Measurement of air fluorescence light yield induced by an electromagnetic shower

P. Colin [a d 1], A. Chukanov [b], V. Grebenyuk [b], D. Naumov [b], P. Nédélec [a], Yu. Nefedov [b], A. Onofre [c], S. Porokhovoi [b], B. Sabirov, [b] L. Tkatchev [b]

The MACFLY Collaboration:

[a] *Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3/CNRS, Université de Savoie, Annecy-le-Vieux, FRANCE*

[b] *Joint Institute for Nuclear Research Dubna, Moscow region, RUSSIA*

[c] *Laboratorio de Instrumentação e Fisica Experimental de Particulas Coimbra, PORTUGAL*

[d] *Now at the Department of Physics, University of Utah Salt-Lake-City, Utah, USA*

Abstract

For most of the Ultra High Energy Cosmic Ray (UHECR) experiments and projects (HiRes, AUGER, TA, JEM-EUSO, TUS,...), the detection technique of Extensive Air Showers (EAS) is based, at least, on the measurement of the air fluorescence induced signal. The knowledge of the Fluorescence Light Yield (FLY) is of paramount importance for the UHECR energy reconstruction. The MACFLY experiment was designed to perform such FLY measurements. In this paper we will present the results of dry air FLY induced by 50 GeV electromagnetic showers as a function of shower age and as a function of the pressure. The experiment was performed at CERN using an SPS electron test beam line. It is shown that the FLY is proportional to deposited energy in air (E_d) and that the ratio FLY/E_d and its pressure dependence remain constant independently of shower age and more generally independently of the excitation source used (single electron track or air shower).

[1] contact address: colin@physics.utah.edu

1 Introduction

The physics of Ultra High Energy Cosmic Rays (UHECR) is one of the most challenging research in the field of astroparticle physics. There are many questions about their spectrum, their origin and their propagation in space at energies around 10^{20} eV where the GZK effect (1) is predicted.

Most of the past, current and future experiments: HiRes (2), Pierre Auger Observatory (3), Telescope Array (4), OWL (5), EUSO/JEM-EUSO (6), TUS (7), are looking for air fluorescence signal to detect and measure Extensive Air Showers (EAS). This light, observed in the near-UV region (~300-400 nm), is induced by the de-excitation of the air molecules (mainly N_2) occurring along the shower development of EAS.

Since the 60's, when the use of EAS fluorescence light yield for the UHECR's detection was first proposed, the FLY is a subject of extensive laboratory measurements. In 1967, A. N. Bunner summarized the existing data in his thesis (8) and proposed a FLY model with an uncertainty estimated at ~30 %. In spite of electron beam based measurements of Kakimoto et al. in 1996 (9) and Nagano et al. in 2003 (10), the uncertainties are still large inducing important systematics to UHECR experiments.

The controversy and discrepancy between the AGASA (11) and HiRes (2) experiments lead the community to pursue its effort to improve the knowledge of the air FLY and of its dependencies with pressure, temperature, humidity, electron energy, shower age, etc. Since 2002, a dozen of new experiments were proposed and took data [2].

The MACFLY - Measurement of Air Cherenkov and Fluorescence Light Yield - experiment has been designed to measure both the light induced by single electron track and by a high energy electromagnetic shower developing in air (14). The experiment is composed of two devices - MF1 which measures the fluorescence produced by a single track and MF2 which measures the fluorescence induced by an electromagnetic shower. The MF1 device results obtained with different electron energies (1.5 MeV, 20 GeV and 50 GeV) and an air fluorescence light yield model are discussed elsewhere (15).

In this paper, we will focus on the air FLY measurements performed with the MF2 chamber at the CERN SPS-X5 electron test beam line with 50 GeV electromagnetic showers. We will compare this measurements with the predictions obtained from Monte-Carlo simulation of shower development where the FLY model, based on MF1 results, was implemented.

[2] An overview of the FLY experiments presented at the third workshop on air fluorescence - IWFM05 (12) should be found in (13).

