# ARENA 2018 - Acoustic and Radio EeV Neutrino Detection Activities

Tuesday 12 June 2018 - Friday 15 June 2018

# Book of Abstracts

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## Estimating the mass of cosmic rays by combining radio and muon measurements

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The Auger Engineering Radio Array (AERA) is a radio detector at the Pierre Auger Observatory and it is dedicated to measure the radio emission of cosmic-ray air showers. AERA is co-located with the underground muon detectors of the Auger Muons and Infill for the Ground Array (AMIGA). This provides a perfect setup to experimentally test the benefits of combining muons and radio emission for estimating the primary mass.
Cosmic-ray induced air showers consist to a large fraction of electrons and muons. The size of these shower components shows an opposite dependency on the mass of the primary cosmic-ray particles. Thus, combining them allows to estimate the mass. The size of the electromagnetic component can be measured in a calorimetric way via the radio emission produced in the atmosphere. The magnitude of the muonic component can be measured counting particles under ground. We have investigated the combination of radio measurements with muon measurements using air-shower simulations. We compared the performance for mass separation of this new method to alternative methods in which the electrons and muons are measured with particle detectors at the surface. For showers with zenith angles below 50° the new method is of comparable performance, and for showers more inclined than 50° it is clearly superior. In particular in inclined showers, the electrons are mostly absorbed in the atmosphere before reaching the surface, but the radio emission is not. Therefore, measuring the radio signal in addition to the muons significantly improves the mass sensitivity.

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## Measurements of Horizontal Air Showers with the Auger Engineering Radio Array

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The Pierre Auger Observatory is the largest observatory for the detection of cosmic rays. With the Auger Engineering Radio Array (AERA) we measure the emitted radio signal of extensive air showers and reconstruct properties of the primary cosmic rays. For horizontal air showers (zenith angles larger than 60°) the signal is distributed over a larger area of more than several km$^2$. Therefore detection of air showers using a sparse radio antenna array, compatible with the 1500 m distance between the 1600 surface detector stations, is possible. The radio technique is sensitive to the electromagnetic component of air showers. Combining radio detection with particle information from the surface detector of the Pierre Auger Observatory, which mostly detects muons at large zenith angles, allows to study the cosmic ray composition for horizontal air showers.

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## Signal recognition and background suppression by matched filters and neural networks for Tunka-Rex

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The Tunka Radio Extension (Tunka-Rex) is a digital antenna array, which measures the radio emission of the cosmic-ray air-showers in the frequency band of 30-80 MHz. Tunka-Rex is co-located with TAIGA experiment in Siberia consists of 63 antennas, 57 of it in a densely instrumented area of about 1 km². In the present work we discuss the improvements of the signal reconstruction applied for the Tunka-Rex. At the first stage we implemented matched filtering using averaged signals as templates. The simulation study has shown that matched filtering allows one to decrease the threshold of signal detection and increase its purity. However, the maximum performance of matched filtering is achievable only in case of white noise, while in reality the noise is not fully random due to different reasons. To recognize hidden features of the noise and treat them, we decided to use convolutional neural network with autoencoder architecture. Convolution filters take into account different features of noise, while autoencoder is unsupervised neural network with compressed representation, which decodes main features of reconstructed signal. Taking the recorded trace as an input, the autoencoder returns denoised trace, i.e. removes all signal-unrelated amplitudes. We tested designed network using standard validation control with train/test split of CoREAS traces noised with Tunka-Rex background library. The test has shown that neural networks have a potential of lowering the threshold even better than with matched filtering. We present the comparison between standard method of signal reconstruction, matched filtering and autoencoder, and discuss the prospects of application of neural networks for lowering the threshold of digital antenna arrays for cosmic-ray detection.

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## Cosmic ray composition measurements with the Auger Engineering Radio Array

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The mass composition of ultra-high-energy cosmic rays is an important key for answering questions about the origin of these rare particles. A composition-sensitive parameter is the atmospheric depth $X_{max}$ at which the maximum number of particles in the air shower is reached.
The Auger Engineering Radio Array (AERA) detects the radio emission from extensive air showers with energies beyond $10^{17}$ eV in the 30 - 80 MHz frequency band. It consists of more than 150 autonomous radio stations covering an area of about 17 km². From the signal distribution measured at ground by the antennas, it is possible to estimate the $X_{max}$ of the air shower.
In this talk, several independent methods for the reconstruction of $X_{max}$ will be presented. These methods use alternatively, the lateral energy density profile, the frequency spectrum of each individual antenna station or the shower front reconstruction from the arrival time of the signal.
The results of these analysis can be combined to obtain a mass composition reconstruction that uses all the information in the detected radio signal.

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## QCD Processes in Cosmic Ray Air Showers

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The origin and properties of Ultra High Energy Cosmic Rays (UHECR) is a long standing question in astroparticle Physics. Dedicated extensive air shower experiments are in place since many years and have strongly contributed to our understanding of High and Ultra High Energy Cosmic Ray Physics. Recently, in particular, the Pierre Auger Collaboration and the Telescope Array Collaboration, thanks to the excellent performance of their hybrid detector arrays, are providing us new exciting observations of UHECRs. Although these recent results have brought a deeper insight in primary cosmic ray properties, still they are largely affected by the poor knowledge of the nuclear interactions in the earth's atmosphere. The average and RMS of the measured depth of the shower maximum (XMAX) are good indicators of the composition of UHECRs. However the predictions of XMAX by air-shower simulations depend on the hadronic interaction model used in the Monte Carlo. A calibration of the energy scale in the 10ˆ15 ÷ 10ˆ17 eV energy range accessible to LHC provides crucial input for a better interpretation of primary cosmic ray properties, in the region between the "knee"and the GZK cut-off. The Large Hadron Collider forward (LHCf) experiment was designed with the aim to provide a calibration of the hadronic interaction models in the whole energy range spanned by LHC by measuring the neutral forward particle produced in p-p as well as in p-Ion collisions. In this talk an introduction to HECR and UHECR Physics will be provided and the link between cosmic rays physics and accelerator physics will be discussed with particular emphasis to the results obtained at LHC by the LHCf experiment.

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## A surface radio array for the enhancement of IceTop and its science prospects

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Radio detection of air showers in the current era has progressed immensely to effectively extract the information of air showers and their properties. It is mainly applied to the detection of cosmic rays and neutrinos. Primary cosmic rays with energies of hundreds of PeV have been successfully measured with the method of radio detection. Current radio experiments measuring such air showers mostly operate in the frequency range of 30-80 MHz. An optimization of the frequency band of operation can be done for maximizing the signal-to-noise ratio that can be achieved by an array of radio antennas at the South Pole, operated along with IceTop. Such an array can improve the reconstruction of air showers performed with IceTop. The prospects of using such an optimized radio array for measuring gamma-rays of PeV energies from the Galactic Center will be presented in this talk. The current tests of a prototype antenna for this purpose will also be discussed.

