University of Pisa, 15.09.2004

R&D Towards Acoustic Particle Detection

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- The thermo-acoustic model and particle detection
- Sound sensors (hydrophones)
- Sound transmitters and hydrophone calibration
- Beam test measurements
- The next steps …

Our "acoustic team" in Erlangen

Thanks to our group members for their dedicated work over the last 2 years:

▪ Gisela Anton (Prof.)	
▪ Kay Graf (Dipl./PhD)	FAU-PI1-DIPL-04-002
▪ Jürgen Hößl (PostDoc)	
▪ Alexander Kappes (PostDoc)	
▪ Timo Karg (PhD)	
▪ UK (Prof.)	
▪ Philip Kollmannsberger (Dipl.)	FAU-PI4-DIPL-04-001
▪ Sebastian Kuch (Dipl./PhD)	FAU-PI1-DIPL-03-002
▪ Robert Lahmann (PostDoc)	
▪ Christopher Naumann (Dipl./PhD)	
▪ Carsten Richardt (Stud.)	
▪ Rainer Ostasch (Dipl.)	FAU-PI1-DIPL-04-001
▪ Karsten Salomon (PhD)	
▪ Stefanie Schwemmer (Dipl.)	

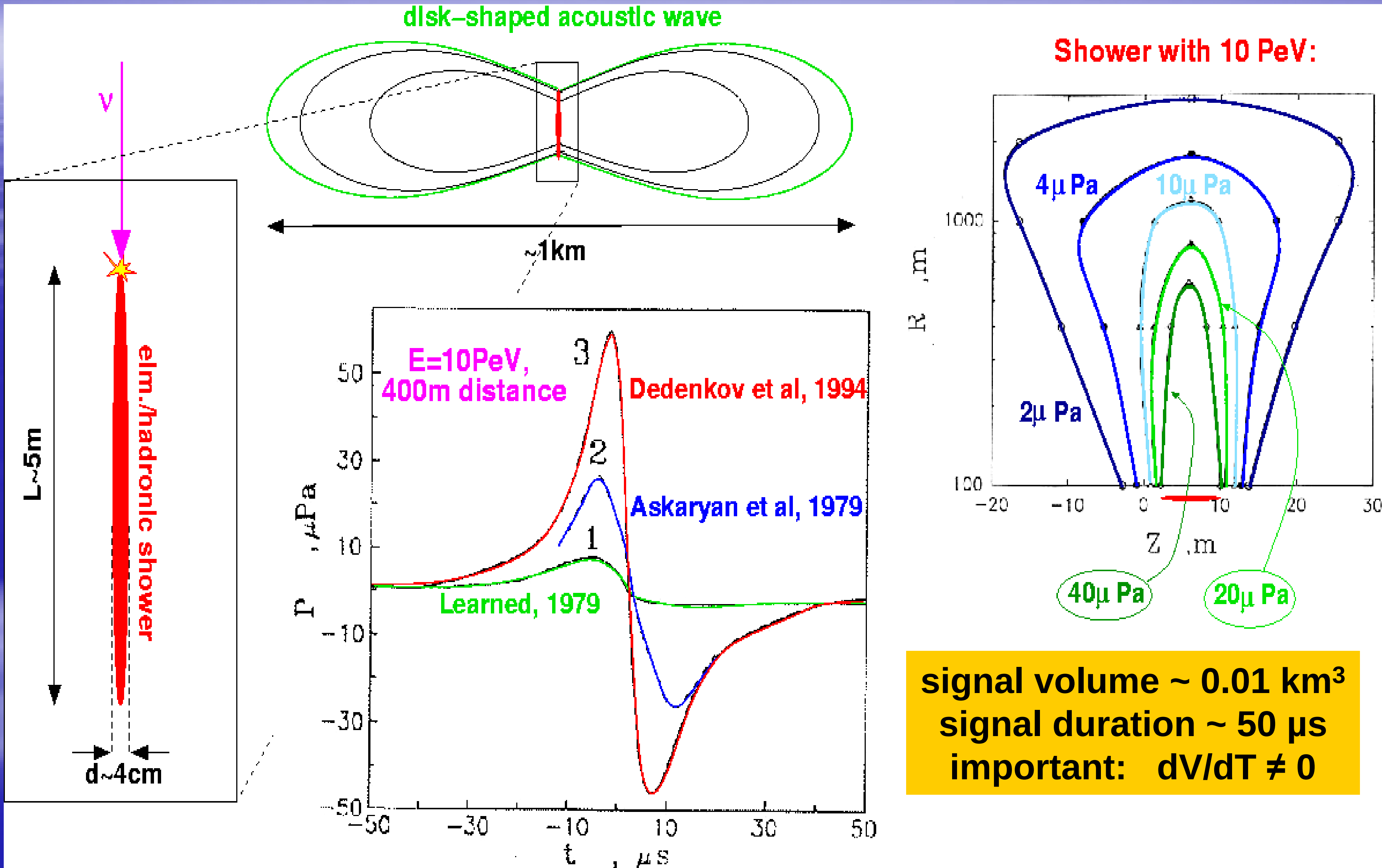
The thermo-acoustic model

- Particle reaction in medium (water, ice, ...) causes energy deposition by electromagnetic and/or hadronic showers.
- Energy deposition is fast w.r.t. (shower size)/c_s and dissipative processes → instantaneous heating
- Thermal expansion and subsequent rarefaction causes bipolar pressure wave:

$$P \sim (\alpha/C_p) \times (c_s/L_c)^2 \times E$$

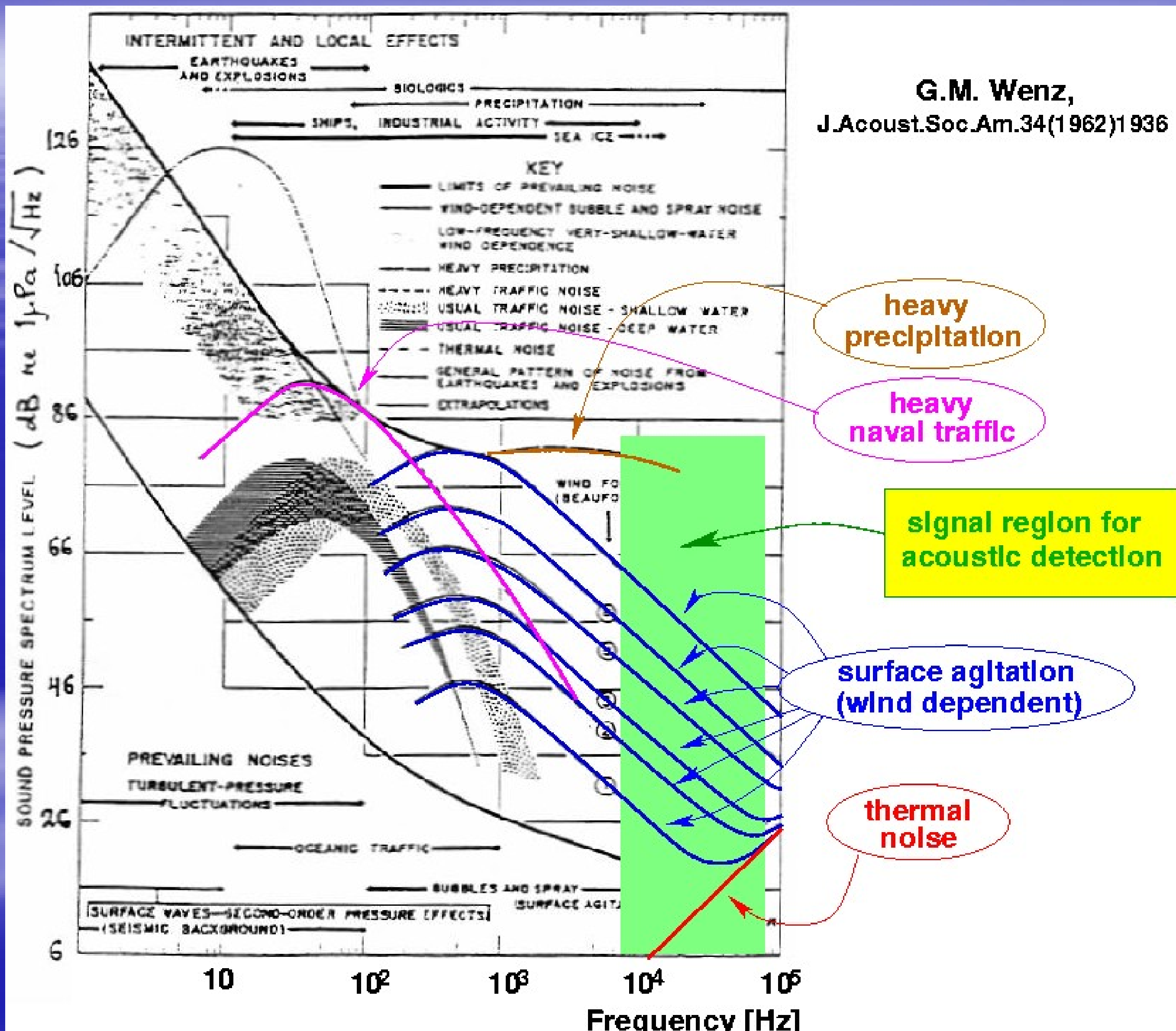
α = (1/V)(dV/dT)
= thermal expansion coefficient of medium
C_p = heat capacity of medium
c_s = sound velocity in medium
L_c = transverse shower size
c_s/L_c = characteristic signal frequency
E = shower energy

The signal from a neutrino reaction



signal volume ~ 0.01 km³
signal duration ~ 50 μs
important: dV/dT ≠ 0

The signal and the noise in the sea

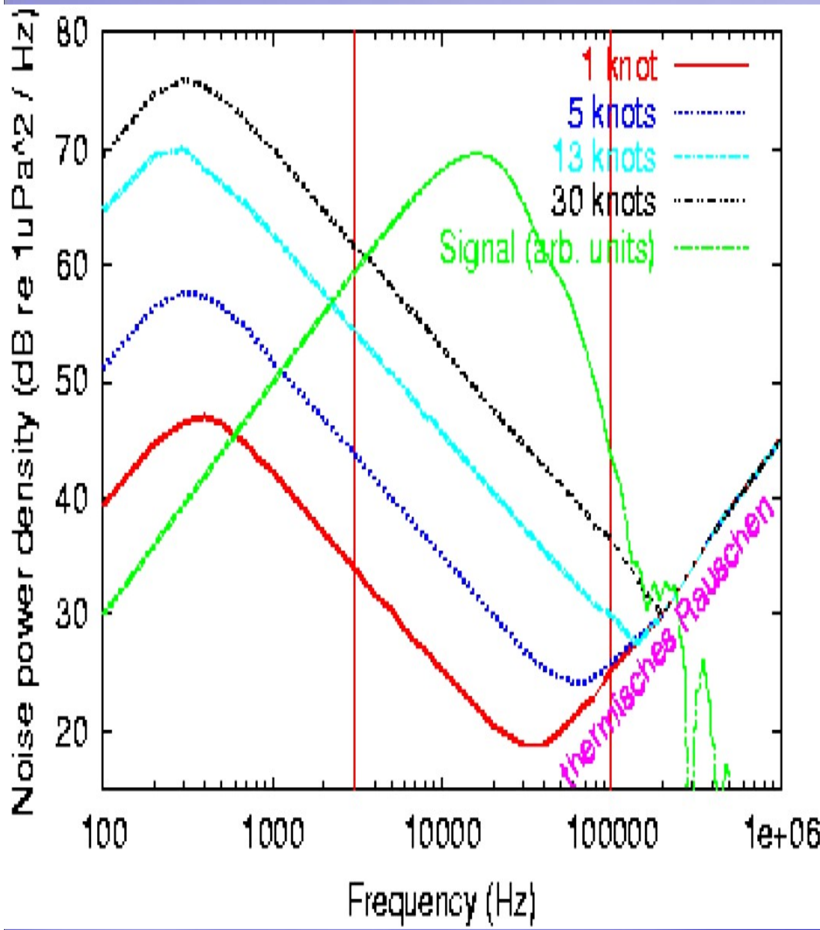


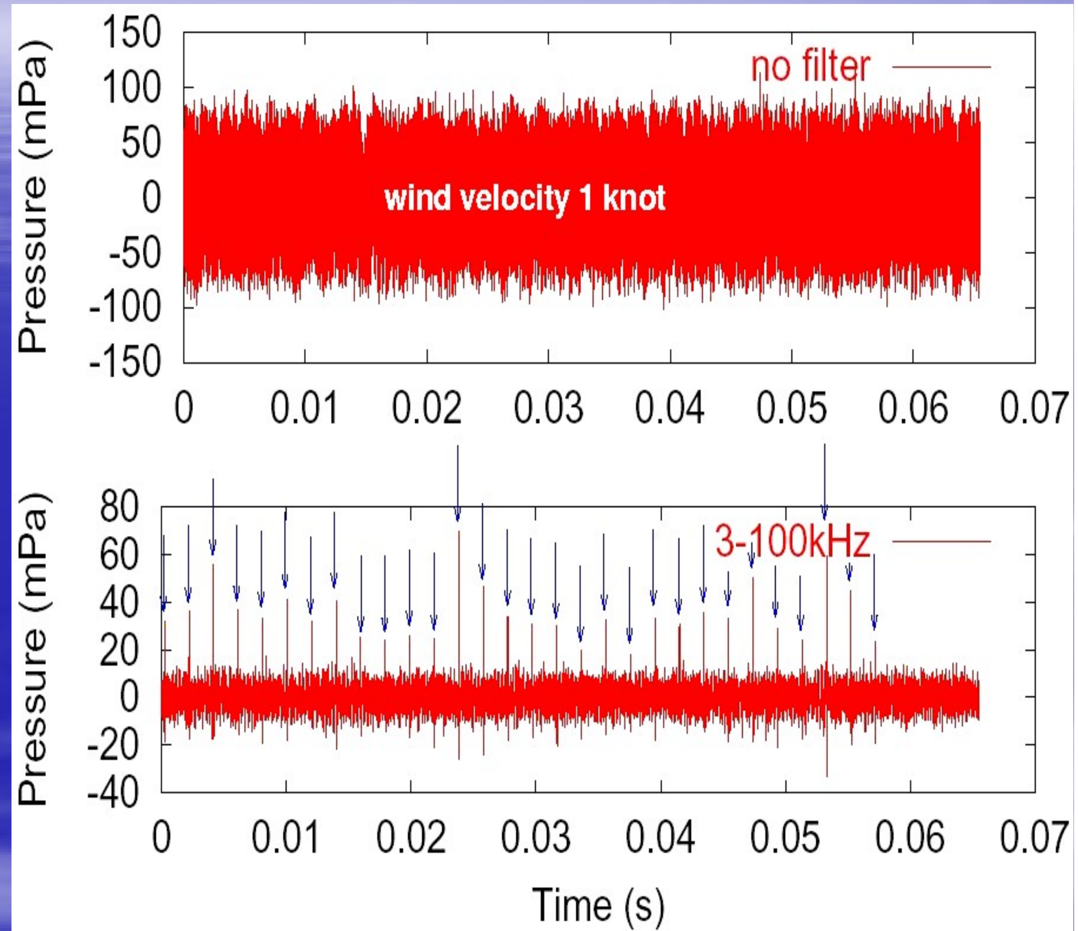
<u>Rough and optimistic estimate:</u>

signal ≈ noise at O(0.1-1 mPa)

(shower with 10-100 PeV @ 400m)

