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The FLASH thick-target experiment

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ABSTRACT

A key assumption in the reconstruction of extensive air showers using the air fluorescence technique is that fluorescence is proportional to energy deposition at all depths in the shower. This ansatz, along with the supposition that particle distribution and energy loss can be well modeled by modern shower simulation software, must be thoroughly verified. We report here the results of the first direct measurement of air fluorescence yield as a function of shower depth, as performed in the thick-target phase of the FLASH (FLuorescence in Air from SHowers) experimental program at the SLAC Final-Focus Test Beam facility. We compare observed fluorescence light yields as a function of shower depth to concurrently measured charged particle yields, to the energy deposition predictions of the EGS and GEANT software packages, and to empirical energy-deposition models. We also examine the extent to which the relative yield versus shower depth is independent of wavelength within the fluorescence spectrum. We find the proportionality hypothesis to be well supported by the data, validating the use of fluorescence profiles in the study of ultra high energy cosmic rays.

1. Introduction and motivation

The purpose of the FLASH (FLuorescence in Air from SHowers) thick-target experiment is to probe fluorescence yield dependence on electron energy over all relevant energies; and to simultaneously check the hypothesis that nitrogen fluorescence is proportional to energy deposition dE/dT, a key assumption in air shower modeling. The SLAC facility [1] provides a unique opportunity in this regard, readily providing 28.5 GeV electrons in bunches of a few $\times 10^7$ particles per pulse. That is, a single SLAC test beam pulse is capable of producing an electromagnetic shower of composition similar to that generated by a 10^{18} eV cosmic ray.

Fig. 1 illustrates the development of an electromagnetic shower in alumina (Al_2O_3). The strategy of the FLASH thick-target experiment is to produce a shower with characteristics similar to an extensive air shower in the lab, and then compare the air fluorescence light observed at different depths in the shower with observed energy deposition models.

2. FLASH thick-target apparatus

The FLASH thick-target apparatus is shown schematically in Fig. 2. The electron beam is incident from the right on the variable-thickness alumina "stack". Ceramic alumina is chosen as the radiating material due to good thermal properties along with possessing a critical energy similar to that of air. The fluorescence vessel and ion chamber sit downstream of the stack. Internally, the fluorescence vessel is lined with flock paper and baffled to suppress reflected light, and the optical path is bent twice through 90° and surrounded by lead to reduce stray particles hitting the photomultiplier tubes. Drop-in shutters and band-pass filters allow background and wavelength-dependence studies, respectively.

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Six parallel photomultipliers viewed the fluorescence vessel. Two of these PMTs were permanently optically isolated from the fiducial volume as a means of monitoring backgrounds. Each PMT was illuminated by a LED, for monitoring gain stability.

The fluorescing medium in the thick-target vessel is ambient SLAC air. No special steps, e.g. forcing air circulation with fans, are taken to reduce ozone buildup in the chamber. The stability of the detector response over time (described further below) was taken as evidence that this was not a significant effect.

Downstream of the fluorescence vessel, a helium ion chamber provided a direct measurement of the ionization produced by beam particles. The ion chamber was an important crosscheck on the data and simulations used in these studies.

3. Data and analysis

An example of the raw data collected by the FLASH thick-target vessel is shown in Fig. 3. Straight-line fits are applied to these scatter plots, resulting in ADC/(beam charge) measurements at each nominal depth in the shower, with (background) and

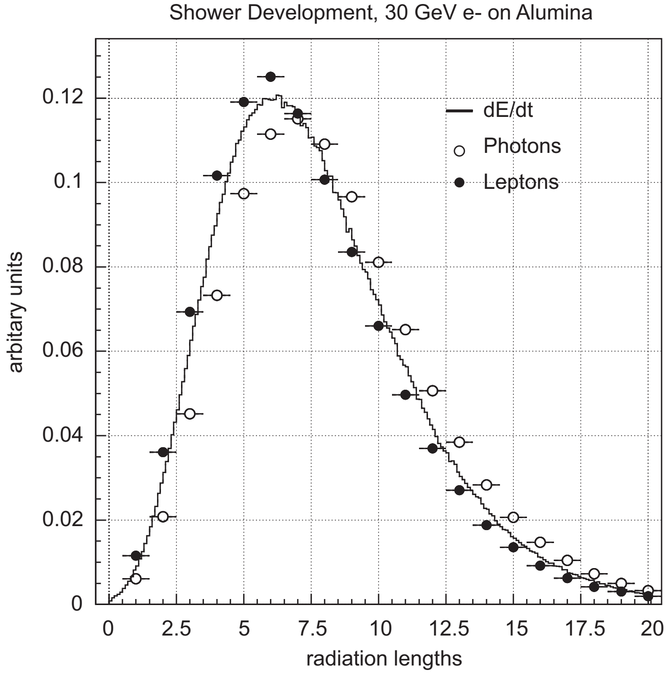

Fig. 1. Energy deposition, photon and lepton counts (arbitrary vertical scale) for an electromagnetic shower generated by 30 GeV electrons incident on alumina (Al_2O_3).