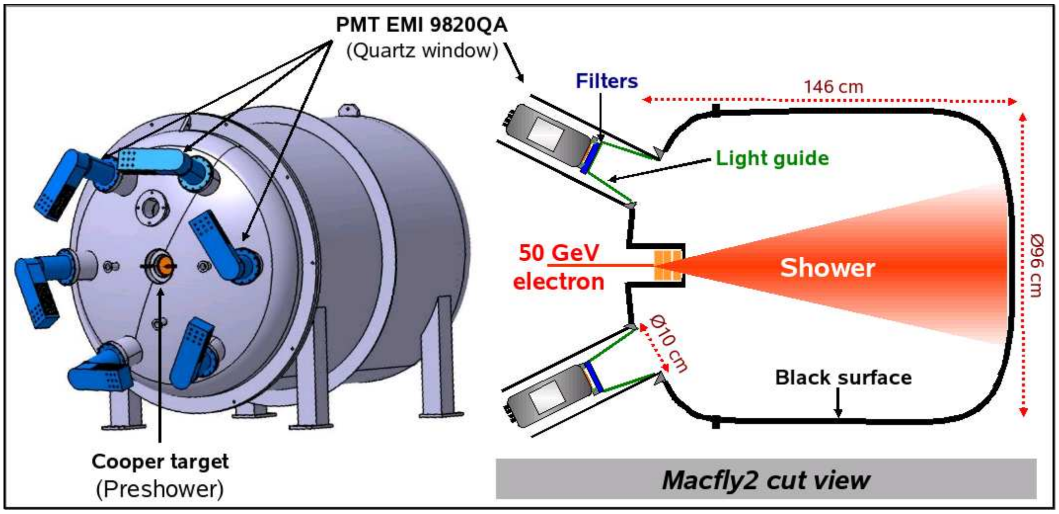

Fig. 1. The MF2 chamber: schematic view (left) and cut view (right).

2 Experimental setup

The MF2 device is composed of an internally black covered quasi cylindrical (960 mm in diameter and 1460 mm long), large volume ($\sim 1\ m^3$), pressurized tank containing the gas under study (see figure 1). The electron beam, aligned with the axial symmetry axis of the chamber, is impinging on a pre-shower target. This variable thickness pre-shower system, is used to initiates electromagnetic showers inside the chamber. It is installed on the beam line, downstream the chamber, in a recess at 150 mm inside the chamber, after the entrance wall of the tank (end-cap).

An optical system collects the fluorescence light produced by the excited air contained in the tank, and focusses it on six UV sensitive phototubes (PMT) EMI9820QA. Theses PMTs are installed on the entrance end-cap on a 350 mm radius circle centered on the beam line. They are watching the gas volume with an axis making a 20.5^o angle with respect to the beam-chamber axis. The optical system is also composed of Winston cones and of different colored glass filters. The PMTs are separated from the inner volume by tight quartz windows. The result presented in this paper corresponds to the measurements performed using the Schott BG3 filters, with a large transmittance band (290-440 nm), which were also used for the MF1 measurements (15).

A external gas system allows to fill the chamber with the desired gas mixture, at a specific pressure. The chamber is equipped with pressure and temperature gauges to control both parameters during the data taking. In this paper we measure the FLY for the following gas mixture: N_2-80% and O_2-20%. This composition is close to the atmospheric dry air which is an admixture: 78.08%(N_2)-0.93%(Ar)-20.99%(O_2). It is worth noting the gas system enable one to fill both chambers, MF1 and MF2, at the same time with the same gas,

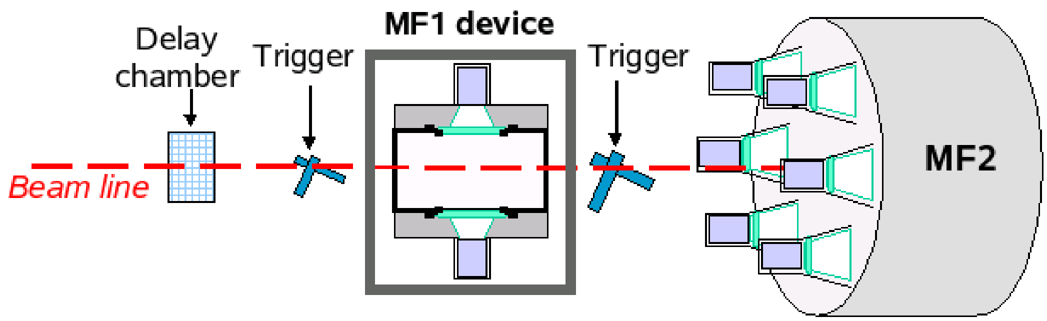

Fig. 2. Schematic view of the experimental devices along the test beam line.

leading to simultaneous measurements with the two detectors.

