PROPOSAL FOR A NEW EXPERIMENT TO THE INFN COMMITTEE V

AMY: Air Microwave Yield

D. Badoni, **F. Bracci**, **G. Salina** and **V. Verzi**

Dipartimento di Fisica, Università di Roma II "Tor Vergata"
and Sezione INFN, Roma, Italy

G. Cataldi, **M. R. Coluccia** and **P. Creti**

Dipartimento di Fisica, Università del Salento
and Sezione INFN, Lecce, Italy

P. Di Carlo, **C. Di Giulio**, **S. Petrera** and **V. Rizi**

Dipartimento di Fisica, Università dell'Aquila
and sezione INFN, l'Aquila, Italy

other groups not associated to INFN partecipating to the project

P. Facal San Luis and **P. Privitera**

University of Chicago, Enrico Fermi Institute &
Kavli Institute for Cosmological Physics, Chicago, USA

J. Alvarez-Muniz and **G. Rodriguez Fernandez**

Depto. de Fisica de Particulas, Universidad de Santiago de Compostela,
Santiago de Compostela, Spain

Abstract

In this paper we propose an experiment to measure and characterize the microwave emission from air shower plasmas. The aim is to obtain an absolute calibration of the process and to measure the spectrum in the frequency range between 1 and 25 GHz. The measurement will be performed at the Beam Test Facility (BTF) of the Laboratori Nazionali di Frascati.

July 2010

1 Introduction

The Pierre Auger Observatory is the largest experimental facility to study ultrahigh energy cosmic rays (UHECR). The Southern Observatory [1] is fully operational and it is located near the town of Malargüe in the province of Mendoza (Argentina). The Northern Observatory [2] will be built in the coming years near the town of Lamar in Colorado (USA).

In order to minimize systematic uncertainties, the Observatory is an hybrid system, a combination of a fluorescence detector (FD) and a large surface array of water Cherenkov detectors (SD). The FD measures the fluorescence light emitted by the de-excitation of atmospheric nitrogen while the SD measures the atmospheric shower size at ground. The two detectors are complementary. With the FD data, the full shower longitudinal profile is reconstructed, providing a calorimetric measurement of the cosmic ray energy. The small FD duty cycle ($\sim$ 10% limited to clear, moonless nights) is compensated by the high statistics of the SD data (100% duty cycle). The shower size at ground measured by the SD is converted into cosmic ray energy using the FD measurements. This energy calibration is done analysing the sub-sample of hybrid showers, i.e. showers simultaneously detected by both FD and SD.

Recently, the observation of a microwave continuum emission from air shower plasmas [3] has raised the interest in a possible new technique for detection of cosmic-ray extensive air showers that may be able to provide a full longitudinal profile measurement (like an FD) with a 100% duty cycle (like an SD). The plasma is created after the release of the energy of the shower onto the atmosphere and it is made by electrons of temperature of about 10^5 K. The cooling process of the plasma holds over a time scale of 1-10 ns and it cames mainly via the excitation of the medium. However, a small part of the plasma energy can be released through bremsstrahlung emission in the collisions of the electrons with the neutral molecules [3] of the atmosphere. The emitted radiation is in the microwave band and it is expected to be isotropic and proportional to the shower energy deposit. This properties of the microwave molecular bremsstrahlung radiation (MBR) open the possibility to develop a radio telescope which is able to reconstruct the full shower longitudinal development and to provide a calorimetric measurement of the shower energy. In comparison to the fluorescence telescopes, the MBR detection technique would have the fundamental advantage of a 100% duty cycle. Moreover, it does not need a program of atmospheric monitoring. In fact the microwave radiation is not significantly attenuated over distances of several tens of kilometers [4].

Currently there are two projects developing a telescope for MBR: AMBER [3] and MIDAS [5]. The working principle is very similar to an FD: both prototypes consist in a dish focusing the radiation over a matrix of feeds with the signal being sampled in time via a Flash ADC. The prototypes are taking data in the area near the laboratories where they were built. Several shower candidates have been found but, the big uncertainties connected to a new detection technique suggest that would be safer to confirm the results observing showers in coincidence with a conventional detector. The Collaboration Board of the Pierre Auger Observatory has approved the installation of both telescopes in the Southern site. The installation will be carried out in the next year.

