# Acoustic Detection of Particles: The RAP Experiment, Present Status and Results

Laboratori Nazionali di Frascati

*Partially funded by EU STREGA Project*

## RAP Collaboration

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TAUP 2005 – Zaragoza

*Lina Quintieri, 10 Settembre 2005*

# Nautilus Cosmic Ray Veto System

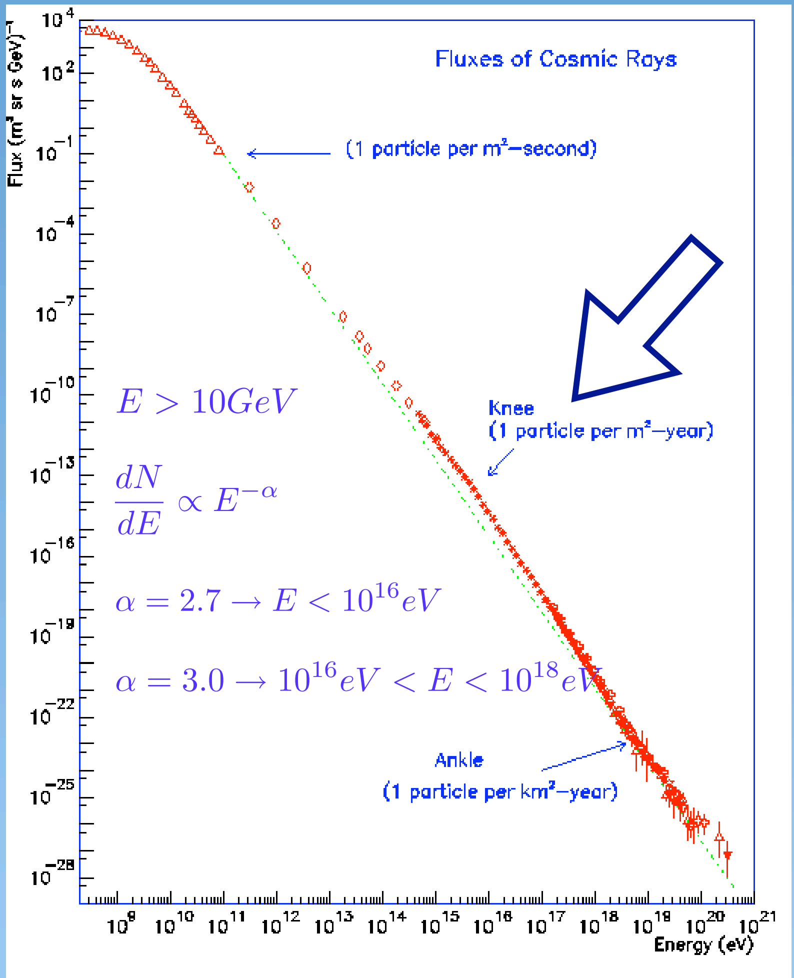
***Since 1992 NAUTILUS is equipped with cosmic ray detectors***

## Streamer Tube:

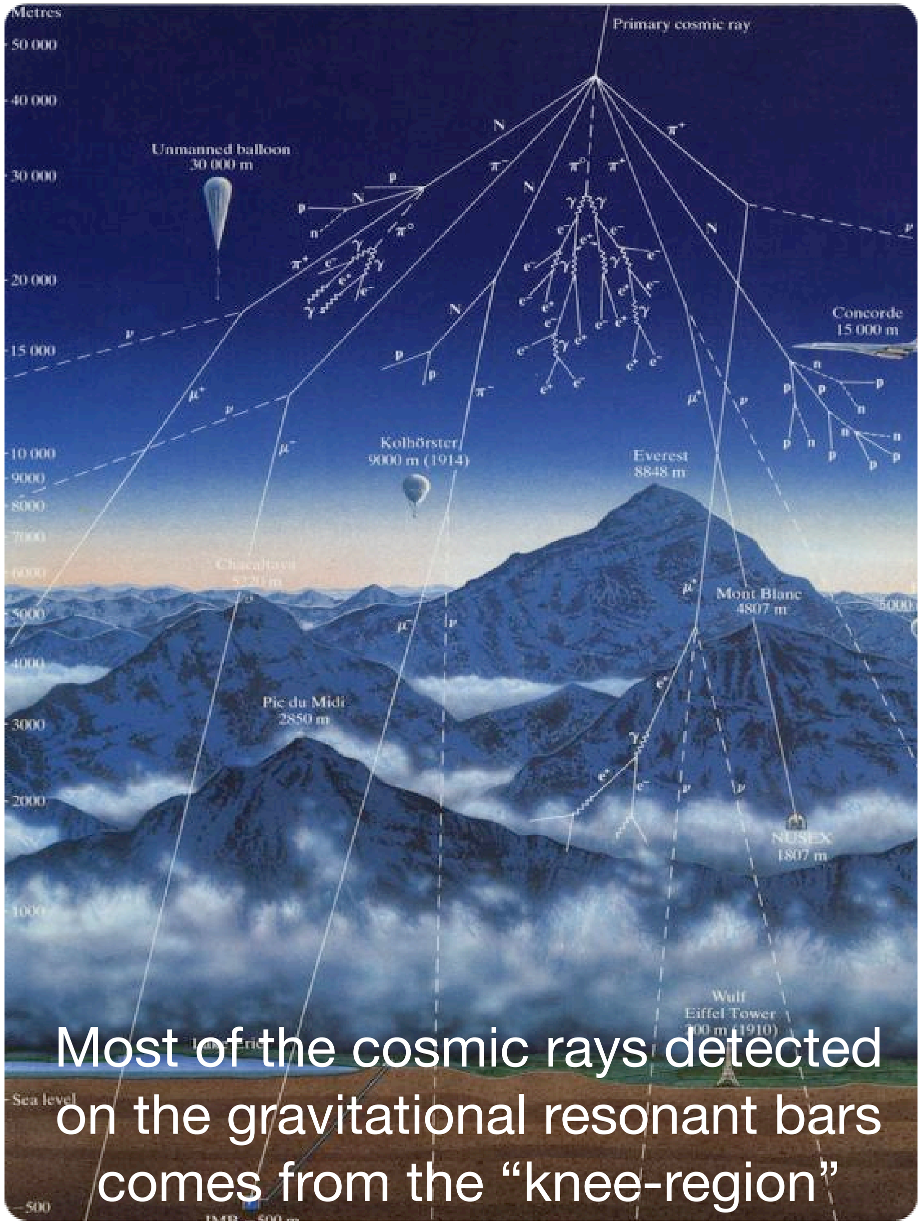
- 3 layers (6x6 $m^2$) above the cryostat (at 3.95 m from the antenna axis) and 4 layers (6x2.75 $m^2$) at ground level
- basic unit: 8 PVC-rectangular cells with cross section 3X3 $cm^2$ and coated with graphite
- Cu-Be 100μm diameter anode
- tubes operated at $\Delta V$=5550 V (single streamer charge of 60 pC)
- Gas mixture:40%Ar+60 Isobuthane

*Nucl.Instrum.Meth.A355:624-631,1995*

# Cosmic Rays and Signals Detected by GW Antennas




**Energy spectrum of primary c.r. impinging the top of the earth atmosphere**




Most of the cosmic rays detected on the gravitational resonant bars comes from the “knee-region”

# Extensive Air Shower

From the top of atmosphere down to sea level

primary cosmic ray (essentially p)

