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Instrumentation for sFLASH

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We will report on the setup and calibration of the instrumentation for sFLASH. The sFLASH experiment is a measurement of the air fluorescence from ~10^{21} eV artificial air showers developed in an alumina target by an electron beam provided from End Station A of the Stanford Linear Accelerator Center (SLAC). sFLASH employs Photomultiplier tubes (PMTs) to detect the fluorescence photons and an Integrating Charge Transformer (ICT) to measure the beam current. The PMTs are positioned ~10m perpendicular to shower axis are used to measure the air fluorescence photons. The absolute gain of the PMTs was measured using CRAYS at the Institute of Cosmic-Ray Research, Japan. CRAYS is a PMT photo-gain calibration system consisting of a vessel containing nitrogen gas and a 14μJ nitrogen (337.1 nm) laser. The gain of each PMT was monitored during the course of the experiment using a YAP pulser (YAlO: Ce + ^{241}Am) potted into an ultraviolet optical filter attached to the surface of the PMT window. We expect to achieve an overall experimental uncertainty of ~6%. The ICT (Bergoz) consists of 20 turns of coil to measure the beam current. In sFLASH experiment we set it ~1 m away from beam exit to measure the beam current just prior to entering the target material. The ICT was calibrated with 2 ns pulse generator at Jet Propulsion Laboratory. The calibration uncertainty of the ICT is ~1%.

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1.Introduction

The air fluorescence yield (AFY) is the primary parameter required for the measurement of the energy of Ultra High Energy Cosmic Rays (UHECR) observed using the air fluorescence technique. The Extensive Air Shower (EAS) is a phenomenon in which the interaction between a high energy cosmic rays (>10^{15} eV) and the atmosphere creates a shower of daughter particles. We can observe EAS via fluorescence photons emitted from nitrogen molecules excited by the passage of charged daughter particles. The AFY is typically defined as the number of air fluorescence photons produced per unit of energy deposited in the atmosphere by an EAS. The spectrum of air fluorescence has roughly 20 emission lines in the near ultraviolet. Approximately 26% of the light is in 337 nm line (2P 0–0) of nitrogen molecules.

Previous attempts to measure the AFY have measured the air fluorescence produced by particle beams in air. To better understand the real AFY from atmospheric EAS, we started the sFLASH experiment to measure air fluorescence produced by actual air showers initiated in alumina by ~10^{21} eV equivalent electron beam provided from End Station A (ESA) of the Stanford Linear Accelerator Center (SLAC). We succeeded with taking data in September in 2016. We described the configuration and instruments of last sFLASH experiments in this paper.

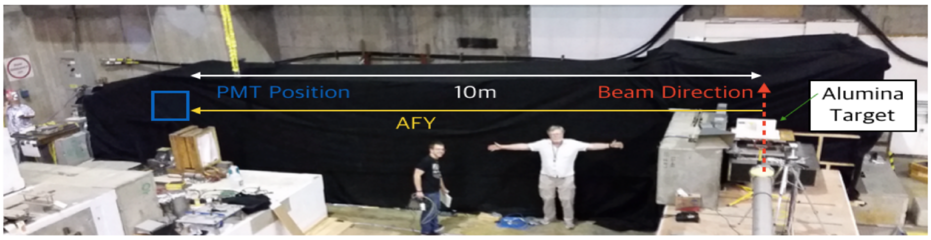

Figure 1. A picture of sFLASH experiment. The shower was generated by beam interaction with alumina target. The PMT for measurement of AFY photons was set 10 m away from shower axis. We covered the path of AFY by block clothes to prevent light from building.

2. Overview of sFLASH Configuration

The sFLASH measured the AFY produced by an air shower of particles developed in alumina from an incident electron beam provided by ESA in SLAC. The definition of the AFY is a number of air fluorescence photons per unit energy deposited in the air. We measured a number of photons using photo-multiplier tubes (PMTs) and estimated the energy deposition by Geant4 simulation with the beam energy obtained from SLAC and beam charge as monitored by Integral Charge Transformer (ICT).

