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

T.SHIBATA[1], M.BEITOLLAHI[2], M.FUKUSHIMA[1], D.IKEDA[1], K. LANGELY[2], J.N.MATTHEWS[2]
H.SAGAWA[1], S.B. THOMAS[2], G.B. THOMSON[2], FOR THE TELESCOPE ARRAY COLLABORATION
[1]*ICRR, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba(277-8582), Japan*
[2]*University of Utah, 115S, 1400E, Salt Lake City, UT(4112-0830), U.S.*
shibata@icrr.u-tokyo.ac.jp

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 at 0.5 Hz. The ELS was developed in KEK, Japan between 2005-08, and it was installed at the Black Rock Mesa Telescope Array(TA) site in March 2009. 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. We have completed the environmental survey for ELS, installed electric power, communication lines, and radiation shielding. 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 report, we will present the status of the ELS.

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

1 Introduction

Ultra-high energy cosmic rays (UHECR) are the highest energy charged particles coming from extra-galactic 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.[3]. Taking data since May of 2008, TA is a hybrid detector which consists of 507 surface scintillation detectors (SD) and 34 air fluorescence telescopes (FD). The other is the Pierre Auger Observatory (PAO) which started data taking from 2004 in Argentina[6]. PAO also is a hybrid detector consisting of 1600 water cherenkov surface detectors and 24 fluorescence telescopes. TA, PAO, and the HiRes experiment have all reported important results in recent years[4][5][7][8][9][10].

2 Electron Light Source

The Electron Light Source (ELS) is an unique and first of it's kind apparatus that can be used for end-to-end absolute energy calibration of an FD in site[11]. The ELS is located 100 m from two of the telescopes at the Black Rock FD station, and can fire a upward going electron beam through the field of view of the telescopes. The typical output beam consists of about 40 MeV$\times10^9$ electrons per pulse at a rate of about 0.5 Hz. The ELS was developed at the High Energy Acceleration Research Organization (KEK) in Japan between 2005 and 2008. The beam line and RF system components were designed to fit into a 40-ft shipping container, and its water cooling system was designed to fit into a 20-ft shipping container. We control and monitor these systems from an office trailer for protection from radiation. The construction of the ELS was completed by January 2008 at the electron/positron injector building in KEK. It was operated there until December 2008 while we optimized the beam and evaluated the measurement of output energy and beam current[13].

2.1 Setup and Operation in TA site

After completion of beam operation and optimization at KEK, the ELS was shipped from Japan to the Black Rock FD site at TA in Utah by March 2009. Preparation for beam operation took from April 2009 to the end of March 2010. A photograph of the ELS site is shown in Fig.1. The measured position of the vertical beam pipe outlet is summa-

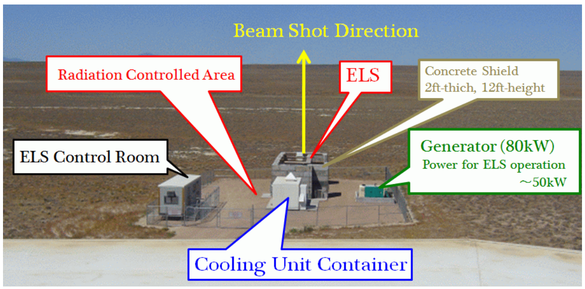

Figure 1: Photograph of the ELS site in TA site.

rized in Table 1. Electric power for the ELS is supplied

	measured value
Latitude	N 39° 11' 19.91717"
Longitude	W 112° 42' 45.96956"
Height	1398 m
Distance from a mirror of FD	99.9 m

Table 1: Measurement value of ELS position.

by an 80 kW diesel generator installed at the site. In addition, electric power is also supplied from generators at the Black Rock FD building to keep the computers and vacuum pumps operating at all times. Preparation of power cables and distribution panels was completed at the end of September 2009. Fifteen cm of foam insulation was applied to the outside of the 40-ft container and two air conditioner units were installed to keep temperatures inside the container constant. A 50/50 mixture of propylene glycol and water is used as coolant for the cooling system since the outside temperatures can vary between + 40 and - 30 °C. Optical LAN cables were connected between the ELS and the Black Rock FD station to allow remote monitoring of the ELS status. Several cameras have been installed inside and outside the containers that can be observed over the internet.

