Acoustic Signals from Proton Beam Interaction in Water

Comparing Experimental Data and Monte Carlo Simulation

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Outlook

Introduction

- Neutrino Astronomy
- Submarine Observatories
  - Eth < 10^{16} eV ⇒ Cherenkov detection
  - UHEν ⇒ **Acoustic Detection**

The Thermo-Acoustic Mechanism and the Acoustic Signal

- Analytical Solution of the Wave Equation
- **Gruneisen Coefficient γ** and **Signal Amplitude as a function of Environmental Parameters** (Temperature, Salinity, Depth)

Test of the Thermo-Acoustic Mechanism at the ITEP Proton Beam

- Experimental set-up and Calibration Measurements
- **MonteCarlo**. AcSource = TestBeam - proton interaction and energy depo. in water (GEANT4)
- **AcPulseComputation**
- **Data VS Sim**
- **Comparison with previous results** (Sulak et al. 1979)

Simulation of Neutrino-Induced Acoustic Pulse

- **MonteCarlo**. AcSource = Neutrino-induced Showers
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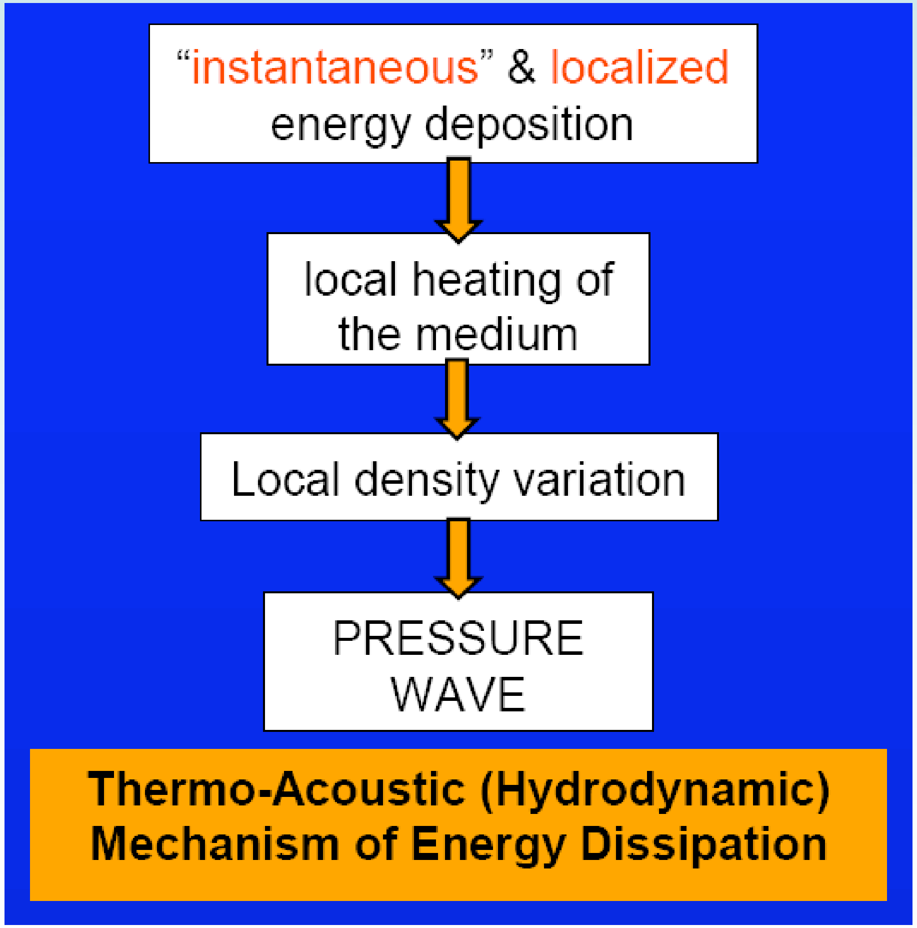
The Thermo-Acoustic Mechanism and the Acoustic Signal



G. A. Askaryan (1979), "Acoustic Radiation by Charged Atomic Particles in Liquids", Nucl. Inst. Meth., 164, 267.

The Wave Equation

Wave Equation

$$\nabla^2 p(\vec{r},t) - \frac{1}{c_s^2}\frac{\partial^2 p(\vec{r},t)}{\partial t^2} = -\frac{\beta}{C_p}\frac{\partial^2 q(\vec{r},t)}{\partial t^2}$$

p(**r**, t)	Pressure
q(**r**, t)	Energy Density
c_s	Sound Speed
β	Thermal Expansion Coefficient
C_p	Heat Capacity

Solution (Kirchoff Integral)

$$p(\vec{r},t) = \frac{\beta}{4\pi \cdot C_p}\int \frac{dV'}{|\vec{r}-\vec{r}'|}\cdot\frac{\partial^2}{\partial t^2} q\left(\vec{r}', t - \frac{\vec{r}-\vec{r}'}{c_s}\right)$$

Introducing the hypothesis of

Instantaneous energy deposition

$$\dot{q}(\vec{r},t) = q(\vec{r})\cdot\delta(t) \qquad (\tau_{dep} \ll \tau_h)$$

the problem is reduced to the homogeneous case with the following initial condition:

$$p(\vec{r},t=0) = \frac{\beta}{C_p}\cdot q(\vec{r}) \qquad \dot{p}(\vec{r},t=0) = 0$$

Solution is given by the **Poisson Formula**

$$p(\vec{r},t) = \frac{1}{4\pi}\frac{\beta\cdot c_S^2}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^R}\frac{q(\vec{r}')}{R}d\sigma$$

The integral is performed over a spherical surface of radius $R=c_s t$, centered at the detector position $\vec{r}$

The Poisson Formula

Energy Density
MonteCarlo Simulation

$$p(\vec{r},t) = \frac{1}{4\pi}\frac{\beta \cdot c_S^2}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^R}\frac{q(\vec{r}\,')}{R}d\sigma$$

Gruneisen Coefficient γ

It is a dimensionless coefficient, depending on **environmental parameters**.
It determines the **signal amplitude**,
and thus it is a measure of the **thermo-acoustic mechanism efficiency**.

c_S – Sound Speed [m/s]

Sound speed dependence on environmental parameters (temperature, salinity, depth) has been investigated experimentally by several authors, resulting to many different empirical formulations.

We consider an approximated and simplified version of the Wilson Formula

$$c_S = 1449 + 4.6 \cdot T - 0.055 \cdot T^2 + 0.0003 \cdot T^3 + (1.39 - 0.012 \cdot T) \cdot (S - 35) + 0.017 \cdot Z$$

- T, water temperature, in *[°C]*
- S, salinity *[psu]*
- Z, depth *[m]*

To measure **depth**, the sea level is the *0* value, and increasing depths are greater *Z* values.

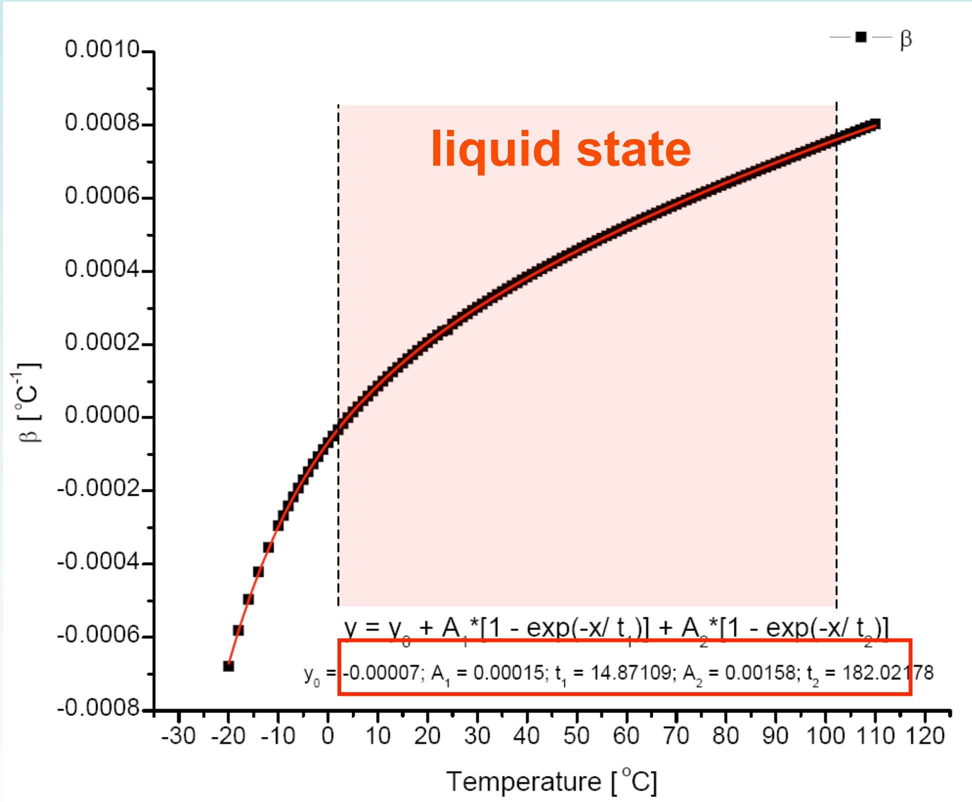
Salinity unity is *psu* (*practical salinity unit).* A typical value of salinity in sea water is 35 psu, that is a mass ratio of about 35‰, i.e. 35 grams of salt for each kilograms of water.

