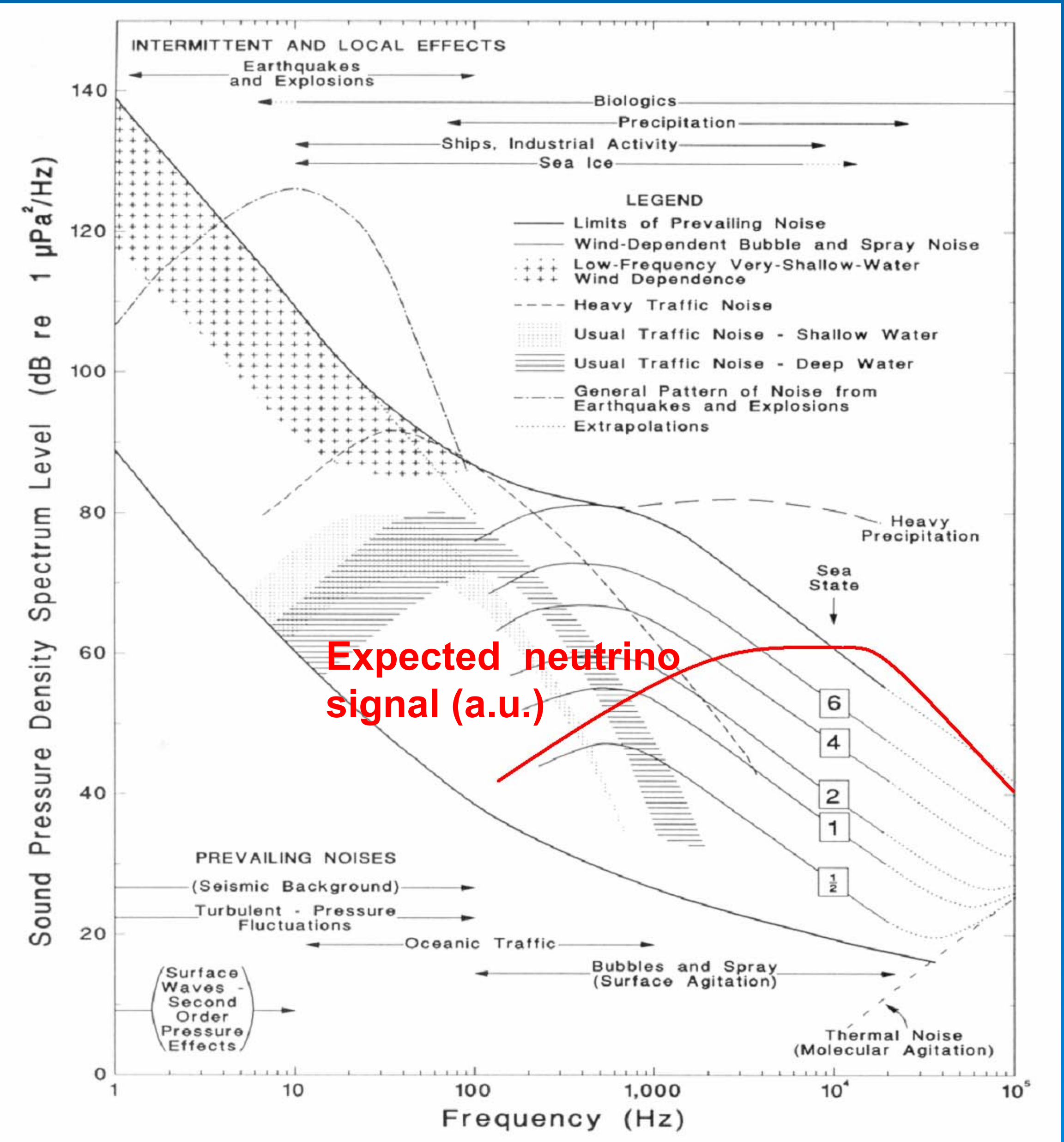
RECENT DEVELOPEMENTS
ON
FIBER OPTIC AIR-BACKED MANDREL HYDROPHONES

- **Introduction**
- **Possible aplications**
- **Prototype**
- **Preliminary results**
- **Future planning**

M.Anghinolfi, A.Cotrufo, S.Cuneo, D.Piombo, A.Plotnikov, L.Repetto
INFN Genova

Acoustic detection of pressure waves in water



Most interesting application:

•Military

•Tracking of mammals

•Detectionof shock waves reflected by the sea bed

.... and possibly
•Detection of hadronic shower produced by UHE ν's

First proposal

О. Л. Песков, В. И. Кротов, Н. Д. Сергеев. Большую работу по обработке экспериментального материала выполнили инженер З. Ф. Дерюгина и техник Н. А. Гущина.

Поступило в редакцию 22 II 1957 г.

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Гидродинамическое излучение от треков ионизирующих частиц в стабильных жидкостях

Г. А. Аскарьян

Прохождение ионизирующих частиц в жидкостях сопровождается увлечением молекул среды расталкивающимися скоплениями одноименно заряженных ионов и микровзрывами при локальных нагревах, создаваемых вблизи треков частиц. Эти процессы могут привести к образованию локальных пустот и зародышей паро-газовой фазы. (Превращение этих зародышевых полостей в пузырьки види-

рующей частицы, и через C—совокупность начальных параметров создания ионных рывков или образования полостей (например, начальные характеристики ионных скоплений или локальных нагревов), однозначно характеризующую процесс излучения. Тогда в широком интервале скоростей частиц

$$dn = n(Z, \beta, C)\, dC \simeq \frac{Z^2}{\beta^2}\, n_1(C)\, dC,$$

G.A Askarian: hydrodinamical emission in tracks of ionizing particles in stable liquids. 1957

and later....

G.A.Askarian, B.A.Dolgoshein, A.N.Kalinovsky, N.A.Mokhov:
Acoustic detection of high energy particle showers in water.
Nucl. Inst. and Meth., 164 (1979), 267.
"... All this gives good reason to believe that the acoustical method of particle detection may find applications both at accelerators of the new generation and for detection of cosmic neutrinos in the Ocean"

experimentally confirmed by

L.Sulak, et al. :
Experimental studies of the acoustic signature of proton beams traversing fluid media", Nucl. Inst. and Meth., 161 (1979),203

Neutrinos from where?

Production mechanism

1. **Emission of jets**

2. **Fermi acceleration mechanism** $\rightarrow$

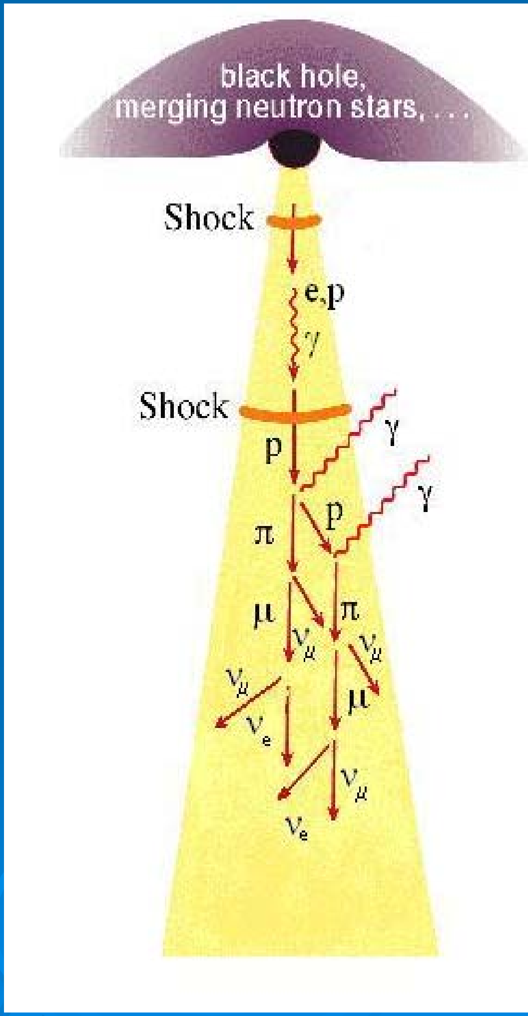
   proton spectrum: $dN_p/dE \sim E^{-2}$

3. **p+p → p + N + π**

$\rightarrow$Neutrinos from succcesive π and μ decay

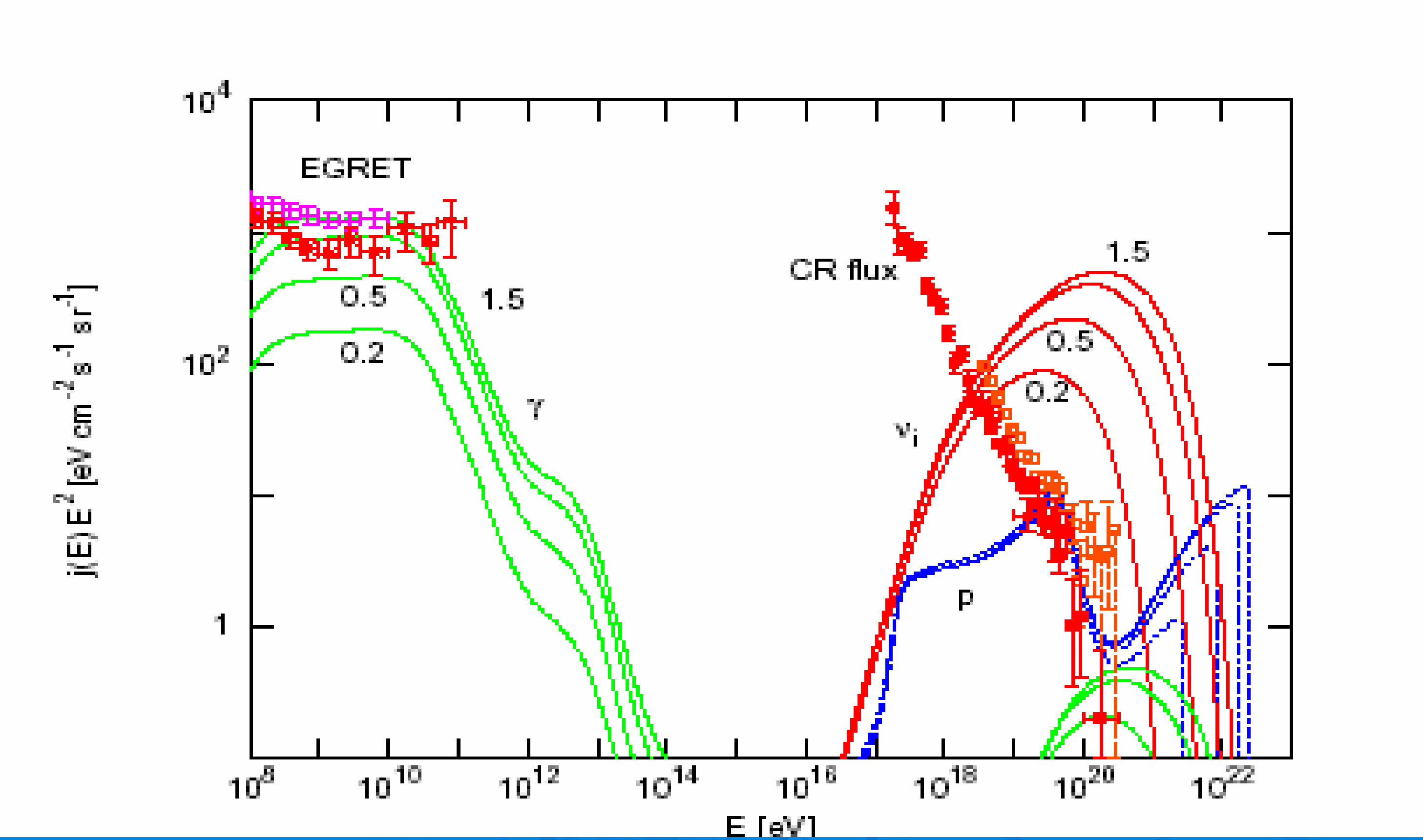
4. **Another mechanism: from π decay produced in the interaction of p with CMB at energies above ~ 10^{19} eV**