The frequency spectrum of the signal



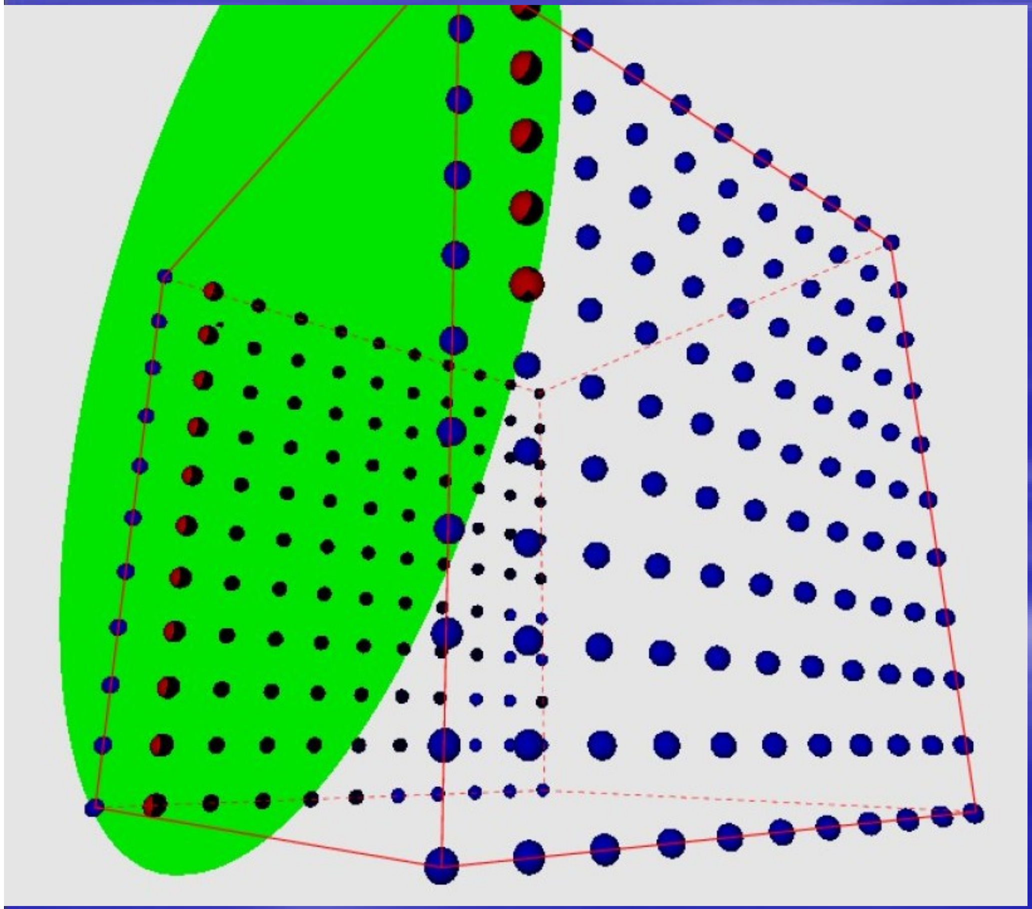


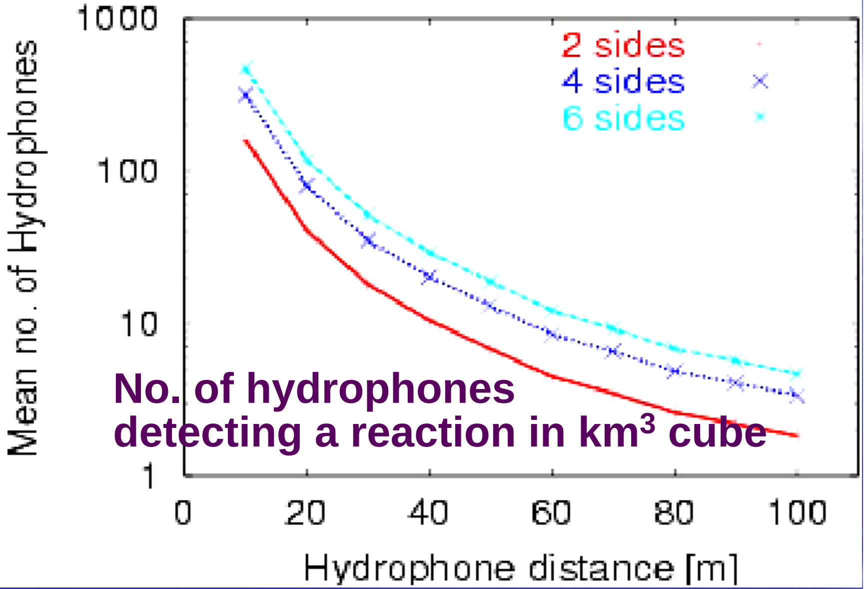
Simulation: band filter 3−100 kHz reduces noise by factor ~10 and makes signals of 50 mPa visible

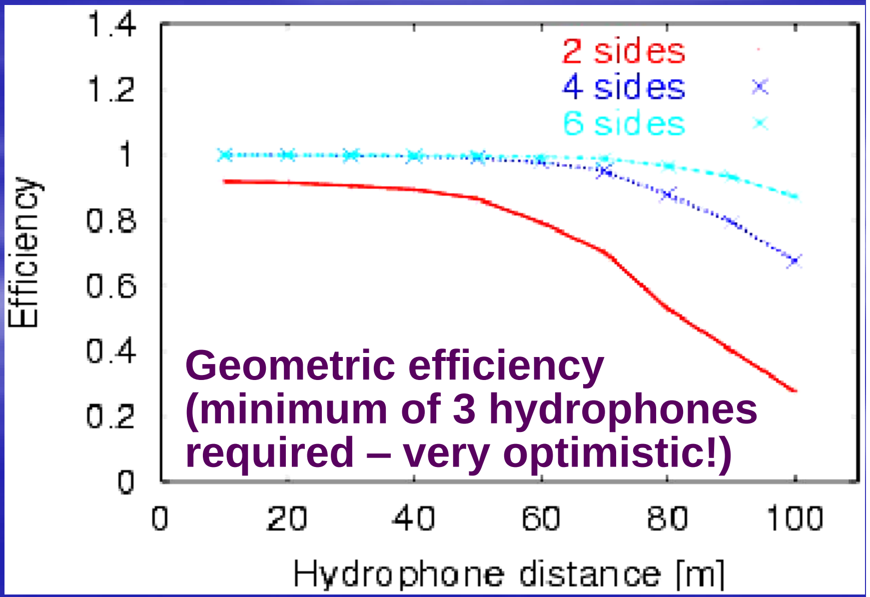
How could a detector look like?

Simulation:

Instrument 2,4 or 6 sides of a km^3 cube with grids of hydrophones







Current experimental activities

- ANTARES, NEMO:
  - hydrophone development;
  - long-term test measurements foreseen.
- SAUND
  - uses military hydrophone array in Caribbean Sea;
  - sensitive to highest-energy neutrinos (10^{20} eV);
  - first limits expected soon;
  - continuation: SAUND-II in IceCube experiment.
- Other hydrophone arrays (Kamchatka, ...)
- Salt domes
  - huge volumes of salt (NaCl), easily accessible from surface;
  - signal generation, attenuation length etc. under study.

International workshop on acoustic cosmic ray and neutrino detection,
Stanford, September 2003
http://hep.stanford.edu/neutrino/SAUND/workshop

Sound sensors (hydrophones)

- All hydrophones based on Piezo-electric effect
  - coupling of voltage and deformation along axis of particular anisotropic crystals;
  - typical field/pressure: 0.025 Vm/N
    yields O(0.1μV/mPa) → -200db re 1V/μPa;
  - with preamplifier: hydrophone (receiver);
    w/o preamplifier: transducer (sender/receiver).
- Detector sensitivity determined by signal/noise ratio.
- Noise sources:
  - intrinsic noise of Piezo crystal (small);
  - preamplifier noise (dominant);
  - to be compared to ambient noise level in sea.
- Coupling to acoustic wave in water requires care in selection of encapsulation material.

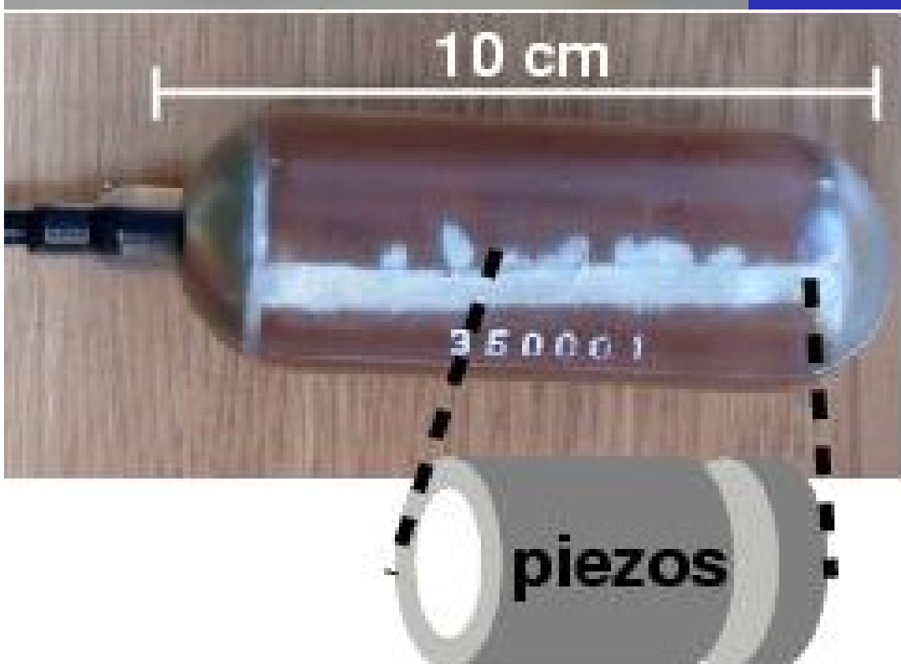
Example hydrophones

Piezo elements →

Commercial hydrophones:

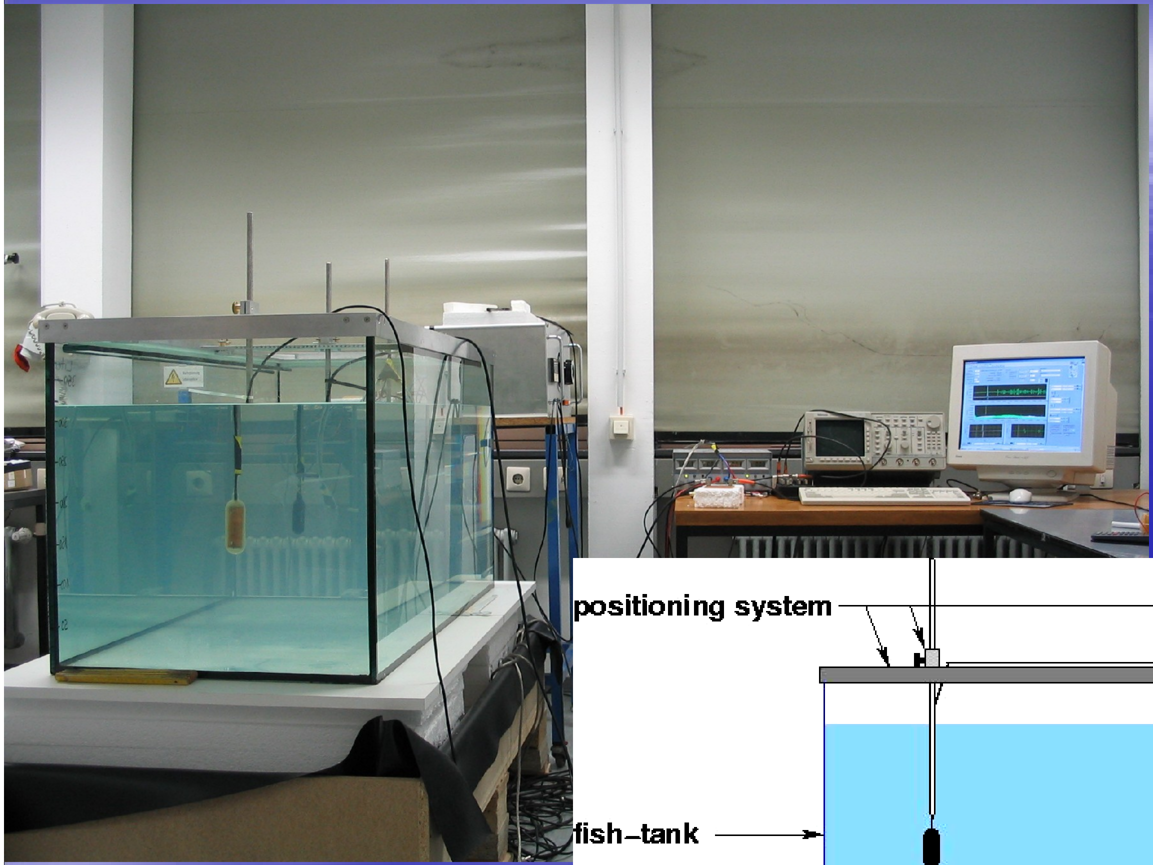
← cheap

↓ expensive



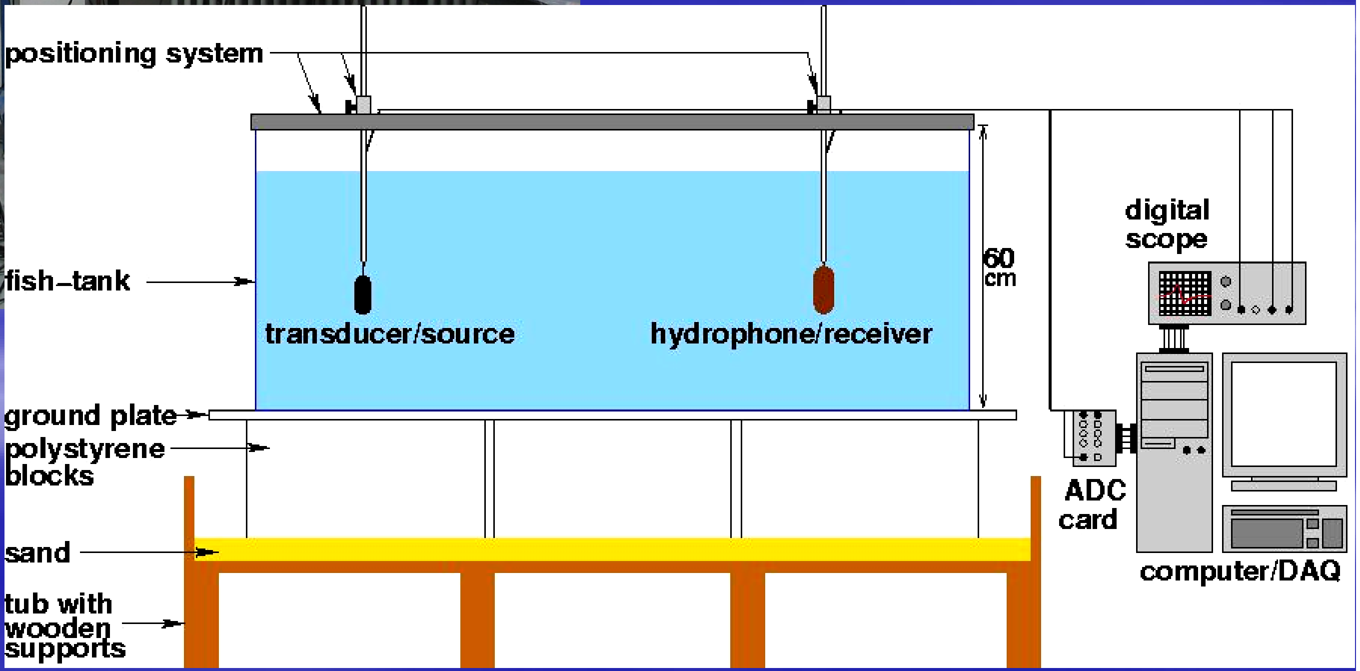
Self-made hydrophones

How we measure acoustic signals



Readout:

Digitization via ADC card or digital scope, typical sampling freq. O(500 kHz)

