An Electron Linear Accelerator for end-to-end absolute energy calibration of atmospheric fluorescence telescopes of the Telescope Array experiment

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***Abstract*. The energy of primary cosmic rays can be calculated using the fluorescence technique, but no absolute energy calibration source exists. We built an electron linear accelerator (ELS, Electron Light Source) to perform an end-to-end absolute energy calibration of the Telescope Array fluorescence telescopes including everything from the air fluorescence spectrum through the telescope optics and electronics. The ELS was constructed at KEK in Japan in February, 2008 and performed a series of beam tuning and tests through the end of 2008. At the beginning of 2009, the ELS was moved to one of the fluorescence detector station in Utah. Beam operation in Utah will begin this summer. We will report the results of beam tests at KEK and detail the status of operations in Utah.**

***Keywords*: CosmicRay, Calibration, Linac**

I. INTRODUCTION

The Telescope Array(TA) experiment, which was started from 2008 in Utah, U.S, is a observatory of the Ultra High Energy Cosmic Rays(UHECRs), and the Pierre Auger experiment is also started to observate the UHECRs in Argentina from 2004 [2]. Obsevation of the UHECRs is important field for searching the point source of the UHECRs in extra galaxy, for understanding their generation and acceleration mechanism, and for the particle physics beyonds standard model. It is most important to measure the primary cosmic ray for observation of the UHECRs. In AGASA experiment [1], the energy of the primary cosmic rays was calculated by using particle density at the ground of air shower which was generated by cosmic ray by using surface detector. On the other hand, in HiRes experiment **??**the energy of the primary cosmic ray was calculated by using fluorescence light which was emitted in air shower. However, there is a large uncertainty in the energy measurement. The total systematic error of AGASA experiment and HiRes were 18% [1] and 17% [4],respectively. The most important thema is improvement of accuracy of energy measurment. TA experiment and Auger experiment [3] is hybrid observation wihch use surface detector(SD) and fluorescence detector(FD) in order to reduce systematic error by complementaion. However, the main reason of the large uncertainties is that there is no calibration source for cosmic ray energy measurement, and then we need new calibration source.

II. ELECTRON LIGHT SOURCE

Electron Light Source(ELS) is a electron linear accelerator which is installed at the distance of 100 m from FD building for absolute energy calibration with FD. An electron beam from ELS which is injected into the air generates air shower and fluorescence light is emitted. Fluorescence light can be detected by FD, and we can reconstruct the energy deposit by electron beam in the air. Moreover, the energy of output electon beam is konwn value, we can estimate the energy deposit in the air by simulation exactly. The absolute energy calibration of FD can be done by comparison of reconstructed energy deposit and estimated energy deposit. This method is an unique end-to-end calibration which we can calibrate all of calibration constants from air shower generation by cosmic rays to ADC counts of FD by using only one calibration source.

TABLE I: The basic specifications of the ELS

the beam energy	$\leq$ 40 MeV
the output current	10^9 e$^-$/pulse
the beam intensity	$\leq$ 6.4 mJ/pulse
the pulse width	$\leq$ 2 μs (typical 1 μs)
the repetition	$\leq$ 1 Hz

The maximum output beam energy is 40 MeV. This is appropriate energy, because electrons in the air shower by the cosmic ray which has energy as 10^{19-20} eV have an energy from $\sim$10 MeV to 1 GeV. The charge of one pulse is 10^9 e$^-$. The total energy deposit of 40 MeV$\times 10^9$ electron beam 100 m far from FD can be scaled to that of 10^{20} eV 10 km far from there. The specfication of ELS is summarized in Table. I.

The detail components of ELS is described in ref.[5]. ELS is consist in a electron gun whose typical energy is 100 keV, a pre-buncer and buncher tube, a main accelerator tube, a 90-degree bending magnet, and a collimator slit. We use four core monitors and one faraday cup as beam current and charge meaurement, and use two screen monitors as beam position monitor. There are five solenoid coils, three steering coils and a doublet tyope quadruple magnets which are used for beam forcusing or correcting the beam direction. We use a high power pulse
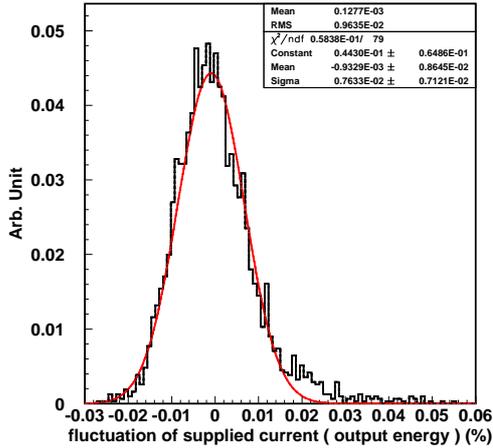
Fig. 1: Fluctuation of output energy and supplied current. Horizontal axis means the residual from mean value. The rms of this distribution is ∼0.01%.

