Final Report

Funding Programme:	**Helmholtz Joint Research Groups**
Project ID No.:	**HRJRG-303**
Project Title:	**Measurements of Gamma Rays and Charged Cosmic Rays in the Tunka-Valley in Siberia by Innovative New Technologies**
Principal Investigator:	**Ralf Wischnewski**

1) Work and Results Report

Please describe the main results and the progress achieved through the Joint Research Group in comparison to the state of the art at the time of writing the application and give an outlook on possible future work and applications.

a) Description of the results (max. 4 DIN A4 pages)

Please describe the scientific and/or technical success of the group as well as secondary results achieved and essential experience gained

Executive Summary

The project aimed at establishing two innovative experimental techniques for Gamma Ray and Cosmic-Ray Physics – using the world-wide unique Russian cosmic-ray facility in the Tunka valley to (1) build wide-angle air Cherenkov detectors (HiSCORE) to open the field of multi-TeV Gamma ray astronomy with a cost-effective technology, and (2) to conduct a precision calibration of the radio detection technique for cosmic rays (Tunka-Rex).

The Tunka facility offers the atmospheric air-cherenkov detector system Tunka-133, which measures cosmic-ray (CR) events with good energy resolution in the Multi-PeV-energy region. For the radio-program Tunka-Rex, a relatively modest experimental extension of the setup, allowed to record radio-pulses of air showers and to start a detailed cross-calibration program. The Gamma Ray program planned the construction of a completely new detector-array (HiSCORE), a task that required relatively large effort in investment and manpower. Due to the strong initial HRJRG success, these resources were delivered already in HRJRG-Year-2 by the creation of a Russian-MEGA-grant (PI: Razmik Mirzoyan, MPI Munich).
We mention that construction of Tunka-133 was done in collaboration between DESY and Russian groups; for KIT and UHH direct work on the Russian Tunka site started in the framework of this HRJRG. The work on Tunka-HiSCORE and Tunka-Rex are described below separately, for easy of presentation.

Both sub-projects have been very successful - reaching all their basic goals, and going well beyond their initial plan: Tunka-Rex has been extended to 44 antennas in the last year of the HRJRG, almost twice as many as originally planned, and HiSCORE building a 28 station prototype system – a 9-fold increase compared to the planned three-station prototype setup given in the proposal. An important outcome of the HRJRG-project is the creation of the new international collaboration TAIGA, aiming at Multi-TeV Gamma Ray and Cosmic Ray astronomy at the Tunka site with instruments of world-competitive sensitivities.

Tunka-HiSCORE:

The main result of the work is an 28-station operating engineering Gamma Ray array of 0.3 km^2-scale, with an active German-Russian collaboration working on physics data analysis and on the upgrade of this setup. The 28 stations form the worldwide largest timing array devoted to gamma-ray astronomy.
With the huge construction effort, far beyond the original HRJRG-project plans, several of the detailed milestones had been adjusted – mainly to concentrate on the early detailed experimental data-analysis, rather than evaluation of future physics applications.
An original technical development, regarding state-of-the-art sub-nsec timing precision technologies was brought to a level that allowed direct cross-application in the upcoming international CTA-project.

The original program was detailed in our HRJRG-application (see Appendix p. 9). In the following, the results achieved for each of the listed items are described.

1. Prototyping and preparatory phase of HiSCORE-EA (items "Prototype 1" / "Prototype 2" / "Finalization of components" / "Preparatory work for HiSCORE-EA"):

During the first year of the HRJRG-303 funding period, 3 prototype stations were deployed, commissioned and operated in the Tunka valley. Optimizations of different detector components were made (summator and readout boards, optical light concentrator, mechanical lid, slow control, White-Rabbit timing system), resulting in a final HiSCORE station design, in agreement with the Russian partners.

Surpassing our original plans, we deployed first 9 stations as a prototype array in 2013. A year later, this was extended to a 28 station array covering a total area of 0.25 km^2, making Tunka-HiSCORE the currently largest timing array dedicated to gamma ray astronomy. While originally only a preparatory phase for the HiSCORE Engineering Array (HiSCORE-EA) was planned, we succeeded in deploying a full HiSCORE-EA within the timeframe of HRJRG-303.

