29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Acoustic Sensor and Transmitter Development for a Large Volume Neutrino Detection Array in Ice

S.Böser[a], R.Heller[a],A. Hallgren[b], R.Nahnhauer[a], M. Pohl[a], J. Stegmaier[a], K. Sulanke[a]
(a) DESY, Platanenallee 6, D-15738 Zeuthen, Germany
(b) University Uppsala, Department of Radiation Sciences, Box 535, S-751 21 Uppsala, Sweden
Presenter: R. Nahnhauer (nahnhaue@ifh.de), ger-nahnhauer-R-abs3-og25-poster

For the detection of acoustic signals resulting from the interaction of highest energy cosmic neutrinos with nucleons of solid materials, cheap but sensitive acoustic sensors have been developed. Application in ice has been tested, using mechanical and electrical excitations as well as a laser and a proton beam for signal simulation. Energy deposits between $10^{16}\,\mathrm{eV}$ and $10^{18}\,\mathrm{eV}$ have been used. In addition, the sensors have been calibrated in water in comparison to a commercial hydrophone. The signal to noise ratio is up to a factor 50 better for the new sensors. However, they don't reach the smooth frequency response of commercial hydrophones.

1. Introduction

The detection of highest energetic neutrinos from the interaction of cosmic rays with the cosmic microwave background and other sources in the range from $10^{17} - 10^{20}\,\mathrm{eV}$ is one of the most interesting topics of astroparticle physics today. Even the biggest experiments under construction like IceCube, AUGER or ANITA will register only a few of such events during their time of operation [1].

New projects are in the proposal stage now, which aim for detector volumes up to several 100 cubic kilometers [2]. Due to the costs involved, such volumes are hard to instrument with optical sensors - the most developed technique today. A combination of optical, radio and acoustic detectors proposed for the IceCube observatory [3] seems to be a promising approach to observe cosmogenic neutrinos with reasonable statistics.

The idea of acoustic detection of highest energy neutrinos, which was first discussed more then 30 years ago [4], has had a strong revival during the last few years [2]. Due to the weak attenuation of acoustic waves in many materials very large detector volumes become possible using a rather large sensor spacing. Applications in ice and salt are favorable in comparison to water due to the much higher expected signal strength [5]. However only for water commercial sensors - hydrophones - are available. That is the reason for the development of the "glaciophones" described below.

2. Detector Concept

Like hydrophones, the acoustic sensors are based on a piezo-ceramics as sensitive elements. Standard lead-zirconium-titanate elements with a diameter of $1\,\mathrm{cm}$ and a height of $.5\,\mathrm{cm}$ are mounted in a housing which contains in addition a three stage low noise amplifier chain. The piezo-ceramics properties ($d_{33} = 500\,\mathrm{pC/N}$) together with an amplification of $\sim 80\,\mathrm{dB}$ allow to measure pulses of $\sim 10\,\mathrm{mPa}$ amplitude. Several housings developed for the application in deep ice have been studied. A collection is shown in figure 1. Apart from the impedance matching between the target material (e.g. ice) and the piezo-ceramic, the sensor response is governed by the resonance behaviour not only of the piezo-ceramic but even more of the housing, which again is determined by material and geometry. This leads to a complicated frequency response of those detectors.

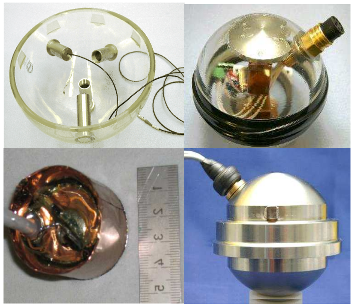

Fig.1: Different glaciophones for application in deep ice

Fig.2: Sensor installation seen through $\sim 1\,\mathrm{m}$ of clear ice

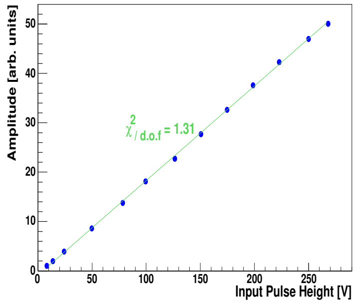

Fig.3: Transmitter pressure amplitude in dependence on input voltage

3. Laboratory Tests

3.1 Transmission media

Apart from water, ice blocks of the size $1.3 \times 0.4 \times 0.35\,\mathrm{m}^3$ were produced in a freezer and cooled down to temperatures of $\approx -30\,^\circ\mathrm{C}$. Transmitters and sensors were installed beforehand in the water and frozen in. The signal transmission through the ice was found strongly dependent on the ice quality. Much effort was spent to get clear homogeneous ice with even very good optical transparency (see figure 2).