Cosmic source



An exemple: the ‘cosmogenic neutrino flux’

created by decaying charged pions produced in interaction of primary nucleons of energy above 5×10^{19} eV with CMB photons, the Greisen-Zatsepin-Kuzmin effect(D.Semikoz, G. Sigl, hep-ph/0309328 29 sep 2003)



Why acoustic detection ?

•High energy neutrinos interact via DIS with matter (1% probability in 1 km of water at 10^{20}eV).

•Energy is shared between a quark ad a lepton; on the average 80% to the lepton and 20% to the hadronic shower (≈ Joule for 10^{20}eV neutrinos) .

•The hadronic shower is confined (typically a 2 cm. Radiux x 20 m length cylinder) and produces detectable pressure waves.

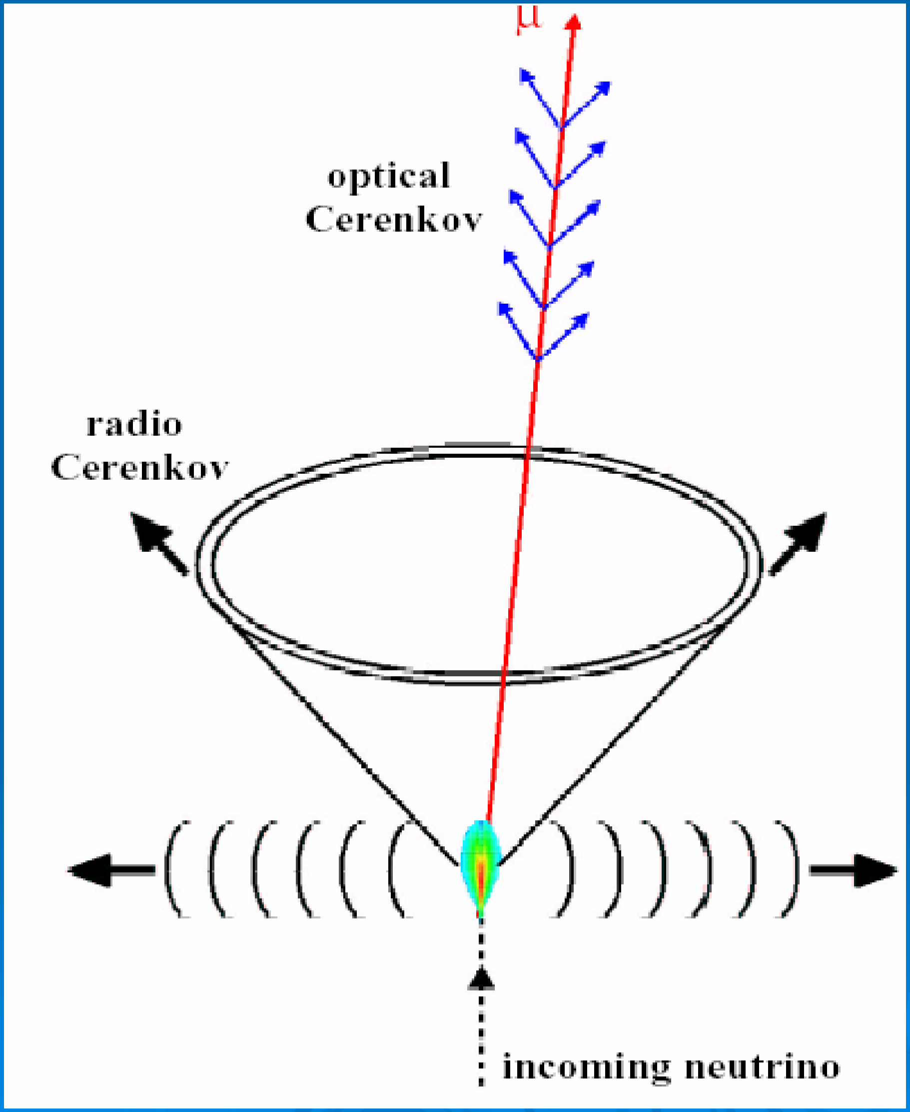
• the acoustic front has a typical disk shape('pancake'), the pressure wave is bipolar, ≈ 50 μs period, amplitude ≅ mPa or higher depending on the initial energy and distance

•The signal propagates for several km (attenuation lenght of 1km at 20 kHz)

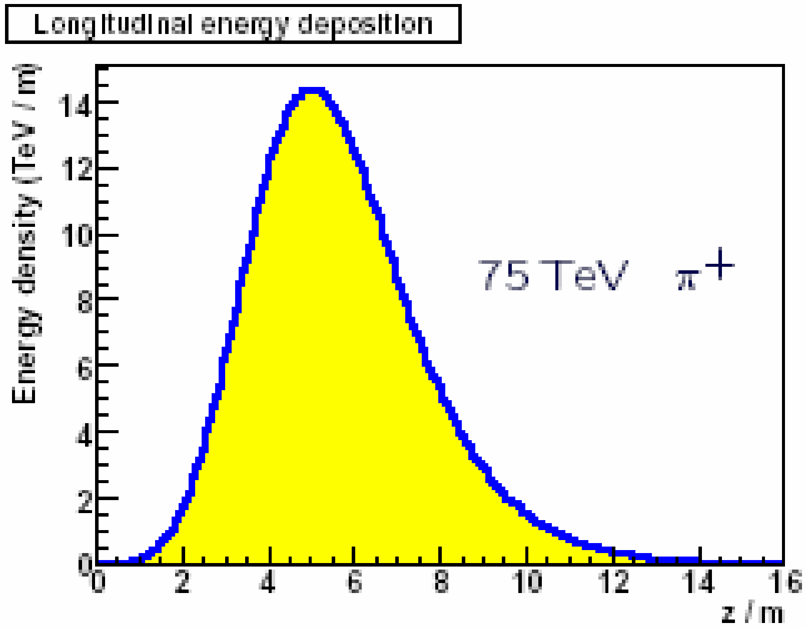
→

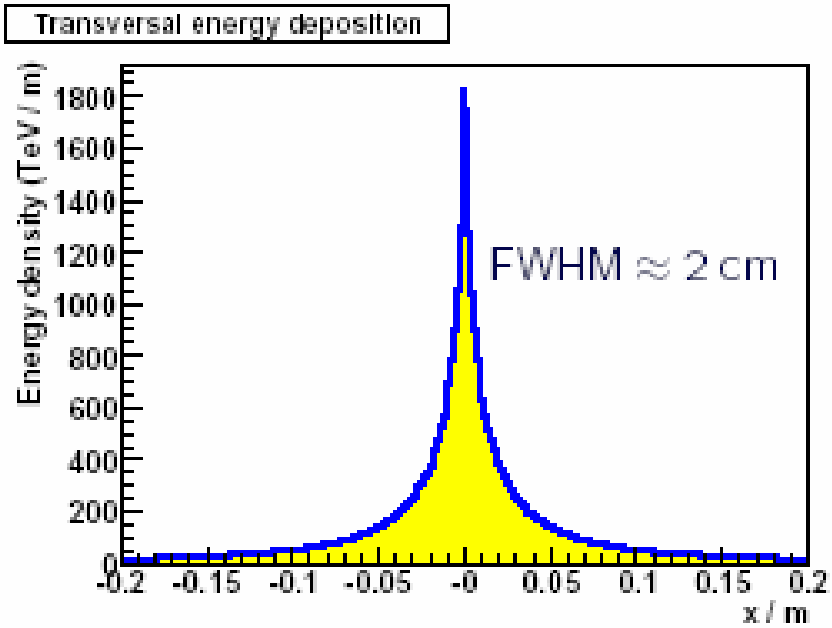
at high energies (≥ 10^{18}eV) the acoustic detection may be an alternative to Cerenkov light detection (attenuation lenght ≅ 50 m)

The production mechanism



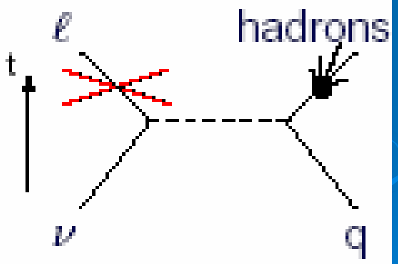
Hadronic Showers





- neglect primary electromagnetic showers due to LPM effect
- full 3D simulation of the energy deposition with GEANT4
  - shower extension (nearly) independent of energy

  $\Rightarrow$ energy density scales linearly with energy
- numeric integration of energy density gives bipolar acoustic signal $p(\vec{r}, t)$



