Recent results from prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST) in both hemispheres

Toshihiro Fujii[1,*], *Justin* Albury[2], *Fraser* Bradfield[1], *Jose* A. Bellido[2], *Ladislav* Chytka[3], *John* Farmer[4], *Petr* Hamal[3], *Pavel* Horvath[5], *Miroslav* Hrabovsky[3,5], *Hiromu* Iwasaki[6], *Vlastimil* Jilek[5], *Jakub* Kmec[5], *Jiri* Kvita[5], *Max* Malacari[4], *Dusan* Mandat[3,5], *Massimo* Mastrodicasa[7], *John* N. Matthews[8], *Stanislav* Michal[3], *Hiromu* Nagasawa[6], *Hiroki* Namba[6], *Xiaochen* Ni[4], *Libor* Nozka[5], *Tomohiko* Oka[5], *Miroslav* Palatka[5], *Miroslav* Pech[5], *Paolo* Privitera[4], *Petr* Schovanek[5], *Francesco* Salamida[7], *Radomir* Smida[4], *Zuzana* Svozilikova[5], *Stan* B. Thomas[8], *Akimichi* Taketa[9], *Kenta* Terauchi[6], *Petr* Travnicek[3,5], and *Martin* Vacula[5] (The FAST Collaboration)

[1]Graduate School of Science, Osaka Metropolitan University, Sumiyoshi-ku, Osaka, Japan
[2]Department of Physics, University of Adelaide, Adelaide, S.A., Australia
[3]Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic
[4]Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, USA
[5]Joint Laboratory of Optics of PU and IF of CAS, Palacky University, Olomouc, Czech Republic
[6]Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto, Japan
[7]Department of Physical and Chemical Sciences, University of L'Aquila and INFN LNGS
[8]High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA
[9]Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan

Abstract. The origin and nature of ultrahigh-energy cosmic rays (UHECRs) are of uppermost importance in astroparticle physics. Motivated by the need for an unprecedented aperture for further advancements, the Fluorescence detector Array of Single-pixel Telescopes (FAST) is a prospective next-generation, ground-based UHECR observatory that aims to cover an enormous area by deploying a large array of low-cost fluorescence telescopes. The full-scale FAST prototype consists of four 20 cm photomultiplier tubes at the focus of a segmented mirror 1.6 m in diameter. Three FAST prototypes have been installed at the Telescope Array Experiment in Utah, USA, and two prototypes at the Pierre Auger Observatory in Mendoza, Argentina, commencing remote observation of UHECRs in both hemispheres. We report on recent results of the full-scale FAST prototypes operated in both hemispheres, including telescope calibrations, atmospheric monitoring, ongoing electronics upgrades, development of sophisticated reconstruction methods and UHECR detections.

1 Ultra-high-energy cosmic rays

The origins and acceleration mechanisms of ultra-high energy cosmic rays (UHECRs) are still largely unknown [1, 2] after the first detection of the cosmic ray with a energy of 100 EeV 60 years ago [3]. They are one of the most intriguing mysteries in a field of the particle astrophysics.

Immediately after the discovery of the 100 EeV cosmic ray, K. Greisen, G. T. Zatsepin and V. A. Kuzmin predicted the UHECR energy spectrum to be suppressed above 60 EeV with the 3 K cosmic microwave background radiation via pion production, known as GZK cutoff [4, 5]. If the GZK cutoff exists, the origin of UHECRs is significantly restricted to nearby sources distributed non-uniformly within 50-100 Mpc. Additionally as UHECRs are deflected less strongly by magnetic fields due to their enormous kinetic energies, their arrival directions are more significantly correlated with their sources. Charged-particle astronomy with UHECRs is hence a potentially viable probe of extremely energetic phenomena in the nearby universe. However, due to their limited flux of UHECRs, less than one particle per century per square kilometer at the highest energies, a very large area must be instrumented to collect significant statistics. The energy, arrival direction, and mass composition of UHECRs can be inferred from studies of the cascades of secondary particles (Extensive Air Shower, EAS) produced by their interaction with the atmosphere of the Earth.