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## A Rotationally Symmetric Lateral Distribution Function for Radio Emission from Inclined Air Showers

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Radio detection of inclined air showers is currently receiving great attention: Inclined air showers illuminate large areas on the ground with detectable radio signals and can therefore be measured efficiently with sparse radio-antenna arrays. In addition, a combined measurement of radio signals and secondary particles of inclined air showers promises high sensitivity to the mass of the primary particle.
To exploit this potential, an event reconstruction for inclined air showers measured with radio-antenna arrays needs to be developed. The first step in this direction is the development of a model for the lateral distribution of the radio signals, which in the case of inclined air showers exhibits asymmetries due to "early-late" effects in addition to the usual asymmetries caused by the superposition of charge-excess and geomagnetic emission.
We present a model for the radio emission from inclined air showers which corrects for all asymmetries and successfully describes the lateral distribution of the energy fluence with a rotationally symmetric function. This gives access to the radiation energy as a measure of the energy of the cosmic-ray primary, and is also sensitive to the depth of the shower maximum.

**Highlight talks / 13**

## Present status and prospects of the Tunka Radio Extension

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The Tunka Radio Extension (Tunka-Rex) is a digital radio array operating in the frequency band of 30-80 MHz and detecting radio emission from air-showers produced by cosmic rays with energies above 100 PeV. The experiment is installed at the site of the TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy) observatory and performs joint measurements with the co-located particle and air-Cherenkov detectors in passive mode receiving a trigger from the latter. Tunka-Rex collects data since 2012, and during the last five years went through several upgrades. As a result the density of the antenna field was increased by three times since its commission. In this contribution we present the latest results of Tunka-Rex experiment, particularly an updated analysis and efficiency study, which have been applied to the measurement of the mean shower maximum as a function of energy for cosmic rays of energies up to EeV. The future plans are also discussed: investigations towards an energy spectrum of cosmic rays with Tunka-Rex and their mass composition using a combination of Tunka-Rex data with muon measurements by the particle detector Tunka-Grande.

**Highlight talks / 14**

## GRAND, a Giant Radio Array for Neutrino Detection: Objectives, design and current status

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The Giant Radio Array for Neutrino Detection (GRAND) aims to answer one of the most pressing open questions in astrophysics: what is the origin of ultra-high-energy cosmic rays (UHECRs)?

It will do so indirectly: UHECRs make secondary UHE neutrinos which encode information about the properties of UHECRs and their sources. GRAND is designed to discover UHE neutrinos even under pessimistic predictions of their flux, reaching a sensitivity of 1.5 x 10^-10 GeV.cm^-2.s^-1.sr^-1 around 10^9 GeV. It will do so by using 200 000 radio antennas covering an area of 200 000 $km^2$, making it the largest air-shower detector ever built. With this sensitivity, GRAND will discover cosmogenic neutrinos in 3 years of operation, even in disfavorable scenarios. Because of its sub-degree angular resolution, GRAND will also search for point sources of UHE neutrinos, both steady and transient.

Moreover, GRAND will be a valuable instrument for astronomy and cosmology, allowing for the discovery and follow-up of large numbers of radio transients - fast radio bursts, giant radio pulses - and studies of the epoch of reionization.

In this contribution we will present the science goals, detection strategy, preliminary design, performance goals, construction plans and current status of the GRAND project.

**Highlight talks / 15**

## Physics Potential of a Radio Surface Array at the South Pole

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A surface array of radio antennas at the location of the IceTop particle-detector array will enable a number of science cases complementary to the current goals of IceCube. First, the accuracy for cosmic-ray air showers will be increased, since the radio array provides a calorimetric measurement of the electromagnetic component and is sensitive to the position of the shower maximum. This enhanced accuracy can be used for a better measurement of the mass composition as a function of energy, for studying a possible mass dependence of weak anisotropies in the arrival directions of cosmic rays, and for more thorough tests of hadronic interaction models. Second, the sensitivity of the radio array to inclined showers will increase the sky coverage for cosmic-ray measurements. Third, the radio array can be used to search of PeV photons from the Galactic Center by searching for muon-poor showers with sizeable radio signal. This contribution will discuss ideas for this radio array. Since IceTop currently is being enhanced by a scintillator array, there is a window of opportunity to additionally install radio antennas with small additional effort and excellent scientific prospects.

**Future and perspectives / 16**

## Keeping an ear to the ground for EeV neutrinos

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Water and ice are the favourite targets for the deployment of acoustic sensors in the search for the characteristic bipolar pressure pulses (BIP) induced by cascades following interaction of very high energy neutrinos with matter. Apparently, there were no previous attempts to try it in bedrock. The reasons are obvious. The costs of deploying a line with sensors into deep sea are considerably lower than drilling into granite. Also, while drilling one test hole in the ground seams feasible, the concept of building a network of such holes covering the required area of around 100 km2 appears to be completely unrealistic. On the other hand, if the required network of deep boreholes in a bedrock were available, there would be a number of strong arguments to explore such a possibility. As the speed of sound in rock is 4 times higher than in water and taking into account differences in the expansion coefficient and in the specific heat capacity, one would expect that the characteristic BIP signal in rock would be 5 times stronger than in water. Also, the attenuation length should be noticeably longer. The ideal place to put this new approach to a test is the Pyhäsalmi mine in Finland –the deepest metal mine in Europe, with the ore deposit located within a cylindrical volume surrounded on all sides by a strong nearly-monolithic rock. Over the many years of explorations, the mine has drilled a network of boreholes reaching far out and deep down in the futile search for new ore deposits. These boreholes, with very well documented geological profile, would be now available for scientific research. In my presentation I would expand on that idea and introduce the infrastructure of CallioLab constructed and used for a variety of new projects. Also, I would present a realistic scheme to reach the required deployment area of around 100 km2 at a reasonable cost and on a realistic timescale.

**Experimental data / 17**

## ARIANNA: Measurement of cosmic rays with a radio neutrino detector in Antarctica

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The ARIANNA detector aims to detect neutrinos with energies above $10^{16}$ eV by instrumenting 0.5 Teratons of ice with a surface array of a thousand independent radio detector stations in Antarctica. The Antarctic ice is transparent to the radio signals caused by the Askaryan effect which allows for a cost-effective instrumentation of large volumes. Several pilot stations are currently operating successfully at the Moore's Bay site (Ross Ice Shelf) and at the South Pole.

As the ARIANNA detector stations are positioned at the surface, the more abundant cosmic-ray air showers are also measured and serve as a direct way to prove the capabilities of the detector. We will present measured cosmic rays and will show how the incoming direction, polarization and electric field of the cosmic-ray pulse can be reconstructed from single detector stations comprising 4 upward and 4 downward facing LPDA antennas. Furthermore, a novel estimator of the cosmic-ray energy is presented that requires only the energy fluence and frequency slope at a single location.