The acoustic signal

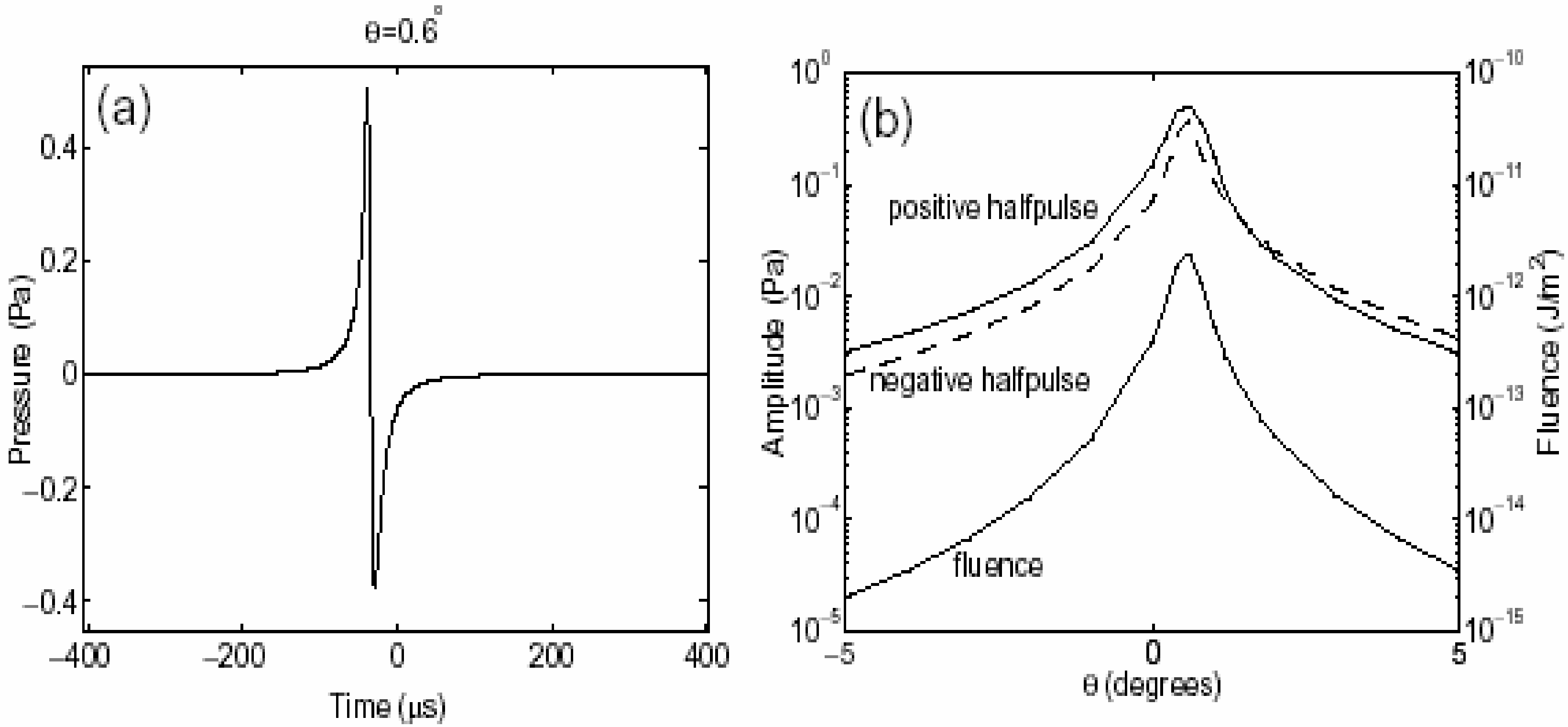
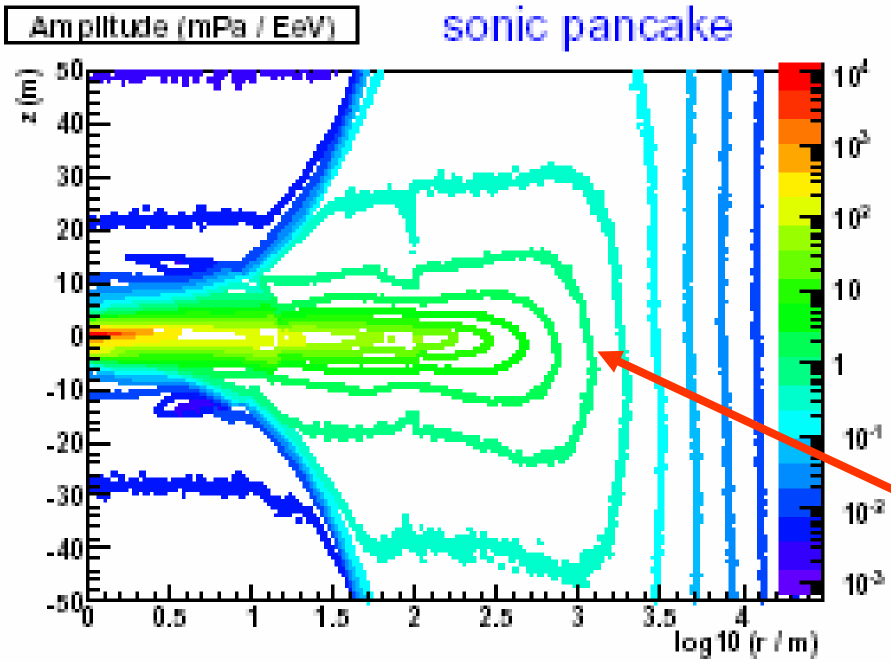


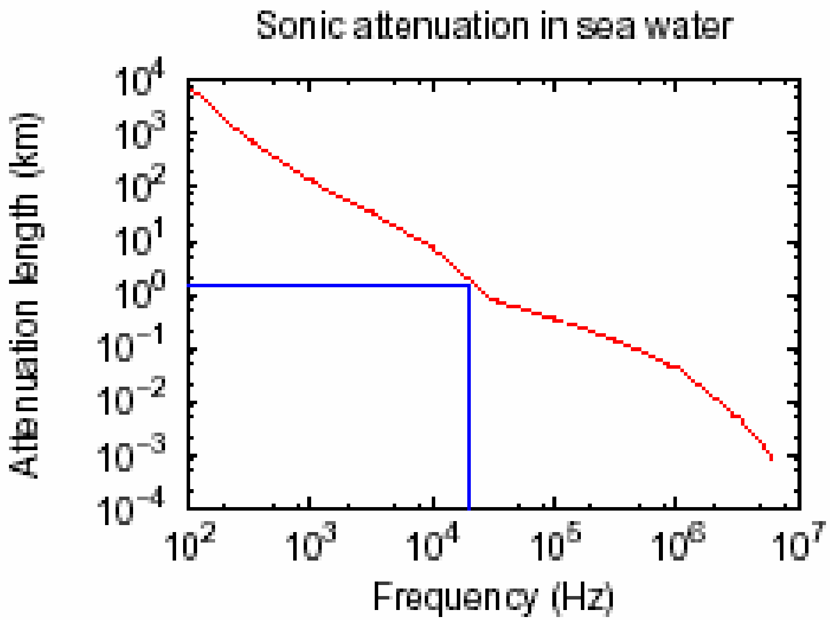
FIG. 4: Results of calculations of the acoustic signal from the hadronic part of the neutrino-induced shower [38], at the distance of 1000 m from the shower axis, for a primary hadronic energy of 10^{20} eV: (a) the pulse shape at the observation angle of $\theta = 0.6^\circ$, where the amplitude is maximal; (b) the pressure amplitude of the pulse and the total energy fluence in the pulse, $(\rho c)^{-1} \int_{-\infty}^{+\infty} p^2\, dt$. These last two quantities are plotted as functions of observation angle as defined in Figure 3.

Signal Propagation

- attenuation length strongly frequency dependent
- central frequency of signal ≈ 20 kHz

⇒ attenuation length ≈ 1 km

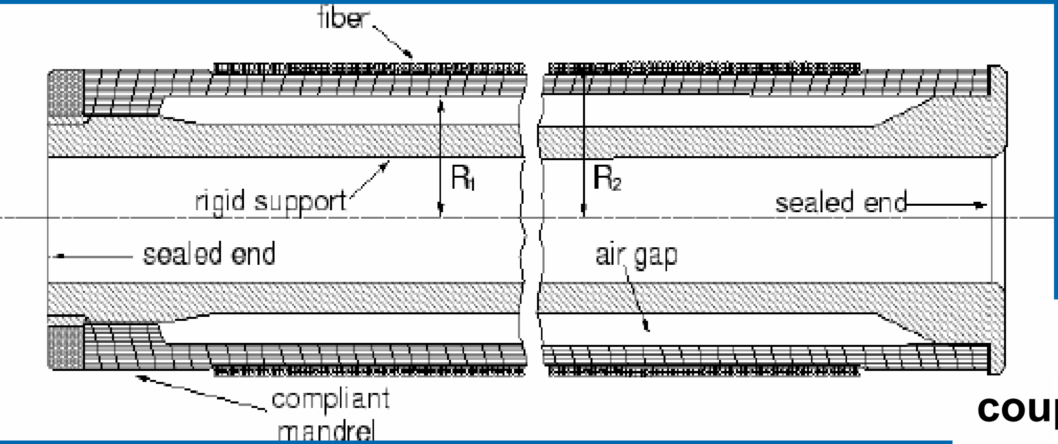


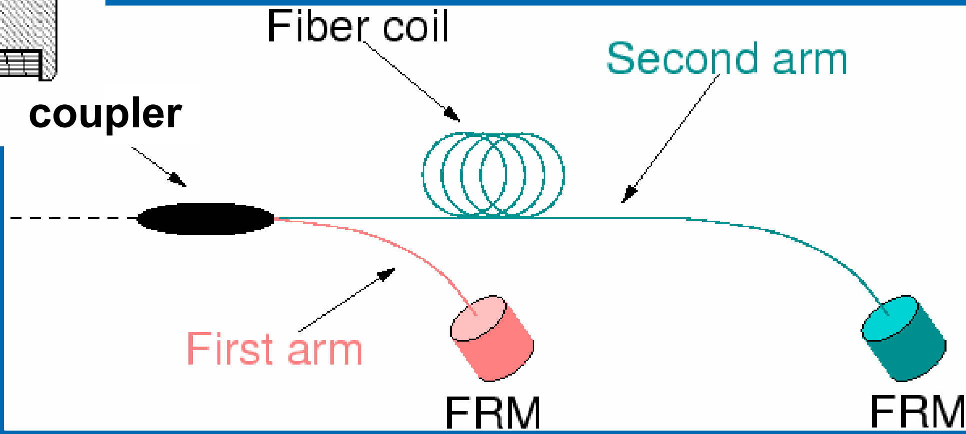


- sonic disc well collimated for distances up to 1 km

~1mPa @1000m distance from a 10^{18} eV ν shower

The air backed mandrel hydrophone





- An optic fiber is wrapped outside a thin walled hallow cylinder
- The cylinder is mounted outside a passive inner tube with sufficient clearance to provide air backing.
- This air gap allow the cylinder to deform in response to incident acoustic waves.
- This deformation, proportional to the pressure, is measured by sensing the corresponding fiber length variation.
- To this purpose a Michelson interferometer is used; Bragg gratings embedded in the core of the fibre reflect the light from a laser

Main advantages

•Quite easy to fabricate
•Not expensive
•Driven by a laser source on shore
•Immune from electrical noise
•Do not require local power supply nor ADC conversion
•Can be arranged in large arrays by using multiplexing technique

Present acheavement

•**high sensityvity: below Sea State Zero at 5 kHz**
•**Brandwidth up to 5-10 kHz**

•Our purpose

•**Increase upper limit of the bandwidth (20 kHz ?)**
•**Increase operational depth (1500 m ?)**

Modeling.....