Two well-established methods are used for UHECR detection: arrays of detectors such as plastic scintillators or water-Cherenkov stations that sample EAS particles at the ground level, and large-field-of-view telescopes that directly measure atmospheric shower development by observing ultra-violet nitrogen fluorescence. The two largest UHECR observatories are hybrid detectors that combine both techniques, employing arrays of ground detectors overlooked by fluorescence detectors (FDs). These are the Pierre Auger Observatory (Auger) in Mendoza, Argentina [7], and the Telescope Array Experiment (TA) in Utah, USA [8, 9].

*e-mail: toshi@omu.ac.jp

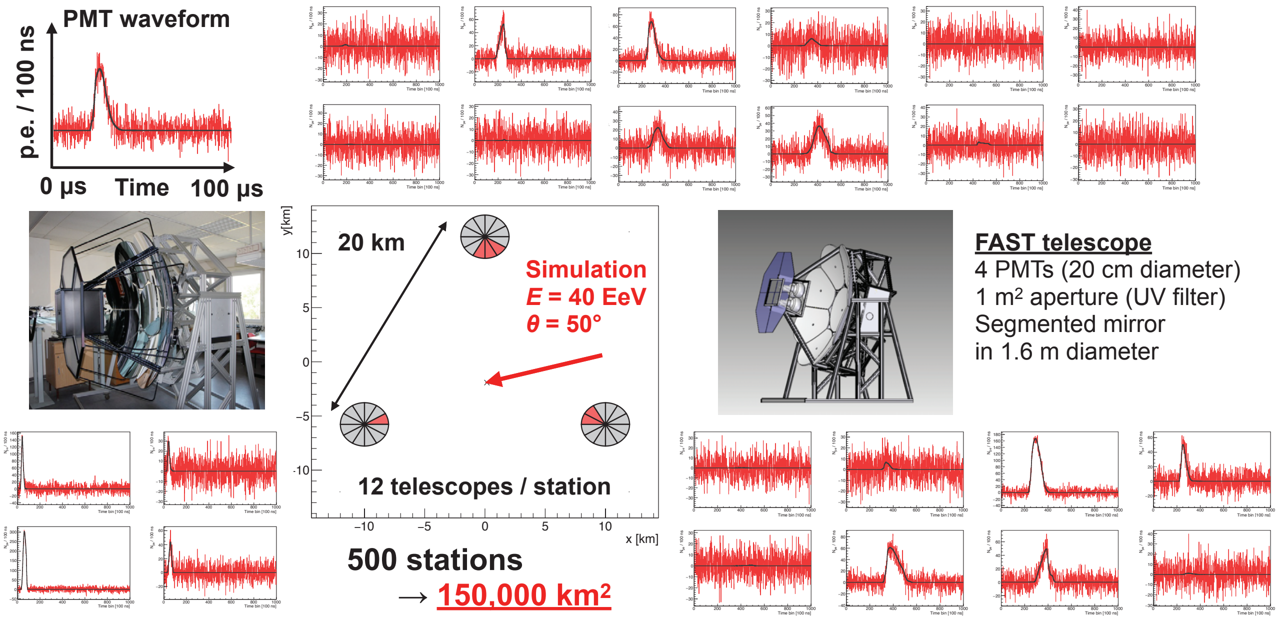


Figure 1. The Fluorescence detector Array of Single-pixel Telescopes: a possible solution for a future giant ground array [6]. The traces show simulated signals emitted from a UHECR with an energy of 40 EeV and a zenith of 50°. The black curves in the waveforms show the simulated traces without contributions of the expected night sky backgrounds

Although the statistics of UHECRs was significantly improved, their reported results at the highest energies are still limited by the statistics due to sharp cutoff of the energy spectrum. Future ground arrays will require an unprecedented aperture exceeding current experiments by an order of magnitude with the mass composition sensitivity above 100 EeV. Future detectors should hence be low-cost and easy to deploy, operate and maintain. A worldwide collaboration is necessary to construct such an array.

