Observing ultra-high energy cosmic rays with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST) in both hemispheres

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Justin Albury, Jose Bellido, Ladislav Chytka, John Farmer, Petr Hamal, Pavel Horvath, Miroslav Hrabovsky, Jiri Kvitá, Max Malacari, Dusan Mandat, Massimo Mastrodicasa, John Matthews, Stanislav Michal, Xiaochen Ni, Libor Nozka, Miroslav Palatka, Miroslav Pech, Paolo Privitera, Petr Schovanek, Francesco Salamida, Radomir Smida, Stan Thomas, Petr Travnicek, Martin Vacula (FAST Collaboration)
25th July 2019, ICRC 2019, Madison, USA
Ultra-high energy cosmic rays (UHECR), $10^{20}$ eV

- Less deflection in galactic/extragalactic magnetic fields
- Related with extremely energetic astrophysical phenomena
- Spectrum suppression,
  - Indicate nearby sources distributed non-uniformly within ~50 Mpc
- Correlation between UHECRs and nearby energetic sources or objects
  - Next-generation astronomy


No conclusive results on UHECR sources...
Target: $> 10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles

Huge target volume ⇒ Fluorescence detector array

Fine pixelated camera

Too expensive to cover a huge area

Smaller optics and single or a few pixels

Low-cost and simplified telescope
Each telescope: 4 PMTs, 30°×30° field-of-view (FoV)

Reference design: 1 m² aperture, 15°×15° FoV per photo-multiplier tube (PMT)

Each station: 12 telescopes, 48 PMTs, 30°×360° FoV

Deploy on a triangle grid with 20 km spacing, like “Surface Detector Array”

With 500 stations, a ground coverage is 150,000 km²

5 years: 5100 events \( (E > 57 \text{ EeV}) \),
650 events \( (E > 100 \text{ EeV}) \)

- Directional anisotropy on arrival directions, energy spectrum, mass composition
1. Detector development for future project
2. Cross-calibration of Energy and $X_{\text{max}}$ scales in current UHECR observatories.
FAST fluorescence prototypes in TA

Reference: D. Mandat et al., JINST 12, T07001 (2017)

Wavelength [nm]

260 280 300 320 340 360 380 400 420

Efficiency [%]

0 10 20 30 40 50 60 70 80 90 100

Mirror reflectivity
Filter transmission
Total efficiency

Figure 5. The typical spectral reflectance of the FAST mirror between 260 nm and 420 nm, along with the spectral transmission of the UV band-pass filter. The resultant total optical efficiency is shown in black.

Filter used on the Cherenkov telescope of the MAGIC [18] observatory. The filter is constructed from a number of small segments in order to fit the FAST prototype's octagonal aperture. The individual segments are fit together using brass "U" and "H" profiles, resulting in an aperture of 1 m².

Telescope support structure

The telescope's mechanical support structure was built from commercially available aluminum profiles. This allows for straightforward assembly/disassembly, and easy packing and transport due to their light weight, while also providing an extremely stable and rigid platform for the FAST optical system to be mounted on. The mechanics consists of a primary mirror stand mounted with a single degree of freedom to facilitate adjustment of the telescope's elevation (the elevation can be set to discrete values of 0°, 15°, 30° and 45° above the horizon). The square camera box (side length 500 mm), which holds four 200 mm PMTs, is mounted on a support structure connected to the perimeter of the mirror dish which also holds the octagonal filter aperture. The mirror stand contains 9 mirror mounts, each with 2 degrees of freedom to allow for mirror segment alignment. The whole mechanical construction, shown in figure 6, is covered with a shroud to protect the optical system from the surrounding environment.

Conclusion

Following the successful proof-of-concept test of a compact, low-cost air fluorescence telescope using the EUSO-TA optics at the Telescope Array site, we present the design of the first full-size prototype telescope having a 30°×30° field-of-view and a 1 m² aperture, along with its mechanical support structure.