3.2 Signal Simulation

Neutrinos of 10^{18} eV interacting with nucleons in a dense material produce particle cascades of a few centimeter diameter and several meter length. Following the approximations in [4], this leads to bipolar pressure waves with an amplitude proportional to the incoming particle energy and the square of their peak frequency, which is determined by the cascade diameter. The pulse expands as a thin ring perpendicular to the cascade direction. Unfortunately these signals are rare in nature and difficult to simulate.

A very simple first test was to drop down small weights onto the surface of the ice block. This will not create a thermo-acoustic process and the acoustic energy transfered to the ice is not well determined. However, it should be less than the potential energy, which is $6 \cdot 10^{15}$ eV for a weight of 1 g in the height of 10 cm and therefore just in the right region for short distances from the source to the sensor. The signal amplitude was growing linearly with increasing weight. The smallest detectable mass which could be handled manually was 5 mg corresponding to $3 \cdot 10^{13}$ eV.

A much more precise method is to use again piezo-ceramics, this time in an inverted mode, where a voltage is applied to generate a pressure pulse. With an arbitrary signal generator different pulse shapes can be produced. Present tests were done either with a gated sine wave burst of selected frequencies or with a short single input pulse yielding a pressure wave with a large frequency spectrum. Again the produced pressure pulse has no thermo-acoustic origin but depends linearly on the input voltage (see figure 3) up to the kV regime. This allows to produce very large pulses, which are important for in-situ tests with long distances between transmitters and sensors. As the directionality of the transmitter signal is strongly connected to the geometry of the piezo-element, in some cases ring shaped ceramics were used to get azimuthal symmetry.

Another method to produce acoustic pulses in ice is the use of a powerful laser. The deposited energy density will decrease exponentially from the entrance point and generate a thermo-acoustic signal which has been observed in water [6]. The energy density is thereby depending on the light absorption length, which makes it difficult to detect waves in the much more transparent ice. Using a ND-YAK laser with $6 \cdot 10^{17}$ eV energy per pulse of 6 nsec length, acoustic signals have been observed also in ink-doped ice. However a more sophisti-

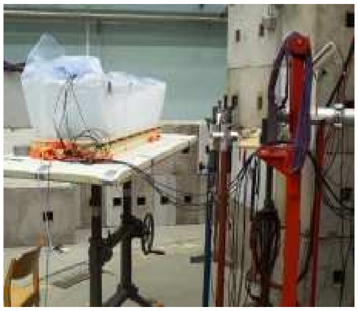

Fig.4: Ice block installed in front of a proton beam at TSL Uppsala

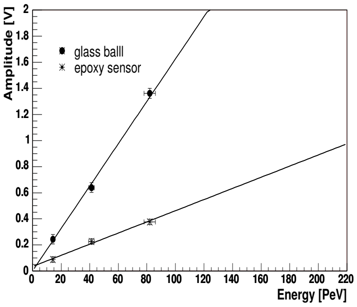

Fig.5:Dependence of measured pressure amplitude on energy in the proton beam

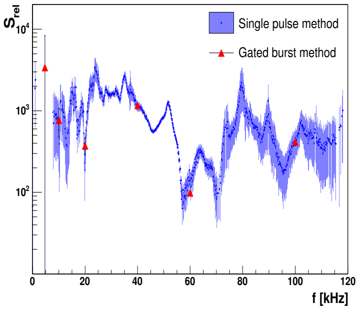

Fig.6: Sensitivity of the Iron ball sensor relative to the hydrophone

cated setup has still to be build to control and vary the incoming laser energy.

Another way to produce thermo-acoustic signals is to dump a high intense particle beam in a very short time in the target material. Several groups have done such tests for water using up to 200 MeV protons, which stop after some 10 cm in the target. An overview can be found in [2]. A similar test has been done for ice, using 180 MeV protons from the synchrocyclotron of the Thè Svedberg Laboratory in Uppsala (see figure 4). A linear dependence of the signal amplitude on the beam intensity was observed (see figure 5). In 1 m distance from the sensor the minimum detectable energy was $\sim 1 \cdot 10^{15}$ eV at $-15\,^\circ\mathrm{C}$ ice temperature. The signal showed a strong increases if the ice gets colder.