The ELS is a radiation generator, therefore we need a radiation safety management system. The University of Utah administers the radiation safety of the ELS, and has supplied Radiation Safety Officers (RSO). During operation of the ELS, there is always an on-site RSO and a Responsible User (RU), who are two different people. A safety fence has been installed about 10 m from the ELS container and delimits a radiation area that is off-limits to all personnel during operation. Interlock switches have been installed at all gates in the fence so if any person opens a gate, the high voltage power supply and beam triggers will be shut down. There is a console panel in the control room used to turn on the master beam trigger and reset the interlocks that prevents remote control of the system from the internet. Large amounts of γ radiation and neutrons are emitted from beam line components, 90 ° bending magnet (BM), and beam slit collimator during operation. Therefore we installed concrete blocks that create a shielding wall 60 cm thick and 3.5 m high outside the ELS container. Furthermore, 50 mm lead bricks were also installed surrounding BM and the vertical beam line. The radiation dose at the boundary of the safety fence with the installed shielding was calculated by the radiation science center at KEK to be 0.1 μSv/hr, which is roughly the same as the natural background level at the site.

After preparation for ELS operation,we made a trial run of the RF system in June 2010. The RF system consists of a 110 MW pulse modulator and a S-Band 40 MW RF Klystron. During this run we measured output RF power pulses with a peak power meter to be as high as ~27 MW, which was more than required to accelerate the electron beam during the tests of the system in KEK[13]. Figure 2 shows the characteristic curves of the klystron which were taken at KEK and at the ELS site.

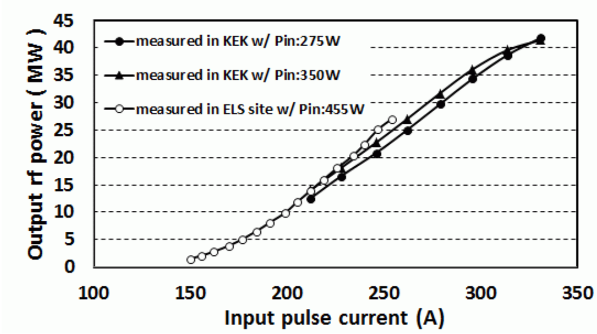

Figure 2: The relation between the pulse current into the klystron and the output rf power from the klystron.

After the trial of the RF system, we set up the pulse type electron gun system. The electron beam was detected with the core monitor along the beam line by the end of June 2010.

We started accelerated beam operation early in September, 2010. As a first step, we detected the accelerated beam along the horizontal beam line with the current transfer and the beam profile monitor. After that we set up the bending magnet and then finally injected the electron beam into the sky. Figure 3 shows an image of the emitted fluorescence photons detected by the FD.

2.2 Accelerated Beam Operation

The output beam energy was calculated by measuring the magnetic field of the BM. Figure 4 shows the estimated energy spectrum detected by collecting the beam charge with a Faraday Cup (FC) located at the top of the vertical beam line. The mean energy was 41.1 MeV, and the RMS was 0.5 MeV. The output energy width is determined by the slit width and beam line geometry. We fixed the slit width to be 6.5 mm, which should make the output energy width ~±0.6% of 40 MeV. In this way we obtain a narrow and precise energy beam.

The ELS beam current is adjusted with the heater current of the electron gun. The beam current is measured by several

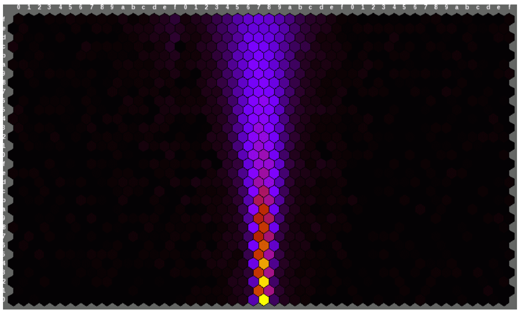

Figure 3: The image of the air-shower detected by FD

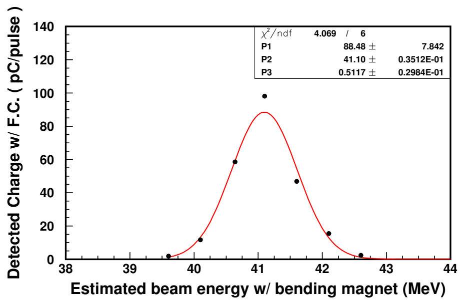

Figure 4: The energy spectrum estimated with BM

monitors. The absolute beam charge is measured by the FC connected to a electrometer. However, this system is not yet fully calibrated.