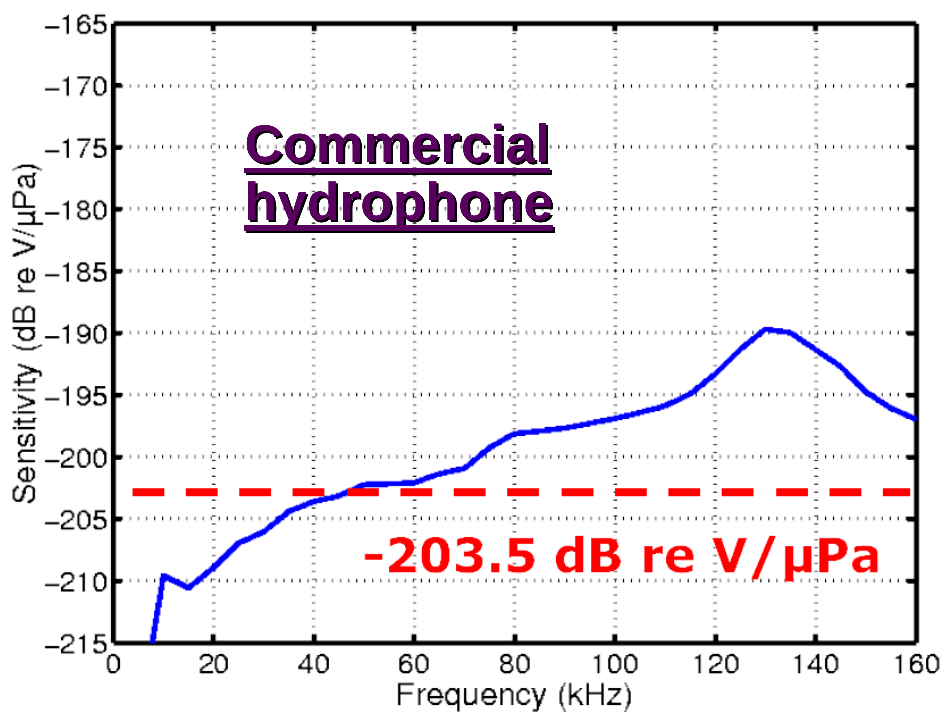


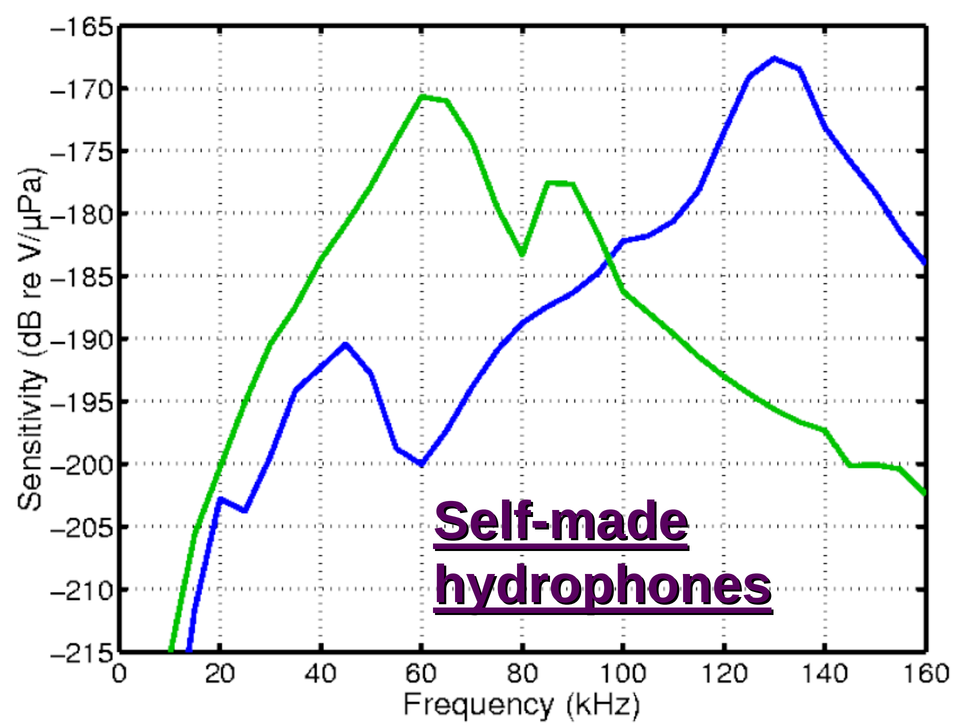
Positioning:

Precision O(2mm) in all coordinates

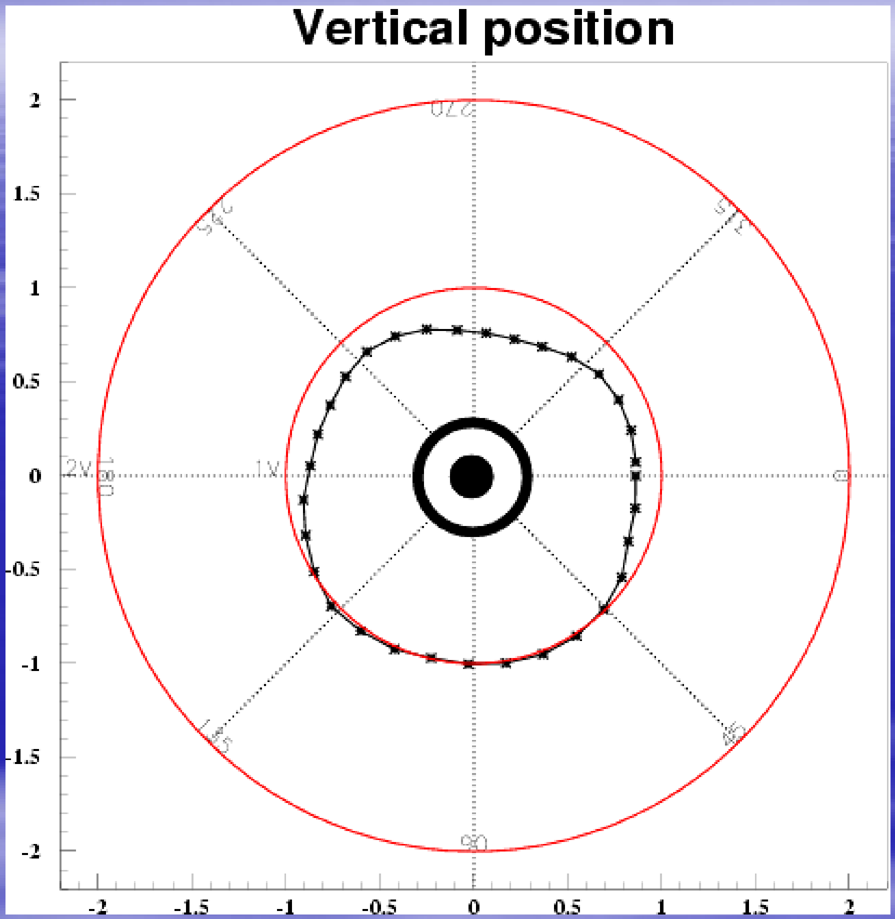
Hydrophone sensitivities

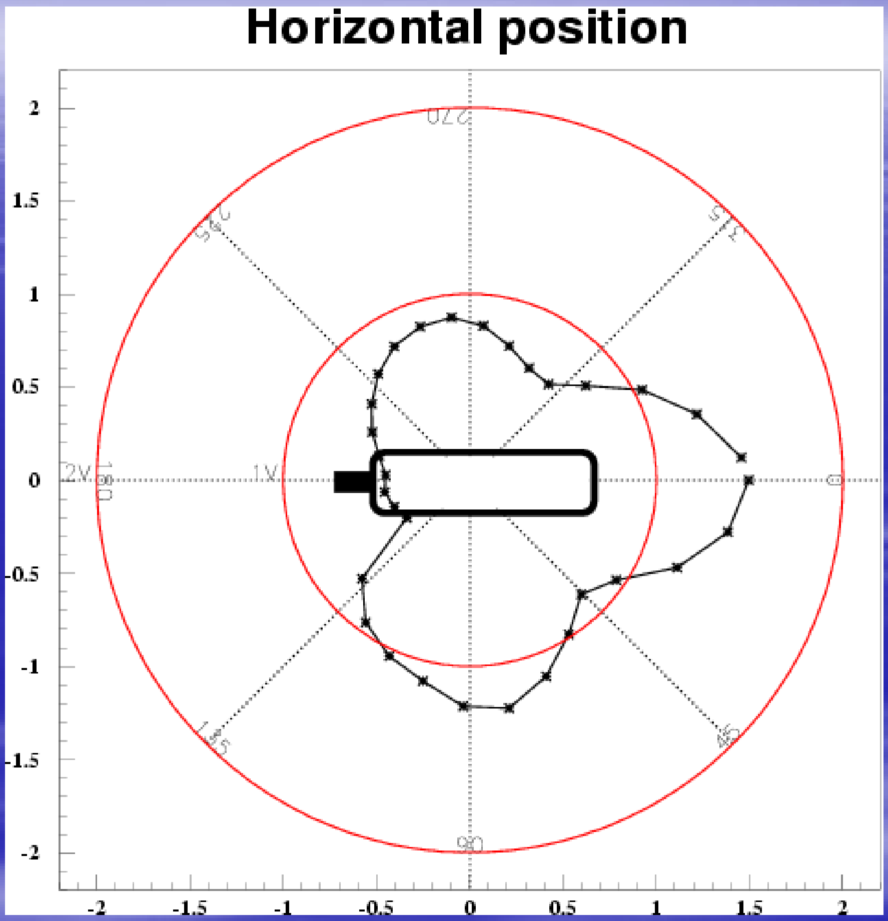
- Sensitivity is strongly frequency-dependent, depends e.g. on eigen-frequencies of Piezo element(s)
- Preamplifier adds additional frequency dependence (not shown)





Directional sensitivity

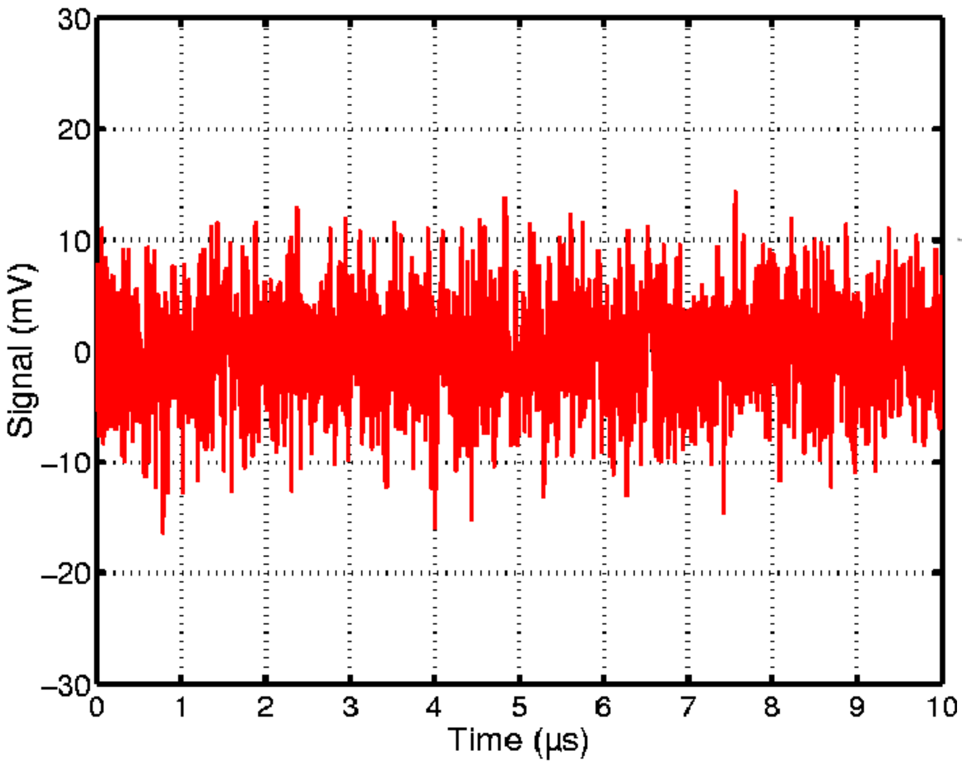


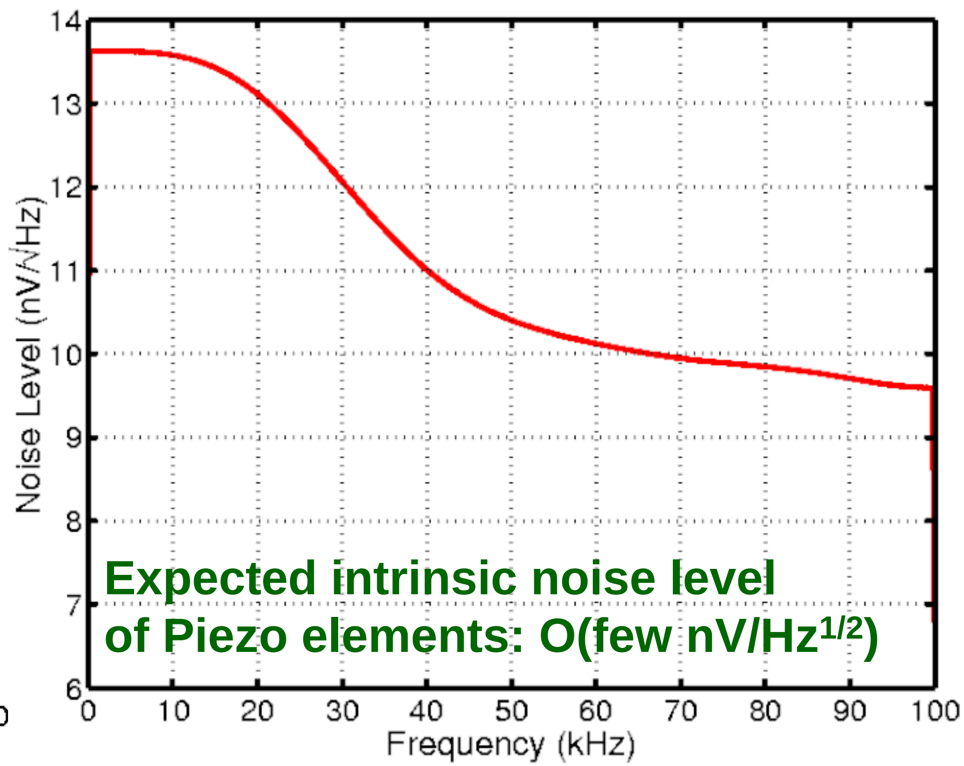


... depends on Piezo shape/combination,
positions/sizes of preamplifier and cable,
mechanical configuration

Noise level of hydrophones

- Currently dominated by preamplifier noise
- Corresponds to O(10 mPa) →
  shower with 10^{18}eV in 400 m distance

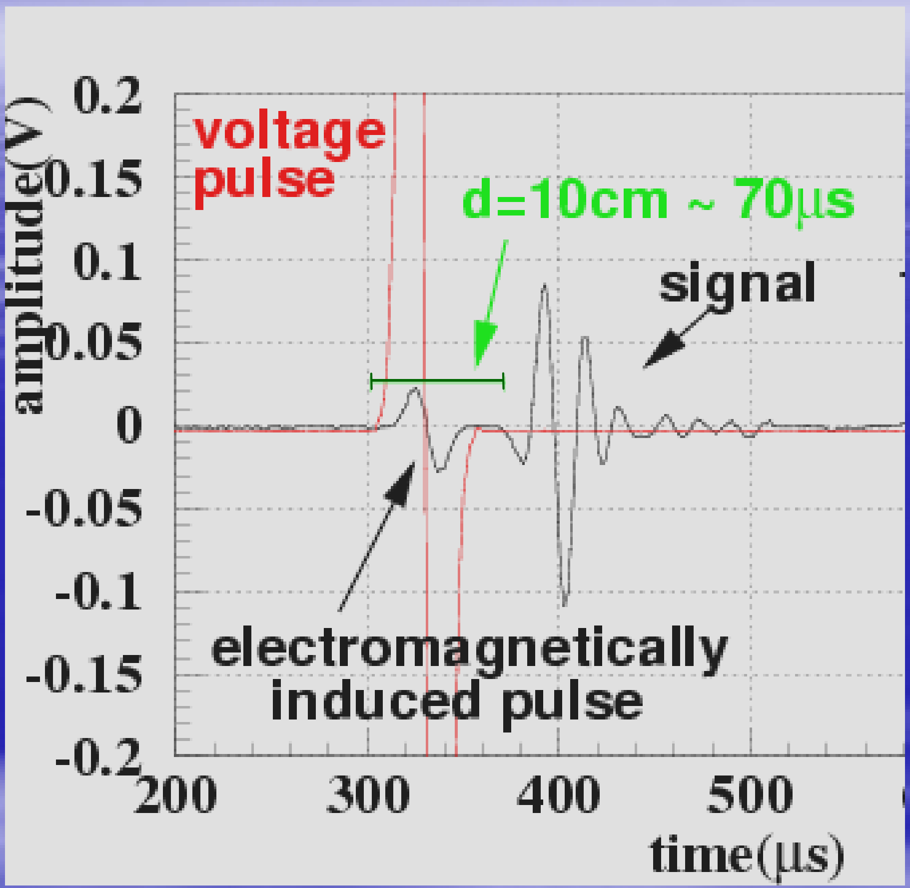


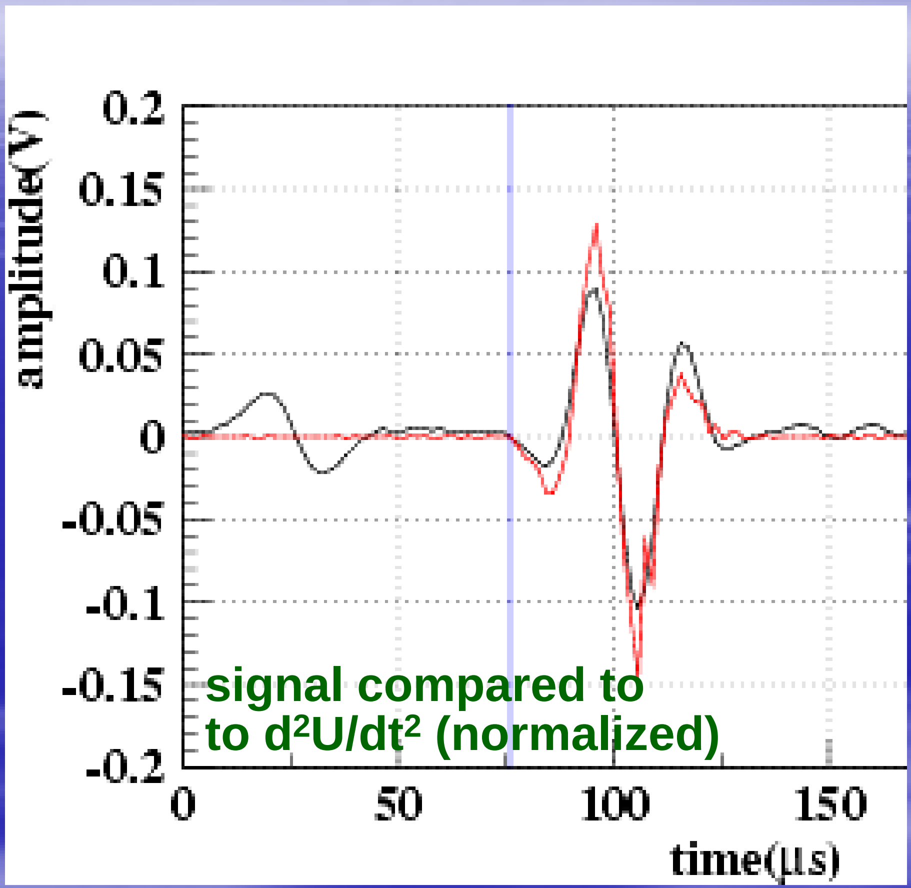


Sound transmitters and hydrophone calibration

- Acoustic signal generation by instantaneous energy deposition in water:
  - Piezo elements
  - wire or resistor heated by electric current pulse
  - laser
  - particle beam
- How well do we understand signal shape and amplitude?
- Suited for operation in deep sea?