W. Wilson (1960), "*Equation for the Speed of Sound in Sea Water*", Journ. Acoust. Soc. Amer., vol. 32, No. 10, p. 1357

β– Thermal Expansion Coefficient [°C⁻¹]

Temperature dependence

exponential fit on Kell data



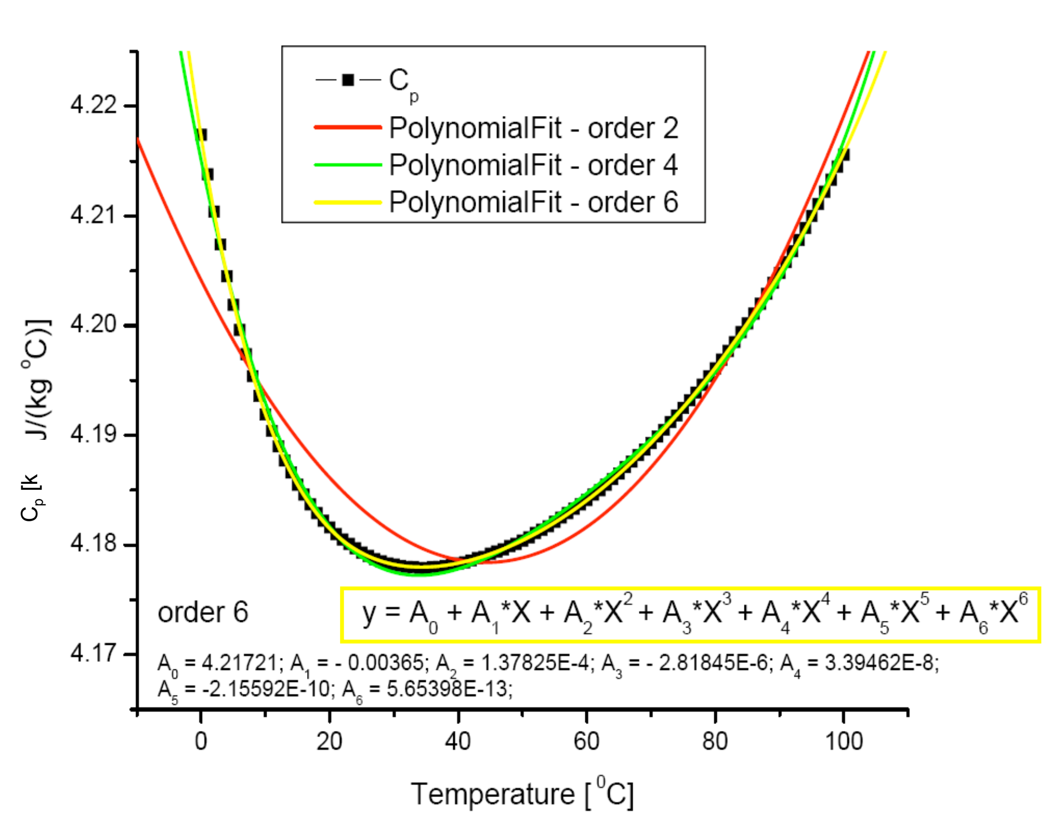
G. S. Kell (1967),
"*Precise Representation of Volume Properties of Water at One Atmosphere*",
J. Chem. Eng. Data 12-1, pp. 66-69

C_p - Specific Heat [J/(kg·°C)]

Temperature dependence

6th order polinomial fit

on Stimson data



H. F. Stimson (1955),
"*Heat Units and Temperature Scales for Calorimetry*",
Am. J. Phys. 23, pp. 614-622

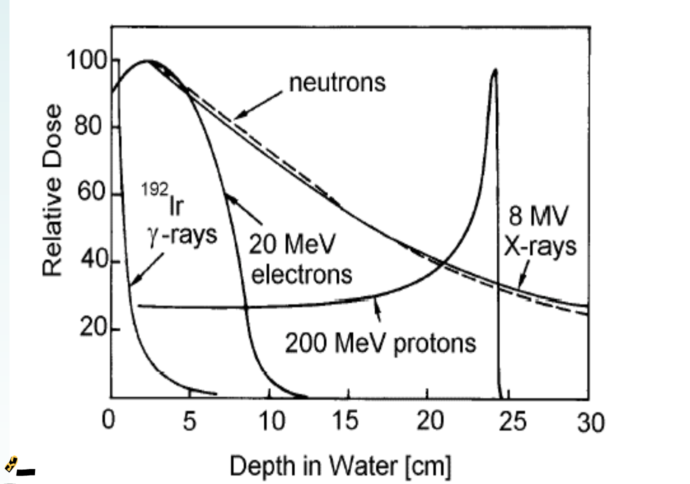
Test of the Thermo-Acoustic Mechanism at the ITEP Proton Beam

Protons Energy Deposition in Water

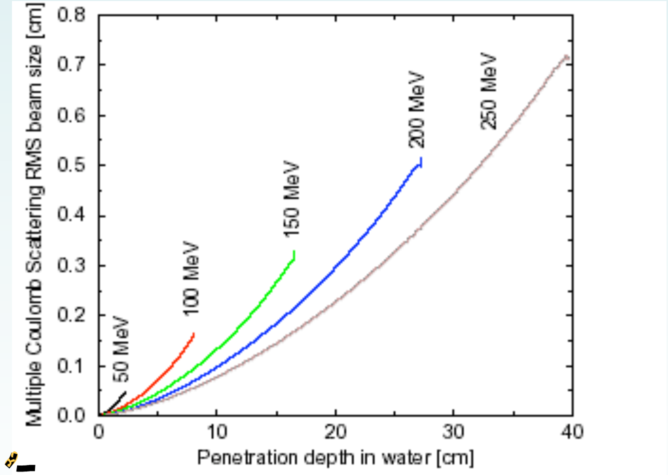
Bragg Peak

If the primary proton energy is in the range 100-200 MeV, most of the energy is released at the end of the particle track, at the so-called **Bragg Peak.**

The Bragg Peak is a local (point-like) energy deposition. The Bragg Peak phenomenon fulfills the hypothesis of the thermo-acoustic model; it can thus work as **acoustic source** for calibration.