Fig. 2: Result of beam charge measurement

modulator whose maximum output power is 110 MW and a S-band(2856 MHz) klystron whose maximum output power is 40 MW as RF source. We constructed a cooling water unit whose cooling power is 20 kW. ELS was developed in High Energy Accelerator Research Organization(KEK), Japan, and completed in Jan.2008. ELS was operated in KEK from Apr.2008 to Dec.2008, and we evaluated the performance of ELS. Afterward, ELS was move from KEK, and the installation in FD site in Utah, U.S., was completed in Mar.2009.

III. BEAM OPETATION OF ELS IN KEK

The main aim of beam operation in KEK was evaluation of the accuracy of output beam energy and beam current measurement within a few %. The beam operation condition is summarized in Table II.

TABLE II: Condition of Beam Operation

the beam energy	39.8 MeV
the output current	10^9 e$^-$/pulse
the beam intensity	6.4 mJ/pulse
the pulse width	1 μs
the repetition	0.5 Hz
the rf power pulse	17 MW×2.5 μs
the electron gun energy	110 keV
the field of bending magnet	0.61 Tesla

To decide the output beam energy, we measured and calibrated the magnetic filed of 90-degree bending magnet using by NMR in 2007, and we measured the calibration constant of magnetic filed from the correlation between NMR value and supplied current. Because we can calculate the magnetic field from supplied current. We also measured the fluctuation of the supplied current, because it affect the output energy and its direction. The Fig. 1 shows the histogram of fluctuation of supplied current, or output energy. We confirmed that the rms is ∼0.01%. This fluctuation is same as 0.001 rad in the beam direction.

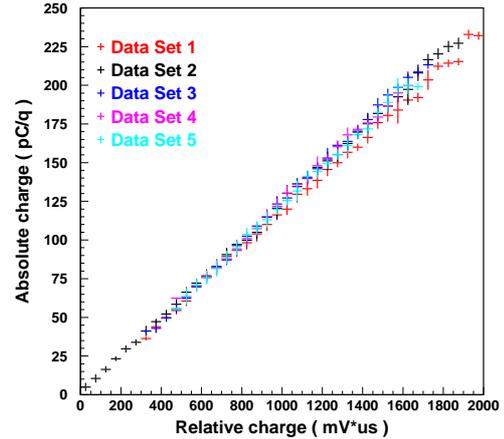The absolute charge of the beam per pulse was measured by using a faraday cup as beam dump an a

electrometer(model 6514 made by KEITHLEY[1]). The resolution of charge measurement by the electrometer is 10 fC, then we can measured the charge of 160 pC with less than 1 % accuracy. We estimated the capture efficiency of beam charge in the faraday cup as more than 99 % by using Geant4 simulation. Therefore, we estimated the accuracy of absolute charge measurement is less than 1 %. We also measued the relative charge the beam per pulse by using four core monitors simultaneously. The output signal from one core monitor which is installed near the output window was amplified by two linear amplifiers(model SA200F3 and 5307 made by NF Corp[2].), and the amplified signal is input into a digital oscilloscope(model TDS3014B made by Tektronix[3]) and the waveform of signal was recorded. We defined the relative charge of the beam as the time integrated value of the waveform, and we measured the correlation between absolute beam charge and relative one in each pulse. The Fig. 2 shows the correlation, and we plotted five data set which was measured in Nov.2008. The difference of each data set was ±5 %, and we can userstand the difference is systematic error. The statistical error of the points of each data set ware ±4 %. From this results, we could measure the beam current of one pulse with ±6%.

The electron beam was collimated by a tantalium slit after 90-degree bending magnet. The optimized width of the slit was 1 mm, which means that the accuracy of output beam energy is about 0.1 %. The ratio of the output beam charge and the output charge from the electron gun is 3-4 %.

We also measured the consumption power for beam operation, beacuse we need a power generator in FD site. The tyipical consumption power was about 30 kW.

