Rivelazione Acustica di Particelle

# *The RAP Experiment: Status and Results*


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*Univ. di Roma Tor Vergata*

In collaboration with:

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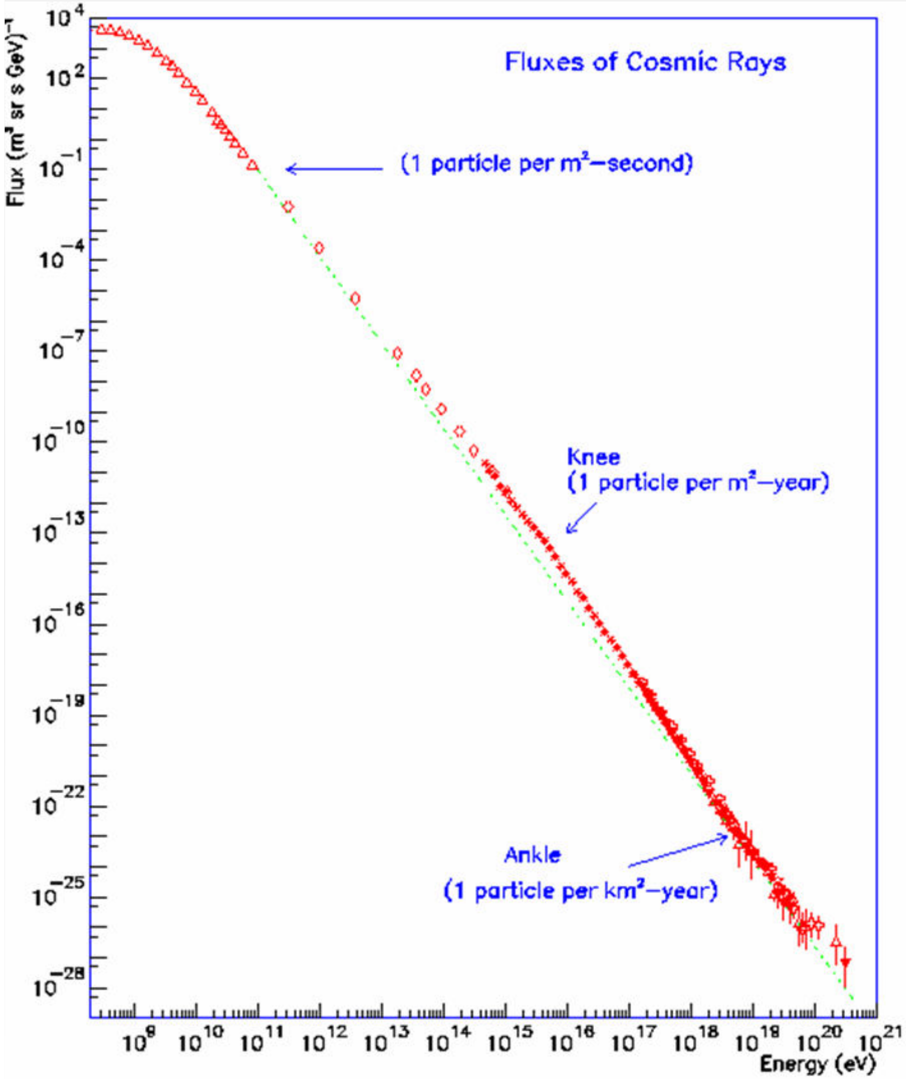
# Cosmic Rays on the ground




From the top of atmosphere down to sea level

primary cosmic ray
(*essentially p*)

nuclear interaction with atmosphere

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

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

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**

# Scientific Motivations

## Interaction CR – GW Antennas

In 1998 the NAUTILUS Gravitational Wave Antenna detected for the first time signals due to the passage of cosmic rays (CR).

Interaction between CR and the antenna has been so far described by the so-called Thermo-Acoustic model

NAUTILUS measurements are in good agreement with the model when the antenna is in normal-conducting state, but large signals of high energy CR at higher rate than expected (1 order of magnitude) have been observed when antenna was operating in superconductive state.

→ Investigation was needed…

→ *RAP* proposal (LNF-01/027(IR) Nov. 2001)

# Scientific Motivations

## Thermo-Acoustic model for cylindrical bars

*Grassi Strini et al., J. Appl. Phys.* ***51****, 948 (1980) – Liu & Barish, Phys. Rev. Lett.* ***61****, 271 (1988)*