nuclear interaction with air

$$p(N) + p \rightarrow n\pi + X$$

$\pi^0 \rightarrow \gamma\gamma$

hadronic cascade

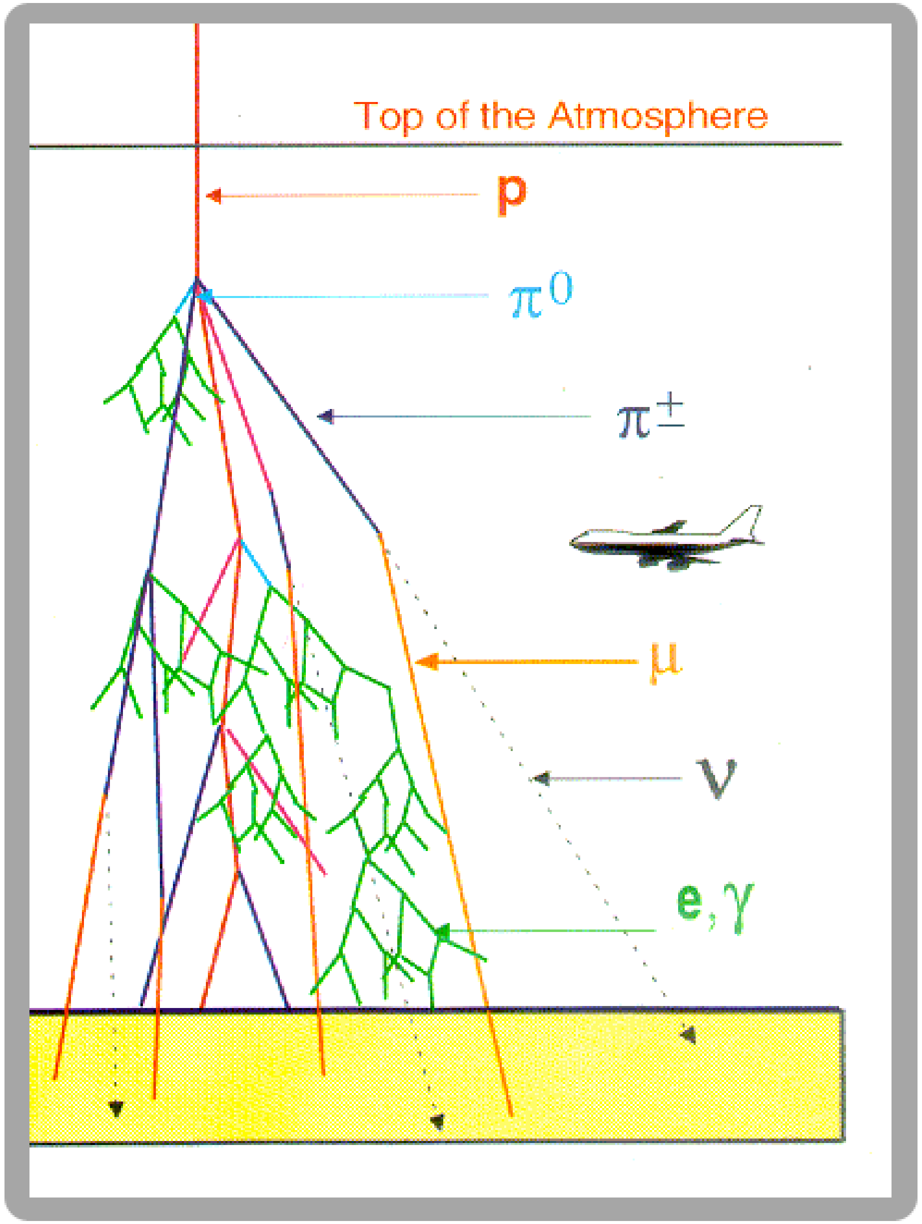
$\pi^+ \rightarrow \mu\nu_\mu$

$\gamma(+N) \rightarrow e^+e^-$

$p, n, \ \pi^\pm, K^\pm$

$\mu \rightarrow e\mu_e\nu_\mu$

Electrons | Hadrons | Muons



# Direct Measurements in Resonators excited by particles

## Past EXPERIMENTS

1

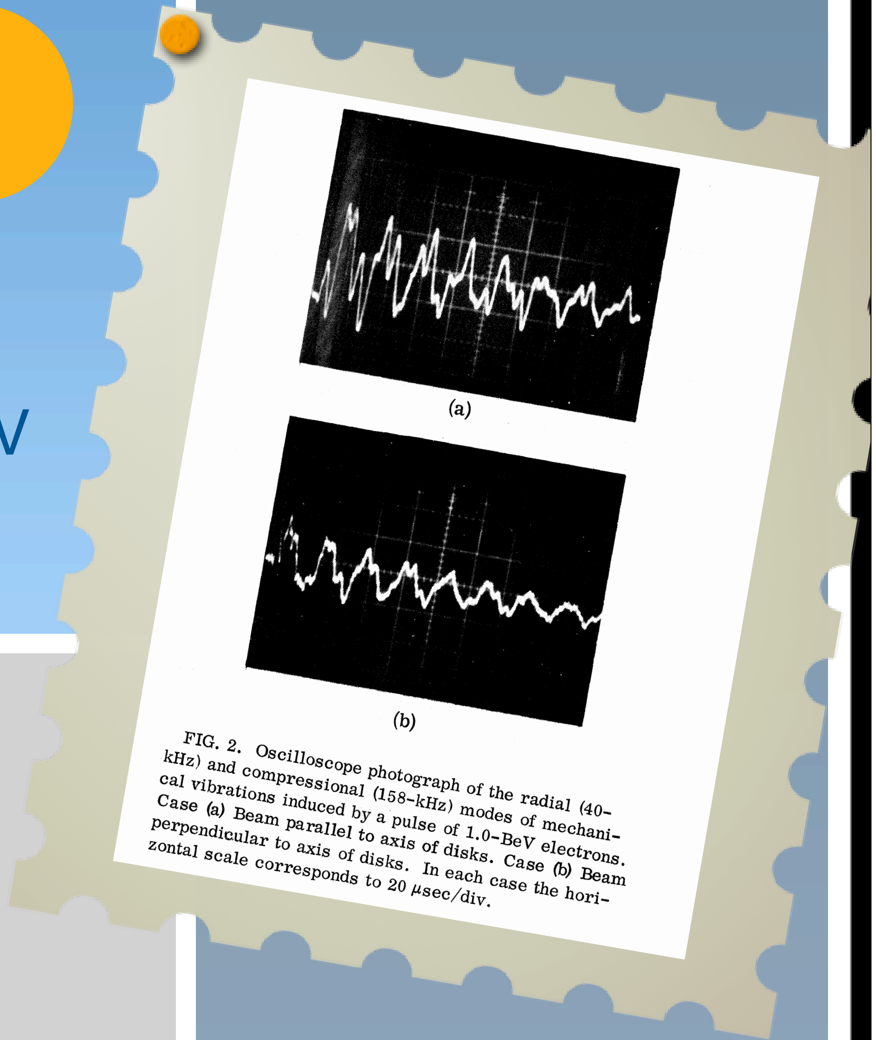
## Results

Radial (40 kHz) and compressional (158 kHz) modes of mechanical vibration induced by a pulse of 1.0 BeV

- **Baron and Hofstander:**

  “Electron beam on piezoeletric “

  Phys.Rev.Lett. 23 184 (1969)



# Direct Measurements in Resonators excited by particles

**Past EXPERIMENTS**

2

**Results:**

for protons (30 MeV):
a satisfactory accord between theory and experiment.

for electrons (500 eV):
somewhat less satisfactory but the results confirm qualitatively the reliability of the model

- **Grassi Strini Tagliaferri:**
"30 GeV protons on a cylindrical bar made of Avional 22"

(J.Appl.Phy. 51 1980)

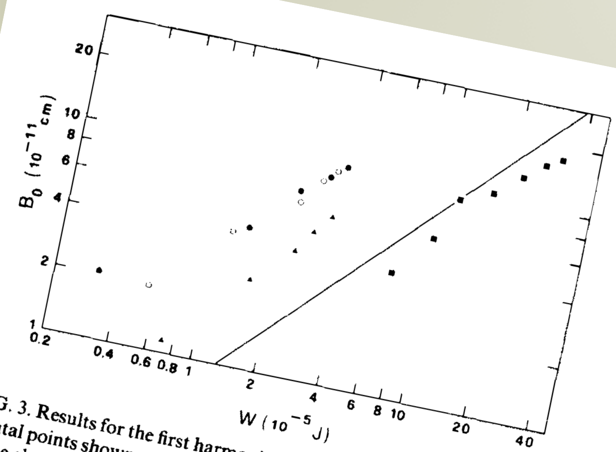



FIG. 3. Results for the first harmonic of the bar vibrational motion. Experimental points shown with squares refer to the proton beam; with solid dots, to the electron beam centered; with circles, to the electron beam displaced to the right; and with triangles, to the electron beam displaced to the left. The straight line is the plot of $B_0$ from the second of Eqs. (10) for the value unity of the cosine factor.

# Direct Measurements in Resonators excited by particles

## Past EXPERIMENTS

3

**Results:**

Calculations w 1 thermo-ac
conversion mo ell agree (wi 2 0%)
with the experimental data


1 2 3

**All these experiments done at room temperature !!**

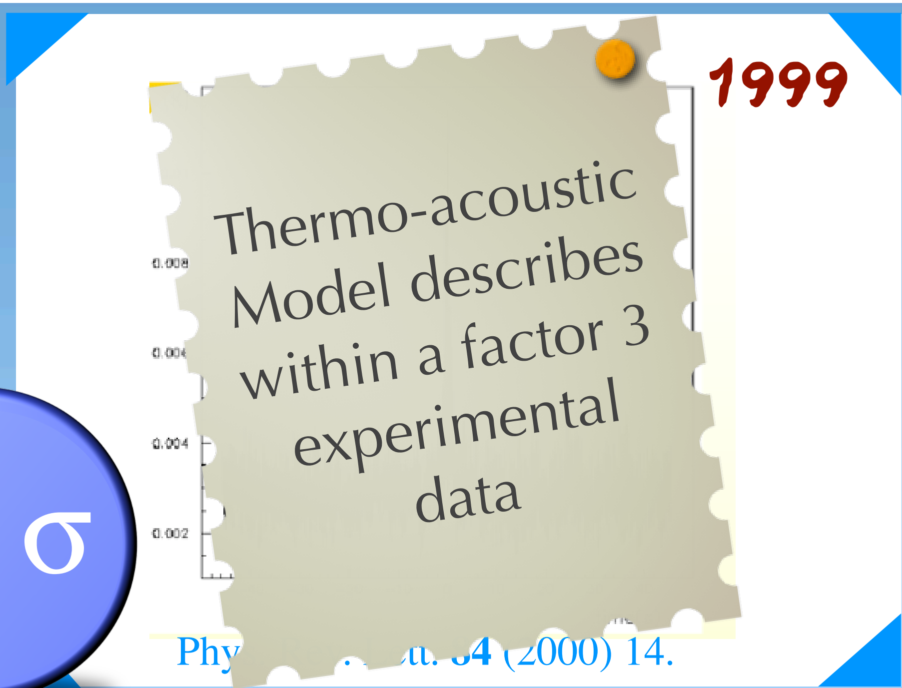
- G.D. van ALbada et al.
  "Measurement of mechanical vibrations in excited aluminum resonators by 0.6 GeV electrons"

  (Nikhef,Rev Sci Inst 2000)

**RAP : 0.1 ÷ 294 K**

# Detection of first c.r. signals in coincidence with Nautilus

20 σ




Average Energy over 46 stretches (M≥ $15 \cdot 10^3$) of NAUTILUS data versus time
(zero @ time arriving of cosmic showers)

Expected energy vs particle density
(for Nautilus detector):

$$E = 4.7 \cdot 10^{-10} \Lambda^2 \, (K)$$

$\Lambda$ = number of particle in the bar

(Eq.1 )
Expected EAS rate at sea level

$$H(\geq \Lambda) = k\Lambda^{-\lambda} EAS/day$$

$$\lambda = 1.32 + 0.038 ln\Lambda$$

$$k = 3.54 \cdot 10^4$$

**Eq.(2)**
Vibrational energy
1st longitudinal mode

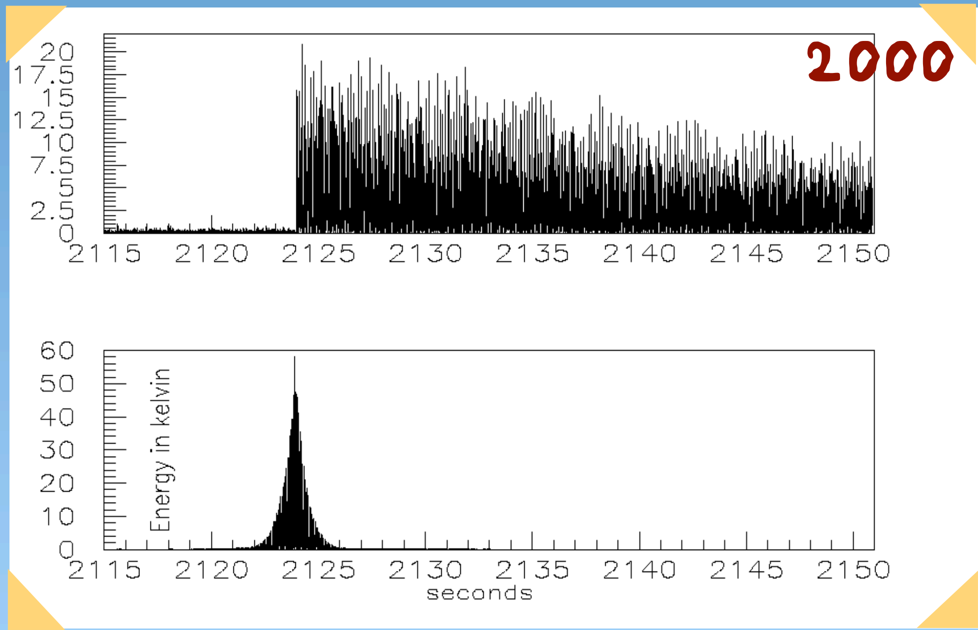
$$E = 7.64 \cdot 10^{-9} W^2 f$$

**W** (GeV)=particle density dissipated in the bar

# Anomalous Signals

Unfiltered Signal ($V^2$)

Filtered Signal (K)




Phys. Lett. **B499** (2001) 16.