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## An analytic description of the radio emission of air showers based on its emission mechanisms

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The spatial signal distribution of the radio frequency radiation from extensive air showers on the ground contains information on crucial cosmic-ray properties, such as energy and mass. A long standing challenge to access this information experimentally with a sparse grid of antennas is an analytic modeling of the radio signal distribution, which will be addressed in this contribution. We

present an analytic model based on the two physical processes generating radio emission in air showers: the geomagnetic and the charge-excess emission. Our study is based on full Monte Carlo simulations with the CoREAS code. Besides an improved theoretical understanding of radio emission, our model describes the radio signal distribution with unprecedented precision. Our model explicitly includes polarization information, which basically doubles the information that is used from a single radio station. Our model depends only on the definition of the shower axis and on the parameters energy and distance to the emission region, where the distance to the emission region has a direct relation to the cosmic-ray's mass. We show with the use of CoREAS Monte Carlo simulation that fitting the measurements with our model does not result in significant contributions in both systematic bias and in resolution for the extracted parameters energy and distance to emission region, when compared to the expected experimental measurement uncertainties.

**Highlight talks / 19**

## ARIANNA: Current developments and understanding the ice for neutrino detection

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The ARIANNA experiment aims to detect the radio signals of cosmogenic neutrinos. It is running in its pilot phase on the Ross Ice-shelf, and one station has been installed at South Pole. The ARIANNA concept is based on installing high-gain log periodic dipole antennas close to the surface monitoring the underlying ice for the radio signals following a neutrino interaction. Especially, but not only in this configuration, it is essential to understand the trajectories that the signals take through the ice. We will report on surprising but strong experimental evidence that horizontal propagation takes place in polar ice and that the concept of shadowing needs to be revisited. We will discuss the implications for neutrino detection, potentially an increase in effective volume, and the sensitivity of the detector.

**Highlight talks / 20**

## Acoustic detection of high energy ions

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First ideas to use thermoacoustic phenomena for particle detection date back to the fifties. The technique has intensely been considered for underwater ultra-high neutrino detectors [1] and appropriate detector arrays are under development [2]. There have been also attempts to use the acoustic signal induced by the characteristic dose deposition of a proton pulse in context of radiation therapy [3]. Recently, the method has seen a resurgence due to technical improvements in proton therapy, where the so-called ionoacoustic signal promises a simple, but very accurate means to measure the Bragg peak position during patient irradiation [4].
In this talk, we will demonstrate the potential of an ionoacoustic particle detector to monitor intense light and heavy ion bunches. For GeV-ions, experiments were performed by exposing a water beam dump to short and intense bunches of various heavy ions (U, Xe, C) with energies around 200 to 300 MeV/u, delivered by the upgraded SIS-18 synchrotron at GSI. The measured ion ranges in water are

in good agreement with Geant4 simulations, opening a new method for stopping power determination at relativistic energies. In another example, Ionoacoustics offers an almost unrivaled detection technique for laser accelerated ions, which are produced in ultrashort bunches with large particle numbers accompanied by an interfering electromagnetic pulse (EMP). Acoustic detectors take advantage of a huge dynamic range and, moreover, the acoustic signal is separated from the EMP due to the transit time of the sound wave. First experimental results will be presented for protons accelerated by state-of-the-art PW class lasers, where the full energy distribution of energetic protons could be reconstructed from the ultrasound signal measured with a single PZT transducer.

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[4] S. Lehrack et al., Phys. Med. Biol. 62 (2017) L20.

**Analisys tools / 21**

## Towards online triggering for the radio detection of air showers using deep neural networks

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The detection of air-shower events via radio signals requires to develop a trigger algorithm for a clean discrimination between signal and background events in order to reduce the data stream coming from false triggers.
In this contribution we will describe an approach to trigger air-shower events on a single-antenna level as well as performing an online reconstruction of the shower parameters using neural networks.

**Experimental data / 22**

## Sensitivity of the 5-station Configuration of ARA

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The Askaryan Radio Array (ARA) is an experiment looking for the Askaryan emission of GZK neutrinos interacting in the Antarctic ice. During the last Antarctic summer, two new stations have been added the experiment, as well as a prototype version of the phased array, attached to one of the new stations. With these stations, ARA sensitivity should become comparable to IceCube's. To confirm this, it is calculated through new simulations developed in the IceCube framework, with an antenna model built from in-situ calibration measurements.

**Experimental data / 23**

## Observation of radio emissions from an electron beam using an ice target

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Askaryan Radio Array (ARA) is being built at the South Pole aiming for observing high energy cosmogenic neutrinos above 50 PeV. The ARA detector identifies the radio emissions from the excess charge in a particle shower induced by a neutrino interaction. Such a radio emission was first predicted by Askaryan in 1962 and experimentally confirmed by Saltzberg et al. using the SLAC accelerator in 2000. We also performed a similar experiment using 40 MeV electron beams of the Telescope Array Electron Light Source to verify our understanding of the Askaryan emission and the detector responses used in the ARA experiment. Clear coherent polarized radio signals were observed with an ice target. The coherences, the polarizations and the angular distributions of the radio signals were measured to characterize them. We also performed a detailed simulation to understand the radio emissions. We found that the observed radio signals are consistent with simulation, meaning that our understanding of the radio emissions and the detector responses are within the systematic uncertainties of the ARAcalTA experiment. The final results of the experiment will be presented in the conference.

**Analisys tools / 24**

## Atmospheric Effects On The Radio Signal of Extensive Air Showers

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One of the major systematic uncertainties in reconstructing X_max from radio emission of EAS is due to limited knowledge of the index-of-refraction of air and its dependence on humidity, pressure, and temperature. Current air shower Monte Carlo simulation codes like CORSIKA/Coreas use one standard atmosphere for all. This calls for the inclusion of real atmospheric data at the time of air shower at a given observational site into the simulation. Using The Global Data Assimilation System(GDAS), a global atmospheric model based on meteorological measurements and numerical weather predictions we have implemented realistic atmospheric profiles in CORSIKA/Coreas, which is available since the latest release. We present the results from re-analyzing LOFAR cosmic-ray data with new improved atmosphere.

**Analisys tools / 25**

## Systematic uncertainty of first-principle calculations of the radiation energy emitted by extensive air showers

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The energy of extensive air showers can be determined with the energy radiated in the form of radio signals. The so called radiation energy can be predicted with modern simulation codes using first-principle calculations without the need of free parameters. Here, we verify the consistency of the radiation energy calculations by comparing a large set of Monte Carlo simulations made with the two codes CoREAS and ZHAireS. For the frequency band of 30 –80 MHz, typically used by many current radio detectors, we observe a difference in the radiation energy prediction of 4%. This corresponds to a modelling uncertainty of 2 % for the determination of the absolute cosmic-ray energy scale. Hence, radio detection offers the opportunity for a precise, accurate and independent measurement of the absolute energy of cosmic rays.