2. Sub-ns Array-timing & DAQ (Data Acquisition System - items "Data analysis amplitude" / "Data analysis time" / "Sub-ns time-sync" / "beacon" / "test usage radio"):

A DAQ system based on commercially available components (DRS4 - board, RaspberryPI, WhiteRabbit timing) was realized, deployed, and operated. This DAQ system was running on the first 9 HiSCORE stations, in parallel with a DAQ system specifically developed for Tunka-HiSCORE.

Sub-ns relative time synchronization between all detector stations is essential for the timing array to work. Both DAQ-systems were realizing a different synchronization approach, which were successfully cross-calibrated with a powerful horizontal LED pulser system and air shower data. The verification measurements of the time-synchronization methods yielded a relative time-synchronization precision of the order of 0.5 ns for the 9 station array (up to 424m distance). Given the success of two independent time-synchronization methods, we decided to discard investigation of the radio-beacon time-synchronization method at this stage. An amplitude calibration run was performed on-site with the first 9 stations using the same LED pulser setup. An independent LED-pulser system was developed in the laboratory.

3. Reconstruction, analysis and simulation ("simulation studies" / "hybrid concepts"):

Independent reconstruction programs/algorithms originally developed for Tunka-133 and the HiSCORE simulation framework were compared based on simulations and real data (chess-board method). These studies resulted in an angular resolution of the 9 station array of better than 0.2°, an energy resolution of 10%, and a core impact position resolution of better than 5 m. Such detector performances lie within expectations for protons at the energy threshold of Tunka-HiSCORE.

Using MC-simulations, a graded array geometry was found to be an optimal detector layout for a larger HiSCORE detector. In addition, a hybrid detector concept that combines the HiSCORE timing array with the imaging technique (i.e. Imaging Air Cherenkov Telescopes (IACTs) such as CTA) was developed. Simulation studies of such a combination, where single IACTs are acting together with HiSCORE stations, have shown that the gamma-hadron separation reachable with a hybrid detector is comparable to that in stereo observations with multiple IACTs (i.e. reached by standard separation with the mean-scaled-width parameter used in classical Hillas-analyses). Together with the significantly lower cost (reduced number of channels per km²), this result demonstrates that a hybrid array can be built from telescopes placed at larger distances from each other compared to an IACT-only configuration; therewith covering a larger area a hybrid detector is very well suited to access the multi-TeV to PeV energy range in a cost effective way.

The achieved results gave us confidence in pursuing a significant extension of the HiSCORE concept to a hybrid imaging+timing detector, leading to the new TAIGA collaboration (see next section b)).

Tunka-Rex

The main goals of the Tunka-Rex project have been completely fulfilled: The radio signal emitted by cosmic-ray air showers has been successfully cross-calibrated against the air-Cherenkov light measured by the Tunka-133 detector. By this cross-calibration, the precision of the radio detector was determined, and it was demonstrated that the radio technique provides a cost-effective way to enhance and improve traditional cosmic-ray air-shower arrays. This had been assumed earlier, but never shown in practice before. As consequence of the Tunka-Rex efforts in the HRJRG-303, the Tunka facility in Russia owns now a running, competitive radio array for detecting air-showers, which is used for further and enhanced scientific goals.

The following paragraphs summarize the efforts and the success of Tunka-Rex in detail: Already in the first year of the HRJRG-303, in summer 2012, the first 18 antennas of Tunka-Rex have been deployed and have been brought successfully in operation in October 2012. This is remarkable, since in many similar projects there are delays compared to the original planning, but not so for Tunka-Rex. This success was only possible, because Tunka-Rex profited from the experience gained and developments done in the Helmholtz-funded LOPES and Pierre Auger projects in Karlsruhe

In the second year, the Tunka-Rex array was completed to 25 antennas. Since October 2013 each of the Tunka-133 clusters triggers and reads out one antenna of Tunka-Rex. The measurements of the first two years (until April 2014) of this setup have been calibrated and used for the cross-calibration analysis, i.e., for the scientific goals of Tunka-Rex. Still even afterwards, supported by KIT's own funding, we started to extent the array by deploying 19 further antennas, which have into operation in November 2015 and will be used for new scientific goals. Those extensions were performed in close connection with the involved Russian institutes which are interested in a sustainable cooperation.