Along the beam line, upstream MF2, we have installed: a beam position monitoring chamber (delay chamber), two trigger systems (2 scintillators and 2 PMTs each) and the MF1 device, as shown on figure 2. The MF2 chamber is located after the last trigger system precisely aligned with the beam line, in order to receive electrons in the center of the pre-shower system.

The SPS beam line used here is a pulsed beam delivering about 10 000 particles by spill (every 16.8 s). The purity of the beam is better than 98% for 50 GeV electrons. The beam spot size measured by the delay chamber is about $4 \times 7\ mm^2$. The trigger system detects electrons on an event by event basis, enabling therefore FLY measurements with MF2, shower by shower.

3 Pre-shower system

When interacting in materials, high energy electrons develop showers. The longitudinal development and the lateral spread of an electromagnetic shower in a material are characterized respectively by the radiation length (X_0) and by the Molière radius (R_{Mo}) of the material (16). In the air, an electromagnetic shower takes several kilometers for developing (at atmospheric pressure $X_0 \simeq 300\ m$). Then in order to be able to sample the shower emitted FLY in laboratory we have to have a fast and compact shower initiator: we use a pre-shower system made of a variable thickness copper target, to initiate the shower.

We choose copper because of its properties: high density ($\rho = 8.96\ g/cm^3$) and low atomic number (Z=29). Then the electromagnetic showers remain compact with a small lateral spread ($X_0 = 14.3\ mm$, $R_{Mo} = 14.9\ mm$). More over the characteristics of the electromagnetic shower induced in the copper target are close to the ones of an extensive air shower: the critical energy is of the same order of magnitude ($\sim 24\ MeV$ in copper and $\sim 80\ MeV$ in air) and the energy of the secondary particles is similar. Moreover, the particle density

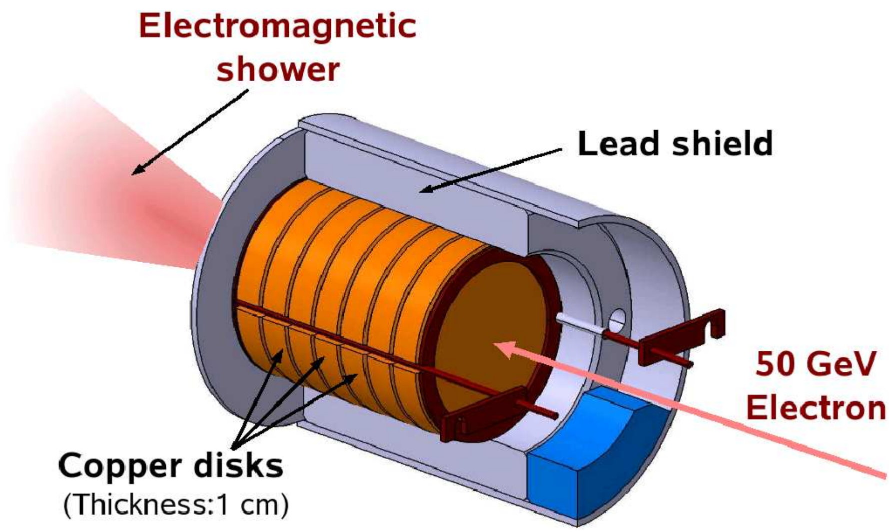

Fig. 3. The MF2 pre-shower target system is a stack of copper disks surrounded by a lead shielding tube.

of the shower in the MF2 chamber after the pre-shower (10^3 to 10^5 $/m^2$) is in the range of the particle density encountered in UHECR EAS at the shower maximum (10^3 to 10^7 $/m^2$) (17).

