International ARENA Workshop

DESY, Zeuthen

17th – 19th of May 2005

Testing thermo-acoustic sound generation in water with proton and laser beams

Friedrich-Alexander-Universität Erlangen-Nürnberg

Kay Graf

Universität Erlangen-Nürnberg

Physikalisches Institut I

bmb+f - Förderschwerpunkt

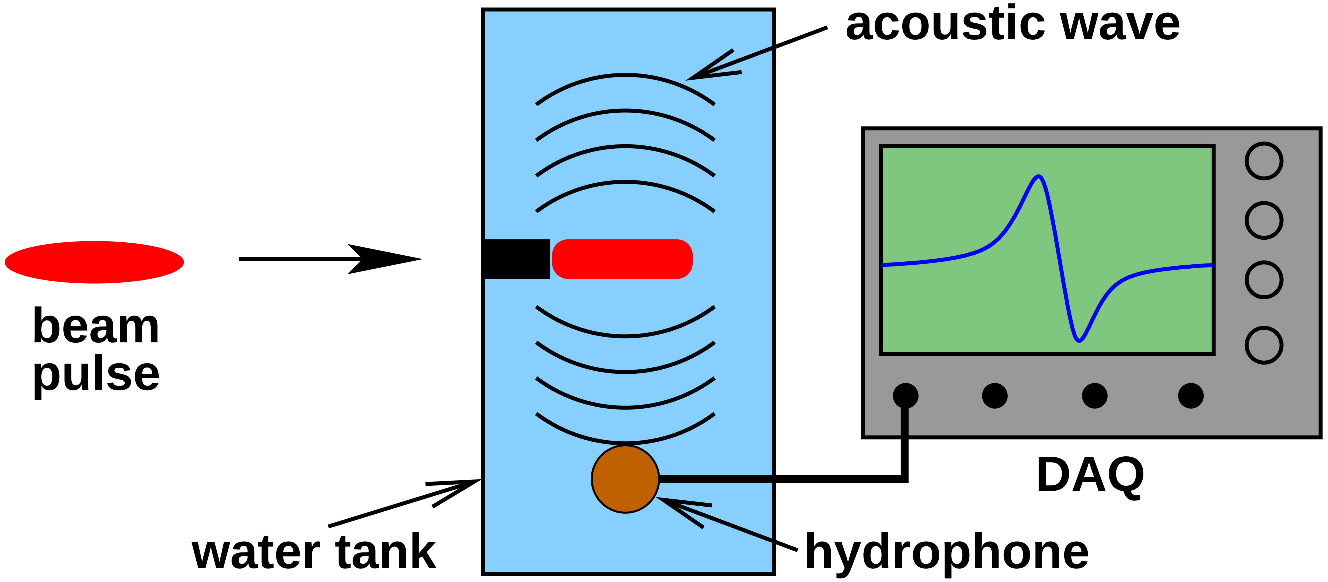
Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

Aims

- study sound generation mechanism of (available) intense pulsed beams
- test thermo-acoustic model & simulation based on it
- use as absolute calibration source for hydrophones

$\Rightarrow$ use proton and laser beams



The Theoretical Model

The thermo-acoustic model (G.A. Askaryan et al. 1979)

wave equation:

$$\Delta P(\vec{r},t) - \frac{1}{c_s^2} \cdot \frac{\partial^2 P(\vec{r},t)}{\partial t^2} = -\frac{\alpha}{C_p} \cdot \frac{\partial^2 \epsilon(\vec{r},t)}{\partial t^2}$$

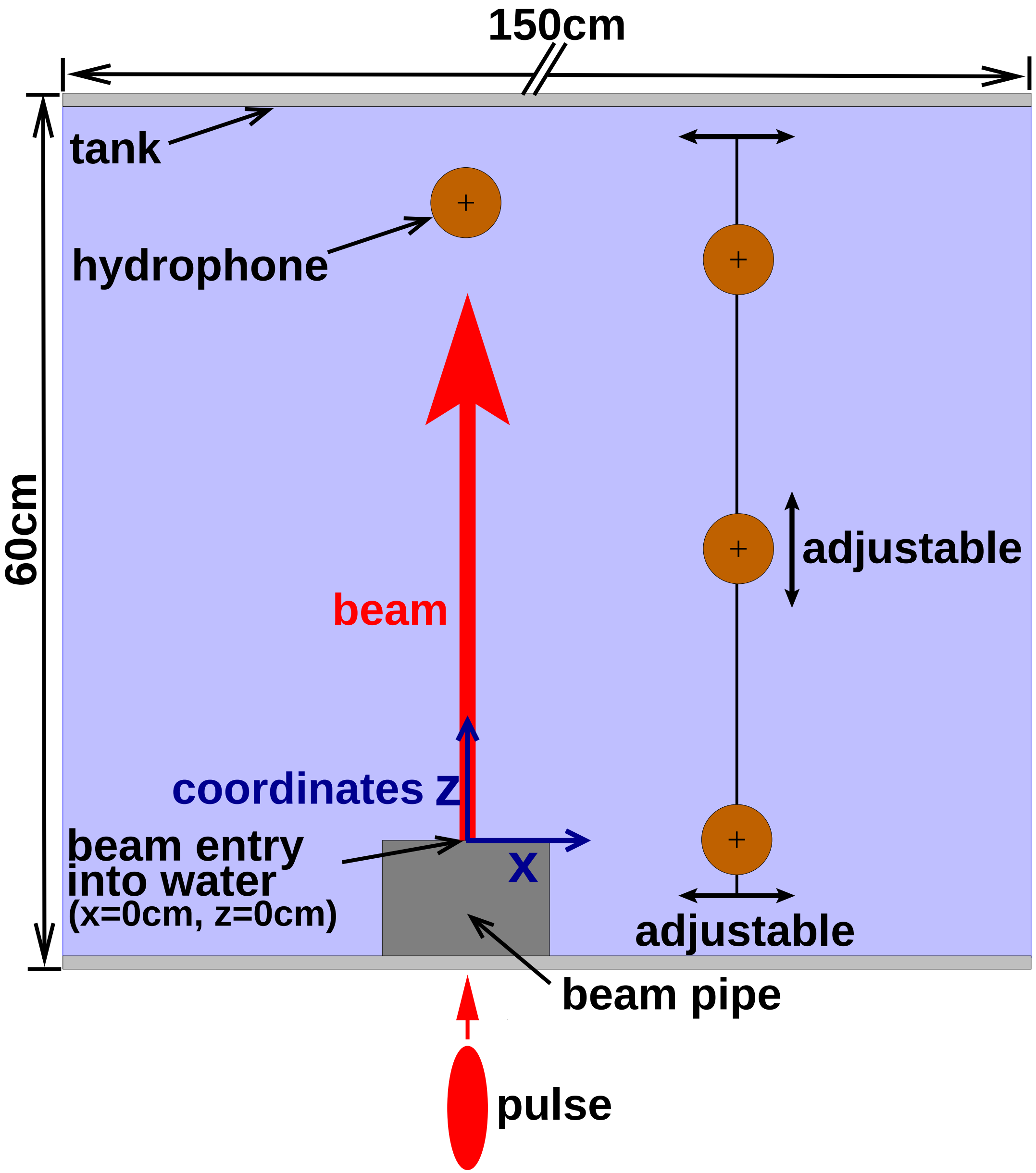
solution (Kirchhoff integral):

$$P(\vec{r},t) = \frac{1}{4\pi} \frac{\alpha}{C_p} \int \frac{dV'}{|\vec{r}-\vec{r}\,'|} \frac{\partial^2}{\partial t^2} \epsilon\left(\vec{r}\,', t - \frac{|\vec{r}-\vec{r}\,'|}{c_s}\right)$$

Parameters controllable in experiments

- $P(\vec{r},t)$ pressure
  $\Rightarrow$ measure at different locations
- α, C_p, c_s volume expansion coefficient, heat capacity, speed of sound
  $\Rightarrow$ measure at different water temperatures
- $\epsilon(\vec{r}\,',t\,')$ energy deposition density
  $\Rightarrow$ use different beam types, profiles and energies