1. Materials

Young modulus E and Poissons' ratio ■ are the leading parameters in the design

Material	Young modulus	Poissons' ratio
	(GPa)	
Aluminum	70	0.33
Ultem1000	3.3	0.44
Ultem2400	11.7	0.37
Core/cladding	72	0.17
coating	1.1	0.45

For a composite material effective elastic parameters are obtained according to their cross sectional area

e.g.: 0.5 mm thick Ultem1000 mandrel +5 layers 80/135 μm fibres: E_{eff}=13.4 GPa

2. Geometry

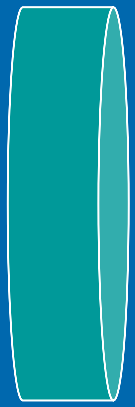
Responsitivity mostly depends on:

- Radius, length, thickness, of the cylinder,
- number of optic fibre layers, type of optic fibre (80/135 – 80/165 μm)
- Effective Young modulus, Poissons' ratio and density

3. Responsitivity

relates the response of the hydrophone to its geometry and the external pressure;

$$\frac{\Delta L}{L} \approx \frac{\Delta \phi}{\phi} \approx \varepsilon_{\phi\phi} \equiv \frac{1-\bar{\nu}^2}{\bar{E}} \frac{R}{t} P$$

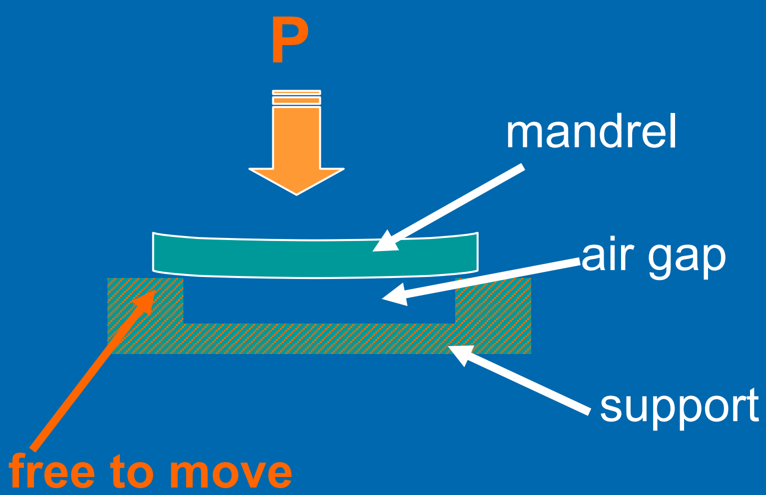


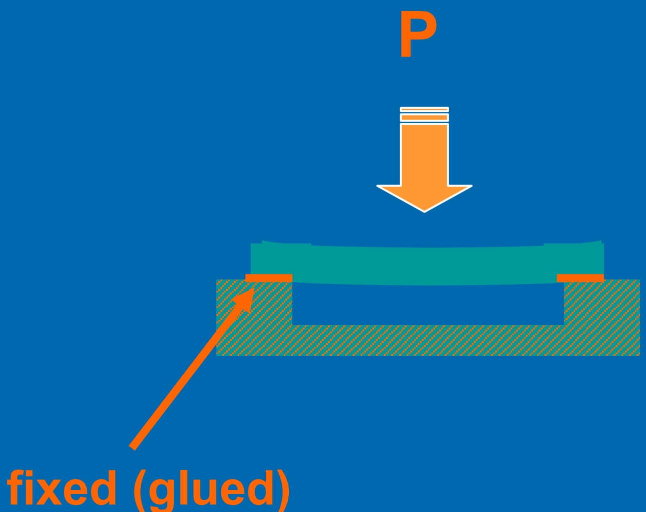
Ultem 2400
2R=40 mm
t = 1mm
5 layers of fibres
$\varepsilon_{\phi\phi}$= -303 dB re μPa

Ultem 1000
2R=15 mm
t=0.5 mm
5 layers of fibres
$\varepsilon_{\phi\phi}$= -308 dB re μPa

Must be corrected for the finite length of the cylinder !!

4.Correction due to the finite length and to the end-constraints





$\varepsilon_{\phi\phi} = \varepsilon_{\phi\phi}(1\text{-}C_1)$

$\varepsilon_{\phi\phi} = \varepsilon_{\phi\phi}(1\text{-}C_2)$

C_1,C_2 are a complicated function of E, ν, r ,t, L

						$\varepsilon_{\phi\phi}$ (dB re μPa)		
type	material	r (mm)	L (mm)	T (mm)	#layer	No edge effects	free	glued
'old'	Ultem1000	10	40	0.5	3	-302	-303	<-330
'slim'	Ultem1000	7.5	26	0.5	5	-308	-309	-326
'fat 1'	Ultem2400	18	10	0.5	5	-302	-307	<-330
'fat 2'	Ultem2400	18	10	1	5	-304	-311	<-330

5.Response in frequency

Obtained from the normal modes of vibration of a cylindrical shell in vacuum

Solutions expressed in terms of the displacements u,v,w in the axial, circumferential and radial directions.

$$u=U_{m,n}(x)\cos(n\theta)\cos(\omega t)$$
$$v=V_{m,n}(x)\sin(n\theta)\cos(\omega t) \qquad 0<x<L$$
$$w=W_{m,n}(x)\cos(n\theta)\cos(\omega t)$$

n, number of circumferential waves, **m** number of axial half periods

→ **The radial “breathing mode” (m,n)=(1,0) gives the major contribution to the fiber length change i.e. to the frequency responsitivity of the idrophone**

Behaviour in air

The frequency associated to the fundamental mode with n=0,m=1

- Increase with shell thikness t
- decrease with radius R
- decrease with length L

$$\varpi_{radial} = \frac{E}{\rho(1-\nu^2)R^2}\left(1+\frac{t^2\pi^4R^2}{12L^4}\right)$$

type	r (mm)	L (mm)	T (mm)	#layer	ω_{radial} (kHz)
'old'	10	40	0.5	3	50
'slim'	7.5	26	0.5	5	63
'fat 1'	18	10	0.5	5	38
'fat 2'	18	10	1	5	41

Behaviour in water

- The fluid lower the frequency of the resonance due to the added mass
- The fluid lower the amplitude of the resonance due to re-radiation of the acoustic wave
- See detailed analysis J.M.Scott: J. Sound and Vibration 125 (1988) 241

For the lowest radial 'breathing mode' the displacement $W_{1,0}(\omega)$

$$W_{1,0}(\omega) = \Delta p_{\omega} \frac{R^2(1-\nu^2)}{Et} \frac{1}{\left(\frac{\rho_{shell}(1-\nu^2)R^2\omega^2}{E}\right)\left(1+\frac{\rho_{fluid}}{t\rho_{shell}}\frac{K_0(\gamma R)}{\gamma K_1(\gamma R)}\right)-1-\frac{t^2\pi^4R^2}{12L^4}}$$

where

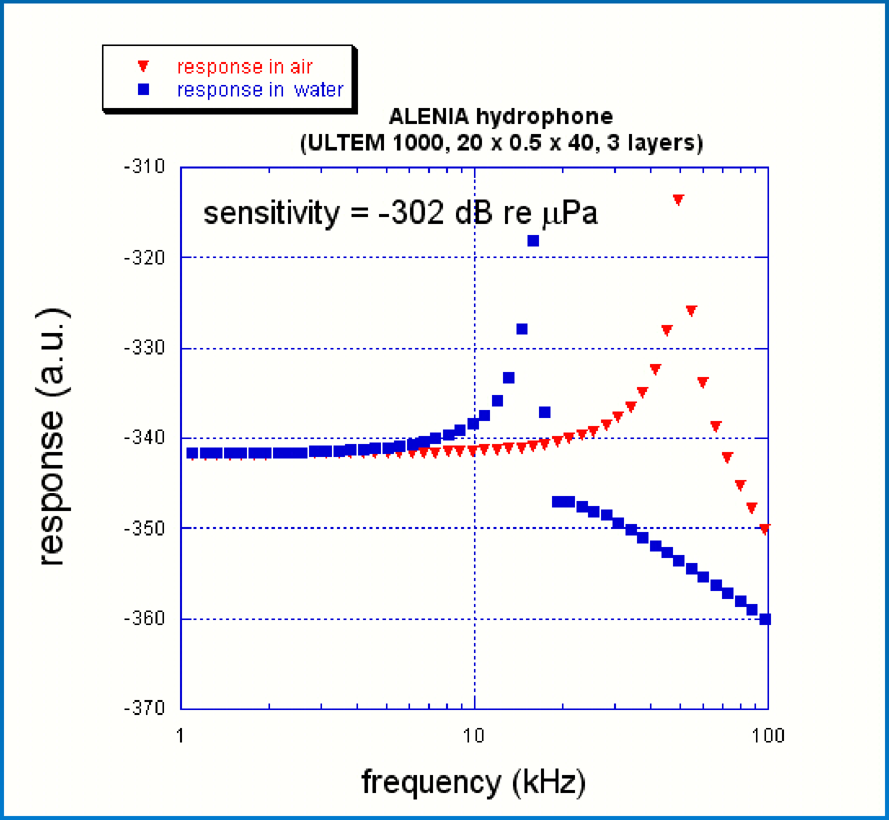
$$\gamma^2 = \frac{\pi^2}{L^2} - \frac{\omega^2}{V_s}$$

