ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF046

PRECISION CHARGE MEASUREMENT OF 40 MEV ELECTRON-BEAM TO CALIBRATE AIR FLUORESCENCE TELESCOPE FOR COSMIC RAY OBSERVATION

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Abstract

An electron beam of 40 MeV has been injected into the air in the field of Utah, USA for the purpose of calibrating the air fluorescence telescope of TA to observe ultra-high energy cosmic rays. The total charge of the injected beam is an important factor for the calibration, and we measured it using a current transformer for each beam injection. The response of the current transformer was calibrated by separate runs using Faraday cups to an accuracy of better than 1%. This will contribute significantly in decreasing systematic uncertainties of TA's energy determination for cosmic rays.

INTRODUCTION

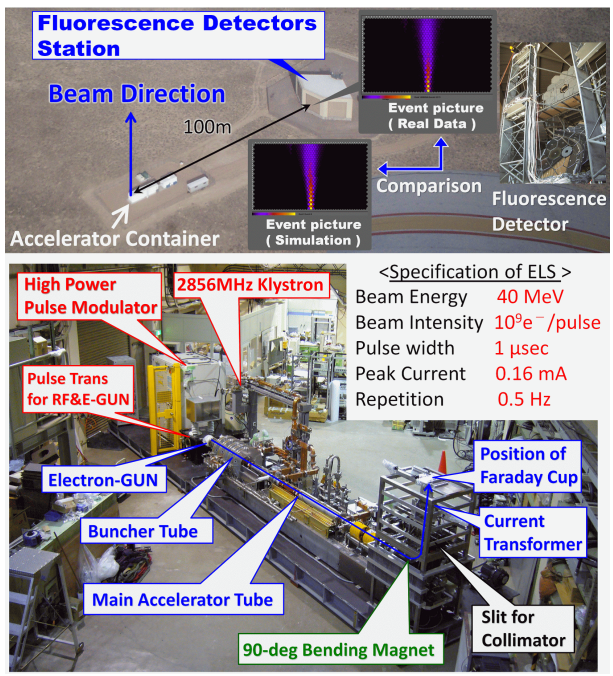

Figure 1: ELS at the TA site in Utah, USA (upper) and its component (lower).

Telescope Array (TA) is an experiment installed in a field of Utah, USA to observe Ultra-High Energy Cosmic Rays (UHECRs) with energies larger than 10^{18} eV [1]. A giant particle cascade is produced when an UHECR enters the atmosphere and interacts. TA measures Air Fluorescence (AF) photons generated by the energy loss of shower particles by the Fluorescence Detector (FD) to determine the primary energy and arrival direction of the UHECR [2]. The measurement is calorimetric and the energy can be determined without heavily relying on a detailed simulation of shower composition and development. Systematic uncertainty of the energy measurement, however, is approximately 20% [3], main sources of which include the uncertainty of the AF yield and the photomultiplier tube gain composing the FD camera.

A compact electron linear accelerator, Electron Light Source (ELS) [4] [5], was developed and installed on one of the TA sites to understand and reduce systematic uncertainties of the FD energy measurement all inclusively (Fig.1). It is installed 100 m in front of one of the TA FDs and produces 30-200 pC of 40 MeV electron-beam for 1 μs duration, and injects it vertically into the air at 0.5 Hz. Generated AF photons are detected by the FD and the signal strength of the FD is directly related with the energy deposits by the ELS beam, thus obtaining a direct end-to-end calibration of the FD. The measurement of injected charge per pulse is one of the most important parameters for this calibration.

CHARGE MEASUREMENT

A schematic of the charge measurement is shown in Fig. 2. We decided to use a Faraday cup (FC) as it is the most straightforward way to determine the beam charge with high precision. However, the FC can not be inserted in the beam line during the injection into the air for obvious reason. We then installed a current transformer (CT) at the exit of the vacuum beam transport just before the FC, and calibrated the CT response with respect to the FC measurement in separate calibration runs. The goal of beam charge calibration is set to 1% accuracy.

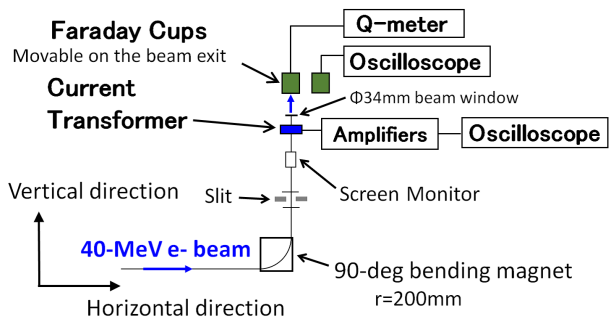

Figure 2: Schematics of the beam charge measurement.

The major noise sources which affected initial CT and FC measurements were from thyratron and klystron of the

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ELS. Some of them were suspected coming along the accelerator vacuum beam transport and came through the beam exit window made by 0.13 mm thick Titanium. They contributed to a few pC equivalent noise in the charge measurement. For the new FC system, the noise was reduced to a negligible level by strengthening the shield of the FC, CT and connecting cables, and installing most of the electronics, network devices in a grounded copper box (Fig. 3).