The Test Setup I

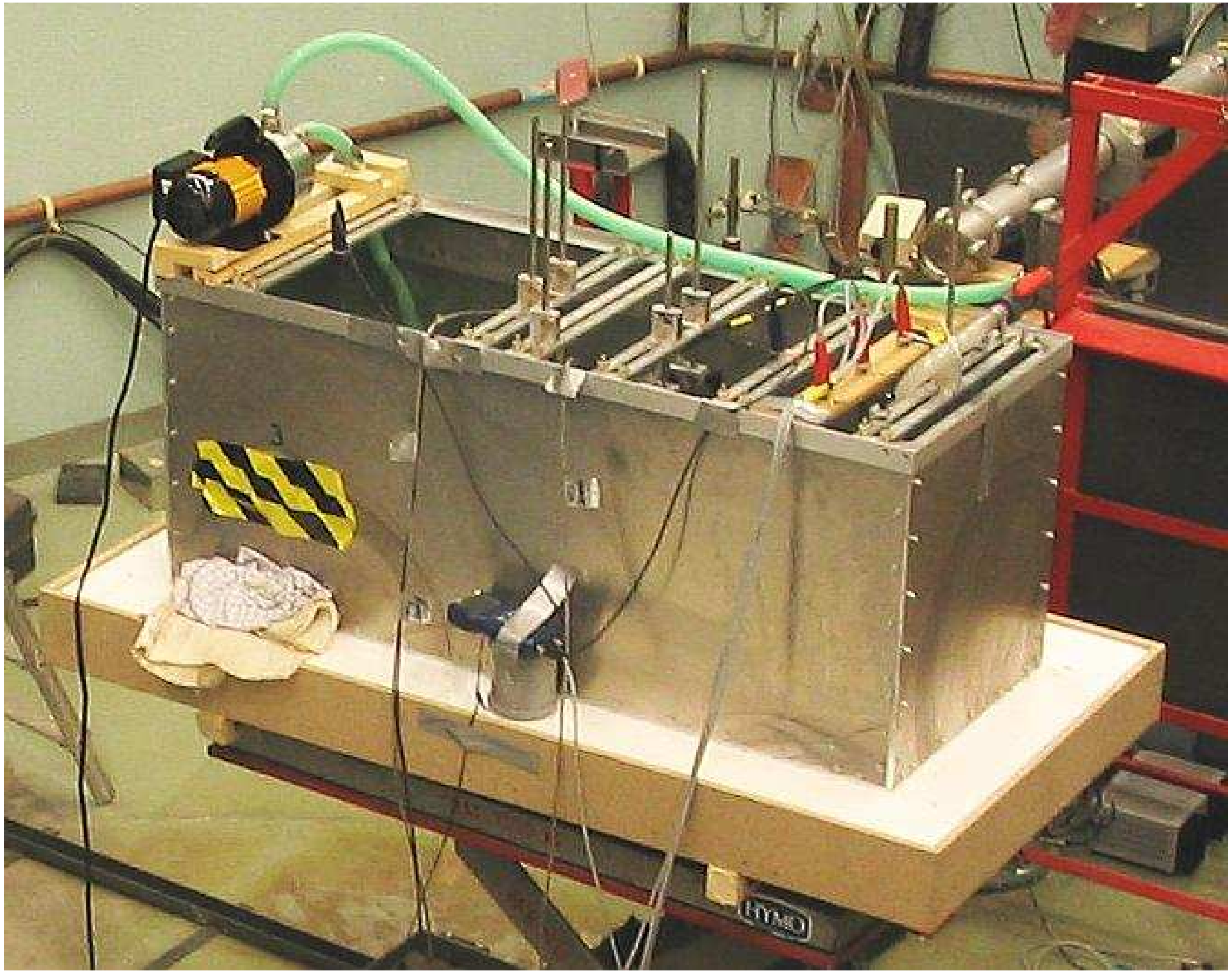


- Aluminum tank:
  $150 \times 60 \times 60$ cm^3 (ca. 450 l)
- positioning of sensors:
  in whole tank with
  a few mm precision
- water temperature:
  ca. $1 - 50\,^\circ$C with
  0.1°C precision
- DAQ (not shown):
  digital readout up to
  4 sensors simultaneously
  (10 MSamples/s, 8 bit)

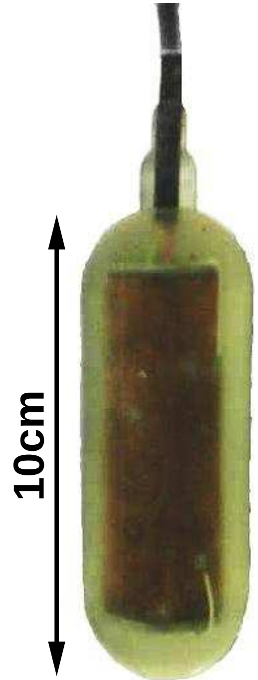
beam entry not at walls to
seperate signal ↔ reflections

The Test Setup II

Setup in action



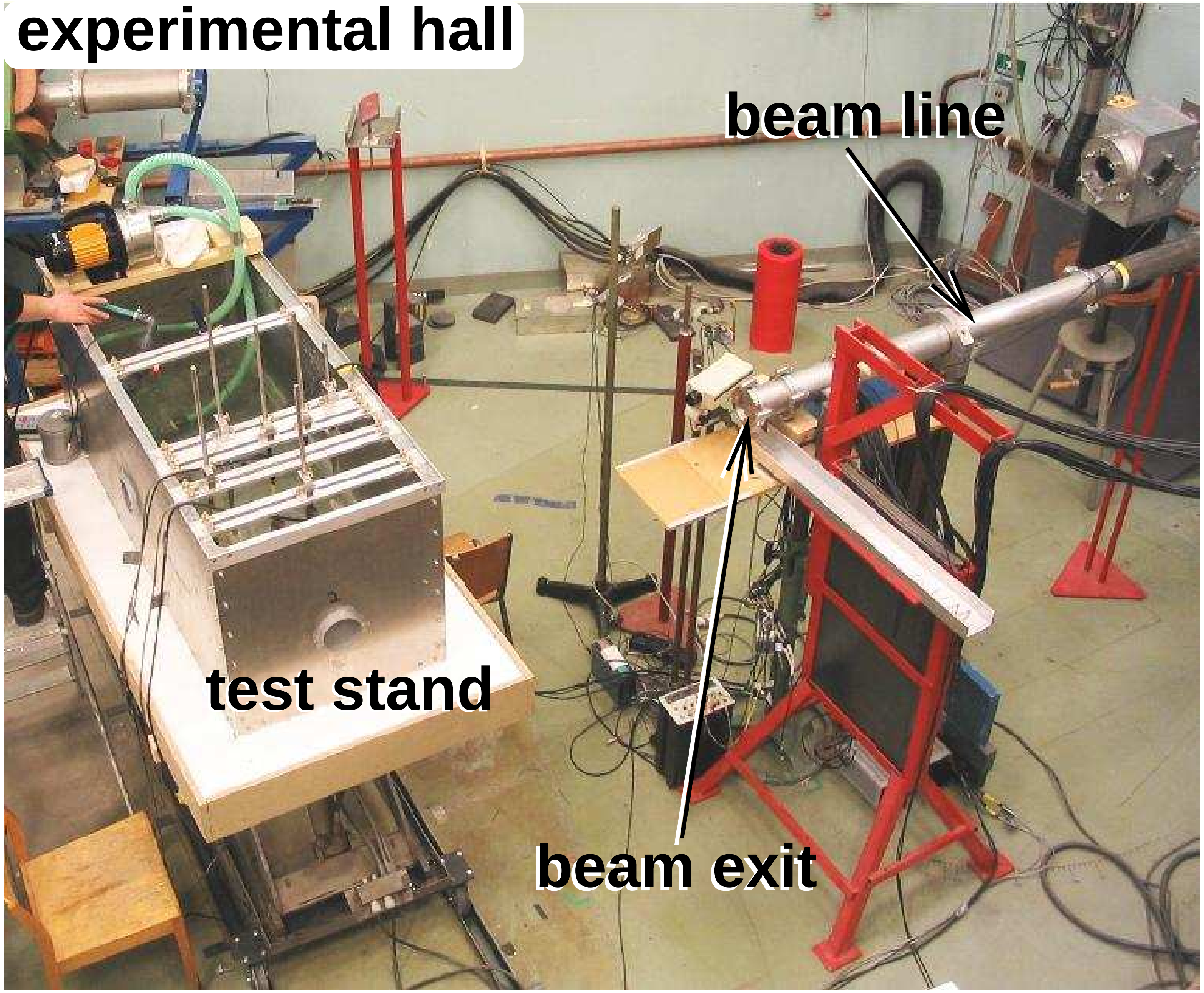
Hydrophones



by High Tech, Inc.