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## Modeling the Acoustic Field generated by a Pulsed-Beam for Experimental Proton Range Verification

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*Introduction.* Proton range verification by ion-acoustic wave sensing is a technique under development for applications in hadron therapy as an alternative to nuclear imaging. It provides an acoustic imaging of the proton energy deposition vs. depth using the acoustic wave Time of Flight (TOF). State-of-the-art (based on simulations and experimental results) points out as this detection technique achieves better spatial resolution (< 1 mm) of the proton range comparing with Positron-Emission-Tomography (PET) and prompt gamma ray techniques.
This work presents a complete Geant4/K-Wave model that allows understanding several physical phenomena and evaluating the key parameters that affect the acoustic field generated by the incident proton radiation.
*Methods.* The proposed system models the energy deposition in a water absorber of a 20 MeV mono-energetic pencil-like beam and with stress and thermal confinement conditions standing. It has been simulated assuming the current time profile of the beam to be a flat pulse with Gaussian rising and falling edges and the spatial energy distribution to be a homogeneous disk with Bragg Peak FWHM region dimensions. The simplified environment is composed of a water phantom with a reflective polyammide layer on one side and the sensing points lie on the disk axis in the direction away from this reflection surface. The parameters that completely describe the current pulse are time width, raising time, total dose and peak dose in unit time.
*Results.* By running sweep-simulations of the model, it appears that the signal amplitude depends

neither on the total deposited dose, nor on the pulse time. This confirms theoretical expectations that only changes in the deposition rate should generate a pressure wave. Rising time has been varied between 50 ns and 1000 ns showing a linear decrease of pressure wave amplitude at 0.5 cm from 17.7 Pa down to 4.9 Pa. Dose in unit time, which is strictly linked to the beam current intensity, affects the signal in the opposite way: the strength increase linearly from 90 mPa up to 948 mPa in the 0.89-82.4 MGray/s range. The evidence that only two beam parameters influence the measure in a controlled environment allows to plan of appropriate detection systems, to design clinical particle accelerators with the right characteristics and to concentrate scientific efforts on the in vivo setting uncertainties.
*Acknowledgments. This activity has been supported by the Proton Sound Detector (ProSD) project funded by the INFN (Italian National Institute for Nuclear Physics).*

**Future and perspectives** / **27**

## Analog and Digital Signal Processing for Pressure Source Imaging induced by a 20 MeV Proton Beam

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*Introduction.* Hadron therapy is an extremely interesting option for cancer treatment, comparing with photon-based radio-therapy. The ion beam deposits very low energy at the interface, practically no dose after the tumor and releases a specific energy peak inside the tissues. This peak is called Bragg Peak and its shaping is also very sharp, increasing this way the dose deposited in depth. Thus, the efficacy of this technique is strongly related to the capability to detect the Bragg Peak during the on-going clinical treatment.
The first experimental results concerning the proton-induced thermo-acoustic effect for BP range verification were presented in 1979 by Sulak et al. using a 200 MeV pulsed beam at 100 TeV deposited energy [1]. Then this technique was clinically tested by Hayakawa et al. [2] measuring a clear acoustic signal generated in a patient irradiated by a pulsed proton beam. The sensors superficially placed over the skin of the patient detected a clear acoustic signal. Unfortunately, sensors and electronics measurements were affected by a significant noise power, leading to a relatively low accuracy (3mm, however comparable with PET/gamma). Both experimental [2] and modeling [3] studies on the iono-acoustic setup give scarce attention to the sensing part that however strongly affects the detection accuracy, like in [2] where commercial sensors and electronics read-out (i.e. not optimized for iono-acoustic detection) induces a very high BP detection error (>2 mm) comparing with simulations. Hence the state-of-the-art heavily lacks advanced and/or dedicated integrated circuits (IC) solutions, for accurate and low-noise acoustic signal detection and processing in both analog and digital domain.
*Methods.* This paper follows this important research trend presenting a complete proton-to-voltage analysis, that starting from beam physical characteristics (energy, pulse shaping, etc) calculates the pressure signal at the BP and emulates the sound waves propagation in water. The proton beam has been simulated using Geant4 to estimate the spatial distribution of the energy deposition in a case-of-study of a 20 MeV energy with a total deposited dose of 2 Gy and beam pulse of 50ns. Pressure waves simulations are used as input signal of a dedicated analog front-end specifically optimized for this application. The analog signal sensed by the acoustic sensor array is conditioned by a Low-Noise-Amplifier (LNA), a 2nd-order 5 MHz -3dB-Bandwidth Sallen-Key band-pass filter feeding a 10b 50 MSample/rate A-to-D converter for digitalization. Thanks to the high-resolution digital data, the pressure signal provides very accurate ToF measure and, more importantly, a beam-forming algorithm can be adopted to estimate the proton source and perform a 3-D acoustic imaging of the pressure source.
*Results.* The hereby described model provides the tools to accurately simulate both bandwidth and

power of the acoustic signal generated by the proton beams. The acquisition and conditioning electronics was therefore developed and optimized for iono-acoustic experiments. Finally experimental results providing a 3-D imaging of the acoustic source referred to this specific case of 20 MeV protons will be presented.

*Acknowledgments. This activity has been supported by the Proton Sound Detector (ProSD) project funded by the INFN (Italian National Institute for Nuclear Physics).*

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**Highlight talks / 28**

## Radio detection of ultra high energy cosmic rays with the Auger Engineering Radio Array

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The Auger Engineering Radio Array (AERA) located at the Pierre Auger Observatory in Mendoza, Argentina, measures the radio emission of extensive air-showers initiated by cosmic rays with energies above 0.1 EeV. More than 150 autonomous antenna stations, spread over 17 km² measure radio signals in the frequency range of 30 –80 MHz. The operation of AERA within the Pierre Auger Observatory offers a unique opportunity to cross-calibrate the radio measurements with the water-Cherenkov detector and the fluorescence detector. With AERA a precise measurement of the energy of cosmic rays has been achieved including a detailed analysis of the systematic uncertainties. The optimized reconstruction of the maximum shower depth can be validated using the longitudinal profile coincidently measured by the fluorescence detector. Enlarged footprints have been detected for horizontal air showers with signals at the surface up to 15 km from the shower core. This contribution gives an overview of the AERA detector with the different stages and station- types, as well as of the AERA results.

