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First results from the microwave air yield beam experiment (MAYBE): Measurement of GHz radiation for ultra-high energy cosmic ray detection

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Abstract. We present measurements of microwave emission from an electron-beam induced air plasma performed at the 3 MeV electron Van de Graaff facility of the Argonne National Laboratory. Results include the emission spectrum between 1 and 15 GHz, the polarization of the microwave radiation and the scaling of the emitted power with respect to beam intensity. MAYBE measurements provide further insight on microwave emission from extensive air showers as a novel detection technique for Ultra-High Energy Cosmic Rays.

1. INTRODUCTION

With the confirmation of the strong suppression of the flux of Ultra-High Energy Cosmic Rays (UHECRs) by both HiRes and Auger [1, 2] it has become important to explore alternative techniques for detecting Extensive Air Showers (EAS) induced by UHECRs. Recent beam test measurements by Gorham et al. [3] found emission from air shower plasmas induced by an electron beam which had coherent scaling and a power flux that suggested it may be possible to detect UHECRs in the GHz frequency regime. An instrument based on microwave detection techniques built from modest, commercially sourced equipment would be suitable to detect the flux levels measured in [3]. This type of detector would be an analog of the successful fluorescence detection technique [4], observing the EAS development through the atmosphere at kilometer distances away from the EAS. A number of prototype GHz detectors have been deployed in an effort to search for GHz emission from EAS [5, 6]. The Microwave Air Yield Beam Experiment (MAYBE), a new test beam experiment, was performed in an effort to create air plasmas under laboratory conditions searching for an understanding of the microwave emission and energy scaling of EAS initiated air plasmas.

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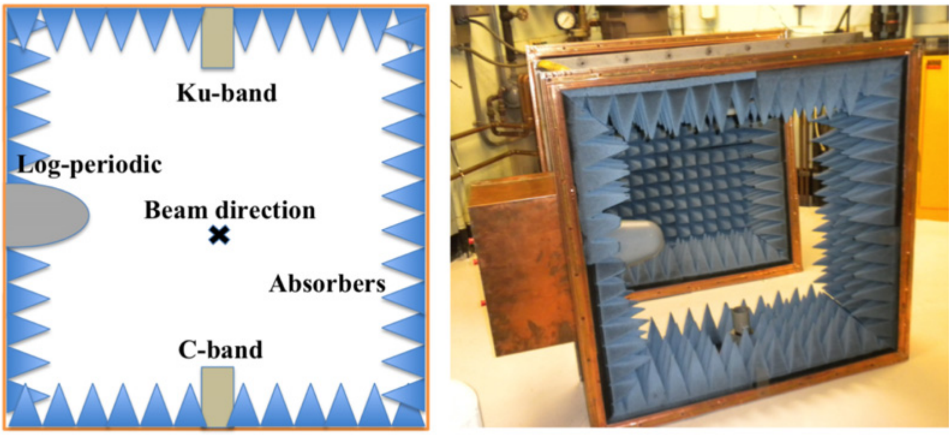

Figure 1. *Left*: layout of the antennas inside the chamber in a plane perpendicular to the beam direction. *Right*: picture of the central module of the chamber with the 3 installed antennas. The external copper box on the left accommodates part of the electronics such as the low noise amplifiers and the connectors to send the signal to data acquisition.

2. EXPERIMENTAL DESIGN

The experimental design of MAYBE is based around the electron beam produced by the Van de Graaff generator of the Chemistry division at Argonne National Lab [7]. The Van de Graaff beam can produce bunches of 3 MeV electrons that range in pulse length from 5 ns to milliseconds: for MAYBE we use pulse lengths of order 1 μs. We found the Van de Graaff generator to be particularly well-suited for MAYBE because the 3 MeV electron energy is below the threshold of Cherenkov radiation in air. This provides a measurement which is completely free of the very strong, polarized Cherenkov signal which was present in the beam test performed by Gorham et al. [3].

2.1 Anechoic chamber

The anechoic Faraday chamber used in the measurements of [3] was also used for MAYBE. The chamber is a one meter cubed copper shielded box lined internally with radio absorbers from AEMI inc., seen in Figure 1, providing at least 30 dB of RF attenuation above 1 GHz. It consists of three modules assembled together with shielded joints and filled with ambient air. The chamber stands on a hydraulic height-adjustable cart that allows 3 dimensional position adjustment relative to the exit of the beam pipe. The chamber has a circular port of 3 cm diameter to allow the entry of the collimated 3 MeV electron beam that otherwise would be strongly attenuated and scattered in the 1 mm thick front wall.