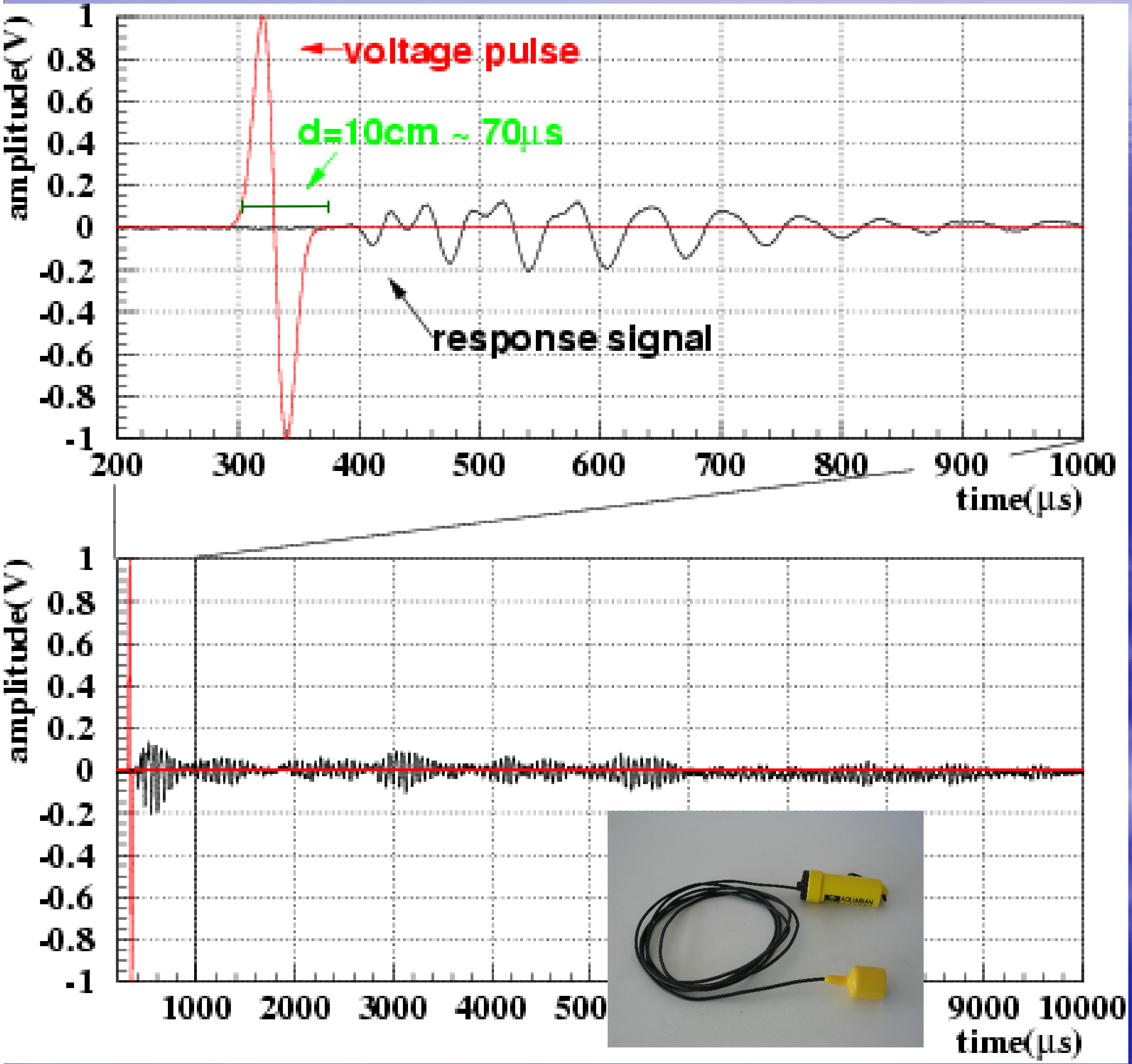
How Piezo elements transmit sound





$P \sim d^2U / dt^2$ (remember: $F \sim d^2x / dt^2$)

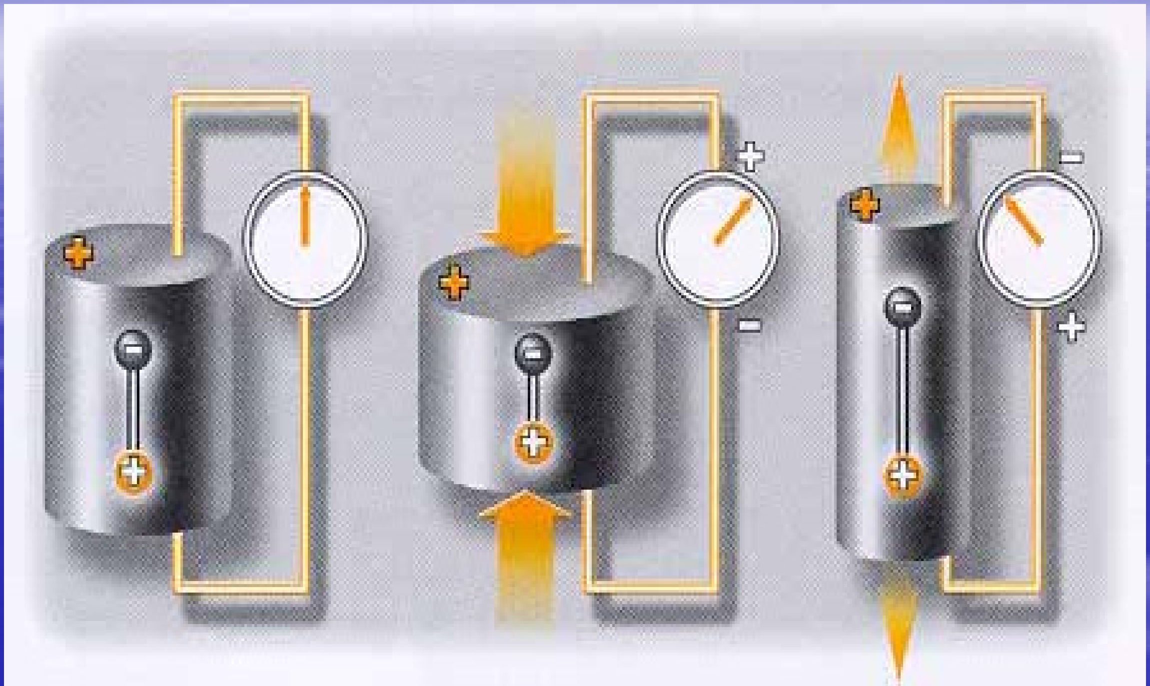
… but it may also look like this:



Important issues:

- Quality & assessment of Piezo elements
- Acoustic coupling Piezo-water, impact of housing or encapsulation
- Impact of electronics

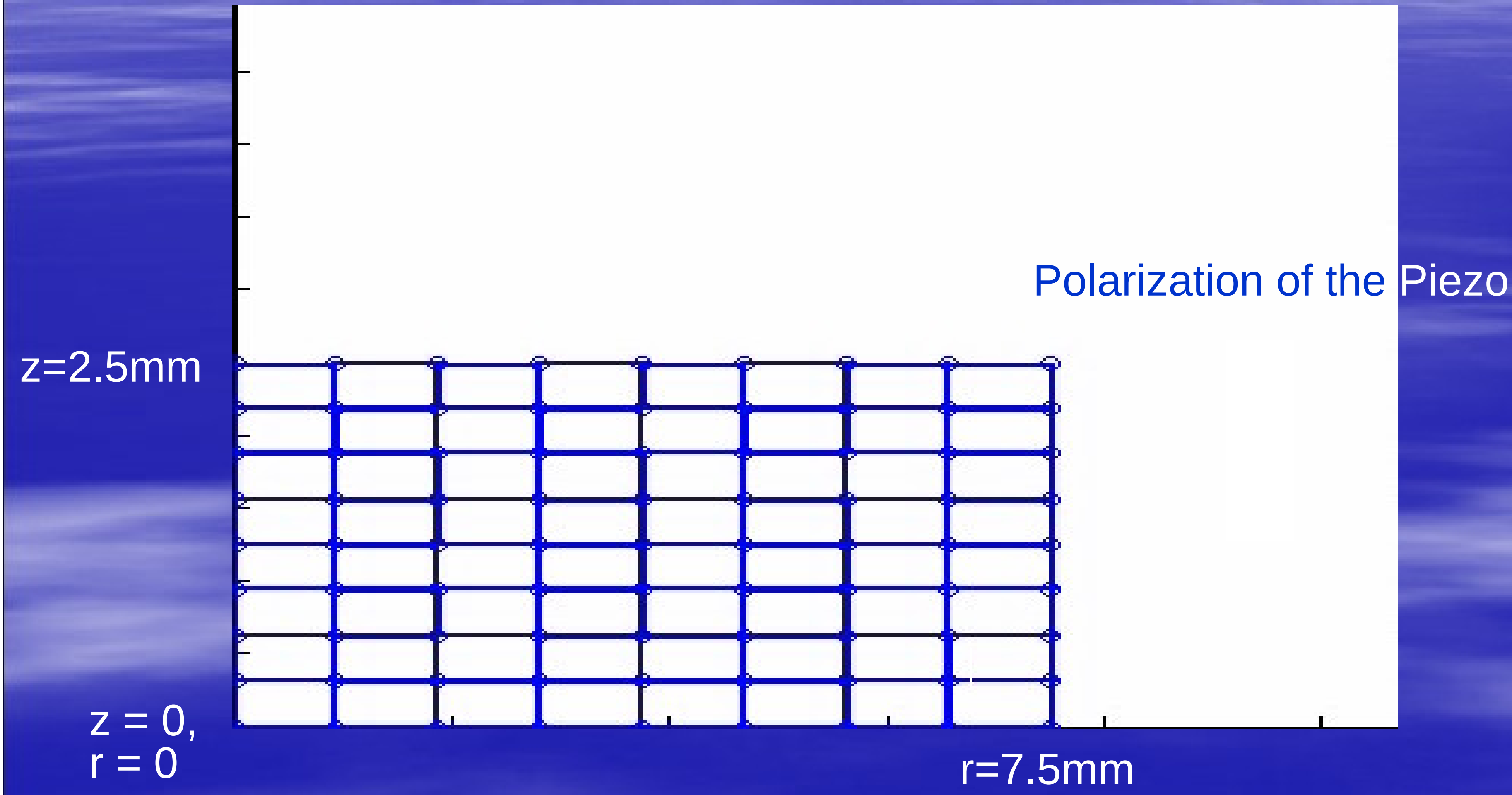
Going into details of Piezo elements



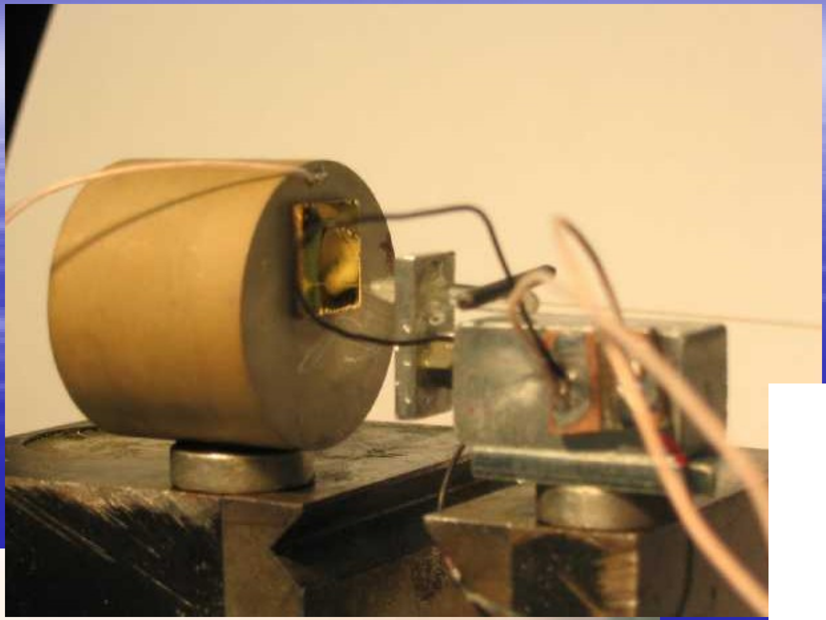
- Equation of motion of Piezo element is complicated (coupled PDE of an anisotropic material):
  - Hooks law + electrical coupling
  - Gauss law + mechanical coupling
- Finite Element Method chosen to solve these PDE.

