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Absolute energy calibration of the Telescope Array fluorescence detector with an Electron Linear Accelerator

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Abstract: The measurement of primary energy and spectrum is one of the most important themes for the experiments of Ultra-High Energy Cosmic Rays (UHECRs). The Electron Light Source (ELS) is an electron linear accelerator, which was installed 100m in front of the Fluorescence Detector (FD) of Telescope Array (TA) experiment operating in the field of Utah, USA for the observation of UHECRs. A beam of 40MeV electrons is vertically injected into the air from the ELS and generated Air Fluorescence (AF) photons are detected by the TA/FD telescope. A direct calibration of the TA/FD is achieved by comparing the measured ELS signal with the predicted signal by simulation using a model of AF generation. In this report, we present the status of ELS operation and the first result of calibration.

Keywords: Cosmic ray, Fluorescence Light, LINAC, End-to-End calibration

1 Introduction

The maximum energy of the UHECRs exceeds 10^{20}eV, and they are observed by the Telescope Array [1][2][3] and Yakutsk array [4] in the northern hemisphere, and by the Pierre Auger Observatory (PAO) in the southern hemisphere [5]. Both TA and PAO are hybrid detectors which consist of an array of Surface Detectors (SDs) and Fluorescence Detectors (FDs). Both take the calorimetric energy scale obtained by the FD as the standard of the data analysis. It has been pointed out that the energy spectra measured by TA and PAO agree well only if one decreases the energy of TA by 10% and increases the energy of PAO by 10% [6] suggesting there is approximately 20% difference in the energy scale between two experiments. Understanding the source of the discrepancy and improving the energy calibration of the FD is the priority item in both experiments.

In TA, we are trying to make a precise, in-situ and end-to-end calibration of the FD using an electron beam generated by the ELS[7]. The ELS injects upward-going 40MeV electron beam into the air 100m in front of the TA/FD. A typical beam pulse is 1μs long and is containing 10^9 electrons (160pC). It is shot at 0.5Hz. The ELS was constructed at KEK in 2008 and transported to the TA site in 2009[8]. The first shooting into the air was made in 2010, and the data taking for the FD calibration was started in November, 2011[9]. We report here on the first result of calibration using the ELS data taken in July, November in 2012 and March in 2013.

2 Electron beam

The electron beam is accelerated horizontally in the ELS linac, bent 90° upward, then is guided vertically in the vacuum tube equipped with the Core Monitor (CM) made by the toroidal ferrite. The 90° bending magnet has a movable slit (50mm thick tantalum) at the exit and serves also for the momentum analyzer. The beam is injected into the air through the titanium vacuum window of 127μm thick and a copper noise shield of 100μm thick. The beam goes through a hole (200mm in diameter) in the ceiling of the accelerator container before being ejected to the air.

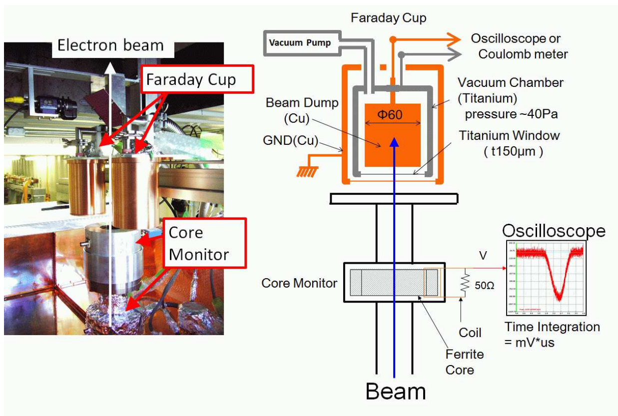

Fig. 1: Faraday Cup (FC) and Core Monitor (CM) for the ELS beam charge measurement.

For a precise measurement of the beam charge, we periodically interrupted the ejected beam by placing a retractable Faraday Cup (FC) in the beam line, approximately 10cm above the beam window of the vertical beam pipe. A construction of the FC used in March 2013 run is shown in Fig.1. It consists of a cylindrical beam dump made by pure copper, 60mm in diameter and 60mm in height. The beam dump is installed in a titanium vacuum chamber and is supported from the chamber wall with teflon insulator. The vacuum of 40Pa was maintained during the ELS operation. The whole vacuum chamber is installed in a copper case serving for the electrical shielding and grounding. The titanium vacuum chamber and the outer-most copper case have beam entrance windows of 150μm thickness each.