**Analisys tools / 29**

## A semi-analytic code for the calculation of the radio footprint from an from an arbitrary shower LDF, MGMR3D

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The radio intensity and polarization footprint of a cosmic-ray induced extensive air shower is determined by the time-dependent structure of the charge and current distribution residing in the plasma cloud at the shower front. For extracting physics, such as cosmic ray mass or atmospheric electric fields, it is important to determine this charge-current distribution in the plasma cloud, the longitudinal shower structure. To determine the longitudinal shower structure from its footprint requires

solving a complicated inverse problem.
For this purpose we have developed a code that semi-analytically calculates the radio footprint of an extensive air shower given an arbitrary longitudinal structure and thus can be used in an chi-square optimization procedure to extract the longitudinal shower structure form a radio footprint, where intensity as well as polarization observables are fitted.
On the basis of air-shower universality we propose a simple parametrization of the radial structure of the plasma cloud. This parametrization is based on the results of Monte-Carlo shower simulations. Deriving the parametrization also teaches which aspects of the plasma cloud are important for understanding the features seen in the radio-emission footprint. The calculated radio footprints are compared with microscopic CoREAS simulations.

**Analisys tools / 30**

## Determining atmospheric electric fields from the cosmic-ray radio footprint

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We present measurements of radio emission from extensive air showers during thunderstorm conditions. Both intensity and polarization signatures of these events are very different from those measured during fair weather. The reason for this difference is due to the action of the atmospheric electric field. We have developed a procedure to extract from the radio footprint in intensity and polarization observables the structure of these atmospheric electric fields. This method can be regarded as a tomography of electric fields in (thunder)clouds using cosmic rays as probes.
We show that, in order to reconstruct these showers, atmospheric electric fields in thunderclouds generally are composed of at least three layers. We find that the electric fields extracted from these events have some similar characteristics. Large horizontal components of the electric fields are observed in the middle and the top layers. The height of the bottom layer depends on the season.

**Highlight talks / 31**

## Results from the Third Flight of ANITA

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The Antarctic Impulsive Transient Antenna (ANITA) payload has now completed four flights. ANITA is sensitive to impulsive Askaryan radio emission from neutrino-initiated showers in the Antarctic ice sheet, and also to geomagnetically-induced radio emission from extensive air showers (EAS) initiated by cosmic rays or upward-going tau leptons that could be created by tau neutrino interactions in the Earth. I will report on recent results from the third flight of ANITA, both in the search for Askaryan emission from neutrinos interacting in the ice sheet and a dedicated search for EAS signals.

**Experimental data / 32**

## Determination of cosmic-ray primary mass on an event-by-event basis using radio detection

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Traditionally, the depth of maximum shower development $X_{\max}$ has been used as a surrogate observable for composition. Most current methods to reconstruct $X_{\max}$ from the information collected with arrays of antennas are based on a method developed in the context of the LOFAR experiment. These methods use comparisons between the measured electric fields with simulations of proton and iron initiated showers, allowing one to infer the $X_{\max}$ of the detected event. In this work we show that this type of $X_{\max}$ reconstructions lose accuracy in the case of showers with large zenith angles.

We also investigate the differences in the radio footprint that arise due to different primary compositions, leading to a new methodology to discriminate between light and heavy ultra-high energy cosmic-ray primaries on an event-by-event basis using information from the radio detection of extensive air showers at MHz frequencies. This method is also based on comparisons between detected radio signals and Monte Carlo simulations for multiple primary cosmic ray compositions. But, unlike other methods that first reconstruct $X_{\max}$ to relate it to the nature of the primaries, we instead try to infer the cosmic-ray composition directly. We show that a large discrimination efficiency could in principle be reached for zenith angles above $\theta \simeq 65^{\circ}$, even when some of the typical uncertainties in radio detection are taken into account.

**Experimental data / 33**

## Interferometric Reconstruction and Analysis Methods for the Askaryan Radio Array

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Reconstruction of potential ultra-high-energy (UHE) neutrino events at the Askaryan Radio Array (ARA) is complicated by the variable index of refraction of South Pole ice, leading to curved radio signal paths from the interaction vertex. We solve this computational challenge by using a multi-step spline table framework that provides information about the "firn shadow"region along with both direct and reflected signal paths. We then use this framework to enable a GPU-accelerated interferometric reconstruction of the event vertex that can be used both for online event filtering and offline analysis. We present the sensitivity of an ARA UHE neutrino search using this framework, along with potential gains of using both direct and reflected signals in reconstruction.

**Highlight talks / 34**

## The Askaryan Radio Array —current status and design considerations for a larger array

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The South Pole is an excellent location for a radio neutrino detector, with exceptional quality of ice and significant existing South Pole station and IceCube infrastructure. The Askaryan Radio Array (ARA) at the South Pole has successfully deployed two more stations, one of them with a phased array string, in the 2017–2018 austral summer season.
I will discuss some design changes and explain their motivation as well as design questions for future detector stations. For example, how does the station size, the depth of sensors, and the choice of bandwidth impact the effective area for neutrinos and the quality of event reconstruction? What lessons can we learn from past ARA deployments for the future? I will discuss these questions and will present sensitivities for various detector scenarios.

**Future and perspectives** / **35**

## Radio Phased Arrays for the Detection of Ultra-High Energy Neutrinos

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Ground-based radio arrays offer a promising future for the measurement of ultra-high energy neutrinos, including the prospect of reducing the radio-detection energy threshold to a level necessary to overlap with the high-energy range probed by IceCube (˜10 PeV). Here we describe a phased array of antennas and beamforming electronics, which serves as a highly sensitive and directional trigger system for nanosecond-scale plane wave impulses. A prototype in-ice phased array was successfully installed during the 2017/18 austral summer at the South Pole in collaboration with the Askaryan Radio Array. We present the phased array system design, first results, and potential for future optimization.

**Analisys tools** / **36**

## Reconstruction of air-shower measurements with AERA in the presence of pulsed radio-frequency interference

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The Auger Engineering Radio Array (AERA) is situated in the Argentinian Pampa Amarilla, a location far away from large human settlements. Nevertheless, a strong background of pulsed radio-frequency interference exists on site, which not only makes radio self-triggering challenging, but also poses a problem for an efficient and pure reconstruction of air-shower measurements.
We present how our standard event reconstruction exploits several strategies to identify and suppress pulsed noise. We make consequent use of the event geometry as determined with the Auger surface detector to reliably identify cosmic-ray radio pulses. Polarization information, pulse-shape information, the contiguity of the spatial distribution of antennas with a detected pulse, and the consistency of the arrival times of the measured radio pulses provide further ways to discriminate RFI pulses from cosmic-ray pulses.
We discuss our algorithms and quantify their efficiency and purity. These strategies can be employed by any experiment taking data in the presence of pulsed RFI.