Finally, we also deployed three antennas attached to HiSCORE stations in order to test joint operation. Test measurements showed that in principle joint operation is possible, i.e., the antennas can be triggered and read out by HiSCORE electronics. However, with the present HiSCORE electronics optimized for air-Cherenkov measurements, the frequency resolution is worse compared to the standard Tunka-Rex measurements using the Tunka-133 electronics. Thus, for the moment it has been more efficient, to attach the antennas to Tunka-133 instead of HiSCORE. Still, for the future also a radio extension to HiSCORE remains an option.

One of the mayor activities for preparing the scientific analysis was the calibration of the Tunka-Rex measurement. It required the further development of existing calibration methods, and the calibration of all individual parts in the electronics. These calibration measurements of individual parts have been confirmed by an end-to-end calibration of a Tunka-Rex antenna deployed at KIT for this purpose using a calibrated reference source of the LOPES experiment. As a result, Tunka-Rex now features an absolute calibration which is equal in accuracy to the other world-best radio arrays for air-showers. As unexpected side achievement, by these efforts an oversight in the LOPES calibration was discovered. Solving this, the calibration of LOPES and also LOFAR improved, and the results are published by a subset of the HRJRG-303 participants as initiative co-authors.

For the main cross-calibration analysis, existing methods for the reconstruction of the energy and shower maximum, a statistical estimator for the cosmic-ray mass, have been further developed, published, and also implemented in the semi-open software framework of the Pierre Auger Collaboration. These methods have been tuned on CoREAS Monte Carlo simulations of the radio emission of air-showers, where CoREAS was developed earlier at KIT and is the state-of-the-art program for this purpose. Then, the methods have been applied on the first year of data, fixing details in the analysis procedure, like software filters for background reduction. Only after all these details were fixed, the Tunka-133 air-Cherenkov data of the second year have been revealed, and compared to the Tunka-Rex radio measurements of the second year. The results show that the measurements of Tunka-Rex agree on an absolute level to the Tunka-133 measurements of the same air showers within the measurements uncertainties. For the shower energy, the absolute accuracy of Tunka-Rex is about 20% which is almost as good as for the leading fluorescence technique for air-showers, which however is limited to dark and clear nights. For the mass composition of cosmic-rays the accuracy of Tunka-Rex is not yet as good, but further improvements are possible and planned. Nevertheless, the real scientific achievement here is that Tunka-Rex provided the first direct experimental evidence that radio arrays can measure the position of the shower maximum, something which was assumed before, only, based on simulations or indirect evidence. Even with the minor accuracy achieved so far, this is an important milestone for the radio detection technique, since the more accurate air-Cherenkov and air-fluorescence detection is restricted in time to dark and clear nights, but radio measurements are possible around the clock under almost any weather condition.

b) Outlook on future work, sustainability (max. 2 DIN A4 pages)

How far did the JRG intensify the scientific cooperation between Helmholtz and international partners? Did it set new impulses in existing and upcoming research programmes of the Helmholtz Association? Does it form the core of a future, larger scale bilateral or otherwise funded project? Please describe planned activities/ cooperations to further develop the work, if applicable also with additional partners.

…

HRJRG-303 strengthened not only the cooperation of the Helmholtz centers KIT and DESY with our Russian partners, but also with each other, and with UHH.

Tunka-HiSCORE

Not only was the collaboration with Russian partners intensified, but also considerably extended within the funding period of the HRJRG. A successful funding application to the Russian Mega-Grant (PI: Razmik Mirzoyan, MPI Munich) allowed us to start the realization of the hybrid detector concept studied within our HRJRG.

Our cooperation definitely forms the core of a future, larger scale project: we are continuing cooperation within the TAIGA project ("*T*unka *A*dvanced *I*nstrument for Cosmic Ray Physics and *G*amma Ray *A*stronomy"). TAIGA consists today of the 28 HiSCORE stations and one imaging air Cherenkov telescope, that will be deployed in 2016. The development of the HiSCORE-EA (including all components, DAQ and the crucial time synchronization tasks, see above) and our studies of a hybrid detector concept within the HRJRG were instrumental ground work for the TAIGA collaboration.

Tunka-Rex

Due to the HRJRG-303 the loose cooperation between KIT and the Tunka experiment developed into an ongoing, sustainable collaboration. This means in particular that Tunka-Rex would not exist without the HRJRG. Even after the end of the HRJRG-303 this collaboration is actively ongoing with approximately equal contributions from both sides. Since there was no possibility to extent the HRJRG, Frank Schröder, the leader of Tunka-Rex at KIT, and the Russian partners at ISU independently applied for national funding sources to continue Tunka-Rex. In both cases this has been successful. Thus, the continuation of Tunka-Rex is ensured until end of 2017, but not yet further. In particular at KIT Tunka-Rex is now funded by a DFG grant of Frank Schröder, which provides a postdoc position until end of 2017 and travel funds.