*2000 run:*
*Time behaviour*
*of the*
*largest event*
*in coincidence*
*with Nautilus*

E a:

(E /)

RAP

Scientific Motivation

~~Thermo-acoustic model:~~
~~*under the hypothesis of electron shower*~~

~~***E=0.019 K***~~

# Hadronic component and T.A.M

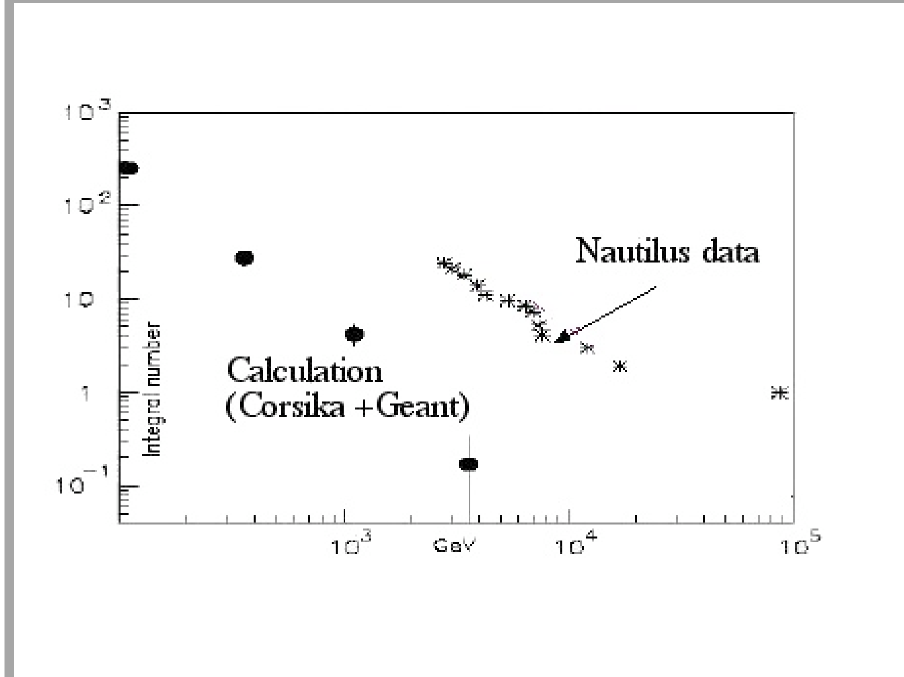
MONTE CARLO CALCULATION DETAILS:

The calculation was done using a mixed composition of the primary c.r (from protons up to iron).

RESULTS:

- The observation rate 2 order of magnitude higher than expected
- the energy 2 order of magnitude larger than one computed by T.A.M

Hadrons + T.A.M unable to explain the extremely energetic C.R. observed

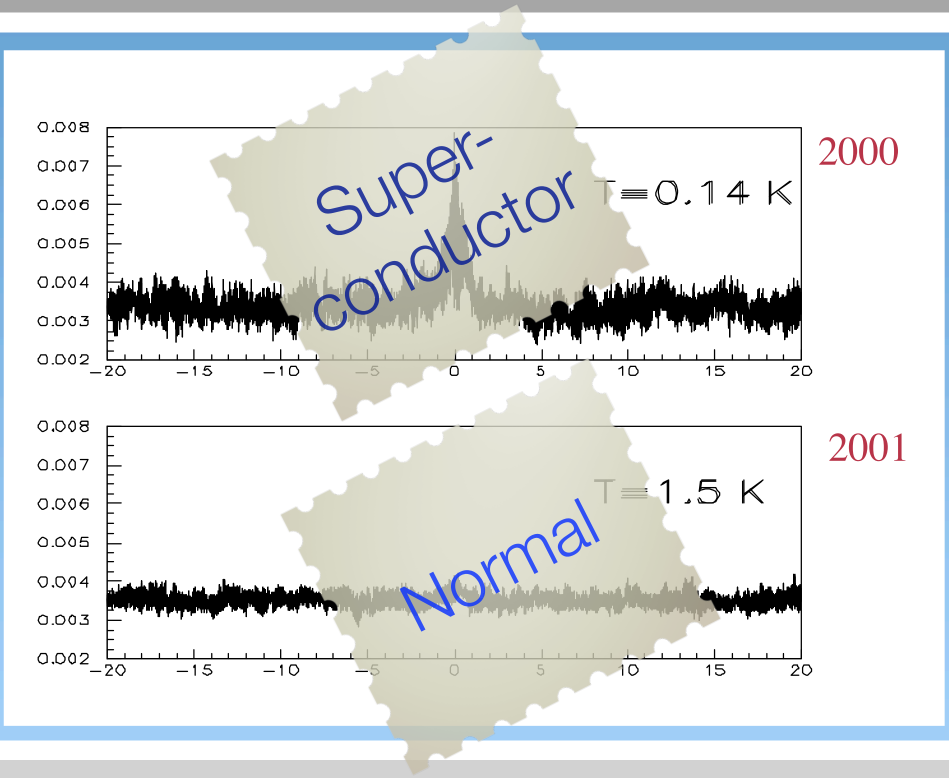



**Comparison between calculations and measurements**

* Integrated number of coincident events in NAUTILUS

- Number of events due to hadrons expected in NAUTILUS

# Why T.A.M. doesn't work with 2000 data?




NAUTILUS DATA

2001

Data collected again in agreement with T.M.A.

Why 2000 so special?

## Data vs thermodynamic temperature

Feb-Jul 2000 ➪ 308 stretches
Mar-Sep 2001 ➪ 968 stretches

particle density>300/m$^2$

# RAP PROPOSAL

**Possibilities to explain experimental data:**

- Something strange in the cosmic rays composition at the energy of interest (exotic nuclei, monopoles, etc).
- Creep phenomena: impulsive release of accumulated internal tension
- Unexpected response of a massive superconductor to the passage of particles:

In superconductive state:

Enhancement of Grüneisen factor **?**

$$\gamma(T) \propto \frac{\alpha}{C_V}$$

Enhancement of energy conversion (dE/dx)**?**

## Coefficient of Thermal expansion α (pure Al)

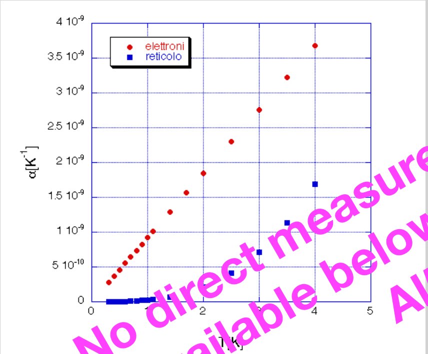


Figura 1.2 - Alluminio puro nello stato normale; contributi elettronico e reticolare ad $\alpha$

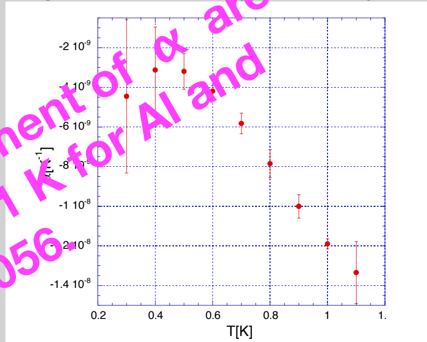


Figura 1.3 - Alluminio puro nello stato superconduttore; contributo elettronico ad $\alpha$

No direct measurement of α are available below 1 K for Al and Al5056

## Specific Heat at constant volume (pure Al)

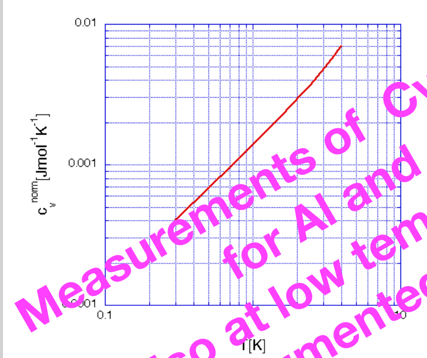


Figura 3.2 - Alluminio puro nello stato normale ($T \leq 4$ K); $c_v$ totale

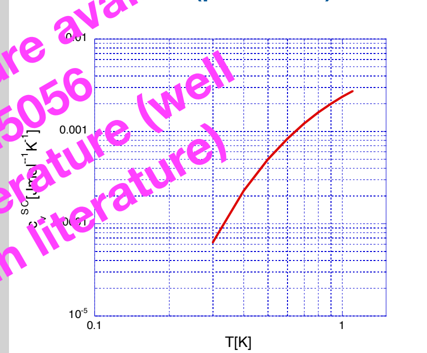


Figura 3.3 - Alluminio puro nello stato superconduttore ($T \leq 1.1$ K); $c_v$ totale

Measurements of Cv are available for Al and Al5056 also at low temperature (well documented in literature)