**Experimental data / 37**

## Measurements of radio emission induced by Ultra-high energy Cosmic rays with energies above 1 EeV with AERA

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Radio emission of extensive air showers is used to reconstruct prop-
erties of the ultra-high energy cosmic rays. With an area of 17 km$^2$, the Auger Radio Engineering Array has recorded a sizable number of cosmic rays with energies exceeding 1 EeV. Especially interesting are measurements of air showers
at large zenith angles because these induce sizable footprints recorded in
many radio stations. New challenges in reconstructing these showers
arise from the superposition of the two emission mechanisms leading
to the radio signal. We discuss the shower reconstruction with empha-
sis on the energy estimation where the aim is to provide an absolute
energy measurement of the primary cosmic ray exclusively from the recorded radio signal.
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**Highlight talks / 38**

## The ANTARES and KM3NeT neutrino telescopes: status and outlook for acoustic studies

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ANTARES, the largest underwater neutrino telescope in the Northern Hemisphere, has been continuously operating since 2007 in the Mediterranean Sea. It consists of an array of vertical lines, hosting triplets of optical modules that detect the Cherenkov light emitted by charged particles originating from neutrino interactions in and around the detector. The transparency of the water allows for a very good angular resolution in the reconstruction of signatures of interactions from neutrinos of all flavors. This results in unprecedented sensitivity for neutrino source searches in the Southern Sky at TeV energies, so that valuable constraints can be set on the origin of the cosmic neutrino flux discovered by the IceCube detector. ANTARES also comprised an acoustic test system, dubbed AMADEUS, featuring 36 acoustic
sensors, which have been taking data from 2008 to 2015 in the context of a
feasibility study towards acoustic detection of ultra-high energy neutrinos in sea water.

Building on the successful experience of ANTARES the next generation KM3NeT neutrino telescope is now under construction in the Mediterranean Sea. Two detectors with the same technology but different granularity are foreseen: ARCA designed to search for high energy (TeV-PeV) cosmic neutrinos (~Gton instrumented volume, offshore Capo Passero, Italy) and ORCA that will focus on atmospheric neutrino oscillations at the GeV scale (with ~few Mtons instrumented volume, offshore Toulon, France), addressing the question of the neutrino mass hierarchy. KM3NeT provides an excellent framework for an improved acoustic detection test setup. The acoustic sensors dedicated to the position calibration of the detector can be used for neutrino detection investigations. New concepts, in particular fibre-based hydrophones, are also under study to further increase the sensitive volume of KM3NeT beyond the volume instrumented with optical detectors.

This talk presents an overview of the status and of the main results of ANTARES, and discusses the scientific perspectives for KM3NeT, with a focus on acoustic detection devices and methods.

**Future and perspectives** / **39**

## A New Concept for High-Elevation Radio Detection of Tau Neutrinos

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Cosmic neutrinos are expected to include a significant flux of tau neutrinos due to flavor mixing over astronomical length scales. However, the tau-neutrino content of astrophysical neutrinos is poorly constrained and a significant flux of cosmogenic tau neutrinos awaits discovery. Earth-skimming tau neutrinos undergo charged-current interactions that result in a tau lepton exiting the Earth. The tau lepton decay generates an extensive air shower and geomagnetic radio emission. To target the tau neutrinos, I will present a new tau neutrino detector concept that uses phased antenna arrays placed on high elevation mountains. Simulation studies indicate that a modest array size and small number of stations can achieve competitive sensitivity, provided the receivers are at high enough elevation.

**Future and perspectives** / **40**

## Expansion of the LOFAR Radboud Air Shower Array and Updated Calibration of the LOFAR Antennas

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The LOFAR radio telescope measures radio emission from air showers in great detail. Now, we seek to extend our data taking capabilities.
In this contribution we discuss the expansion of the LOFAR Radboud Air Shower Array (LORA). LORA is a particle detector array located at the dense LOFAR core and is used to trigger the read-out of the LOFAR antennas. By doubling the size of the array, we increase its effective area, allowing us to trigger on higher energy cosmic rays which are more likely to produce a strong radio signal. In addition, the expansion reduces the composition bias inherent in detecting low energy showers. We also revisit the calibration of the LOFAR antennas in the range of 30-80 MHz. Using the galactic background and a detailed model of the LOFAR signal chain, we find a calibration that provides an absolute energy scale and allows us to study frequency dependent features in measured signals.

**Experimental data / 41**

## SLAC T-510: Experimental validation of particle-level simulations of radio emission from particle cascades

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The SLAC T-510 experiment measured radio emission from particle cascades in a controlled laboratory setting. An electron beam incident upon a dense dielectric target produced a particle cascade in the presence of a strong magnetic field. The goal of the experiment was to compare controlled laboratory measurements of radio emission to predictions using particle-level simulations. We previously reported the agreement between data and simulations within systematic uncertainties, the largest being the reflection of radio emission within the target. A follow up experiment has since been carried out to characterize the reflections and include them in simulations. In this contribution we report these new results, which show the uncertainties in the experiment are greatly reduced, and the features in the observed emission are well understood.

**Analisys tools / 42**

## Radio morphing: towards a full parameterization of the radio signal from air-showers

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Over the last decades, radio detection of air showers has been established as a promising detection technique for ultrahigh-energy cosmic rays and neutrinos. Very large or dense antenna arrays are necessary to be proficient at collecting and understanding accurately these particles. The exploitation of such arrays require to run massive air-shower simulations to evaluate the radio signal at each antenna position, taking into account features such as the ground topology. In order to reduce this computational cost, we have developed a full parametrisation of the emitted radio signal on the basis of generic shower simulations, called radio morphing. The method consists in computing the radio signal of any air-shower by i) a scaling of the electric-field amplitude of a reference air shower to the target shower, ii) an isometry on the simulated positions and iii) an interpolation of the radio pulse at the desired position. This technique enables one to gain many orders of magnitude in CPU time compared to a standard computation. In this contribution, we present this novel tool, explain its methodology, and discuss its application extents. In particular, radio morphing will be a key element for the simulation chain of the Giant Radio Array for Neutrino Detection (GRAND) project, that aims at detecting ultra-high-energy neutrinos with an array of 200 000 radio antennas in mountainous regions.

**Analisys tools / 43**

## A new LDF parametrization for the air shower radio footprint applied to LOFAR data

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poster:

A new function is addressed to describe the radio footprint of air showers using physical reasoning. The air shower induced by a cosmic-ray primary particle emits radio emission due to the Geomagnetic effect and the Askaryan effect. The function describes these two mechanisms separately. CoREAS simulations of LOFAR events are used to parameterize the function in order describe as a function of the shower characteristics: the shower maximum and the primary particle energy. The parameterization is applied to simulations and measured LOFAR data. This contribution shows the resolution to determine the shower energy and the shower maximum and compares the results with previous outcomes.