C. Grupen, arXiv:physics/0004015 (2000)

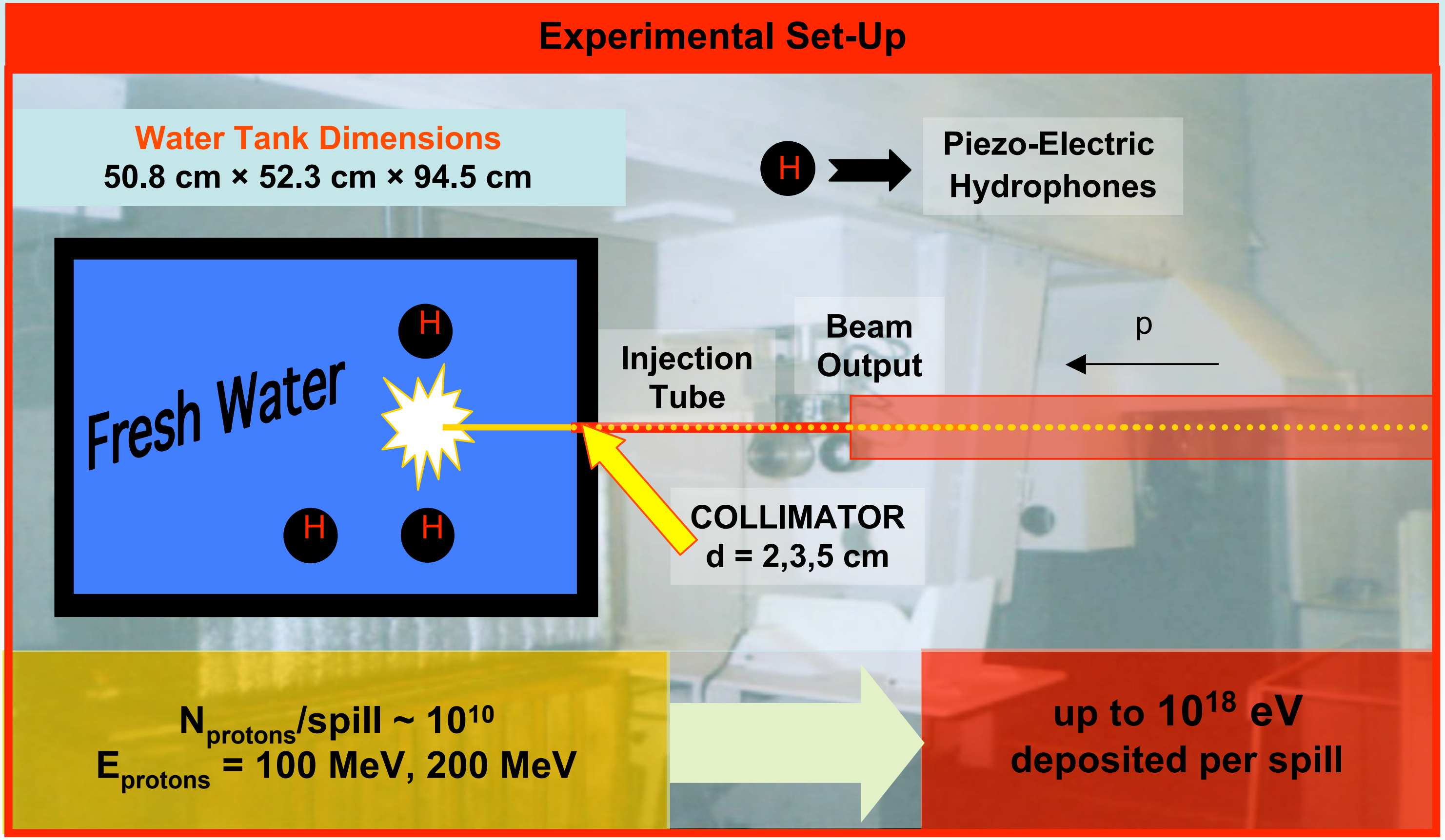


T. Satogata et al., C-A/AP/#120 (2003)

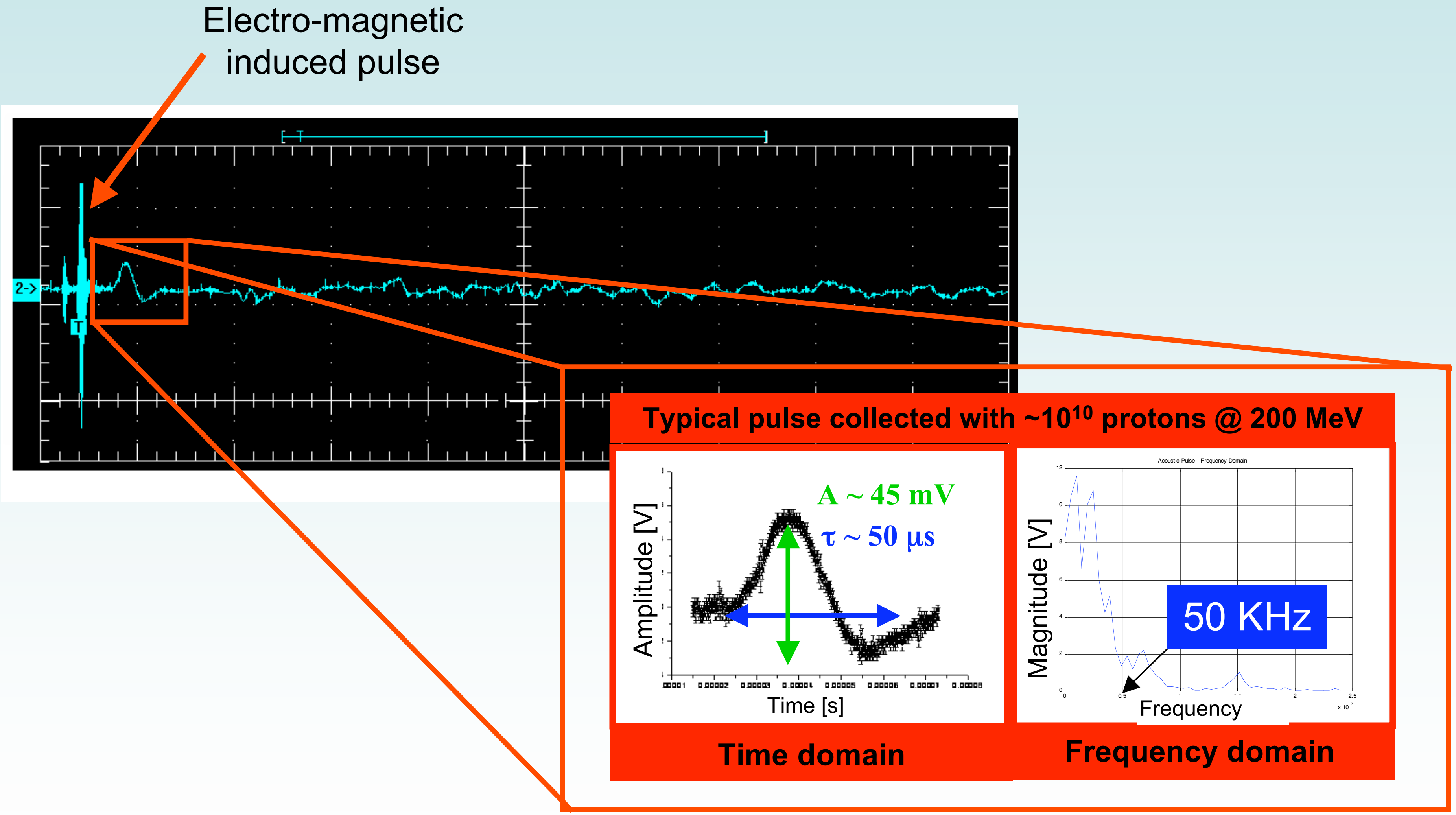
Test @ ITEP (Moscow) Proton Beam

June 2004

GDB, G. Riccobene, R. Masullo, A. Capone, V.Lyashuk, A.Rostovstev



Hydrophones Data - a Zoom View

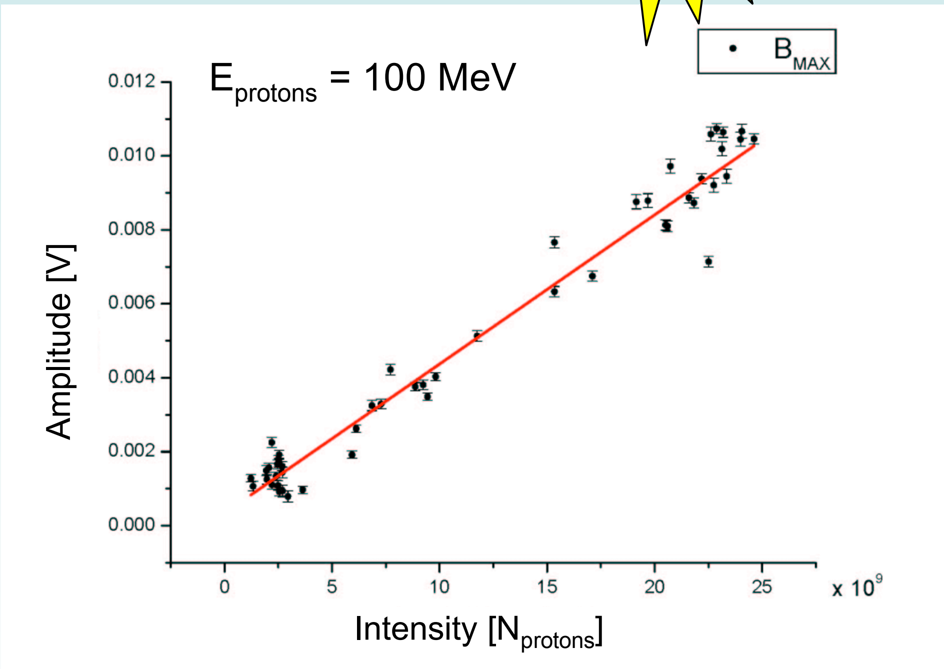


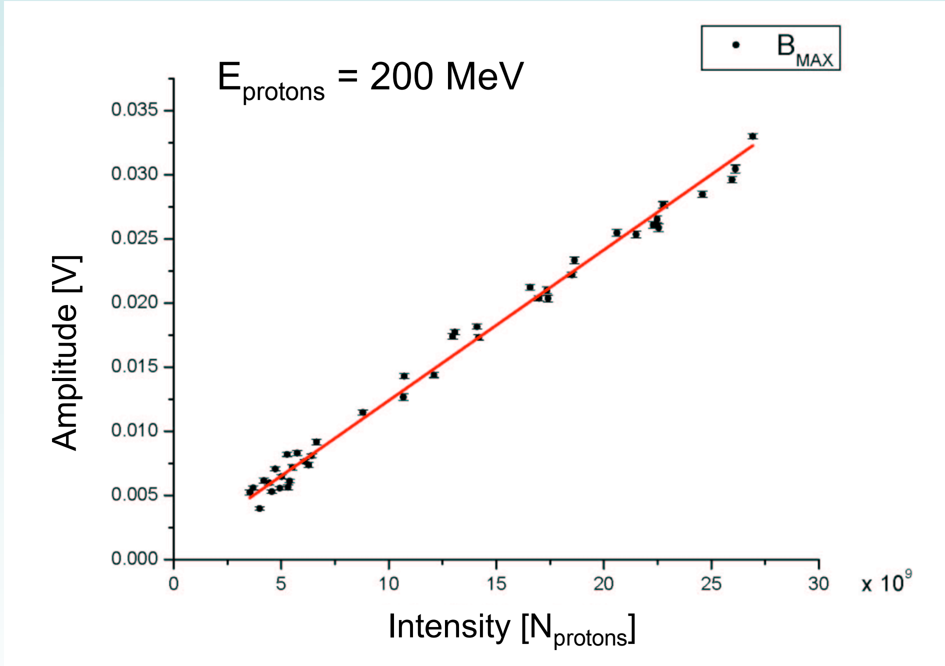
Hydrophones Energy Calibration

LINEAR FIT

$A_{\substack{signal\\amplitude}} \propto N_{protons}$

Collimators reduce the number of interacting protons;
the effect is taken into account in the computation of $N_{protons}$