There is another project under development, EASIER [6], that aims to install antennas detecting MBR on the SD tanks of the Auger Observatory. The EASIER antennas will complement the SD data providing information on the shower longitudinal profile.

Given the increasing interest on the possibility to use MBR to detect atmospheric air showers, we propose a test beam to study in detail the emission process. With the AMY (Air Microwave Yield) project we plan to measure the MBR absolute yield and its spectrum in a wide frequency range. This would improve significantly the current knowledge of the MBR and will help the design of new extensive air showers detectors.

2 The physics program

The microwave continuum emission from air shower plasmas has been observed in a test beam performed at Argonne Wakefield Accelerator laboratory and subsequently at the Stanford Linear Accelerator Center (SLAC) [3]. In the test at SLAC, a 28 GeV electron beam was collided with a target to make showers with varying particle number. The showers entered an air-filled ~ 1 m^3 copper anechoic Faraday chamber which prevented interference from outside electromagnetic radiation. A log periodic antenna operating in the $1.5 \div 6.0$ GHz band was mounted on the inside of the chamber and was connected to a digital oscilloscope to measure the subsequent radio emission.

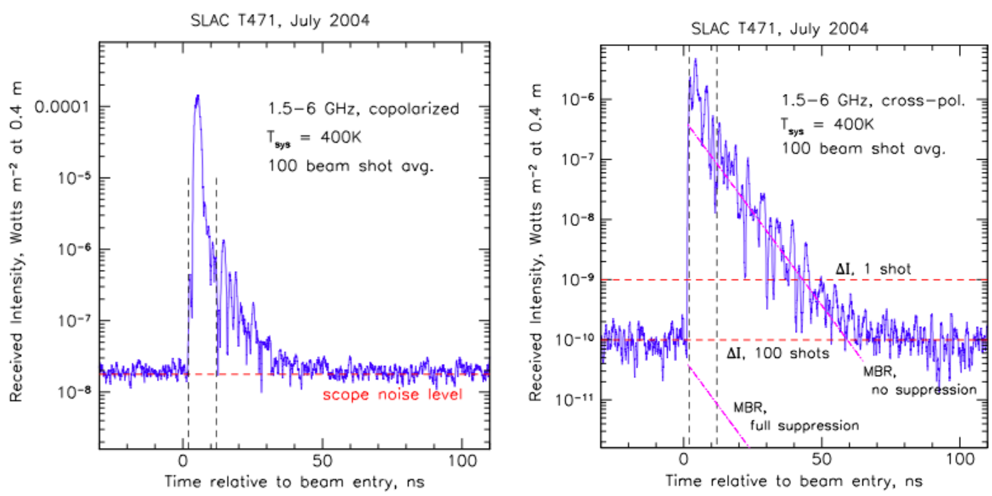

Figure 1: Microwave emission meaured at SLAC [3]. The plot on the left was obtained using an antenna copolarized with the beam axis. In this way the antenna was sensitive to the strong and fast radiation produced directly from the relativistic electrons (Cherenkov and transition radiation produced at the entrance of the Faraday chamber). Using an antenna cross-polarized with the beam axis the strong peak disappeared as shown in the right figure.

Figure 1 shows the measured signal as a function of the time relative to the beam entry in the chamber. In the left figure the signal was measured using an antenna copolarized with the beam axis. In this way the antenna was sensitive to the strong and fast radiation produced directly from the relativistic electrons (Cherenkov and transition radiation produced at the entrance of the Faraday chamber). The right figure shows the measurement obtained with an antenna cross-polarized with the beam axis. The strong and fast peak disappears and the remaining signal is interpreted as MBR. The signal was found to decay exponentially with $\tau \sim 10$ ns and to scale with the square of the beam energy, indicating that the coherent portion of the emission dominates completely over incoherent emission.

The merit of the Argonne/SLAC measurements is to have proved the existence of a microwave radiation emission when the air is ionized by shower particles. However, there is only an indication of what the MBR flux density can be and, for example, the emission dependence with the wavelength has not been studied.