- frequency range: $\approx 2 - 150\,\mathrm{kHz}$
- sensitivity: $\approx$ -155 dB re V/μPa

The Proton Beam Experiment

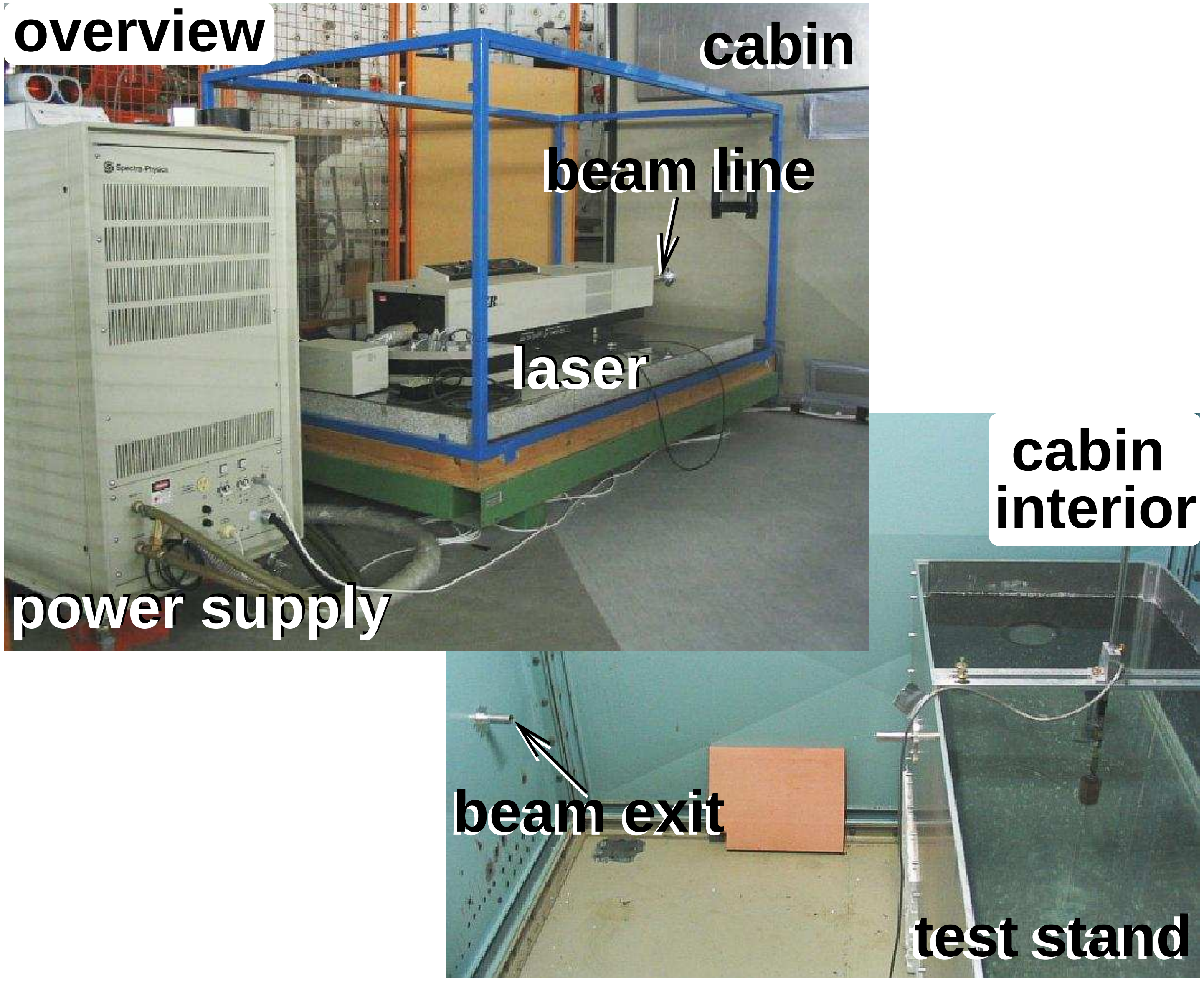


performed at Theodor Svedberg Laboratory (Uppsala, Sweden)

in February 2004

together with groups of DESY-Zeuthen and Uppsala Univ.

The Laser Beam Experiment



located at our institute

⇒ always available

diploma thesis of S. Schwemmer, Erlangen

Experimental Parameters

- proton accelerator:
  Gustaf Werner Cyloctron at 'The Svedberg Laboratory'
- laser:
  pulsed infrared Nd:YAG-Laser (Spectra Physics)

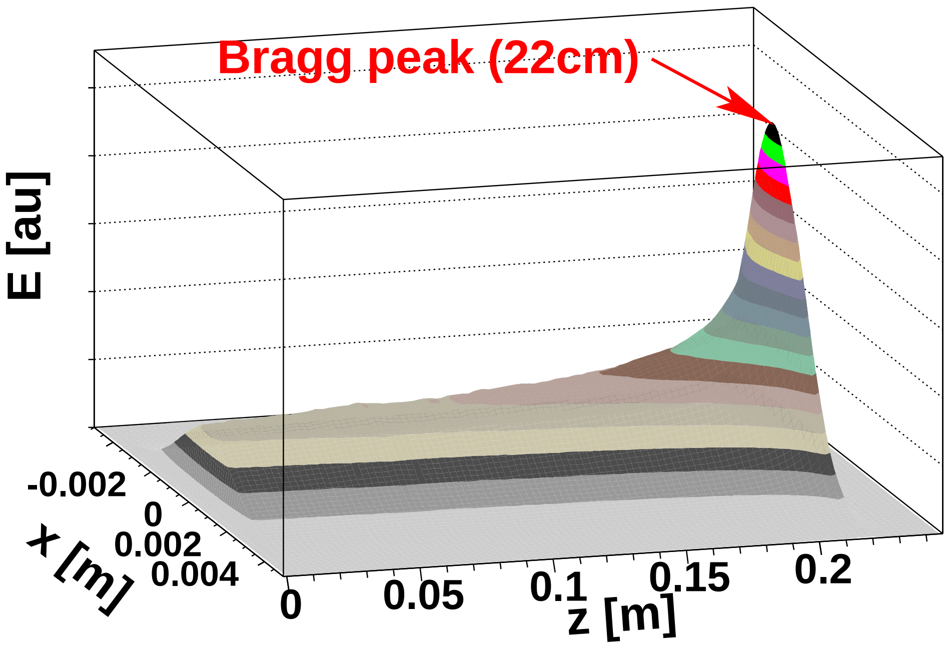
parameter	**proton beam**	**laser beam**
• particle properties	$E_p = 177\,\text{MeV}$	$\lambda = 1064\,\text{nm}$
• penetration depth	22 cm (Bragg peak)	6 cm (absorption length)
• pulse energy	10 PeV − 0.4 EeV	0.1 EeV − 10 EeV
• pulse duration	$\approx 30\,\mu\text{s}$	$\approx 10\,\text{ns}$
• beam width	0.6 cm − 2 cm	1 mm − 1 cm
• pulse frequency	10 Hz	0.01 Hz − 10 Hz

$\Rightarrow$ signal shape dominated by
pulse duration (proton beam) and beam width (laser beam)

Simulation of Acoustic Pulse I

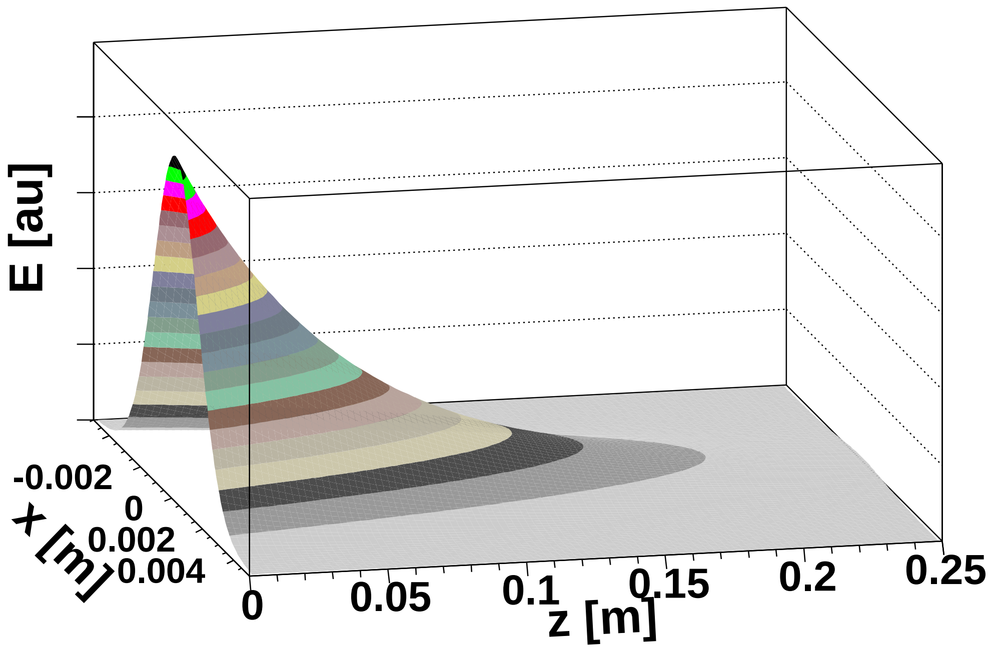
Energy deposition $\epsilon(\vec{r}, t)$

proton beam



- z-profile: simulated with GEANT4
- xy-profile: gaussian ($\sigma_{xy} \approx 5\,\text{mm}$)
- pulse shape: gaussian ($\sigma_t \approx 6\,\mu\text{s}$)