cosmic rays crossing the antenna, interact with the material and lose energy

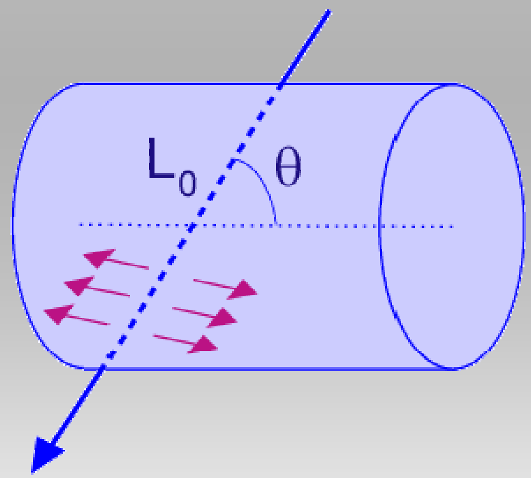
→ warming up of the material

↓

local thermal expansion

↓

mechanical vibrations



# Scientific Motivations

## Thermo-Acoustic model for cylindrical bars

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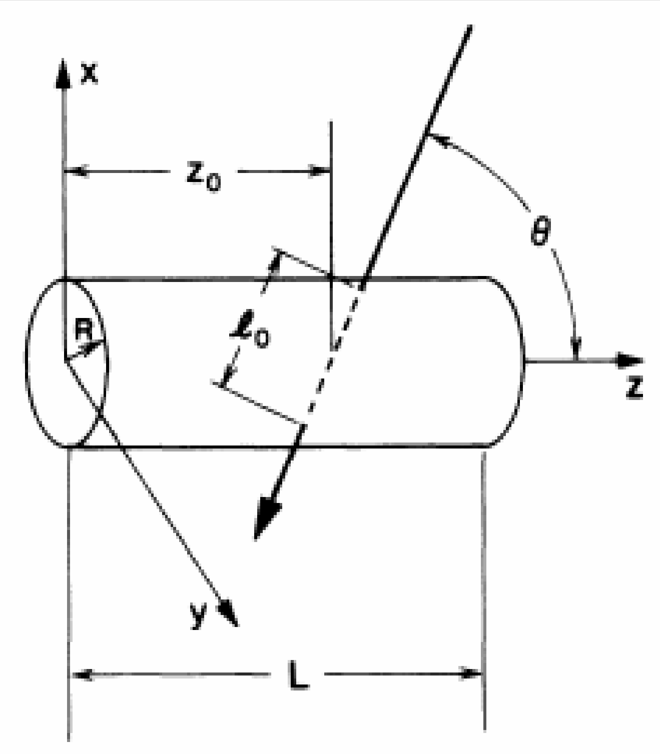



$$E_n \propto \left(\frac{\alpha}{C_V}\right)^2 \cdot \left(\frac{dE}{dx}\right)^2 \cdot F_n^2(L,R)$$

$$\left[\sin\left(\frac{n\pi z_0}{L}\right)\frac{\sin(n\pi l_0\cos\theta/2L)}{n\pi R\cos\theta/L}\right]^2$$

→ the amplitude of the 1st longitudinal mode of oscillation of the bar is:

$$B_0^{therm} = \frac{2}{\pi}\frac{\alpha W L}{C_V M}$$

where *W* is the total energy released by the interacting particle in the bulk

Note that: 1) These relations are valid in the *R* « *L* limit
2) $E_0 \propto B_0^2$

# Scientific Motivations

## Thermo-Acoustic model for cylindrical bars

The amplitude of the 1st longitudinal mode of oscillation is

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

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

accounts for:

a) $O[(R/L)^2]$ corrections

b) beam structure (from complete MC simulation)

→ $\varepsilon$ = – 0.04 for Al5056

→ $\varepsilon$ = – 0.08 for Nb

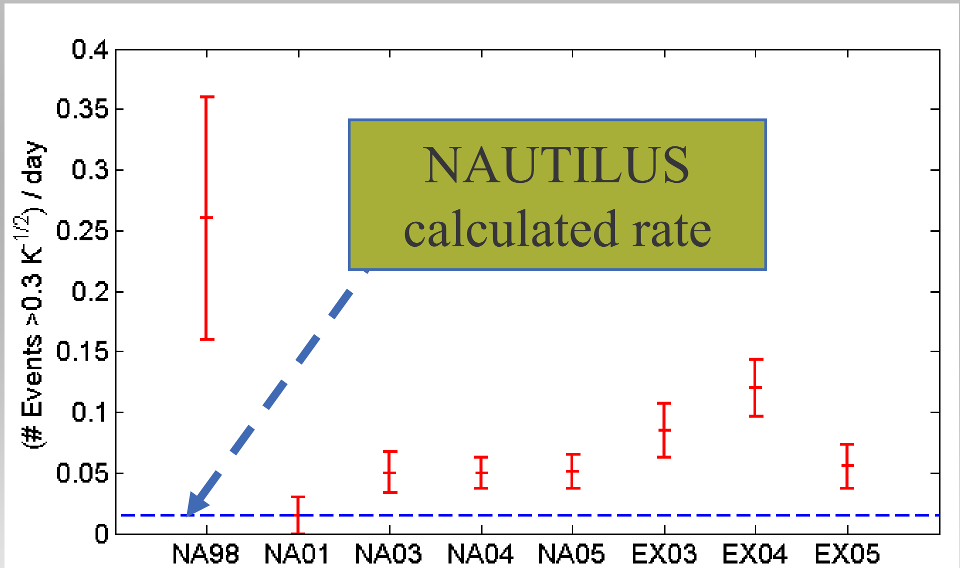
*"Grüneisen parameter"* ($\gamma$)

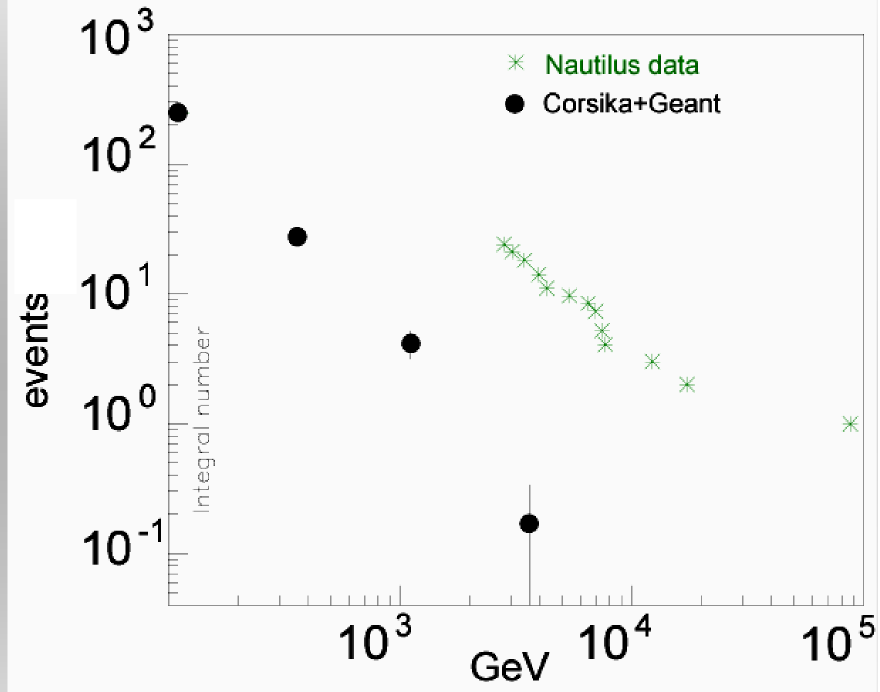
- ✓ is proportional to $\alpha/C_V$
- ✓ is nearly constant between $T$ = 10 ÷ 300 K
- ✓ what happens in SC state?