- 4 PMTs (20 cm, 8 dynodes R5912-03MOD, base E7694-01)
- 1 m² aperture of the UV band-pass filter (ZWB3), segmented mirror of 1.6 m diameter
- Total 3 telescopes installed at TA site by October 2018
- Total 545 hours by June 2019
Fast observation set-up

- Remote controlling observation
- Synchronized operation with external triggers from Telescope Array fluorescence detector (TA FD)
- 80% FoV of TA FD

TA FD FoV (12 telescopes, 33°×108°)

Vertical laser at a distance of 21 km

Vertical laser signal (280 shot average)

FAST FoV (3 telescopes, 30°×90°)

Azimuth [deg]

Preliminary
UHECR signal and reconstruction

FAST waveform + expected signal from top-down reconstruction
(Data, simulation by the best-fit parameters)

TA FD (Preliminary)
Energy: 19.0 EeV
Rp: 6.1 km

FAST top-down reconstruction (Preliminary)
Zenith Azimuth Core(X) Core(Y) Xmax Energy
59.8 deg -96.7 deg 7.9 km -9.0 km 842 g/cm² 17.3 EeV
Coincidence shower search between TA FD and FAST

- Data period: 2018/Oct/06 - 2019/Jan/14, 52 hours with 3 FAST prototypes
- Event number: 236 (TA FD) -> 37 (significant signals with FAST, S/N > 6σ, Δt > 500 ns)
- The shower parameters are reconstructed by TA FD monocular analysis.

- Maximum detectable impact parameter: ~20 km at $10^{19.5}$ eV with brighter signal showers
- 2 events above 10 EeV in 52 hours $\rightarrow$ ~25 events/year (15% duty cycle)
Highest energy event

**TA data**

**FAST data**

**FAST top-down reconstruction (Preliminary)**

Zenith Azimuth Core(X) Core(Y) Xmax Energy
33.9 deg 19.3 deg 4.6 km -4.7 km 808 g/cm² 18.8 EeV

**TA SD (Preliminary)**

Zenith Azimuth Core(X) Core(Y) Energy
36.2 deg 18.0 deg 5.0 km -4.5 km 15.8 EeV

**TA FD (Preliminary)**

33.2 deg 35.8 deg 6.1 km -5.3 km 20.0 EeV
② Second highest energy event

**TA data**

<table>
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Installation of 1st FAST prototype in Auger

Pierre Auger Observatory
Malargue, Argentina

Start observation from April 11th, 2019

Cherenkov signal

Horizontal laser signal
Summary and future plans

Fluorescence detector Array of Single-pixel Telescopes (FAST)

- **10\times statistics** compared to Auger and TA\times 4 with $X_{\text{max}}$
- **Directional anisotropy on arrival direction, energy spectrum and mass composition**

Installed total 3 telescopes at Telescope Array site and 1st telescope in the Pierre Auger Observatory

- Stable observation with remote controlling
- UHECR detections, and their reconstruction method implemented.

We will continue to operate the telescopes and search for UHECR in coincidence with current observatories.

- A resolution study with the full FAST array
- Developing new electronics, and preparing for stand-alone operation

http://www.fast-project.org

**New collaborators are welcome!**
✦ Install the FAST prototypes at Auger and TA for a study of systematic uncertainties and a cross calibration.

✦ Profile reconstruction with geometry given by surface detector array (1° in direction, 100 m in core location).

✦ Energy: 10%, \(X_{\text{max}}: 35 \text{ g/cm}^2\) at \(10^{19.5} \text{ eV}\)

✦ Independent check of Energy and \(X_{\text{max}}\) scale between Auger and TA

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Pierre Auger Observatory

Identical simplified FD

Telescope Array Experiment


Auger collab., NIM-A (2010)

TA collab., NIM-A (2012)
Data analysis and simulation study

**FAST hybrid reconstruction**

Geometry (given by TASD or FD)

Shower Profile (FAST)

Simulation 32 EeV

Energy: 10%, Xmax : 35 g/cm² at 10^{19.5} eV

Independent cross-check of energy and Xmax scale with simplified FD.