Figure 1 and 2 show a picture and a schematic of final setup and configuration of sFLASH during September 2016 in ESA. We installed the PMTs ~10 meters perpendicular from beam line and ICT between the movable table with alumina brick targets and the beam dump. To reject unexpected photons from extraneous sources and gamma rays from targets and beam dump, we covered the area including the PMTs and air shower volume with black cloth to create a dark box and set concrete shields between the PMTs and potential noise sources. A window of width 1000 ± 1 mm in beam direction was set ~94 cm away from shower axis to precisely limit the volume of energy deposition viewed by the PMTs. The window was optionally blocked by a remotely controlled shutter to permit the measurement of the background contribution to the air fluorescence signal. The total energy in this experiment was close to maximum energy of real UHECR (~10^{21} eV), the so-called GZK limit [1][2]. We develop the air shower by the electron beam interaction with various thicknesses of alumina (AlO3) targets to create 10^3 or 10^4 times more particles or lower energy than the original beam. The target blocks were arranged as shown in Figure 2 (green box) to prevent incident beam electrons from potentially passing through gaps between the target alumina blocks. The alumina blocks are on a remotely controlled moveable table to change the depth of target in discrete steps from 0 to 10 inches.

We evaluated the beam background with PMT during June 2016 and succeeded with taking air fluorescence data in September in 2016 with this configuration. The details the instruments what used for the precise measurement of AFY in September 2016 are described in the following sections.

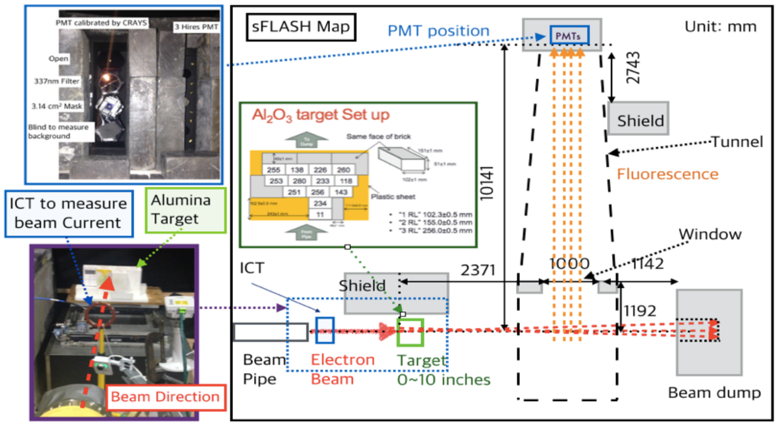

Figure 2. Right) Map of sFLASH configuration, Left top) a picture of PMT setup, sFLASH used 7PMTs. Left bottom) a picture of beam exit, the target is ~2 m away from beam window and the ICT measured beam charge between beam window and target.

2.1 Photomultiplier Tubes

Figure 2 left top is a picture of PMT setup of sFLASH. We used seven PMTs which are the same models used in the air fluorescence telescopes of the TA experiment [3]. The left four PMTs (R9508, HAMATSU) are used at the Black Rock (BR) station positioned at the south-east of TA array. The other three PMTs (XP30620-FL, Photonics) are used at the Middle Drum (MD) station position at the north of TA site. A 337.1 nm narrow bandpass filter was installed on one of BR PMTs to examine the fraction of air fluorescence observed at this wavelength as compared to the total AFY. Another PMT has 3.14 cm^2 mask to evaluate the systematic uncertainty by comparison of a fully exposed PMTs with one with only the central most sensitive area of the photocathode exposed. All of the MD PMTs used a 2.54 cm diameter of mask.

Independent PMT calibrations to get a relation between a number of detected photons and output charge from PMT anode were performed for the two types of PMTs. The absolute gain of the BR PMTs were determined using the CRAYS system at the Institutes of Cosmic Ray Research, Japan. The MD PMTs were independently calibrated using a Roving Xenon Flasher (RXF) at The University of Utah, USA. The RXF calibration was performed primarily as a basic cross check.

The most recent absolute calibration of the RXF was performed in November 2003. The 2003 RXF calibration had an uncertainty of ~7%. The primary absolute calibration for sFLASH is the CRAYS calibration. The calibration constant of GPMT is defined number of detected photons (Np) per output charge from PMT anode (Q_{PMT}) which shown in below,

$$\mathbf{G_{PMT} = Np/Q_{PMT}.} \qquad \mathbf{(1)}$$

The CRAYS is system of PMT calibration which consists of laser and scattering chamber. A PMT was set on the chamber which is orthogonal to laser shooting direction. And 337.1 nm wavelength, ~ 5 ns laser pulse is injected into a scattering chamber filled with 99.9% purity nitrogen gas. 90 degree scattered photons illuminate the PMT photocathode through a 16 cm^2 window which located at a distance of 4 cm perpendicular to the beam axis [4]. The PMTs have a small light source YAP ($YAlO_3$) potted on the UV filter to monitor any relative change in gain between the CRAYS calibration and the measurements at SLAC.