# Scientific Motivations

## Interaction CR – GW Antennas

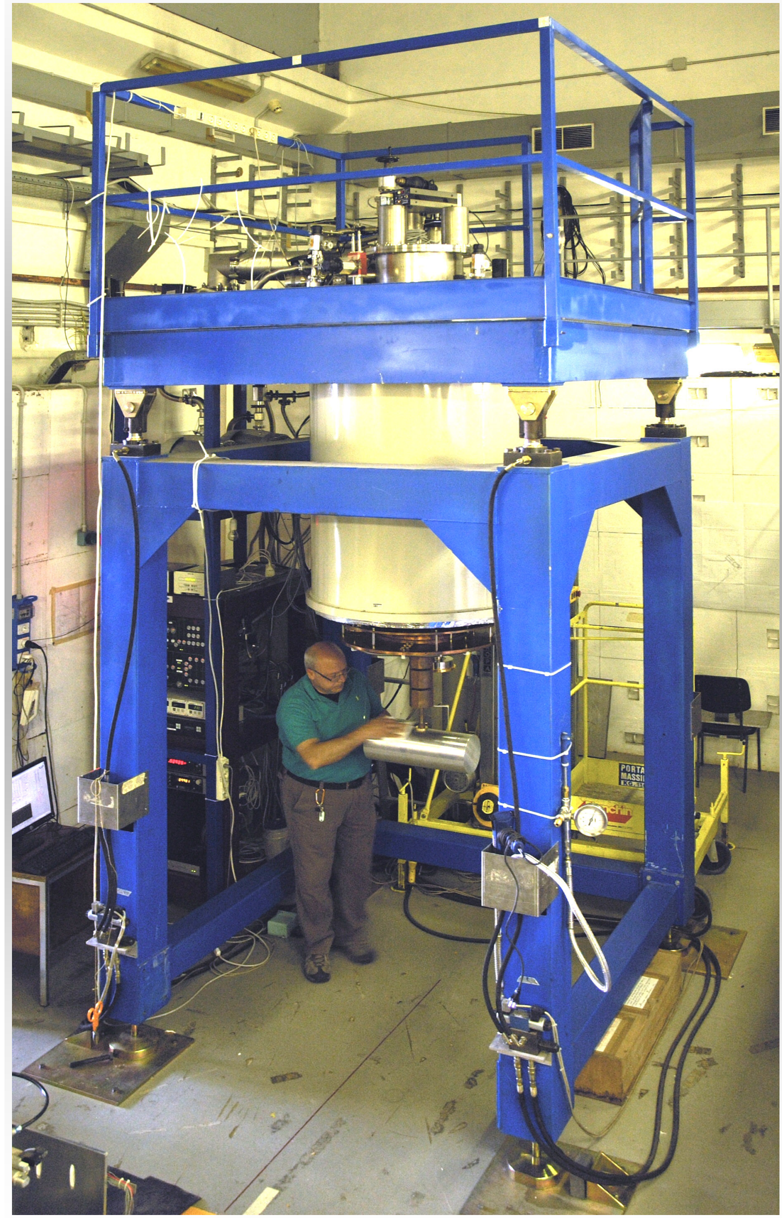
Cosmic ray rates observed in NAUTILUS and EXPLORER in the period 1998 – 2005. The first measure (NAUTILUS '98) was taken with the bar in superconducting state

