Absolute energy calibration of FD by an electron linear accelerator for Telescope Array

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Abstract. The primary energy of the ultra-high energy cosmic rays(UHECR) are measured with the number of fluorescence photons which are detected with fluorescence detectors(FD) in the Telescope Array experiment(TA). Howevery since there is large uncertinty as 19 % in the measurement of the energy scale, the most important theme is improvement of the energy calibration. The electron light source(ELS) is a small electron linear accelerator for new energy calibration. The ELS is located 100 m far from the FD station, and injects electron beam which is accelerated to 40 MeV energy into the sky. We can calibrate the FD energy scale by detection the air shower directly which is generated by the electron beam. The ELS was developed in KEK Japan, and moved to the TA site in March 2009. We started the beam operation in September 2010, in consequence we detected the air shower which was generated by electron beam in the air. The output kinetic energy of the electron beam was 41.1 MeV, we adjusted the output charge from 40 to 140 pC/pulse. We expect that we can improve the uncertinty of the energy scale to about 10 % with the ELS, futhermore ELS will be a very useful apparatus for R&D of future UHECR observation.

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

The ultra-high energy cosmic rays(UHECR) are most highest energy cosmic charged particles which are detected at the earth. Although their source points, the mechanism of their generation, their chemical composition and their acceleration and propagation system from their source to the earth are not understood. The candidates of their source point are extra-galaxtic AGN and gamma ray bursts. Greisen, Zatsepin and Kuz'min predicted that the UHECR loss their energy by Δ resonance with cosmic microwave background during propagation from source point, thereby they can not arrive from more than 100 Mpc far from the earth(GZK cutoff)[1][2]. The candidate of their chamical composition is proton or ion.

The two large experiments have started the observation of UHECR. One is the Telescope Array(TA) experiment which have started from 2008 at Utah state in north U.S. The TA experiment has the hybrid type detectors which consist of 507 surface scintillation counters and 34 fluorescence telescopes(FD)[3]. Meanwhile the another one is the Pierre Auger Observation which have started from 2004 in Argentina[3], The Pierre Auger observatory has also hybrid type detectors which consist of about 1600 water cerenkov detectors and 24 FDs. The TA, HiRes experiment and the Pierre Auger observatory have reported their important results in recent years[4][5][6][7][8][9].

MEASUREMENT OF UHECR WITH FD

Measurement of the energy of the UHECR is most important for UHECR observation. The TA and PAO experiments measure their primary energy by calorimetic method. The UHECR which inject in the earth generate giant cascade shower by collision with the atmospheric molleculars. Then the FD at the ground detect the fluorescence photons which are emitted from the air shower, and the primary energy can be calculated by using the nubmer of the detected photons. The TA experiment developed a new reconstruction method named as inverse monte calro method[10].

There are many calibration parameters for measurement of primary energy. The main important calibration parameters are the absolute fluorescence yield, their spectrum, the atmospheric condition, the attenuation coefficients and their phase function, and the FD. The calibration parameters of the FD are reflectance of the mirrors, the transparency of the UV-pass filters, the quan-

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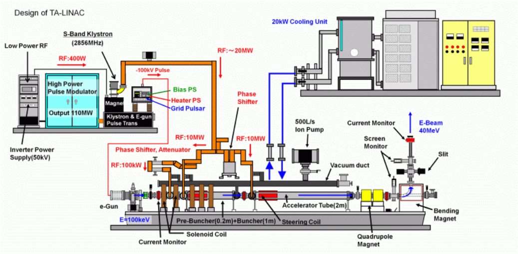

FIGURE 1. Illustration of the Electron Light Source. The ELS consists of the S-band high power rf system, the electron source, accelerator tubes and the 20 kW cooling power unit. The 40 MeV electron beam is bent by the 90° bending magnet to the vertical upward, and injected into the sky.