The MD PMTs were calibrated using the Roving Xenon Flasher (RXF). The RXF is used for the absolute calibration at the MD FD and for relative calibration between TA FD telescopes. A PMT and RXF were set ~2.1 meters away each other in dark room. The known output of the RXF was used to obtain a calibration factor for the PMTs. The RXF produces ~11 photons per mm^2 at this distance and near room temperature.

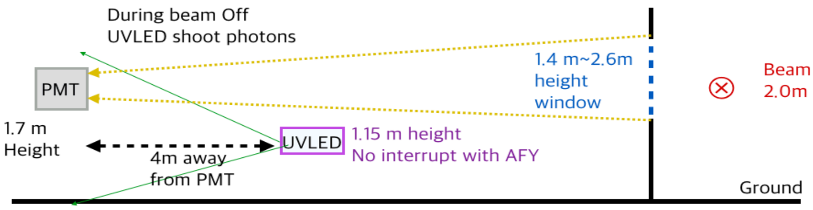

Figure 3. On site calibration using UVLED, The calibration was operated when beam off. The UVLED was position at lower than a path of AFY, so it was not interrupt with AFY measurement.

For on-site monitoring of the PMT calibration, we used a temperature stabilized UV LED light source. The UV LED was developed to prÍovide a new type standard candle for cross calibration between telescopes in TA. The ~367 nm light output of the UV LED can be adjusted in frequency, pulse width, and amplitude. The temperature of the UV LED and associated electronics is stabilized to ±0.01 ℃ accuracy to provide a high stability output independent of the temperature of environment. Figure 3 shows setup in the sFLASH experiment. The UVLED was set ~4 meters away from PMTs and ~1.15 m from the ground for avoiding obscuration of air fluorescence photons from the window. The UV LED settings were temperature = 45.00 ℃, amplitude = 160 mA (~263.2 pJ) , and width = 1.00 μsec. The table 1 is a data set measured at sFLASH and comparison between BR PMT1 and MD PMT5.

PMT Name	HV	Energy [pJ]	Width [us]	Q [nVs]	Gain [Np/nVs]	λ eff	AREA [cm2]	Np/Cm2	Ratio
BR PMT1	679	263.2	1.0	9.439	2540.40	1.007	31.06	7.77E+02	100.00%
MD PMT5	886.6	263.2	1.0	13.670	258.57	0.981	5.06	6.85E+02	88.19%

Table 1, the preliminary result of UVLED run in sFLASH. The discrepancy of photo density between two PMT was 12%.

The comparison of measured photon-density is about ~ 12% discrepancy. This is consistent with the relative uncertainty of each calibration. We are presently evaluating the UV LED light yield and cross calibration between two types of PMTs in a laboratory of the University of Utah. The Number of detected photon (Np) for AFY measurement by PMT was calculated shown in below formula,

$$\mathbf{Np = (Np_{open} — Np_{close})/\omega} \qquad \mathbf{(2),}$$

where NP_{open} and NP_{close} are the numbers of photons calculated from the product of Q_{PMT} and G_{PMT} in the condition of the shutter opened and closed, respectively, to reject background photons. The factor ω is a correction for the wavelength distribution of AFY. As a result of past FLASH experiment, AFY has ~20 wavelengths band spectrum in a range of 290~420 nm. So the ω is calibration factor of GPMT considering of AFY spectrum with the transmittance of UV filter (T_{Filter}) on the photocathode of PMT and quantum efficiency (QE) of each type of PMT shown in below.

$$\omega = \Sigma\ R_\lambda \times T_{filter\_\lambda}/T_{filter\_std} \times QE_\lambda/QE_{std} \qquad (3),$$

where R_λ is a relative yield fraction for wavelength λ and std means the wavelength of light source for PMT calibration. The resulting set of AF Np measurement of two PMTs is shown in Figure 4. The x and y axis in Figure 4 indicate the target depth and detected photon density on the PMT cathode. The red and black dots are the results for BR and MD PMTs, respectively. We obtain a similar relative photon density ratio between MD and BR PMTs as compared to the UV LED. We will further examine the ~12% uncertainty between two types of PMTs with careful calibration of the UV LED.

