PROCEEDINGS OF SCIENCE

First results from the full-scale prototype for the Fluorescence detector Array of Single-pixel Telescopes

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The Fluorescence detector Array of Single-pixel Telescopes (FAST) is a design concept for the next generation of ultrahigh-energy cosmic ray (UHECR) observatories, addressing the requirements for a large-area, low-cost detector suitable for measuring the properties of the highest energy cosmic rays. In the FAST design, a large field of view is covered by a few pixels at the focal plane of a mirror or Fresnel lens. Motivated by the successful detection of UHECRs using a prototype comprised of a single 200 mm photomultiplier-tube and a 1 m^2 Fresnel lens system [Astropart.Phys. 74 (2016) 64-72], we have developed a new full-scale prototype consisting of four 200 mm photomultiplier-tubes at the focus of a segmented mirror of 1.6 m in diameter. In October 2016 we installed the full-scale prototype at the Telescope Array site in central Utah, USA, and began steady data taking. We report on first results of the full-scale FAST prototype, including measurements of artificial light sources, distant ultraviolet lasers, and UHECRs.

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1. Fluorescence detector Array of Single-pixel Telescopes (FAST)

The origin and nature of ultrahigh-energy cosmic rays (UHECRs) is one of the most intriguing mysteries in particle astrophysics [1]. Given their minute flux, less than one particle per century per square kilometre at the highest energies, a very large area must be instrumented to collect significant statistics. The energy spectrum, arrival directions, and mass composition of UHECRs can be inferred from studies of the cascade of secondary particles (extensive air shower, EAS) produced by their interaction with the Earth's atmosphere. Two well-established techniques are used for UHECR detection: 1) arrays of detectors (e.g. plastic scintillators and water-Cherenkov stations) sample EAS particles reaching the ground; 2) large field of view telescopes allow for reconstruction of the shower development in the atmosphere by imaging ultraviolet (UV) fluorescence light from atmospheric nitrogen excited by EAS particles.

The Pierre Auger Observatory (Auger) [2] and the Telescope Array Experiment (TA) [3, 4], the two largest UHECR experiments currently in operation, combine the two techniques, with arrays of particle detectors overlooked by fluorescence detector (FD) telescopes. Auger covers an area of over 3000 km^2 close to the town of Malargüe in the province of Mendoza, Argentina. TA is located near the town of Delta in central Utah, USA, and covers an area of 700 km^2. Significant advances in our understanding of UHECRs have been achieved in the last decade by these experiments [5]. However, these results are limited by low statistics at the highest energies. To further advance the field, the next generation of experiments will require an aperture which is larger by an order of magnitude. This may be accomplished by fluorescence detection of UHECR showers from space, as in the proposed JEM-EUSO mission [6], or with a giant ground array. Low-cost, easily-deployable detectors will be essential for a future ground-based experiment.

We present a ground-based FD telescope concept which would fulfill these requirements. The Fluorescence detector Array of Single-pixel Telescopes (FAST) would consist of compact FD telescopes featuring a smaller light-collecting area and far fewer pixels than current-generation FD designs, leading to a significant reduction in cost. In the FAST design, a $30^\circ \times 30^\circ$ field of view is covered by just a few 200 mm photomultiplier-tubes (PMTs) at the focal plane of a mirror or Fresnel lens with a ~ 1 m^2 aperture. FAST stations, powered by solar panels and with wireless connection, could be deployed in an array configuration to cover a very large area at low cost.

2. The full-scale FAST prototype

A first test of the FAST concept was performed in 2014 using a single 200 mm PMT at the focus of a 1 m^2 Fresnel lens system at the Telescope Array site. Using the first prototype we detected 16 highly significant UHECR shower signals, and demonstrated excellent operational stability under conditions typical of field deployment (changes in temperature, night sky background and atmosphere; airplanes in the field of view; unexpected power cuts) [7]. Motivated by these encouraging results, we have developed a full-scale FAST prototype. The new prototype, shown in Figure 1, consists of a segmented spherical mirror of 1.6 m diameter (produced at the Joint Laboratory of Optics in Olomouc, Czech Republic), and a UV band-pass filter (ZWB3, Shijiazhuang Zeyuan Optics) with a 1 m^2 aperture. Four 200 mm PMTs (mod. R5912-03, Hamamatsu) and active bases (mod. E7694-01, Hamamatsu) are installed at the focal plane of the segmented mirror

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in a 2 $\times$ 2 matrix, covering a 25° $\times$ 25° field of view. The telescope frame is covered with a shroud to shield the optical system from dust and stray light. Details of the optical design of this prototype are presented at this conference [8].