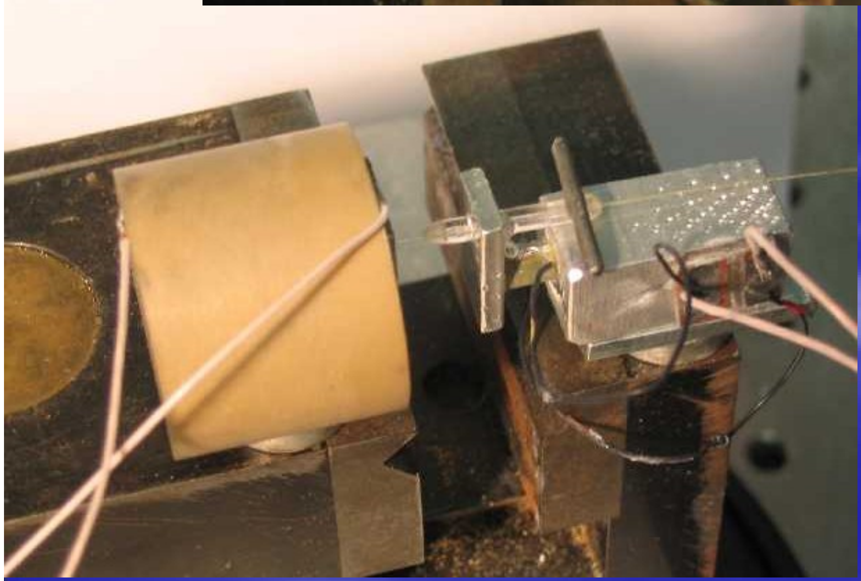
How a Piezo element moves

20 kHz sine voltage applied to
Piezo disc with r=7.5mm, d=5mm

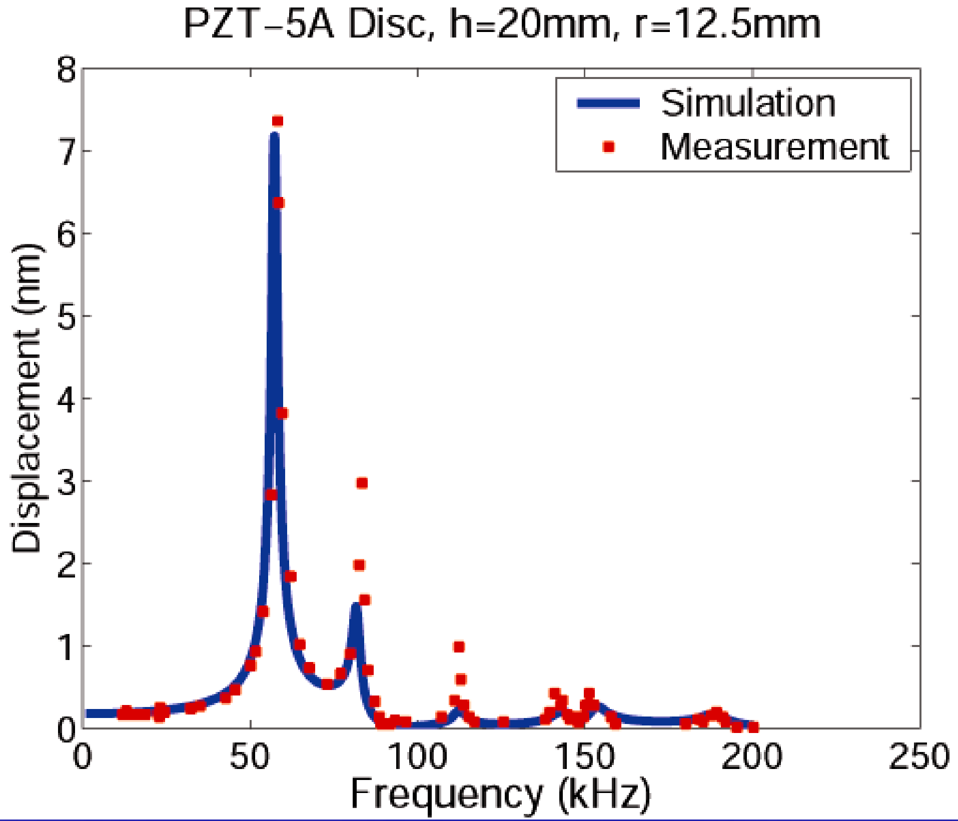


Checking with measurements

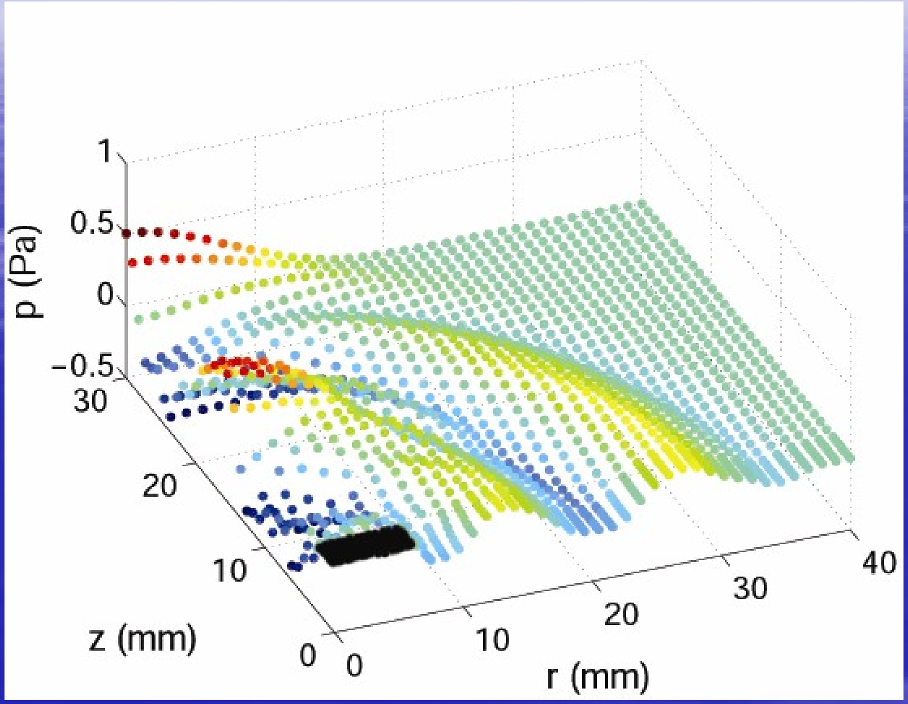


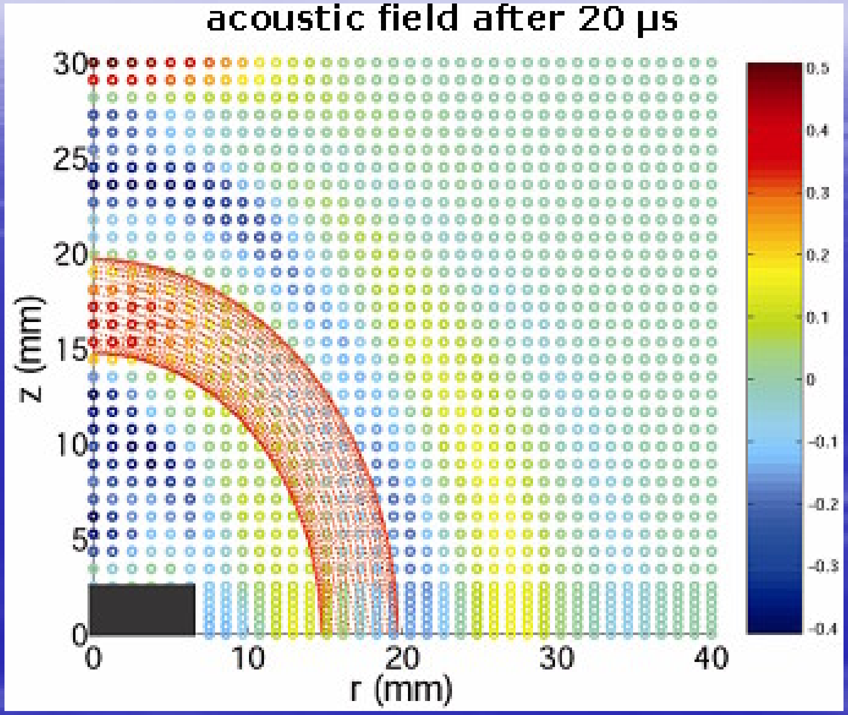


Direct measurement of oscillation amplitude with Fabry-Perot interferometer as function of frequency



The acoustic wave of a Piezo @ 20kHz

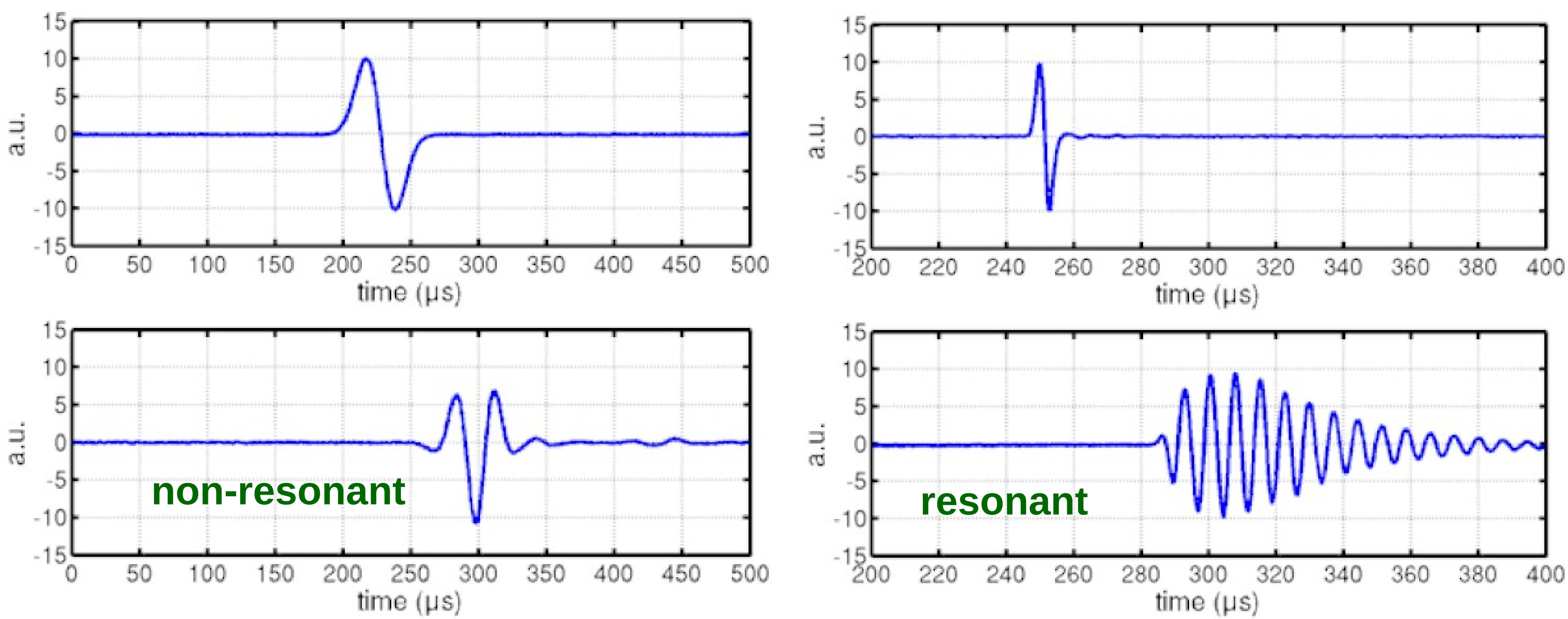




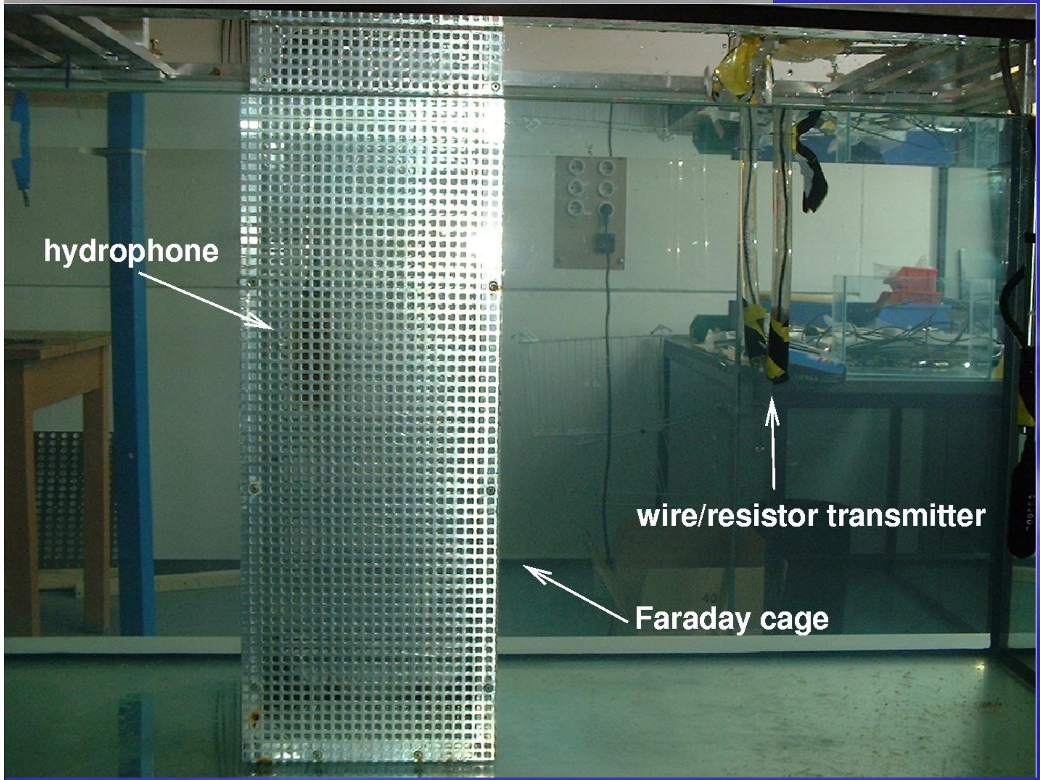
- Detailed description of acoustic wave, including effects of Piezo geometry (note: λ ≈ 72 mm)
- Still missing: simulation of encapsulation
- Piezo transducers probably well suited for *in situ* calibration

Resonant effects

- Piezo elements have resonant oscillation modes with eigen-frequencies of some 10-100 kHz.
- May yield useful amplification if adapted to signal but obscures signal shape.

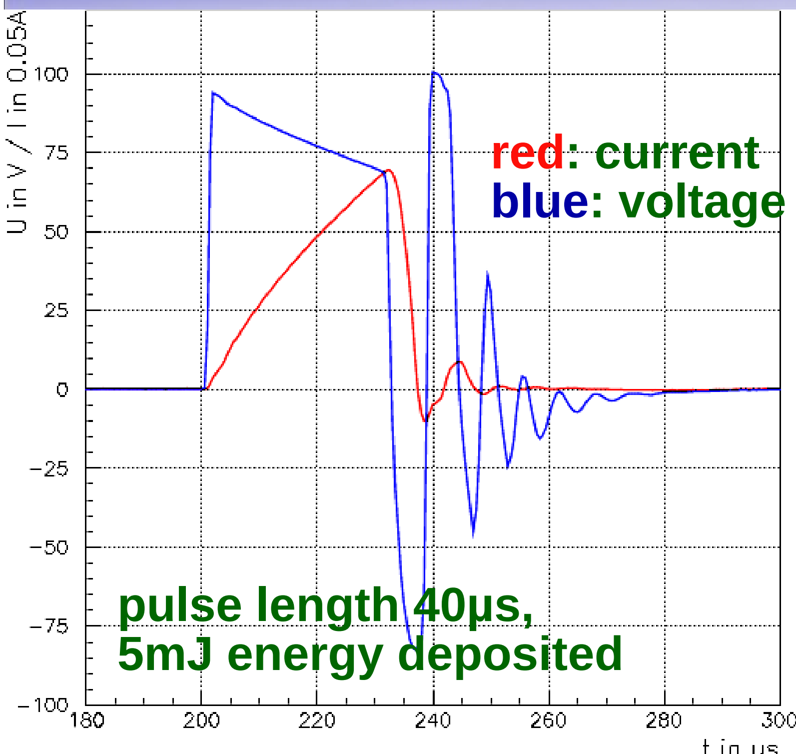


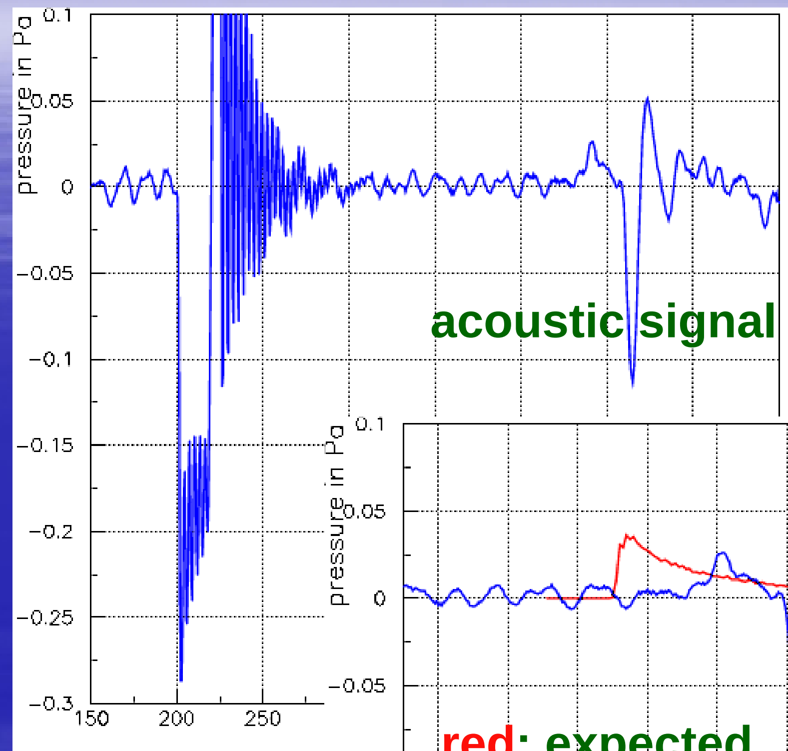
Wires and resistors

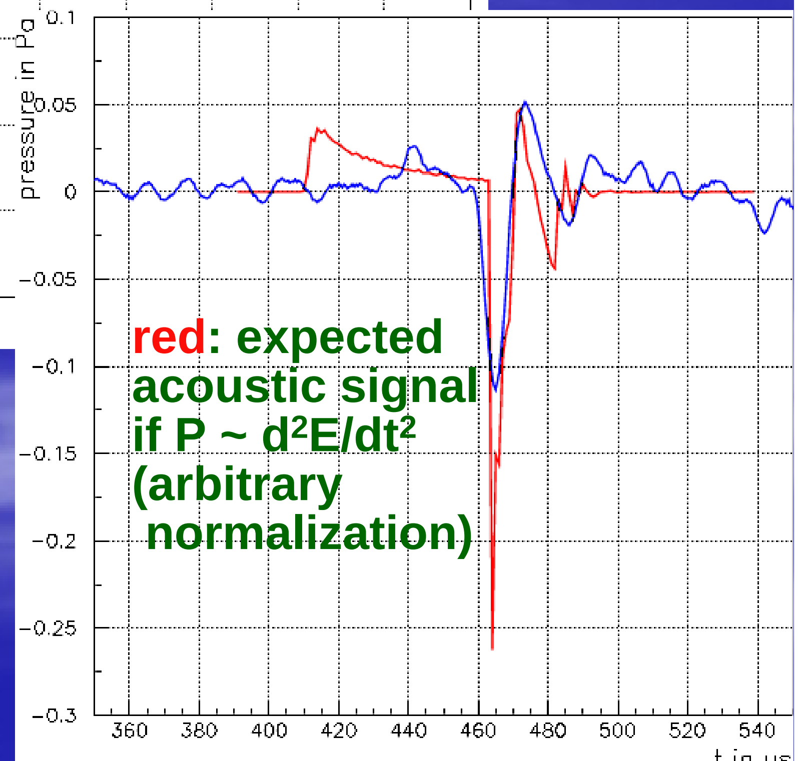


- <u>Initial idea:</u>
  instantaneous heating of wire (and water) by current pulse
- <u>Signal generation</u>
  - by wire expansion (yes)
  - by heat transfer to water (no)
  - by wire movement (no)
- <u>Experimental finding:</u>
  also works using normal resistors instead of thin wires.
- Probably not useful for deep-sea application but very instructive to study dynamics of signal generation.