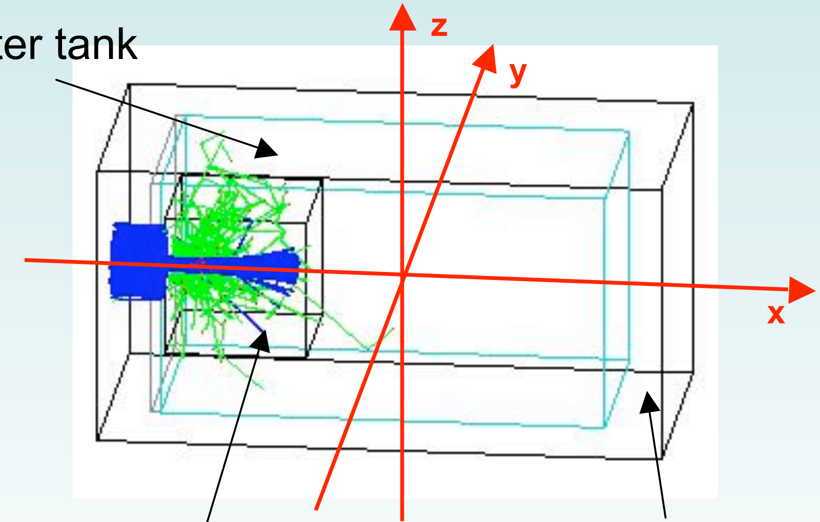


A. Capone, GDB, "Preliminary Results on Hydrophones Calibration with Proton Beam", Proc. Int. Conf. ARENA2005, World Scientific (2006).

MonteCarlo
AcSource = TestBeam (Geant4)

The GEANT4 Simulation Toolkit is used to reproduce the ITEP Test Beam experimental set-up.

water tank



mother volume

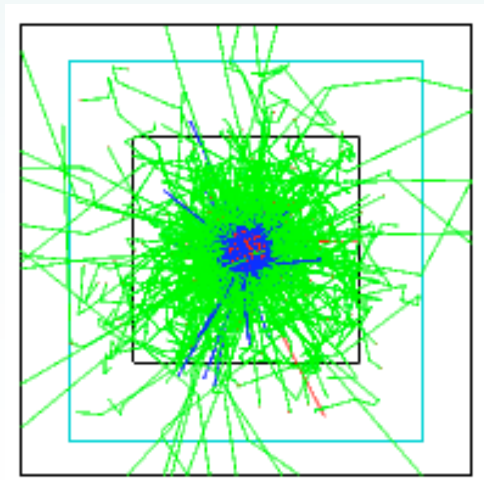
sensitive volume

The sensitive volume is a cube with a side of 30 cm, divided in cubic cells (tri-dimensional grid), each one with a side of 0.2 cm and a volume of 0.008 cm^3

A detailed simulation of the water tank
- including the collimator -
(class ItepDetectorConstruction)
and of the proton injector
(class ItepPrimaryGeneratorAction)
has been performed.

The result is an output ASCII file with the “map” of the energy density deposition *rhoE(x,y,z)* over a tri-dimensional grid.

Pictures are produced with DAWN (GEANT4 graphics tool) from a .prim file



AcPulseComputation
the Bipolar Pulse

The main frame of reference is a set of Cartesian coordinates (O, x, y, z) centered at the middle of the water tank (target volume).

A set of spherical coordinates (H, R, θ, φ) is placed at the hydrophone position, with:

$R = (R_{min}, R_{min})$ (sorrounding the source)

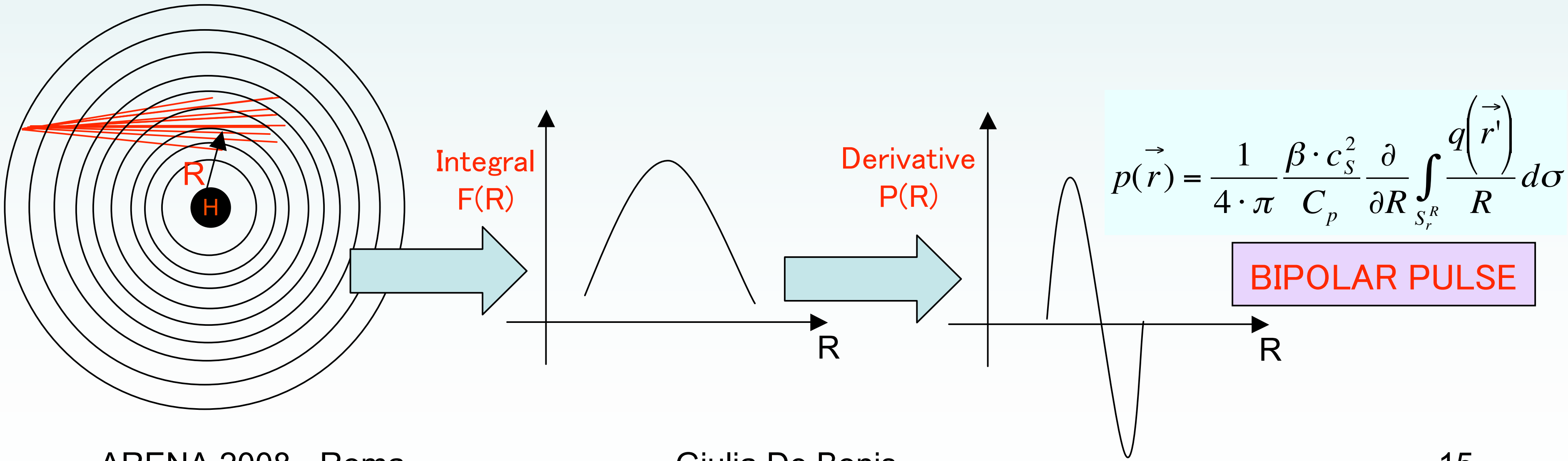
$\theta = (0, \pi)$

$\varphi = (0, 2\pi)$

(In a discrete computation, the coordinates variation is defined by rstep, θstep, φstep)

The “pointer” moves all around, scanning the space, and computing the integral F(R) over spherical surfaces.

Space derivative is computed between two adjacent spherical surface.



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AcPulseComputation
the Block Diagram

GEANT4 MC

INPUT FILE Selection

Energy: E=100 MeV, E=200 MeV

Collimator: d=2cm, d=3cm, d=5cm

Beam Profile (Source Size/Shape)

N_protons

Read the INPUT FILE

and fill the energy density matrix rhoE[i][j][k]

Integration Parameters

Select *rstep*, *thetastep*, *phistep*

Hydrophone Position

Select *xH*, *yH*, *zH*

Environmental Parameters

Select *Temperature*, *Salinity*, *Depth*

⇓

Computation of the Gruneisen Coefficient

AcPulseComputation

The Integration Surfaces are spherical surface centered at the hydrophone position.

The Integral is computed summing the rhoE matrix elelments over the spherical surface.

The Derivative is computed as the different quotient between two adjacent surfaces.