Figure 3 shows a sketch of the pre-shower system. The target is made of a stack of copper disks, 10 mm thick each. The age of the shower changes as function of the number N of disks in the stack. The equation 1 gives the pre-shower thickness (expressed in X_0) as a function of N. One copper disk corresponds to 0.7 ± 0.002 X_0 and all the matter on the beam line before the copper target (Trigger scintillator, MF1 chamber, etc.) corresponds to 0.27 ± 0.05 X_0.

$$X_N = (0.27 + N \times 0.7)X_0 \ . \tag{1}$$

In our measurements, we have chosen the sampling values for the pre-shower thickness in order to reproduce the air shower development in real atmosphere, on several kilometers. In copper at 50 GeV, the maximum of the shower development is at 7 $X_0(\sim 10\ cm)$. In order to range from zero to the shower maximum, we are using: 0, 1, 3, 5, 7 and 10 copper disks.

The pre-shower system copper disk stack is surrounded by a lead shielding (20 mm thick) which protects the PMTs from the backscattered particles from the showers. The pre-shower device was carefully designed to minimize the background in the PMTs.

4 Data taking and FLY reconstruction

The recording of the events is done on an event per event basis. We use a VME based DAQ system running a Labview program. The signal from the PMTs (MF1, MF2 and triggers) are recorded by QADC (CEAN-V792) which integrate the charge during a gate of 100 ns.

We define two kinds of event: Beam Events (BE) and Random Event (RE). For BE the gate is trigged when an electron passes through the trigger scintillator (FLY measurement). For RE the gate is randomly trigged (background measurement).

For every run about one million events are recorded: 500 000 BE and 500 000 RE. The FLY is rather weak and the majority of photons emitted are lost in the chamber. So the typical mean number of photon detected by a PMT is about 0.01 pe/evt (photoelectron per event).

The method to extract the mean Detected Light (DL) of a run from the data is described in the MF1 paper (15). It can be used to reconstruct the DL at the level as low as 0.01 pe/evt with an uncertainty smaller than 4%.

The detected light (DL) could come from several sources: Fluorescence (FDL), Cherenkov (CDL) or Background (Bgd). The overall signal is then:

$$DL = FDL + CDL + Bgd\ . \tag{2}$$

Figure 4 shows the DL reconstructed from data and the estimation of CDL and Bgd contributions to the total measured light. The FDL is determined by substracting CDL and Bgd to DL. We can see that the main part of the DL comme from the fluorescence whatever the conditions (50 GeV showers in dry air at 500 hPa for the left panel and 100 hPa for the right one).

The background is determined from RE of the run and from BE in vacuum (no light from neither fluorescence nor Cherenkov is expected). The MF2 experimental setup has been designed to minimize it. As one can see in figure 4, this background is quite low compared to the fluorescence signal but it grows with the shower age (pre-shower thickness). That is why we limit our FLY measurements to the shower maximum.

We estimate the Cherenkov radiation contribution with a Geant4 (18) based Monte-Carlo simulation program. The Cherenkov light yield is important (~ 20 ph/m/electon) at atmospheric pressure. However it was not contributing so much to the detected signal because it is mainly emitted in the forward direction, downstream, where it is absorbed on the black surface of the chamber. The Cerenkov contribution grows with pressure (density) in such a way