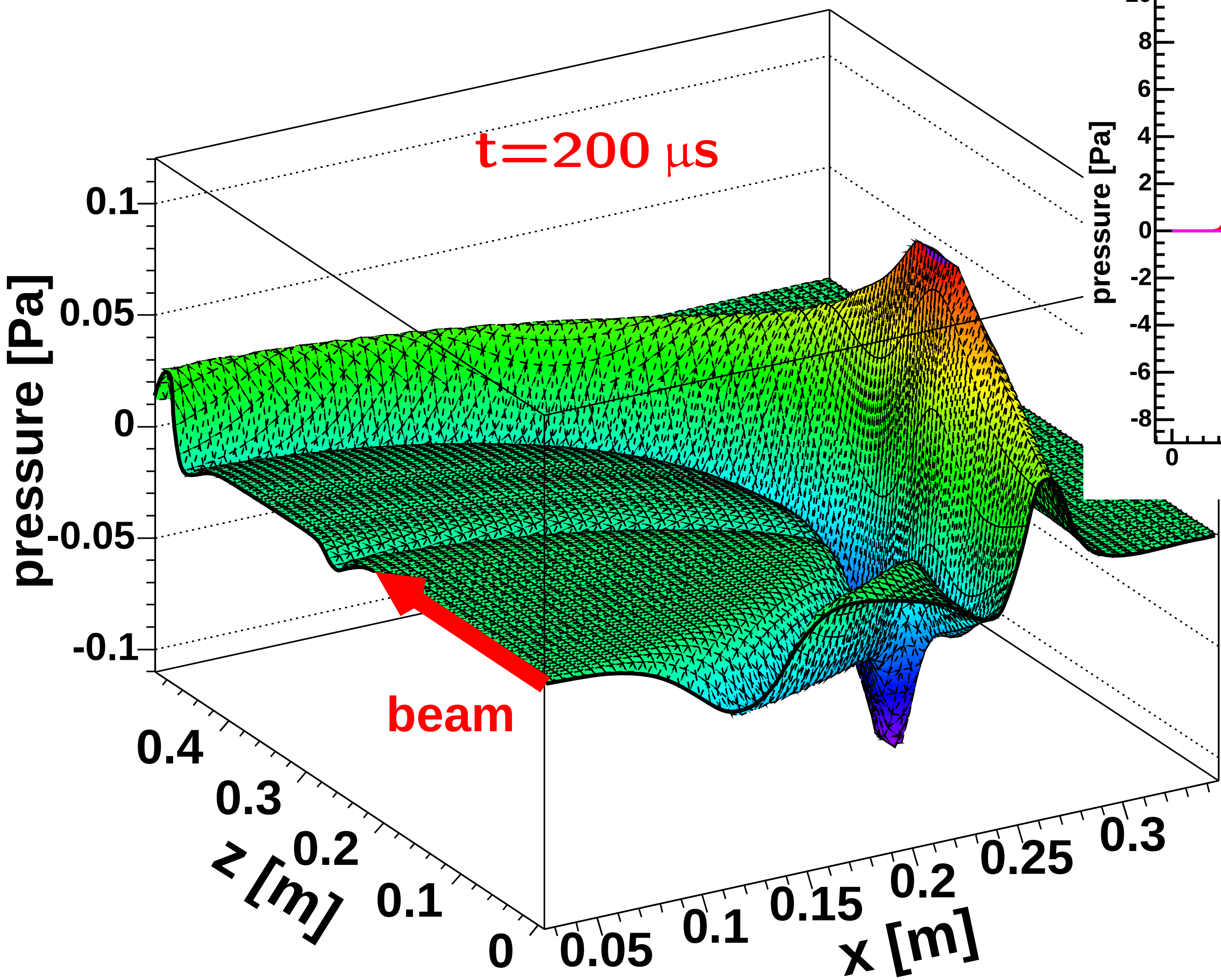
laser beam

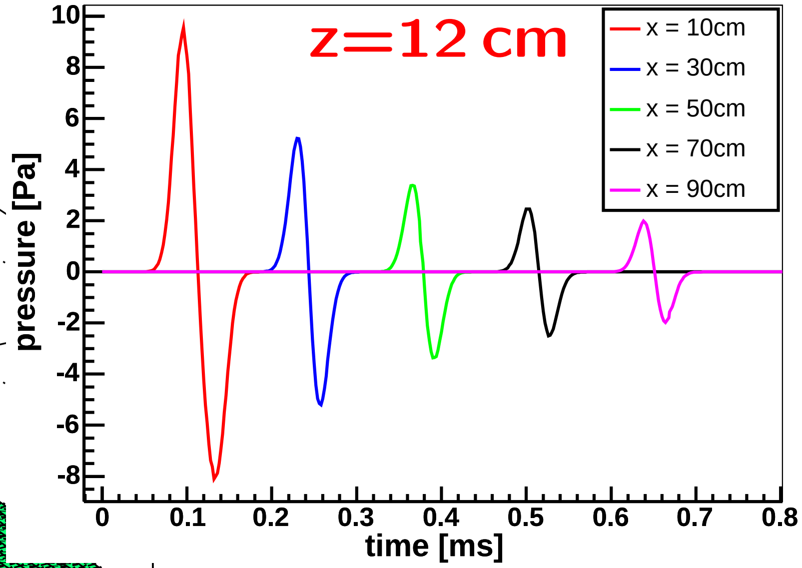


- z-profile: exponential decrease (absorption length 6 cm)
- xy-profile: gaussian ($\sigma_{xy} \approx 5\,\text{mm}$)
- pulse shape: gaussian ($\sigma_{xy} \approx 1\,\text{ns}$, instantaneous)

Simulation of Acoustic Pulse II

Sonic field and acoustic pulse (proton beam)

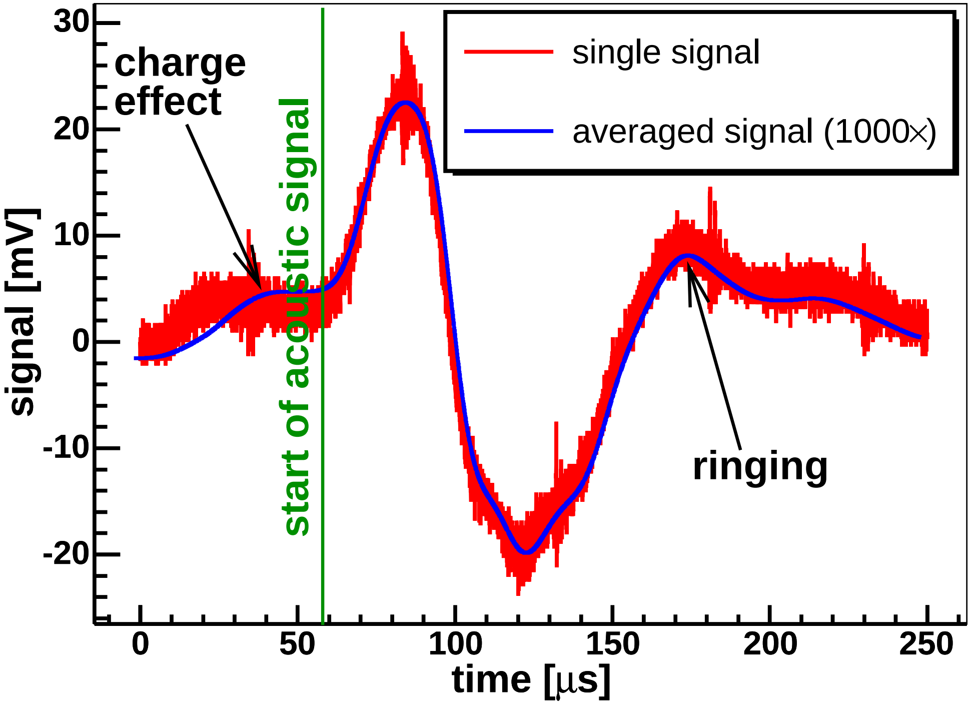




sonic field and acoustic pulse by numeric solution of wave equation for a beam pulse

