The Tunka experiment: from cosmic ray to gamma-ray astronomy.

N.Budnev, Irkutsk State University
For Tunka&TAIGA - collaboration
High energy charged particles and gamma – ray detections

Atmosphere as a huge calorimeter

For electrons with $E_e > 25$ MeV
$V_e > C/n$

- Charged particles
- Cherenkov light
- Fluorescence light
- Radio emission

Measurement of Cherenkov light with telescopes or wide angle prims
Measurement of particles with tracking detectors or calorimeters
Measurement of low energy muons with scintillation or tracking detectors
Measurement of high energy muons deep underground

First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Some of the particles reach the ground
Measurement with scintillation counters
Measurement of radio emission
Measurement of fluorescence light

P, N, γ

~25 km

Atmosphere as a huge calorimeter
EAS Energy

\[ E = A \cdot [N_{ph}(200m)]^g \]

Density of Cherenkov light at distance 200 m from core

\[ g = 0.94 \pm 0.01 \text{ (for } 10^{16} - 10^{18} \text{ eV)} \]

EAS Cherenkov light wide-angle detection technique

Average CR mass \( A \)

\[ \ln A \sim X_{\text{max}} \]

\[ X_{\text{max}} = F(P) \]

- Steepness of a Lateral Distribution Function (LDF)

\[ X_{\text{max}} = C - D \cdot \log \tau (400) \]

(\( \tau(400) \) - width of a Cherenkov pulse at distance 400 m EAS core from)
Tunka-133 array: 175 optical detectors distributed on 3 km$^2$ area

50 km from Lake Baikal
Tunka Collaboration

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Advantage of the Tunka-133 array:

1. Good accuracy positioning EAS core (5 -10 m)  
2. Good energy resolution (~15%, in principal up to - 5% )  
3. Good accuracy of primary particle mass identification (accuracy of $X_{\text{max}}$ measurement ~ 20 -25 g/cm$^2$)  
4. Low cost: the Tunka-133 – 3 km$^2$ array ~ 10$^6$ Euro

Disadvantage:

Short time of operation (moonless, cloudless nights) – 5-10%
Five seasons of Tunka-133 array operation

- **1540 h** of good weather for observation with a trigger frequency ~ 2 Hz
- **10 000 000 events**
- > **12 000** events with an energy $\geq$ 50 PeV
- > **3000** events with an energy $\geq$ 100 PeV.

**Distribution of the number of hit detectors in an event.**

**Trigger counting rate during one night.**

- > **10 events** during every night with number of hit detectors more than 100.
An event example

Hitted detectors

ADF
Amplitude distant function

LDF
Lateral Distribution function

Delay time vs. Distance from core

WDF – width distant function
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.
Mass composition: two methods of $X_{\text{max}}$ measurement:

$$\Delta X_{\text{max}} \leq 25 \text{ g} \cdot \text{cm}^{-2}$$

ADF steepness: $b_A$

Pulse width at core distance 400 m: $\tau_{\text{eff}}(400)$
1. The Xmax do not contradict to that of HiRes-MIA and Auger data.
2. CR composition changes to heavy from 10 PeV to 30 PeV and changes back to light in the range 100 – 1000 PeV.
Spectra of light (p+He) and heavy (all other) CR components
Towards High Energy Gamma-Ray Astronomy array at Tunka Valley

TAIGA — Tunka Advanced Instrument for cosmic rays and Gamma Astronomy — 5 arrays

Tunka-HiSCORE array -net of non imaging wide-angle optical stations
- Shower front and LDF sampling technique for core position and energy reconstruction.
- Angular resolution — 0.1 deg.
- Xmax measurement for hadron rejection.

Tunka-133

Tunka-IACT array -net of Imaging Atmospheric Cherenkov Telescopes with mirrors - 4 m diameter about.
- Charged particle rejection using imaging technique.