# The thermo-acoustic model

$$E_n = \frac{1}{2}\frac{l^2}{V}\frac{{G^2}_n}{\rho v^2}\gamma^2\left(\frac{dE}{dx}\right)^2$$

n-mode vibration energy

$$G_n \propto \int_l (\nabla \cdot \underline{u})\ dl$$

Shape Factor

$$\gamma = \frac{\beta \cdot k_t}{\rho \cdot C_V}$$

Gruneisen Factor

Energy lost
for ionization

Local Heating
along the trajectory

$$dT = \frac{dE}{\rho C_V}$$

Volumetric Expansion Coefficient

$$\beta = \left(\frac{\partial lnV}{\partial T}\right)_p$$

The Bulk Modulus (the inverse of compressibility)

$$X_T = \frac{1}{K_T} = -\left(\frac{\partial V}{\partial p}\right)_T$$

Local impulse of
pression

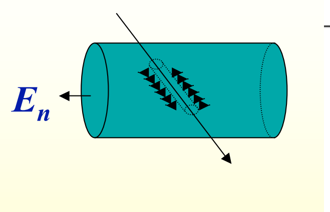
$$dp = \gamma\frac{dE}{V}$$

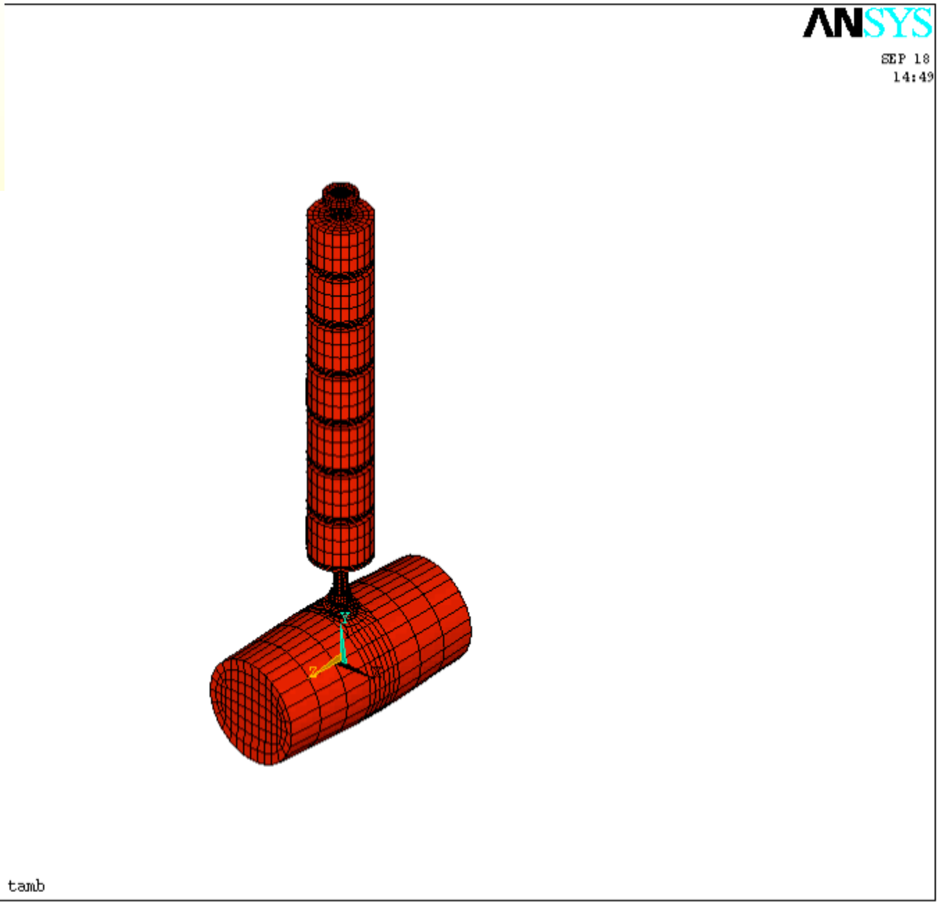
Eccitation of
natural modes

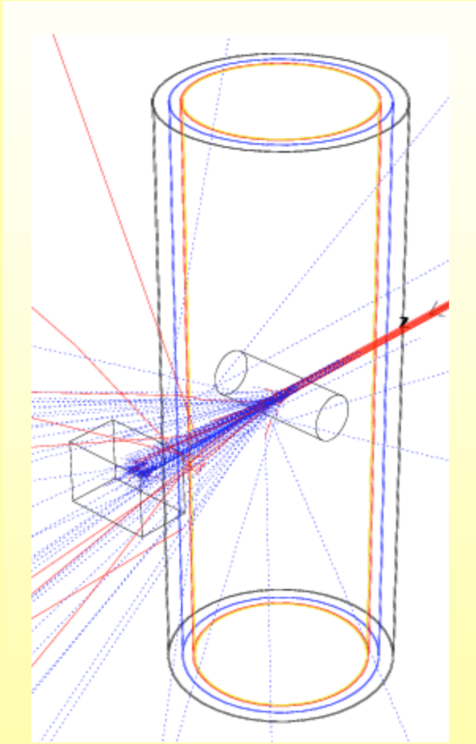
A.De Rujula & B.Lautrup Nucl.Phys.B242 (1984)
Allega A. &Cabibbo N. Lett.Nuovo Cim (1983)

# Primary scope of the RAP Experiment

To Measure the 1st longitudinal vibrations of a cylindrical test mass when impinged by electron beam (DAΦNE BTF) to investigate if higher efficiency mechanism for the particle energy loss conversion  takes place in superconductive state



*GEANT* simulation

# $B_{TH}$: The Mode Amplitude Expected from T.A.M

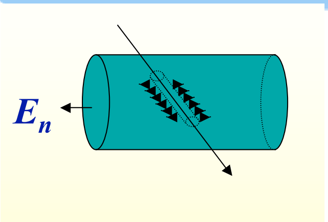
**Simplified Approach**

$$B_0 = \frac{2\alpha l}{\pi C_V M} W$$

maximum oscillation amplitude

**Corrective factor**

$$B_{TH} = B_0(1+\epsilon)$$




$$\frac{\partial^2 u(x,t)}{\partial t^2} = v^2 \frac{\partial^2 u(x,t)}{x^2}$$

- Assumption of thin cylinder: monodimensional elastic system
- Beam spot in the middle of the cylinder
- All the energy is transformed into thermal energy
- The energy of the beam spreads out uniformly on the whole cross section of the bar
- The beam pulse length short in comparison with the period of the harmonic of highest order examined
- Equation of motion without damping

- $\epsilon$ To take into account the corrections estimated by Monte Carlo methods due to O $[(R/L)^2]$+finite spread of beam
- $W$ Total energy released by the particles into the bar ( Monte Carlo simulation + Beam charge measurement)
- $\alpha$ Linear thermal expansion coefficient

  $$\beta = 3\alpha$$

  for aluminum and Niobium
- $\propto \frac{1}{M}$ on the contrary for g.w the oscillation amplitude of the bar is proportional to $1/\sqrt{M}$

# Simulation of the Beam Interaction in the bar

## Monte Carlo simulation: secondary particles for 510 MeV primary electrons impinging on the bar

Simulation takes into account

- real geometry and material of the cryostat and the bar
- realistic parametrization of the BTF beam: spot size and divergence

### AVERAGE ENERGY LOSS PER ELECTRON

$$< \Delta E > \pm \sigma_{\Delta E} =$$

Al5056:

$$192.5 \pm 70.6 MeV$$

Niobium:

$$456.5 \pm \delta\, MeV$$

# $B_{meas}$: The measured Oscillation Amplitude

$$\lambda = \frac{2\pi l}{C_2 + C_{cables}} \cdot \sqrt{\frac{MC_1}{2}}$$

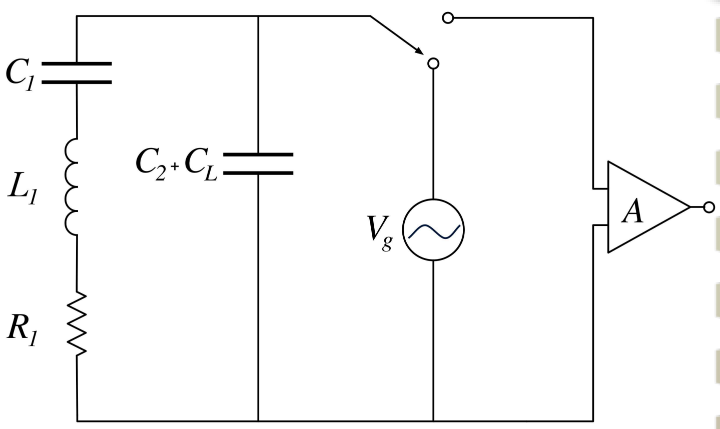
| Material | T=300 K | T=77 K | T=4.4 K |
| --- | --- | --- | --- |
| Al5056 | 1.32e+7 V/m | 1.48e+7 V/m | 1.32e+7 V/m |
| Nb | 1.81e+6 V/m | 1.73e+6 V/m | 1.49e+6 V/m |

$$B_m = \frac{V_m}{G \cdot \lambda}$$

**Vm:** maximum value of the piezoelectric output signal after excitation

**G:** Amplifier Gain

**λ:** the electro-mechanical coupling constant




Equivalent electrical circuit and calibration scheme
*R1 -L1-C1*
*(dissipation,mass, elasticity)*

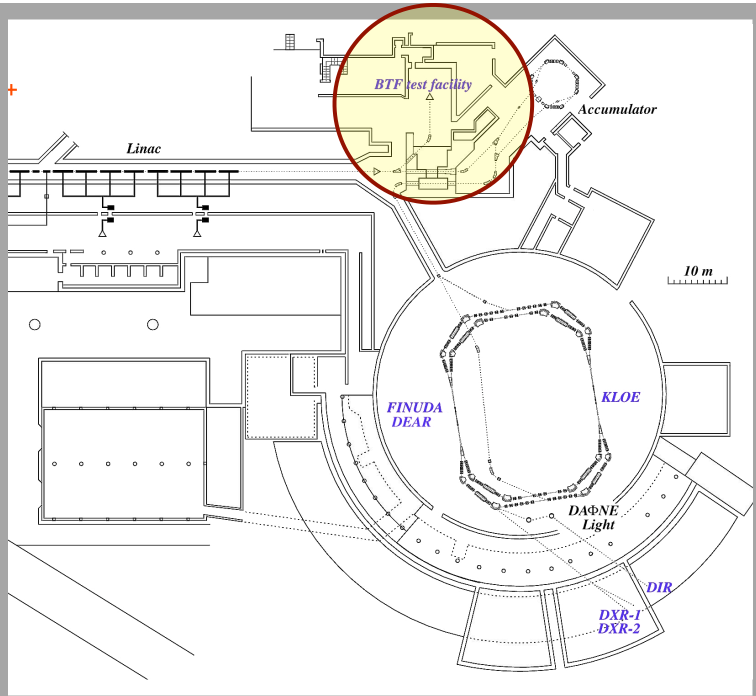
$$C_1 = \frac{V_0}{V_g \Delta t \pi f_0}[C_2 + C_L]$$

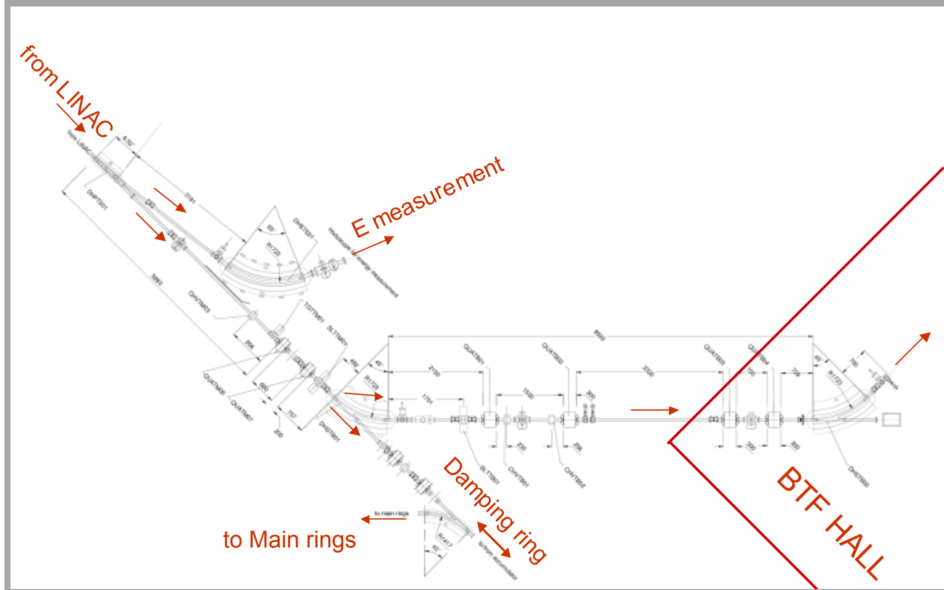
*C2: Pz24 capacity*

CALIBRATION SCOPE:
to determine λ
at the different temperatures

λ (T)