Although Tunka-Rex is not yet part of any Helmholtz program, there is direct benefit for the program *Matter and the Universe* on several levels. The technical experience and the scientific results on the radio technique for cosmic-ray air showers are both very valuable for the program – especially, since direct knowledge exchange is ensured, because program funded personnel at KIT works in the same floor and has joint meetings with HRJRG (and now DFG) funded personnel working on Tunka-Rex. Finally, Tunka-Rex uses and further develops the same software as the Pierre Auger Observatory, so that again there is a direct benefit for program funded activities of the Pierre Auger Collaboration. The evaluation of the Program recognized the strong experience of KIT/DESY in developing new technologies for air-shower measurements which would not had been possible without participation in several and diverse experimental activities.

For the future, we recommend to continue the collaboration with the Russian partners in the frame of the Tunka experiment on the same level – if funding permits. Thus, it would be very beneficial if Helmholtz would foresee any way of continuing funding for successful HRJRG projects, e.g., by the possibility of reapplication. This would be in particular helpful, since the 3 years period of the HRJRG was not matched to the PoF periods.

c) Potential for application/exploitation (max. 2 DIN A4 pages)
How do you yourself assess the potential for application or exploitation of the results? Where do you see future possibilities? Please describe realized or planned measures for applying the results. Please also include information on patents, licences, co-operations with industry, etc.

Tunka-HiSCORE

The future timing stations for a large HiSCORE / TAIGA array will be based on the developments and optimizations carried out during this HRJRG project. After a commissioning phase, we are currently taking data on a regular base. These data will allow to evaluate the actual power of our installation. The analysis of our data will allow an exploration of the accelerator sky in a so far unexplored energy range. The analysis methods developed within the HRJRG can be directly applied to the future array.

Recent IceCube results on the detection of multi-TeV to PeV neutrinos have further strengthened the motivation to search for corresponding signals in the gamma-ray regime.

With the current HiSCORE setup, we expect to be able to detect the Crab Nebula in the TeV regime and our goal is to first to extend the energy spectrum of this object to 100 TeV with the hybrid array, showing the feasibility of the hybrid detector concept.

This work, started within the HRJRG has formed the ground work for a future hybrid large scale wide angle gamma-ray survey instrument that might ultimately find the long sought cosmic ray Pevatrons. The HRJRG also substantially helped in forming the Russian-German collaboration that continues to work with on this new technology.

Tunka-Rex

Tunka-Rex has been a significant achievement in the development of the radio technique for cosmic-ray air shower detection. It provided the technical proof that antenna arrays can be a cost-effective extensions for cosmic-ray observatories, and the experimental proof that such antenna arrays indeed are sensitive to the cosmic-ray mass composition. These results will be used in future by us and also by others.

We will use Tunka-Rex for more accurate measurements on cosmic-rays in the energy range above 10^{17} eV in order to study the transition of the origin of cosmic rays from galactic to extragalactic sources. Thus, the results of the HRJRG are an important step towards better understanding the most energetic particles in the Milky Way as well as in the whole Universe. Furthermore, our results will be very useful for the design of any future antenna arrays, and the analysis methods developed for Tunka-Rex can be directly applied by other experiments. In this sense, Tunka-Rex provided not only basic research, but also technology development for the field of astroparticle physics.

2) Qualification of Junior Researchers (max. 2 DIN A4 pages)
Please describe the main achievements regarding personal qualifications (Diploma, bachelors or masters degrees, conferring of doctorates, "habilitations", appointments/junior professorships, etc.). How far have new career perspectives for young scientists inside the foreign country been developed?

A large fraction of the HRJRG-303 funds went into young researches, and this has been essential to promote their careers. The HRJRG-303 was a large benefit for junior researches on different levels. At the same time, the project's success was only possible due to the efforts of students and young scientists.
All junior researchers were responsibly integrated in to the project. In particular, they were regularly participating into the on-site activities at the Tunka facility (during construction and operation).

As a starting event of this project, in spring 2013 "HRJRG-303 PhD-days", a 2-days meeting of all german PhD students and senior researchers, was organized in Hamburg.