We used two FCs of identical construction attached on an electric slide and alternatively installed them in the beamline. One FC was connected to a Coulomb meter (Keithley 6514) and another was connected to an oscilloscope (Tektronix TDS3014). The Q-meter was read out regularly at 0.5Hz in between two beam shots, and the increment was taken as the newly injected beam charge. The electric noise during accelerator operation is around 0.1pC, and the S/N ratio was good for a typical 160pC charge. The oscilloscope was directly connected to the FC by 50 Ohm coaxial cable and the beam spill was recorded at a sampling rate of 1.25Gs/sec. A cutoff frequency was 100MHz.

The beam current was also continuously monitored by the CM without destroying the beam. A typical CM signal is 0.3mV for 1μs long 160pC beam pulse, and we used two cascading amplifiers for amplification and shaping before recording by the oscilloscope. The CM was calibrated by injecting a calibration pulse to one-turn coil sharing the same ferrite toroid.

Figure 2 shows the correlation of three beam charge measurements by two FCs and the CM obtained by the ELS run in March 2013. The X-axis is the integration of the CM signal and the Y-axis is the corresponding charge measurement by the FC. Both FC readouts, by Q-meter and oscilloscope, are plotted. Also plotted is the test charge given to the one-turn coil of the CM for calibration. The charge measurement of the CM and two FCs with different readout agree within $\pm 2\%$ as seen in the Figure.

Precise determination of the beam charge is important because it is the dominant factor to determine the accuracy of FD energy calibration. The uncertainty of the beam energy is not as important because 40 MeV electron loses only $\sim$1/3 of its energy in the FoV of the FD.

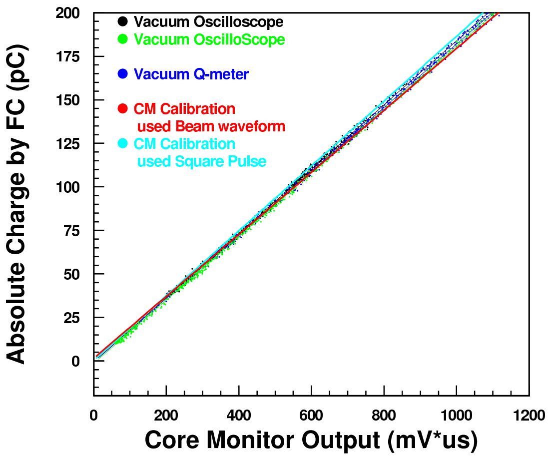

Fig. 2: Calibration of the CM. Plotted is a correlation between the integrated CM signal (X-axis) and the observed charge in FC or the supplied charge to the CM by calibration pulse (Y-axis).

We evaluated the capture rate of the beam electrons at the FC and the back-scattering effect by GEANT-4 simulation; approximately 98% of the primary beam charge is retained in the FC beam dump including the secondary electrons and positrons, The back-scattering leakage was estimated to be less than 1%. Other effects arising from the beam background generated at the bending magnet, the slit, and the wall of the beam duct are estimated small but will be further investigated.

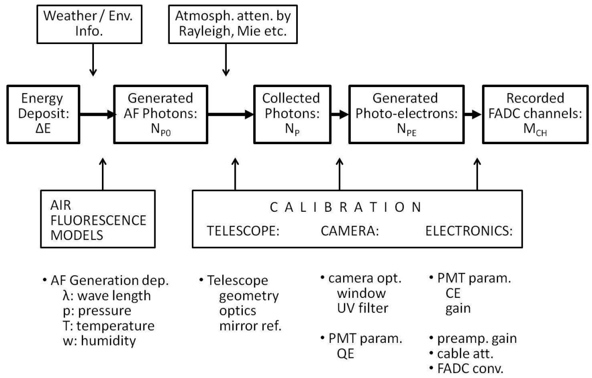

Fig. 3: Sequence of AF signal generation and detection.