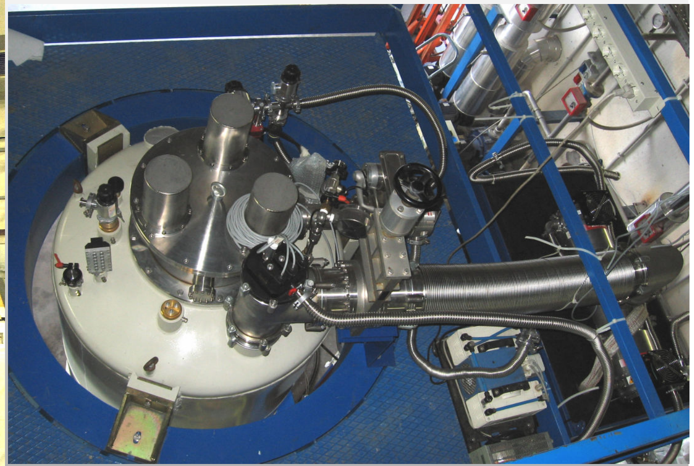


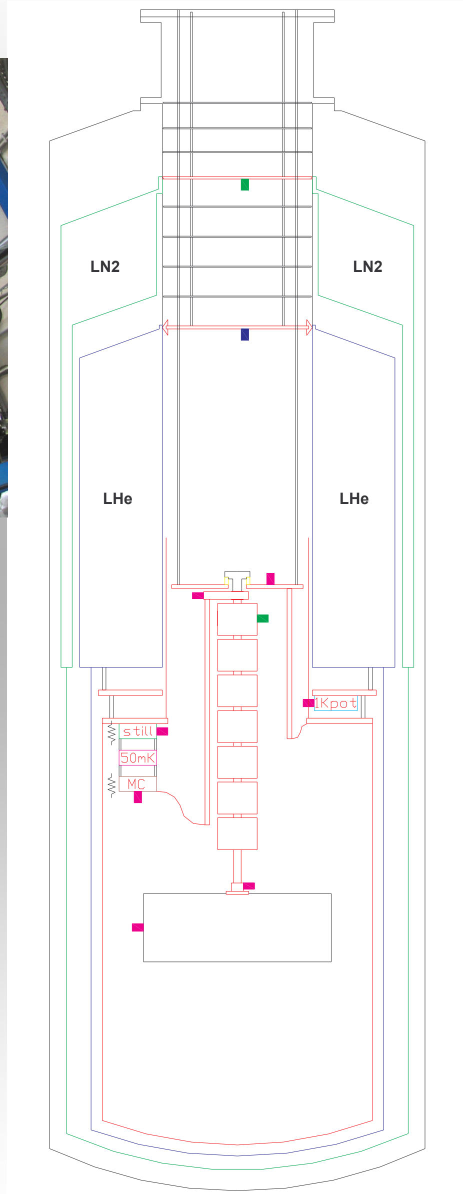




Green: NAUTILUS measurements
Black: predictions for the CR showers with the Thermo-Acoustic model applied to the normal-conducting state

# Experimental Setup



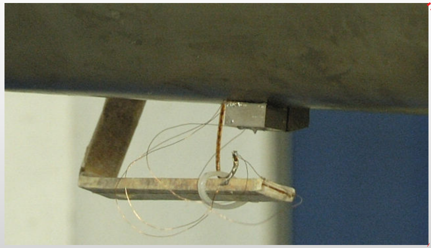


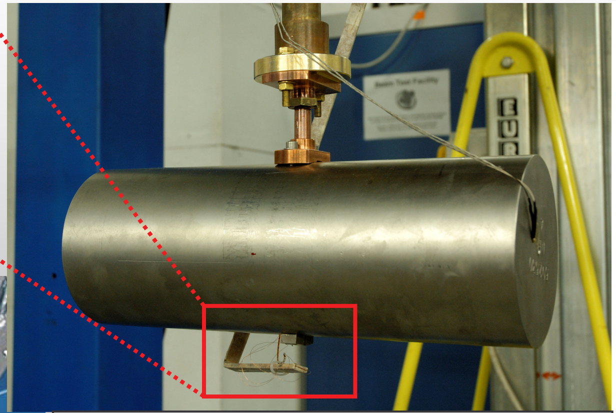



**KADEL Liquid Helium Cryostat**
(+ Dilution Refrigerator)

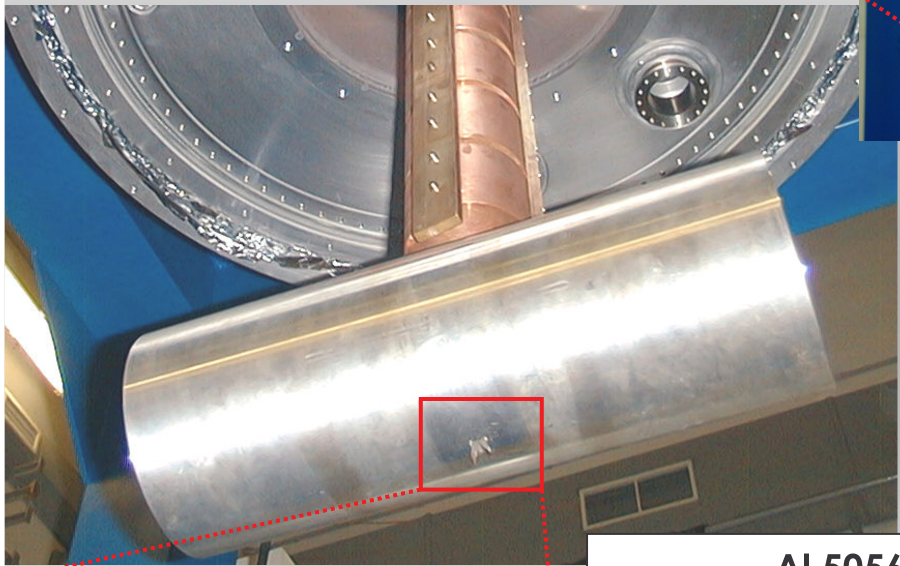
Experimental volume = 0.6 $m^3$
Height = 3.2 $m$
Diameter = 1 $m$
LHe static boil rate = 1.5 *lt/hour*
$LN_2$ static boil rate = 1 *lt/hour*