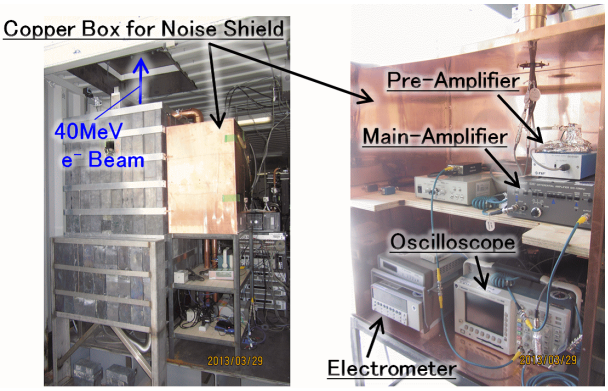
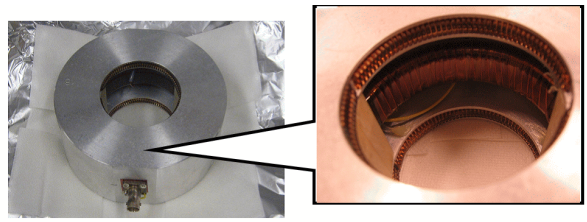


Figure 3: Installed electronics in a noise shield copper box.



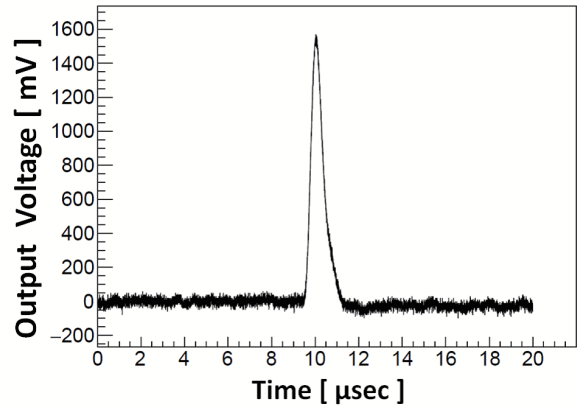


Figure 4: Photograph of the CT (upper), and its waveform when detecting the electron-beam (lower).

Current Transformer

We used a CT developed for the TRISTAN collider and its injector at KEK [6]. It consists of a ferrite core with 25-turn coil. The induced current is taken out by the coaxial cable and converted into a voltage signal by a 50 Ω termination. Since the beam pulse duration is rather long, 1 μs for the standard operation of the ELS, the expected output voltage is approximately 0.3 mV for the beam charge of 160 pC. We used two-stage low noise amplifier system with gains respectively of ~100 and ~20 [1] and recorded the signal with a digital oscilloscope [2]. The time integration of the digitized waveform was used as a beam charge monitoring during the injection into the air. The photographs of the CT and its waveform for an electron-beam of 130 pC are shown in Fig. 4.

Design of Faraday Cup

We developed a series of FCs optimized for the measurement of 40 MeV electron-beam under difficult environmental and electrical noise conditions.

The first version was produced in 2007 and was used for the ELS test operation at KEK in 2008. A cylindrical bulk carbon of 60 mm dia. and 140 mm long was used for stopping the beam and collecting the charge. The carbon stopper was installed in a lead shielding to avoid excessive secondary radiations emitted from the FC. We used a q-meter, an electrometer [3] in Coulombs function, to measure the amount of charge captured by the FC. The minimum resolution of this q-meter is 10 fC and its accuracy is approximately 1.5 pC at 30 °C. An accuracy of ±6% was obtained at KEK for the charge measurement using this FC [7].

This version of the FC was used in the initial ELS operations at the TA site in 2010, but it had a large fluctuation of the dark current and no good reproducibility of measurements was obtained. The main source of the problem was suspected as the leakage of the charge through the glass epoxy, which is mechanically supporting and electrically isolating the carbon stopper from the lead shield. We found the problems worsen when the environmental humidity was high and the isolation resistance was not enough, e.g. after raining. The ELS was installed in a 40-ft long shipping container, and a hole of 20 cm dia. was made in the container roof in order to extract the beam into the air. The hole was protected by a remotely controlled cover box, but a good protection of the FC from high humidity outside the container was difficult.

After a series of trials for improvement, we reached a design of FC with a copper collector, 60 mm dia. and 60 mm long, installed in a Titanium chamber and supported from the chamber using teflon insulators. The Titanium chamber was reduced in pressure to 40 Pa for better electrical isolation and reduced ionization surrounding the copper collector [8] (Fig. 5). The entire chamber was further installed in a copper cylinder to suppress electromagnetic interferences. The beam entrance window of the vacuum chamber is 0.15 mm thick Titanium and the copper shield window was 0.1 mm thick. The capture rate of 40 MeV electron beam was estimated to be 97±1% by GEANT4 [9] and FLUKA [10] simulations using the measured beam spot of 10 mm dia. on the FC. The loss of back-scattered electrons

[1] NF corporation, model SA-200F3 and 5307.
[2] Textronix, model TDS3014C
[3] Textronix Keithley, model 6514.