2.2 Receivers

Three different radio receivers were mounted inside the chamber to characterize the microwave emission in a broad frequency spectrum (see Fig. 1). The main receiver used for data taking was a Rohde & Schwarz (R&S) HL050 Log-Periodic Antenna (LPA). Due to its broad frequency response (0.85–26.5 GHz) this antenna is suitable to measure the microwave emission over a wide spectral range. The nominal gain of the antenna is at the level of 8.5 dBi and the polarization isolation is better than 30 dB in the frequency range of interest. The LPA is a single polarized receiver with measurements in both polarizations possible through a physical rotation of the antenna. This functionality has been designed into the LPA mount allowing for measurements which are cross polarized and co-polarized relative to the direction of electron beam travel through the chamber. During data taking the LPA was connected to three different Miteq low noise (0.4–0.9 dB noise figure) amplifiers with nominal frequency bands of 1–2 GHz, 4–8 GHz, and 8–12 GHz and minimum amplification gains of 45, 40, and 51 dB respectively (the gain flatness within the frequency band is better than 1.5 dB for all amplifiers). The amplifier gains have been tested in the laboratory and the combination of the three amplifiers have been found to be suitable to study the emission process in the frequency range from 1 to 15 GHz.

Additionally, two commercial Low Noise Block Feeds (LNBFs), one C-band (3.4–4.2 GHz) and one Ku-band (12.2–12.7 GHz) were used for cross-checking measurement consistency. These receivers can measure two orthogonal, linear (C-band) or circular (Ku-band), polarizations selected via input voltage. The LNBFs are single package feeds equipped with low noise amplifiers (58 dB of gain for C-Band and 50 dB of gain for Ku-band) and frequency downconverters with an output frequency range of $\sim$1–2 GHz, built into the device. All the antennas are located in a central plane perpendicular to the beam direction and pointing towards it so the distance from beam axis to the antenna is always $\sim$0.5 m.

Downconverted signals from C and Ku band antennas were transmitted to the control room through approximately 14 m of quad-shield RG-6 coaxial cable that has an average loss of 0.3 dB per meter in the frequency range of the transmitting signal ($\sim$1–2 GHz). The coaxial cable is also used to provide DC power to the feeds. A power inserter and a 75 to 50 Ohm impedance adapter are connected to the end of the cable to allow the RF signals from the antenna to pass to the data acquisition instrumentation. The LPA signal after amplification is directly transmitted for readout trough a high-frequency cable that is suitable for transmission up to 18 GHz. Losses from cable, adapters and connectors were properly evaluated and corrected for in measurements.

2.3 Data acquisition

The data acquisition for MAYBE was performed in both the time domain and frequency domain during the course of the experiment. Time domain measurements were taken with a Tektronix TDS6154C oscilloscope. This oscilloscope operates at 40 GS/s and has 15 GHz of analog bandwidth. The oscilloscope was triggered on the signal from a pick-up coil placed at the beam exit which was also used to monitor the beam intensity during data taking operations. Frequency domain measurements were taken using a R&S FSV 30 spectrum analyzer. Spectra were taken by providing a gating window on the signal pulse with a trigger from the pick-up coil. Data was collected in this way from 1 to 7 GHz in the frequency domain.

3. SIMULATIONS

GEANT4 [8] simulations reproducing the setup and running configurations were performed in order to characterize the energy deposition inside the chamber. The energy deposit in the chamber gives a quantitative estimate of the number of ionization electrons generated, its density and spatial distribution. The left panel of Figure 2 shows the energy deposit in the chamber as a function of both longitudinal z and transversal y (to the beam axis) directions (the distribution in x is symmetrical to the one in y) for a typical configuration containing a total of 2.5×10^9 electrons inside the chamber. The area selected to integrate the energy deposit is $1 \times 1\,\mathrm{cm}^2$. As is seen clearly in the left panel of Figure 2, the energy deposit is not uniformly distributed in the chamber but denser in a conical region centered in the beam trajectory with a radius increasing from a few mm to about 15 cm at the end of the chamber. The total energy deposit in the chamber for this particular conditions is $E_{\mathrm{dep}} = 5 \times 10^{14}$ eV. The right panel of Figure 2 shows the integrated energy deposit as a function of z and the corresponding density calculated in cylindrical slices of 1 cm thickness and radius of 15 cm where almost all the energy deposit is contained. This density, that increasing fast in the first portion of the chamber and then decreases to about half of its maximum, will be proportional to the ionization electron density. Assuming all the energy deposit is invested in ionization we obtain typical values for the ionization electron density of