V_s is the sound velocity in water

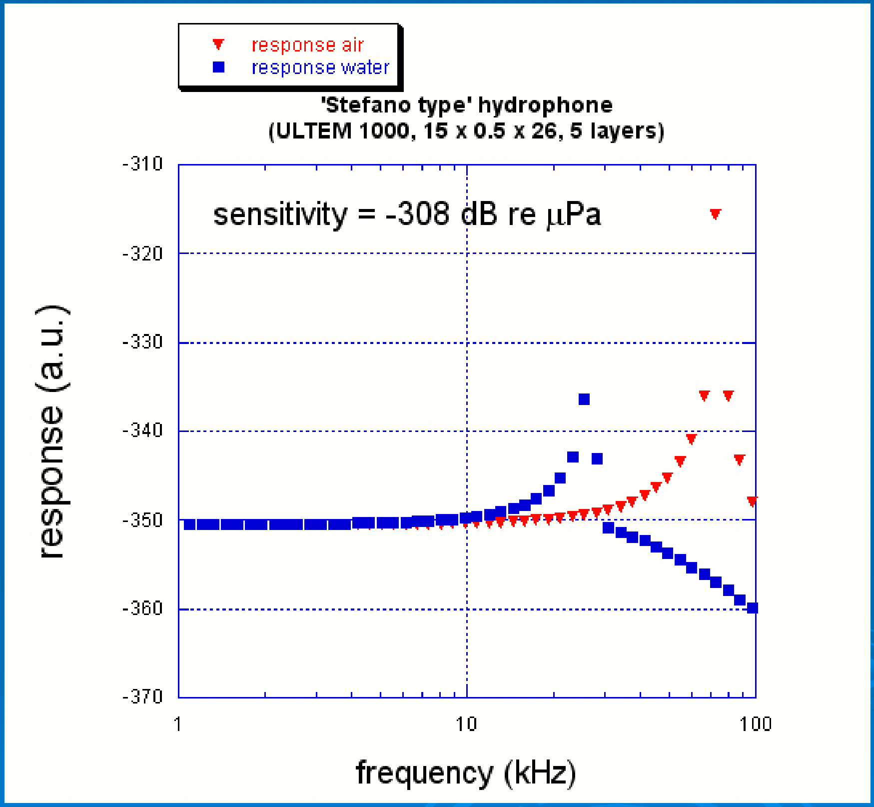
$$K_0(\gamma R), K_1(\gamma R)$$

Modified Bessel functions, may be complex

Response in water vs air

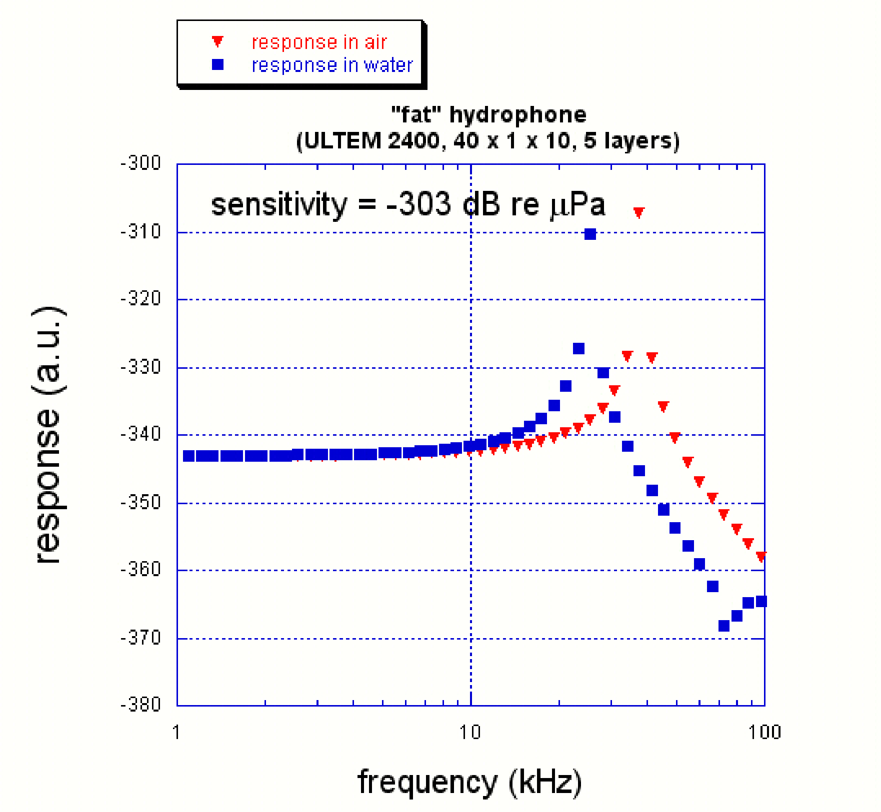


ALENIA

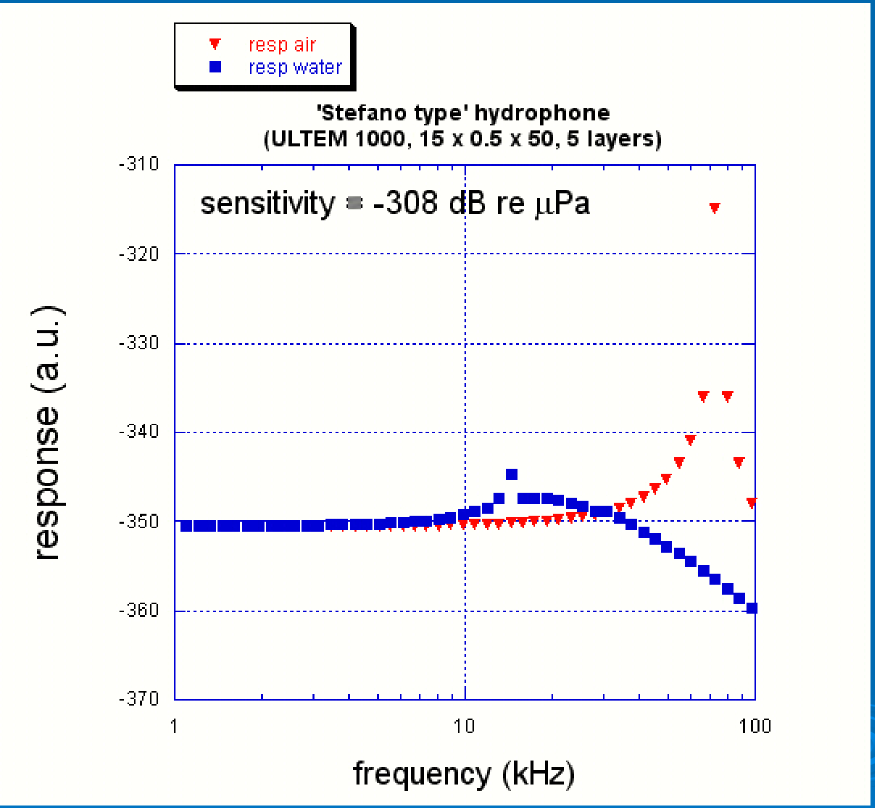


'slim'

Response in water vs air



‘fat’

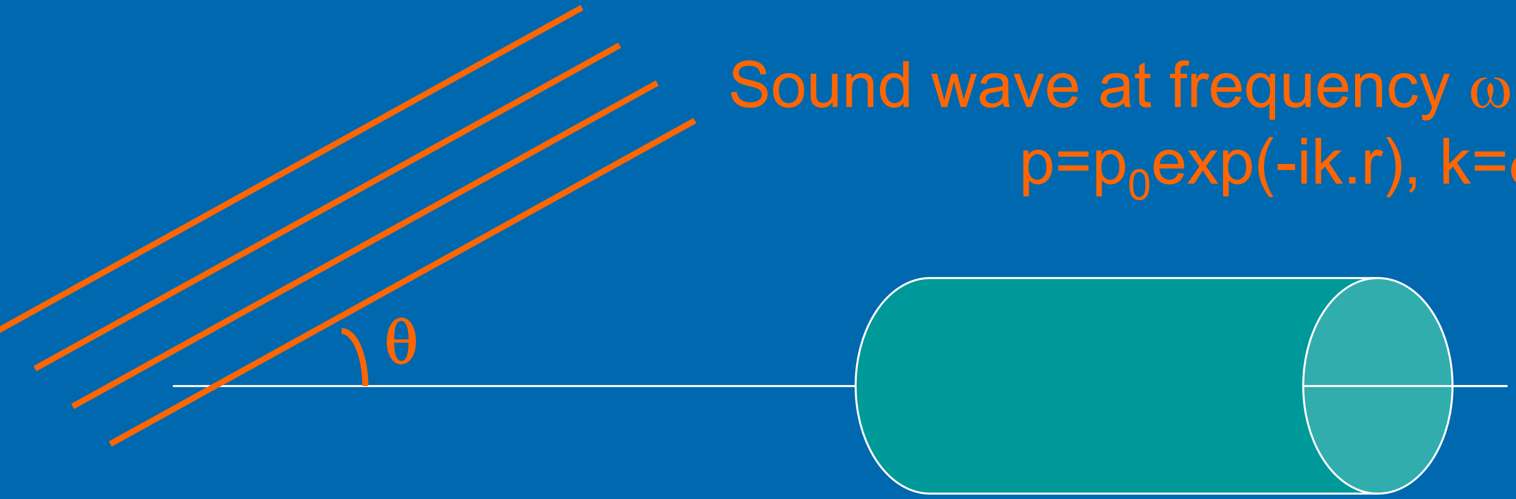


‘slim and long’

Directionality

Sound wave at frequency ω and angle θ:

$p=p_0\exp(-ik.r)$, $k=\omega/v_s$

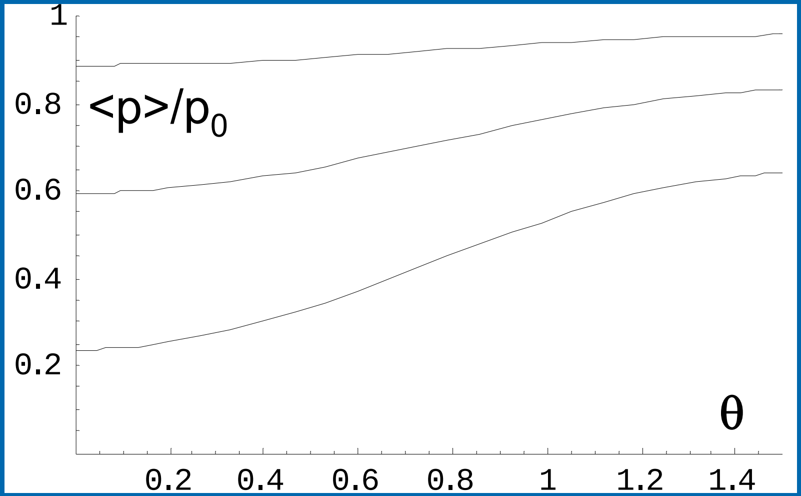


Calculate the mean pressure <P> over the cylinder surface of radiur R andlength L:

$$\frac{<P>}{P_0}=\frac{1}{L}\frac{1}{2\pi R}\int_0^L\int_0^{2\pi}\exp(-i(KR\sin\theta\cos\phi+Kx\cos\theta)Rd\phi dx$$

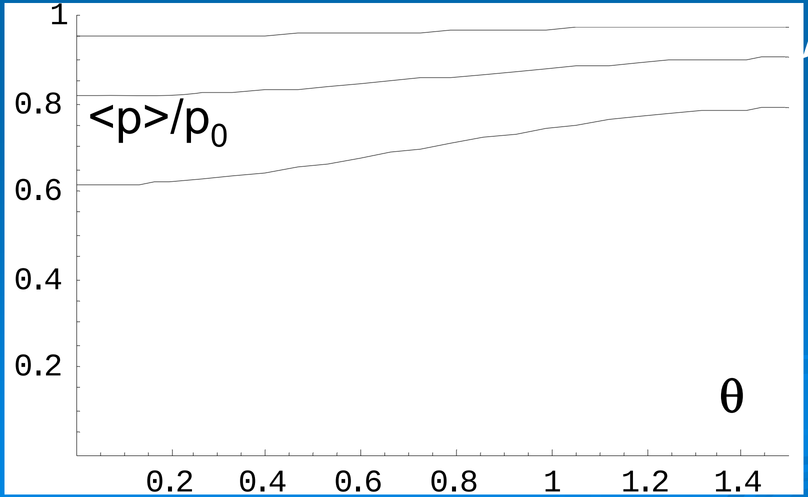
$$\frac{<P>}{P_0}=\frac{\sin\left(\dfrac{\omega L}{2v_s}\cos\vartheta\right)}{\dfrac{\omega L}{2v_s}\cos\vartheta}J_0\left(\frac{\omega R}{v_s}\sin\vartheta\right)$$

Response in water (v_s=1500m/s)

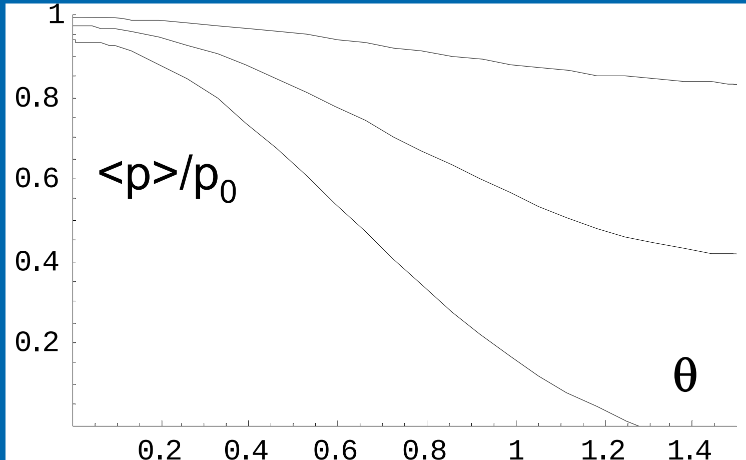


10 kHz
20 kHz
30 kHz

'**Alenia**' type: R=10mm, L=40 mm



'**slim**': R=7.5 mm, L=26 mm



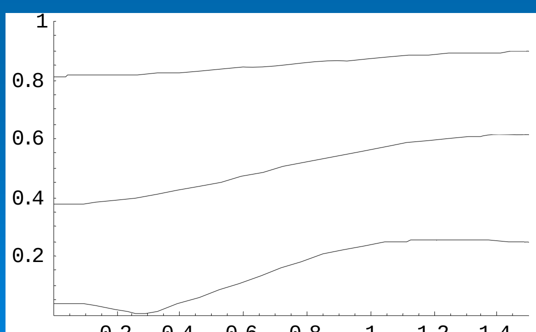
10 kHz

20 kHz

30 kHz

‘**fat**’: R=20 mm, L=10 mm
directionality more pronounced

Exemples of directionality in air: v_s 1500m/s→ 340 m/s
$\lambda_{air} \approx 1/4\ \lambda_{water}$ directionality much more pronounced

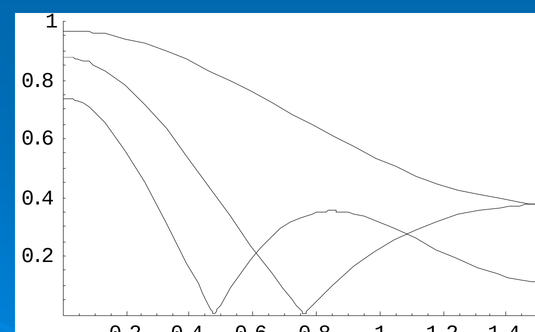


‘**slim**’