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by the copper collector and beam windows was less than 1%. We produced a pair of such FCs in 2013, installed them on a horizontally movable stand by motor-sliders to remotely position or remove from the beam axis, thus we could switch from the calibration run to the injection into the air smoothly. Two FCs are identical in construction, and one is readout by the q-meter and the other is connected to the digital oscilloscope via 50 Ω coaxial cable for waveform recording. The purpose for using two readout devices is to make sure the results are unaffected by the difference of signal integration intervals, the beam rate (2 s) for the q-meter, and beam spill duration (1 μs) for the oscilloscope. We wanted to confirm the q-meter readout is not contaminated by additional noise pick-ups and droops out during the signal integration interval.

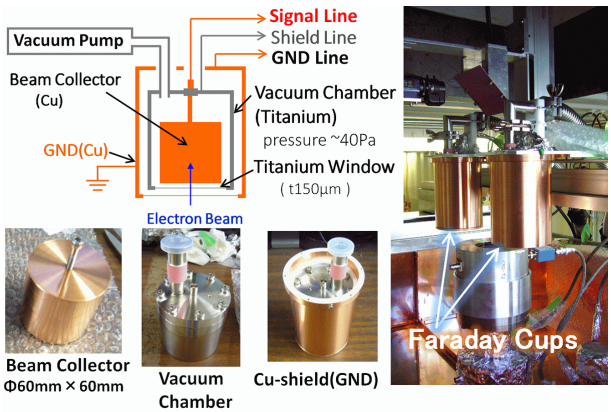

Figure 5: Vacuum chamber type FCs.

BEAM CHARGE MEASUREMENT

The latest result of the beam charge measurement in 2016 using the vacuum chamber FC and the CT is shown in Fig. 6. During this measurement, ELS was operated at 0.5 Hz and its beam current was slowly scanned between 30 and 200 pC by tuning the electron gun current. The beam was first measured by CT before being stopped by one of the two FCs inserted in the beam line. Fig. 6 is the scatter-plot in which the integrated charge of the FC (in Y) is plotted against the integrated signal of the CT (in X) for each ELS beam shot. The plot demonstrate a good linearity between FC and CT measurements, giving a fitted slope of 0.1356±0.0003 for the q-meter measurement and 0.1354±0.0003 for the oscilloscope measurement. Two measurements agree within 0.2%. Fig. 6 also shows the result of a separately performed CT calibration using 1 μs wide wire current generated by a function generator going through the CT. A slope of 0.1400±0.0002 was obtained for this calibration, which is 3.3% larger than above two slopes obtained by the FCs. The results are also plotted in Fig. 6 after correcting 3% charge loss, or 97% capture rate of the FC, to compare with the FC charge measurement results.

CONCLUSION

The ELS was developed to calibrate the energy measurement of UHECRs for TA. The total charge of 40 MeV electron beam injected into the air is an important parameter for the calibration, and we measured it using newly developed vacuum chamber type FCs and a CT simultaneously. All three measurements, two by FC using q-meter or oscilloscope, and one by CT after test-pulse calibration and FC capture rate correction, are consistent within 1%. Amount of systematic uncertainties for each measurement is being studied now, but above results suggest we have achieved an accuracy of about 1% for the ELS beam charge measurement. This is sufficiently accurate to be used for the precise energy calibration of the TA experiment.

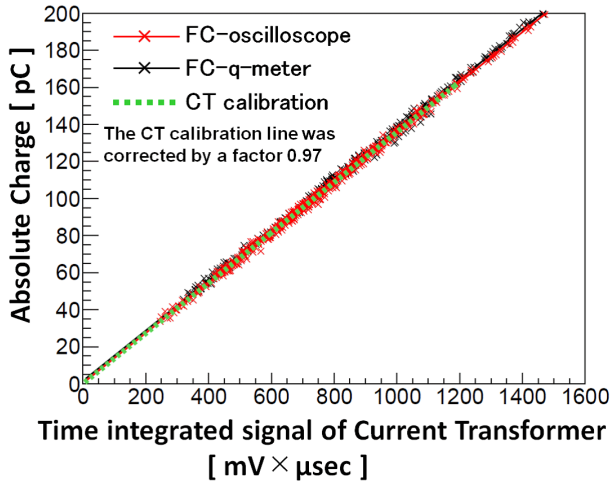

Figure 6: Beam charge measurement with the FC and CT in 2016.

ACKNOWLEDGEMENTS

We appreciate colleagues in TA for interesting discussions, and experts in KEK and SLAC for giving us encouragements and advises to achieve a precision in the beam charge measurement.

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[9] GEANT4, `http://geant4.cern.ch/`

[10] FLUKA, `http://www.fluka.org/fluka.php`