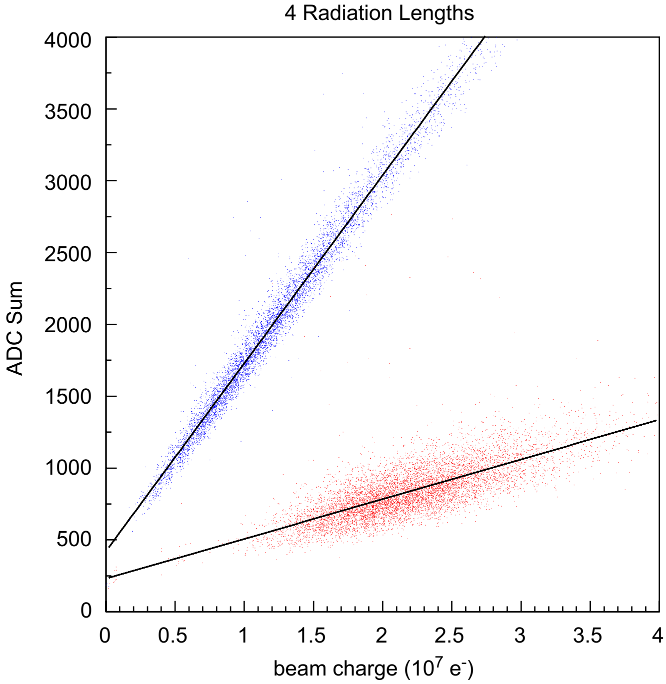

Fig. 3. Raw data collected by FLASH thick-target vessel, with four radiation lengths of alumina in the beam path. Blue: Sum of four PMT ADC's versus beam charge, optical shutter removed. Red: ADC sum versus beam charge, optical shutter in place (lower marks).

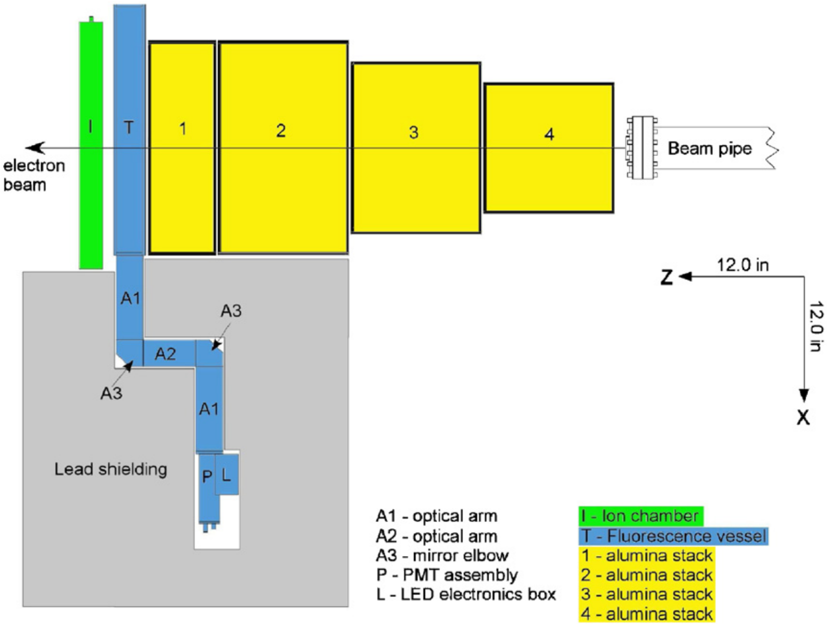

Fig. 2. Schematic of the FLASH thick-target apparatus. See description in the text.

without (signal plus background) the optical shutter in place. The difference in slopes is the background-subtracted signal for a given detector configuration.

Several series of runs at nominal depths of 2, 4, 6, 8, 10, 12 and 14 radiation lengths of alumina were taken as a check of signal stability. In Fig. 4 the signals from these runs are superimposed. The RMS variation in points is approximately 0.8% at six radiation lengths and 7% at 14 radiation lengths, consistent with expectation from statistical fluctuations.

