

Absolute energy calibration of the Telescope Array fluorescence detector with an electron linear accelerator

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Abstract. The Electron Light Source(ELS) is a new light source for the absolute energy calibration of cosmic ray Fluorescence Detector(FD) telescopes. The ELS is a compact electron linear accelerator with a typical output of 10^9 electrons per pulse at 40 MeV. We fire the electron beam vertically into the air 100 m in front of the telescope. The electron beam excites the gases of the atmosphere in the same way as the charged particles of the cosmic ray induced extensive air shower. The gases give off the same light with the same wavelength dependence. The light passes through a small amount of atmosphere and is collected by the same mirror and camera with their wavelength dependence. In this way we can use the electron beam from ELS to make an end-to-end calibration of the telescope. In September 2010, we began operation of the ELS and the FD telescopes observed the fluorescence photons from the air shower which was generated by the electron beam. In this article, we will report the status of analysis of the absolute energy calibration with data which was taken in September 2010, and beam monitor study in November 2011.

1 Introduction of ELS

Ultra-high energy cosmic rays (UHECR) are the highest energy charged particles coming from extragalactic sources. However, their sources, chemical composition, and the mechanism of generation, acceleration, and propagation are not understood. Greisen, Zatsepin, and Kuz'min predicted a high energy limit to the flux of UHECR by photopion production with the cosmic microwave background[1][2]. Two large experiments have started observing UHECR. One of which is the Telescope Array (TA) located in the west desert of Utah in the U. S. and started taking data since May of 2008. TA is a hybrid detector which consists of 507 surface scintillation detectors (SD) and 38 air fluorescence telescopes (FD)[3][4][5]. The other is the Pierre Auger Observatory (PAO) which started data taking from 2004 in Argentina. PAO also is also a hybrid detector consisting of 1600 water cherenkov surface detectors and 24 FD[6][7][8][9]. We have serious problem in energy scale which are determined with each FD. According to the latest results at UHECR2012 at CERN[15], the more than 20% discrepancy in energy scale was reported. No source for calibrating of the absolute energy scale of FD is one of the main reason of the problem.

The Electron Light Source (ELS) is a unique and first apparatus that can be used for end-to-end absolute energy calibration of a FD in site[11]. The ELS is located 100 m from two of the telescopes at the Black Rock FD station, and can fire an upward going electron beam through the field of view of the telescopes. The typical output beam consists of about $40 \text{ MeV} \times 10^9$ electrons per pulse at a rate of 0.1-1.0 Hz. The ELS was developed at KEK in Japan. The beam line and the rf system components were designed to fit into a 40-ft shipping container, and its water cooling system was designed to fit into

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a 20-ft shipping container. We control and monitor these systems from an office trailer for protection from radiation. The construction was completed by January 2008, and was moved to the Black Rock FD site at TA in Utah in March 2009[12]. Electric power for the ELS is supplied by an 80 kW diesel generator installed at the site. We started the beam operation from September 2010[13].

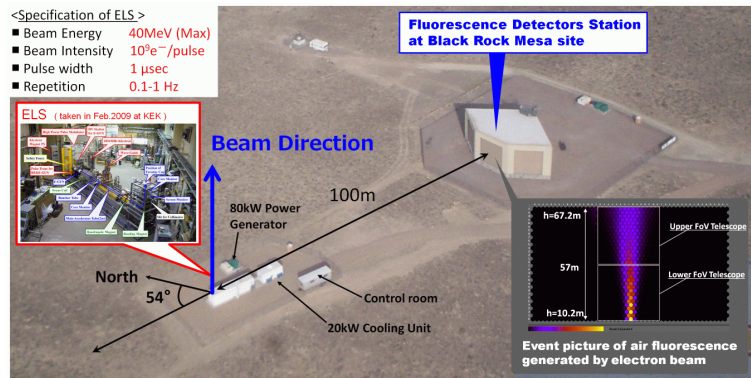


Fig. 1. Photograph of the ELS site in TA site, and list of specification of ELS output beam.