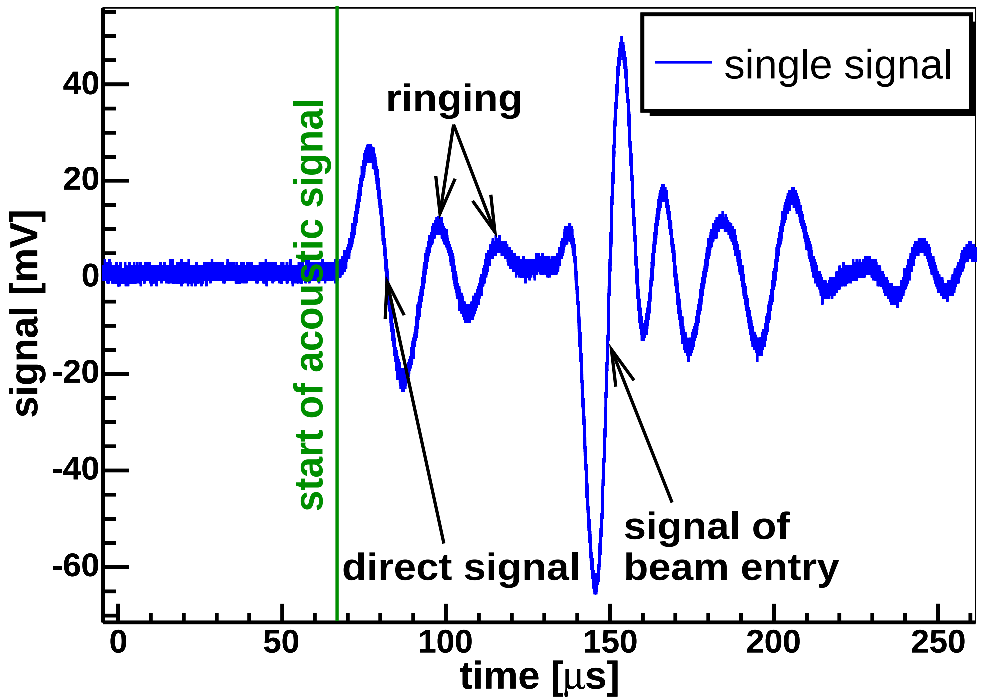
Properties of Measured Signals

Proton beam



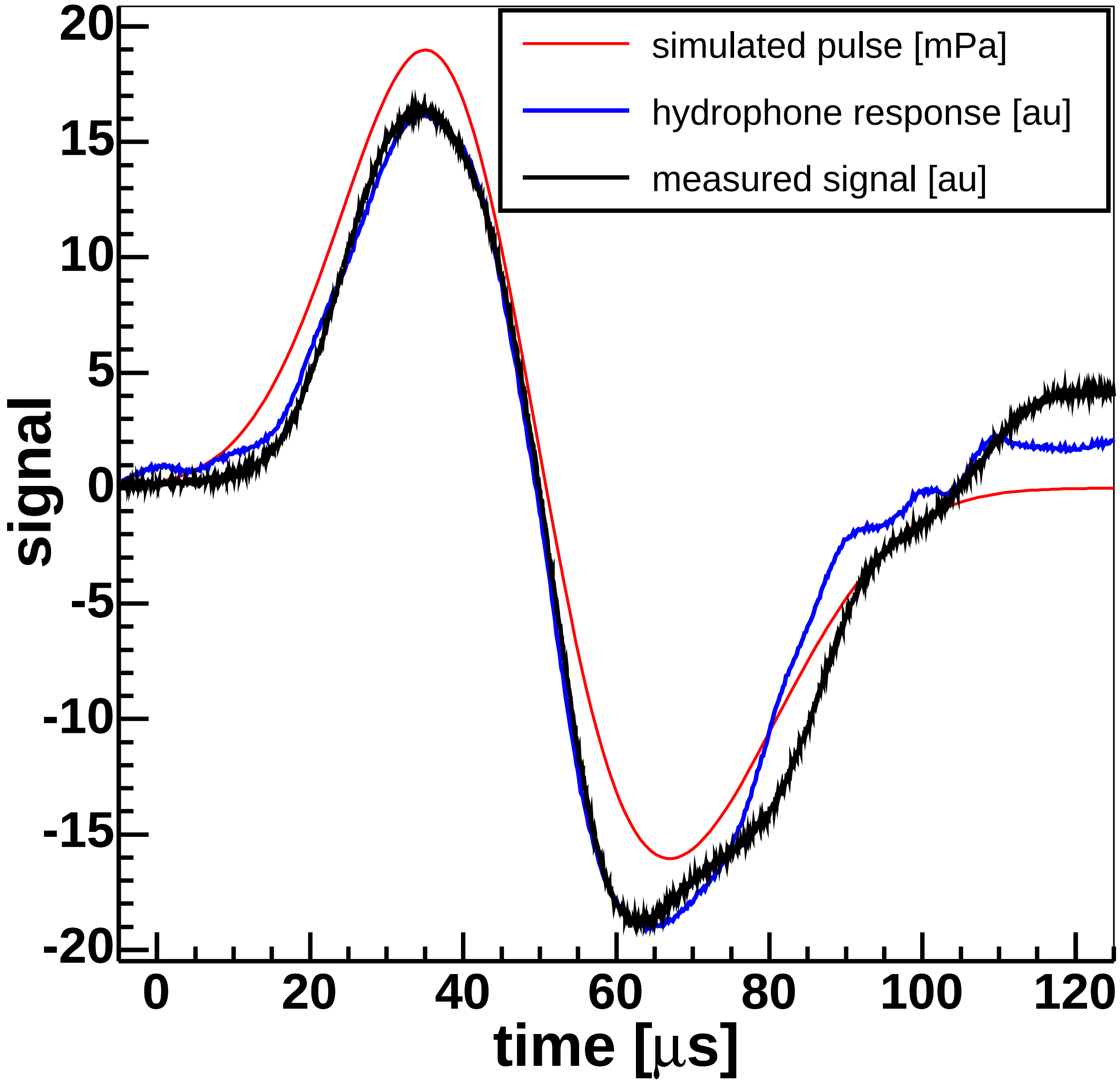
- x ≈ 10 cm, z ≈ 12 cm, E ≈ 0.4 EeV (highest energy)
- main frequency ≈ 15 kHz
- charge effect of proton beam
- little ringing of sensor

Laser beam



- x ≈ 10 cm, z ≈ 20 cm, E ≈ 0.5 EeV (low energy)
- main frequency ≈ 60 kHz
- no charge effect (photons)
- strong ringing of sensor

Measured Signal Shape vs. Simulation



approach:

simulate pulse

↓

transmit pulse with transducer in water

↓

receive hydrophone response of pulse

↓

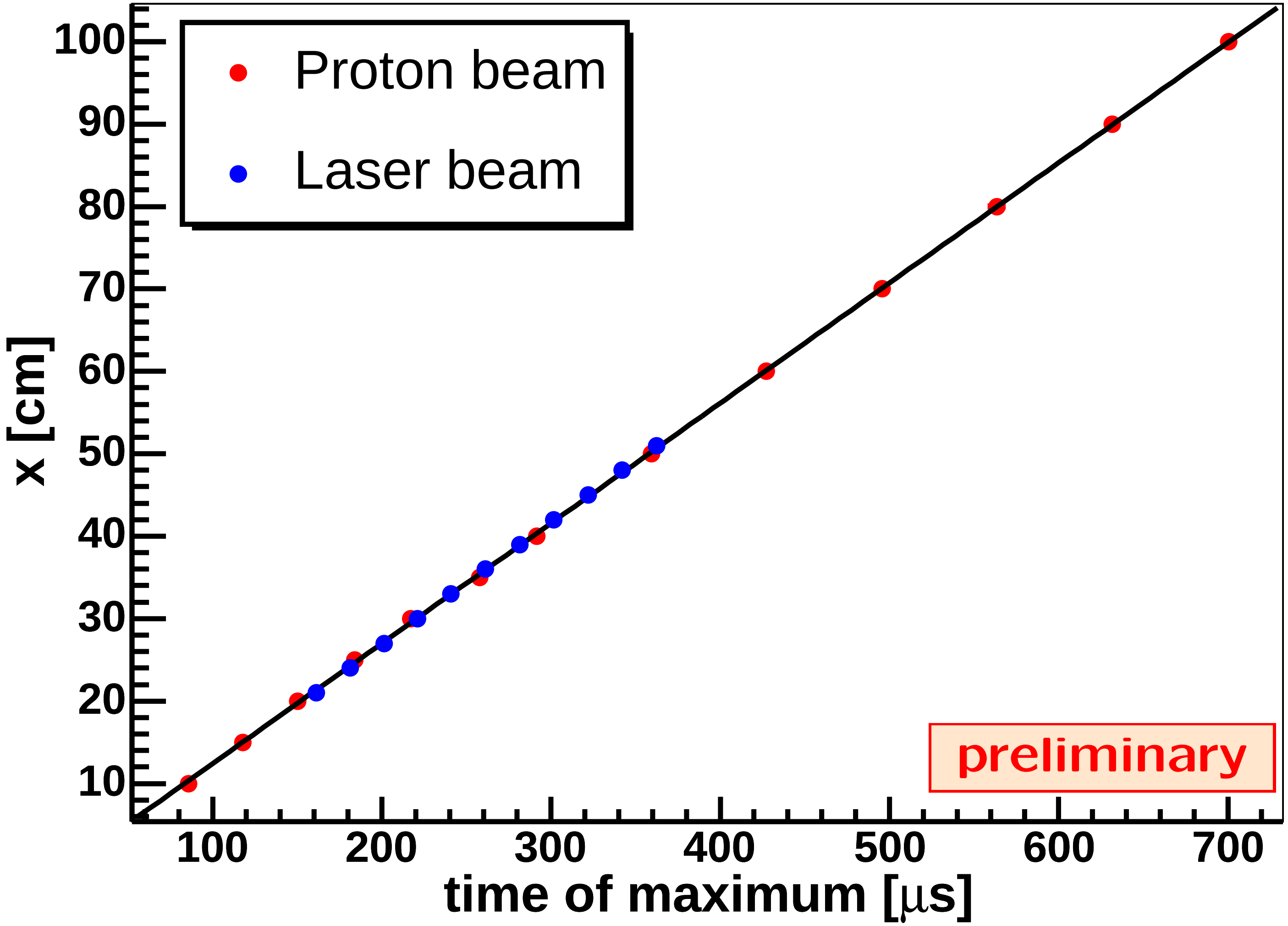
compare with signal measured at proton beam