AcPulseComputation
the Block Diagram

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in the following:
investigating on the MC
(E=200 MeV, d=5 cm)

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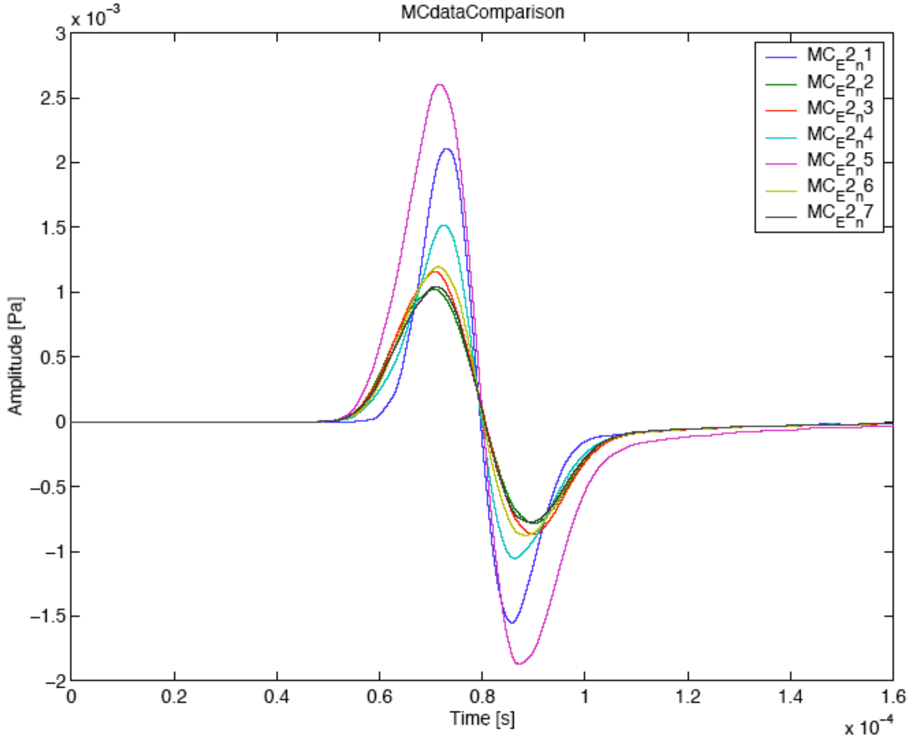
Investigating on the MonteCarlo

[N_protons=10^5]

Source Size dependence



The beam profile determines the size and shape of the energy deposition in the water tank.
No clear indication is given on the beam profile.
Results shown in this page assume the beam profile as a convolution of two gaussians

	σ_1 [cm]	σ_2 [cm]	p
E2_n1	0.55	2.0	65
E2_n2	1.0	2.0	40
E2_n3	1.0	2.0	50
E2_n4	0.55	2.0	40
E2_n5	0.70	2.0	40
E2_n6	0.80	2.0	40
E2_n7	0.80	2.0	30

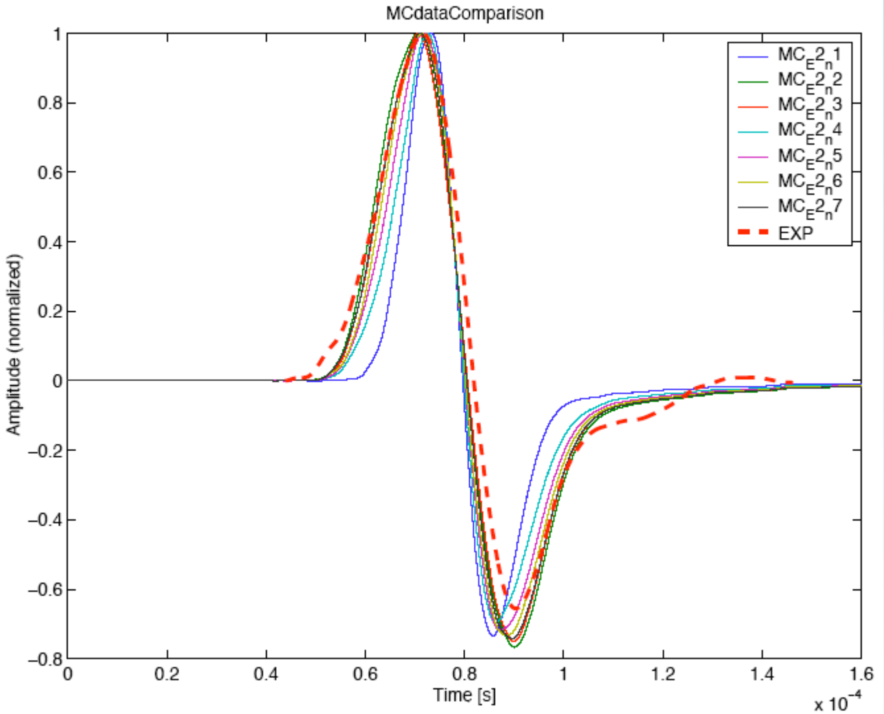
Results are consistent with expectations from Askaryan (1979)

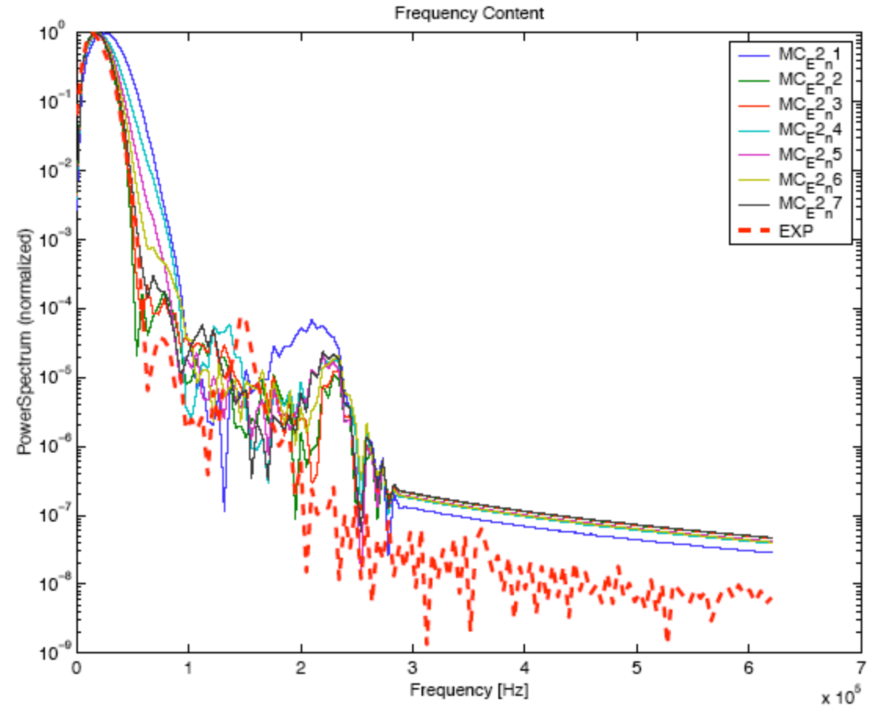
The frequency spectrum is up to the value $f_{MAX} = \frac{c_s}{\ell}$ where ℓ is the transversal extension of the source.

Considering the time domain, the pulse duration τ is connected with f_{MAX} and therefore it is in the following relation with the source size:

$$\tau = \frac{1}{f_{MAX}} = \frac{\ell}{c_s}$$

Investigating on the MonteCarlo
Source Size dependence





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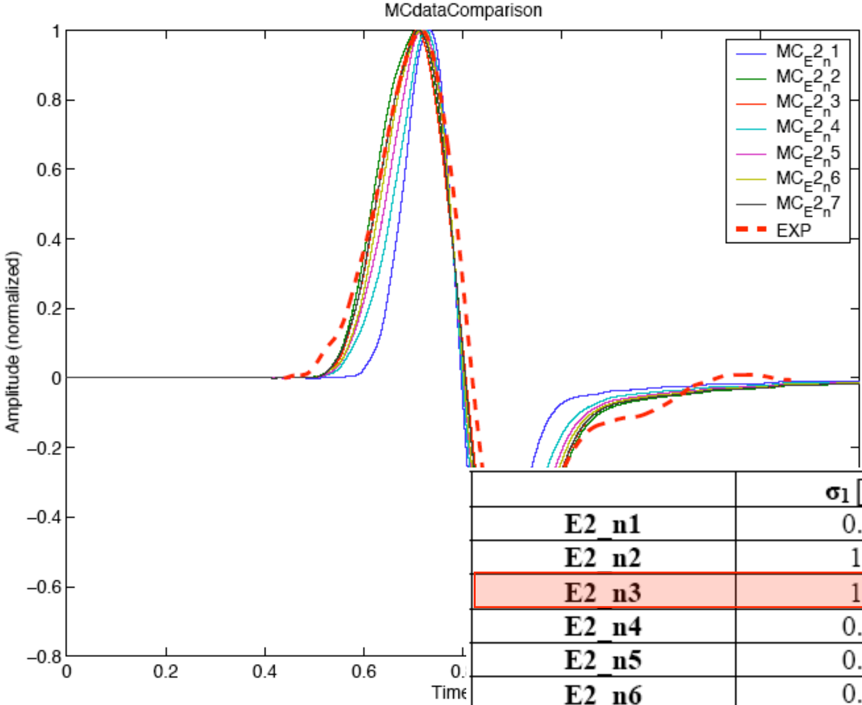