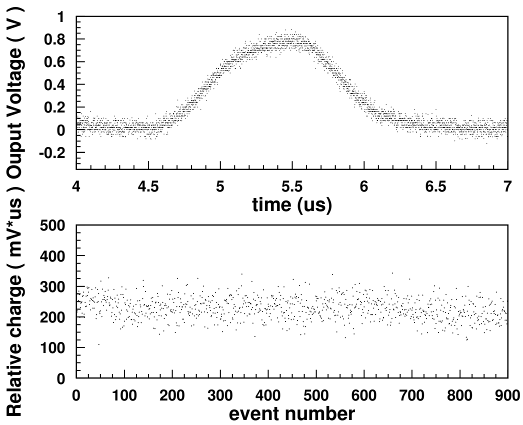

Figure 5: The output waveform of output of core monitor, and time variation during the beam operation.

During beam injection into the sky, the relative beam charge is measured with the core monitor by integrating the output waveform. Figure 5 shows the output waveform of the core monitor and its time variation during beam operation. The beam parameters are summarized in Table 2.

parameter	value
repetation	0.5 pps
rf output pulse power	∼20 MW
electron gun energy	∼93 kV
output beam energy	41.1 MeV
beam pulse width	1 μs

Table 2: The beam tuning parameters.

3 Data Analysis

Here we describe the principle of the method of absolute calibration of an FD telescope 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 counts collected by the FD. By comparing simulated and real data we can correct the calibration parameters. The best quantities to compare are the longitudinal and lateral development of the electron beam.

3.1 Monte Calro Simulation

We use the FD simulation which was developed by the TA experiment. We use GEANT-4 to simulate the air shower generated by the electron beam and calculate the energy deposited in the air. However, for absolute energy calibration we should check the air shower production using several different codes, specifically to check the multiple scattering and energy deposited which can vary between codes (ref[14][15][16]). Input parameters for these simulations are beam energy, beam position, air temperature, air pressure, and humidity. These parameters are measured during beam operation with beam monitors and weather monitors installed at the Black Rock site. The output of the simulation is energy deposited and its position relative to the FD telescope. These outputs are used as inputs to the detector simulation which was developed for the TA experiment

3.2 Comparison between data and simulation

We compare the data which was taken on September 5, 2010, and simulation. We used data of 612 pulses that were seen by two FD telescopes to compare the simulation. The simulated data was produced with the parameter values for that date which are summarized in Table 3. The results are shown in Figure 6. The top plot in Figure 6 is the normalized FADC output per PMT for a given row of PMTs (horizontal axis) versus the row number (vertical axis) for both real and simulated data. The bottom plot shows the width of the distribution of PMTs that see signals in each row for real and simulated data. The real data and the simulation agree well for the longitudinal distribution in the top plot, except for some rows in the lower telescope (PMT rows 1-16). For the lateral distribution in the lower plot, the agreement is good for the lower mirror, but less good for

parameter	value
air condition	
date	Sep.5th.2010 04:15 (UTC)
temperature	26.8 °C
pressure	853.1 hPa
relative humidity	11.9%
beam parameters	
beam energy	41.1 MeV
beam spot size	5 mm×10 mm

Table 3: The input parametes of the air-shower priduction

the upper telescope (PMT rows 17-32). In the future, we expect to evaluate background photons from beam losses in the beam line, and calibrate the FC system.

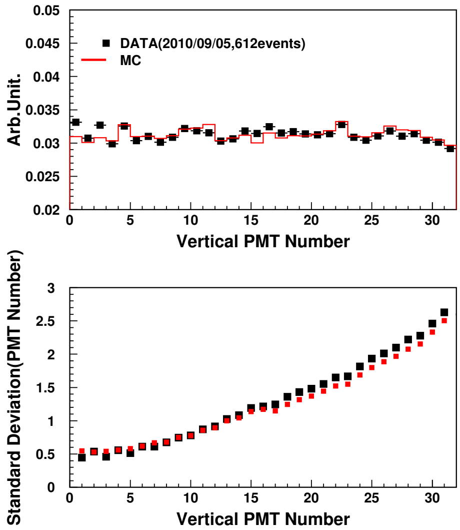

Figure 6: The comparison of longitudinal and lateral distribution between real data and simulation .

4 Summary

The electron light source(ELS) is anelectron linear accelerator as an unique light source for the absolute energy calibration of the fluorescence detectors(FD). The ELS was installed in TA site in in March 2009. We started the operation from Sep.2010, and started the data analysis with real data and monte carlo simulation.

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