⇒ **good agreement in shape**

⇒ sensor changes signal

working on absolute calibration

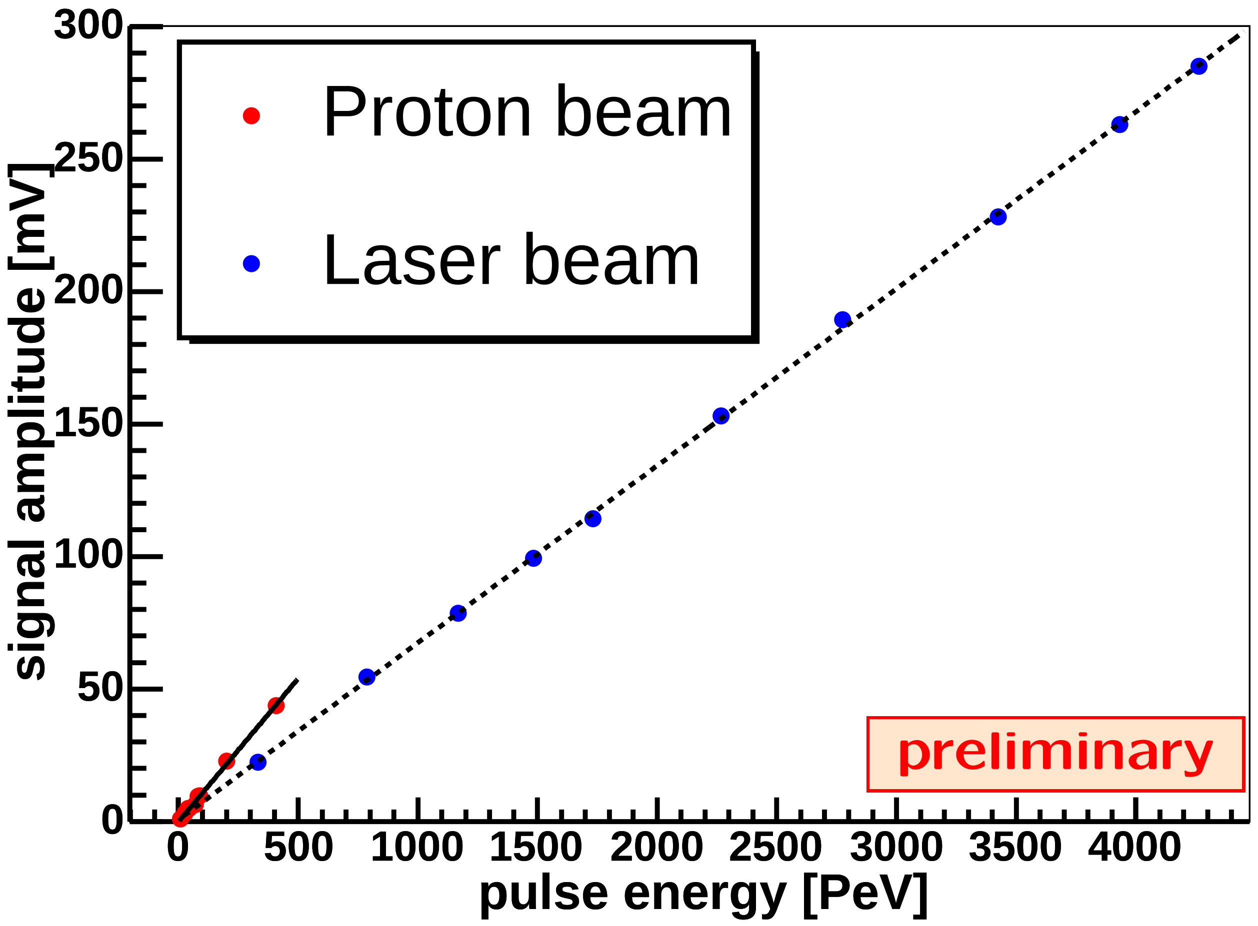
Signal is Acoustic



measured at same temperature, time offset corrected

from slope: $c_s = 1458 \pm 3\,\frac{\mathbf{m}}{\mathbf{s}}$ **(Lit.** $1455 \pm 1\,\frac{\mathbf{m}}{\mathbf{s}}$**)**

Energy Dependence



different slopes due to:

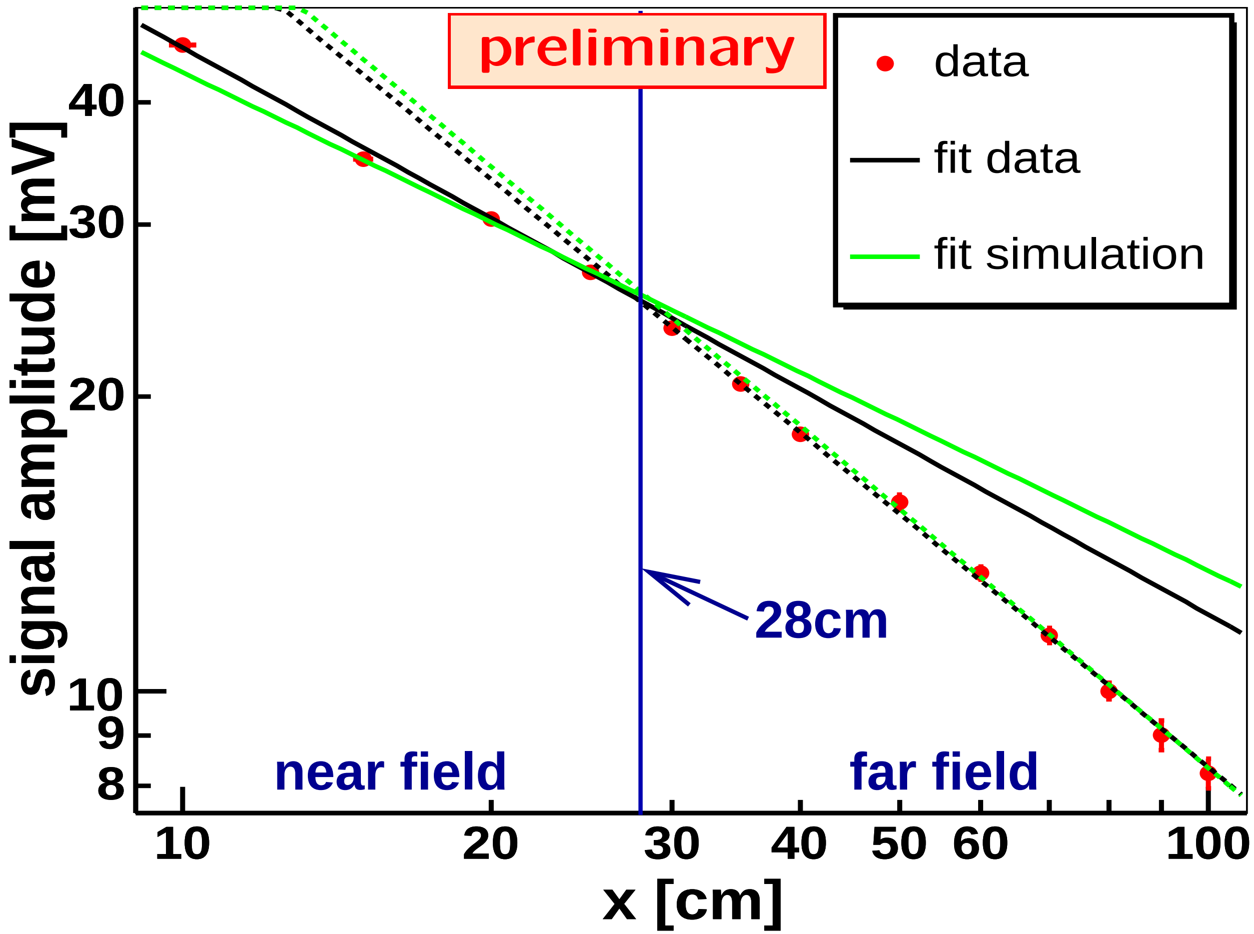
- different energy deposition profiles
- different pulse lengths
- 10% systematic uncertainty in energy determination