The main objective of AMY is to make a precise measurement of the MBR absolute yield and to study the spectrum in frequency in the wide band between 1 and 25 GHz. The knowledge of the absolute yield is necessary to understand the feasibility and the best way to design an air shower detector. A detailed knowledge of the spectrum is also very important. In addition to the continuum bremsstrahlung emission, other processes can cause the production of microwave radiation. If bright spectral lines are found, the frequency band of an extensive air shower detector can be restricted around this lines in order to maximize the signal to noise ratio. Otherwise one can restrict the detection to the satellite television bands, in order to benefit of the low cost of commercial instrumentation. With AMY we also plan to verify the exponential decay in time of the signal and we will study the degree of coherence of the radiation.

The test beam will be performed at the DAFNE Beam-Test Facility (BTF) of the Laboratori Nazionali di Frascati. Here, up to 10^{10} electrons in the energy range between 25 and 750 MeV are provided in bunches with a maximum repetition rate of 50 Hz. As we will see below, with this beam we expect an MBR flux at least a factor 10 larger than the one observed in the previous tests.

3 Detector design

As in the previous test beams the MBR radiation will be measured inside an air-filled copper Faraday chamber whose interior walls will be covered with an RF absorber. We foresee to use two antennas. One will be directly connected to a spectrum analyzer and it will measure the spectrum in frequency. The other one will be read by a fast flash ADC in order to measure the signal behaviour in time.

The absolute calibration of the process will be obtained with the spectrum analyzer. This type of devices are calibrated to give directly the detected power as a function of the frequency. An absolute flux density can be easily obtained knowing the antenna gain and the chamber geometry.

3.1 The anechoic Faraday chamber

As already said, the chamber must satisfy two fundamental requirements: it must screen the electromagnetic radiation present in the test beam area and it must prevent reflections in its internal walls (otherwise it is impossible to calculate the antenna acceptance). For these reasons we need an anechoic Faraday box: its external walls will be covered by copper connected to the ground while the internal walls will be covered by RF absorbers.

There are several types of RF absorbers. The so called AEP series provide an excellent absorption over a wide frequency band up to 20 GHz. They have a pyramidal shape and their height defines the lowest frequency at which the absorption is guaranteed. For example with the AEP-18 model the pyramid height is 18 in (45 cm) and absorption ranges from 30 dB at 0.5 GHz to 45 dB at 3 GHz. At higher frequencies it is 50 dB. With the AEP-12 model the height is 12 in (30 cm) and absorption ranges from 35 dB at 1 GHz to 45 dB at 6 GHz. Also for this model the absorption is 50 dB at higher frequencies.

An anechoic chamber works better when it is large. Its dimensions are clearly constrained by the space available in the BTF area. The beam height from the floor is 124,5 cm and it would be better to have a beam crossing the middle of the box. So the maximum available height (H) is about 2 m and, for symmetry reasons, we prefer to have the width (D) equal to the height. Even if desirable for practical reasons, we cannot significantly reduce such dimensions. In fact, we have seen that RF absorbers working in a wide frequency band have dimensions typically larger than 30 cm. The heigth of the antenna that we plan to use is also about 30 cm, therefore, for a 2 m box, the effective distance of the antenna to the beam is about 70 cm. Considering that, at 5 GHz the wavelength is 6 cm, we cannot decrease significantly the box dimension if we want to guarantee the far field approximation, condition for which the antenna patterns are well known.