**FAST reconstruction**

57 EeV Simulation

Fluorescence detector array with a 20 km spacing.

Reconstruct geometry and profile
Data/MC comparison with vertical UV laser

Spot-size

focal plane  50 mm offset

A UV vertical laser at 21 km away

Simulation (Preliminary)

Directional characteristic (PMT2)  (PMT 4)

Work: Miroslav Pech, Max Malacari
Coincidence shower search between TA FD and FAST

✧ Data period: 2018/Oct/06 - 2019/Jan/14, 52 hours, 3 FAST prototypes
✧ Event number: 236 (TA FD) -> 37 (significant signals with FAST, S/N > 6σ, Δt > 500 ns)
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Event number: 236 (TA FD) -> 37 (significant signals with FAST, S/N > 6σ, Δt > 500 ns)

The shower parameters are reconstructed by TA FD.
Coincidence showers between TA FD and FAST

- Maximum detectable impact parameter, \(~20 \text{ km at } 10^{19.5} \text{ eV}\), with brighter signal showers
- 2 events above 10 EeV in 52 hours \(\rightarrow \sim25 \text{ events/year} \text{ (15\% duty cycle)}\)
Installation of 1st FAST prototype in Auger

Malargue, Argentina

April 11th, 2019

FAST

FD (Los Leones)

LIDAR dome

Telescope Array: 700 km

Pierre Auger: 3000 km
Top-down reconstruction

- Using a $\chi^2$ test to compare pulses bin-by-bin

$$\chi^2 = \sum_{\text{pixel } i} \sum_{\text{time } t} \frac{(x(i, t) - A\mu(i, t))^2}{\sigma_{\text{NSB}}^2(i) + A\sigma_{\text{signal}}^2(i, t)}$$

- $A$ is a scale factor for shower energy

Data: $\text{Expected}(\theta, \phi, x, y, E, X_{\text{max}})$

Work: Justin Albury, Jose Bellido
**DAQ system**

- **FAST Camera**, PMT R5912-MOD (8 dynodes)
  - Base E7694-01 (AC coupling), HAMAMATSU

- **Portable VME Electronics**
  - FADC 50 MHz sampling, SIS3350
  - GPS board, Hytec GPS2092
  - Single board PC, GE 7865

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High voltage power supply, N1470 CAEN

Gain = $5 \times 10^4$

15 MHz low pass filter

50x Amplifier
- Phillips
- Scientific 777

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Low dark count
- Fast time response
- High energy physics

**APPLICATION**

- PHOTOMULTIPLIER TUBES
  - LARGE PHOTOCATHODE AREA

**SPECIFICATIONS**

- PMT R7081-100
  - Diameter: 253 / 10 mm (cm)
  - Weight: approx. 1400 g
  - Number: 14
  - Minimum dynode:
    - Phillips R3600-02
    - Low dark count
  - Fast time response
  - High energy physics

- PMT R5912-100
  - Diameter: 380 mm (cm)
  - Weight: approx. 1100 g
  - Number: 14
  - Minimum dynode:
    - Phillips R3600-02
    - Low dark count
  - Fast time response
  - High energy physics

- PMT R7250
  - Diameter: 430 mm (cm)
  - Weight: 1080 g
  - Number: 10
  - Minimum dynode:
    - Phillips R3600-02
    - Low dark count
  - Fast time response
  - High energy physics
Real-time night sky monitoring