2 Fluorescence detector Array of Single-pixel Telescopes (FAST)

A possible solution to fulfill these requirements is a ground-based fluorescence detector array. The Fluorescence detector Array of Single-pixel Telescopes (FAST)[1] features compact FD telescopes with a smaller light-collecting area and fewer pixels than current-generation FD designs, leading to a significant reduction in cost that allows for the production of more FD units [10]

In the FAST design, a 30° × 30° field-of-view is covered by four 20 cm photomultiplier-tubes (PMTs)at the focal plane of a compact segmented mirror of 1.6 m diameter [11]. Its smaller light-collecting optics, smaller telescope housing, and fewer number of PMTs significantly reduces its cost to be ∼35 kUSD per telescope. Each FAST station would consist of 12 such telescopes, covering 360° in azimuth and 30° in elevation. These stations would be deployed in a triangular array with a 20 km spacing, suggested by simulations.

Figure 1 shows the simulated waveforms from a UHECR shower detected in 3-fold coincidence by such an array. The arrival direction and shower profile of the primary particle are included in the shapes of the recorded waveforms. The most sensitive parameter of the mass composition, $X_{\max}$ at which the number of EAS particles reaches at maximum, is reconstructed from the observed shower profile. To achieve the unprecedented exposure exceeding current experiments by an order of magnitude, 500 stations covering 150,000 km^2 are required, after accounting for the standard FD duty-cycle and additional moon-night operation.

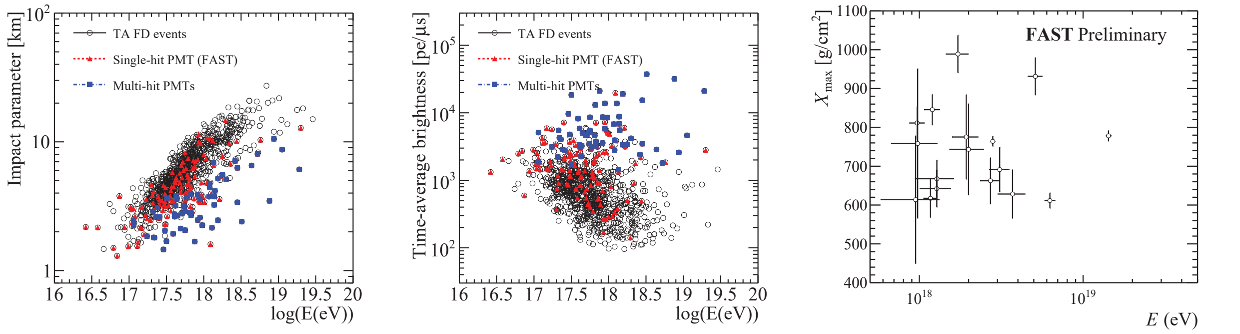
[1] https://www.fast-project.org

3 Recent progress of developments on the FAST prototypes

Motivated by UHECR detections with a single 20 cm PMT at the focus of a 1 m^2 Fresnel lens in 2014 [6], we installed three full-scale FAST prototypes at the TA site in Figure 2(a)-left [12]. We assembled the telescope frames on-site, mounted the PMTs in their camera boxes and installed ultra-violet band-pass filters at their apertures. We then astrometrically aligned the telescopes using a camera mounted to their frames' exteriors [11]. Following this, we began observation via remote connection, using external triggers from the adjacent TA fluorescence detector. We used an automated all-sky monitoring camera to record cloud coverage and atmospheric transparency [13].

As shown in Figure 2(a)-right, two identical FAST prototypes were installed at the Auger site. These identical FAST prototypes installed at TA and Auger will allow for a cross-calibration of the energy and $X_{\max}$ scales between TA and Auger, as well as a comparison between the atmospheric transparency at both sites, an important source of systematic uncertainty in the fluorescence technique.

(a) FAST prototypes installed at TA (left) and Auger (right) observatories



(b) Impact parameter for coincidences between TA FD and FAST (c) Time-average brightness for coincidences between TA FD and FAST (d) Energy and X_{max} reconstructed by FAST top-down reconstruction

Figure 2. (a) The three FAST prototypes installed at the Black Rock Mesa site of the Telescope Array Experiment and the one prototype installed at Los Leones site of the Pierre Auger Observatory. (b) Impact parameter and (c) time-average brightness for the coincidence search between TA FD and FAST. (d) Preliminary result of top-down Energy and X_{max} reconstructions for multi-hit events above 1 EeV.