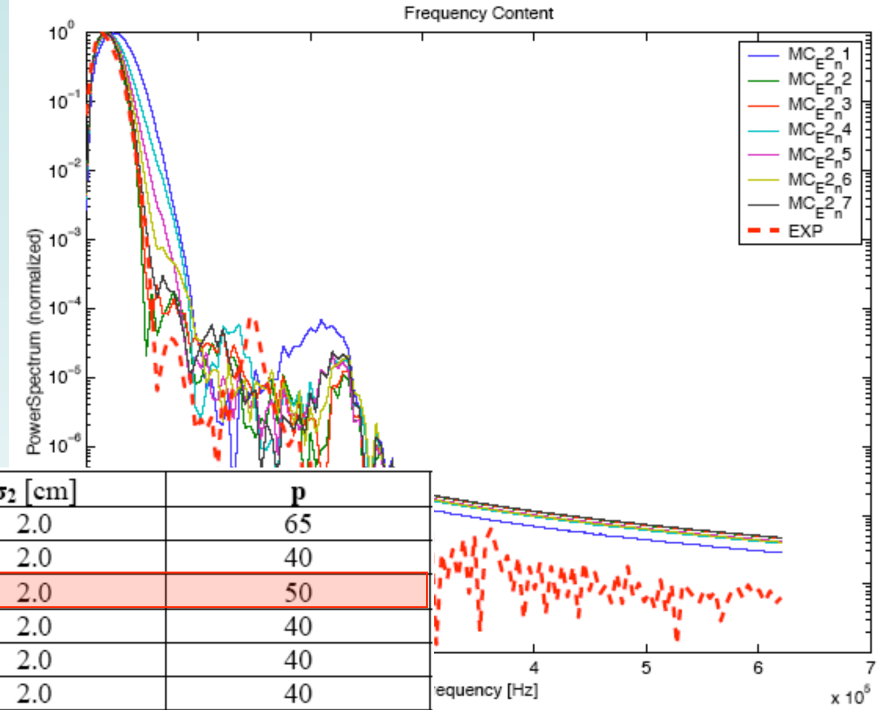

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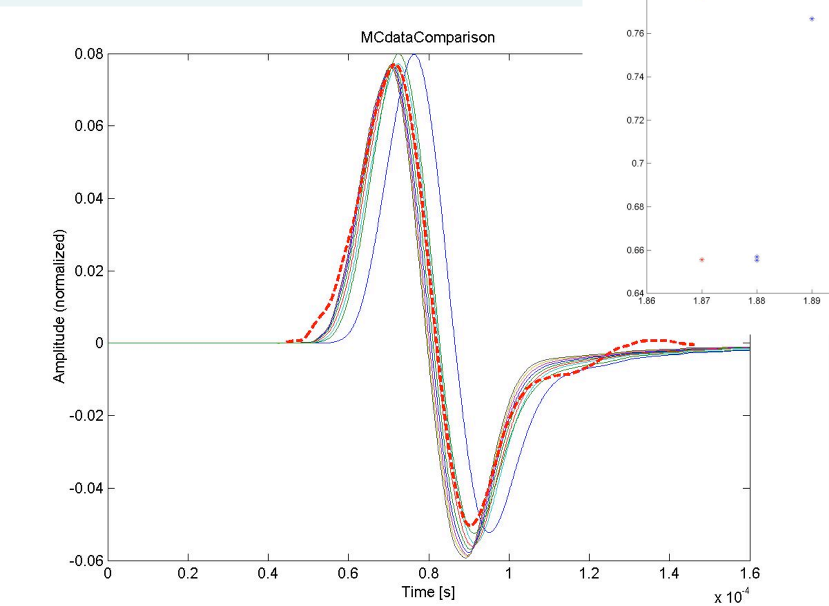
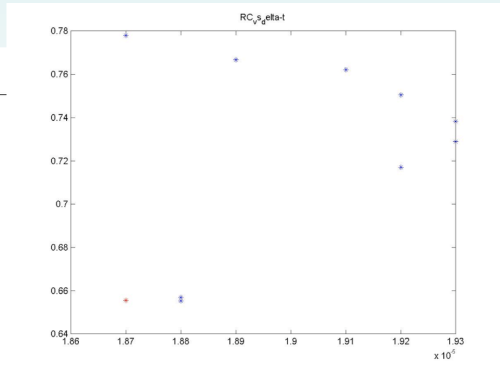
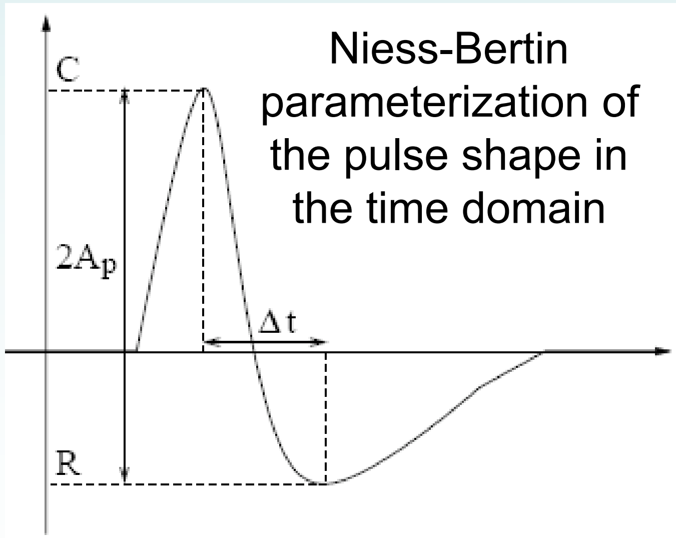
Investigating on the MonteCarlo
Hydro pos dependence

- The amplitude of the pulse depends on the Gruneisen coefficient
- The shape of the pulse depends on the shape of the source (i.e. beam profile and energy deposition in water) and the geometry of the detection (i.e. hydrophone position with respect to the source)
- Once that the beam profile is selected, one can "**move the hydrophone**" in order to find the position of the detector that best reproduces the experimental data.

A quantitative approach can be obtained using the **Niess-Bertin parametrization**





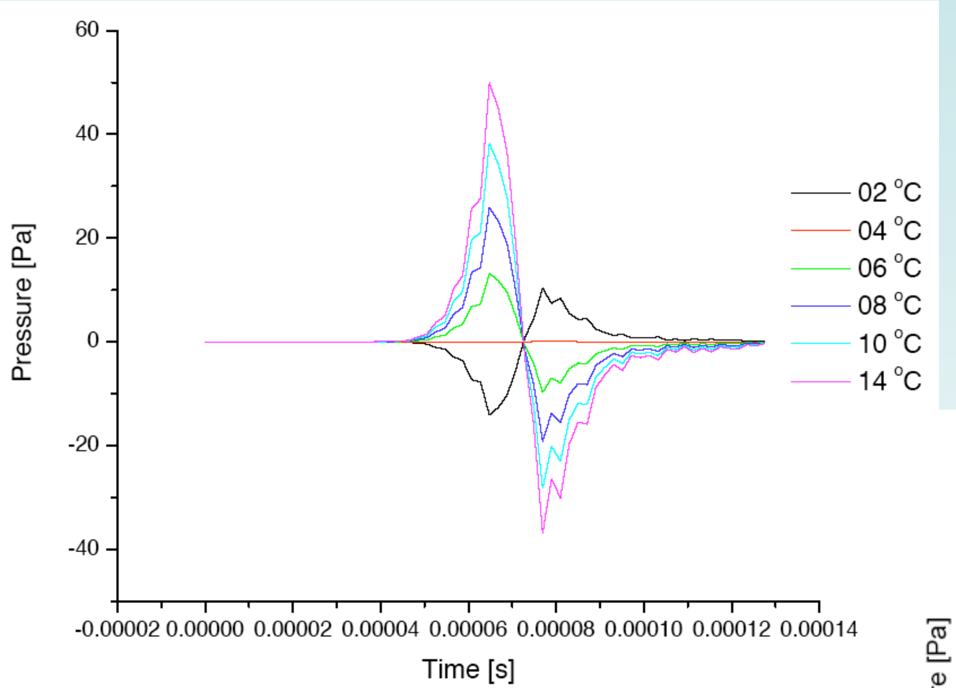


Niess-Bertin parameterization of the pulse shape in the time domain

Giulia De Bonis

V. Niess, V. Bertin, Astropart.Phys. Vol. 26, Issues 4-5, pp. 243-256 (2006), e-Print astro-ph/0511617.

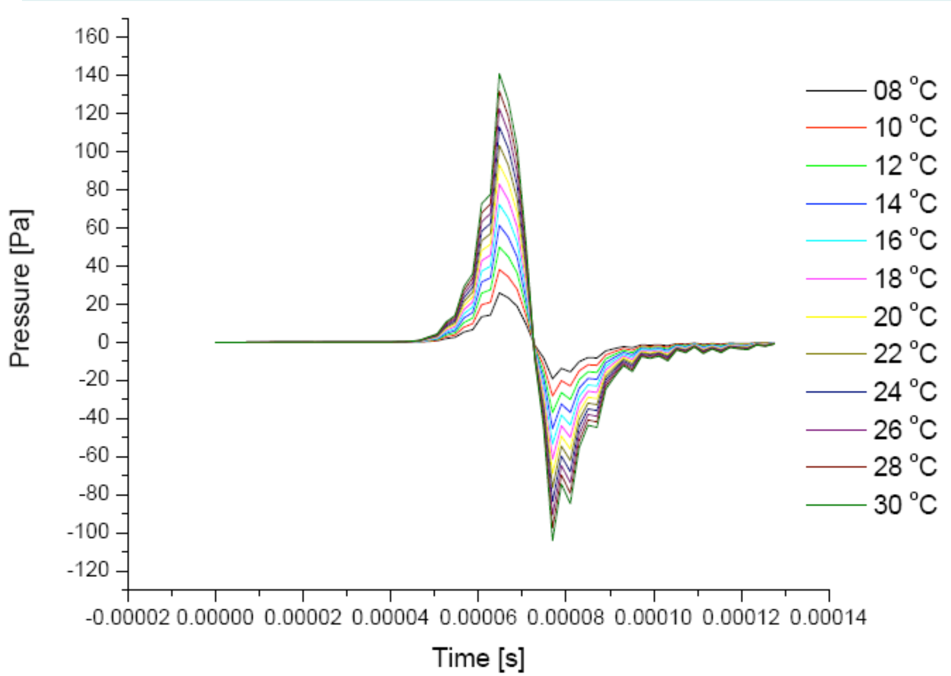
Investigating on the MonteCarlo
Temperature dependence