Listening to a resistor

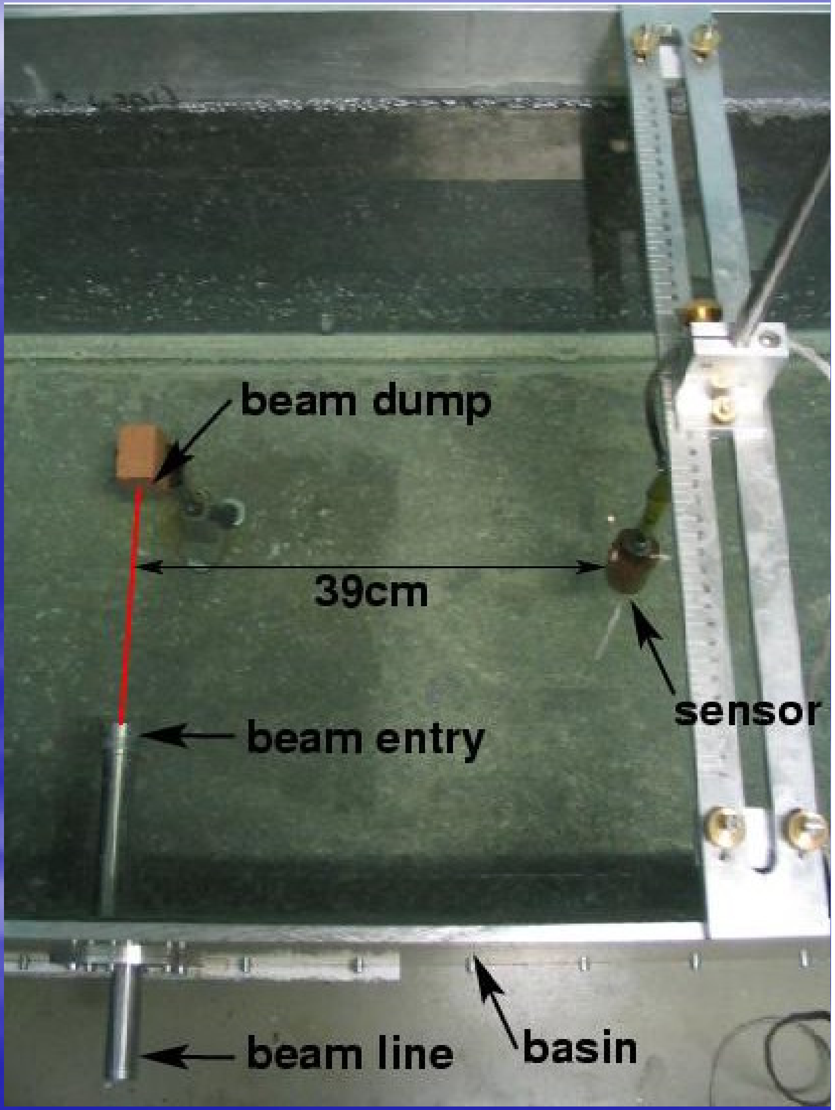






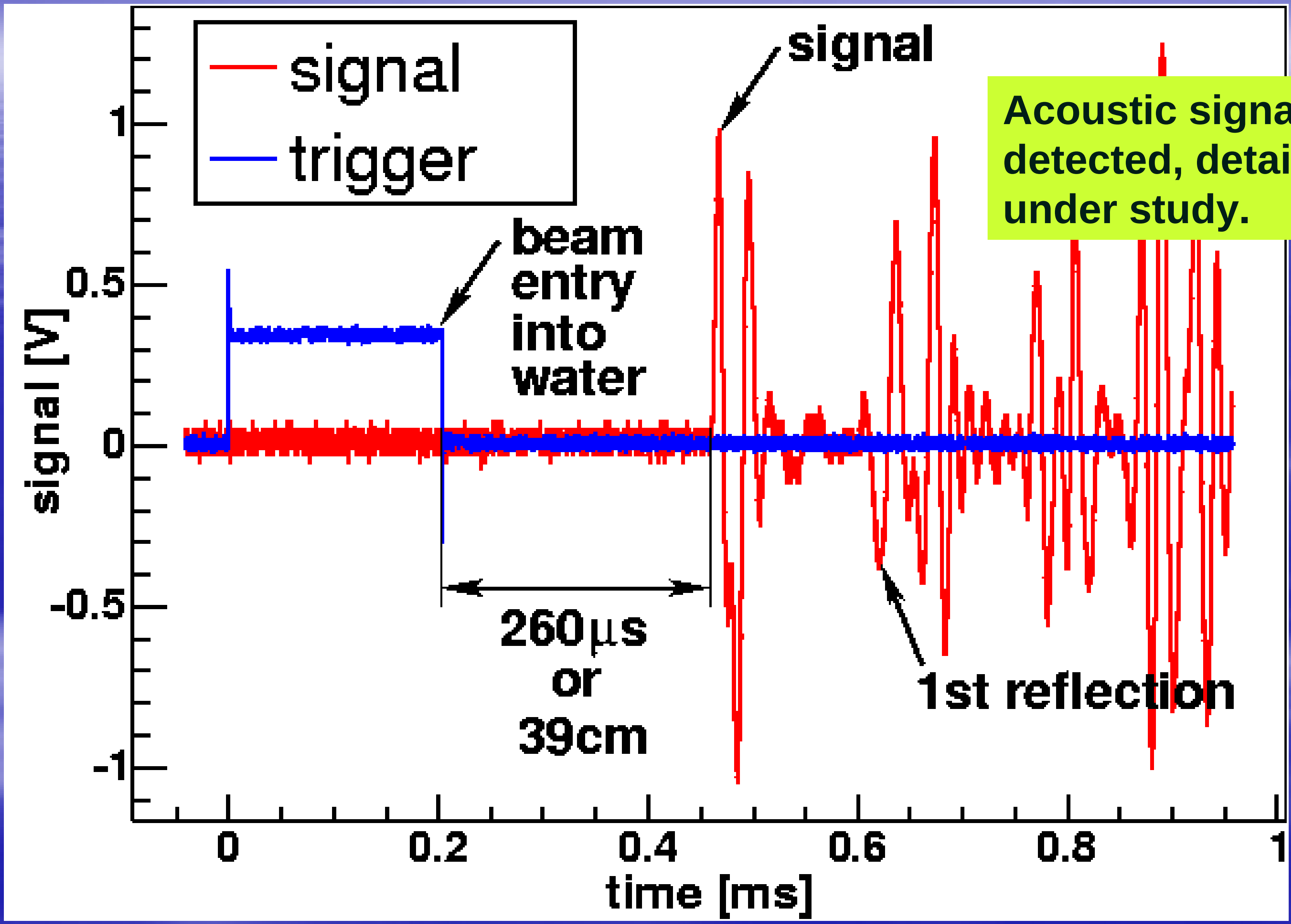
… more detailed studies ongoing

Dumping an infrared laser into water ...



- NdYag laser (up to 5J per 20ns pulse);
- Time structure of energy deposition very similar to particle shower.

… and recording the acoustic signal

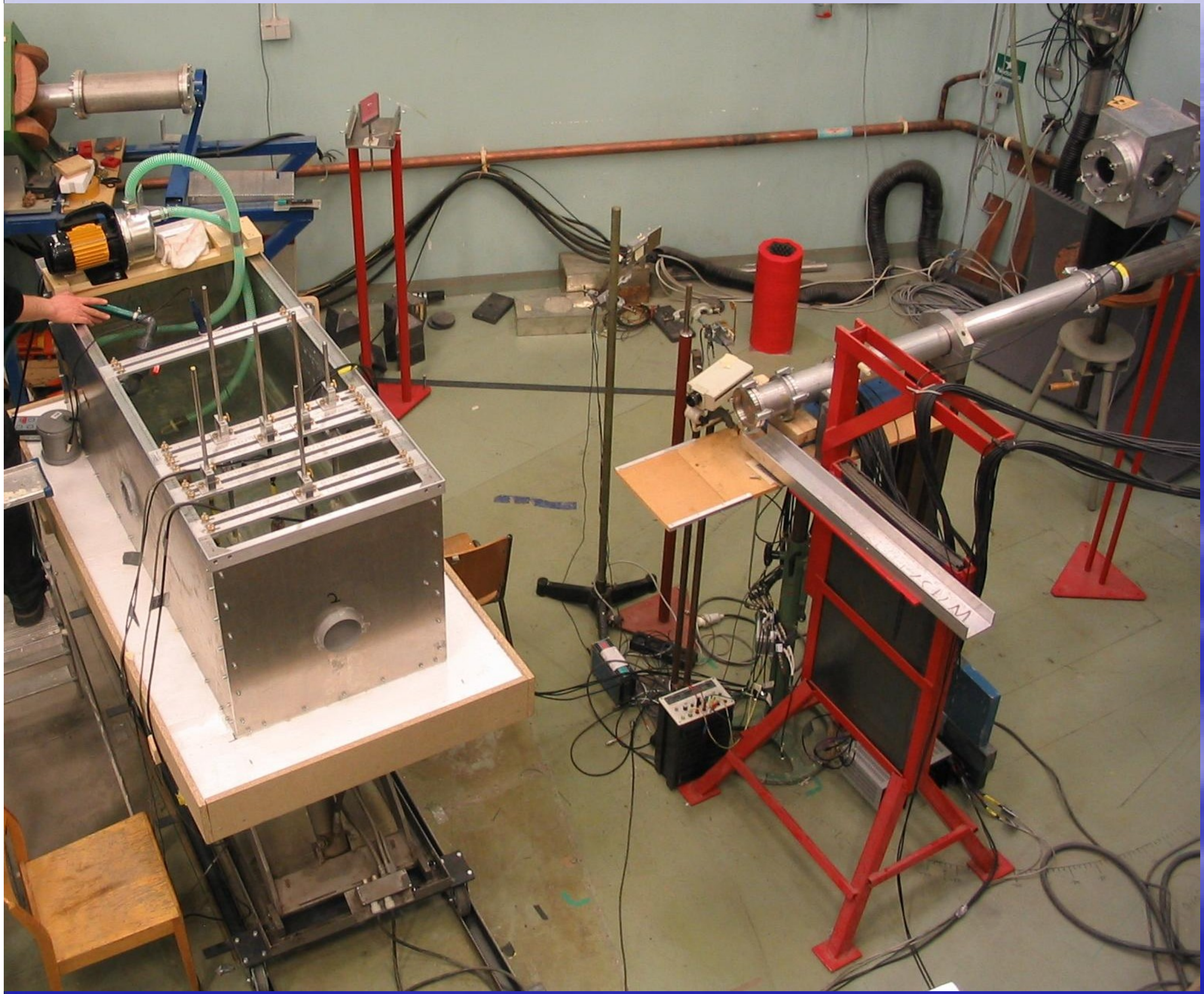


Acoustic signal detected, details under study.

Measurements with a proton beam

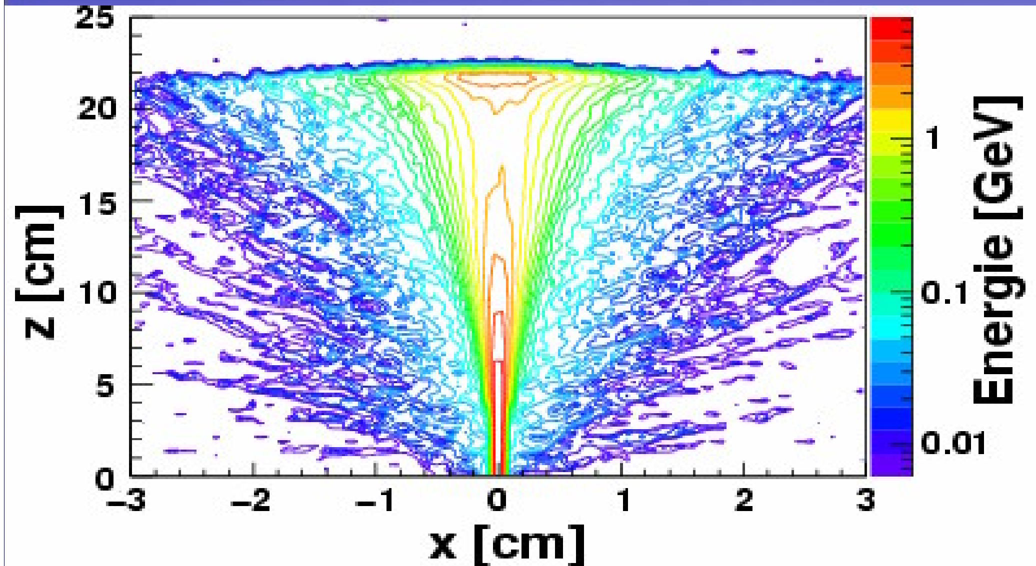
- Signal generation with Piezo, wire/resistor and laser differs from particle shower (energy deposition mechanism, geometry)
  → study acoustic signal from proton beam dumped into water.
- Experiments performed at Theodor-Svedberg-Laboratory, Uppsala (Sweden) in collaboration with DESY-Zeuthen.
- Beam characteristics:
  - kinetic energy per proton = 180 MeV
  - kinetic energy of bunch = 10^{15} – 10^{18}eV
  - bunch length ≈ 30μs
- Objectives of the measurements:
  - test/verify predictions of thermo-acoustic model;
  - study temperature dependence (remember: no signal expected at 4°C);
  - test experimental setup for "almost real" signal.

The experimental setup

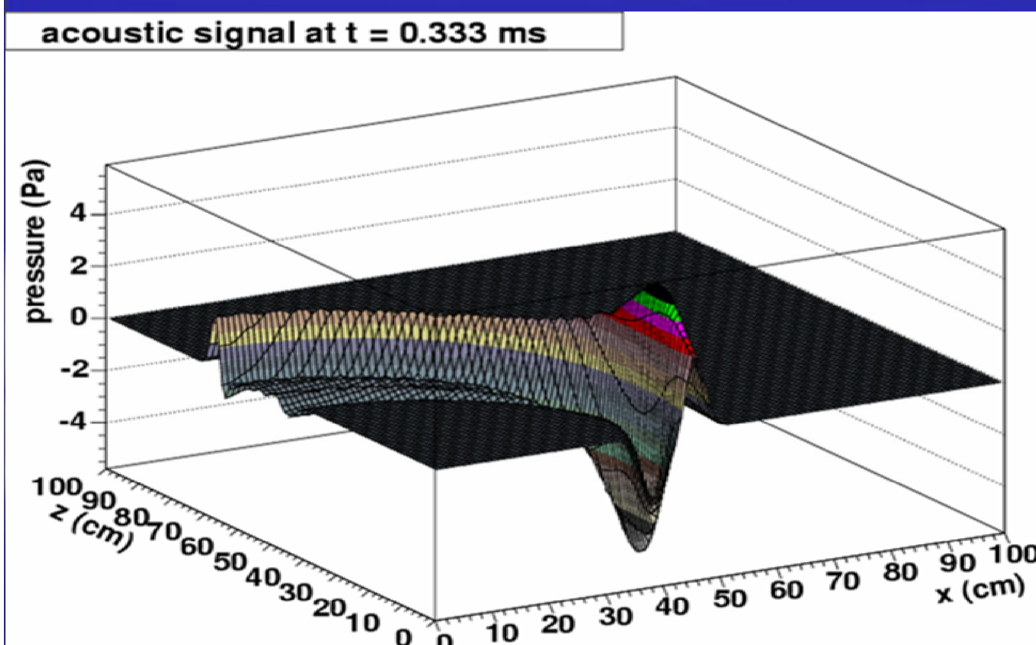


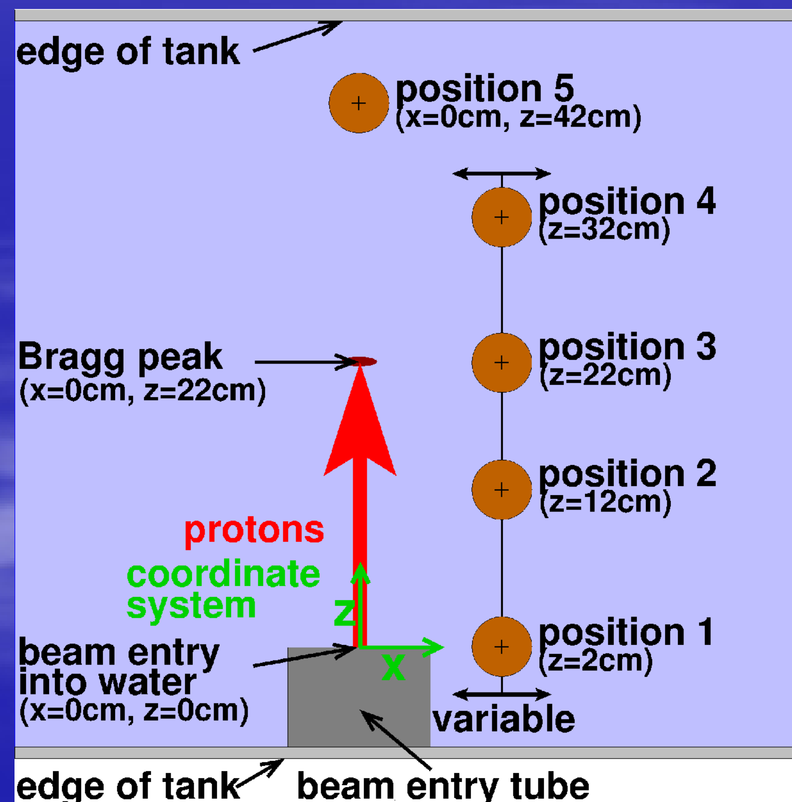
- Data taken at
  - different beam parameters (bunch energy, beam profile);
  - different sensor positions;
  - different temperatures.
- Data analysis not yet complete, all results preliminary
- Problem with calibration of beam intensity.

