The TAIGA observatory - a hybrid detector complex for high energy gamma-ray astronomy and cosmic ray physics in the Tunka valley

N. Budnev, Irkutsk State University
For the TAIGA collaboration
More than 160 sources of gamma rays with energy more than 1 TeV were discovered with IACT arrays. But no gamma quantum with energy more than 80 TeV were detected up to now. An area of an array should be a few square kilometers as minimum to detect high energy gamma. Cost of an IACT array 30 M$ /km$^2$ at least!
EAS Energy
\[ E = A \cdot [N_{ph}(200m)]^g \]
\[ g = 0.94 \pm 0.01 \]

Average CR mass \( A \)
\( \ln A \sim X_{\text{max}} \)

\( X_{\text{max}} = C - D \cdot \lg \tau (400) \)
(\( \tau(400) \) - width of a Cherenkov pulse at distance 400 m EAS core from).

\( X_{\text{max}} = F(P) \)
\( P \) - Steepness of a Lateral Distribution Function (LDF)

EAS Cherenkov light detection with non-imaging timing wide-angle detectors
\[ \theta, \varphi \]
Tunka-133 timing array: 175 wide-angle Cherenkov detectors distributed on area 3 km² (constructed during 2006-2012y)

50 km from Lake Baikal
The all particles energy spectrum $I(E) \cdot E^3$

1. Agreement with KASCADE-Grande, Ice-TOP and TALE (TA Cherenkov).
2. The high energy tail do not contradict to the Fly’s Eye, HiRes and TA spectra.

First knee
- Tunka-25
- Tunka-133

Second knee

Mean logarithm of primary mass

$\gamma_1 = -3.23 \pm 0.01$
$\gamma_2 = -2.99 \pm 0.01$
$\gamma_3 = -3.07 \pm 0.03$
$\gamma_4 = -3.34 \pm 0.11$
1. Good accuracy positioning of EAS core (5 -10 m)
2. Good energy resolution (~15%)
2. Good accuracy of primary particle mass identification (accuracy of $X_{\text{max}}$ measurement ~ 20 -25 g/cm$^2$).
3. Good angular resolution (~0.5 degree)
4. Low cost: the Tunka-133 – 3 km$^2$ array ~ 10$^6$ Euro
TAIGA Collaboration

- Irkutsk State University (ISU), Irkutsk, Russia
- Scobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), Moscow, Russia
- Institute for Nuclear Research of RAS (INR), Moscow, Russia
- Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of RAS (IZMIRAN), Troitsk, Russia
- Joint Institute of Nuclear Physics (JIRN), Dubna, Russia
- National Research Nuclear University (MEPhI), Moscow, Russia
- Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk, Russia
- Novosibirsk State University (NSU), Novosibirsk, Russia
- Altay State University (AGU), Barnaul, Russia
- Deutsches Elektronen Synchrotron (DESY), Zeuthen, Germany
- Institut fur Experimentalphysik, University of Hamburg (UH), Germany
- Max-Planck-Institut für Physik (MPI), Munich, Germany
- Fisica Generale Universita di Torino and INFN, Torino, Italy
- ISS, Bucharest, Romania
The main idea: A cost effective approach for construction of large areas array is common operation of wide-field-of-view timing Cherenkov detectors (the non-imaging technique) with a few relatively cheap, small-sized Imaging Air Cherenkov Telescopes.
TAIGA: combine of Imaging and Non-Imaging technique

Hybrid concept

HiSCORE (Timing): direction, core location, energy

IACT (Imaging): gamma – hadron separation

IACT operated in Mono-Mode at large distances
Gamma-ray Astronomy

Study of high-energy edge of spectrum of galactic gamma-ray sources. Search for the PeVatrons.
VHE spectra of known sources: what are the highest energy?
Absorption of high energy gamma.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition
Anisotropies from $10^{14}$ to $10^{18}$ eV.
Apply the new hybrid approach (common operation of IACTs and wide-angle timing array) for study of cosmic rays mass composition in the “knee” region ($10^{14}$-$10^{16}$ eV).

Particle physics
Axion/photon conversion.
Lorentz invariance violation.
**TAIGA-HiSCORE** *(High Sensitivity Cosmic Origin Explorer)*

- Wide-angle time-amplitude sampling non-imaging air Cherenkov array.
- Spacing between Cherenkov detectors 80-100 m ~ 100-150 channels / km².

1. Accuracy positioning EAS core - 5 -6 m
2. Angular resolution ~ 0.1 – 0.3 deg
3. Energy resolution ~ 10 - 15%
4. Accuracy of Xₘₐₓ measure ~ 20 -25 g/cm²
5. Large Field of view: ~ 0.6 sr

Total cost ~ 2 · millions $ (for 1 km²)
TAIGA-HiSCORE DAQ system: Cherenkov detectors & central part, including redundant GPS/Rb Clocks.
An accuracy of EAS axis direction reconstruction with TAIGA-HiSCORE

The RMS = 1.1 ns for TAIGA-HiSCORE provides an accuracy of an $\gamma$ and CR arrival direction about 0.1 degree.
First TAIGA-HiSCORE result - an accuracy of a point source direction measurement is about 0.1 degree

- Excellent HiSCORE calibration source
  - flat timing profile
  - precision pointing

Precision verification with Laser on-board International Space Station (ISS) < 0.1deg
TAIGA: status winter 2017-2018 y.