IV. INSTALLATION OF ELS IN FD SITE

After beam operation in KEK, the accelerator unit and cooling unit were installed into a 40 ft container, and a

[1]http://keithley.com/
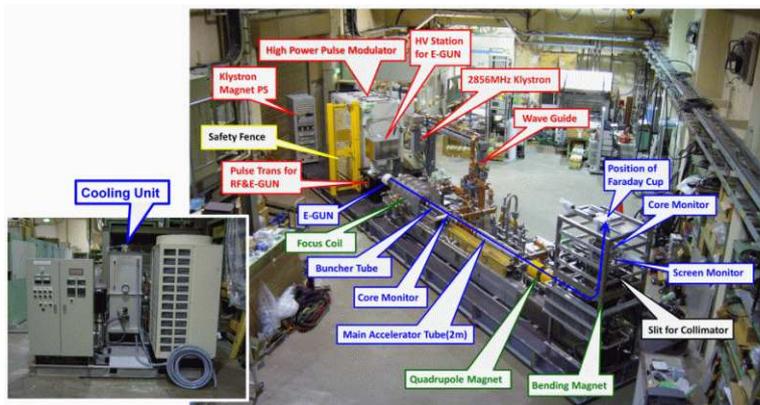[2]http://nfcorp.co.jp/
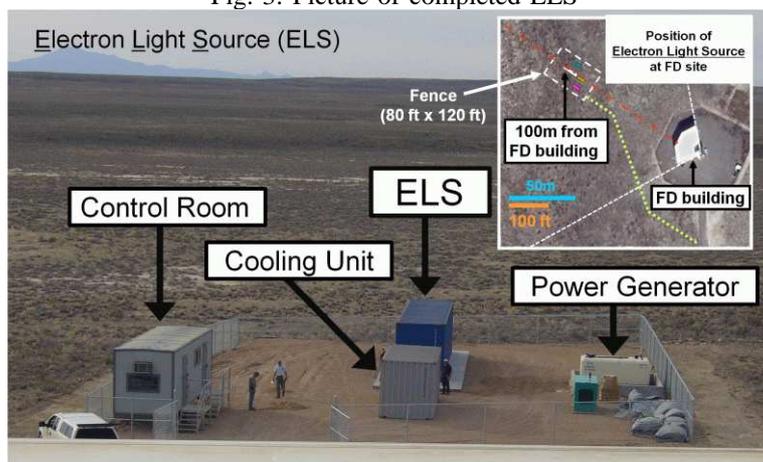[3]http://www.tek.com/

Fig. 3: Picture of completed ELS

Fig. 4: Picure of installation of ELS in FD site

20 ft container, respectively. The two containers were moved from Japan in Feb.2009, and were installed at the distance of 100 m from FD building in Mar.2009. A container for cotrol room and a 75 kW power generator were also installed. The Fig. 3 and 4 shows the picture of completed ELS (Fig. 3) and the installation at the FD site (Fig. 4). The ELS will be monitored and controlled from the control room, and the power is supplied from the power generator. One optical fiber for communication line is connected between control room and FD building in order to monitor from remote. A power line is also connected between ELS and FD building for using ∼30 kW power for backup power. We locate concrete blocks outside of ELS container for shielding from radiation from beam line of ELS. After locating the concrete blocks, we will start the beam operation. We have plan to operate the beam shot and observation of the air shower of electron beam by FD from this summer. We can evaluate the accuracy of energy measurement of FD directly by using ELS. It is expected that the results of absolute energy calibration will be published in this fiscal year.

We also consider the possibility óf calibration of fluorescence yield. The fluorescence yield is meaured by some experiments [6][7][8][9],[10][11], however since these results has large difference and large systematic, it is important that which results we should use in reconstruction of energy of primary cosimc rays. The possibility of fluorescence yield by using ELS is described in ref.[5].

V. CONCLUSION

In Telescope Array experiment, we proposed the absolute calibration of fluoresence detector by using a electron linear accelerator(ELS). The ELS was developed in KEK, and completed to constuction in Jan.2008, then we had beam operation from April to December 2008. We confirmed that the accuracy of output electron beam energy is much less than 1 %, and its fluctuation is less than 0.01 %. We measured absolute and relative beam charge of one pulse by using faraday cup and core monitor, respectively. The systematic error was ±5 %, and the statistical error was ±4 %. The ELS was installed in FD site in Mar.2009, and beam shot will be started from this summer. We expect to publish the result of absolute energy calibration in this fiscal year.

VI. ACKNOWLEDGEMENTS

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