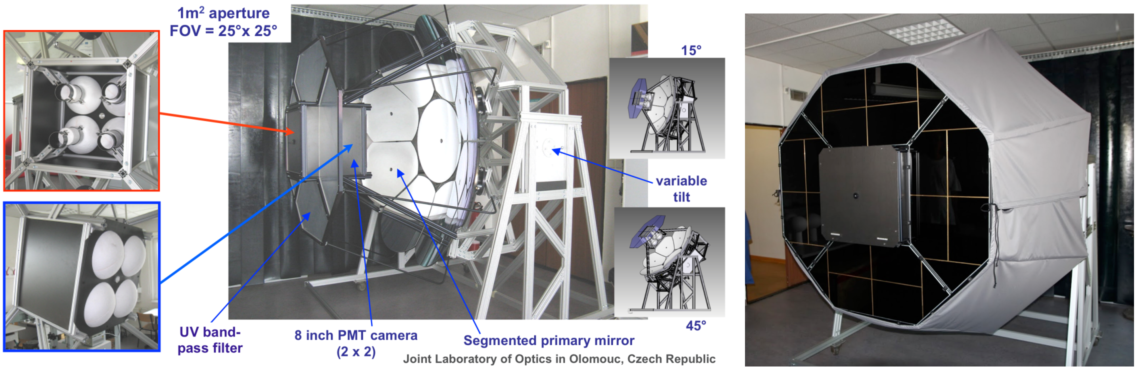


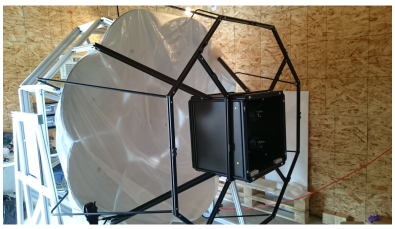
Figure 1: The full-scale FAST prototype developed at the Joint Laboratory of Optics in Olomouc, Czech Republic.

3. Installation of the full-scale FAST prototype and the first light operation

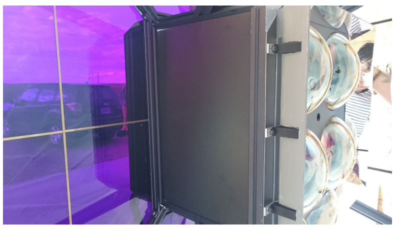
(a) Transportation to the field.

(b) Frame assembly.

(c) Mirror segment installation.



(d) Camera mount.



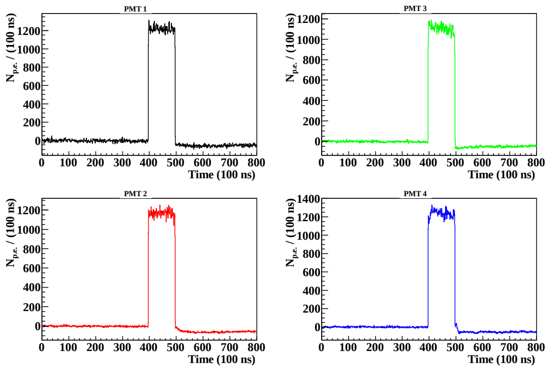
(e) PMTs and UV band-pass filter.

(f) Telescope alignment.

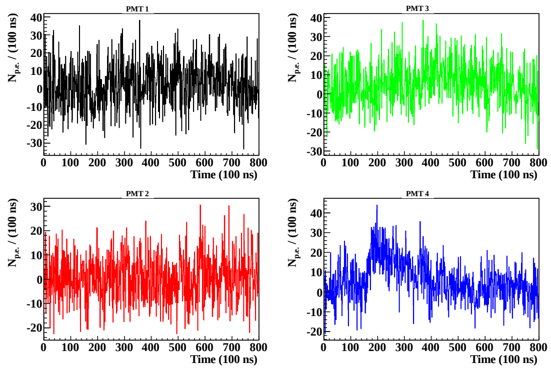
Figure 2: Photographs taken during the installation of the full-scale FAST prototype at the Telescope Array site.

In October 2016 the full-scale FAST prototype was installed at the Telescope Array site. Some photographs taken during the installation of the full-scale FAST prototype are shown in Figure 2. The telescope frame was assembled on site, before the PMTs were mounted in the camera box and the UV band-pass filter was installed at the telescope aperture. The telescope was aligned astrometrically using a camera mounted to the exterior of the frame [8]. Following its installation, first light operation of the prototype began, utilizing external air shower triggers from the adjacent TA fluorescence detector.

High voltage is supplied to the four PMTs, which were calibrated in the laboratory [9] to a nominal gain of 5×10^4, by a high-voltage power supply (mod. N1470, CAEN). The PMT signals are amplified by a factor of 50 using a fast amplifier (mod. 777, Phillips Scientific), and passed through a 15 MHz low-pass filter before digitization by a 12-bit FADC (mod. SIS3350, Struck Innovative Systeme) at a 50 MHz sampling rate. The digitizer is hosted in a portable VME crate (mod. VME8004B, CAEN), together with a controller (mod. V7865, GE Intelligent platforms) and a GPS unit (mod. GPS2092, Hytec) which provides event time stamps. When a fluorescence telescope in the adjacent TA building is triggered by a candidate UHECR shower, an external trigger is issued to the FAST DAQ with a typical rate of ~ 3 Hz. A trigger initiates the capture of a 4000 bin frame of data, corresponding to 80 μs.