**Highlight talks / 44**

## A large radio array at the Pierre Auger observatory

**Authors:** Jörg Hörandel[1]; Pierre Auger Collaboration[None]

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poster:

Our understanding of radio detection of cosmic rays has been greatly improved over the last years. Extensive air showers are now routinely measured with experiments like Tunka-Rex, the LOFAR radio telescope, or the to date biggest radio detector for cosmic rays, the 17 km$^2$ Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory. The properties of the incoming cosmic rays are measured with state-of-the-art resolution.

The next step in radio detection is the application of the technique on very large scales. We aim to add a new detector layer in form of radio antennas to the 3000 km$^2$ Surface Detector of the Pierre Auger Observatory. This effort is complementary to the ongoing upgrade of the observatory in which a layer of scintillation detectors is added to each water Cherenkov detector of the Surface Detector. The radio detector provides a clean measurement of the electromagnetic shower component for cosmic rays arriving from the zenith up to the horizon. Thus, the aperture of the Auger upgrade will be significantly enlarged. We will outline the physics potential and the envisaged technical implementation of the large radio array.

**Future and perspectives / 45**

## Towards real-time cosmic-ray identification with the LOw Frequency ARay

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poster:

When a cosmic ray interacts with the Earth's atmosphere, it produces a cascade of secondary particles, known as Extensive Air Showers (EAS). Associated with the cascade, a radio signal is emitted through Geomagnetic and Askaryan mechanisms, which can be used for reconstructing the properties of the primary particle.
The LOw Frequency ARay (LOFAR) observatory is a multipurpose radio antenna array aimed to detect radio signals in the frequency range 10-240 MHz. Radio antennas are clustered into over 50 stations, and are spread along central and northern Europe, with a higher density in the northern Netherlands. The LOFAR core, where the density of stations is highest, has been used since 2011 for detecting radio signals from cosmic-ray air showers in the energy range 10ˆ16 - 10ˆ18 eV, in association with the LOfar Radboud air shower Array (LORA).
One of the biggest challenges for assessing the Radio detection as a valuable technique for cosmic-ray observation is to have a real-time recognition system for the very short radio pulses induced by the secondary particles cascades over the overwhelming background noise. A study for developing a real-time cosmic-ray detection system has been carried out in the last years on the LOFAR Low Band Antenna, which are sensitive between 10 and 90 MHz. The latest results of this study are here presented.

**Experimental data / 46**

## Latest results on the analysis of the radio frequency spectrum emitted by high energy air showers with LOFAR

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poster:

The LOw Frequency ARay (LOFAR) is a multipurpose radio antenna array aimed to detect radio signals in the frequency range 10-240 MHz, covering a large surface in Northern Europe with a higher density in the Netherlands. Analytical calculations and simulation studies performed in the 2000s indicates a dependence of the radio frequency spectrum on cosmic-ray air shower characteristics. The high number density of radio antennas at the LOFAR core in Northern Netherlands allows to measure the frequency spectrum in the energy range 10ˆ16 –10ˆ18 eV, and to characterise the geometry of the observed cascade in a detailed way.
The radio signal emitted by high energy cosmic rays in the atmosphere has been studied accurately in the 30 –80 MHz frequency range, and is here presented. The study has been conducted on simulated events and on real data detected by LOFAR since 2011.
The final aim of this study is to find an independent method to infer information of primary cosmic rays for improving the reconstruction of primary particle parameters.

**Analisys tools / 47**

## Radio universality and template-based pulse synthesis

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When discussing radio emission from cosmic ray air showers we commonly make a number of assumptions regarding the production and propagation physics. Incorporating all of these it should be possible to construct a forward model to predict the radio signal produced by an air shower from simple parameters, an application and generalisation of shower universality to radio emission.

In terms of particle detection shower universality focuses on the one-dimensional longitudinal profile, counting only the number of particles. This appears insufficient in the context of radio emission, the particle cascade develops on the scale of traversed atmospheric depth while electromagnetic radiation scales with the geometric trajectories of the sources. Further a real shower extends several radio wavelengths in the lateral direction while analyses often assume a point source on the shower axis. Thus we perform simulations to assess the validity of assumptions such as point-like emission, scaling of the radio output with particle number and mean free path length, spherical propagation and symmetries in the radio footprint as predicted by the analytical descriptions of geomagnetic and charge excess emission.

**Future and perspectives** / **48**

## Preparations for radio air-shower studies with the Murchison Widefield Array

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The Murchison Widefield Array (MWA) is a low-frequency (70-300 MHz) aperture-array radio telescope that has the potential to study geomagnetic radio emission from cosmic-ray air showers commensally with its regular astronomical observations. This mode of operation has proven highly effective with the LOFAR telescope, and its implementation with the MWA is a vital step towards its future use with the Square Kilometre Array at the same site. Preparatory work has been carried out for this application of the MWA, including radio-triggered engineering tests, and the development of a particle-detector system for particle-triggered observations in the near future.

**Future and perspectives** / **49**

## Acoustic parametric techniques for neutrino telescope

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In this work, we present a compact transmitter array with three elements based on the parametric acoustic sources effect able to reproduce the acoustic signature of an Ultra-High Energy neutrino interaction in water. We also propose to use directive transducers using the parametric technique for the characterization of piezo-ceramic sensors contained in the KM3NeT DOMs. This technique can minimize the need for an anechoic tank. Finally, some studies of the technique for the application of directive underwater communications are also presented.

**Experimental data / 50**

## First analysis of inclined air-showers detected by Tunka-Rex

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The Tunka Radio Extension (Tunka-Rex) is a digital antenna array for the detection of radio emission from cosmic-ray air showers in the frequency band of 30 to 80 MHz and with energies above 100 PeV.
The standard analysis of Tunka-Rex includes events with zenith angle of up to 50 degrees.
This cut is determined by the efficiency of the external trigger.
However due to the air-shower footprint increasing with zenith angle and due to the more efficient generation of radio emission (the magnetic field in Tunka valley is almost vertical), there are a number of ultra-high-energy inclined events detected by Tunka-Rex.
In this work we present a first analysis of a subset of inclined events detected by Tunka-Rex.
A comparison of detected radio signals with CoREAS end-to-end simulations is presented.
Using these simulations we estimate the energies and shower maxima of the selected events and test the efficiency of Tunka-Rex antennas for detection of inclined air-showers.

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## Properties of the Lunar Detection Mode for ZeV Scale Particles with LOFAR

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The steep decrease of the flux of ultra-high energy cosmic rays (UHECR) provides a challenge to answer the long standing question about their origin and nature. A significant increase in detector volume may be achieved by employing Earth's moon as detector that is read out using exisiting Earth-bound radio telescopes by searching for the radio pulses emitted by the particle shower in the lunar rock. In this contribution we will report on the properties of a corresponding detection mode currently under development for the LOFAR Radio telescope.