Analyzing 224 hours of data measured by the FAST prototypes at the TA site from March 2018 to October 2019, we found 964 showers with corresponding monocular reconstructions from the TA FD [14]. We searched for significant signals (defined as a $\geq 6\sigma$ signal-to-noise ratio over $\geq$ 500 nanoseconds) in time coincidence with these FD events and found 179 significant FAST events out of the 964 TA EASs, with 59 events producing significant signals in more than one PMT. Figure 2(b) and (c) show the impact parameter and time-average brightness of the detected EASs as a function of energy, split by single-PMT and multi-PMT events. These parameters are reconstructed by the TA FD.

A "top-down" reconstruction algorithm has been implemented that determines the best-fit shower parameters by comparing our measured traces to the simulated ones [12]. Because FAST features only four pixels, rather than use the entry and exit times for each pixel as traditional reconstruction methods do, we extract timing information from each individual bin of the traces. Figure 2(d) shows preliminary X_{max} and energy values reconstructed by this method for multi-hit events above 1 EeV using only FAST prototypes.

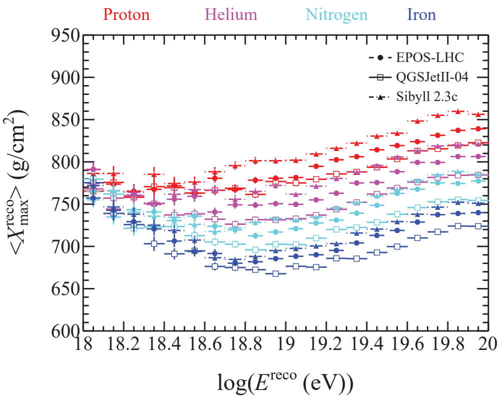
3.1 Neural network first-guess estimation

The top-down reconstruction requires a reasonable first-guess geometry to reduce computational time. This is provided by a neural network first-guess estimation [17]. The total signal, centroid time, and pulse height of each PMT with a significant signal are used as inputs. The outputs are six parameters: X_{max}, energy, zenith, azimuth and west-east/south-north core positions. The model uses the Keras/Tensorflow library with two hidden fully-connected layers.

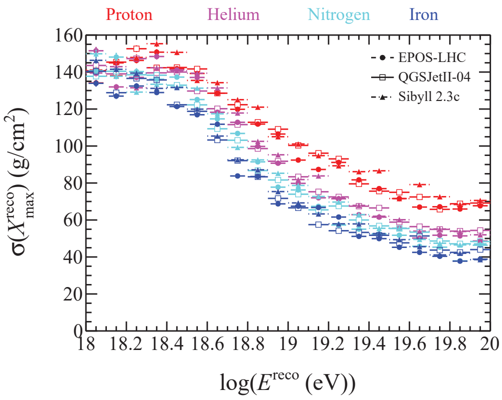
The resolution and detection bias on X_{max} are evaluated by only applying this first-guess estimation for EASs of four primaries (proton, helium, nitrogen, and iron) with three hadronic interaction models (EPOS-LHC, QGSJetII-04 and Sibyll 2.3c) [18]. The EASs are generated with uniformly-distributed arrival directions and core positions randomly generated in the triangular array's inner circle. The typical resolutions are 4.2 degrees in arrival direction, 465 m in core position, 8% in energy, and 30 g/cm^2 on X_{max} at 40 EeV for the 3-fold coincidence events.

Figure 3 shows a preliminary detection bias on $\langle X_{max} \rangle$ and $\sigma(X_{max})$, and also reconstructed X_{max} distributions in each energy bin. Although the reconstructed elongation rate of X_{max} is biased below 10 EeV due to the limitation of field-of-view, it is reproduced above 10 EeV. As seen in the reconstructed X_{max} distribution, the FAST with the neural network estimation is possible to distinguish primary species using a statistical method. Note that this performance is evaluated by only the neural network first-guess estimation. The full-chain performance of both the top-down reconstruction and the neural network first-guess estimation is being investigated.