Tunka-HiSCORE

Apart from regular meetings between the DESY and UHH HRJRG-groups, several working visits with MSU colleagues took place in 2012-2015, as well as a 1-month working stay of 2 PhD students from Russia in Hamburg.

The results produced within our HRJRG were presented by young researchers on many occasions during national and international conferences.

Qualifications, HiSCORE (de-side): 3 PhD theses, 3 Diploma & Master theses, 2 Bachelor theses:

1. S. Epimakhov: "Exploring cosmic ray origins with ground-based EAS arrays Tunka and HiSCORE" (PhD thesis, University of Hamburg, July 2015)
2. A. Porelli: "Gamma ray astronomy and cosmic ray studies with the HiSCORE Engineering Array" (PhD thesis, HU/DESY, ongoing)
3. M. Kunnas: "Simulation of a combination of the timing and imaging techniques" (PhD thesis UHH, ongoing)
4. D. Spitschan „Simulation und Bewertung alternativer Konfigurationen für den HiSCORE-Detektor" (Diplomarbeit UHH 07/2013)
5. M. Büker: "Timing studies for the HiSCORE detector", (Diplomarbeit UHH, 12/2012)
6. U. Einhaus: "HiSCORE simulations" (Master.Sc. thesis) Universität Hamburg
7. A. Hübner: "LED calibration" (Bachelor thesis, 12/2015)
8. D. Wehrheim: "Average pulse shape of PMT ET9352KB" (Bacherlor thesis, 10/2015)

Tunka-Rex

In Germany at KIT, the Tunka-Rex group was led by Frank Schröder, who was recognized as young group leader (Nachwuchsgruppenleiter) by KIT because of his role in the HRJRG-303. The results of the HRJRG-303 will be essential part of his habilitation foreseen in 2017. Moreover, two PhD students have been employed for Tunka-Rex at KIT who successfully finished their Doctorates ja few months ago, both with grade "very good". One of them got a short-term postdoc extension by the local graduate school KSETA, the other will stay at KIT working as postdoc on Tunka-Rex until end of 2017 funded by DFG (see section 1 b). We also involved students, in particular an Italian student of Torino doing his bachelor work at KIT on the Tunka-Rex calibration, and a master student of KIT who currently is working on her master thesis aiming at Tunka-Rex timing and wavefront analyses.

In Russia at the Irkutsk State University (ISU), several students have been involved in Tunka-Rex as well. One PhD student is about to defend her thesis on Tunka-Rex in the next weeks and will continue as postdoc at ISU. Another PhD student just started last year on Tunka-Rex. In addition, one student did his diploma thesis on Tunka-Rex at ISU, and several more students have been involved temporarily in Tunka-Rex, e.g., during the deployment of the antennas or during measurement shifts.

During the HRJRG-303 we greatly profited from the possibility of student exchanges, in addition to the short trips and meetings funded by the HRJRG itself. Two of the ISU students applied successfully for the iProgress grant by the Helmholtz Alliance of Astroparticle Physics (HAP), which enabled them to stay for 1 and 2 months, respectively, in the Tunka-Rex group at KIT. This was also the seed for a one-year stay of the Russian PhD student at KIT funded by a successful application to a grant of the Russian president. In the other direction there also has been plenty of exchange because the experimental site is close to Irkutsk, and all members of the Tunka-Rex group travelled several times there, in particular for deployment, shifts, and meetings with the ISU group.

Summarizing, a large fraction of the HRJRG-303 funds went into young researches, and has been essential to promote their careers.

3) Public relations

By which means did you gain publicity (e.g. reporting in media, own website)?

In addition to scientific publications and conference presentations, we had several other means of providing publications within the HRJRG-303, e.g., we created and maintained webpages on the different subprojects as well as on the whole HRJRG, see e.g.
http://tunka-hrjrg.desy.de/
http://www.ikp.kit.edu/tunka-rex/
The new TAIGA collaboration has also a detailed website http://taiga-experiment.info/ .

The success of this HRJRG-project was well presented on the HRJRG-meeting in Moscow in spring 2014.

Moreover, we ensured outreach in other ways. In particular we provided information for Wikipedia articles, see e.g.
https://en.wikipedia.org/wiki/Tunka_experiment
https://de.wikipedia.org/wiki/HiSCORE,
as well as press releases http://www.desy.de/aktuelles/@@news-view?id=1621&lang=ger.