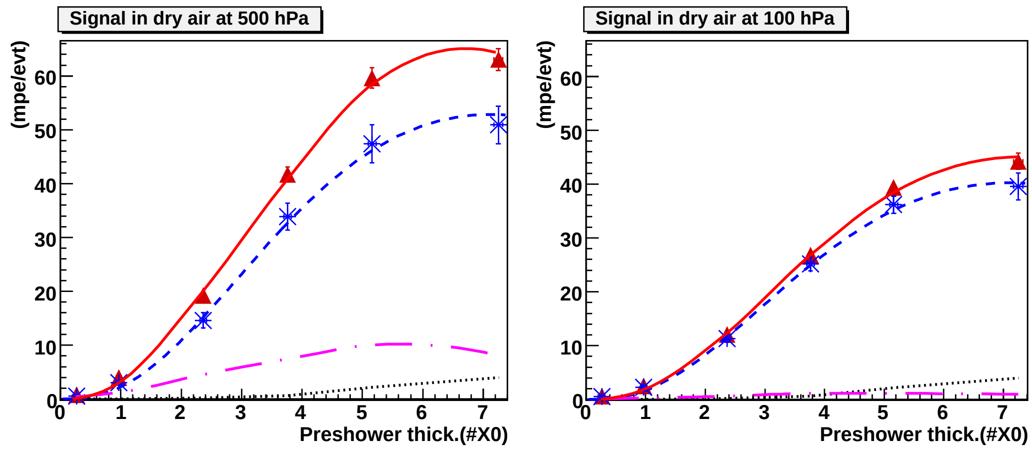

Fig. 4. Measured light in dry air at 500 hPa (left) and 100 hPa (right) in milli-photoelectron per event (mpe/evt) as a function of the pre-shower thickness (in X_0). Triangles represent the total signal (DL); dotted line is for the Bgd estimation from vacuum measurements; dot-dashed curve is the CDL simulation; stars are the FDL data (after substraction of Bgd and CDL); dashed line is the FLY model for showers. The solid line is the sum of the all contributions.

that the uncertainty on the measurement is smaller at low pressure (100 hPa) than at high pressure (500 hPa).

Finally we extract the FLY in MF2 from the FDL, after dividing it by the MF2 efficiency ε_{MF2}:

$$FLY = \frac{DL - CDL - Bgd}{\varepsilon_{MF2}} \tag{3}$$

5 Calibration and systematic errors

All the phototubes used in the MACFLY experiment are tested and cross calibrated in laboratory with test bench using stabilized UV LED (370 nm) (14). Then, to calibrate the MF2 device we use the MF1 chamber which is well calibrated (15).

In order to do that, we performed measurement in both chambers filled with the same gas at same pressure and temperature, and without pre-shower target in front of MF2 (0 disk). In this configuration, both chambers measure FLY induced by a single electron track. Then assuming that the FLY/E_d is the same in the two chambers. We measure in MF1 a raw signal which is about 12 time higher than in the MF2 chamber. From the MF1 efficiency and from deposited energy ratio between the two chambers simulated by Geant4, we estimate the MF2 efficiency: $\varepsilon_{MF2} = (0.007 \pm 0.0015)\%$.

Errors sources	Absolute	relative
MF1 calibration	13.7%	-
MF1/MF2	18%	-
DL reconstruction	$\sim 3\%$	$\sim 3\%$
CDL Simulation	$\sim 1.5\%$	$\sim 1.5\%$
Bgd Measurement	$\sim 1.5\%$	$\sim 1.5\%$
TOTAL	**23%**	$\sim$ **3.7%**

Table 1
Systematic uncertainties of MF2 measurements in dry air at 100 hPa and for 5 X_0 thick pre-shower.

The single electron track induced FLY measured by MF2 (no pre-shower) is weak (< 1 *milliphotoelectron*). The uncertainty on this measurement is large and the absolute calibration of MF2 is not as good as MF1 (see detail in table 1).

However one can notice that the systematic errors of relative measurements is rather good. Background and Cherenkov radiation represent a small fraction of the raw measured light (see figure 4) and induce small systematic errors.

At low pressure (100 hPa), a shower produces a small amount of Cherenkov radiation and the relative measurement uncertainty is less than 4%. At high pressure (500 hPa), there is more Cherenkov light produced, the uncertainty grows to about 7%.

6 Result and discussion

We have measured fluorescence light yield of dry air induced by electromagnetic showers at several pressures and several shower age values. Figure 5 shows the number of fluorescence photons emitted when a 50 GeV shower traversing a one meter thick layer of air as a function of the shower age. We have performed such measurements for two different pressures: P=100 hPa and P=500 hPa. The dotted lines are proportional to a model of energy lost (dE_d/dX) by a 50 GeV electron induced shower developing in copper, based on Geant4 simulations. One can see that air FLY follows well the expected shower development.