# Experimental Setup

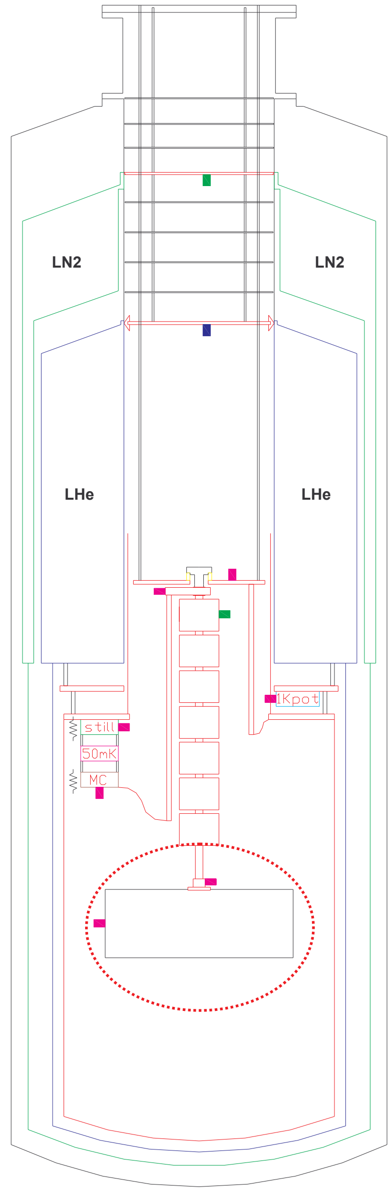




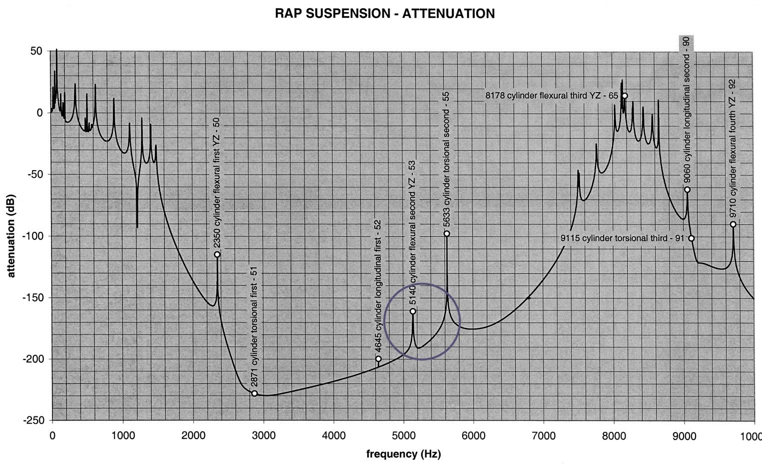
**Niobium Bar**
- 27.4x10 *cm*, 18.4 *kg*
- $\nu$ = 6373 *Hz* @ 290 *K*
- annealed, purity > 99%
- 2 PZ24 ceramics in parallel glued to the bottom center
- $\lambda \sim 10^6$ *V/m*

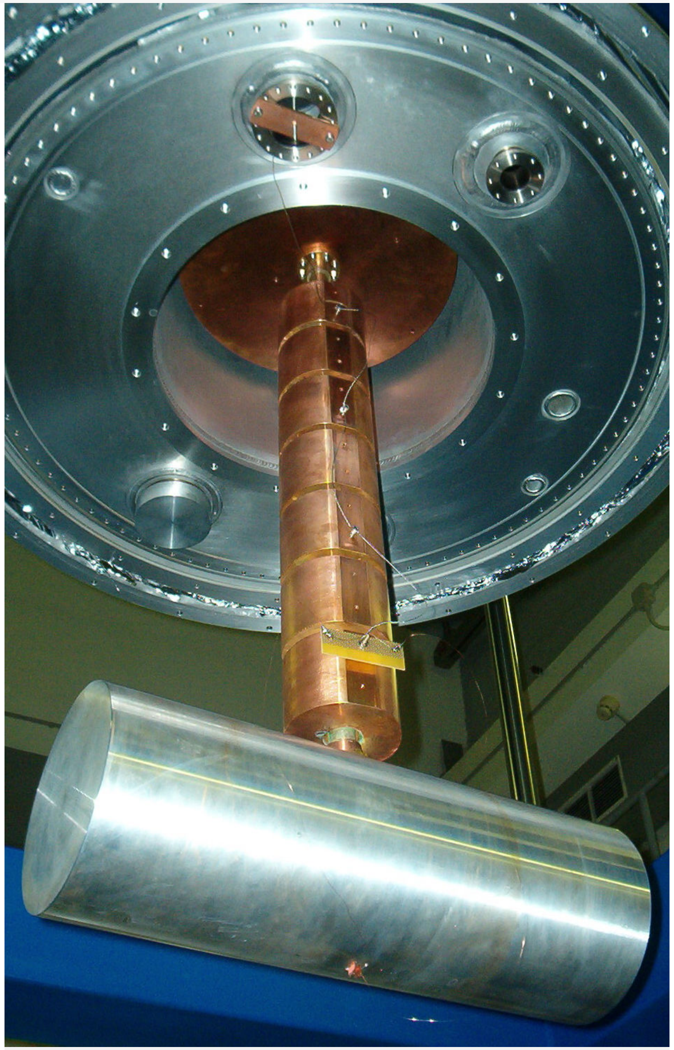


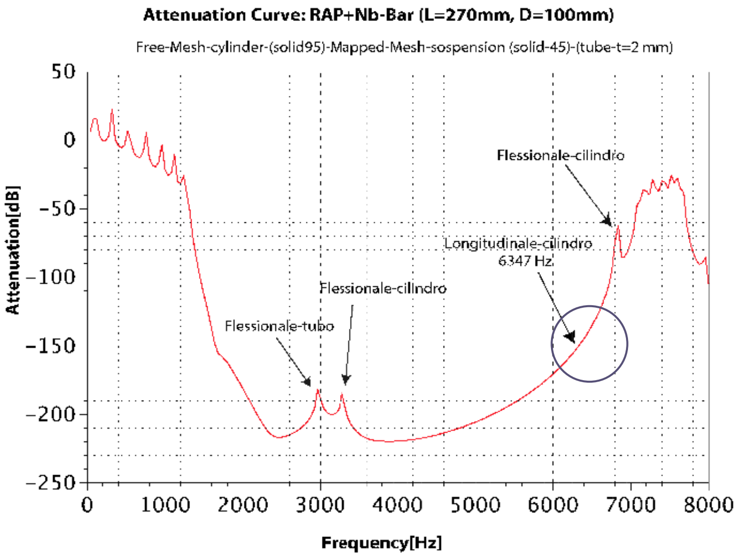
**Al 5056 Bar**
- 50x18.1 *cm*, 34.1 *kg*
- $\nu$ = 5096 *Hz* @ 296 *K*
- 2 Pz24 ceramics in parallel embedded in the bar
- $\lambda \sim 10^7$ *V/m*