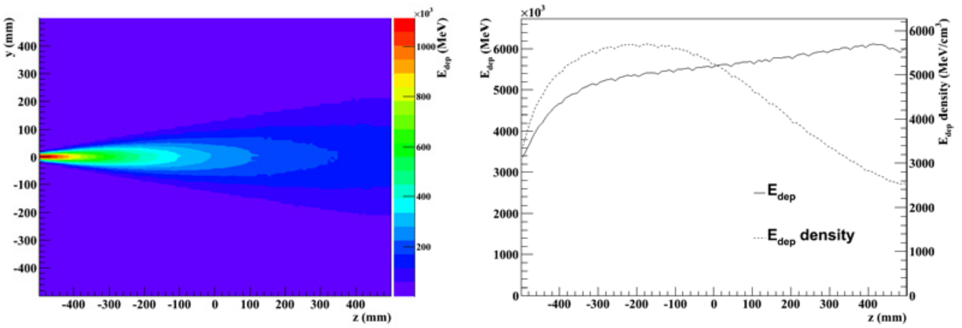

Figure 2. Results from GEANT4 simulations. *Left*: energy deposit inside the 1 m^3 chamber as a function of both longitudinal z and transversal y directions for a configuration containing a total of 2.5×10^9 electrons. *Right*: integrated energy deposit and its density along the beam axis.

$\sim 10^8$ electrons per cm^3 (typical values for the different beam configurations range from 2×10^8 to 4×10^9 e/cm^3).

The total energy deposit inside the chamber calculated over the number of electrons pulsed in 3ns will differ for the different running conditions between 10^{14} and 10^{16} eV. The measured signal comes from the contribution of electrons inside the chamber at a certain time that can be calculated from the time the electrons need to cross the 1 m long chamber. This amount of energy deposit is comparable to the total energy deposit in a 1 m length layer at the depth of maximum development by an extensive air shower originated by a cosmic ray of energy 10^{18}–10^{20} eV.

4. SPECTRUM

The measurement of the power spectrum for MAYBE is done using both the R&S spectrum analyzer directly taking data from 1 to 7 GHz. Pulse-to-pulse time jitter in the Van de Graaff made it impossible to use the spectrum analyzer above 7 GHz. The measurement using data averaged over many thousand pulses can be seen plotted in Figure 3 with cross polarized data shown as black squares and co-polarized data shown in red squares. Power spectrum analysis was also done using the time stream traces from the oscilloscope. Time traces were filtered using a Fourier analysis to select the frequency range of interest and power was calculated from the trace assuming a flat spectrum in the selected frequency band with RF power $P = \left(V^2_{rms,sig} - V^2_{rms,bkg}\right)/R$, where $V^2_{rms,sig}$ is the root mean square of the voltage in a signal time window and $V^2_{rms,bkg}$ is the root mean square of the voltage in a background time window of equivalent width before the signal trigger. R is the impedance of the system measured in the lab using a white noise source and identical analysis method.

The resulting total power spectrum is plotted in Figure 3 for both cross polarized and co-polarized configurations covering a frequency range of 3 to 15 GHz using two amplifiers. The power flux is measured by the acquisition system and plotted after removing total system gain which has been measured a posteriori for the full spectral range. Good agreement is seen between the three amplifiers used for the measurement and two different methods of measuring power. As is seen in Figure 3 we measure a continuum power spectrum over the entire range of 1 to 15 GHz with equivalent power fluxes for both cross polarized and co-polarized configurations. This is consistent with expectations for unpolarized isotropic emission. We believe the small deviations in the spectrum are likely due to the measurement set-up and not a feature of the emission. We are currently working towards a better understanding of these small systematics.