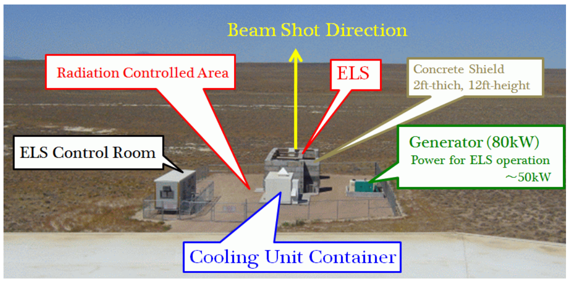

FIGURE 2. Photograph of the ELS site in TA site. The ELS site was constructed at the 100 m far from the FD station. Three containers and the 80 kW power generator were installed in the ELS site. The area inside the safety fence was defined as the radiation controll area.

tum efficiency, the collection efficiency and the gain of the photomultipliers(PMT). The usual energy calibration need measurement of each calibration parameter. The TA experiment uses the absolute fluorescence yield and spectrum which were measured with electron beam or isotopes in laboratories.[11][12][13]. The atmospheric condition are measured by radiosndes, or we use U.S. atmospheric standard model. The attenuation parameters in atmosphere are measured with the lidar systems[14]. Thereby the calibration parameters of the FD, we measured the refrectance of all of the mirrors regularly, and calibrate the relative gain of the PMT with Xe flasher[15]. On the other hand, we use the transparency of the filters as catalog value. However, these calibration parameters have large uncertainties. The total systematic uncertainty in energy scale of the FD which was estimated is 19%. The main systematic uncertainties are the fluorescence yield(12%), the atmosphere(11%), the detector(10%)[16]. Thus, the improvement of the systematic uncertainties of the energy measurement is most important for UHECR observation.

ELECTRON LIGHT SOURCE

We proposed a new absolute energy calibration method with an electron linear accelerator(Electron Light Source;ELS) which can calibrate all of the parameters in a lump except atmosperic attenuation[17]. The ELS is an unique and first apparatus which be used for end-to-end absolute energy calibration of the FD. The ELS is located at 100 m far from the FD, and the vertical upward accelerated electron beam is injected into the sky. The typical output beam is 40 MeV $\times$ $10^9 e^-$/pulse$\times$0.5 Hz. The merit of the using of the calibration with the ELS is that the calibration includes the fluorescence yield from the energy deposit in the air which can not do with only the laser system. The ELS was developed at High Energy Acceleration Research Organization(KEK) in Japan from 2005 to 2008. The illustration of the ELS is shown in Fig.1. The main components of the ELS are the S-band high power rf system which maximum output is 40 MW, the electron source which the output kinetic energy is 100 keV, the prebuncher-buncher tube, the main accelerator tube, a few focus magnets, the 90° bending magnet which are used for energy spectrometer, water cooling unit and remote controll and monitor system. The rf system and the beam line components were constructed for installation into a 40-ft container, while the water cooling unit were constucted for installation into a 20-ft container. We control and monitor of these systems from the other office container for safety from radiation. The ELS is a recycle accelerator which the almost all components in ELS were dismantled from electron position injector in KEK[18][19][20]. The construction of the ELS was completed in January 2008 in the electron-position injector in KEK. We operated until December 2008, and we optimized the 40 MeV beam condition and evaluated their performance of measurement of their energy and beam current[21].

SETUP THE ELS IN TA SITE

After the performance evaluation of the ELS at KEK, the ELS was shipped from Japan and installed in the TA experiment site in north U.S. in March 2009. The preparation for beam operation took from April 2009 to the end of March 2010. We will describe the detail of the preparation in next subsection.

Infrastructure of the ELS

The photograph of the ELS site is shown in Fig.2. We constructed a new site for ELS and installed that at the 100 m far from the FD station. About 40 kW electric power for the ELS operation is supplied with the 80 kW power generator which was installed in the ELS site. In additionary, the electric power is supplied from the generators for FD station due to keep the high vacuum in inner side of the waveguides and the beam lines, and the computures. The preparation of the power was completed in the end of September 2009.

The two air conditioning were installed into the ELS container in order to keep the temperature, and futhermore we installed the 6-inch heat insulators to the outside wall of the containers for protection from the influence of outside air. We use the antifreeze as coolant in cooling system for freeze proofing, because the outside air temperature falls to about -30 °C during winter. The antifreeze is non-toxic propylene glycol which the frozen point is -35 °C.

The optical LAN cables were connected between ELS control container to FD station due to monitor the status of ELS. We installed some cameras inside and outside of ELS container for safety, and we can watch the all of camera's pictures from internet.

Vacuum of the ELS beam line

We must make and keep ultrahigh vacuum inside the electron gun chamber, the beam lines, the waveguides and the klystron. We started making the vacuum of electron gun chamber from October 2009, and we keep the pressure to $\sim 10^{-7}$ hPa, while we started makeing the vacuum inside of the beam lines and waveguides from June 2010, and we keep the pressure to $\sim 10^{-7}$ hPa. The pressure is recorded with the AD converter all the time, and we monitor the vacuum gauge contollers with some cameras.