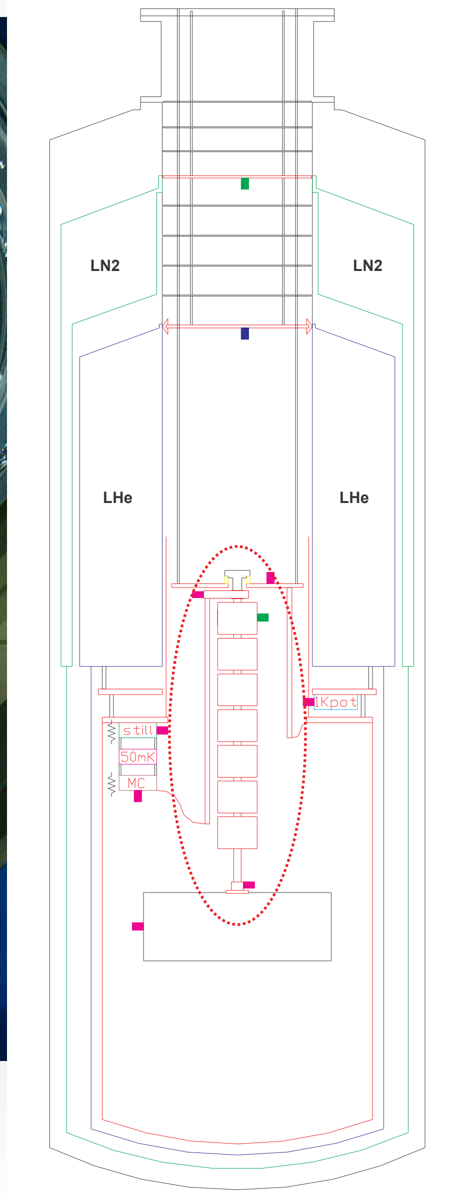


# Experimental Setup



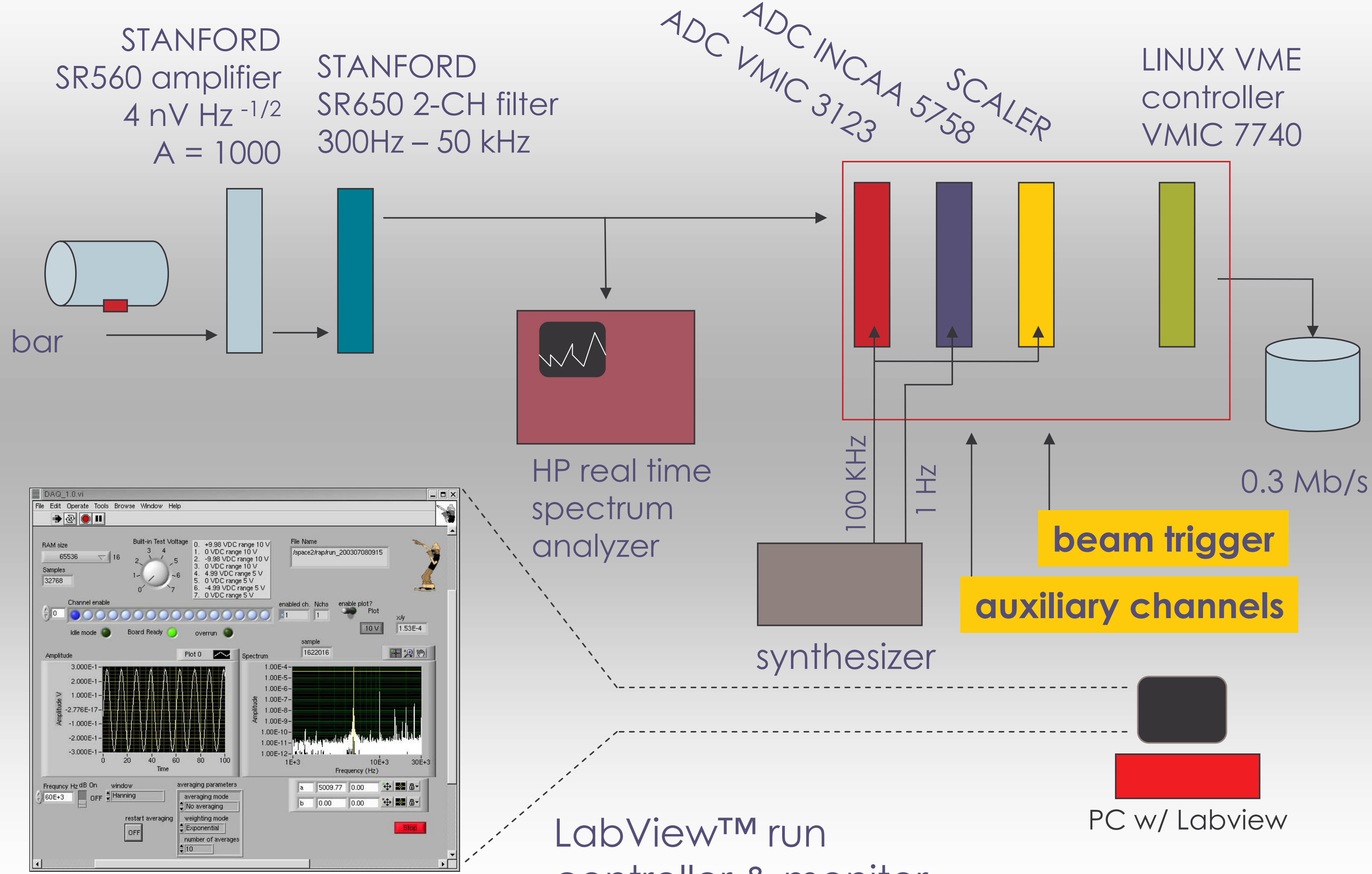






**Suspension:** 7 OFHC copper masses
Attenuation: –150*dB* @ 1.7 ÷ 6 *kHz*

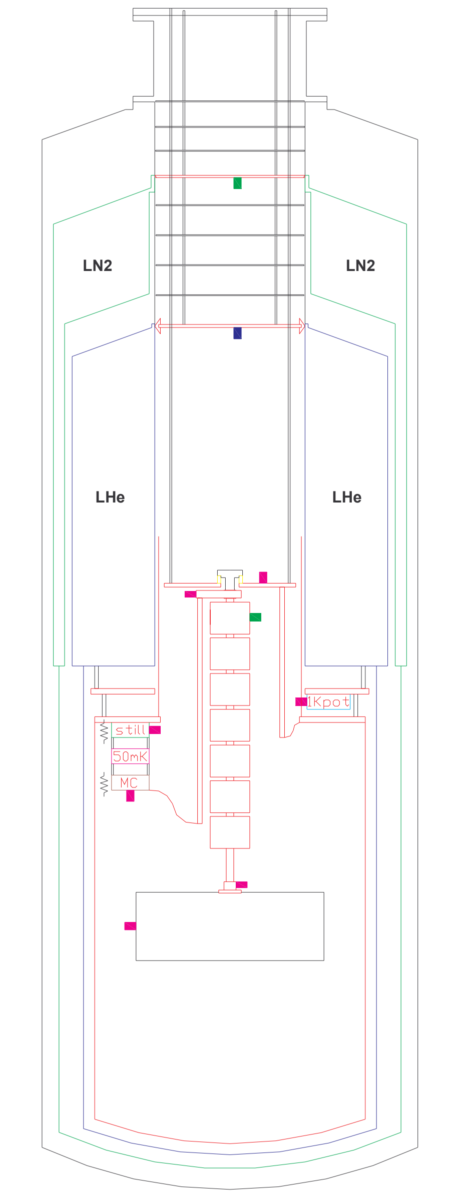