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## Simulation studies for large scale acoustic neutrino detectors

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The AMADEUS system was a submarine acoustic array operating from 2008 until 2015 as a part of the ANTARES neutrino telescope in the Mediterranean Sea. Its design goal was to investigate the feasibility of acoustic neutrino detection in the deep sea. The data taken during its eight years of operation provide a wealth of information for setting up realistic simulations of future acoustic neutrino detectors. Using in addition simulations of neutrino interactions in water, effective volumes of various potential acoustic neutrino detector designs were investigated and methods for suppressing background and reconstructing energy and direction of incoming neutrinos were developed. The talk will give an overview of the latest results.

**Highlight talks / 53**

## History of acoustic neutrino detection

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The history of acoustic neutrino detection will be reviewed.

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## RadioPropa: A Modular Raytracer for In-Matter Radio Propagation

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Experiments for radio detection of UHE particles such as e.g. ARA/ARIANNA or NuMoon require detailed understanding of the propagation of radio waves in the surrounding matter. The index of refraction in e.g. polar ice or lunar rock may have a complex spatial structure that makes detailed simulations of the radio propagation necessary to design the respective experiments and analyse their data. Here, we present RadioPropa as a new modular ray tracing code that solves the eikonal equation with a Runge-Kutta method in arbitrary refractivity fields. RadioPropa is based on the cosmic ray propagation code CRPropa, which has been forked to allow efficient incorporation of the required data structures for ray tracing while retaining its modular design. This allows for the setup of versatile simulation geometries as well as the easy inclusion of additional physical effects such as e.g. partial reflection on boundary layers in the simulations. We discuss the principal design of the code as well as its performance in example applications.

**Highlight talks / 55**

## Measurement of Cosmic Rays with LOFAR

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We give an update on the mass composition of cosmic rays between $10^{17}$ and $10^{17.5}$ eV measured by the LOFAR radio telescope. By matching observations with two-dimensional radio intensity footprints simulated with Corsika/CoREAS we reconstruct X_max with a resolution of $\sim$20 g/cm$^2$. We present improvements that were introduced in the reconstruction pipeline and their implications for the composition analysis. Most importantly, systematic uncertainties due to variations in the atmopshere have been reduced by using realistic atmospheric profiles from the GDAS (Global Data Assimilation System) database.

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## Using FDTD simulations to study radio propagation effects

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Propagation of radio emission through surfaces or media with inhomogeneous properties is usually simulated by means of ray-tracing. It is however possible that there are cases where it more suitable to treat the radiation as waves. We use a Finite-Difference Time-Domain (FDTD) code to simulate the propagation of radio emission through ice, with a particular focus on the role of an inhomogeneous firn layer.

**Experimental data / 57**

## Hydrophone characterization for the KM3NeT experiment

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With the KM3NeT experiment, which is presently under construction in the Mediterean Sea, a new neutrino telescope will be installed to study both neutrino properties as well as their astrophysical sources. To do so, about 6000 optical modules will be installed in the abyss of the Mediterean Sea, and are used to observe the Cherekov radiation induced by energy particle interactions in the deep sea. As each module of the KM3NeT the telesope includes a hydrophone, KM3NeT will alo provide a unique matrix of underwater hydrophone. We report on characterization measurements of the piezo-hydrophones in our laboratories. Results from these measurements will be used to assess the potential of KM3NeT in acoustic detection of neutrinos.

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## Fiber optic hydrophones in an acoustic neutrino telescope

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The technology of ber optic hydrophones provides an attractive means to establish an acoustic neutrino telescope. To implement the technology in a large sensor network, however, additional requirements have to be met. As the expected number of sensors in the network will be large, i.e. in the order of 1000-10000, signal multiplexing algorithms is one of the design drivers that should be addressed when adapting the technology for acoustic neutrino telescope. As the expected signals from cosmic neutrinos is expected to be low compared to the sea state noise, methods are investigated to enhance the sensitivity of the telescope. One such method could be beamforming, in which the signal from a large number of hydrophones are combined to suppress noise. In this talk we give an update of the ber hydrophone technology and we discuss how multiplexing could be compatible with beam forming to gain sensitivity in order to observer the minute acoustic signals from neutrinos interactions in the deep sea.

**Highlight talks / 59**

## Theory and phenomenology of UHE neutrinos

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Review invited talk

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## KM3NeT acoustic positioning and detection system

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In the Mediterranean Sea, new generation neutrino detectors for astrophysics and oscillations studies are under construction within the activities of the KM3NeT deep-sea research infrastructure. In the KM3NeT neutrino detectors the Cherenkov radiation induced by the secondary charged particles produced in the interaction of cosmic and atmospheric neutrinos within a large volume of sea-water is detected by an array of thousands of photomultipliers. Photomultipliers are installed in pressure-resistant glass spheres, referred to as Digital Optical Modules (DOMs), attached on vertical string-like detection units (DUs) about 700 m high, anchored on the sea-bottom. Each DU hosts 18 DOMs containing 31 photomultipliers, several calibration instruments and readout electronics.
The direction of charged particles emerging from neutrino interactions needs to be reconstructed with high precision in order to accomplish the scientific objectives of KM3NeT. To achieve this, DUs

must be geo-referred with an uncertainty of about two meters and the relative positions of the DOMs must be continuously monitored with an precision better than 20 cm .
These requirements are met through a long baseline (LBL) acoustic positioning system composed of a number of transponders (emitter-receiver couple) installed at fixed positions on the sea-bottom and of an array of time-synchronized piezo-acoustic receivers installed inside DOMs. Knowing the sound velocity profile along the water column and the time of flight of the acoustic pulses emitted by the LBL transponders to reach each piezo-acoustic receiver, DOM positions are calculated through multi-lateration procedures.
Thanks to an innovative data acquisition system based on "all data to shore"philosophy, data acquired by the acoustic receivers of the KM3NeT positioning system can be also used for the detection and tracking of underwater acoustic sources (natural and anthropogenic) and to develop innovative techniques for very high energy neutrino detection founded on thermo-acoustic model.

**Highlight talks / 61**

## 15 years of acoustic detection studies at INFN

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Since the early 2000s, thanks to national, regional and European projects, a number of abyssal detectors equipped with acoustic sensors have been installed and operated by INFN in two cabled submarine research infrastructures off Eastern Sicily. The INFN's interest in underwater acoustics arises from the need to develop an acoustic positioning system for the KN3NeT telescope and to study the possibility of neutrino acoustic detection.
The use of innovative technologies for data acquisition and transmission systems have enabled the first long-term studies on the deep marine environment of the Ionian Sea with a variety of lines of research. Data acquired through the INFN underwater infrastructures have allowed the continuous monitoring of the underwater acoustic noise and several studies on cetacean species present in the area and on seismic sources . An overview of the main activities of INFN on detection and localization of underwater acoustic sources will be presented.

**Highlight talks / 62**

## Recent results from IceCube

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## Future neutrinos radio

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## Status and past UHE neutrino radio

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## Shower Radio

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