# The DAΦNE Beam Test Facility



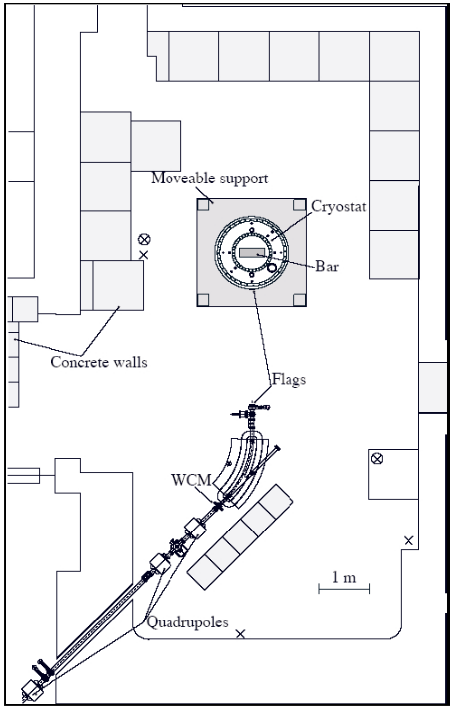




- n(average)=1-$10^{10}$ particles
- Energy 25-750 MeV
- Repetition rate:up to 50 Hz or single shot
- Pulse duration 1-10 ns
- 1% energy resolution

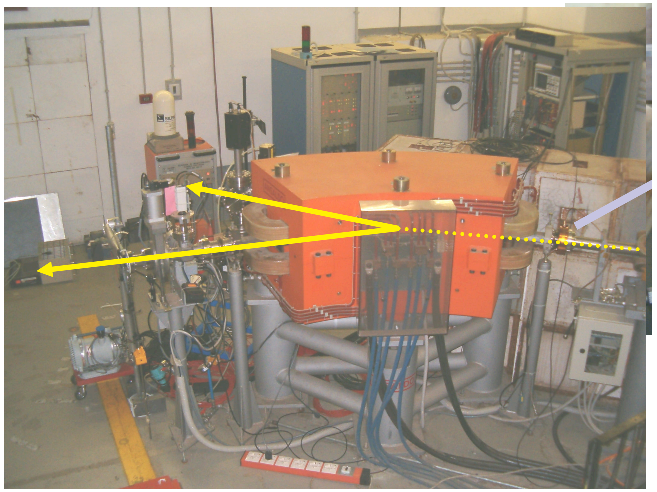
$e^-$ | $e^+$

# Beam setup for RAP Experiment

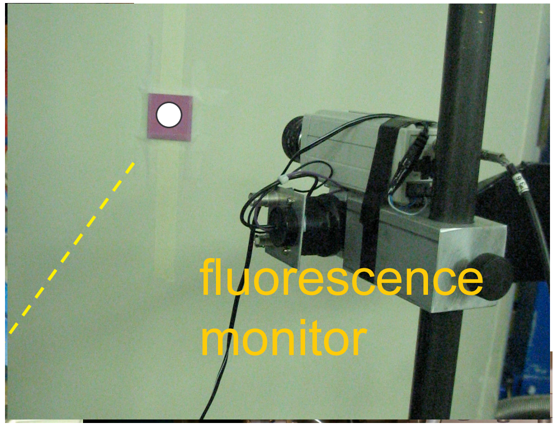
| BTF Layout | Bending Dipole and B.C.M | Fluorescence Monitor |
|---|---|---|




BTF experimental hall 100 $m^2$



At intensity above $3 \cdot 10^6$ particle flux delivered in BTF can be measured by a Beam Charge Monitor (Bergoz) positioned just bef the last bending magnet



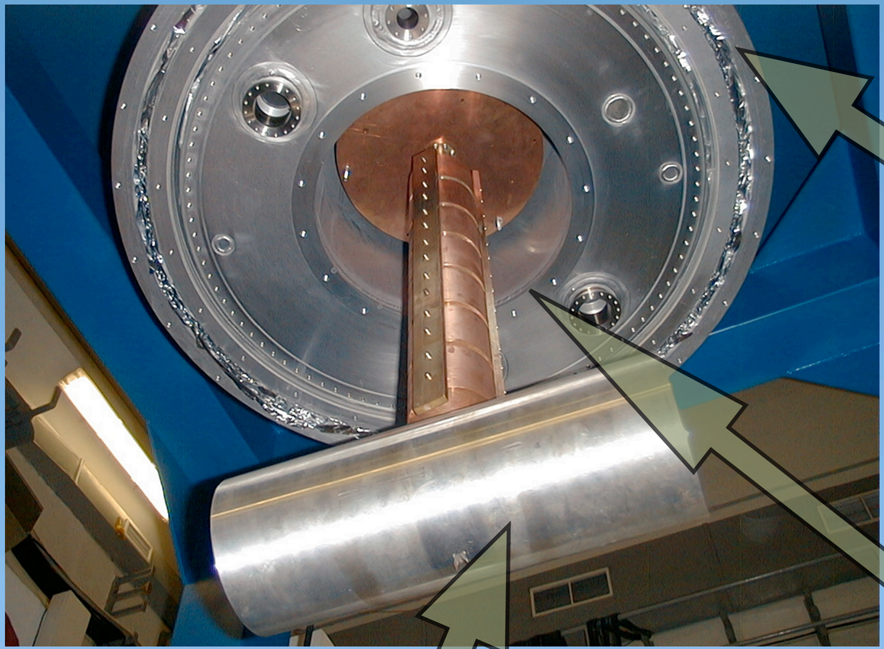

**spot size**
**1 ÷ 1.5 cm**

# RAP Experimental setup

The main component of the detector are:

- Mechanical structure needed to host and suspend the cryostat
- The cryogenic and vacuum system
- The suspension system
- The cylindrical test mass
- The read-out and DAQ

# Al5056 Experimental setup: Suspension System, Test Mass,Cryogenic System



KADEL Liquid Helium Cryostat
+
Dilution Refrigerator
Working Temp: 100 mK

**Suspension**

7 OFHC copper masses
1 OFHC copper tube
Attenuation: –200db@ 5KHz

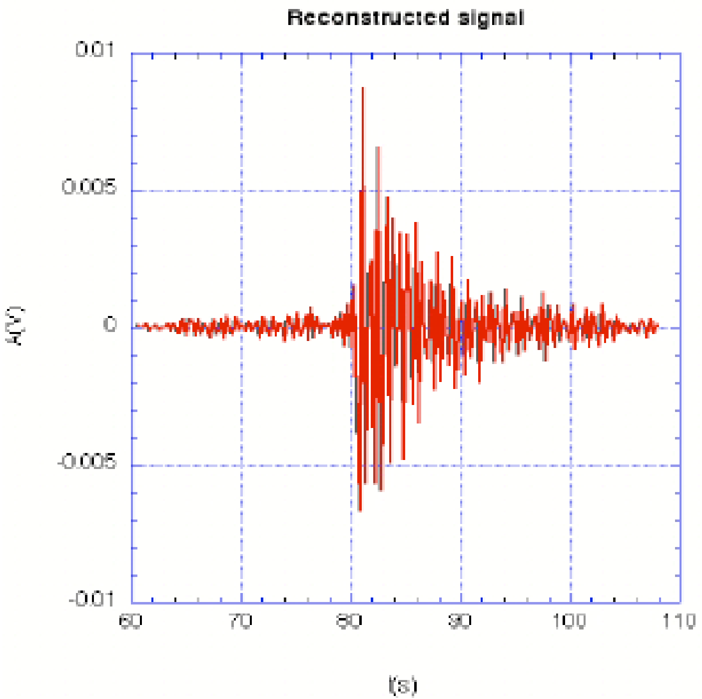
Test Mass

| Material | Al 5056 bar |
| --- | --- |
| L | 50 cm |
| Φ | 18 cm |
| M | 35.17 kg |
| $f_{1L}$ | 5096 Hz @ 300 K |

# Data Analysis in details

**The offline analysis:**

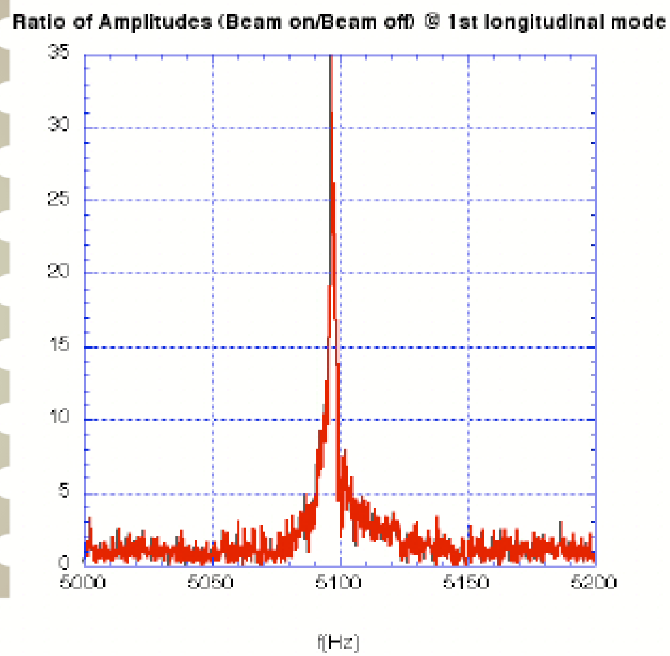
- FFT on a record of 2.6 sec before and after the arrival time of the beam ---> this allows to correctly identify the value of the excited frequency
- A frequency window of 10 Hz is taken around the excited harmonic to reconstruct the signal -- > data out of such window put =0
- An Inverse FT is then applied to obtain the optimal estimation of the amplitude at the resonance frequency