For a **fixed geometry** (hydrophone position and source shape), the amplitude of the signal depends only on the Gruneisen Coefficient, that is a **function of temperature**

E_p=200 MeV
$N_p=10^{10}$

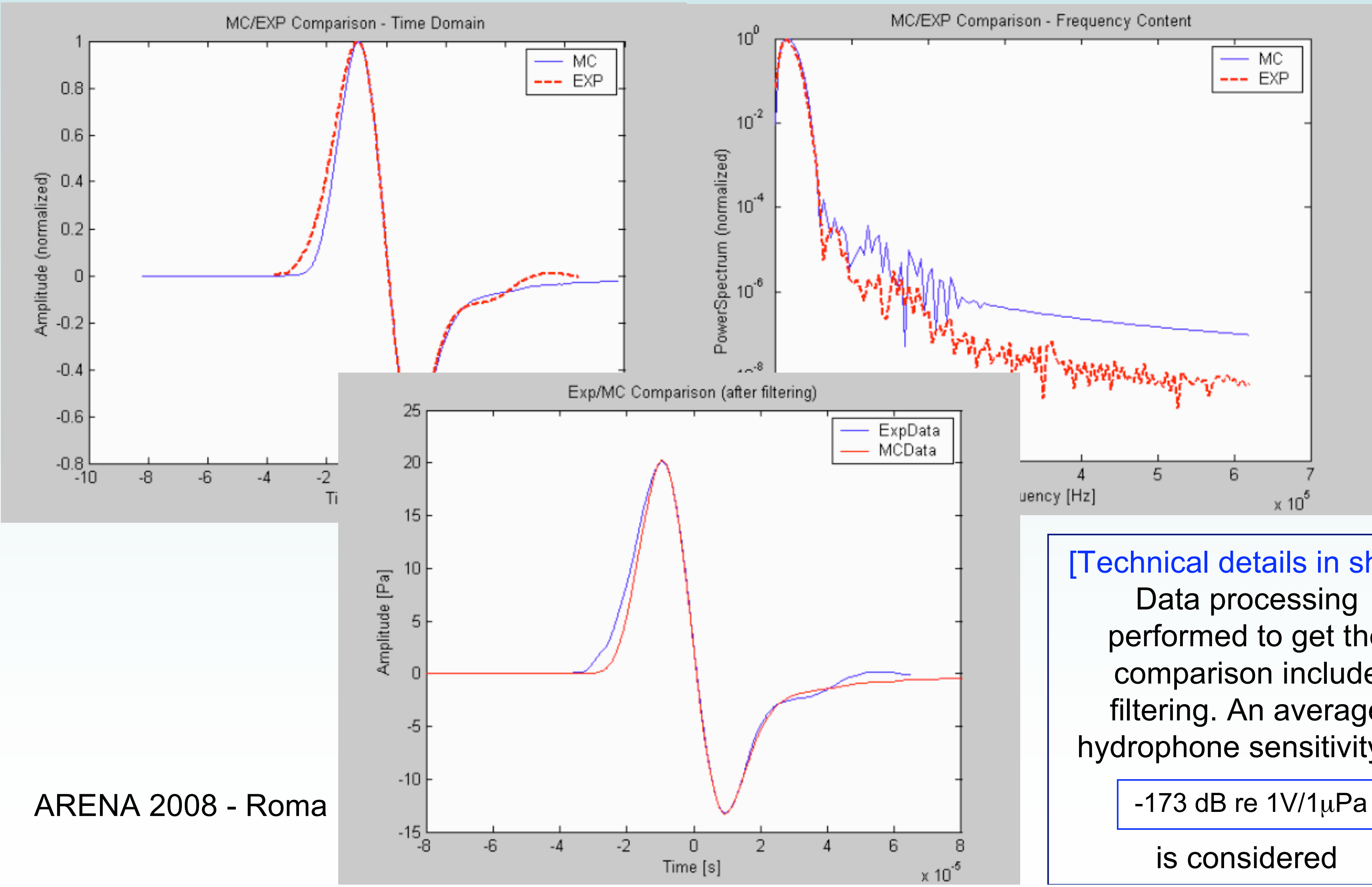
$$p(\vec{r},t) = \frac{1}{4\pi}\frac{\beta \cdot c_S^2}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^R}\frac{q(\vec{r}\,')}{R}d\sigma$$



The best agreement data/MC

[E=200 MeV, d=5 cm]

Selecting the “best” beam profile and the “best” hydrophone position, the best agreement data-MonteCarlo is obtained with T=15°

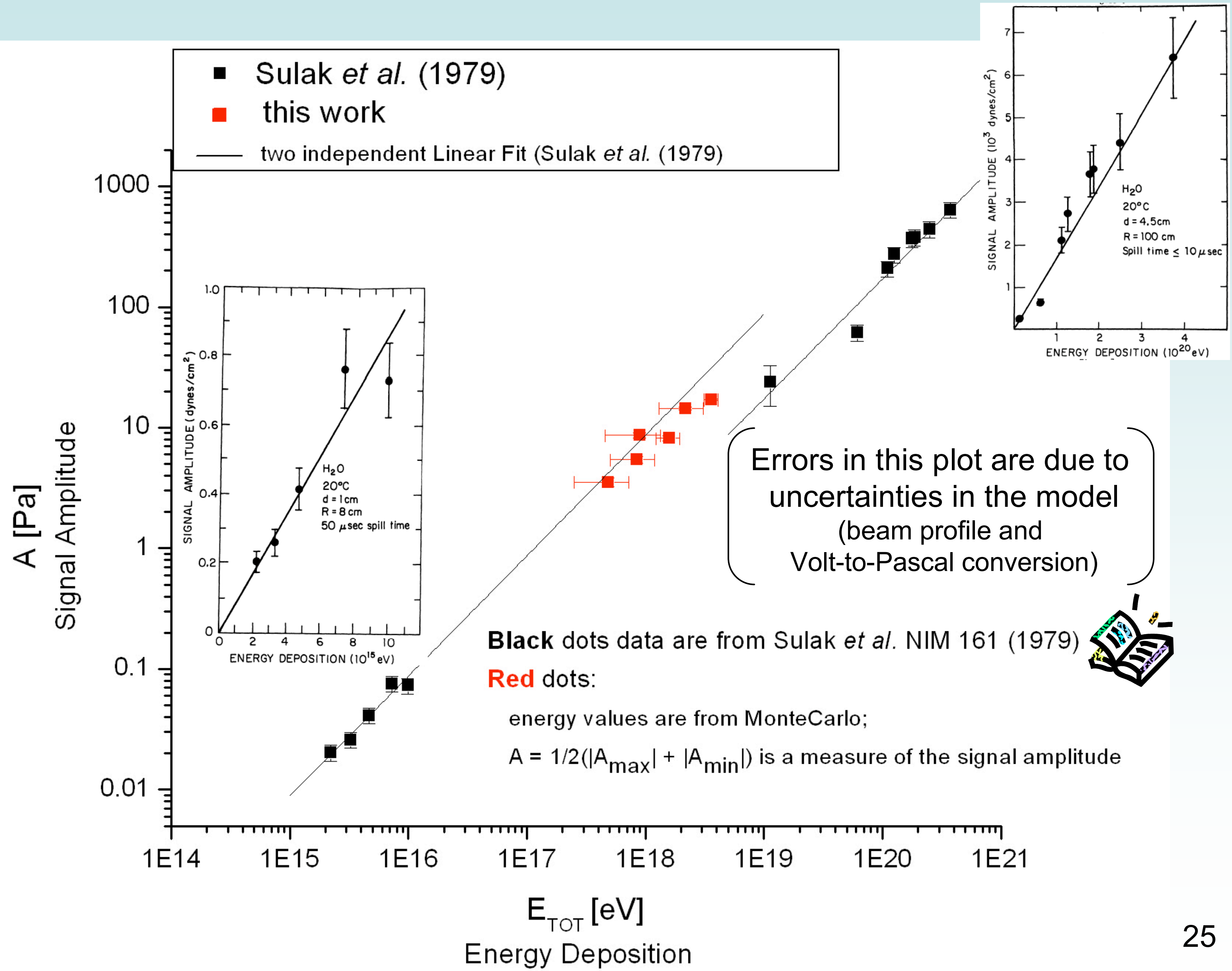


[Technical details in short]
Data processing performed to get the comparison include filtering. An average hydrophone sensitivity of