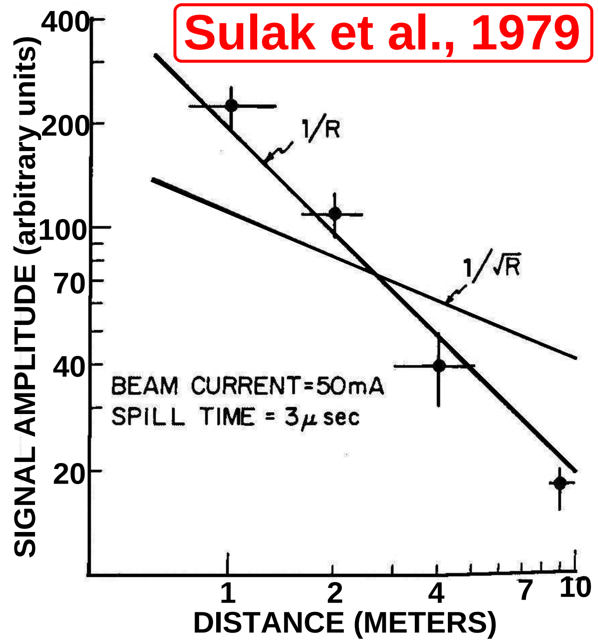
$\Rightarrow$ different slopes expected (simulation)

measured with same hydrophone

expected linear dependence

Position Dependence





data from proton beam experiment

simulation and measurement match well

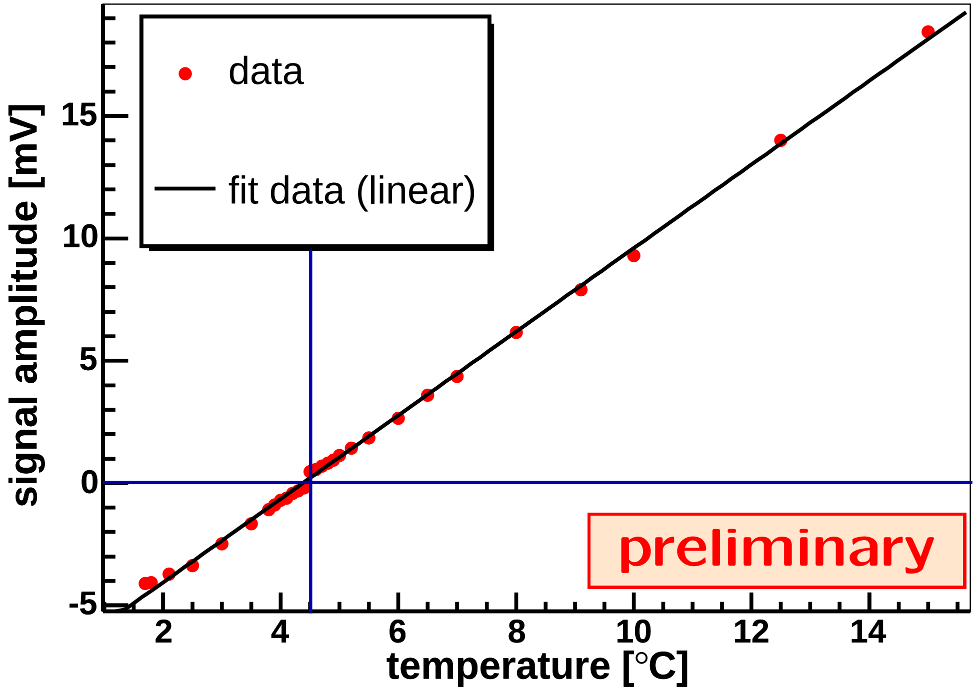
(simulation matched to data at $x = 100\,\text{cm}$)

← **fit parameters:**

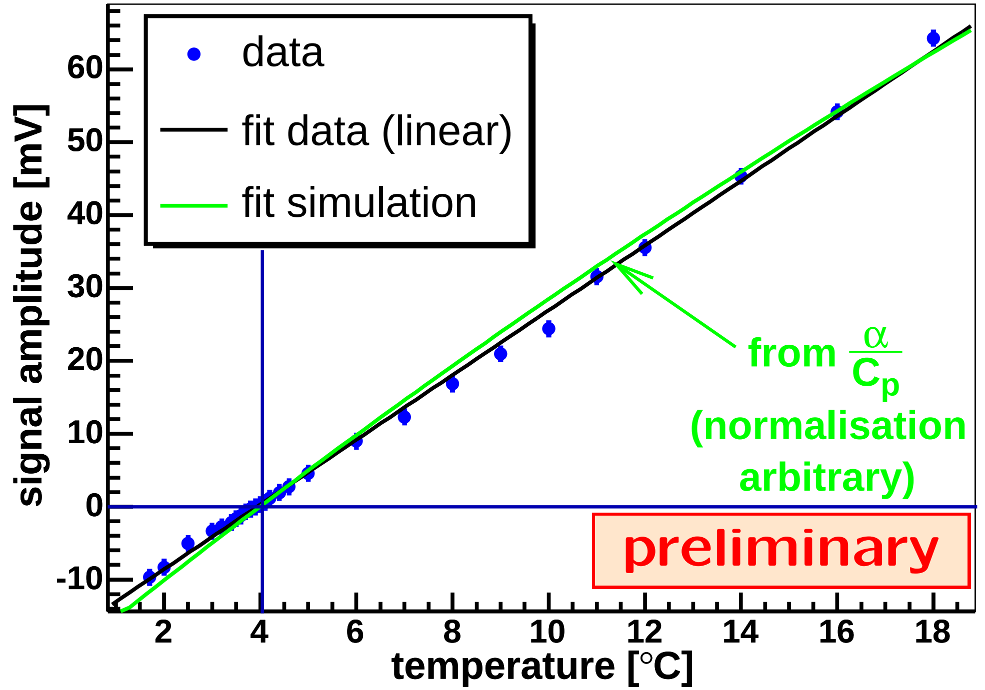
- near field: $x^{-0.57\pm0.02}$ (sim: $x^{-0.51\pm0.03}$)
- far field: $x^{-0.86\pm0.02}$ (sim: $x^{-0.88\pm0.01}$)
- transition: 28 cm (sim: 27 cm)

Temperature Dependence I

Proton beam



Laser beam



preliminary - analysis ongoing!

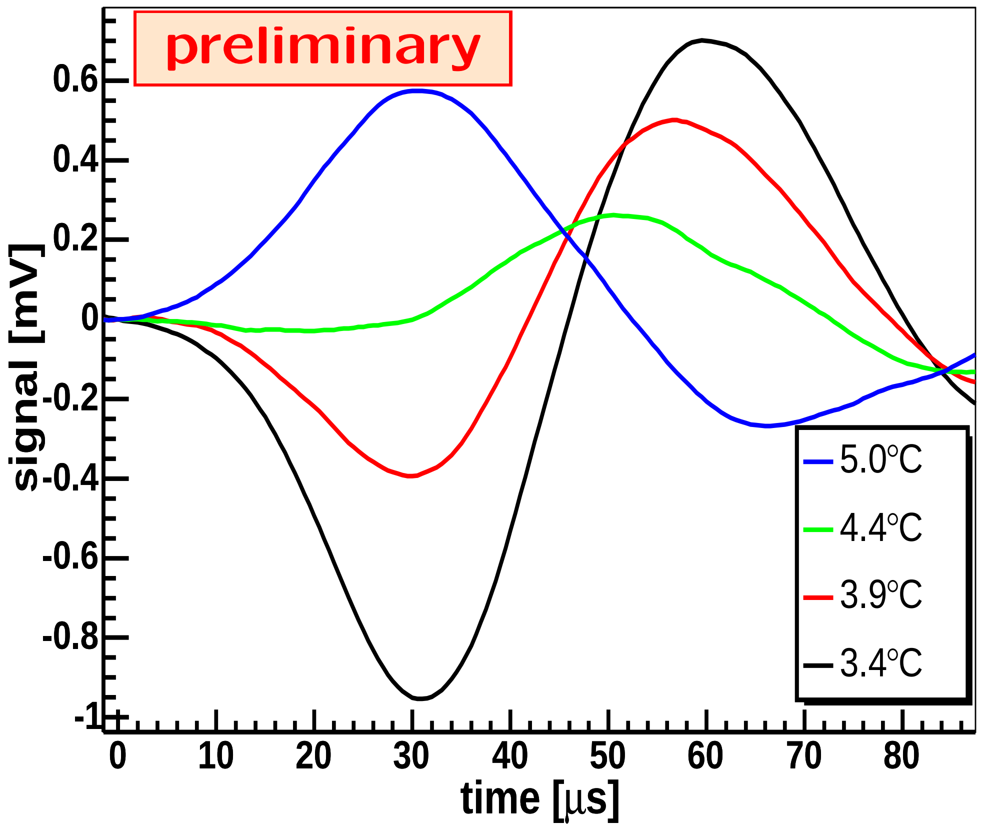
- temperature dependence more linear than expected
  $\Rightarrow$ sensor or signal features?
- zero crossing at 4.5 ± 0.1°C (proton) and 3.9 ± 0.1°C (laser)
  (α: 4.0°C, Sulak et al. 1979: 6.0 ± 0.1°C, Hunter et al. 1981: 6°C)