We gave lectures to students, introduced the Tunka experiment in presentations of science slams to non-scientific audience, and included the HRJRG activities in the general outreach program of the Helmholtz Alliance of Astroparticle Physics (HAP).

The Tunka-Cosmic-Ray facility was been presented several times as an example of successful international science collaboration on Russian TV-Channels (Central Moscow, as well as local stations).

4) Networking
What co-operation and communication structures have been developed during the course of the funding? What is the contribution of the group to the networking of international partners and the Helmholtz Centre(s)?

Close collaboration in mid- to large-scale international teams are typical for astroparticle physics projects that build and operate detector systems to study cosmic rays or high energy gamma rays. For the unique Tunka cosmic ray facility, this integration into the international community was substantially promoted due to this HRJRG-project; only few international links were existing prior to that.

The HRJRG-303 was well integrated in the networking activities of the Helmholtz Alliance of Astroparticle Physics (HAP). HiSCORE was presented on two HAP Workshops on “Advanced Technologies”.

In fact, this HRJRG lively enriched the existing cooperation with the Russian partners of HAP. Regular meetings in person, twice per year, and additional online meetings have been established and are continued.

5) List of Publications
Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.

Articles on HRJRG-303 results in peer-reviewed journals:

Radio measurements of the energy and depth of maximum of cosmic-ray air showers by Tunka-Rex, P.A. Bezyazeekov et al. - Tunka-Rex Collaboration, JCAP 01 (2016) 052, doi:10.1088/1475-7516/2016/01/052

Measurement of cosmic-ray air showers with the Tunka Radio Extension (Tunka-Rex), P.A. Bezyazeekov et al. - Tunka-Rex Collaboration, Nucl. Instr. and Meth. A 802 (2015) 89-96, doi:10.1016/j.nima.2015.08.061

Reconstruction of air-shower parameters for large-scale radio detectors using the lateral distribution, D. Kostunin, P.A. Bezyazeekov, R. Hiller, F.G. Schröder, et al., Astroparticle Physics 74 (2016) 79

The HiSCORE concept for gamma-ray and cosmic-ray astrophysics beyond 10 TeV, Tluczykont, Hampf, Horns, et al., Astroparticle Physics 56 (2014) 42

Event reconstruction techniques for the wide-angle air Cherenkov detector HiSCORE, D. Hampf, M. Tluczykont, D. Horns, Nuclear Instruments and Methods in Physics Research A

712 (2013) 137

Articles in peer-reviewed journals jointly with other Collaborations (with participation of HRJRG-303 as co-authors):

Improved absolute calibration of LOPES measurements and its impact on the comparison with REAS 3.11 and CoREAS simulations, W.D. Apel et al. - LOPES Collaboration, Astroparticle Physics 75 (2016) 72, doi:10.1016/j.astropartphys.2015.09.002

Calibrating the absolute amplitude scale for air showers measured at LOFAR, A. Nelles et al. - LOFAR Collaboration, JINST 10 (2015) P11005, doi:10.1088/1748-0221/10/11/P11005

Proceedings of international conferences on HRJRG-303 results (partly published in peer-reviewed journals):

The Taiga project
I. Yashin et al. , TAIGA Collaboration, Proceed. ICPPA 2015, J.Phys.Conf.Ser. 675 (2016) no.3, 032037, DOI: 10.1088/1742-6596/675/3/032037

Calibration of the absolute amplitude scale of the Tunka Radio Extension (Tunka-Rex),
R. Hiller et al. - Tunka-Rex Collaboration, Proceedings of the 34th ICRC 2015, The Hague, Netherlands, Proceedings of Science, PoS (ICRC2015) 573

The Tunka Radio Extension: reconstruction of energy and shower maximum of the first year data, D. Kostunin et al. - Tunka-Rex Collaboration, Proceedings of the 34th ICRC 2015, The Hague, Netherlands, Proceedings of Science, PoS (ICRC2015) 285

Imaging Camera and Hardware of TAIGA-IACT Project
I. Yashin et al. – Tunka-HiSCORE Collaboration, Proceedings of the 34th ICRC 2015, The Hague, Netherlands, Proceedings of Science PoS(ICRC2015) 986