5 kHz

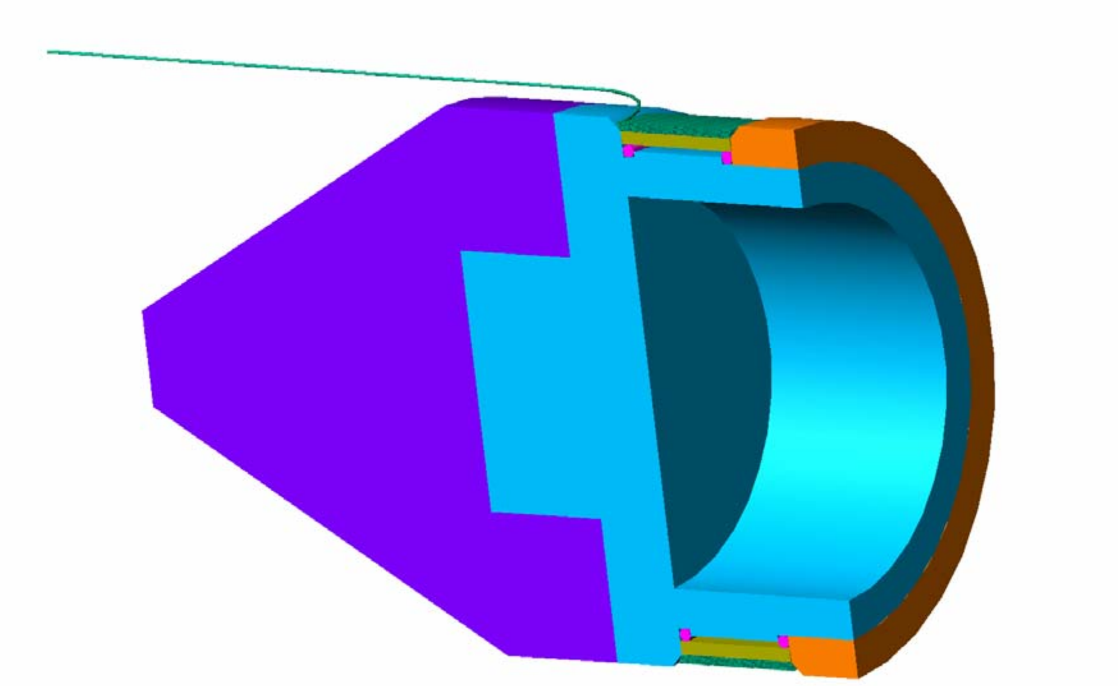
10 kHz

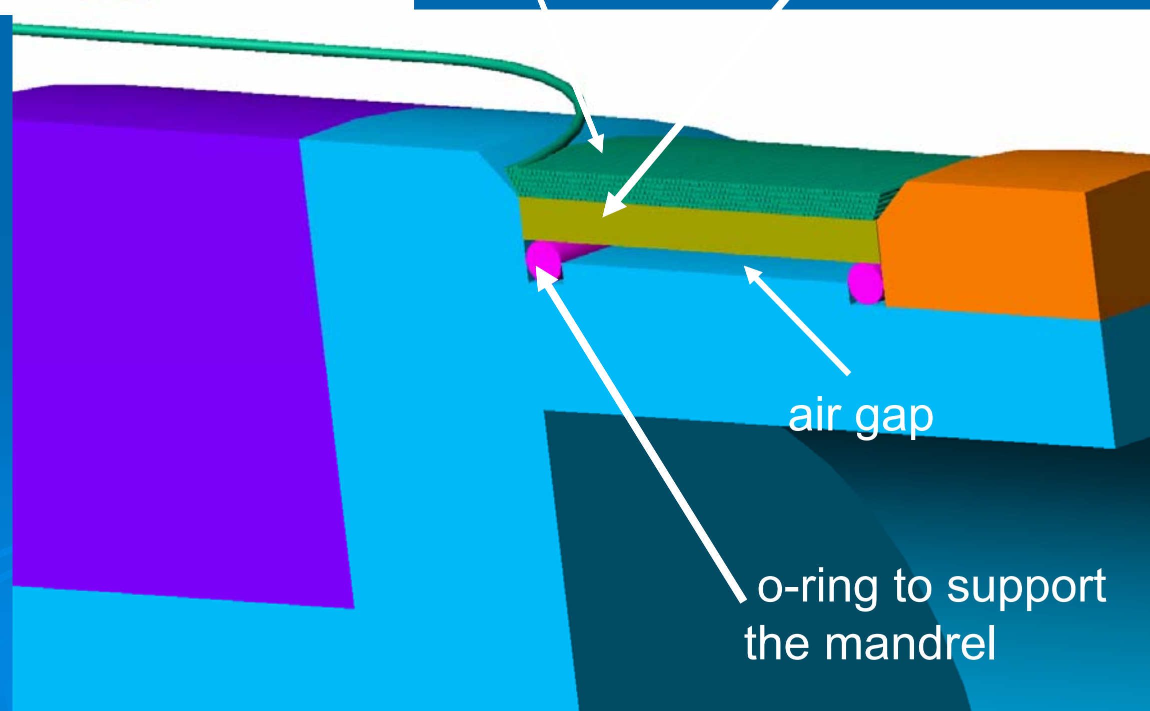
15 kHz

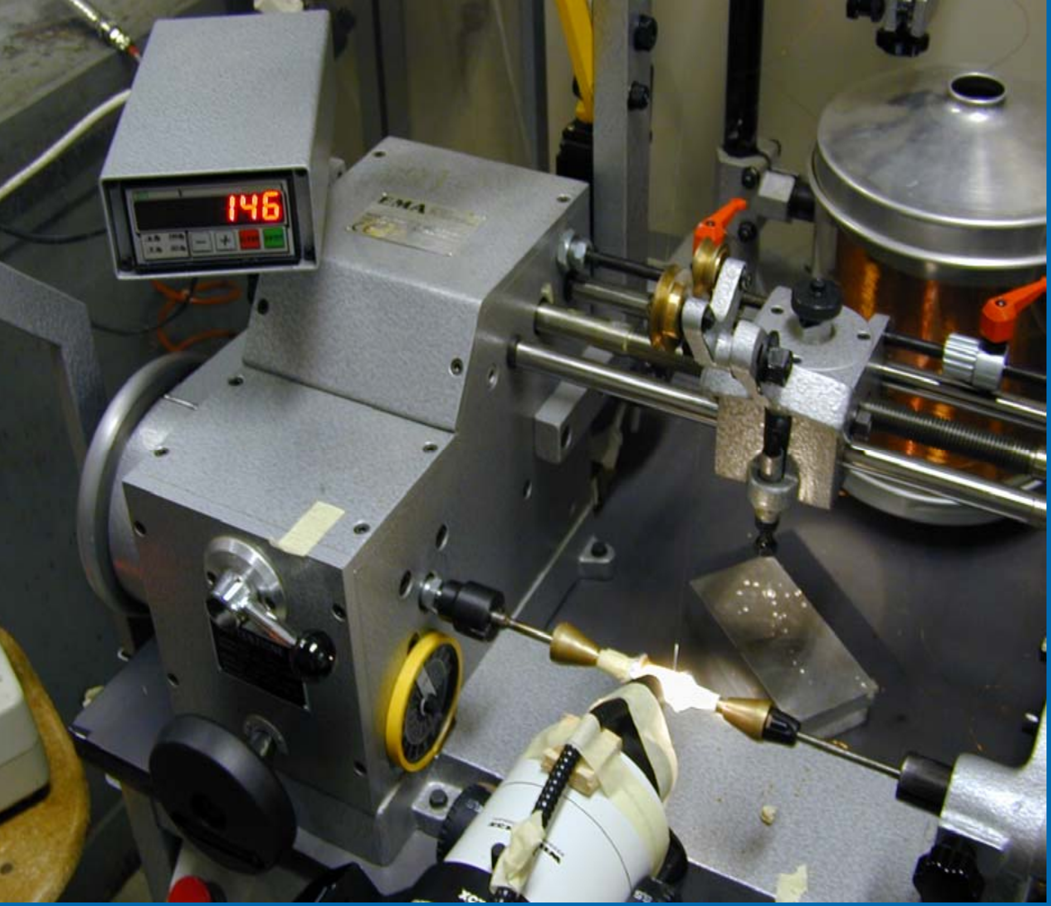


‘**fat**’