3 ELS data and simulation

A sequence of the FD signal generation and detection, from the energy deposit ΔE to the integrated FADC signal M_{ch}, is explained in Fig.3. We use GEANT-4 simulation to inject 40MeV electrons into the air and the ΔE in the FoV of the TA/FD is calculated. Approximately 100,000 electrons in a monochromatic pencil beam configuration are simulated for each ELS run. The ΔE in the air was converted to AF photons (N_{p0}) using an AF model with environmental parameters (pressure p, temperature T and humidity w) measured at the ELS site. The generated AF photons are ray-traced to the TA/FD camera and converted to photo-electrons (N_{pe}), and finally to the integrated counts of the FADC (M_{ch}). All these processes are followed using the calibration data base of TA/FD.

The calibration of the telescope components are pre-evaluated before the experiment, and are updated during the observation by regular calibration procedures such as the xenon flasher and YAP pulser runs every one hour, continuous monitoring of camera temperature, and measurement of mirror reflectivity a few times a year. The telescope geometries and optics are updated from the original setting by the star position measurement. Results of these calibrations are stored in a time dependent data-base and are used for the analysis of observation data, Monte Carlo (MC) event generation and its analysis.

The atmospheric attenuation of fluorescence lights by the molecular and aerosol scatterings is included as the Rayleigh and Mie attenuation lengths, but its effect is less than 2% due to a short distance between the fluorescence generation and its detection ($\sim$100m) for the ELS.

Comparisons were made between the ELS data and the simulation by converting the FADC waveform into a number of 337nm equivalent photons $N_p^{337}(i)$ where i denotes the i-th PMT in the camera. A fixed wavelength of 337nm is chosen for this conversion as we do not a priori know the wavelength of the detected photon. In Fig.4, longitudinal distributions of AF photons are plotted and compared between the data and the simulation; The Y-axis is a summation of N_p^{337} photons from 16 PMTs in one row, and the X-axis is the corresponding elevation angle of that row. The number of N_p^{337} is re-normalized to the total number of detected photons $\sum_i N_p^{337}(i)$, i=1,512 for both the data and the simulation. The agreement is better than 5% for any of the elevation angles as seen in the Figure. The same is plotted in Fig.5 for the transverse distribution for several fixed elevation angles. The transverse spread of the measured ΔE is well reproduced by the GEANT simulation.

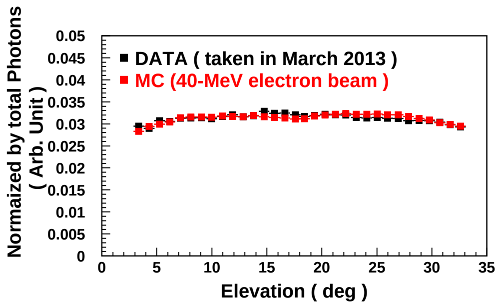

Fig. 4: Longitudinal distribution of AF photons from the ELS beam. One FD camera covers the elevation of 3° – 18°, and another covers 18° – 33°.

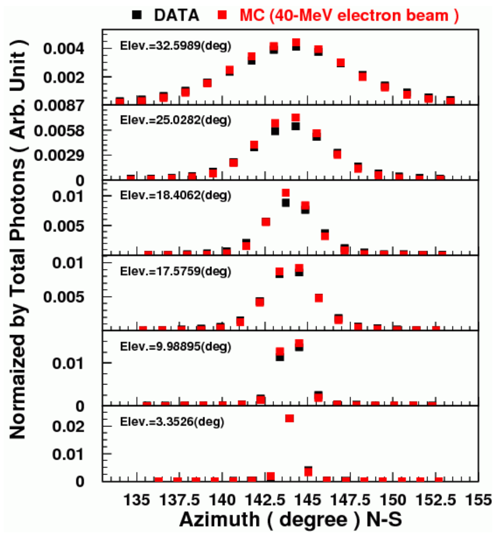

Fig. 5: Transverse distribution of AF photons from the ELS beam.