$9.4 \cdot 10^{10}$ electrons @ 500 MeV

Energy released in the bar=$1.7 \cdot 10^{-3}$ J

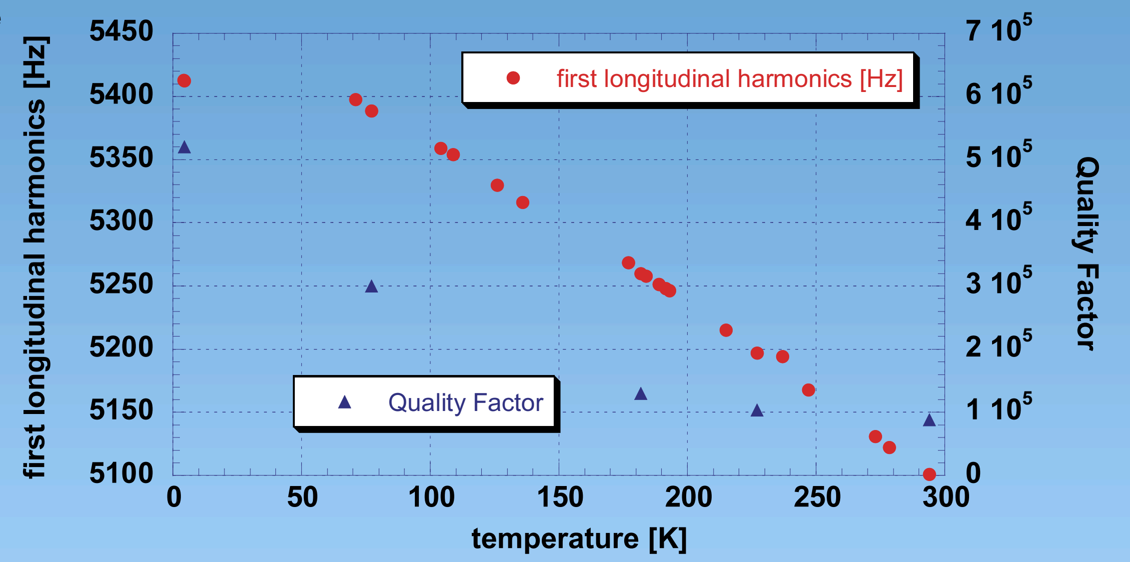
Amplitude of 1L mode =$4.13 \cdot 10^{-13}$ m



2004 run:

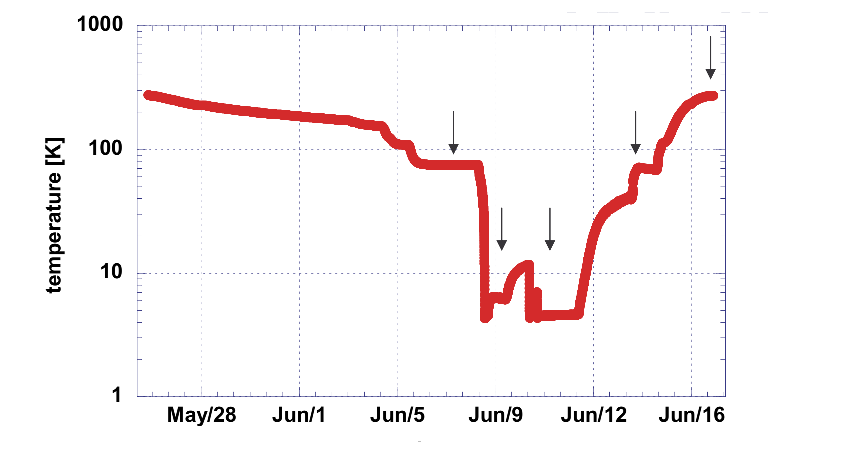
Measurements with Al5056

# 2004 Al5056 First Cool-down




ILIAS-GW meeting, 5-6 Nov 2004

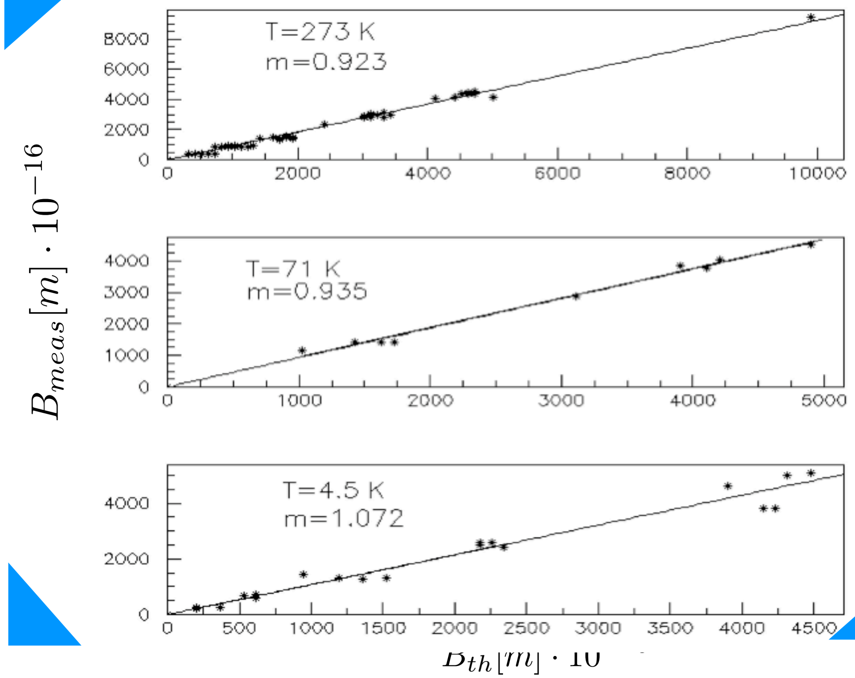
| Date | Temperature |
|---|---|
| 28/05/2004 | 300 K |
| 5/06/2004 | 77 K |
| 9/6/2004 | 8 K |
| 10/6/2004 | 4.4 K |
| 14/06/2004 | 77 K |
| 17/06/2004 | 300 K |

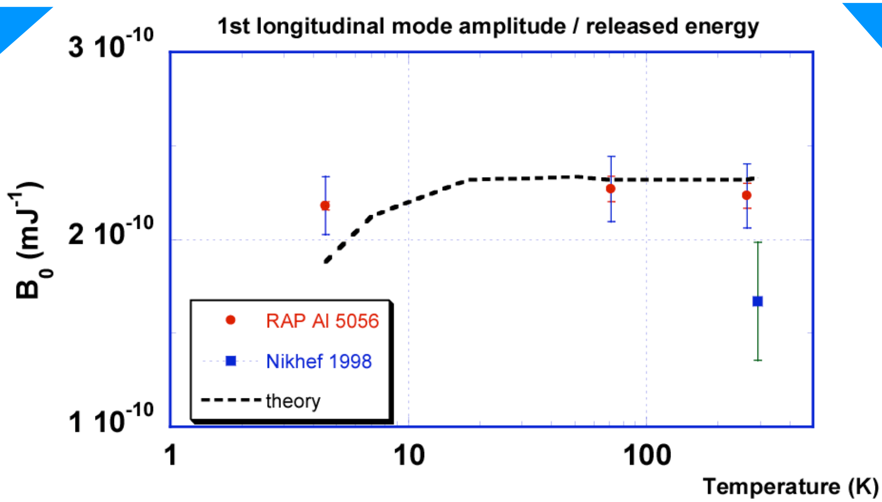



Decay time of 1st longitudinal harmonic:

τ=6.25 s @ T=264 K
τ=24.0s @ T=71 k
τ=84.0 s @ T=4.5 K

# Al5056 Measurement Results




A systematic error of 7% (quadrature beam monitor (3%) + calibration (6%) accuracies) affects the measurements

- **Good global agreement (about 10%) with the expectations (T.A.M)**
- **First experimental results for Al5056 below 270 K**
- **Amplitude @ T=4K are slightly higher than expected: imperfect knowledge of the parameters α/Cv (sensibly depends on the temperature)**

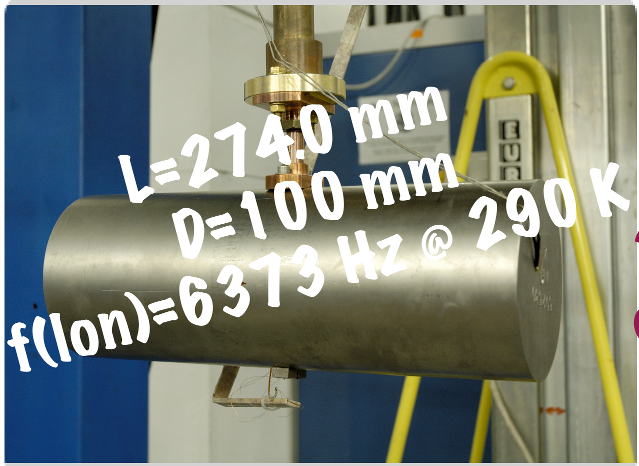
# 2005 run
# Measurements with Niobium

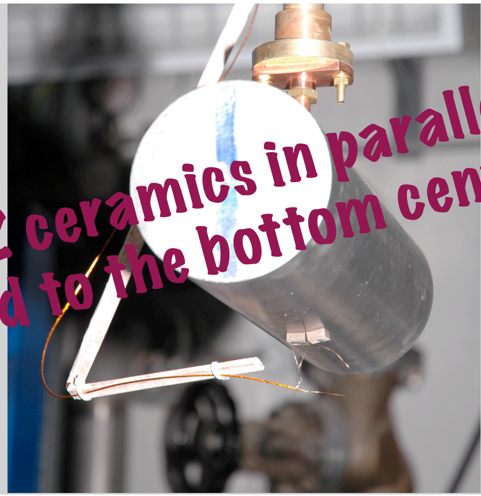
# Niobium bar setup

Due to the delay of dilution refrigeration delivery, we decided to use a material with transition temperature, from normal to superconductive greater than 9 K:

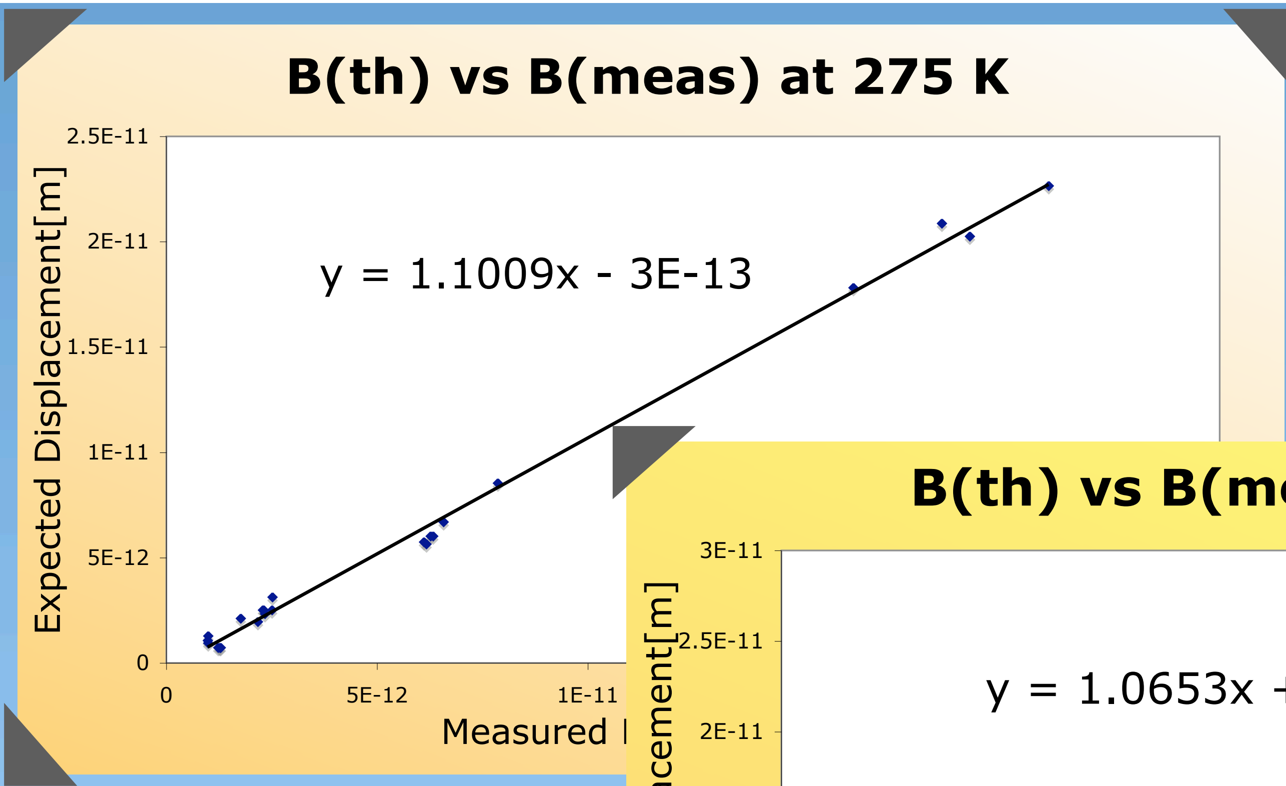
**For Niobium $\Longrightarrow$ $T_c \cong 9$ K**

| Niobium at 293 K | Value |
|---|---|
| ρ [kg/m$^3$] | 8560.01 |
| Vmol [m$^3$/mol] | 0.10853 |
| α [K^{-1}] | 0.709D-05 |
| Bulk [Pa] | 0.171D+12 |
| Young [Pa] | 0.105D+12 |
| Poisson | 0.39821 |
| Vbar (snell bar) [m/s] | 34953.3 |
| Cv [J/g/K] | 0.26531 |