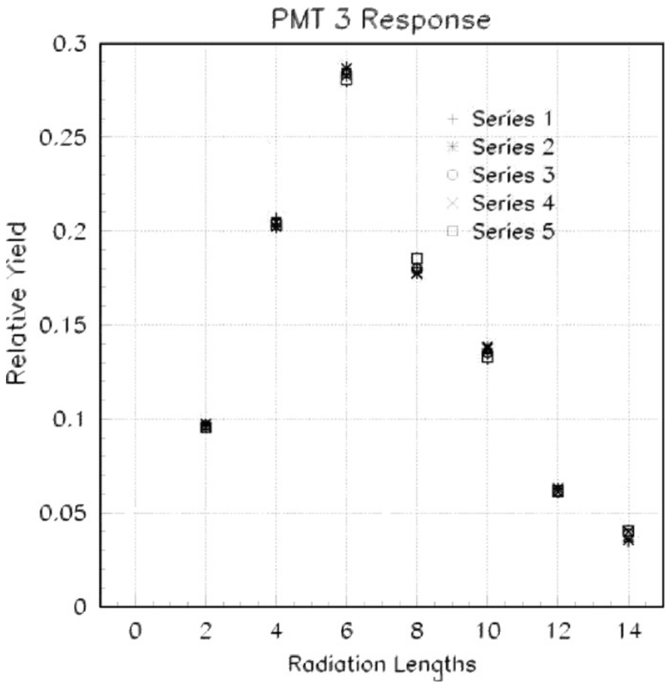

Fig. 4. Signals versus alumina stack depth for five series of runs. Data from runs individually normalized to unit area.

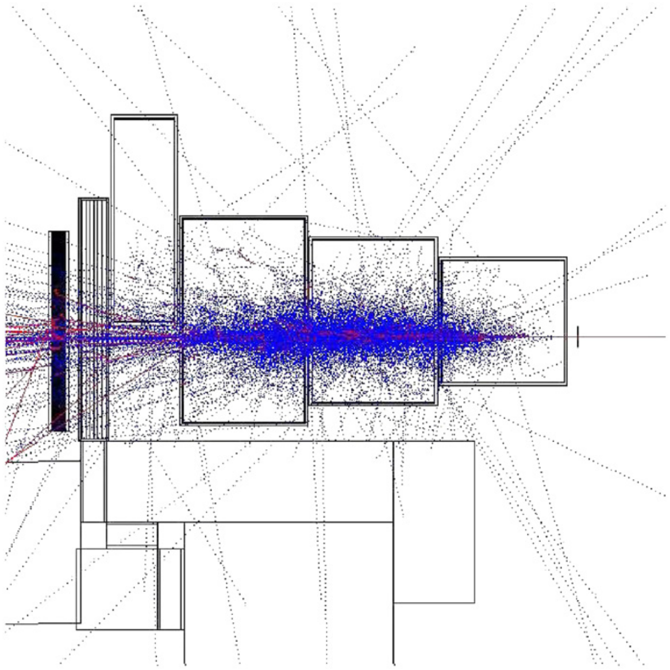

Fig. 5. GEANT 3.2 simulation of a single 28.5 GeV electron incident from the righton a 12 r.l. alumina stack.

Comparison with energy deposition models was carried out by independent groups modeling the detector with the EGS4 [2] and GEANT 3.2 [3] simulation programs. Fig. 5 shows a typical GEANT-simulated interaction, illustrating the attention to detail taken in this detector modeling.

Fig. 6 shows the results of comparing the EGS energy deposition (normalized to unit area) to the average of PMT signals from various run series. The ratio is well within ±5% of unity over the full range of radiator depths probed.

We can also make use of the GEANT and EGS simulations, as well as the ion chamber data, to demonstrate that the relative fluorescence yield can be very simply parametrized. In Fig. 5, one can see that the final (2 r.l.) alumina block was not completely outside the generated shower and actually “absorbed” some of the fluorescence signal for the configurations in which it was

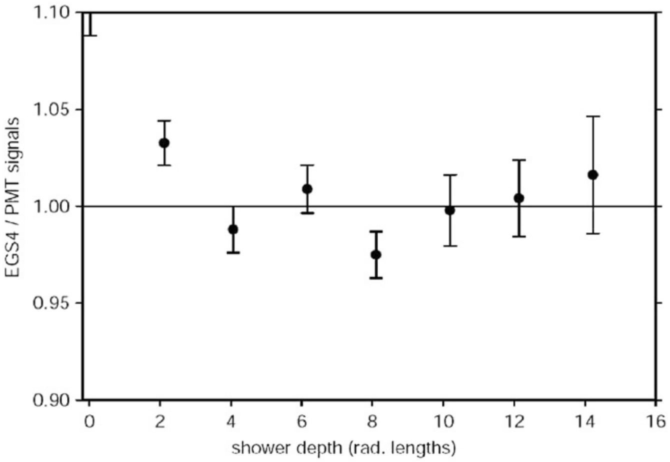

Fig. 6. Ratio of EGS4 results to weighted average of PMT signals versus shower depth.