4 Measurement of fluorescence yield

As a first step of performing the TA/FD calibration using the ELS, we report here the measurement of the AF yield obtained by using all the existing calibrations of the TA/FD telescope. In doing so, we select two AF models, generate MC samples of FADC data, and compare the data and the simulation. Two AF models used are;

- **FK model:** This model uses a fluorescence spectrum measured by FLASH experiment[10] for 300-420nm. The normalization is set such that the fluorescence yield integrated over 300-400nm is equal to the yield observed by Kakimoto et al.[11]. The quenching effect depends only on the square root of the temperature, and a change of the collision cross-section with temperature is not implemented. The effect of humidity is not included. This model is used by TA in the analysis of air shower data.
- **SM model:** A Standard Model (SM) of air fluorescence was proposed in 2012 as a composite of several measurements by the dedicated working group of UHECR2012 symposium[12]. This model adopts the fluorescence spectrum measured by AirFLY. The temperature and the humidity dependent quenching is implemented using the weighted averages of several dedicated experiments. The normalization is taken for the AF yield of 337nm, but the actual value is left open such that the best value may be selected in future by scrutinizing the existing measurements. In the following analysis, we uses a yield obtained by the latest AirFLY measurement[13] to produce simulated ELS samples.

The measurement of the AF yield is achieved by comparing the ELS data with the simulation. We define a ratio R as follows:

$$R = \sum_{i=1}^{512} M_{ch}^{data}(i) \; / \; \sum_{i=1}^{512} M_{ch}^{sim}(i) \qquad (1)$$

where $M_{ch}^{data}(i)$ is the integrated waveform [FADC channels] of the i-th PMT for the ELS data, and $M_{ch}^{sim}(i)$ is the same for the simulated ELS events. The R is obtained for each AF model, i.e. R_{FK} for the SK model and R_{SM} for the SM model. By construction, the value of R is equivalent to the ratio of the measured AF yield by the ELS to the AF yield in the simulation used to generate the Monte Carlo events.

The value of $M_{ch}^{data}(i)$ or $M_{ch}^{sim}(i)$ is obtained by integrating the AF signal -1500ns before and 2500ns after the signal leading edge. A dc offset determined as the average of "no-signal" region, 5-6μs before the leading edge, was subtracted before the signal integration. The integration over the FoV is taken for all the 512 PMTs in two TA/FD cameras containing the AF signal from the ELS.

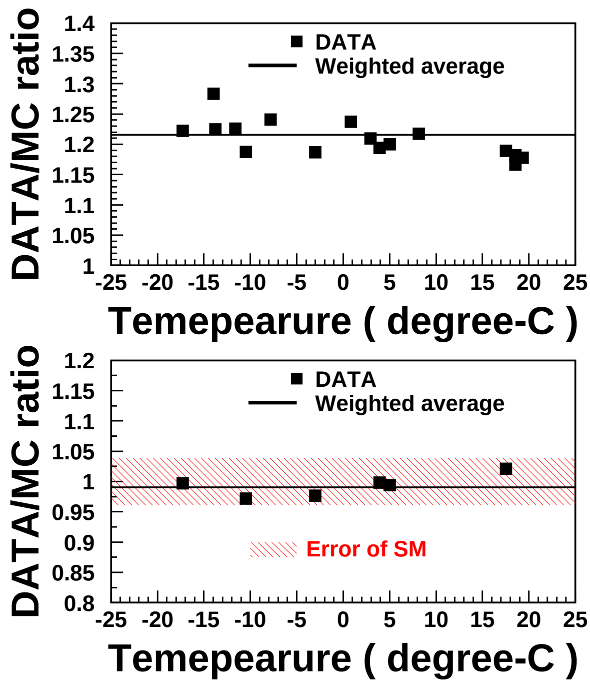

Fig. 6: Air fluorescence yield ratio R_{FK}(top) and R_{SM}(bottom) measured by the ELS.