$\Rightarrow$ laser: zero crossing as expected by thermo-acoustic model

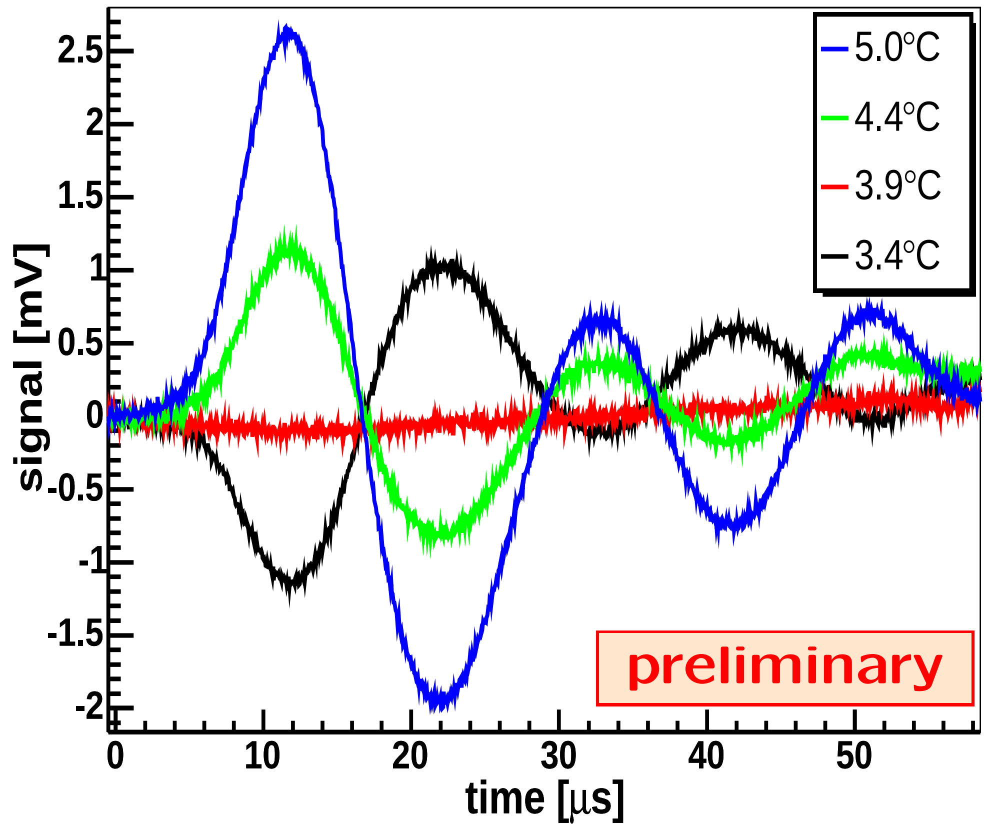
$\Rightarrow$ protons: superposition with non-thermal pulse could explain behaviour

Temperature Dependence II

Averaged proton beam signals



Single laser beam signals



preliminary - analysis ongoing!

- inversions of signals clearly visible (3.4 $\leftrightarrow$ 5.0°C)
- for protons: pulse shape changes, signal amplitude never zero

$\Rightarrow$ signals confirm amplitude behaviour

Summary and Outlook

Summary

proton and laser beam experiments confirm:

thermo-acoustic sound generation

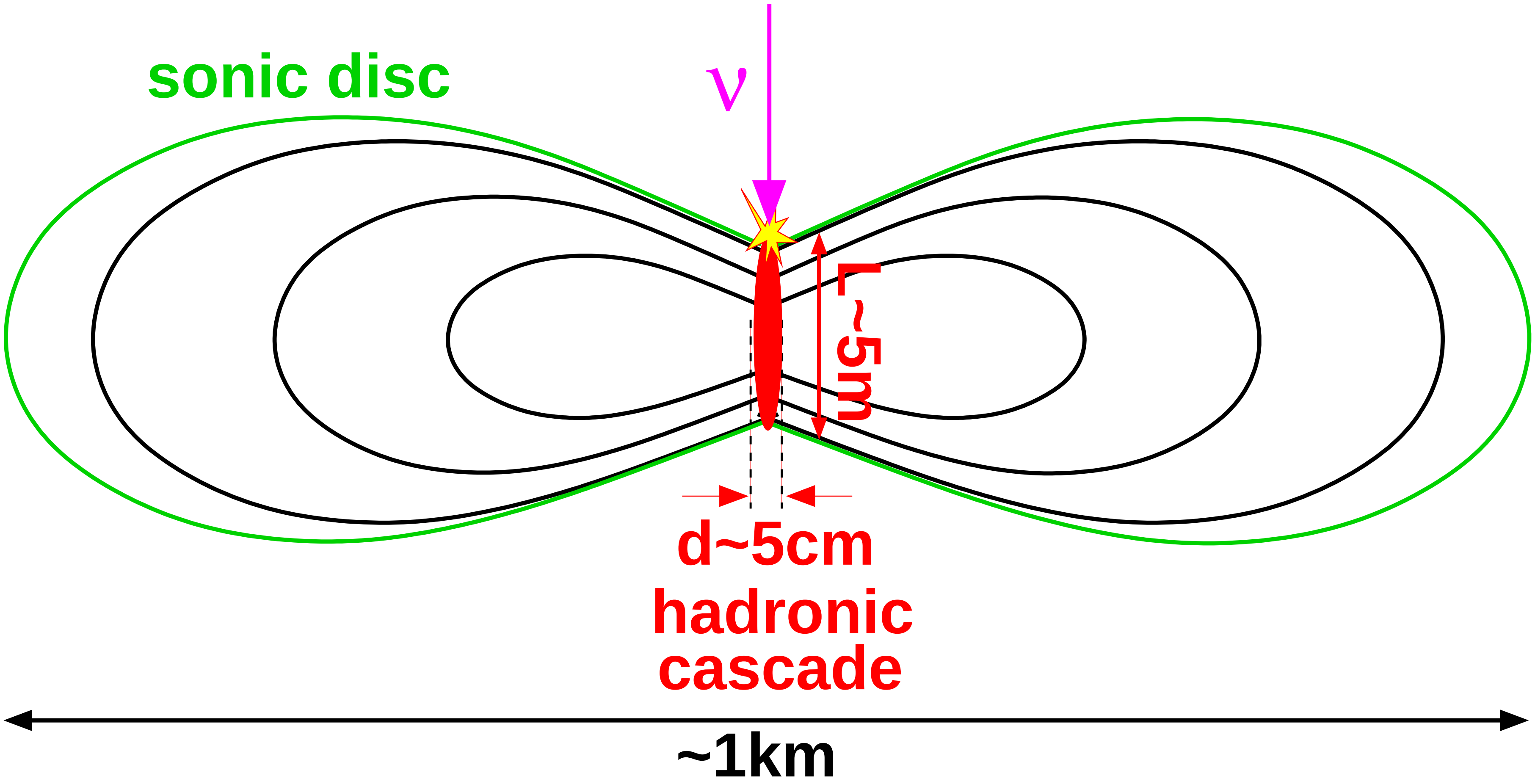
is primary effect

- high-precision data
- simulation and model predictions in good agreement with measured signals

Outlook

- some minor effects (around 4°C) need to be clarified
- work on the calibration of sensors ongoing
- use laser as calibration source

Thermo-acoustic Sound Generation



$\nu \Rightarrow$ hadronic cascade $\Rightarrow$ water gets heated and expands $\Rightarrow$ energy dissipates hydrodynamically

$\Rightarrow$ **acoustic pulse**