2 Beam Operation

After first shot, we operated for beam conditioning in December 2010 and January 2011. We also measured the alignment of the vertical beam line, in specially around the beam exit window. However, one high voltage cable in the rf system was broken by accidental discharge from electron-gun during beam operation in January. New high voltage cable was replaced in the end of February. In March 2011, the DC meter module and thyatron power supply were broken during beam operation because of large noise. Then, we stopped the any more operations. The DC memter was fixed in next month, on the other while we replaced thyatron trigger module, E2V model MA2458A, to a new module(E2V model MA2709A) in November 2011. We restarted beam operation after the replacement. Total ELS operation time until the end of 2011 was 81.3 hours, and total time of beam shot into the sky was 5.4 hours. In next section, we will describe about the status of analysis of absolute energy calibration with the data which was took in September 2010, and the study of beam monitoring system.

3 Status of Data Analysis

Here we describe the status of absolute calibration of FD telescopes with the ELS. We can calibrate all of the parameters needed for the reconstruction of a UHECR shower with the FD in a lump by comparing the energy deposited in the air by the electron beam and the FADC or photon counts collected by the FD. The best quantities to compare are the longitudinal and lateral development of the electron beam in the air. We used the data of 612 events which was taken with two FD telescopes on September 5, 2010, and simulation.

3.1 Monte Calro Simulation

We used two simulation tools for generation of air shower and detector simulation. One is GEANT4.9.4.p02 to simulate the air shower generated by the electrons and calculate its energy deposite in the air. Another one is FD simulation which was developed by TA experiment.

GEANT4 simulation generates from electron generation and injection into the air and to output the energy deposit in the air. Input parameters for the simulation are injection position of ELS, output beam energy, current, direction, spot position and size, the time structure of the beam(waveform), and air condition. These parameters were measured during beam operation with some beam monitors and a weather sensor. The injection position was measured as relative position from one FD telescope in April 2011. It is difficult to measure the beam energy directly, but it can be calculated by the magnetic field of the 90° Bending Magnet(BM) which is used to bent the accelerated electron from horizontal to vertical direction. We record the magnetic field value of the BM all the time. Figure 2 shows the estimated energy spectrum which was measured during the operation in September 5, 2010. The mean energy was 41.1 MeV, and the RMS was 0.5 MeV. The output energy spread is determined by the slit width and beam line geometry which is constructed downstream of the BM. We fixed the slit width to be 6.5 mm, which should make the output energy width $\sim \pm 0.6\%$ of 40 MeV. In this way we obtained narrow and precise energy beam. Beam direction was not measured well, and we assumed the beam direction as vertical with no slant. We did not include any time structure, and it means all of electrons are injected in exactly same time in simulation. The beam spot position and size were measured in December 2010 and January 2011 with the screen monitor which were installed in the vacuum beam line. The position was measured as 5 mm shifted from the center of beam line, and the size was measured as 5 mm \times 10 mm. The air temperature, air pressure, and humidity were recorded with a weather sensor which is installed at the FD station building in Black Rock site. All of beam parameters and air condition which were used for absolute energy calibration are summarized in the table 1. The geomagnetic field was not included in the simulation, because we have never measured it directly. However, if we include the geomagnetic field which is calculated with International Geomagnetic Reference Field(IGRF) the electron beam is bent about 0.5 m at the height of 100 m, because of above we can not ignore this effect. We have a plan to measure of geomagnetic field at the Black Rock site in next operation.

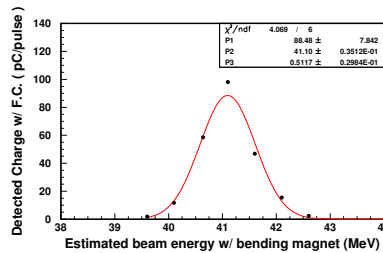


Fig. 2. The beam energy spectrum which was estimated with the BM.