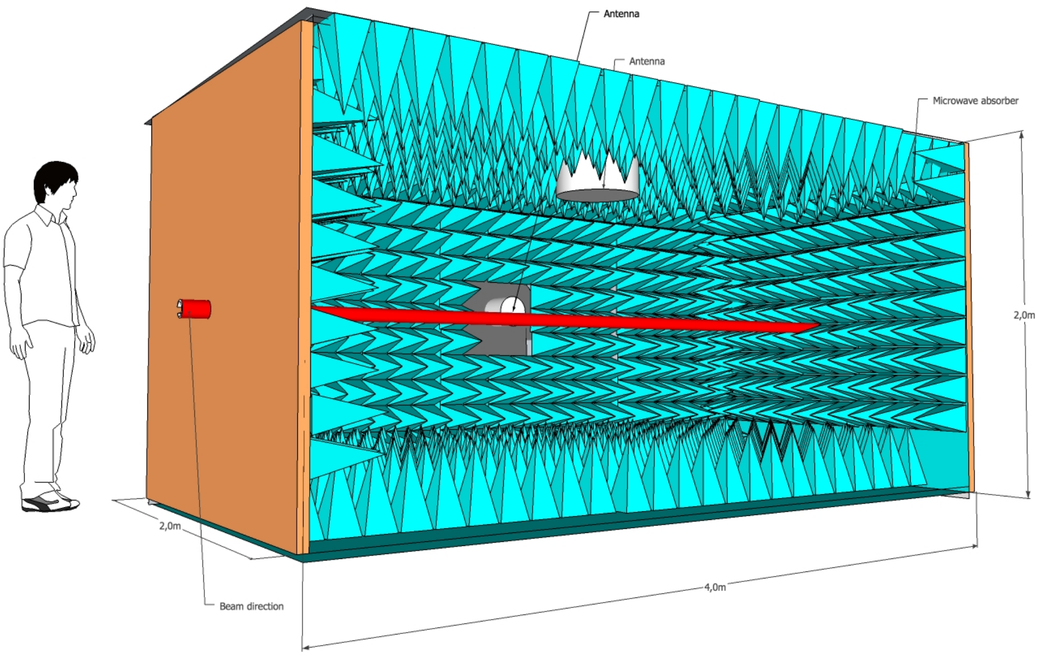

Figure 2: Sketch of the AMY camera.

A reasonable criteria to fix the chamber lenght (L) is to avoid the antenna seen the entrance and exit walls. In fact, transition radiation is produced at entrance point and almost all Cherenkov radiation is firing a region around the exit point. For a typical half power beam width of $\theta_{HP} = 60°$ the condition would be:

$$L > 2D \tan \frac{\theta_{HP}}{2} \simeq 2.3 \text{ m}$$

The available space in the BTF area is about 5 m, so we can foresee a box whose lenght is between 3 and 4 m. Figure 2 shows a sketch of a camera with H=D=2 m and L=4 m.

3.2 The antenna

In order to allow a precise absolute calibration of the microwave emission process, the antenna must have patterns with lobes of regular shape and preferably a flat gain over the wide frequency band between 1 and 25 GHz.

The Rohde & Schwarz HL050 is a log-periodic antenna satisfying all those requirements. Figure 3 shows that the gain is about 8.5 dB and it remains constant within few %. The same figure shows the pattern. It is very regular, almost symmetric under rotation, with very small sidelobes and it does not change significantly in the full frequency range. The half power beam width θ_{HP} ranges from 65° at 1 GHz to 55° at 25 GHz. Notice that the radiation pattern follows approximatively the $(\cos\theta)^2$ functional form.

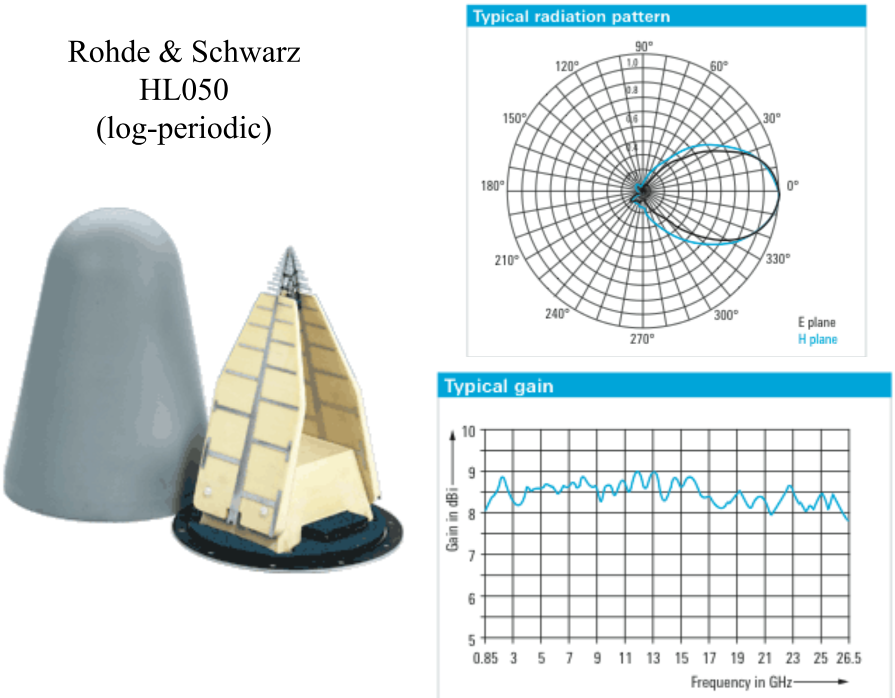

Figure 3: Rohde & Schwarz HL050 log-periodic antenna.