4. Calibration

Measurements of acoustic signals in lab-sized media are often strongly influenced by reflections of the signal at the media boundaries, prohibiting a calibration of sensors and transmitters. In order to avoid this problem, sufficiently large and homogeneous media have to be chosen, which in the case of ice are not easily accessible. In order to still get an estimate of the sensitivity of the developed sensors, a calibration in a large water tank has been performed first. At a distance of 10 cm one pair of sensors and transmitters was mounted in the center of a tank with dimensions of $12\,\mathrm{m} \times 10\,\mathrm{m} \times 5\,\mathrm{m}$. At a water temperature of $-0.1\,^\circ\mathrm{C}$ and a salt content of 7 ppm the speed of sound is $1413\,\frac{\mathrm{m}}{\mathrm{s}}$ [8] which is well confirmed by the measured value of $1410 \pm 3\,\frac{\mathrm{m}}{\mathrm{s}}$.

A hydrophone (Sensortech SQ03) of a well known sensitivity of 163 ± 0.3 dB rel. $1\mathrm{V}/\mu\mathrm{Pa}$ in the frequency range of $5-65$ kHz was used as a reference and compared to the *iron ball* and *glass ball* sensors shown on the right side in figure 1. A cylindrical piezo-ceramic of dimensions of $8\,\mathrm{mm} \times 5\,\mathrm{mm}$ cast in epoxy for electrical insulation has been used as a transmitter. For the excitation of the ceramic an arbitrary waveform generator was used. To compensate for the limited dynamic range of the sensor amplifiers and the large variation in the sensitivity, the input signals amplitude was varied in a range of $0.10\,\mathrm{V_{pp}} - 20.00\,\mathrm{V_{pp}}$ and was corrected for in the recorded signal by linear rescaling. For reduction of background noise, for each configuration 100 recordings with a length of 10 ms were taken at a sampling rate of 1.25 MHz.

Two different waveforms were used for a relative comparison of the signals. First, a gated burst of a sinusoidal wave at 6 different frequencies from $5-100$ kHz was sent. With a burst length shorter than the signal traveling time of the reflection at the container walls the direct signal can be separated by application of a time window. The time for the system to overcome initial resonant excitation from the abrupt onset of the sinusoidal wave and go in a steady forced mode was estimated from sending short single pulses and was subtracted from the signal time window. In the remaining time window the signal amplitude was estimated by fitting with a sine function with a fixed frequency allowing for a linear offset term to accommodate low-frequency background fluctuations. By comparison of the sensors to the reference hydrophone, a very precise measurement of the

Table 1. Equivalent self noise level in the frequency range from $5 - 65\,\mathrm{kHz}$.

	Hydrophone	Glass Ball	Iron Ball
$\sigma_{noise}\,[\mathrm{mPa}]$	40.3 ± 8.3	15.9 ± 1.7	4.7 ± 0.7

relative sensitivity with an error of $\lesssim 10\%$ could be achieved for single frequencies.

As a second waveform a fast step function with a slow return to the baseline was sent to the piezo-ceramic. This results in a short bipolar pressure pulse with a width of $\sim 10\,\mu$s containing a broad spectrum with peak frequencies up to $\sim 100\,\mathrm{kHz}$. As in contrast to the signal the noise is not coherent, from the variation of frequency components in the single recordings the noise spectrum could be estimated and showed very good agreement with an independent direct noise spectrum measurement. Fourier spectra of measurements with the self-built sensors were than compared to the reference hydrophone, excluding frequency regions were either of the spectra is dominated by background noise. In contrast to the previous measurement, this method yields the relative sensitivity on a large frequency spectrum in one configuration, though with less precision.

Figure 6. shows a comparison of the results from both methods for the *iron ball*. For all sensors good agreement of the methods has been observed. Please note that the errors given are only statistical. Systematic errors are probably smaller and will be accessed in further measurements. Although strongly frequency dependent, an enhanced sensitivity of both the iron ball and the glass ball in the order of $10^2 - 10^3$ can be seen, being probably mainly achieved by the larger gain of the electronic amplifiers in the self-build sensors. However, also the signal to noise ratio is increased up to a factor of 50 for some frequencies. The equivalent self noise level that can be derived for the frequency range where the hydrophone is calibrated is given in table 1. In comparison to the reference hydrophone, a clear improvement for both sensors can be observed.

5. Outlook

Sensors and transmitters similar to those described above will be used in the SPATS project [7], aiming for the measurement of acoustic properties of South Polar ice, in particular the attenuation length and the in situ noise level. Although already quite well suited for that purpose, the sensors and transmitters still leave room for improvement. Therefore a large scale detector array might use a quite different design, which is optimized for the conditions that will be found with the SPATS setup.

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