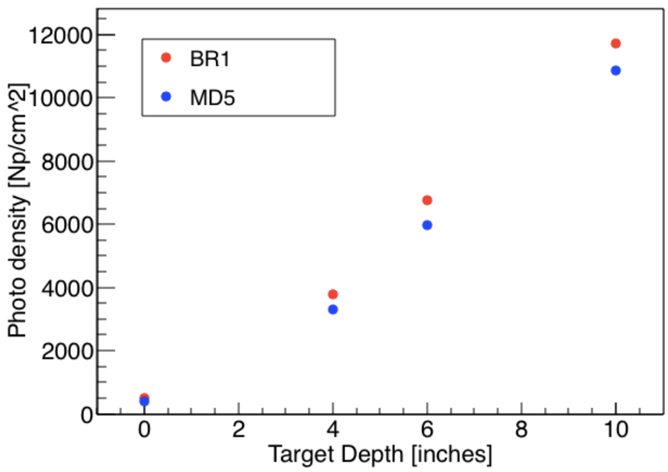

Figure 4. AFY photon density by two PMTs.The x-axis shows the depth of target and the y-axis shows photon density. The photon density is calculated Np over area of photo chathode. The result shows that a BR PMT is about 10% higher than a MD PMT. We will investgate with UVLED calibration.

2.3 Beam Monitoring

We monitored the charge of the beam pulse using an Integrating Charge Transformer (ICT) and a horn. The ICT (In-air ICT, Bergoz) is designed to measure the beam charge with an accuracy of ±0.4 pC in the air. The ICT was positioned ~50 cm from beam exit window between the window and the alumina target. The output of the ICT was read out using an oscilloscope (TDC694C, Tektronix) with a preamplifier.

The number of electrons (Ne) was estimated from the measured pulse area from ICT (Q_{ICT}) multiplied by calibration factor (F_{ICT}). The FICT was calibrated using pulse generator in a laboratory of JPL. The ICT was calibrated with a pulse generator and an oscilloscope. For calibration we used 2 ns and 160 pC pulse which is the similar to conditions from the electron beam used in sFLASH. Then we measured output charge of ICT with preamp which was used in sFLASH and input pulse with an oscilloscope. The result of F_{ICT} is determined 0.08016032 [pC/nVs].

Figure 5 shows number of electrons of a data set. The beam charge was 1.057×10^9 (or ~160 pC) and shoot to shoot fluctuation was 2%. The beam charge was stable while we measure the AFY.

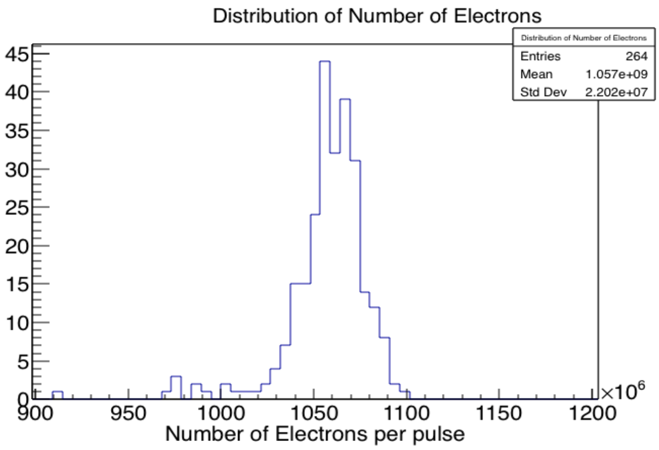

Figure 5. the distribution of number of electrons of beam. The beam charge was about 109 electrons and shot to shot fluctuation was 2% which is stable during beam shooting.

The Beam spot size was monitored using two screens with web cameras. One screen was set on the beam exit window and the other screen was set on the beam dump shown in Figure 6. Beam spot size was ~ 1 cm in diameter at beam exit and dump which means the beam was well focused and does not coherence with ICT.