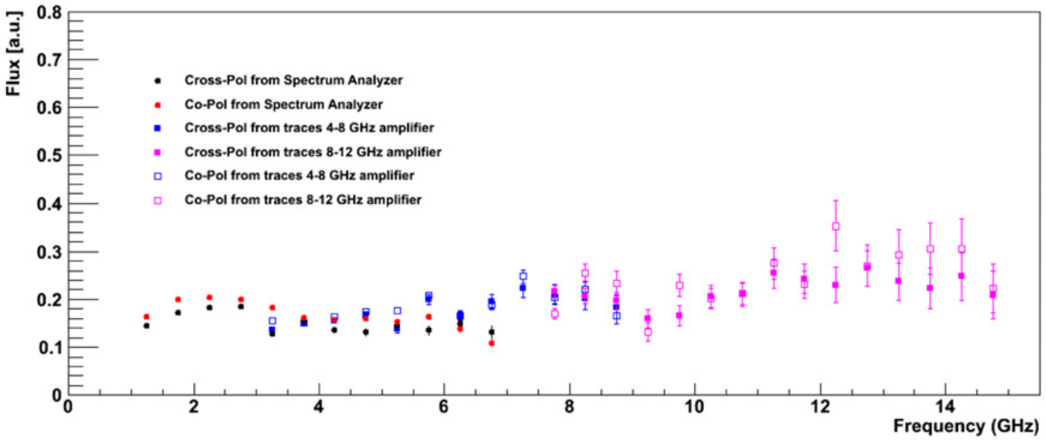

Figure 3. Frequency spectrum of the measured emission. Spectrum is measured using both time domain and frequency domain data. With the red and black points corresponding to data taken with spectrum analyzer, the blue and magenta points are data taken with the oscilloscope. Power flux is corrected for system gain measured in the laboratory.

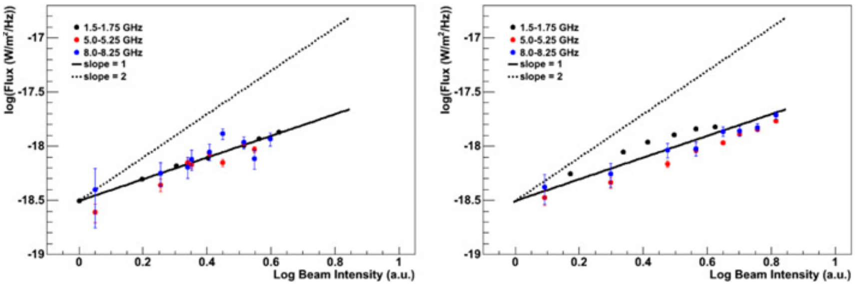

Figure 4. Measured power flux as a function of beam energy for different frequency bandwidths. Lines with slopes 1 and 2 are also shown for comparison. *Left*: cross polarization. *Right*: co-polarization.

5. ENERGY SCALING

A scan in deposited energy was made by varying the beam current of the Van de Graaff. This changes the instantaneous number of electrons in the beam which in turn changes the energy deposit in the chamber. This scan makes it possible measure the emission scaling with energy deposit. Data was taken with all three of the low noise amplifiers in different frequency bands and in both cross polarized and co-polarized configurations. The beam intensity was monitored with the pick-up coil at the beam exit and a power analysis like that performed for the power spectrum measurements was performed.

The resulting data from the energy scan is plotted in Figure 4. It is clearly seen that the signal level is consistent in both polarizations and between amplifiers. In both polarizations we have measured a signal which is increasing linearly with energy deposit.

6. CONCLUSION

We have measured a microwave emission signal from electron beam induced air plasma between 1 and 15 GHz. This emission is unpolarized and isotropic with a broadband continuum spectrum. This is consistent with predictions of EAS induced molecular Bremsstrahlung emission. We measure a linear scaling with energy deposit which is inconsistent with previous beam test measurements performed by Gorham et al. [3]. Our preliminary power estimates for a reference air shower of 3.36×10^{17} eV are also significantly lower than the value measured in [3], however, analysis is ongoing of the measurement systematics and the differences between the two beams and the plasma produced in an EAS. The Air Microwave Yield (AMY) experiment, another beam test experiment is also being performed at the Frascati linear accelerator. AMY aims to use a higher energy beam with shorter pulse lengths similar to that of [3] which will introduce a different set of systematics, details can be found in Verzi et al. [9]. Ultimately, only through a coincidence detection or robust null result at a cosmic ray observatory will this mechanism of emission be understood in full and tested as a viable technique for studying UHECRs.

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