Tunka-Rex

Tunka – Grande array net of scintillation detectors, including underground muon detectors with area - $10^2 \rightarrow 2 \times 10^3 \text{ m}^2$ area
- Charged particle rejection.
From Tunka-Collaboration to TAIGA-Collaboration

Germany

Hamburg University (Hamburg)
DESY (Zeuthen)
MPI (Munich)
KIT (Karlsruhe)
Humboldt University (Berlin)

ITALY
Torino University (Torino)

Russia

MSU (SINP) (Moscow)
ISU (API) (Irkutsk)
JINR (Dubna)
IZMIRAN (Moscow)
INR RAS (Moscow)
MEPHI (Moscow)
Kurchatov Institute (Moscow)
IPSM (Ulan-Ude)
Gamma-ray Astronomy
Search for the PeVatrons.
VHE spectra of known sources: where do they stop?
Absorption in IRF and CMB.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics
Energy spectrum and mass composition anisotropies from $10^{14}$ to $10^{18}$ eV.
$10^8$ events (in 1 km$^2$ array) with energy $> 10^{14}$ eV

Particle physics
Axion/photon conversion.
Hidden photon/photon oscillations.
Lorentz invariance violation.
pp cross-section measurement.
Quark-gluon plasma.
## Observation time for some gamma sources per one year with TAIGA array (short list)

<table>
<thead>
<tr>
<th>Name</th>
<th>RA degrees</th>
<th>Decl</th>
<th>Flux $F$ at 1 TeV, $10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ $\Gamma$</th>
<th>Flux $F$ at 35 TeV, $10^{-17}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ (from Milagro)</th>
<th>Time of observation per one year (x 0.5 - weather factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tycho SNR (J0025+641)</td>
<td>6.359</td>
<td>64.13</td>
<td>$0.17 \pm 0.05 \quad \Gamma = 1.95 \pm 0.5$</td>
<td>$32.6 \pm 9.0 \quad \Gamma = 2.6 \pm 0.3$</td>
<td>236h</td>
</tr>
<tr>
<td>Crab</td>
<td>83.6329</td>
<td>22.0145</td>
<td>$3.6 \pm 9.0 \quad \Gamma = 2.6 \pm 0.3$</td>
<td>$56.2 \pm 9.4$</td>
<td>110h</td>
</tr>
<tr>
<td>SNR IC443 (MAGIC J0616+225)</td>
<td>94.1792</td>
<td>22.5300</td>
<td>$0.58 \pm 0.12 \quad \Gamma = 3.1 \pm 0.30$</td>
<td>$28.8 \pm 9.5$</td>
<td>112h</td>
</tr>
<tr>
<td>Geminga MGRO C3 PSR</td>
<td>98.50</td>
<td>17.76</td>
<td>$37.7 \pm 10.7$</td>
<td>$102h$</td>
<td></td>
</tr>
<tr>
<td>M82 (Starburst Galaxy)</td>
<td>148.7</td>
<td>69.7</td>
<td>$0.25 \pm 0.12 \quad \Gamma = 2.5 \pm 0.6$</td>
<td>$50\text{-}200 \quad \Gamma = 2.0\text{-}2.6$</td>
<td>325h</td>
</tr>
<tr>
<td>Mkn 421 (BL, z=0.031 Variable)</td>
<td>166.114</td>
<td>38.2088</td>
<td>$1.42 \pm 0.33 \pm 0.41 \pm 0.30 $</td>
<td>$70.9 \pm 10.8$</td>
<td>140h</td>
</tr>
<tr>
<td>SNR 106.6+2.7 (J2229.0+6114)</td>
<td>337.26</td>
<td>61.34</td>
<td>$1.26 \pm 0.18 \quad \Gamma = 2.61 \pm 0.24 \pm 0.2$</td>
<td>$177h$</td>
<td></td>
</tr>
<tr>
<td>Cas A (SNR, G111.7-2.1)[6]</td>
<td>350.853</td>
<td>58.8154</td>
<td>$1.3 \quad \Gamma = 2.3$</td>
<td>$266h$</td>
<td></td>
</tr>
<tr>
<td>CTA_1(SNR,PWN)</td>
<td>1.5</td>
<td>72.8</td>
<td>$1.3 \quad \Gamma = 2.3$</td>
<td>$266h$</td>
<td></td>
</tr>
</tbody>
</table>
Tunka - HiSCORE (Hundred*i Square-km Cosmic Origin Explorer).

Non-imaging air Cherenkov array
Angular resolution: ~ 0.1 degree
Large Field of view (FOV): ~ 0.6 sr
Area: from 1 km$^2$ → 100 km$^2$
Spacing between Cherenkov stations 100-200m
~200 channels / km$^2$.
Total cost ~ 5 ·millions Euro (for 10 km$^2$)
50 ·millions Euro (for 100 km$^2$)
- Cosmic-rays with energy: 30 TeV - 10 EeV
- Gamma-rays: $E_\gamma > 20$ TeV, up to PeV, ultra-high energy regime
- Particle physics: beyond LHC range

Wide-angle Cherenkov technique is very suitable way to study high energy gamma-rays.
Tunka-HiSCORE Cherenkov detector