To check the properties of air FLY induced by air shower, we compare our results to the air fluorescence model developed by Colin (14) found to reproduce well the MF1 result (15). In this model we assume the air FLY to be proportional to the energy deposited (E_d) in the air volume. The deposited

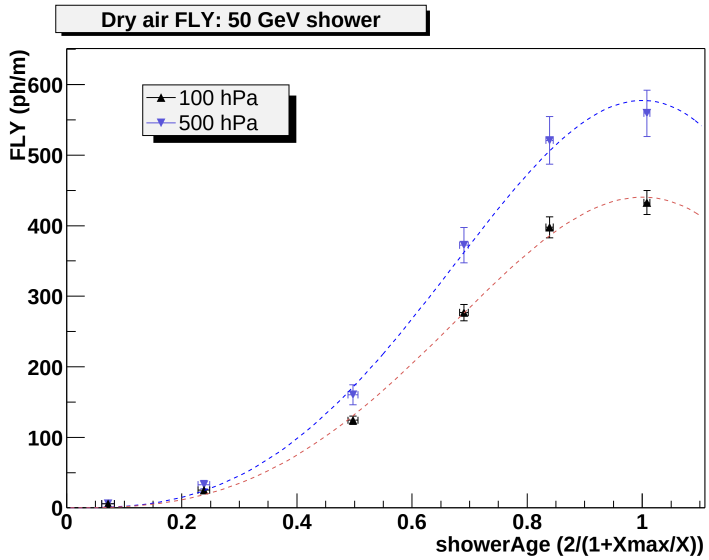

Fig. 5. Fluorescence Light Yield in dry air (100 hPa & 500 hPa) emitted by 50 GeV electromagnetic showers (in photon per meter) as a function of the shower age. Dotted lines correspond to a model of shower development in copper.

energy in the MF2 chamber was estimated for each measurement with our Geant4 based Monte-Carlo simulation program.

We study the ratio FLY/E_d given in photons per MeV. Figure 6 shows the variations of FLY/E_d as a function of the pressure (on left) and of the shower age (on right). The pressure dependence was measured for two pre-shower thickness: 2.36 X_0 and 5.16 X_0. The dotted line corresponds to our FLY model, based on MF1 results (15). One can see that at this two shower ages, we measure the same variation as for the air FLY induced by a single electron track.

The shower age dependence was measured at two pressures: 100 hPa and 500 hPa. In both case, we do not find any significant variation of FLY/E_d with the shower age, in agreement with the FLY model (doted lines).

This result shows clearly that FLY/E_d properties are independent of the excitation source of the air. There is no clue of special behavior from saturation effect at the EAS density or from low energy electron excitation of air molecules as it could be expected (19). Within the experimental uncertainties ($\sim 5\%$), we can claim that air FLY results obtained from electron beams can be directly used in simulation and reconstruction programs of extensive air showers.

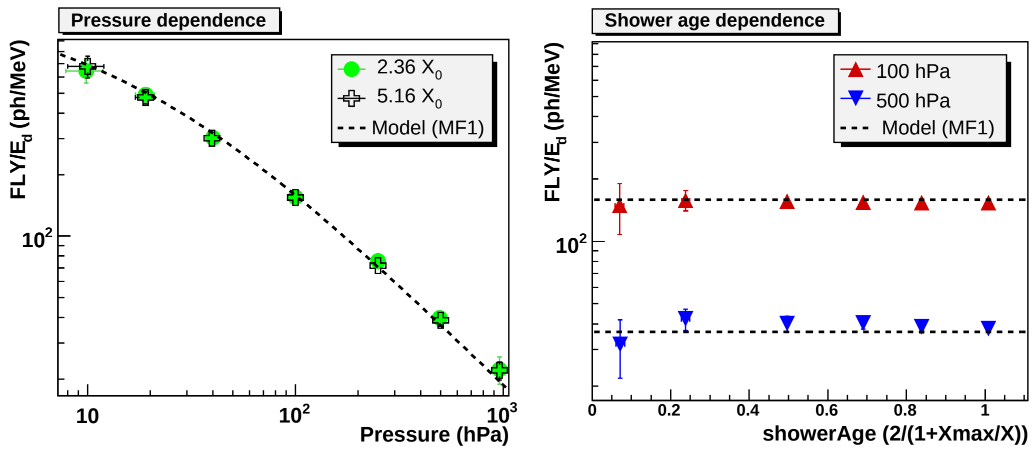

Fig. 6. Variation of the dry air Fluorescence Light Yield (in photon per MeV) as a function of: (left) gas pressure, for two thicknesses of the pre-shower; (right) shower age, for two values of the pressure . A comparison with our FLY model (15) is also shown (dotted curve).