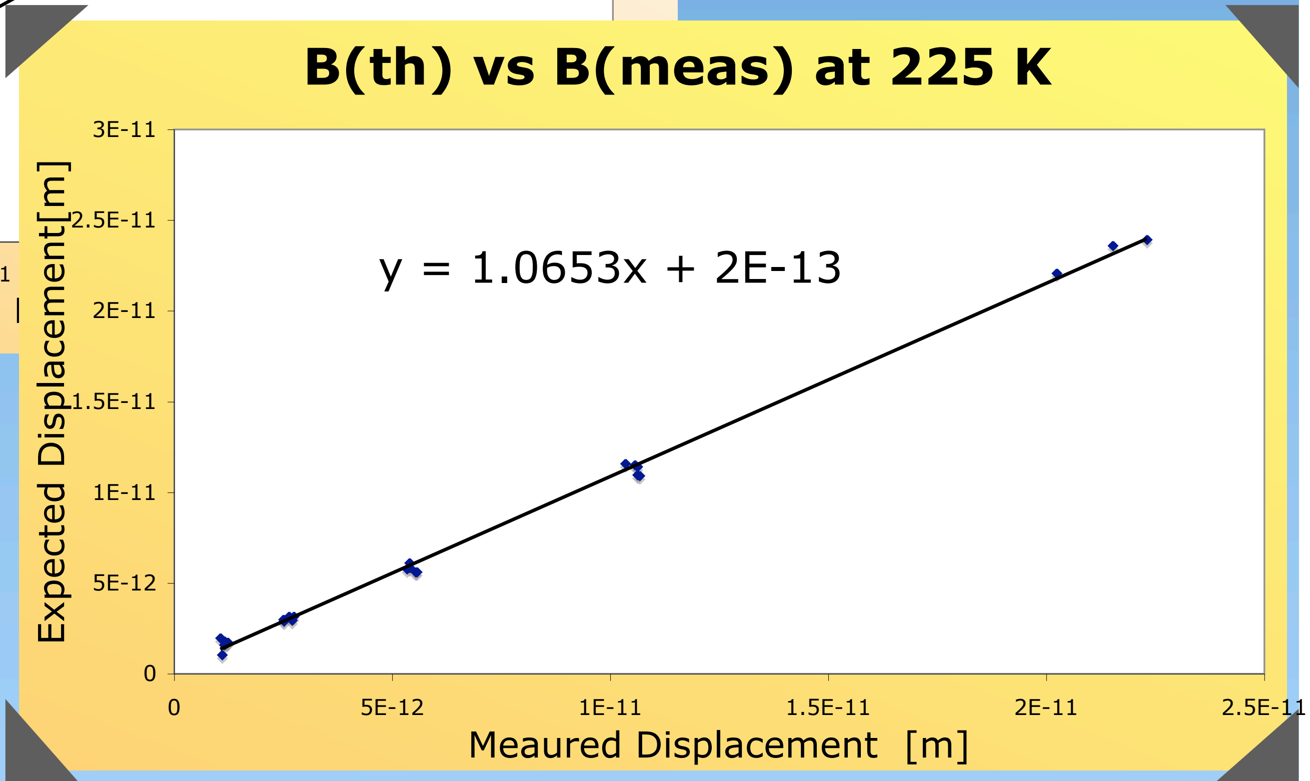


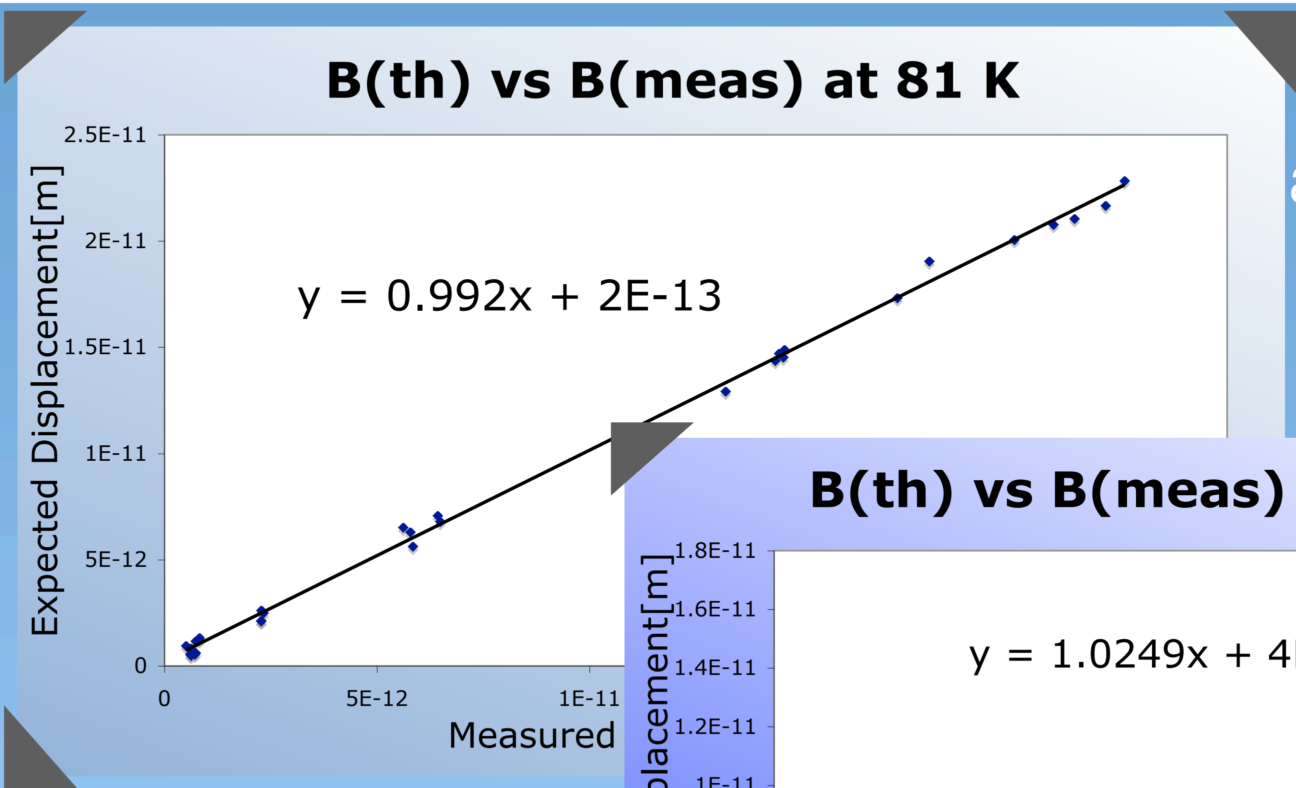

# Preliminary Results at 275 K and 225 K



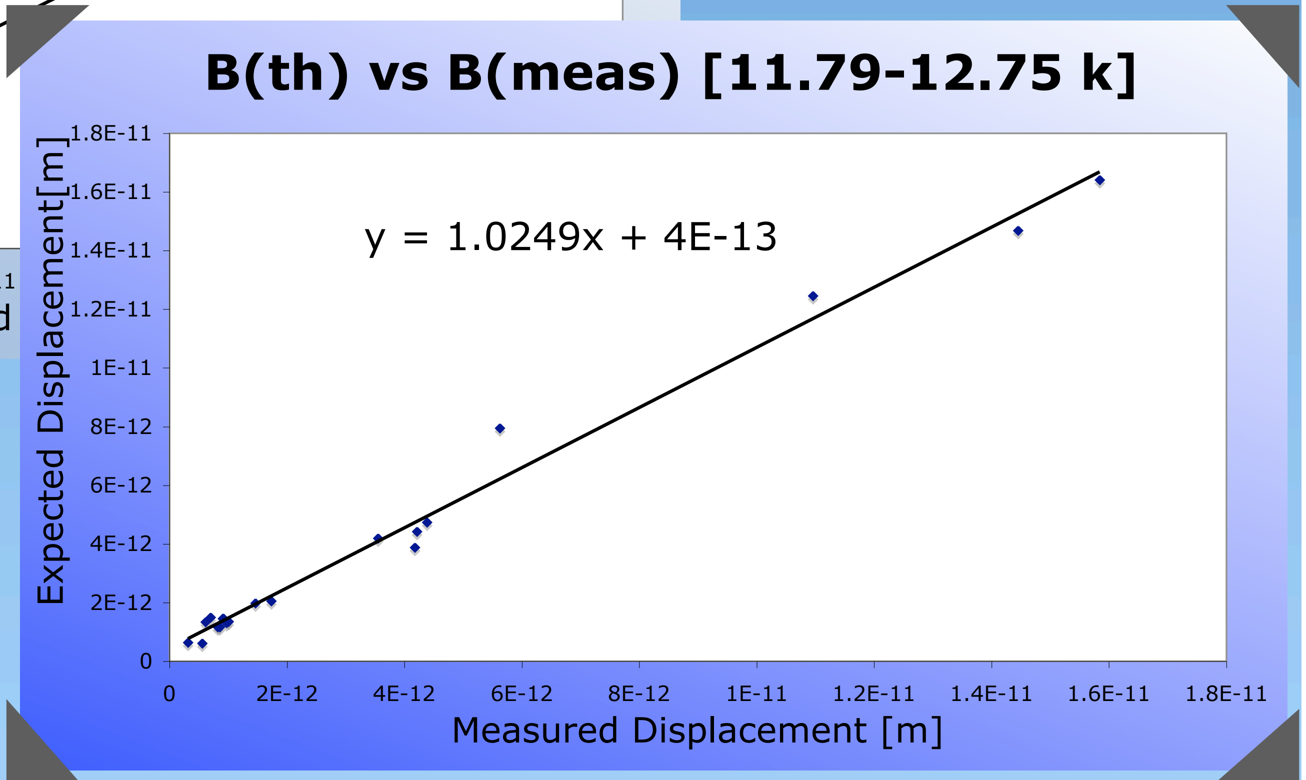

good agreement between expected and measured values.



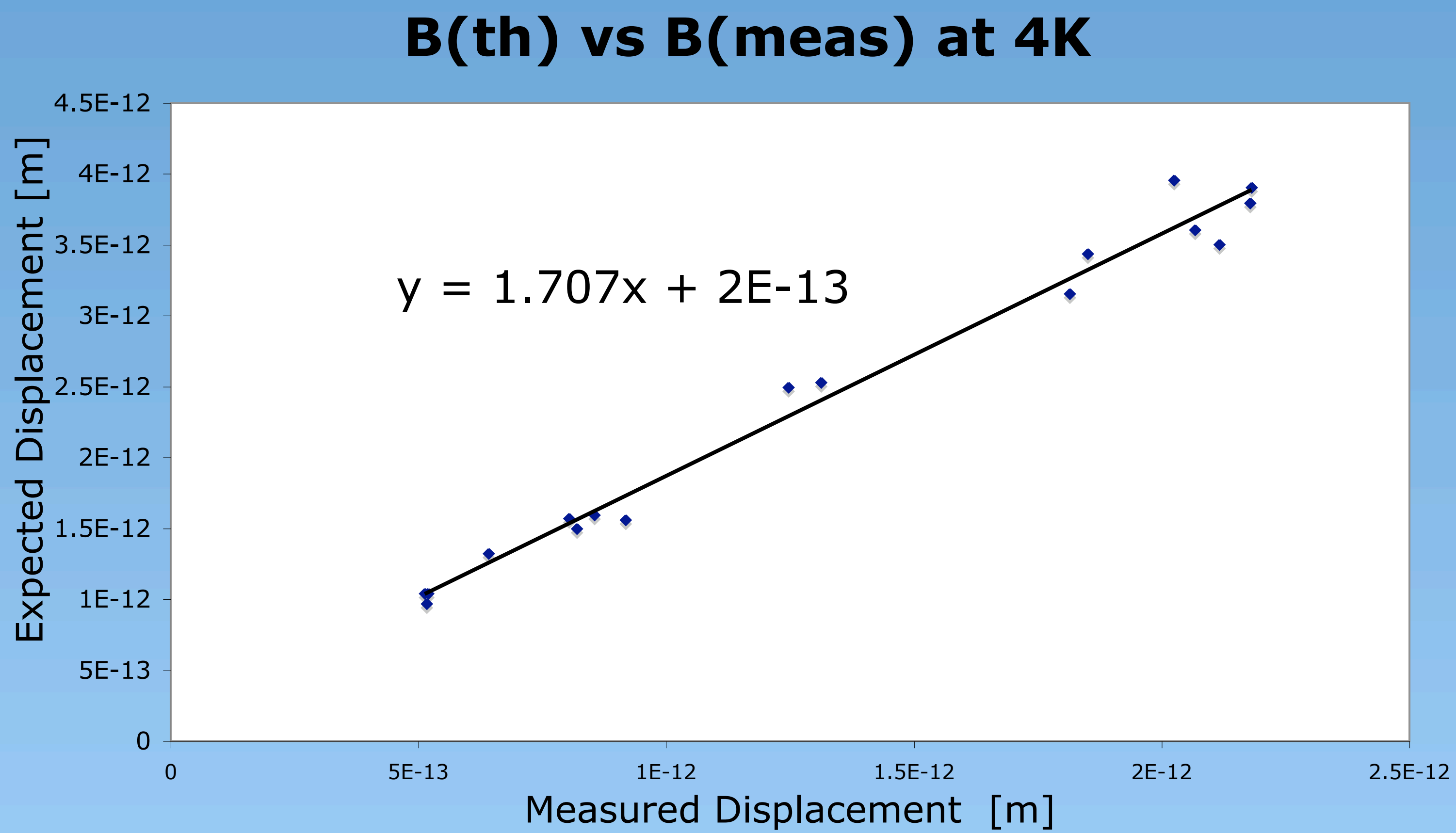
# Preliminary Results at 81 K, 12 K




Again, good agreement between expected and measured values.

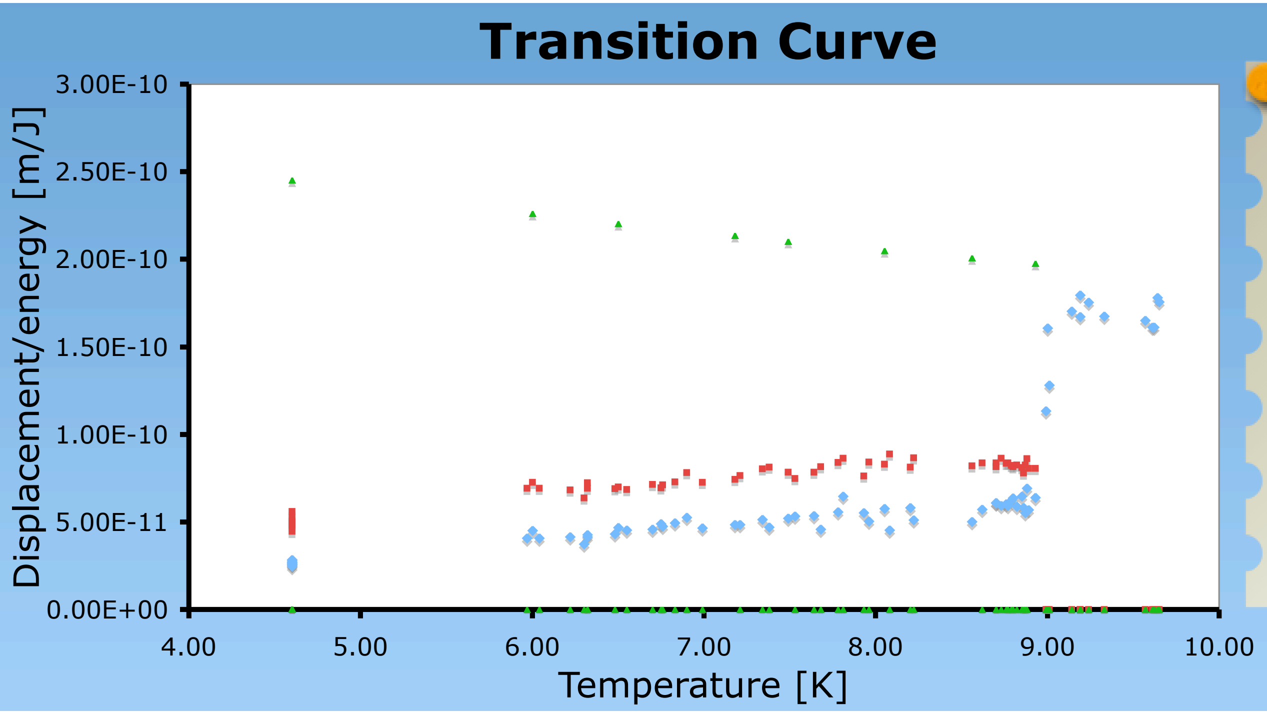


# Preliminary Results at 4 K




These value don't take yet into account the correction of $\varepsilon\ (o(R/L)^2)$

# Preliminary Results at 4 K (below the transition)




Green=estimated values normal state

Red=estimated values superconductive state

Bleu= Measured value

- Measured values disagree with the expectations (T.A.M) if parameters of the normal state are used for calculations. They fairly agree taking into account the s.c parameters. **It seems that superconductivity isn't broken locally**
- First time that the transition region is measured with this method
- IMPORTANT: In the case of Aluminum, calculation gives $B_0(SC)>B_0(NC)$ (an order of magnitude) at $T < T_c$) according to available data of Hc vs T,p

# Conclusion 1

**Results Al5056:**

- The T.A.M expectations confirmed for Al5056 in all the investigated temperature range (from 294 to 4K).
- Better agreement than previous experiments with T.A.M (@room temperature)
- First measurement performed on BULK of Al5056 below 270 K, that could be of interest in several other fields other than that of gravitational wave detectors

# Conclusion 2

**Results**
**Nb:**

- The T.A.M expectations have been preliminarly confirmed above the transition (from > 9 to 294 K).
- Below the transition: data analysis to be finalized. A deep interpretation to be performed

**This kind of measurements could be useful for g.w detectors that foresee to operate in superconductive state !!**

# Future Plans

**Work in Progress:Nb**

Filtering Optimization + accurate Data Analysis and Errors Evaluation

**superconductive Al5056**

Installation and measurement with a dilution refrigerator ( superconductive) before the end of 2006

**Other Materials**

To test other materials like Silicon or special Al alloy (Cu,Be) that are going to be used for g.w detectors of new generation (resonant and interferometers)

# RAP on the WEB


**www.lnf.infn.it/esperimenti/rap/**