Electronics box

4 PMT

Calibration light source
In October 2012 first setup of 3 Tunka-HiSCORE Cherenkov detectors were put in operation combined with Tunka-133.
October 2013
Prototype of Tunka-HiSCORE
9 Cherenkov stations

36 PMT R5912 (8’’)
New readout system.
New DAG based on DRS-4 bord

For $E_0 > 3 \times 10^{15}$ eV:
- Arrival direction difference – $\Delta \psi < 0.5^\circ$
- EAS core coordinate difference – $\Delta X < 7$ m, $\Delta Y < 7$ m
- LogE0 difference – $\Delta \log E_0 < 0.051$ (1.2%)
- Tunka-HiSCORE:
  - "see N.Budnev (previous talk), and M.Tluczykont (plenary
    - Ground array detector
    - Stations spacing ~150m over 1-100 km
    - nsec-time resolution between stations needed for optimal EAS-pointing
  - MC simulations:
    - angular resolution degrades for >1nsec time resolution

- A distributed DAQ system for the HiSCORE detector based on the WhiteRabbit (WR) timing system has been developed in order to achieve a sub-ns time resolution
WR main components

WR Master: WR Switch

1Gbit fiber

FMC DIO mezzanine

Trigger out 2
Trigger in

PPS out 2
PPS out

USB terminal

Spec card

SFP  FMC  FPGA

HiSCORE station 1
HiSCORE station 2
HiSCORE station 3

HiSCORE station 4
HiSCORE station 5
HiSCORE station 6

HiSCORE station 7
HiSCORE station 8
HiSCORE station 9

Early test in 2012/13

Phase stability < 0.2ns
Absolute time precision ~ 1ns

1ms ~0.17ns

Stability LabTest 50 hrs
- **PMTs + Summator**: signal
  - 4 Anodes Sum (AS)
- **WR SPEC FPGA:**
  - Trigger on the AS (9ns above the threshold)
- **RaspberryPi**: Connected to SPEC and DRS boards
  - When SPEC triggers: DRS start recording
  - When DRS recording is finished: ready flag sent to SPEC to trigger next event
  - Send data to the DAQ center
- **WR Switch**: synchronize all the array stations trigger time
An accuracy of EAS axis direction reconstruction

The RMS=1.1 ns for Tunka-HiSCORE provides an accuracy of an $\gamma$ and CR arrival direction about 0.1 degree
An amplitude spectrum of PMTs pulses of a Tunka-HiSCORE optical station

Threshold (120 photoelectrons)

Counting rate = 12 - 16 Hz

Threshold Čerenkov photons flux:
0.25 – 0.3 ph / cm²
LDF of Cherenkov light from gamma-rays induced EAS

And Threshold distances from core

Threshold distances from core

- $E_\gamma = 30$ TeV
- $E_\gamma = 100$ TeV

EAS Cherenkov photons threshold flux

- 120 m
- 230 m

- 100 TeV
- 30 TeV
Efficiency of gamma ray detection with Tunka-HiSCORE

Threshold condition – \( N_{\text{hit}} \geq 5 \) hitted optical station

- 30 TeV
  - for 2 stage

- 80 TeV
  - 1 stage

- 64 det. q=0.1, s=0.5m2, rate 23
- 64 usual +40 HAMAMATSU R7081-100
  - with q=0.14, s=0.75, rate 49

\( 10^1 \) \( 10^2 \) \( 10^3 \)

\( 1\% \) \( 10\% \) \( 100\% \)
Tunka-HiSCORE event example
Zenith angle = 7.2°
Energy = $10^{16}$ eV
Tunka-HiSCORE: All particle energy spectrum.

PRELIMINARY

84 h during 13 clean moonless nights in February and March of 2014

~ 145 000 events with $E_0 > 3 \cdot 10^{14}$ eV
   – 100% efficiency

~ 21 000 events $E_0 > 10^{15}$ eV

~ 200 events $E_0 > 10^{16}$ eV
All particle spectrum
Tunka – Grande array consisting of TAIGA

228 KASCADE-Grande scintillation counters (0.64 m²) in 19 stations on the surface

152 KASCADE-Grande scintillation counters in underground containers (muons detectors, total area 100 m² about)

Future plan: 2000 m² muon detectors (0.2% of array area)
Rejection of p-N background with Tunka-Grande

\[ \gamma \text{ EAS, } \theta = 40^\circ \]
\[ \text{E}_0 = 3 \times 10^{13} \text{ eV} \]

\[ N_{\mu}, \text{ events} \]

\[ \gamma \text{ EAS, } \theta = 0^\circ \]
\[ \text{p EAS, } \theta = 40^\circ \]
\[ \text{p EAS, } \theta = 0^\circ \]
Tunka –IACT array consisting of TAIGA

A system of 16 IACT (Imaging Atmospheric Cherenkov Telescopes) which will operate together with TUNKA-133 Tunka-HiSCORE and Tunka-Grande.