2107 events (≥ 4 stations)
Angular resolution ~ 0.1 – 0.3 deg

HiSCORE = High Sensitivity Cosmic Ray Origin Explorer
Stations with large FOV: ~ 0.6 sr
Spacing: 10^6 m

TAIGA-IACT

43 TAIGA-HiSCORE Cherenkov detectors with FOV: ~ 0.4 sr
Spacing: 106 m
Area about 0.4 km^2
First TAIGA-HiSCORE results

A hint of signal compatible with expectation (~40 TeV < E < 100 TeV)

Energy spectrum
More details in V. Prosin talk

Tentative Crab-search

RA = 83.63°
DEC = 22°.00”

Very preliminary
The first TAIGA - IACT
Is in commissioning since early 2017:
- 34-segment reflectors (Davis-Cotton)
- Diameter 4.3 m, area ~10 m²
- Focal length 4.75 m
- Threshold energy ~ 1.5 TeV

Next 2 IACTs are in construction.

The final TAIGA-IACT array will include
16 IACTs over 10 km²
with > 800 m spacing
(i.e. in “mono-mode”).

Operation in Hybrid-Mode,
with TAIGA-HiSCORE and TAIGA-Muon.
The Camera of the TAIGA-IACT

- 547 PMTs (XP 1911) with
- 15 mm useful diameter of photocathode
- Winston cone: 30mm input size
- each pixel = 0.36 deg
- FOV 10 x 10 deg

Basic cluster: 28 PMT-pixels. Signal processing: PMT DAQ board based on MAROC3 ASIC
Season 2017 -2018: TAIGA-IACT and TAIGA-HiSCORE
17000 joint events.

Most of them are “Hadron-like”
E = 880 TeV
width = 0.4°

300 events in 0.7° around direction on Crab.
Expected number of gammas: 10-20 with E > 40 TeV

More details in L.Sveshnikova presentation and E.Postnikov poster
But some events looks as “Gamma-like”.

$E = 50 \text{ TeV}$

Width = 0.19°
Another “Gamma-like” event.

$E = 50 \text{ TeV}$

$\theta = 37.0$

$\phi = 331.12$

Core position
Size (IACT) vs. Size (HiSCORE)

day 20.02.17
The integral spectra of size for IACT and JOINT events

Integral spectra by size

Experiment IACT

- 161117 IACT
- 281017
- 141117
- Joint events

Monte Carlo

$E = 3-1000$ TeV, $g = -2.6$

$N(>\text{size})/t$, sec$^{-1}$

Size, ph.el.

Joint events

Monte-Carlo,

$1000$ TeV

$100$ TeV
Number of joint events depending on an angle $\gamma$ between the IACT pointing direction and the shower arrival direction measured with HiSCORE.
- Counter dimension 1x1 m$^2$.
- Wavelength shifting bars are used for collection of the scintillation light on the PMT.
- Mean amplitude from cosmic muon is 23.1 photoelectrons with ±15% variation (minimum to maximum).
- A clear peak in amplitude spectrum is seen from cosmic muons in a self trigger mode.
Upgrades of the TAIGA experiment

Funded TAIGA upgrade 2017-2019:
- 120 TAIGA-HiSCORE non-imaging wide angle
- Cherenkov detectors (area 0.4 km\(^2\) (2017) \(\rightarrow\) 1 km\(^2\) (2019))
- 3 Imaging Cherenkov Telescopes of TAIGA - IACT
- 200 m\(^2\) Muon detectors of TAIGA - Muon

Long term plan:
Upgrade up to 10 km\(^2\) array with 1000 non-imaging wide angle Cherenkov detectors of TAIGA-HiSCORE
16 Imaging Cherenkov of TAIGA - IACT
+ 3000m\(^2\) of muon detectors.
TAIGA-HiSCORE
120 detectors

TAIGA-IACT

3 TAIGA-IACT

1km² + 3 IACT
TAIGA: A possible future 10 and more km\(^2\) upgrade

**TAIGA** — Tunka Advanced Instrument for cosmic rays and Gamma Astronomy

**TAIGA-HiSCORE** - array of 1000 non-imaging wide-angle detectors distributed on area 10 km\(^2\).
An EAS core position, direction and energy reconstruction.

**TAIGA-IACT** - array -of 16 IACT with mirrors – 4.3 m diameter.
Charged particles rejection using imaging technique.

**TAIGA-Muon** (including Tunka – Grande) - array of scintillation detectors, including underground muon detectors with area - 10\(^2\) → 3 10\(^3\) m\(^2\) area
Kind of primary particles separation.
TAIGA an integral point source sensitivity

- TAIGA-HiSCORE: 200 h
- TAIGA-IACT: 50 h
- Spectral resolution: 10-20%

Graph showing energy flux per erg cm² s⁻¹ vs energy per TeV for different sensitivities and experimental configurations.
Conclusions

TAIGA aims at establishing a new, hybrid gamma-ray detection technology for $>30$ TeV

TAIGA in 2017/18: 0.4 km$^2$ array + first IACT
- Stable operation, the threshold for joint operation $E_{th} \sim 30$ TeV
- CR energy spectrum below the knee
- Hint of a signal from Crab (in agreement with expectation)
- Precision absolute pointing better than 0.1 degree: from Laser on-board ISS
- Joint operation of TAIGA-HiSCORE and IACT: data analyses is in progress.

TAIGA pilot complex in 2019 (funding complete)
- 1 km$^2$ array: 120 wide-angle timing optical stations + 3 IACTs
- Point source sensitivity: $2.5 \times 10^{-13}$ TeV/cm$^2$/s (300 hr 30–200 TeV)

Future option:
- 10 km$^2$ array: 1000 wide-angle timing optical stations + 10-16 IACTs
- Point source sensitivity: $\sim 5 \times 10^{-14}$ TeV/cm$^2$/s
Thank you for attention!