The measurement of R was made for 3 datasets collected in July and November 2012 and in March 2013. Obtained values of R_{FK} and R_{SM} are plotted in Fig.6 for the temperature range of -17°C and 20°C. The average of the ratio over the temperature range is:

$$R_{FK} = 1.22 \pm 0.01(\text{stat}) \pm 0.18(\text{sys}) \quad (2)$$
$$R_{SM} = 0.99 \pm 0.01(\text{stat}) \pm 0.15(\text{sys}) \quad (3)$$

where the statistical error comes from the number of ELS events and generated MC events. We remind that the AF yields, Y_{FK} and Y_{SM}, at 1013 hPa and 293 K used in the simulation are[11][13]:

$$Y_{FK} = 16.4\ [\text{photons/MeV}]\ \text{for}\ 300-420\text{nm} \quad (4)$$
$$Y_{SM} = 5.61\ [\text{photons/MeV}]\ \text{for 337nm line} \quad (5)$$

The systematic uncertainty of Y_{FK} and Y_{SM} is estimated to be 10% and 4% respectively.

The systematic uncertainty of R measurement is composed of 3 major components as evaluated below:

1. **Less than 10% for estimating ΔE**
   The major component of this error is the uncertainty of the measured beam charge. All 3 measurements by the 2 FCs and the CM coincide within 3% for March 2013 runs, but the agreement was worse for runs in July and November 2012 due to incomplete FC construction and pickup noises on the FC and CM readout. The leakage of charged particles from the FC was estimated to be less than 3% by the GEANT simulation. The effect of background photons from the accelerator and the beam line element is estimated at the level of a few %. We also confirmed that the energy deposit of 40MeV electron in the air calculated by GEANT-4 and CORSIKA agree within 1%. This is important to check because the inverse MC method for the FD air shower reconstruction uses the CORSIKA simulation whereas most of the ELS analysis is based on GEANT-4 simulation.

2. **10% for FD telescope parameters:**
   The major part of this uncertainty comes from the calibration of absolute PMT sensitivity and its short-term (mostly by the temperature cycling) and long-term (drift) instabilities. The seasonal difference of mirror reflectivity is another consideration. The quoted error of 10% is the remaining uncertainty after all the calibrations are implemented from the calibration data base [14].

3. **5% for the telescope geometry and optics:**
   The photon acceptance by each PMT is calculated by the ray tracing MC using the known geometrical parameters and the optical design of the FD telescope. A disagreement at the level of 5% is observed by changing the integration area over the FoV of the camera. A significant part of this may be attributed to the incompleteness of the ray tracing simulation.

A total systematic uncertainty of R is 15% or less by summing 3 error components in quadrature. We remind that the uncertainty of the final FD calibration depends only on the ΔE measurement(1). This uncertainty will be significantly reduced in the future ELS runs and analyses.

5 Summary and Prospects

The electron beam calibration of TA/FD has been performed by using the ELS since 2011. As a first step of calibration, we obtained the air fluorescence yield based on two AF models; the FK model used for TA data analysis and the SM (standard model) proposed in 2012. The ELS measurements from July 2012 to March 2013 are used to derive the yield ratio R_{FK} for the FK model and R_{SM} for the standard model with AirFLY's latest yield measurement. Their average values are R_{FK}=1.22 and R_{SM}=0.99 with a statistical error of 0.01 and with the systematic error of 15% or less. The accuracy of the calibration of TA/FD using the ELS is presently at the level of 10% and is steadily improving by good charge measurement of the ELS beam and with better understanding of the beam background.

The ELS has been operated stably since 2012 on TA site and it has been used also for the test of radio emission at MHz and GHz region, and the bistatic radar.

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Errata

We measured the R with 3 datasets collected in July and November 2012 and in March 2013 as follows.

$$R_{FK} = 1.22 \pm 0.01(\text{stat}) \quad (6)$$
$$R_{SM} = 0.99 \pm 0.01(\text{stat}) \quad (7)$$

We made an overall correction of -3% background photons, Cherenkov photons and charge leakage from the FC. The average of the ratio over the temperature range is:

$$R_{FK} = 1.18 \pm 0.01(\text{stat}) \pm 0.18(\text{sys}) \quad (8)$$
$$R_{SM} = 0.96 \pm 0.01(\text{stat}) \pm 0.15(\text{sys}) \quad (9)$$