Mirror diameter – 4 m about (34 mirrors with 60 cm diameters), 4.8 m focal distance
Spacing 300 – 600 (?) m
Covering an area of 1 km x 1 km
An energy range - TeV-EeV
Threshold energy ~ 2-3 TeV
Field of imaging cameras view of 8° x 8°
Pixel size -0.4°,
Low cost

Camera: 400 PMTs (XP 1911) with 15 mm useful diameter of photocathode
Winston cone: 30 mm input size, 15 output size
1 single pixel = 0.36 deg
full angular size 8.3 deg

DAQ - MAROC3
Very near future of Tunka experiment

Spring 2014 y:
1. Tunka-133 175 detectors single PMT of Ø 20 cm
2. Tunka-HiSCORE 9 stations 4 PMT with Winston cones
3. Tunka-Rex 25 radio antennas
4. Optical telescope of “Master” net

November 2014 y:
1. Scintillation station for electrons and muons detection (based on former KASCADE-Grande detectors) - 19 stations (total area for muons 100 m²)
2. Tunka-HiSCORE - 33 stations
3. Prototype of IACT with mirrors of 15 m² area
4. Tunka-Rex + 25 radio antennas
Tunka-HiSCORE October 2014y
– 33 stations
Decreasing of a threshold for $\gamma$ to $\sim 30$ TeV

All the stations will be tilted for 30° to the South for observation of Crab Nebulae

About 10-20 $\gamma$-events from Crab are expected during 100 h of observation.
Stage 2 (2014-2016 years):
104 wide angle Tunka-HiSCORE Cherenkov detectors

- 40 detectors with 10” PMT R7081
- 64 detectors with 8” PMT R5912

S ~1km²
Stage 3 (2015-2018 years): net of wide angle Cherenkov detectors + 16 imaging telescopes (IACT) + 2000m² muon detectors
Sensitivity for gamma rays

1st stage (2015y)
Tunka–HiSCORE
64 stations with 150 m spacing
(50 events 500 hours)

2nd stage (2016 y)
Tunka–HiSCORE
+ 5 IACT-telescopes
(very preliminary)

10 км² TAIGA (2013 – 2018) ~10 -12 Millions Euro

CTA (2017-18) - ~400 Millions Euro (!)
LHAASO (2013-2018) ~150 Millions $
33 Tunka-HiSCORE optical stations in October 2014

S=1 km², 64 stations, 150 m step, 240 PMTs (250 PMTs are available), 1 M Euro, 2013 – 2015

Decreasing of energy threshold

S = 1 km², +40 station with
160 PMT HAMAMATSU R7081-100 (10")
+ 5 Tunka- IACT
with mirrors ( D = 4,2 m )
Cost: 2 M Euro.

2014-2016

2014-2018

Extension of the array up to 10 km²

2000 m² scintillation detectors Tunka-Grande
(0.1% of the whole area)
– 2-5 muons from 250 TeV protons
Cost: 2.5-3 M Euro.
Summary and outlook

1. Cherenkov technique is very suitable way to study high energy cosmic rays as well gamma-rays, Tunka valley is one of the best place for construction of large Cherenkov arrays.

2. The structure of CR energy spectrum in the energy range of $10^{14}$ to $10^{18}$ eV were measured with high resolution. The second “knee” at energy $\sim 3 \cdot 10^{17}$ eV point out on transition from Galactic to extragalactic sources of CR.

3. The new gamma – observatory TAIGA will allow:
   - To perform search for local Galactic sources of gamma-quanta with energies more than 20-30 TeV (search for PeV-trons) and study gamma-radiation fluxes in the energy region higher than 20-30 TeV at the record level of sensitivity.
   - To study energy spectrum and mass composition of cosmic rays in the energy range of $5 \cdot 10^{13}$ - $10^{18}$ eV at so far unprecedented level of statistics.
   - To study high energy part of gamma-rays energy spectrum form the most bright balzars (absorption of gamma-quanta by intergalactic phone, search for axion-photon transition).
   - Etc..........................
Thank you!