The Radiation Safety

The ELS is a kind of the radiation generator apparatus, therefore we need the radiation safety management system. University of Utah administrates the radiation safety of the ELS, and the Radiation Safety Officer(RSO) were organized. We assigned on-site RSO and on-site Responsible User(RU). We made some rules that we must operate the ELS by more than two persions, one persion should be on-site RSO and another person should be on-site RU. The safety fence were installed at 30-ft far from the ELS container, and we defined the area inside the safety fence as radiation contolled are in order to keep out any person during ELS operation. The interlock switches were installed at the gate of the fence, if any person open the gate, the interlock will fire and the high voltage power supply and the trigger are stopped. There is a console panel in the control room to turn on the master beam trigger and reset the interlock system in order to prevent the remote control from internet. We must protect against a large amount of γ-rays and neutrons which are emitted from beam line components, bending manget and slit collimator during beam operation. Thus, we installed the concrete blocks which its thickness and height are 2-ft and 12-ft at the outside of the ELS container. Futhermore, the 50 mm thickness lead blocks were also installed surroundings of the vertical beam line include the 90° bending magnet. The radiation dose at the boundary of the safety fence with the installed shield blocks in case of typical beam output was calculated by the radiation science center in KEK, and radiation dose was estimated as $\sim$0.1 μSv/h which is roughly same level as background radiation level.

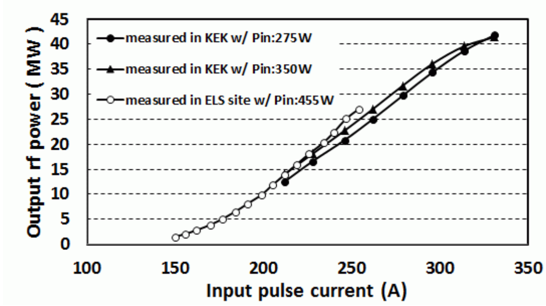

FIGURE 3. The relation between the pulse current into the klystron and the output rf power from the klystron. The closed circle and triangle show the measurement results in KEK. The opened circle shows the results which was measured in ELS site in June 2010. These results are consistent.

The benchmark of the RF the EGUN system

After all of preparation for ELS operation, we made a trial operation of the rf system in June 2010. The rf system consists of the high power pulse modulator which the maximum output power is $\sim$110 MW, and the S-band high power rf klystron. The first item we need to check was the high power pulse from the high power pulse modulator, then we detected it. After that, we measured the power of the output rf pulses from klystron by a power meter. As the results of the measurement, we detected the rf pulses which the maximum pulse power was $\sim$27 MW. That power is enough high, because the opimized power which accelerate the electron beam to 40 MeV was $\sim$20 MW in KEK. Fig.3 shows the correlation between pulse power of the output rf and pulse current of input high power pulse into the klystron. All of resutls in this figure are agreed in roughly. In consequence, we confirmed that the rf system did not have no problem.

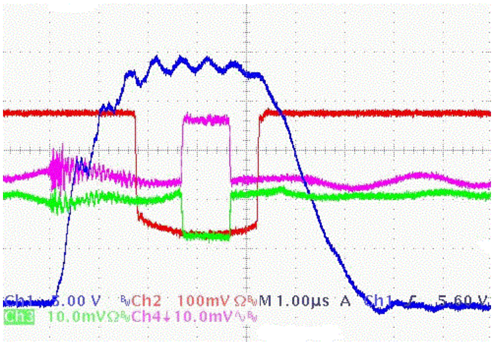

FIGURE 4. Waveforms of the electron beam pulse and rf pulse. The blue shows the current pulse input into the klystron. The red shows the output rf pulse. The purple and green show the ouput pulse from current monitors which installed at the horizontal beam line. The pulse width of the electron beam is 1 μsec.

TABLE 1. Beam Operation and Tuning Parameters

Parameters	value
repetaion	0.5 Hz
RF system	
charging High voltage	37 kV
input current into klystron	234 A
input voltage into klystron	-256 kV
input rf power	400 W
output power from klystron	20 MW
Electron gun	
heater current	1.5 A
bias voltage	80 V
gride pulse voltage	-100 V
gride pulse width	1 μs
Output Energy and Charge	
estimated output Energy	41.1 MeV
output Charge	40-140 pC/pulse

Afterward of the trial operation of the rf system, we made the electron gun system. The ELS uses the electron gun which the output energy is 100 keV. The -100 kV high voltage which is applied to the electron gun are supplied from the same high power pulse modulator for rf system. The electron source is dispenser cathode, and we control the output current by adjustment of the bias voltage, and the heater current. While, the output voltage of the grid pulse which are used as trigger pulse was fixed as -100 V$\times$1 μsec. The electron beam were detected with the current transfer along the beam line in the end of June 2010. Above all, the trial operation of the two main systems of the ELS were completed.