Time Synchronization with White Rabbit - Experience from Tunka-HiSCORE
R. Wischnewski, M. Brueckner and A. Porelli, Proceedings of the 34th ICRC 2015, The Hague, Netherlands, Proceedings of Science PoS(ICRC2015) 1041

Combination of shower-front sampling and imaging in the Tunka Advanced International Gamma-ray and Cosmic ray Astrophysics (TAIGA) project
M. Kunnas et al. – Tunka-HiSCORE Collaboration, Proceedings of the 34th ICRC 2015, The Hague, Netherlands, Proceedings of Science PoS(ICRC2015) 1038

The Tunka Radio Extension (Tunka-Rex): Radio Measurements of Cosmic Rays in Siberia,
F.G. Schröder et al. - Tunka-Rex Collaboration, Proceedings of the 13th Pisa Meeting on Advanced Detectors, Elba, Italy, Nucl. Instr. and Meth. A, 2015, in press

The Tunka-Rex Experiment for the Detection of the Air- Shower Radio Emission,
Y. Kazarina et al. - Tunka-Rex Collaboration, Proceedings of the 6th ARENA 2014, Annapolis, USA, submitted

Amplitude Calibration of the Tunka Radio Extension (Tunka-Rex),
R. Hiller et al. - Tunka-Rex Collaboration, Proceedings of the 24th ECRS 2014, Kiel, Germany, J. Phys. Conf. Ser. 632 (2015) no.1, 012012

The Tunka Radio Extension: Latest Analysis Results,
D. Kostunin et al. - Tunka-Rex Collaboration, Proceedings of the 24th ECRS 2014, Kiel, Germany, J. Phys. Conf. Ser. 632 (2015) no.1, 012096

Towards gamma-ray astronomy with timing-arrays,
M. Tluczykont et al. – Tunka-HiSCORE Collaboration, Proceedings of the 24th ECRS 2014, Kiel, Germany, J. Phys. Conf. Ser. 632 (2015) no.1, 012042, DOI: 10.1088/1742-6596/632/1/012042

Timing calibration and directional reconstruction for Tunka-HiSCORE,
A. Porelli et al. - Tunka-HiSCORE Collaboration, Proceedings of the 24th ECRS 2014, Kiel, Germany, J. Phys. Conf. Ser. 632 (2015) no.1, 012041
DOI: 10.1088/1742-6596/632/1/012041

Amplitude calibration with the HiSCORE-9 array,
S. Epimakhov et al. – Tunka-HiSCORE Collaboration, Proceedings of the 24th ECRS 2014, Kiel, Germany, J. Phys.: Conf. Ser. 632 (2015) no.1, 012007, DOI: 10.1088/1742-6596/632/1/012007

Simulation of the Tunka Area International Gamma-ray Advanced experiment (TAIGA)
M. Kunnas et al. – TAIGA-Collaboration, Proceedings of the 24th ECRS 2014, Kiel, Germany, J. Phys. Conf. Ser. 632 (2015) no.1, 012040, DOI: 10.1088/1742-6596/632/1/012040

The HiSCORE Project,
M. Tluczykont et al. – Tunka-HiSCORE Collaboration, Acta Polytechnica, CTU Proceedings, Vol 1, No 1 (2014) 283

Status of the Tunka-HiSCORE group and first results from the 9-station prototype array,
M. Tluczykont et al. – Tunka-HiSCORE Collaboration, Proceedings of 40th COSPAR Scientific Assembly, 2-10 August 2014, Moscow, Russia

TAIG: the Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy — present status and perspectives,
N. Budnev et al. – TAIGA Collaboration, Int. Conf. Instr. Coll. Beam Phys., Novosibirsk, Russia (2014), doi:10.1088/1748-0221/9/09/C09021

Tunka-Rex: the Cost-Effective Radio Extension of the Tunka Air-Shower Observatory,
F.G. Schröder et al. - Tunka-Rex Collaboration, Proceedings of the 2nd UHECR 2014, Springdale, Utah, USA, accepted by JPS Conference Proceedings, arxiv.org:1504.01541

Tunka-Rex: Status and Results of the First Measurements,
D. Kostunin et al. - Tunka-Rex Collaboration, 2014, Nucl. Instr. and Meth. A 742, 89–94 , Proceedings of RICAP 2013, Roma, Italy, DOI: 10.1016/j.nima.2013.10.070

Hardware and first results of Tunka-HiSCORE,
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