Simulation of the signal

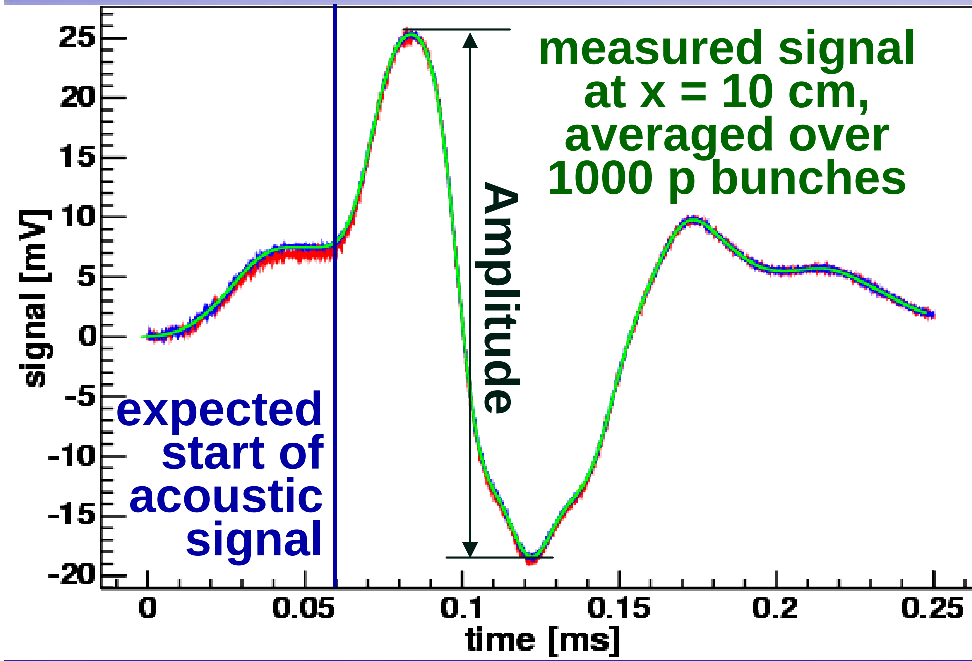


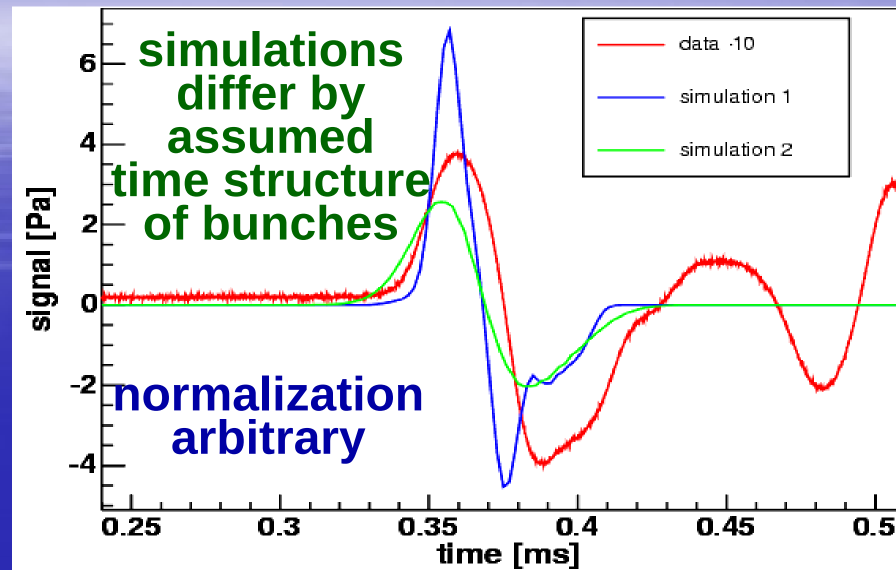
- **Proton beam in water: GEANT4**
- **Energy deposition fed into thermo-acoustic model.**

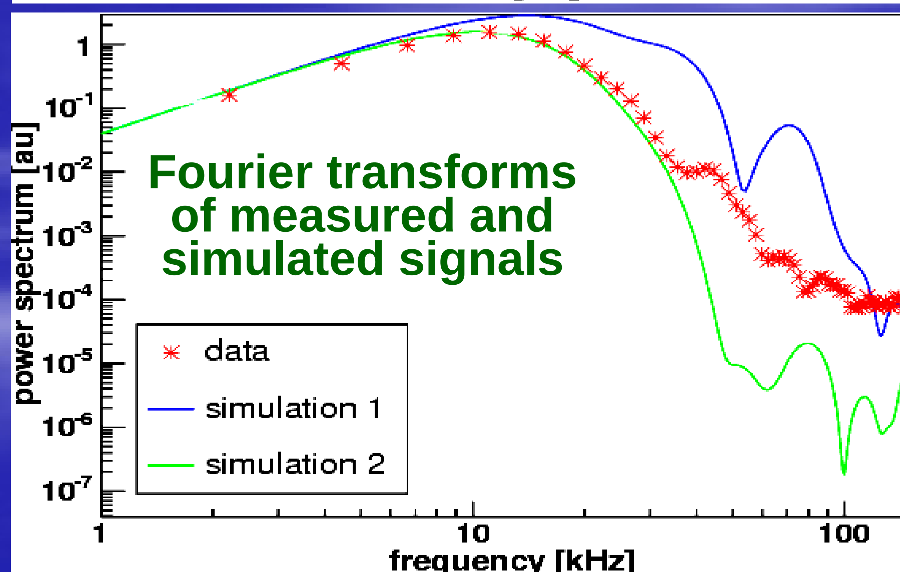




A typical signal compared to simulation

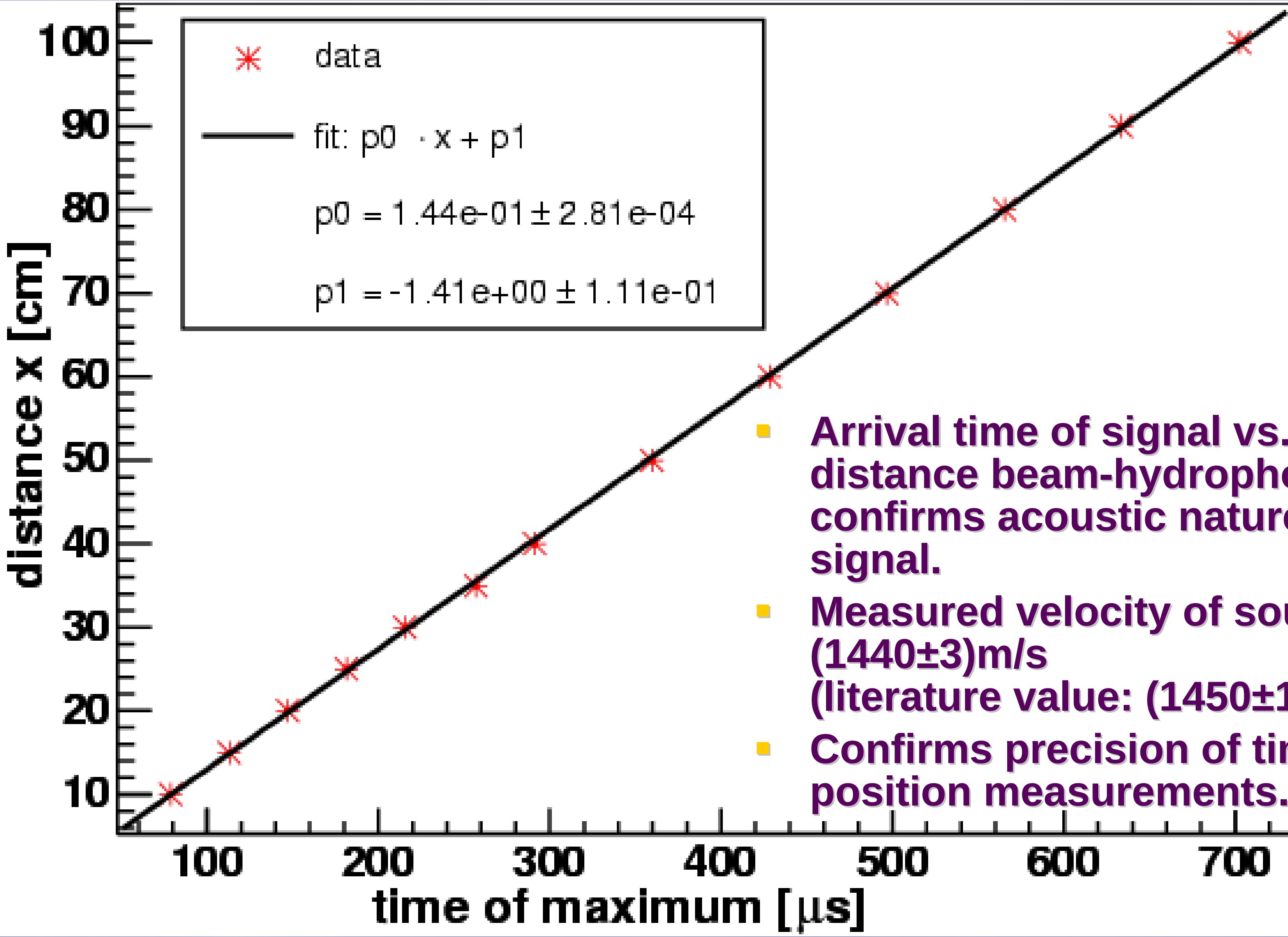






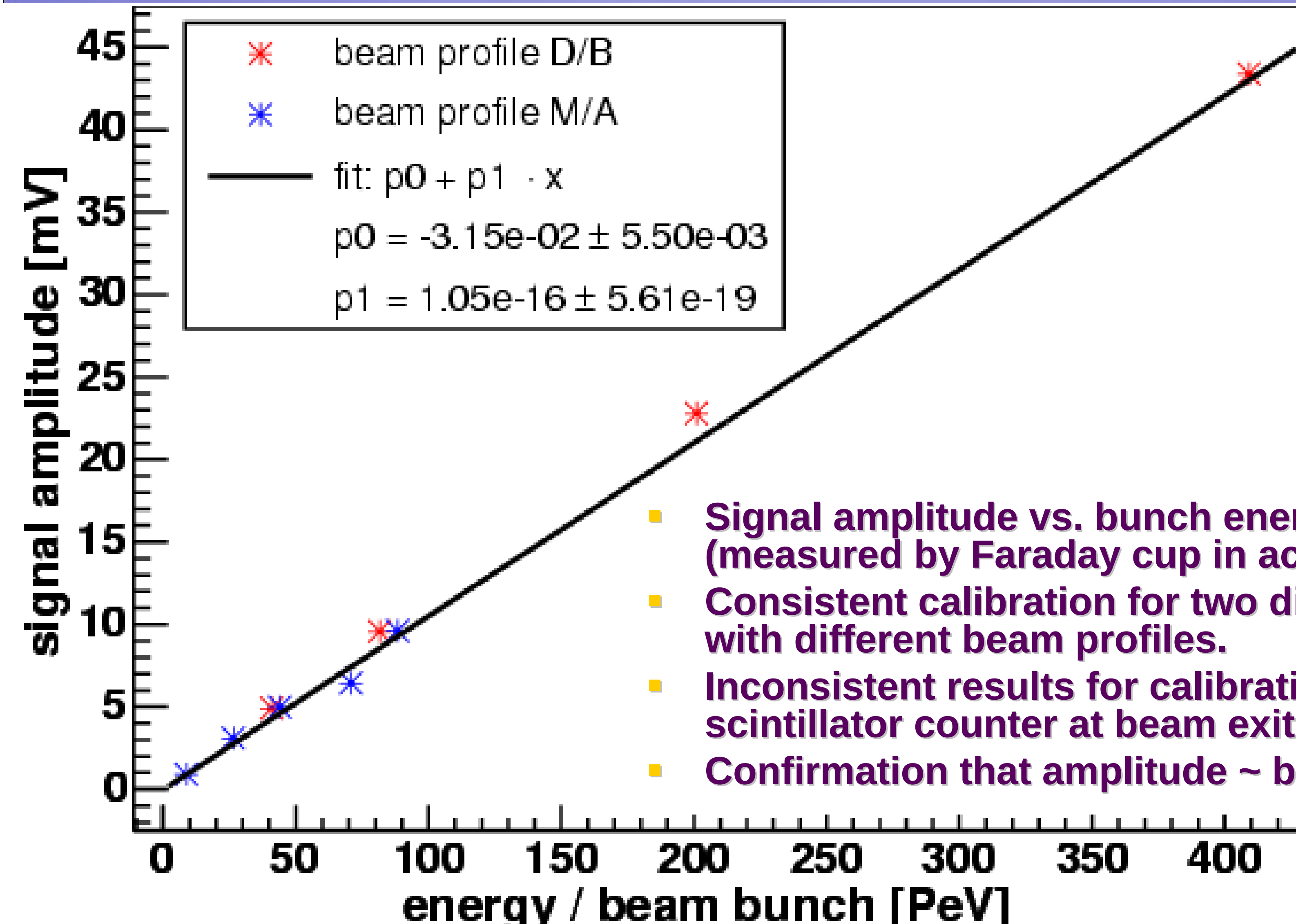
- Expected bi-polar shape verified.
- Signal is reproducable in all details.
- Rise at begin of signal is non-acoustic (assumed: elm. effect of beam charge).

It's really sound!