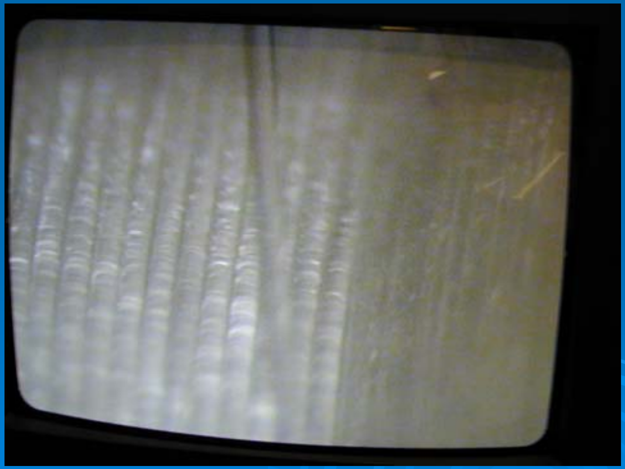
Modeling the ‘fat’ hydrophone





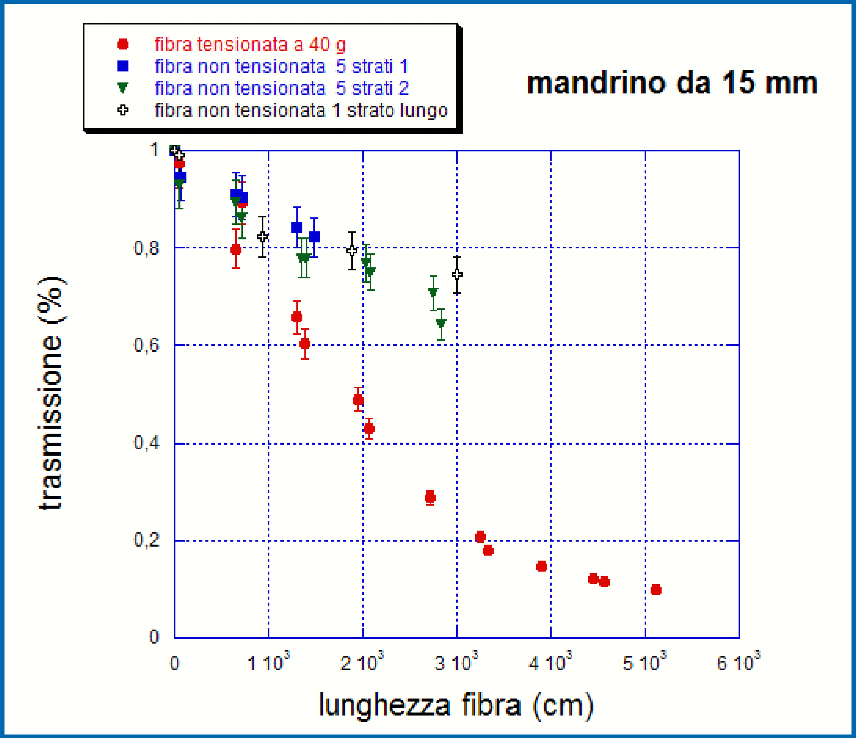


Winding the optic fibre

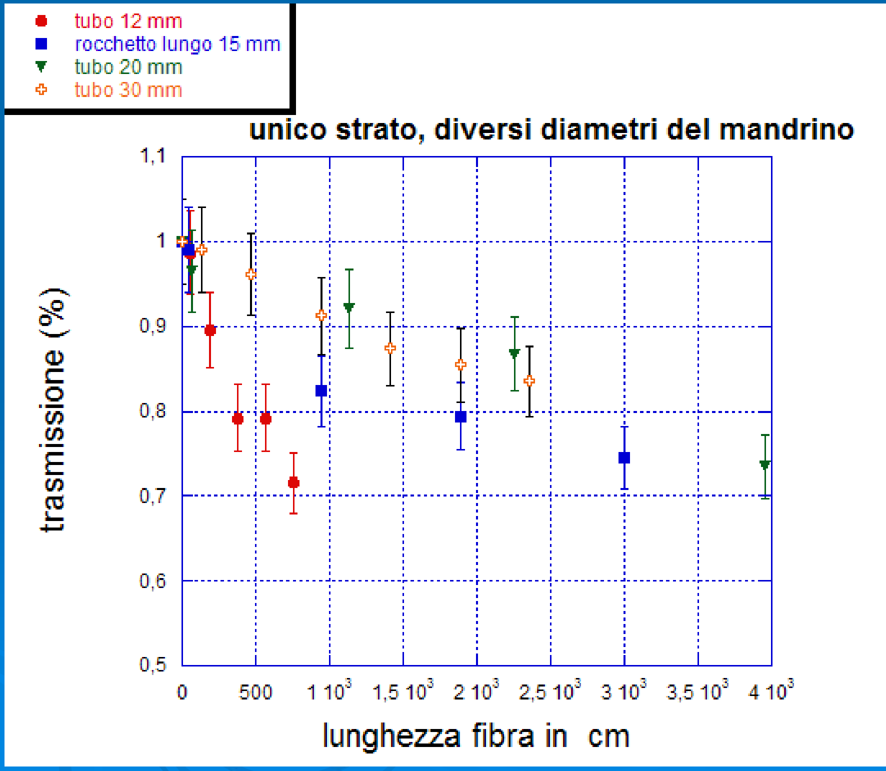


Some tests performed to define the winding procedure

Pre-tensioning of the fibre



Different diameters of the hydrophone

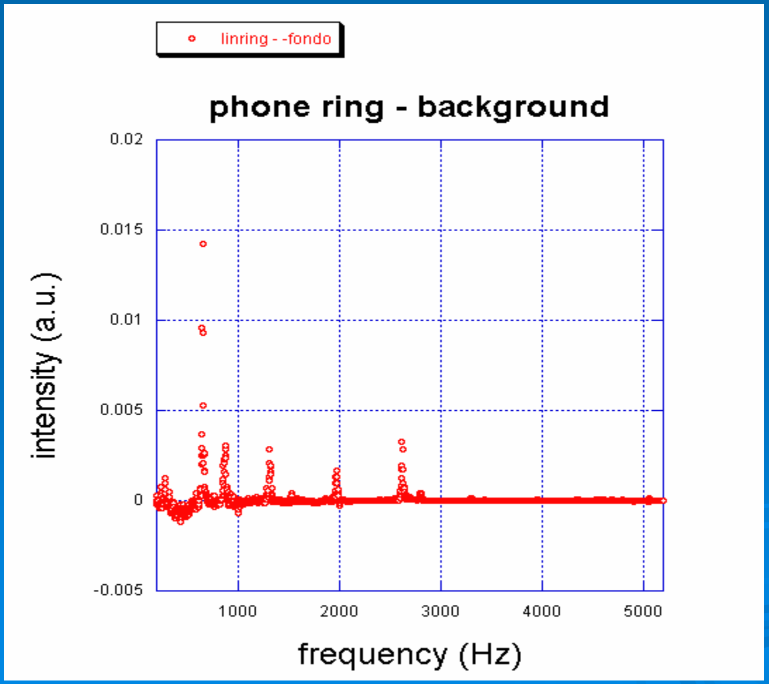


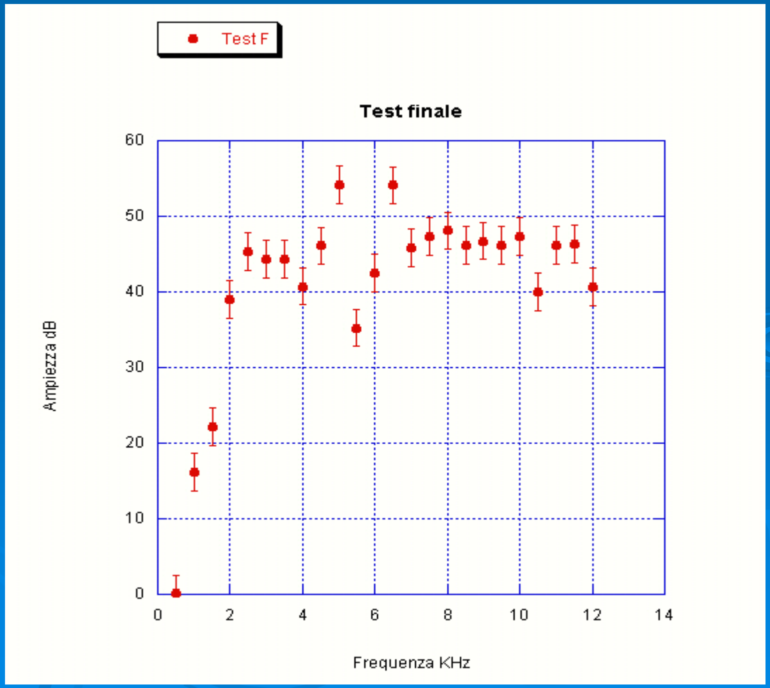
One prototype already realized

The hydrophone without the polyurathane coating

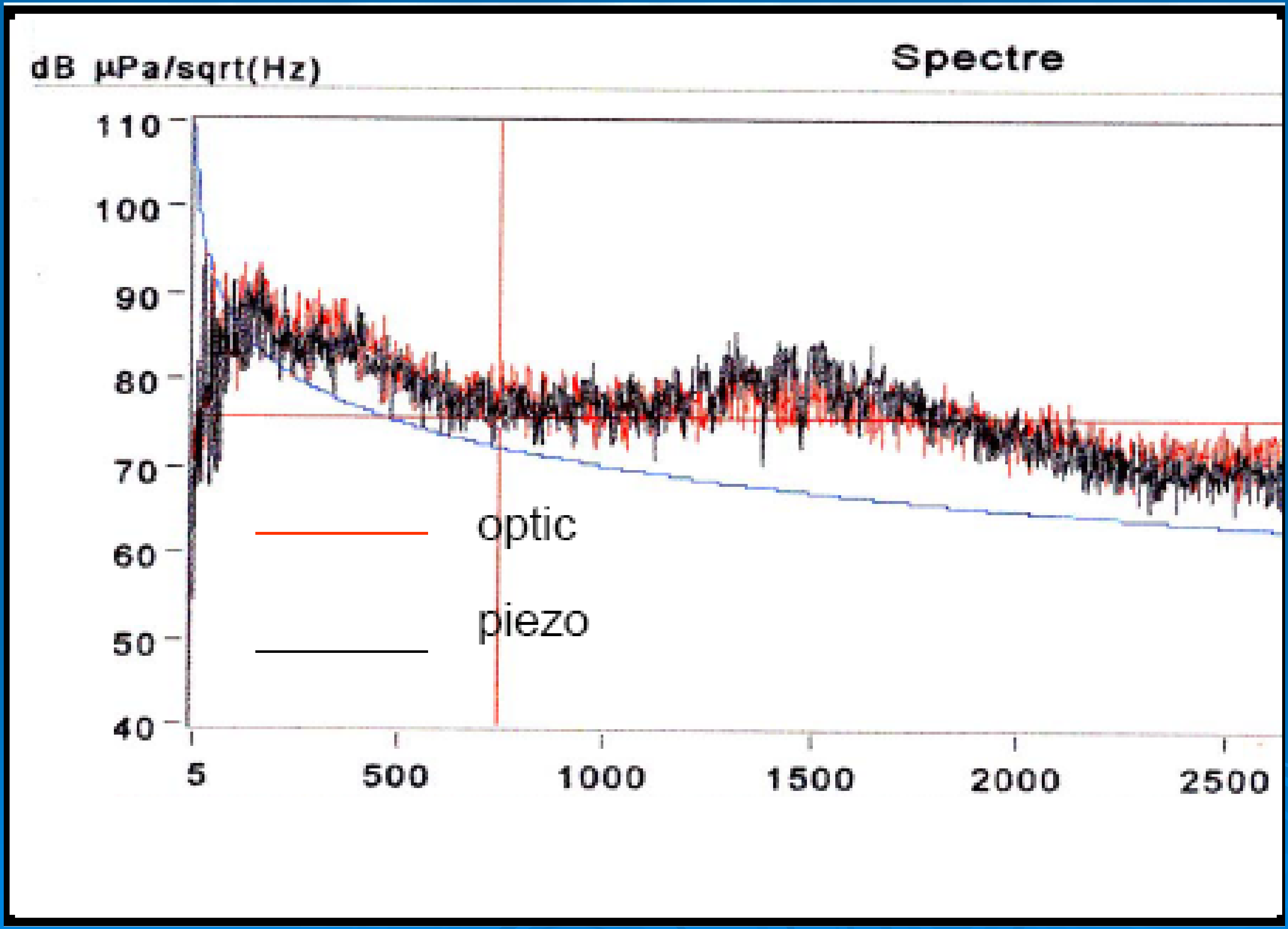
Record of a phone ring

The frequency response in air





comparison with piezo hydrophone



Work is just started... a lot of things ahead

- Complete the present prototype: polyurathane coating.

- Possible alternative : ‘fat’ vs ‘slim’ . Main advantages: less attenuation in the fibres, directionality (?), resistent to deeper depth. Detailed FEA calculations needed.

- Extend the present read out system from 10 to 20 kHz.

- Perform accurate calibration in air and water at different frequencies.

- Realize an hydrophone array.

- Start to calculate optimum geometry configuration and reconstruction tools for a large volume neutrino detector based on hydrophone arrays

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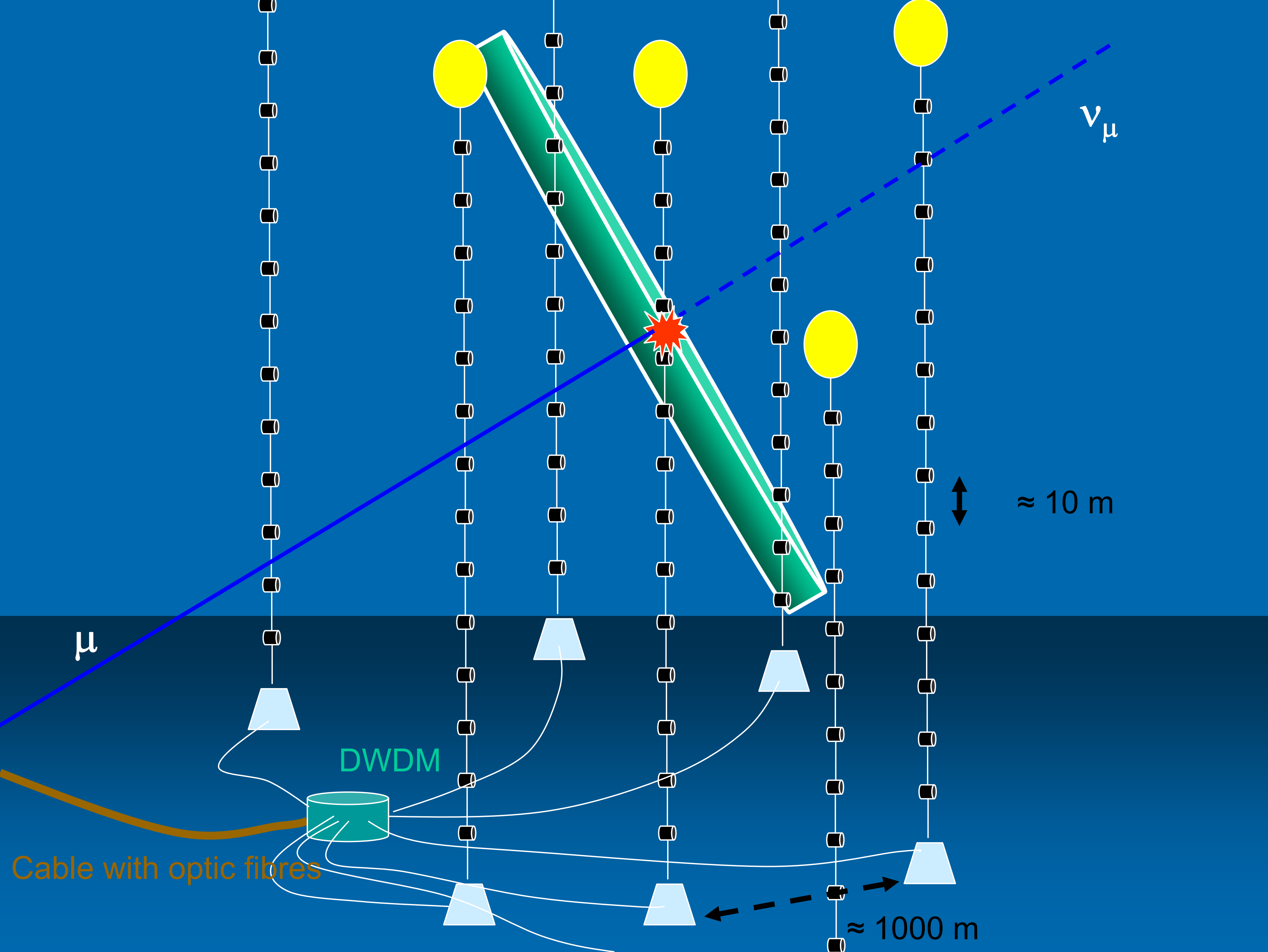

ν_μ
≈ 10 m
μ
DWDM
Cable with optic fibres
≈ 1000 m