All sky camera

Sky quality monitor

Moonless nightsky cloudiness distribution: 65% of clear sky

Work: Dusan Mandat, Ladislav Chytka
Calibrations for FAST

Absolute calibration in laboratory

YAP pulser (YAlO₅:Ce scintillator + ²⁴¹Am source) attached on each PMT surface

Ultraviolet LED illuminating the front of the camera

Detection efficiency

Filter transmittance difference

2 year

1 year
Filter transmittance measurement at site

Intergrating sphere: AvaSphere-80-Refl

Deuterium/halogen lamp 78W deuterium, 5W halogen

Optical Fiber: FC-XX800-2

Spectrophotometr: AvaSpec-ULS2048L-USB2-UA-RS

Colimator

UV filter
Non-uniformity on PMT surface

By a courtesy of the IceCube group in Chiba University, especially thank to Dr. Yuya Makino
Signal detections from laser and showers

- 85 hour observation time
- Remote controlling observation
- Commissioning by self-trigger mode

Cherenkov dominated signals

A horizontal laser shot toward FAST telescope from 26 km away.

PMT 0

PMT 1

PMT 2

PMT 3
Cosmic ray events (Cherenkov)

Ultra zoomed! No close similar events.

Work: Petr Hamal, Jiri Kvita
Results of energy spectrum, mass composition and anisotropy

$E > 8\ EeV$


Increase dipole amplitude above 4 EeV

arXiv:1808.05579

$E > 57\ EeV$

K. Kawata et al., Proc. of ICRC 2015

⇒ Need more statistic of ultrahigh energy cosmic rays (UHECRs)

$E > 100\ EeV$

S. Troitsky et al., Proc. of ICRC 2017
Physics goal and future perspectives

Origin and nature of ultrahigh-energy cosmic rays (UHECRs) and particle interactions at the highest energies

Exposure and full sky coverage

TA×4 + Auger
K-EUSO: pioneer detection from space with an uniform exposure in northern/southern hemispheres

Detector R&D
Radio, SiPM, Low-cost fluorescence detector

"Precision" measurements
AugerPrime
Low energy enhancement (Auger infill+HEAT+AMIGA, TALE+TA-muon+NICHE)
LHCf/RHICf for tuning models

5 - 10 years

10 - 15 years

Next generation observatories

In space (100×exposure): POEMMA
Ground (10×exposure with high quality events): FAST
Cherenkov dominated event (2 telescopes)

**FAST reconstruction:**

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<td>59.8 deg</td>
<td>-96.7 deg</td>
<td>7.9 km</td>
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<td>842 g/cm²</td>
<td>17.3 EeV</td>
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**Comparison with Simulation - best fit**

<table>
<thead>
<tr>
<th>Time bin [100 ns]</th>
<th>Data</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td></td>
<td></td>
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<tr>
<td>250</td>
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<tr>
<td>400</td>
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Event 85: SD: 3.46 EeV, Zen: 33.74°, Azi: -142.35°, Core(-0.819, -17.79), Date: 20180515, Time: 070303.780776

FD: 7.24 EeV, Zen: 51.0°, Azi: -127.1°, Core(-11.15, -20.94), Date: 20180515, Time: 070303.780845657

Event 86: SD: 2.05 EeV, Zen: 36.0°, Azi: -40.84°, Core(-0.379, -5.728), Date: 20180515, Time: 073621.459157

FD: 1.20 EeV, Zen: 21.7°, Azi: 20.6°, Core(5.24, -7.93), Date: 20180515, Time: 073621.459222967


Event 88: SD: 26.89 EeV, Zen: 56.66°, Azi: -95.9°, Core(8.291, -8.72), Date: 20180515, Time: 092721.792484

FD: 19.05 EeV, Zen: 54.6°, Azi: -99.6°, Core(9.27, -8.76), Date: 20180515, Time: 092721.792523028
Reconstructing the highest event

Top-Down Reconstruction
- Using a $\chi^2$ test to compare pulses bin-by-bin

$$
\chi^2 = \sum_{\text{pixel } i} \sum_{\text{time } t} \frac{(x(i, t) - A\mu(i, t))^2}{\sigma_{\text{NSB}}^2(i) + A\sigma_{\text{signal}}^2(i, t)}
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- $A$ is a scale factor for shower energy

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Work: Justin Albury, Jose Bellido