-173 dB re 1V/1μPa

is considered

Comparing with Sulak Data



Errors in this plot are due to uncertainties in the model (beam profile and Volt-to-Pascal conversion)

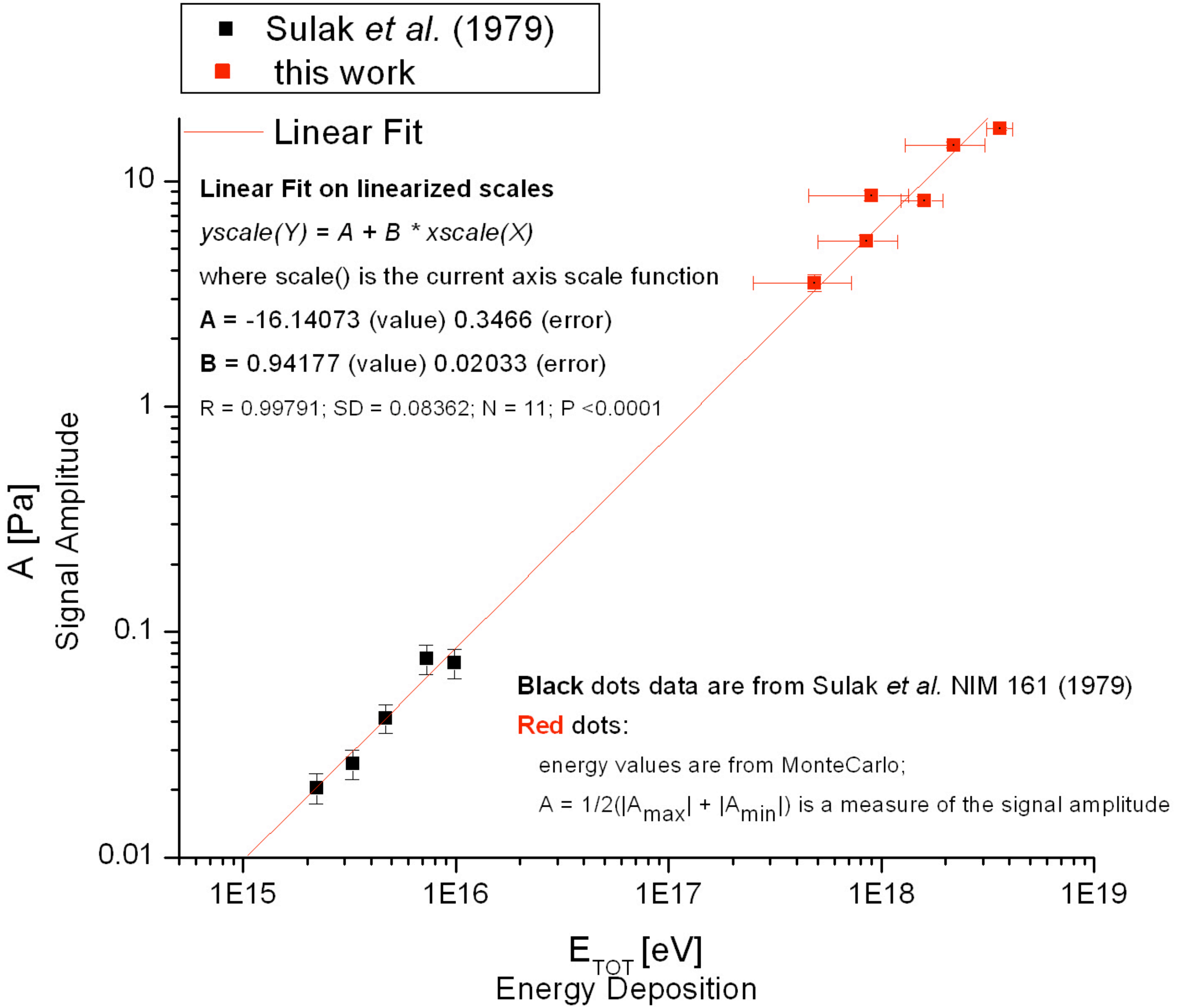
Black dots data are from Sulak *et al.* NIM 161 (1979)

Red dots:

energy values are from MonteCarlo;

$A = 1/2(|A_{max}| + |A_{min}|)$ is a measure of the signal amplitude

Comparing with Sulak Data →FIT



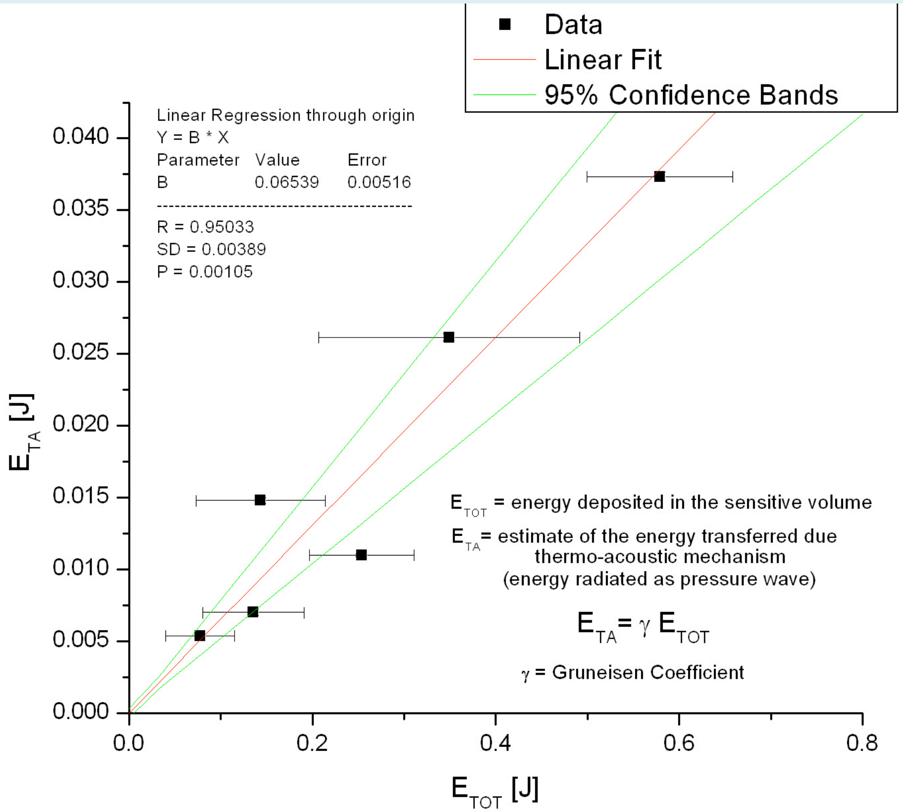
Finding GAMMA

An estimate of the Gruneisen coefficient can be extracted combining experimental data and results from simulation.
The estimate suffers of the same limits already discussed, i.e. **strong indetermination of environmental parameters and geometry**, that reflects mainly on large errors in the energy values.
A good results is, therefore, if the value obtained is compatible, as it is, with a range of expected gamma-values.

[Technical details in short]
The idea is to assume the Poisson formula

$$p(\vec{r},t) = \frac{1}{4\pi}\frac{\beta \cdot c_S^2}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^R}\frac{q(\vec{r}\,')}{R}d\sigma$$

for the experimental pulse and "go back", thus integrate over R and compute the surface integral (assuming an average value on an average sphere) to get an extimate of the amount of energy radiated as pressure wave, i.e converted via the thermo-acoustic mechianism



γ=0.6539

↓

T=12.65°

considering the Confidence Bands, temperature in the range (10.75°, 14.65°) is allowed with 95% confidence

Conclusions & Perspectives

- After the preliminary results presented @ARENA2005 (Zeuthen), the ones presented today can be intended as "conclusive" results from the ITEP-2004 Test Beam.
- The Test Beam produces **confirmation of the thermo-acoustic mechanism of sound generation**, as results in comparing MC and data. An additional confirmation comes from the **good agreement with previous measurements** performed by Sulak *et al* (1979).
- The MC is a valid tool to better understand the acoustic pulse generation. It also can provide (even if with large uncertainties) some clues to extract information on unknown parameters, as water temperature, hydrophone position, beam profile.
- Further test set-ups can be planned to investigate the acoustic signal induced by particles interaction in water. A mandatory recommendation for the future is to include a strict control on environmental parameters and geometry.
- The next step is to **keep concentrate on neutrinos**, **developing simulation techniques** to reproduce neutrino energy losses in water and **going to the far field**, in order to estimate the signal expected in an underwater km3 neutrino telescope – and thus developing reconstruction algorithms to get the best signal-to-noise ratio.