We used the standard electromagnetic interaction process in GEANT4 physics list. The cut energy of electrons and gamma-ray in the air were 1 keV. The most important output value of the air shower simulation is energy deposit. We considered the energy deposit under the process of ionisation, bremsstrahlung, annihilation, photo-electric effect, compton scattering, and pair creation. We did not include the energy deposit by multiple scattering process which the contribution is much less than 1%.

The detector simulation, which is called as TA-Java, calculates the process from generation of fluorescence photons depends on amount of energy deposit, and detection of the photons by the telescopes. The fluorescence photons are generated with Kakimoto-FLASH modified model. The all of official calibration parameters of FD were used.

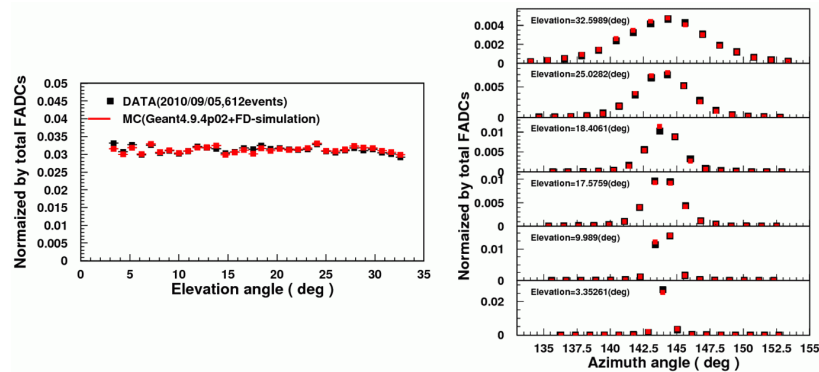
3.2 Results

We analyzed the real data and simulation with relative comparison. In this analysis, we used the data of two telescopes which are located in front of ELS. Then we used the FADC counts which are normal-

Table 1. The input parameters of the air-shower production

parameter	value
date	Sep.5th.2010 04:15(UTC)
<u>beam conditions</u>	
beam energy	41.1 MeV
beam spot size	5 mm×10 mm
beam spot position	5 mm shift from center of beam line
beam direction	vertical without slant
time structure	not be included
<u>air conditions</u>	
temperature	26.8 °C
pressure	853.1 hPa
humidity	11.9%
<u>etc</u>	
geomagnetic field	not be included

ized with total FADC counts of these telescopes. Figure 3(left) shows the longitudinal distribution of the air shower, where horizontal axis is elevation and vertical axis is normalized FADC counts. Figure 3(right) shows the lateral distribution, where the vertical axis is normalized FADC counts. From the both of the plots, the real data and simulation have good agreement.

**Fig. 3.** The relative comparison of longitudinal and lateral distribution between real data and simulation.

4 Beam Monitor Study

4.1 New Screen Monitor

In November 2011, we installed two new beam monitor equipments. One was a screen monitor, which is a kind of beam profile monitor, for measurement of output beam spot size and position in the air. The material of the fluorescent plate is exactly same as the plate of the current two screen monitors. The beam spot size and position can be measured by watching the fluorescence light which is emitted when the beam collides to the fluorescent plate. The pictures which were taken with a camera were recorded in the computer with a video capture. Figure 4 shows the picture of the beam spot which was recorded in November, and we measured beam spot size and position.

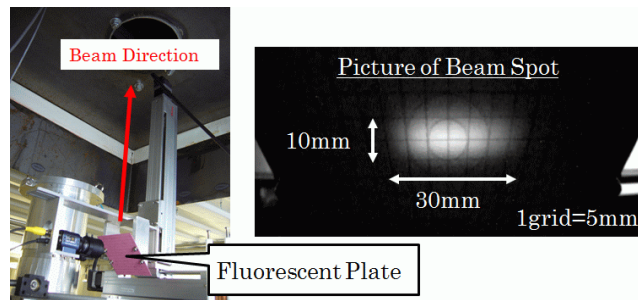


Fig. 4. New screen monitor which was installed in the air area and the picture of beam spot.