In next section we will calculate the expected MBR signal and for that we will need the antenna effective aperture

$$A_e = \frac{\lambda^2}{\Omega_A}$$

where Ω_A is the beam area. As a first approximation, it is given by

$$\Omega_A \simeq \theta_{HP}^2$$

Assuming $\theta_{HP} = 65°$ one has

$$A_e = \frac{7\ 10^{-2}}{\nu^2[\mathrm{GHz}]}\ \mathrm{m}^2$$

Finally we notice that the HL050 antenna can be provided with broadband and low-noise preamplifier of gain > 27 dB. A control unit allowing to bypass the amplification is also available.

3.3 Expected radiation flux density

Like in the previous test beam, at the BTF we plan to use alumina target in order to increase the energy deposit within the camera. At SLAC, the measured flux density at the antenna corresponding to maximum shower development was

$$I_{SLAC} = 4\ 10^{-16}\ \mathrm{W/m^2/Hz}$$

We have simulated the beam interaction with the alumina target and we have verified that the energy deposit in air corresponding to the maximum shower development scales with the product of the electron beam energy (E) and the number of particles per bunch (N). Therefore, assuming that the intensity of the microwave emission scales with the energy deposit, we can extrapolate the SLAC measurement to obtain the expected signal at the BTF:

$$I_{BTF} \propto I_{SLAC} \left(\frac{N_{BTF} E_{BTF}}{N_{SLAC} E_{SLAC}} \right)^{\alpha}$$

where α can range between 1 and 2 depending by the degree of radiation coherence.

The values for the two test beams are

$$\begin{aligned} N_{SLAC} \times E_{SLAC} = 1.2\ 10^7 \mathrm{e^-/bunch} \times 28\ \mathrm{GeV} &= 3.36\ 10^{17}\ \mathrm{eV} \\ N_{BTF} \times E_{BTF} = 10^{10} \mathrm{e^-/bunch} \times 700\ \mathrm{MeV} &= 7\ 10^{18}\ \mathrm{eV} \end{aligned}$$

and then, the expected gain in signal using the BTF beam is a factor between 20 ($\alpha = 1$) and 400 ($\alpha = 2$).

In addition to the beam energy, the flux density depends also by the antenna-beam distance (R) and by the antenna patterns. Seeing that the microwave emission is isotropic, the flux scales as $1/R^2$. At SLAC was $R_{SLAC} = 0.5$ m while in the BTF we will have $R_{BTF} \sim 1$ m. In addition, since the antenna does not see the full shower lenght over 1 electron folding decay time (3 m), the signal scales with the observed shower lenght (L) [3]. As a first approximation, L can be estimated from the half beam width of the antenna

$$L_{BTF} \simeq 2 R_{BTF}\ \tan \frac{\theta_{HP}}{2} \simeq 1.3\ \mathrm{m}$$

which is a factor 2 larger than the SLAC value ($L_{SLAC} = 0.65$ m).

Considering all above factors, the expected flux density at the BTF is

$$I_{BTF} = I_{SLAC}\ \left(\frac{N_{BTF} E_{BTF}}{N_{SLAC} E_{SLAC}} \right)^{\alpha} \left(\frac{R_{SLAC}}{R_{BTF}} \right)^2 \frac{L_{BTF}}{L_{SLAC}} \sim 10 \div 200\ I_{SLAC}$$

depending by the degree of radiation coherence. We notice that these intensities have been obtained at the maximum shower development. Figure 4 shows the expected flux density as a function of the thickness of the alumina target.

We finally notice that the SLAC measurements demostrate that the signal scales quadratically with the beam energy. However the BTF beam conditions are different and we cannot have the confidence that the same kind of scaling will happen going from the SLAC to the BTF beam. We prefer to be cautious and, in the next sections, we will demonstrate the feasibility of our project also in the worst case of a linear scaling.