THE BEAM OPERATION AND THE FD OBSERVATION

We started the accelerated beam operation from early of September 2010. In first step, we detected the accelerated beam along the horizonral beam line with the current transfers and the beam profile monitor. After that, we detected the vertical beam which was bent with the 90° bending magnet. We estimated the the output beam energy as 41.1 MeV which was calculated by the magnetic field of the 90° bending magnet. The absolute beam charge can be measured by the faraday cup which is installed at the end of the vertical beam line. The accelerated beam pulses which were detected with current monitors and output rf pulse are shown in Fig.4. The electron beam which the pulse width is 1 μsec was accelerated in the timing with the rf pulse.

The accelerated electron beam was injected into the sky after beam conditioning, then the FD detected the fluorescence photons from the air shower. The output power of the beam was 41.4 MeV$\times$40-140 pC/pulse$\times$0.5 Hz.

Fig.5 shows the first image of the shower event detected with the FD, and the histogram of the longditudinal development of the shower. Table.1 describes the beam operation and beam condition parameters. The beam condition parameters were almost same as the final parameters of the trial operation in KEK, thus, we confirmed the reproductibility of the beam conditioning in KEK.

METHOD OF THE ENERGY CALIBRATION

The main aim of the using of ELS is absolute energy calibration of the FD. In this session, we describe the principle of the method of the absolute energy calibration with the ELS. We can calibrate the all of the parameters, which we need for reconstruction of the primary energy of the UHECR with the FD, in a lump because we can compare between the energy deposit in the air by the electron beam and the FADC counts detected with FD. The simple calibration method is comparison of the result of the simulation data and real data, and we will correct the calibration parameters which are used in the simulation code. There are two way for the correction of the simulation. The one of the method is comparison of the summation of the FADC counts of all of PMTs between simulation and real data. The correlation between the simulation data and real data can be fitted by linear function. We can define the fitted linear function as the correction function. The definition of the correction function is most simple and easy to calibrate the FD. The second one is inverse monte carlo method which is used for reconstruction of the primary energy of the UHECR with the FD. We define the the total gain from energy

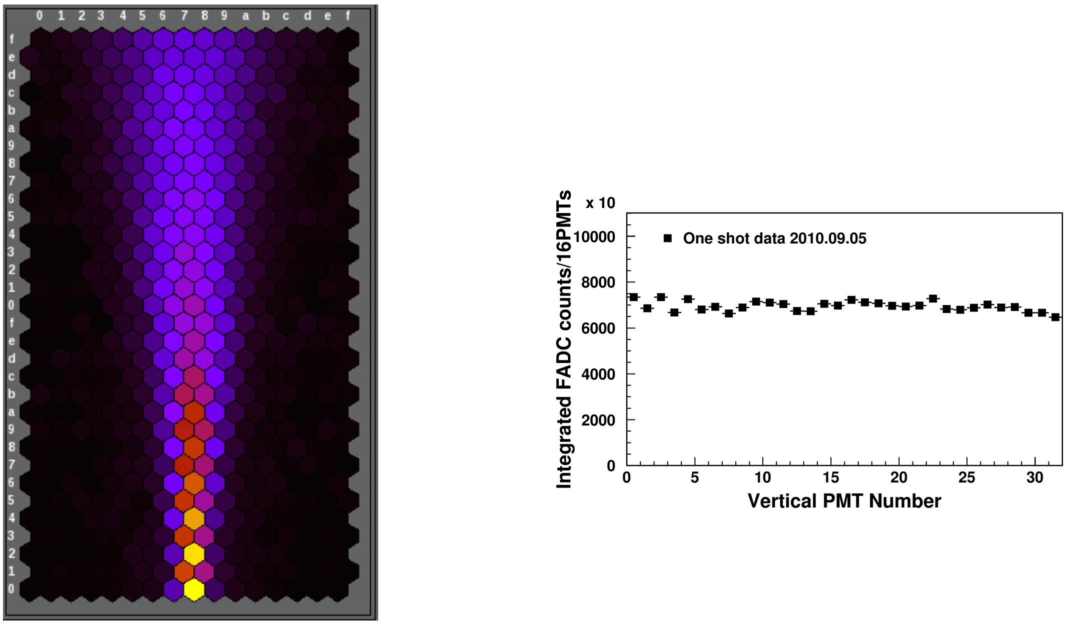

FIGURE 5. left:The image of the first shot of the electron beam from the ELS. right:The longitudinal development of one electron beam pulse. The horizontal axis is vertical PMT number, and the vertical axis shows the summation of FADC counts detected in the 16 horizontal PMTs.

deposit to FADC count as free parameters, and comparison of the shower longitudinal and lateral developments between simulation data and real data. We can fit the parameters with the maximum likelihood fitting.