4.2 Beam Charge Measurement

The measurement of beam charge per pulse is most important quantity for absolute energy calibration of FD. The faraday cup(FC) and current transfer(CT) can be used for measurement of beam charge per pulse. In November, we installed a new FC which is more simple structure and lighter than previous one. The weight of the previous FC was about ~ 35 kg, and the material of the beam capture was lead, while the weight of the new one is about ~ 2.5 kg and the material is copper. The shape of the FC is cylinder and its diameter is 60 mm and length is 100 mm (Fig.5-(a)). So far, the number of electrons which are captured in the FC were counted with only an electrometer. However in November, we tried to measure the beam charge with an oscilloscope which was connected to the FC output line directly. The merit of this method is that we can measure not only the beam charge, but also its time structure of the beam. The beam charge can be calculated by time integration of the waveform. Figure 5-(b) shows the recorded waveform of the beam with the oscilloscope. By the way, the beam charge can be measured with the CT with time integration of output waveform, however the peak voltage of the output pulse of the CT in case of typical beam is very small, ~ 0.3 mV, then we used two amplifiers. Therefore, it was necessary to calibrate the input and output response of the CT. We calibrated the CT by input test pulse which was generated with a signal generator in last summer. We also calibrated the CT with the new FC which the output line was connected with an oscilloscope during this operation. Figure 5-(c) shows the plot of the correlation between the output of the CT and measured beam charge with the new FC. The black line is calibration line of the CT with the test pulse. As the result, the correlation does not agree well. The one of the candidate source of this disagreement is radio noise which inserted into the FC. We confirmed the radio noise which was generated by the electron beam affected the charge measurement, and we found that we need construct noise shielding. The another candidate is frequency dependence of the response function of the amplifiers in the CT. The test pulse was simple square shape pulse of $1 \mu\text{sec}$ and $0.5 \mu\text{sec}$ width. However since the real beam pulse shape had high frequency component, we found that we also need consider the response of high frequency component in input beam pulse.

5 Summary

The electron light source is an electron linear accelerator as an unique light source for the absolute energy calibration of the fluorescence detectors. The ELS was developed in KEK, and it was moved in TA site in March 2009. We started the operation from September 2010, and also started the data analysis with real data and monte carlo simulation. As the results of the relative comparisons of longitudinal and lateral development of the air shower which was generated by the electron beam, the real data and simulation agreed well. The beam monitor study was also done in November 2011 with a new screen monitor and faraday cup. We measured beam spot size and position well, and its time structure. However, the charge measurement still had problem which we need solve immediately.

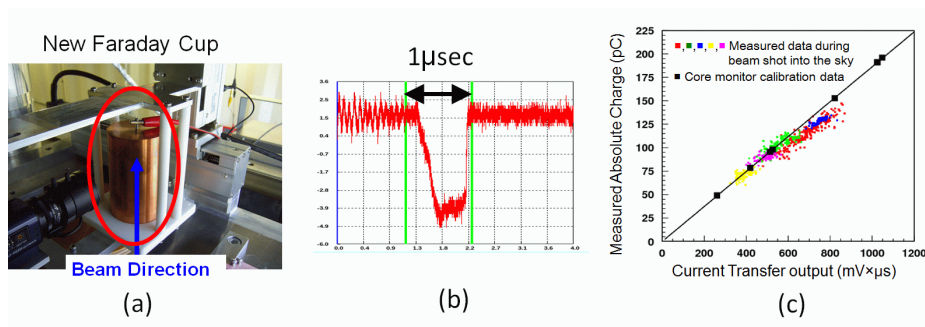


Fig. 5. (a) New faraday cup which the material is copper. (b) Time structure of the beam which was recorded with oscilloscope. (c) Correlation between the output of the CT and measured beam charge with the oscilloscope.

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