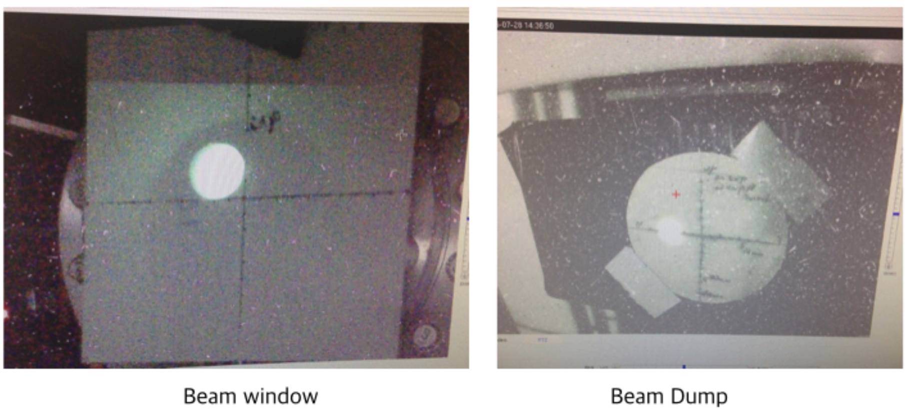

Figure 6. The beam spots at beam window (left) and beam dump (right). The size of beam spots were ~1 cm at beam window and dump. It means beam was well focused and not interuppt with ICT.

2.4 Atmospheric condition

The atmospheric conditions temperature, humidity, and pressure are important parameters of AFY [5]. And PMT gain depends on temperature. The temperature and humidity were monitored by thermometer (1922T, KN Lab) with 0.5℃ accuracy in temperature and 5% accuracy in relative humidity. We set the two thermometers in the AFY dark box and near the PMTs. Figure 7 shows a history temperature and humidity during sFLASH. The temperature and relative humidity were 23.0 ± 1 ℃ and ~40 ± 5%. The local atmospheric pressure was obtained from a SLAC weather station. This weather station is about 100 m away from ESA where sFLASH is operated.

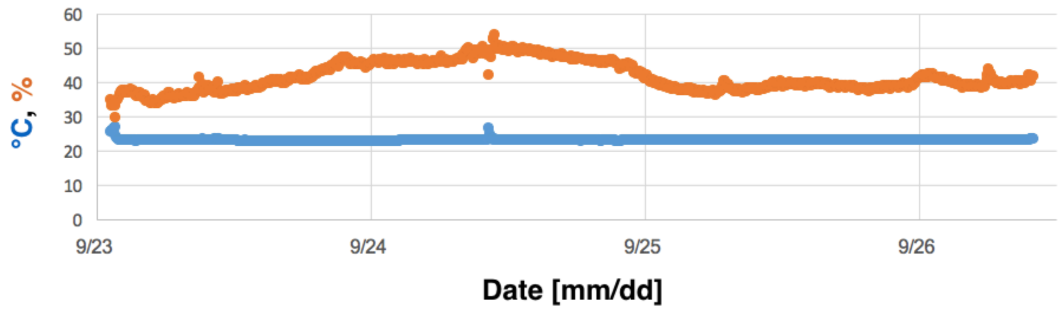

Figure 7. Atomosphereic condition in the ESA during sFLASH. The air termperature and humidity in building were very stable. The temperature was 23.0 ± 1 ℃ and relative humidity was ~40 ± 5 %.

4. Summary

The main target of sFLASH experiment is to measure AFY precisely for the study of UHECRs. We used ~10^{21} eV energy artificially generated air showers which is an energy of primary interest for the study of UHECRs. The shower was generated by electron beam provided from SLAC with various depths of alumina targets. The definition of AFY is a number of AF photons per unit energy deposition. The number of photons is determined by two types of PMTs and energy deposition is estimated by Geant4 simulation with the beam energy and charge measured by SLAC and ICT. To detect AF photons from energy deposition of the shower and to measure the charge of the beam, we set the PMTs 10 m way from shower center and ICT between a bunch of targets and beam window. As an uncertainty of preliminary result is higher than 12% which the main contribution from the discrepancy of photo density between two types PMT. However, we expect to solve this with UV LED calibration. After solving this we can achieve more accuracy result.

We also report the preliminary result of sFLASH in 2016 and simulation of energy deposition in this conference.

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