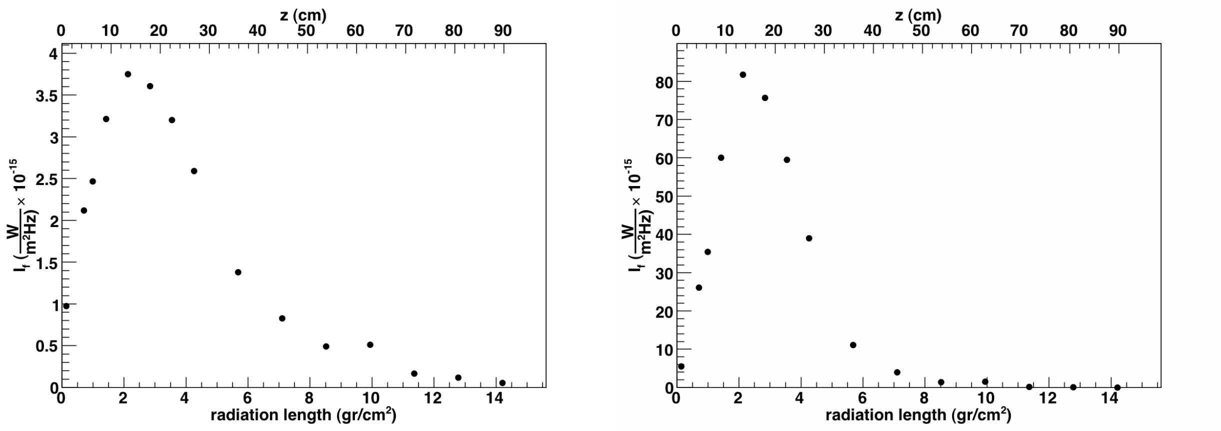

Figure 4: Expected flux density at the BTF as a function of the thickness of the alumina target and the corresponding radiation lenght. The flux has been calculated in the two cases of incoherent (plot on the left) and coherent (plot on the right) emission.

3.4 Expected signal in the spectrum analyzer

We plan to read the signal of the log-periodic antenna Rohde & Schwarz HL050 using a spectrum analyzer. In the calculation of the expected signal we have neglected the attenuation of the signal in the cable because we foresee to keep the spectrum analyzer within the BTF hall close to the camera and to read it via a network connection.

The expected signal is

$$S = I_{BTF} A_e \Delta f$$

where Δf is the resolution bandwidth of the spectrum analyzer.

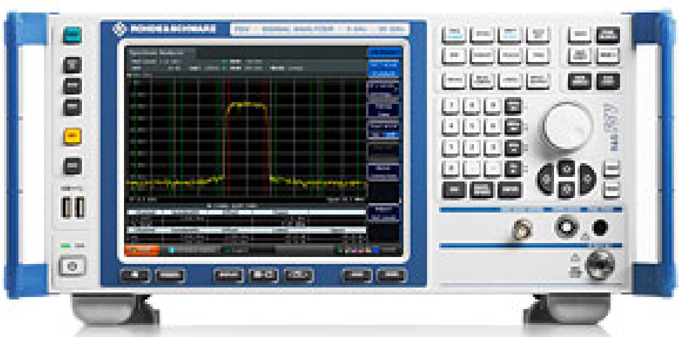

Figure 5: Rohde & Schwarz FSV signal and spectrum analyzer series. Frequency range up to 40 GHz and analysis bandwidth up to 40 MHz.

Rohde and Schwarz provides a wide choice of spectrum analyzers in the frequency range of interest. The largest bandwidth available is 40 MHz but they are very expensive. We will calculate the expected signal using a more common bandwidth of 10 MHz.

Assuming a linear scaling of the signal and using the effective aperture of the Rohde

& Schwarz HL050 antenna one has

$$S = \frac{28\ 10^{-10}}{(\nu[\mathrm{GHz}])^2}\ \mathrm{W}$$

that is

$$\begin{aligned} 5\ \mathrm{GHz} : S = 10^{-10}\ \mathrm{W} \quad &\rightarrow \quad -70\ \mathrm{dBm} \\ 20\ \mathrm{GHz} : S = 7\ 10^{-12}\ \mathrm{W} \quad &\rightarrow \quad -80\ \mathrm{dBm} \end{aligned}$$

where dBm refers to decibel of mW. Notice that in case of a quadratic scaling we gain 13 dBm.