We use Geant4 simulation code as the shower generator of electron, and we calculate the energy deposit in the air. Geant4 is one of the most famous code which simulates the interaction and tracking of the particles. However, we will use another shower generator for corss check and simulation code dependence. It is nessesary that we use the correct air condition parameters, for example the temperature and pressure and humidity, because the energy developmenet depends on the air condition. We use the air condition parameters which are recorded with the weather station in the ELS site. Then, we use the FD simulation which was developed by the TA experiment.

We describe the expected improvement by the absolute energy calibration with the ELS. The main source of the systematic uncertinties in the fluorescence yield is the absolute yield. The absolute fluorescence yield is measured by several experiments. However since these results have large discrepancy[11], futhermore each result has large systematic uncertaintly. In contrast, our absolute energy calibration with the ELS has no systematic uncertanty in absolute fluorescence yield. Moreover, we can evaluate the absolute fluorescence yield of each result. The remaining uncertainty about the fluroescence yield is its spectrum. However the uncertainties of the spectrum is smaller than its absolute yield, we can improve the systematic uncertainties of the fluroescence yield to a few %. The absolute energy calibaration with the ELS also has no systematic uncertainies in the FD ideally. However, the ELS is no protable and we can calibrate only two FDs. We will calibrate the remaining FDs by using the new portable laser system which was developed for the photon counts calibration of the FD. The systemtic uncertainties of the FD will be imporved to a few %. In finally, we can not ignore the systemtics of the electron beam parameters. The important quantities are total energy depoit in the air and beam current in each pulse. The uncertainty of the total energy deposit in the field of view is small, because it does not have strong dependence on the kinetic energy of the electron beam. On the other hand, the uncertainty of the beam current is the uncertainty of the absolute energy calibration with the ELS directory. According to the results of the evaluation of the ELS peformance in 2008 at KEK, the accuracy of the measurement of the ELS beam with current monitor as about 4%[21]. The total systematic uncertainties of the energy scale can be improved to about 10%. In future, we will improve the final systematic uncertanties less than 10% with the new LIDAR system for the more precise measurement of atmospheric attenuation.

THE APPLICATION OF THE ELS

The goal of the ELS is the estabishment of the new method of the absolute energy scale calibration for the

FD. Moreover, the ELS is the usefull apparatus for R&D of the several new UHECR observation. For example, there are some methods for observation the air shower with microwave. One of the method of the observation is direct detection of the microwave synchrotron or bremsstrahlung. The microwave synchrotron photons is emitted by the electron in the geomagnetic field. The microwave bremsstrahlung is emitted by the collision of the air moleculars and the free electrons which are generated by the ionization[22]. Another way of the observation is using the bistatic radar which is detection of the refrection microwave which is sent from the transmitter to air shower. The power and time variation of the refrection microwave depend on the primary energy of the UHECR. The TA experiment has plans for the direct detection of the microwave synchrotron or bremsstrahlung, and the refrected microwave. The ELS is usefull and unique artificial microwave source, and it is expected that we can detect the direct microwave, and the refrected microwave from the air shower generated by the electron beam.

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 construction of the ELS was started from 2005, and was completed in 2008 at KEK Japan. We made the trial operation and evaluated its performance. The ELS was carried out from KEK and installed in the TA site in Utah state, north U.S. in March 2009. We finished the environment improvement, the radiation safety management system and the radiation protection and safety interlock system for ELS operation until the end of May 2010. We operated the rf system and electron gun system without any problem in June 2010. Then, we operated the accelerated electron beam and injected the vertical upward beam in to the sky. The FD detected the fluorecnce photons emitted by the electron beam in the air. Our goals are improvement of the systematic uncertainty, from 19% to about 10%, and the estabishment of the new method of absolute energy scale calibration with the ELS. We expect that the ELS can be used for R&D of new UHEC observation by detecting the microwave.

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