# Experimental Setup

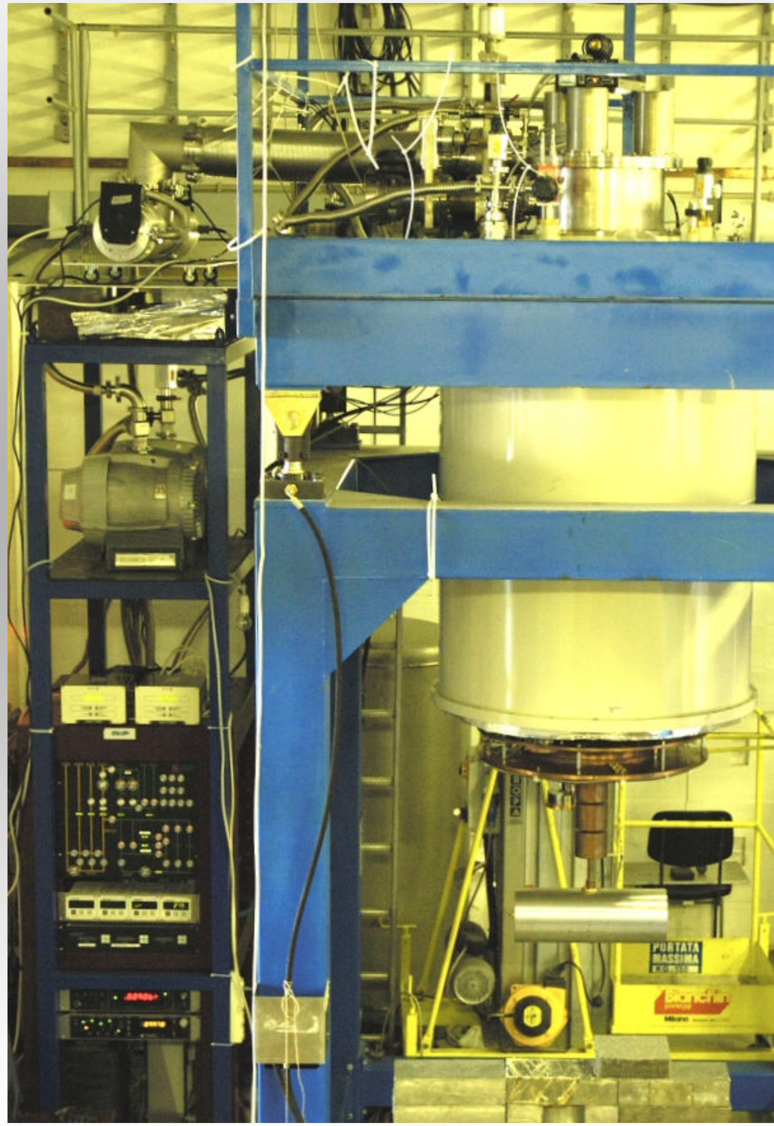


# Experimental Setup

## the dilution refrigerator

- made by Leiden Cryogenics
- $T_{final}$ = 100 *mK*
- Power = 1 *mW* @ 120 *mK*
- Installed in end 2006
- not yet fully characterized