The feasibility of the measurements depends on the background level

$$B = \frac{KT}{A_e\sqrt{\Delta f \Delta t}}$$

where T is the system temperature. T will depend by many factors (e.g. spectrum analyzer, antenna, cables, radiation in the hall) and to keep it small, it is very important that the Faraday box works properly. It is diffucult to predict the correct T value without measuring it directly in the experimental environment. Following [3] we can assume T at the level of 500-600 K.

Δt is the sampling time of the instrument, i.e. the lenght of the trigger gate. Considering only one bunch, one may have $\Delta t = 100$ ns. Therefore

$$B \simeq 10^{-17}\ \mathrm{W/m^2/Hz}$$

which is at least 2÷3 orders of magnitude smaller than the flux density I_{BTF}. At the level of signal in spectrum analyzer this means -100 dBm. Notice that averaging the signal over more beam bunches, the background can be further reduced.

In case of an higher backround, we can increase the signal to noise ratio using a pre-amplifier at the output of the antenna (as commonly done in RF measurements). The model ZVA-213+ of the Mini-Circuits company provides a 26 dB gain in the wide band of interest.

We notice the semplicity of the instrumentations needed to measure the spectrum in frequency. In fact we will not use filters band, frequencies shifter, etc. which may complicate the interpretation of the data. In this way we are confident that a spectrum analyzer will also allow to obtain a precise measurement of the MBR absolute yield.

3.5 Measuring the time structure of the signal

With the measurement of the signal as a function of the time (relative to the beam entry in the camera) we plan to verify the exponential decay with $\tau \simeq 10$ ns observed in [3]. The time measurement is also important to monitor the behaviour of the RF absorber. In fact, an unexpected long tail would signal that multiple reflections occur within the camera.

In [3] the signal as a function of the time was measured with an oscilloscope with a very high bandwidth. Maybe, this is the easiest way to see the signal with very high accuracy, but we should also consider the high cost of such oscilloscopes. In order to keep the project cost acceptable, we are evaluating the use of a power detector read-out by a flash ADC. Another advantage of this choice is the DAQ flexibility provided by a VME system. We want to install detectors monitoring the beam conditions and with a VME system it will be possible to study the MBR-beam correlation at the bunch level.

Many companies provide analog to digital converters working at the ns level. We have experience with the model SIS3350 of the Struck Innovative Systems. It is a 12 bit 4 channels FADC working with a sampling rate up to 500 MS/s.

Finding a power detector with a time resolution at the ns level is not easy. Fast detectors are produced by the Analog Device company. They provide a series of logarithmic detectors with a wide bandwidth and high dynamic range. For example the model AD8318 (AD8317) can detect signals up to 8 GHz (10 GHz) with a 70 dB (55 dB) dynamic range. Figure 6 shows the response of the AD8318 model. The rise time of the output signal between the two conditions of no and maximum input signal is at the level of 10 ns. Notice that 10 ns are over a 70 dB dynamic range. In a more realistic situation, in which we detect signal variations of few dB, the time response should be better. Of course the effective time resolution achievable has to be studied in laboratory.

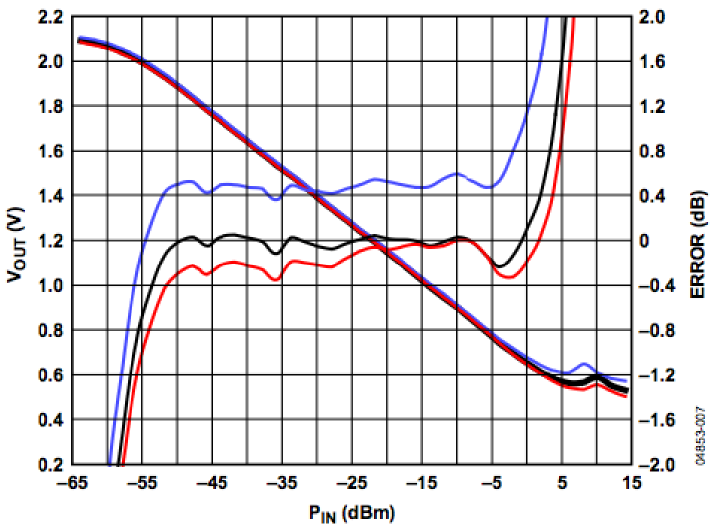

Figure 6: Typical response of the AD8318 logarithmic power detector of the Analog Device at 5.8 GHz. P_{IN} is the input power and V_{OUT} is the tension in the output.