7 Conclusion

We have performed the first air shower induced fluorescence light yield measurement in a laboratory controlled air. We have studied both pressure and shower age dependencies. The FLY variations with pressure, measured at every shower age, are the same as those measured with the single electron track device MF1. The FLY variations with shower age are well reproduced by the shower development simulations implementing our air fluorescence model which assumes a FLY proportional to the deposited energy.

8 Acknowledgments

The fund for this work has been partly provided by the Institut National de Physique Nucléaire et de Physique des Particules and by the Joint Institute for Nuclear Research. We would like to thank the Centre Européen de Recherche Nucléaire who allocated two weeks of beam test on the SPS beam line and particularly the CERN PH-DT2 (Detector Technology) group. Many thanks to our colleagues from the Alice experiment who helped and supported our activity in the test beam area and to M. Maire for his Geant4 expertise.

References

[1] K. Greisen, *Phys. Rev. Lett.* **16** 748 (1966) ;
V. A. Kuzmin, G. T. Zatsepin, *Pisma Zh. Eksp. Teor. Fiz.* **4** 114 (1966).

[2] R.U. Abbasi *et al.*, *Phys. Rev. Lett.* **92**, 151101 (2004).
[3] J. Abraham *et al.*, *Nucl. Instrum. Meth. A* **523**, 50 (2004).
[4] G.B. Thomson and the TA/TALE coll., *Prepared for 28th International Cosmic Ray Conferences (ICRC 2003), Tsukuba, Japan*, Proceedings 1061 (2003).
[5] J. Linsleyand the OWL coll., *Prepared for 26th International Cosmic Ray Conference (ICRC 1999), Salt Lake City, USA*, Proceedings Vol. **2**, 423.(1999).
[6] L. Scarsi and the EUSO coll., *Prepared for 27th International Cosmic Ray Conferences (ICRC 2001), Hamburg, Germany*, Proceedings 839 (2001);
I.Inoue and the JEM-EUSO coll., *Prepared for 36th COSPAR scientific assembly*, Proceedings 2902 (2006).
[7] L. Tkatchev and the TUS coll., *Prepared for 29th International Cosmic Ray Conferences (ICRC 2005), Pune, India* (2005).
[8] A. N. Bunner, *"Cosmic Ray Detection by Atmospheric Fluorescence"* Ph. D. thesis (Cornell University) (1967).
[9] F. Kakimoto *et al.*, *Nucl. Instrum. Meth.*, **A 372** 527 (1996).
[10] M. Nagano *et al.*, *Astropart. Phys.* **20** 293 (2003);
[11] M. Takeda *et al.*, *Astro. J.* **522**, 255 (1999).
[12] http://wwwlapp.in2p3.fr/IWFM05/
[13] P. Nedelec and P. Colin *Prepared for 40th "Rencontres de Morriond" 2005, La Thuile, Italie*, Proceedings 27 (2005).
[14] P. Colin, *"Reconstruction des gerbes atmospheriques et mesure de la fluorescence de l'air..."*, Ph. D. thesis (University Joseph Fourier, Grenoble) LAPP-T-2005-06 (2005).
[15] P. Colin *et al.* (MACFLY coll.), in press in *Astropart. Phys.* (2007). *(astro-ph/0612110)*
[16] S. Eidelman *et al.*, "Passage of particles through matter (Rev.)" *"Particule Data Groupe"*, *"Phys. Lett."* B592, 1 (2004).
(`URL: http://pdg.lbl.gov/`) and references therein.
[17] M. Risse and D. Heck *astropart. Phys.* **20**, 661 (2004).
[18] `http://geant4.web.cern.ch/geant4/`
[19] F. Arqueros *et al.*, *astropart. Phys.* **26**, 231 (2006).