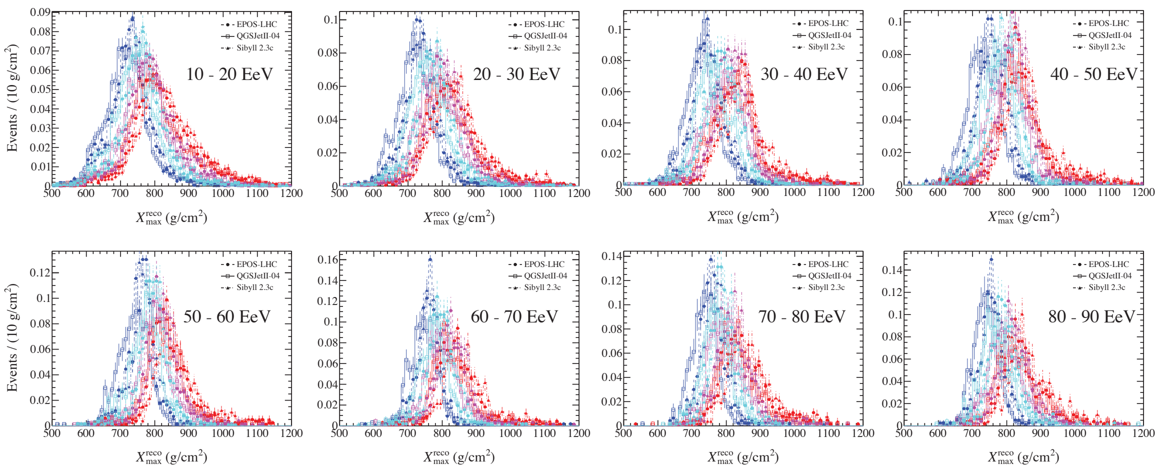
With this simulation study, the trigger efficiency for 3-fold detections is evaluated as shown in Figure 4(a). The FAST array has a 100% efficiency above 20 EeV.



(a) Reconstructed $\langle X_{\rm max} \rangle$



(b) Reconstructed $\sigma(X_{\rm max})$



(c) Reconstructed $X_{\rm max}$ distributions

Figure 3. Reconstruction bias on (a) $\langle X_{\rm max} \rangle$ and (b) $\sigma(X_{\rm max})$ of four primaries (proton, helium, nitrogen and iron) with three interaction models (EPOS-LHC, QGSJetII-04, Sibyll 2.3c) reconstructed by the neural network first-guess estimation. (c) Their reconstructed $X_{\rm max}$ distributions in each energy bin.

The energy threshold is related to the bias on the average $\langle X_{\rm max} \rangle$ and $\sigma(X_{\rm max})$ as shown in Figure 3. Figure 4(b) is the expected sensitivity on the energy spectrum with a full-size FAST array. Assuming an effective exposure of 90,000 km^2 sr per year, the detectable flux under the 95% confidence level is evaluated with FAST, compared to the latest measurements reported from TA and Auger. A full-sized FAST array will extend UHECR measurements beyond 300 EeV.

3.2 Developments for stand-alone observation of FAST array

Since these tests, several advances have been made: improvements in our telescope design and the robust hut for telescope storage, improvements in PMT calibration systems, updates of electronics with low-power consumption as shown in Figure 5. The compact and robust hut is constructed for a long-term operation more than 20 years. The shutter of the hut will be operated by the solar panel and batteries.

The PMTs are calibrated to measure the absolute gain using single photo-electron measurement and the gain curve as a function of the high voltage. The non-uniformity of gain on the PMT surface is also investigated by the commercial robotic arm with the position sensitivity of 0.2 mm. The new PMT (R14866) is recently developed to improve the non-uniformity on the PMT surface, showing more homogeneous sensitivity compared to the current one (R5912).

The improved electronics is particularly important as previous tests have capitalized on the infrastructure of existing FD detectors. These new electronics will allow for the first deployment of an independent, solar-powered FAST station, as well as permit stand-alone operation with the FAST array, an important step in validating our design and testing our expected resolution. The potential infield calibration will be performed using an extended uniform light source such as the integrating sphere [19].