The typical minimum input power of such log-detectors is not so low, at the level of -60 dBm, that have to compared with the signal given by the flux density expected at the BTF. Using the Rohde & Schwarz log-periodic antenna to detect the radiation up to 10 GHz (the bandwidth of the power detector) the signal corresponding to the maximum peak intensity is -45 dBm in case of linear scaling and -32 dBm for the quadratic scaling. Of course, being limited by the -60 dBm detectable signal, it will be not possible to measure the exponential decay over a 40 dB dynamic range. For that, we would need an RF amplifier where the typical gain is at the level of 20÷30 dB.

Another possible and cheap solution is to use a commericial LNBF as receiver. For example MIDAS uses the DMX241 feed manufactured by *WS International*. It works in the C band (3.4÷4.2 GHz), performs a down conversion in frequency (with an intermidiate frequency output between 950 and 1750 MHz) and has an amplifier with a 70 dB gain. The smaller bandwidth will be clearly compensated by the high gain. Reading these receivers with a power detector, a dynamic range even larger than 40 dB will be achievable.

We are evaluating other possibilities. Ideally we would like to measure the signal vs time in different frequency bands in the range between 1 and 25 GHz. For example we can use several narrow filters to select different small frequency bands and a broadband down converter to shift the frequency at lower values, where the amplification is easier. In general the problem of measuring the RF signals over a wide frequency band is the high cost of the instrumentation.

We feel that the LNBF solution is a good compromise for a first test beam. After an accurate measurement with the spectrum analyzer, we can restrict the time measurements to the frequency bands that we find to be more interesting.

3.6 Costs

In this section we list the equipment and their costs needed for our experiment. Some instrumentation has been described in previos sections. In addition to that we need a microwave signal generator and an extra log-periodic antenna for calibration purposes.

The table shows the list of the equipment needed and their costs based on company quotations.

device	**model**	**price**
Faraday chamber	assemblage in the university	3 k€
	copper	2.5 k€
	SATIMO RF adsorber AEP12	11 k€
	other (chassis, supports, etc.)	3 k€
	total cost	19.5 k€
Spectrum analyzer	Rohde & Schwarz FSV30, 9 kHz - 30 GHz	32.1 k€
	extension to 40 MHz bandwidth (FSV-B70)	7.2 k€
	external generator control (FSV-B10)	0.52 k€
	additional input/output ports (FSV-B5)	0.48 k€
	precision frequency reference (FSV-B4)	1.82 k€
	spectrogram measurement applicatione (FSV-K14)	1.25 k€
	total cost	43.37 k€
Signal generator	Rohde & Schwarz SMA100A, 1 GHz - 22 GHz	18.6 k€
	precision frequency reference (SMF-B1)	0.87 k€
	removable GPIB (SMF-B83)	0.77 k€
	narrow pulse modulation (SMF-K3)	3.1 k€
	pulse generator (SMF-K23)	0.87 k€
	total cost	24.21 k€
2 Log-peridoc antennas	HL050	2×4.2 k€
2 amplifiers	ZVA-213-S+	2 ×1.5 k€
Power detector	Analog device AD8318	< 0.5 k€
FADC	Struck Innovative Systems SIS3350	10 k€
VME-cpu	GE Intelligent Platforms V7865	5 k€
Other accessories	cables/connectors/feed etc	1÷2 k€

References

[1] J.Abraham *et al.*, *Properties and performance of the prototype instrument for the Pierre Auger Observatory*, Nucl. Instrum. Meth. A523 (2004) 50.

[2] J.Abraham *et al.*, *The Northern Site of the Pierre Auger Observatory*, New Jour. of Phys. 12 (2010) 035001.

[3] P.W. Gorham *et al.*, *Observations of microwave continuum emission from air shower plasmas*, Phys. Rev. D 78, 032007 (2008).

[4] J.D. Kraus and R.J.Marhefka, *Antennas for All Applications*, McGRAW-HILL (2003).

[5] P.Facal *et al.*, *The MIDAS experiment: MIcrowave Detection of Air Showers*

[6] A.Letessier-Selvon *et al.*, *EASIER* Presentation to the March 2010 Pierre Auger collaporation meeting.