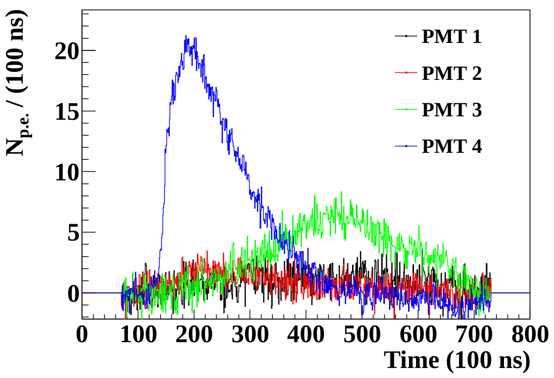


(a) Measured signal from a UV LED flasher.

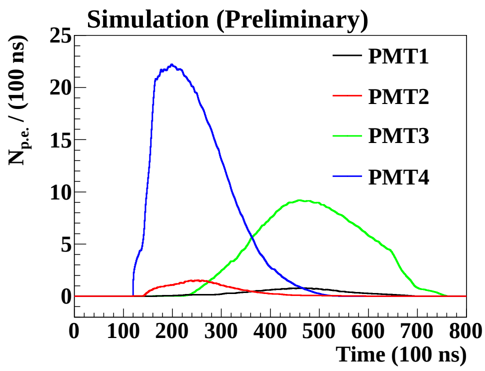


(b) Measured signal from a distant laser pulse.

Figure 3: Example waveforms recorded with the full-scale FAST prototype. (a) Signal in each of the four PMTs following illumination of the telescope aperture with a UV LED flasher. (b) Signal from a vertical UV laser pulse at a distance of 21 km.



(a) Measured signal from a distant vertical UV laser (284 shots averaged).

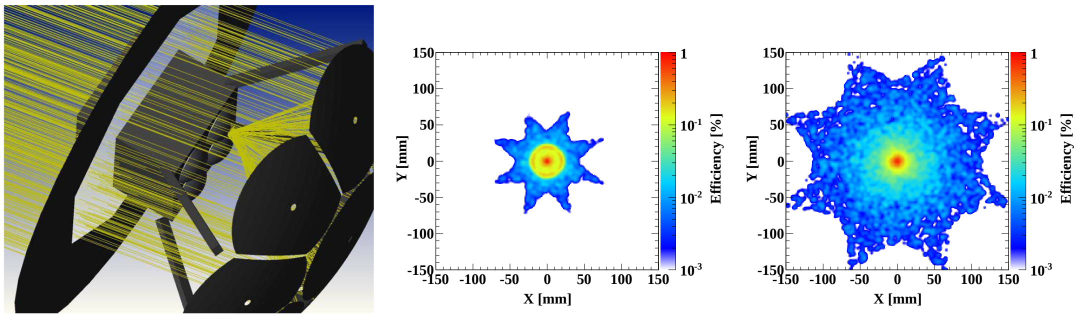


(b) Simulated signal.

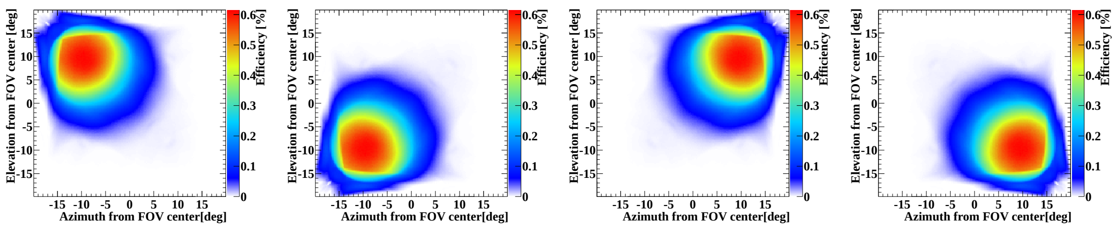
Figure 4: (a) Average waveform from 284 vertical UV laser pulses at a distance of 21 km and (b) simulated waveform from a raytracing simulation (without night sky background included).

Figure 3(a) shows example waveforms recorded with the FAST DAQ from a UV LED flasher illuminating the telescope aperture, confirming the timing synchronization between the signals, as well as the uniformity in the PMT gains. The measured signal was converted to a photo-electron count using a calibration factor measured in the laboratory. Figure 3(b) shows the measured signal from a 355 nm vertical UV laser at a distance of 21 km [10]. The laser signal, with a nominal pulse energy of 4.4 mJ, is approximately equivalent in intensity to a $\sim 10^{19.5}$ eV UHECR at a distance of 21 km.