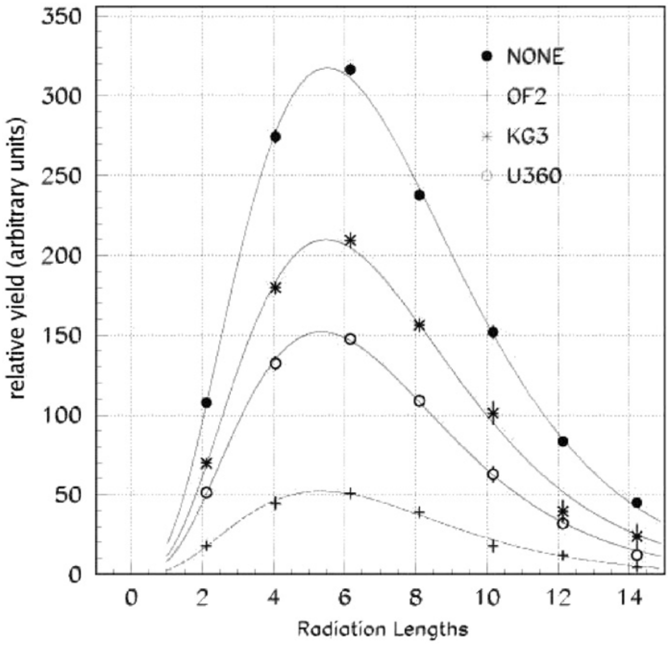

Fig. 7. Thick-target light yield, arbitrary units, for various bandpass filters. Yields have been corrected for detector geometric effects (see text). Curves shown correspond to fits of the data to the function given in Eq. (1, with best-fit values of $t_{\max} = 5.5$ and $b = 0.58$, in good agreement with predictions from the critical energy model [4].

Table 1
Band pass filters used in FLASH thick-target experiment

Filter	Band
"None"	$310<\lambda<400\,\mathrm{nm}$
OF2	$370<\lambda<400\,\mathrm{nm}$
KG3	$330<\lambda<390\,\mathrm{nm}$
U360	$330<\lambda<380\,\mathrm{nm}$

nominally absent. This effect reduced the observed fluorescence signal at 4, 8, and 12 radiation lengths. If this effect is corrected for, by an amount which can be confirmed by ion chamber observations and simulations, we obtain data which is well modeled by the smooth curve [4]:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = E_0 b \frac{(bt)^{a-1}\,\mathrm{e}^{-bt}}{\Gamma(a)} \tag{1}$$

where a and b are fit parameters, E_0 is the primary particle energy and t is the depth in radiation lengths into the radiating medium. The corrected data and fit curves are shown in Fig. 7.

Finally, we consider the correspondence between fluorescence energy deposition and fluorescence yield at different wavelengths. We took data with the bandpass filters listed in Table 1. Results are shown in Fig. 7, indicating that the shape of the fluorescence light profile is unchanged.

4. Summary and conclusions

FLASH collected excellent data in thick-target mode during the summer of 2004. The analyses performed to date indicate that the results are well understood. EGS and GEANT energy deposition has been shown to be a good predictor of relative fluorescence yield versus shower depth, with relative yields agreeing to better than ±5% for most of the shower profile. Air fluorescence yield also shows good agreement with the predictions of an empirical energy deposition model. Finally, band-pass filter data indicate that the proportionality of fluorescence to energy deposition is wavelength-independent. Further discussion of this result is contained in Ref. [5].

References

[1] C. Field, P. Hüntemeyer, S. Thomas, Proceedings of the Fifth Fluorescence Workshop, Nucl. Instr. and Meth. A 597 (2008) 32.
[2] W.R. Nelson, H. Hiragama, D.W.O. Rogers, The EGS4 Code System, SLAC-265, Stanford Linear Accelerator Center, 1985.
[3] CERN Applications Software Group, Geneva, Switzerland, 1993.
[4] Particle Data Group, Phys. Lett. B592 (2004).
[5] J. Belz, et al., Astropart. Phys. 25 (2006) 57.