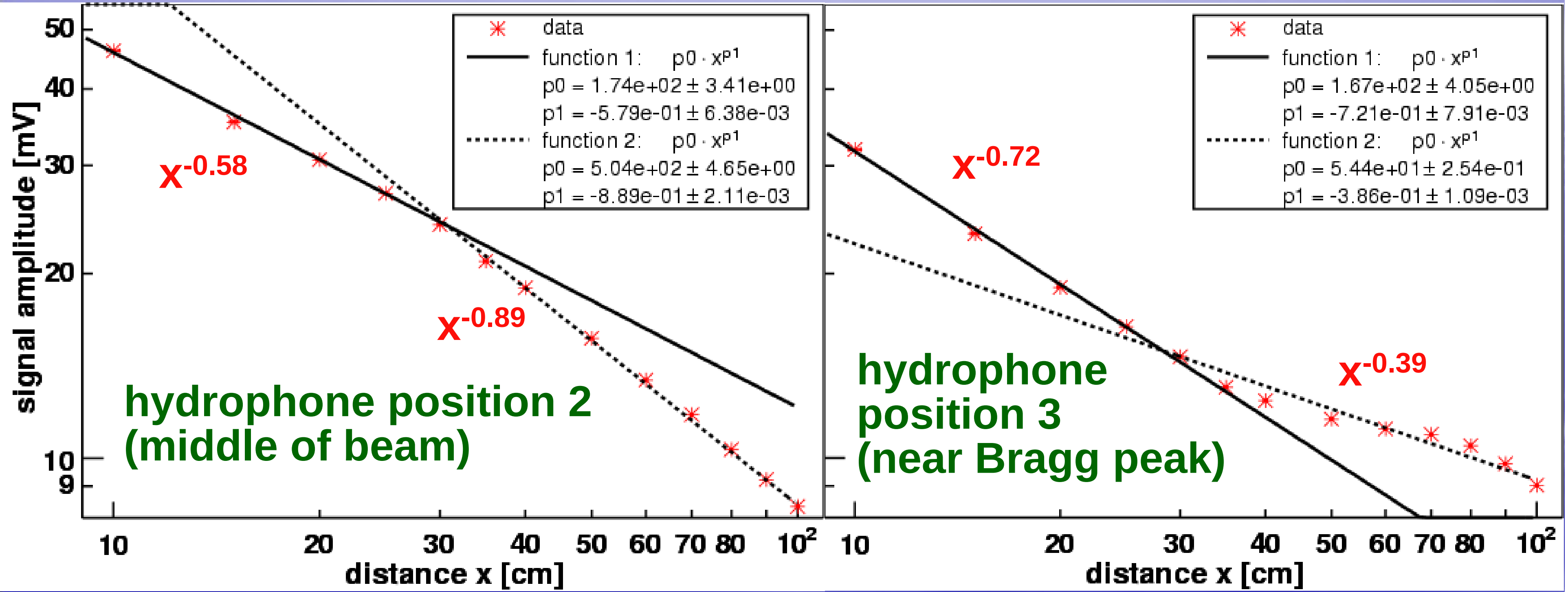
- **Arrival time of signal vs. distance beam-hydrophone confirms acoustic nature of signal.**
- **Measured velocity of sound = (1440±3)m/s (literature value: (1450±10)m/s).**
- **Confirms precision of time and position measurements.**

Energy dependence



- **Signal amplitude vs. bunch energy (measured by Faraday cup in accelerator).**
- **Consistent calibration for two different runs with different beam profiles.**
- **Inconsistent results for calibration using scintillator counter at beam exit window.**
- **Confirmation that amplitude ~ bunch energy**

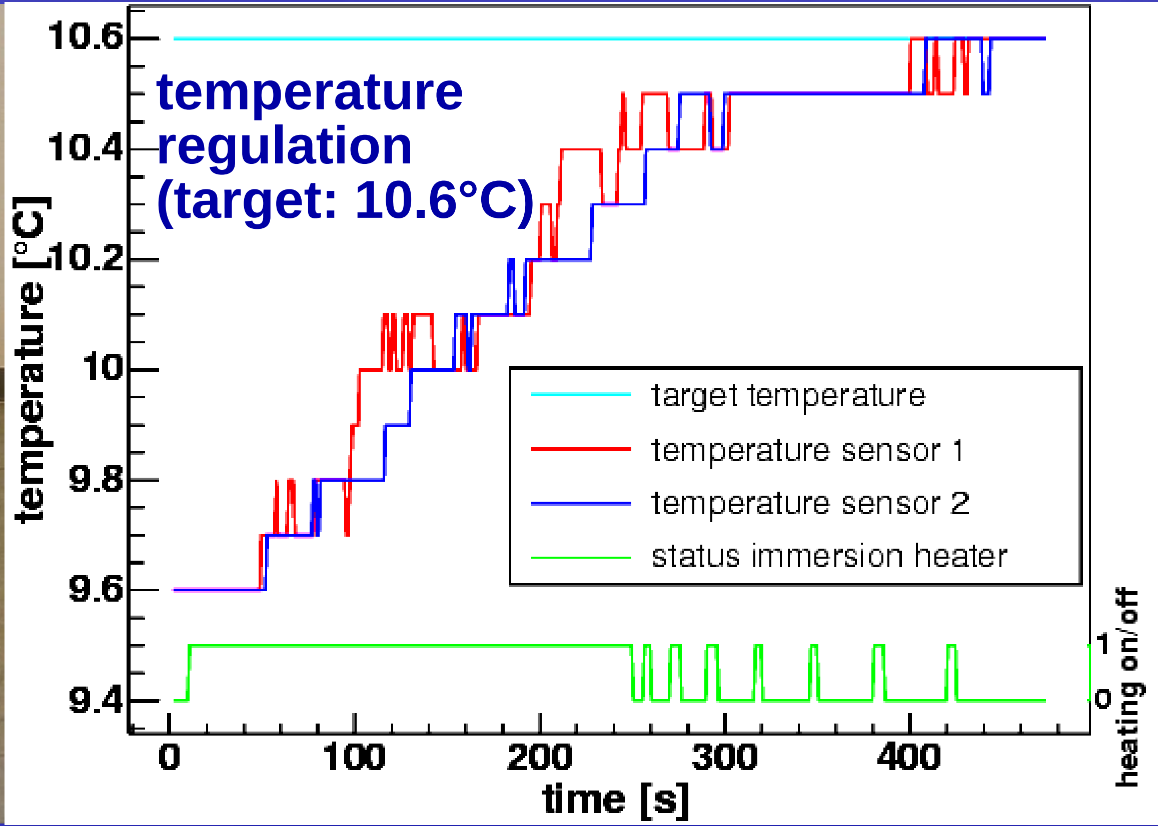
Signal amplitude vs. distance



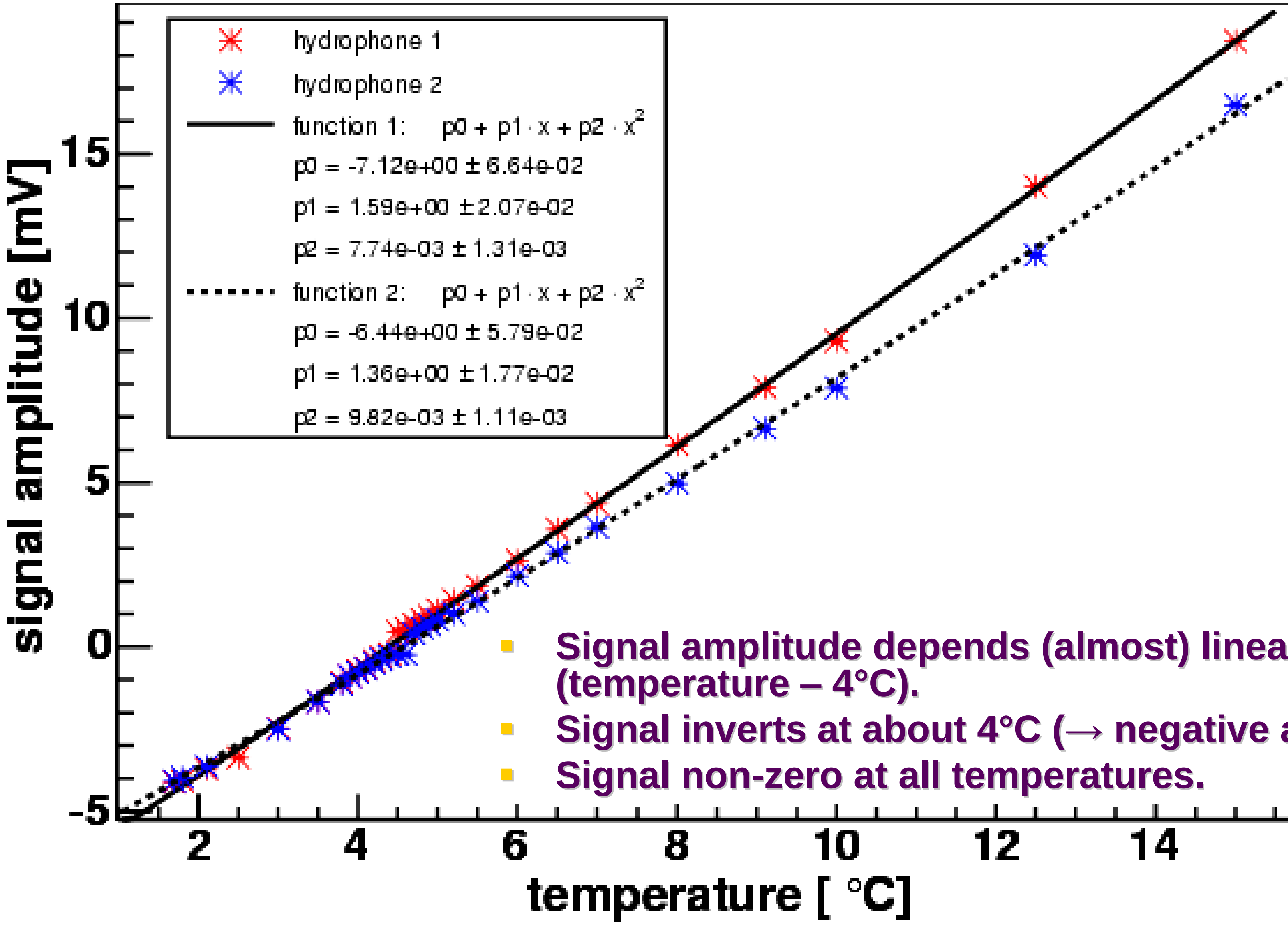
- **Signal dependence on distance hydrophone-beam different for different z positions.**
- **Clear separation between near and far field at ~30cm.**
- **Power-law dependence of amplitude on x.**
- **Well described by simulation (not shown).**

Measuring the temperature dependence

- Motivation: observe signal behavior around water anomaly at 4°C.
- Water cooling by deep-frozen ice in aluminum containers.
- Temperature regulation with 0.1°C precision by automated heating procedure controlled by two temperature sensors.
- Temperature homogeneity better than 0.1°C.

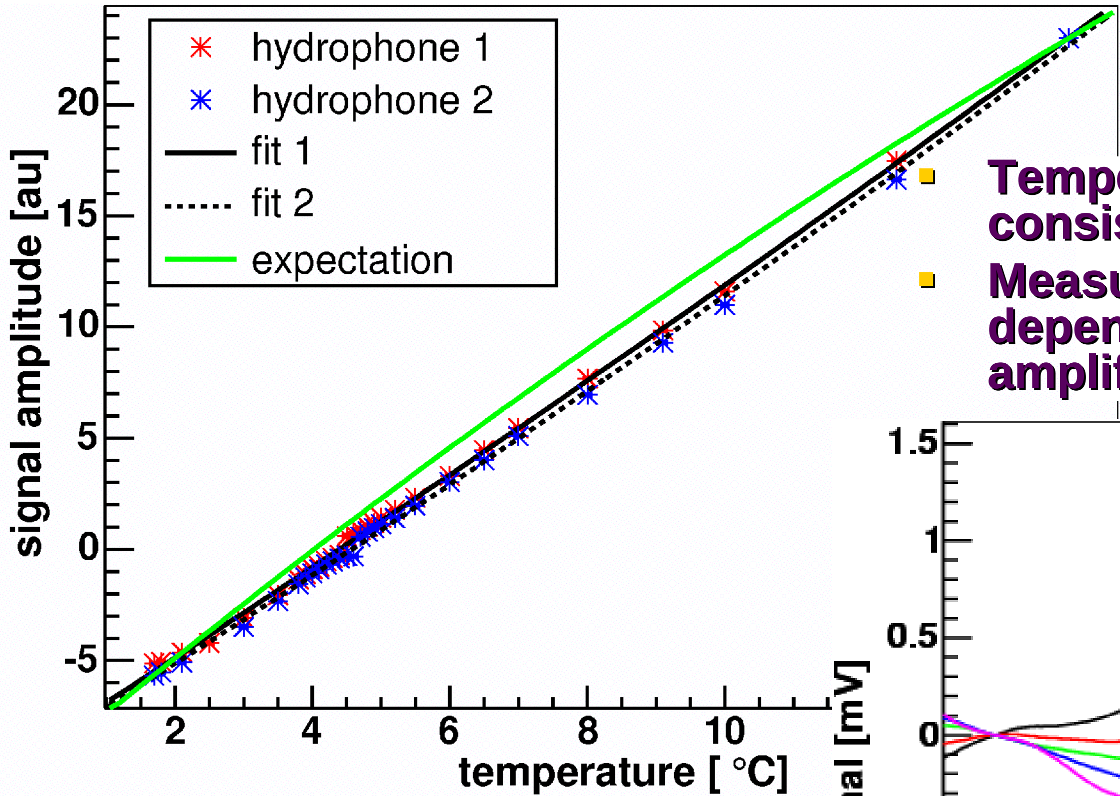


The signal is (mainly) thermo-acoustic !

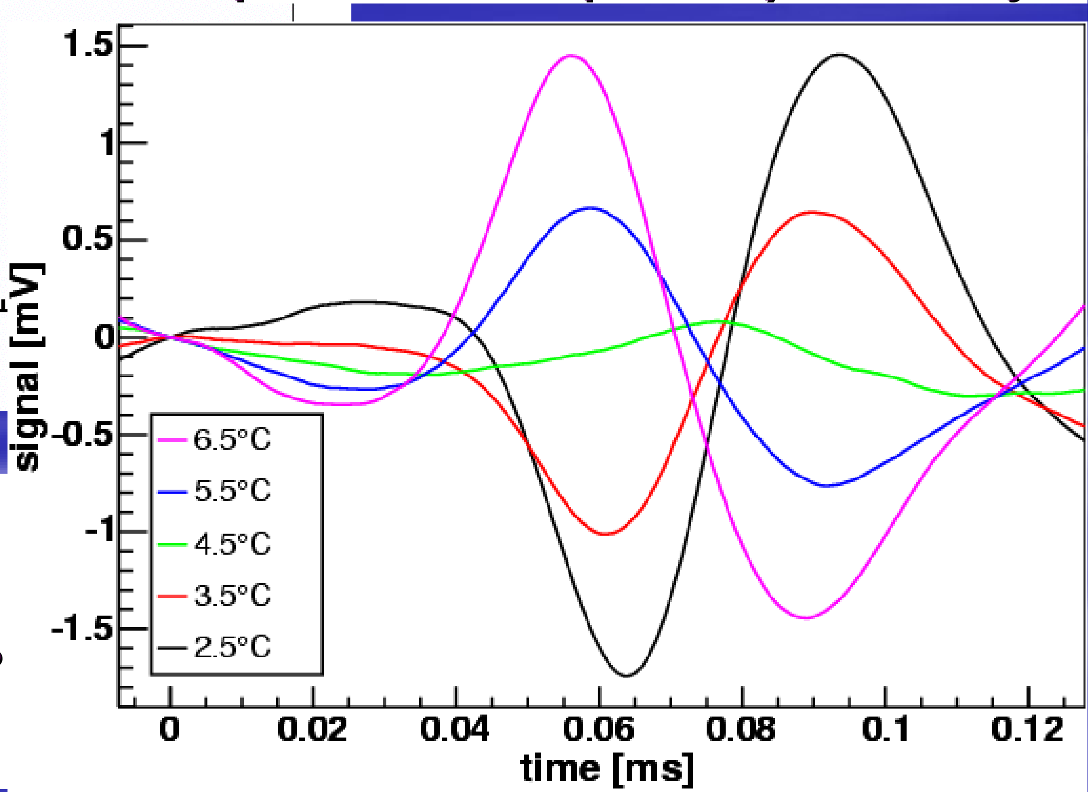


- **Signal amplitude depends (almost) linearly on (temperature – 4°C).**
- **Signal inverts at about 4°C (→ negative amplitude).**
- **Signal non-zero at all temperatures.**

… but not all details understood at 4°C



- Temperature dependence not entirely consistent with expectation.
- Measurements of temperature dependences (Piezo sensitivity, amplifier, water expansion) under way.



- Signal minimal at 4.5°C, but different shape (tripolar?).
- Possible secondary mechanism (electric forces, micro-bubbles)?
- Time shift due to temperature dependence of sound velocity.

Next steps …

- Improve hydrophones (reduce noise, adapt resonance frequency, use antennae)
- Perform pressure tests, produce hydrophones suited for deep-sea usage.
- Study Piezo elements inside glass spheres.
- Equip 1 or 2 ANTARES sectors with hydrophones, perform long-term measurements, develop trigger algorithms, ...

Conclusions

- Acoustic detection may provide access to neutrino astronomy at energies above ~10^{16} eV.
- R&D activities towards
  - development of high-sensitivity, low-price hydrophones
  - detailed understanding of signal generation and transport
  - verification of the thermo-acoustic model

  have yielded first, promising results.
- Measurements with a proton beam have been performed and allow for a high-precision assessment of thermo-acoustic signal generation and its parameter dependences.
- Simulations of signal generation & transport and of the sensor response agree with the measurements and confirm the underlying assumptions.
- Next step: instrumentation of 1-2 ANTARES sectors with hydrophones for long-term background measurements.