altimeter radars, reducing the effective bandwidth of the system to $\Delta\nu \approx 600$ MHz.

The power of the frequency-shifted signal is obtained from a power detector (logarithmic amplifier, Mini-Circuits ZX47-60-S+) from which we removed a capacitor to increase the video bandwidth to ~ 25 MHz (corresponding to a rise time of 4 ns). The signal of the power detector was digitized with a USB scope (Pico Technology PicoScope 6402; 8-bit dynamic range, 0.8 ns sampling time, 350 MHz analog bandwidth). Time traces of 50 μs length were taken (12.5 μs pre-trigger, 37.5 μs post-trigger).

The DAQ was placed in a car which also served as power supply via an up-converter.

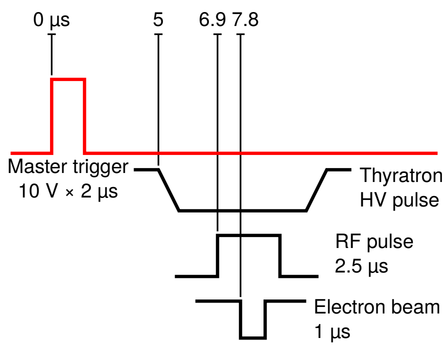

Figure 3: Estimated time delays between the ELS trigger signal and the electron beam pulse of 1 μs duration.

3 Measurement campaigns and first results

The first measurement campaign was conducted in March 2012 using two Norsat LNBs of type 8215F (15 K nominal noise temperature, 60 dB gain). The two LNBs were mounted cross-polarized on a commercial, linearly polarized feed horn and read out independently. The antenna was pointed at the beam with an elevation angle of 60° at a distance of 18 m from the beam exit point. A scan in azimuth angle was performed to ensure coverage of the shower by the radiation pattern of the antenna. The ELS was operated with a bunch frequency of 0.5 Hz and a 1 μs bunch duration. The time delays of the different acceleration steps are shown in Fig. 3.

The analysis of the traces averaged over 500 bunches show clearly an RFI signal from the accelerator. No signal

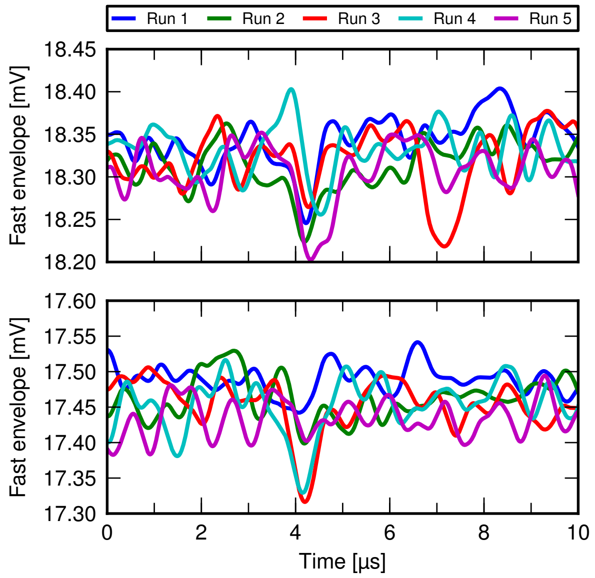

Figure 4: Examples of time traces taken during the first measurement campaign, filtered with a 1 μs moving average. Lower signals correspond to higher power measured in the receiver. Four different camera directions (runs) are shown with one panel for each polarization. The RFI produced by the power-up process of the Thyratron of the accelerator is clearly seen at $\sim 4\,\mu$s after the trigger ($t = 0$). One trace shows a pulse at the expected time of about 7 μs, which appears to be a fluctuation.

was found at the expected time delay of about 7.8 μs after the trigger. Only one trace could have been interpreted as indicating a possible signal (and, hence, only in one polarization direction), see Fig. 4.

Therefore we conducted a second measurement campaign in March 2013. The sensitivity of the experiment was increased by about a factor 100 by lowering the duration of the beam release time from 1 μs to 10 ns with an overall charge output of 120 pC. In addition a camera of 4 dual-polarized LNBs (WS International ESX 242) was used for the measurement to reduce the importance of possible uncertainties in determining the pointing of the antenna.

A first analysis of the data from the second measurement campaign does support the interpretation of the signal shown in Fig. 4 as statistical fluctuation. A more detailed analysis of the measurements is in progress.

4 Conclusions and outlook

A novel experiment searching for microwave radiation of extensive air showers has been carried out at the linear accelerator of the Electron Light Source in Utah. The experimental setup is well-suited for measuring molecular bremsstrahlung that is emitted isotropically and with a flat frequency spectrum, even in the presence of a much stronger forward-peaked signal from other radiation processes. Two measurement campaigns with different setups were performed. Lowering the beam release time of the linear accelerator and using a four-LNB camera allowed us to improve the sensitivity relative to the the initial setup by about a factor of 100 with a larger total field of view.

A weakness of the used setup is the close distance between the antenna and the air shower, corresponding to a measurement in the near field of the antenna. Furthermore verification of the pointing and calibration of the antenna turned out to be difficult.

The data of the first measurement campaign did not show any signal compatible with molecular bremsstrahlung. The analysis of the data of the second campaign is ongoing.

Acknowledgements: This work has been supported by Federal Ministry for Education and Research (BMBF) Aspera-Grant 05A11VKA and by the KIT start-up grant 2066995641.

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