Figure 4(a), the 284 waveforms of the vertical UV laser were averaged to improve the signal-to-noise ratio. As a result of the trigger algorithm used by the TA FD, the leading edge of the laser signal in each waveform has to be adjusted based on the GPS timing. Figure 4(b) shows the expected signal from a distant vertical laser evaluated from angular responses described as below, assuming typical atmospheric attenuation properties. The expected signal is in good agreement with observations. Small differences between the simulated and measured waveforms can be explained by the non-uniformity of the PMT surface, and the temperature dependence of the PMT gains.



(a) Raytracing simulation. (b) Optical axis at focal plane. (c) Optical axis with -50 mm offset.



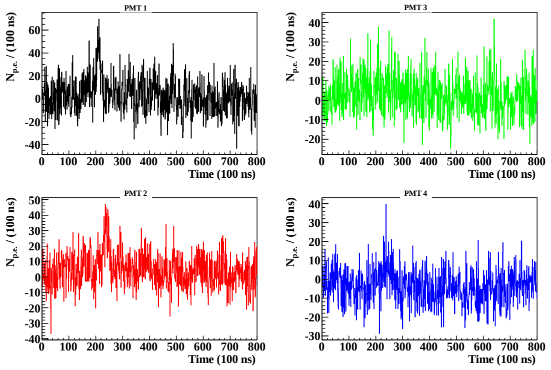
(d) PMT 1. (e) PMT 2. (f) PMT 3. (g) PMT 4.

Figure 5: (a) Schematic view of a raytracing simulation of the full-scale FAST prototype optics. The spot size at the focal plane (b) and with a -50 mm offset (c) (for a beam parallel to the optical axis of the telescope) [8]. The angular efficiency characteristics of PMTs 1-4 are indicated in (d)-(g).

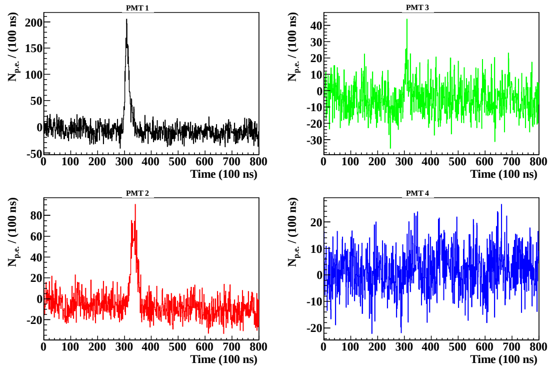
A raytracing simulation was performed to determine the optical characteristics of the prototype. A parallel beam of photons is injected at the telescope aperture, and individual photon paths through the telescope are calculated as shown in Figure 5(a). Figure 5(b) and (c) show the spot size at the focal plane, and with a -50 mm offset (which is of relevance as the PMTs installed in the camera have a spherical surface). Additional information about the optical characteristics of the prototype telescope is presented at this conference [8]. Considering these characteristics, angular responses for all four PMTs are evaluated as shown in Figure 5(d) to (g).

4. UHECR shower search

We continue steady operation of the full-scale FAST prototype, with the system being fully remotely operable. As of May 2017, the total operation time is reached $\sim$ 150 hours. In this dataset, UHECR shower signals are searched for via coincidences in more than 2 PMTs, after excluding airplane events and measurements of the vertical laser. 18 significant shower signals have been found in time coincidence with TA FD reconstructed events. Figure 6(a)(b) are two of the UHECR events observed with the new FAST prototype. The reconstructed energies from the TA FD monocular analysis [11] are $10^{18.08}$ eV at an impact parameter $R_{\rm p} = 2.4$ km and $10^{18.55}$ eV at $R_{\rm p} = 3.0$ km respectively.



(a) UHECR event, $E_{\rm TAFD} = 10^{18.08}$ eV, $R_{\rm p} = 2.4$ km.



(b) UHECR event, $E_{\rm TAFD} = 10^{18.55}$ eV, $R_{\rm p} = 3.0$ km.

Figure 6: First UHECR signals measured with the full-scale FAST prototype.

5. Summary and Future Plans

We have presented a novel concept for a next-generation fluorescence detector, which features just a few pixels covering a large field-of-view. In October 2016, we installed the full-scale FAST prototype at the Telescope Array site in central Utah, USA, and began data taking in coincidence with the TA fluorescence detector. The prototype was used to measure the signal from a UV LED flasher, as well as a distant vertical UV laser beam. We were also successful in detecting 18 UHECR events in time-coincidence with the Telescope Array fluorescence detector. We will continue to operate the prototype and search for UHECR events.

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