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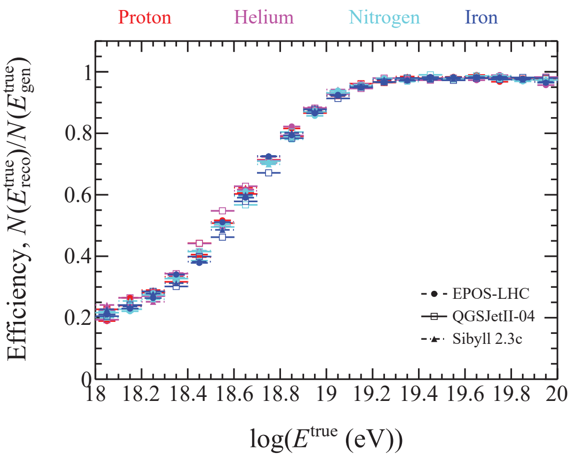
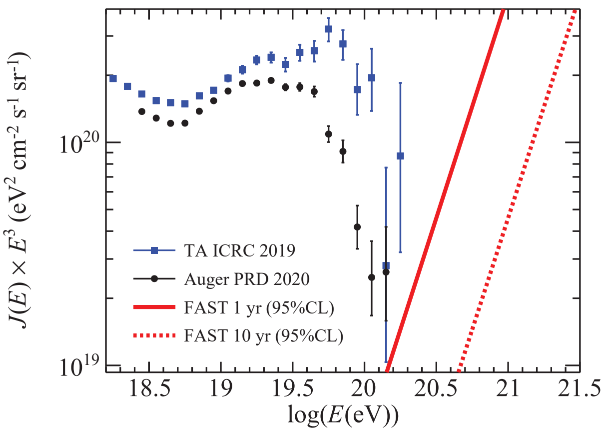


(a) 3-fold Trigger efficiency



(b) Expected sensitivity of full FAST array

Figure 4. (a) Trigger efficiency for 3-fold detections with a hypothetical FAST array. (b) Expected 95% confidence level detectable sensitivities of the energy spectrum with the full FAST array of 500 stations compared to the spectra reported from TA [15] and Auger [16].

4 Summary

We have developed a low-cost, easily-deployed fluorescence detector optimized for detection of the highest energy cosmic rays in anticipation of a future ground array with an unprecedented exposure exceeding current experiments by an order of magnitude with the mass composition sensitivity. Three FAST prototypes have been installed at the Telescope Array Experiment, and two prototype has been installed at the Pierre Auger Observatory. We have begun observations in both hemispheres and have demonstrated the viability of the reconstruction methods such as top-down reconstruction and neural network first-guess reconstruction. Furthermore, measurements of UHECRs with the identical FAST prototypes at both observatories is important to perform a cross-calibration of the TA and Auger energy and X_{max} scales. We will continue the steady operation of these FAST prototypes and developments for the stand-alone operation toward the full-sized FAST array.

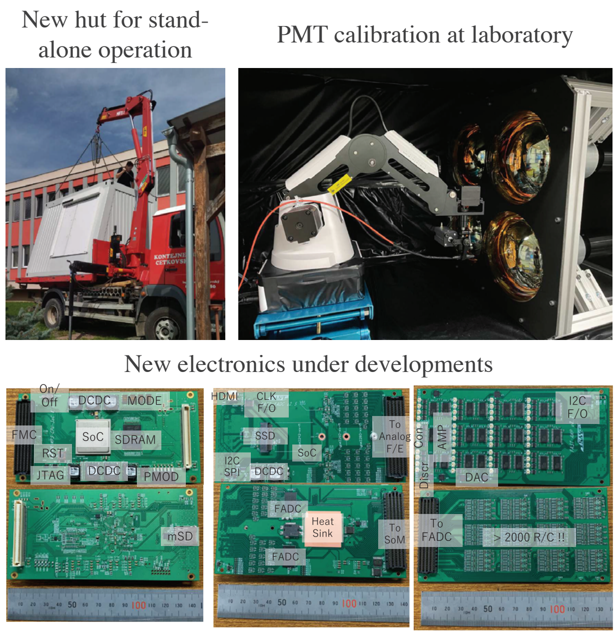


Figure 5. Developments for future stand-alone operations: the robust hut being constructed, PMT calibration system at laboratory and the new electronics under development.

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