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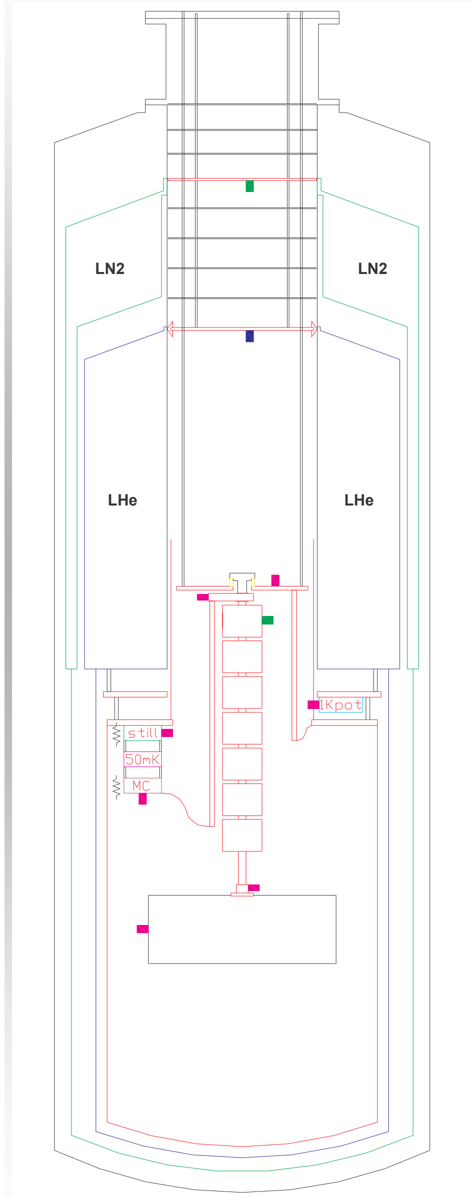


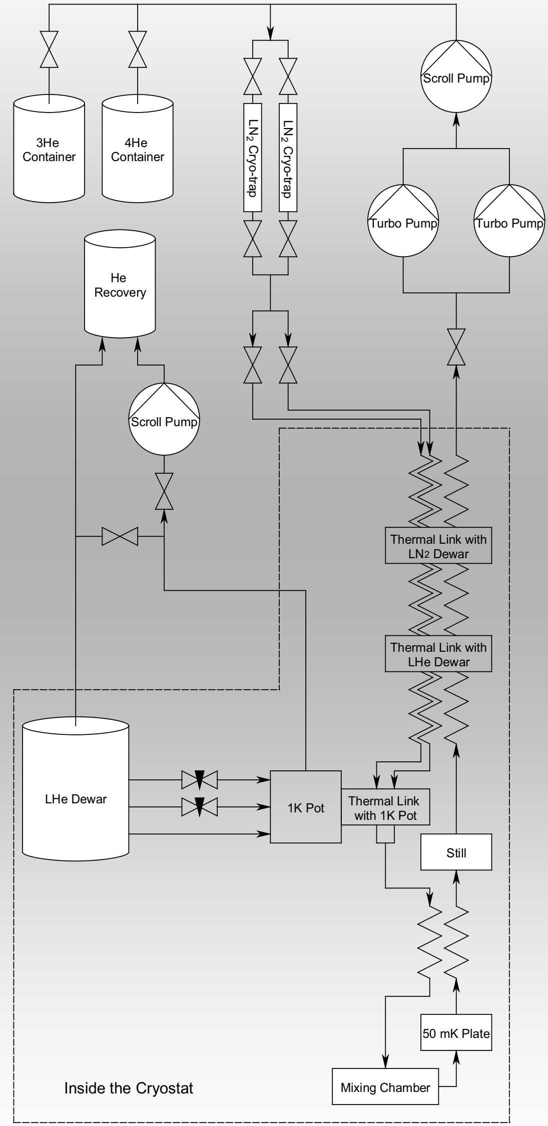

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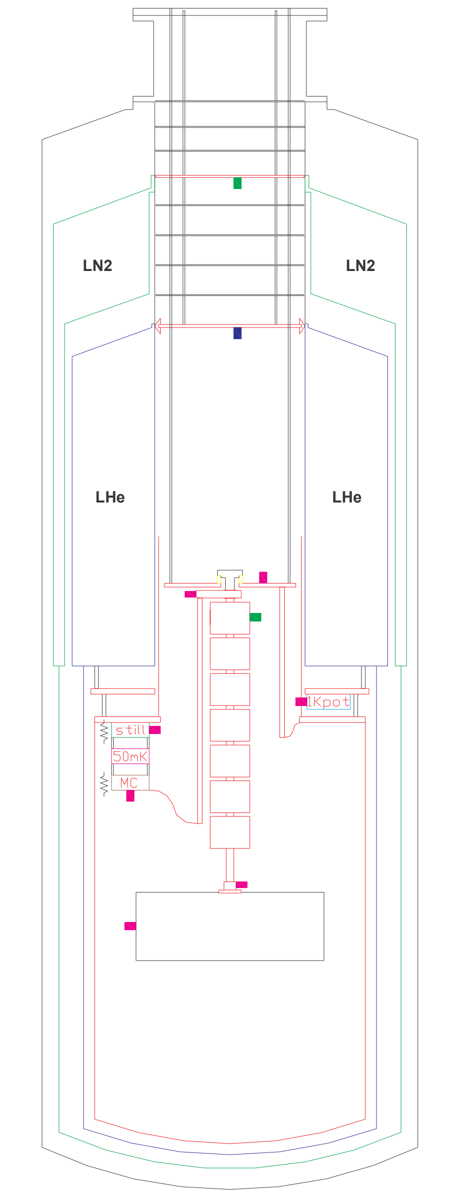



8 $RuO_2$ thermometers (0-4.2 *K*) → resistance bridge

1 FeRh thermometer (4.2-300 *K*) + 2 Pt thermometers (30-300 *K*) → resistance bridge

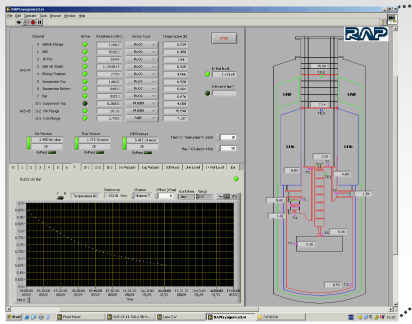
2 dual-gauge pressure sensors pirani+cold cathode ($10^{-9}$-$10^{3}$ *mbar*) → 2 pressure racks

liquid Helium level gauge → level read. rack

1K Pot + Still level gauges → 2 LCR meters

Mix Chamber + Still heaters ← current source

PC w/ Labview



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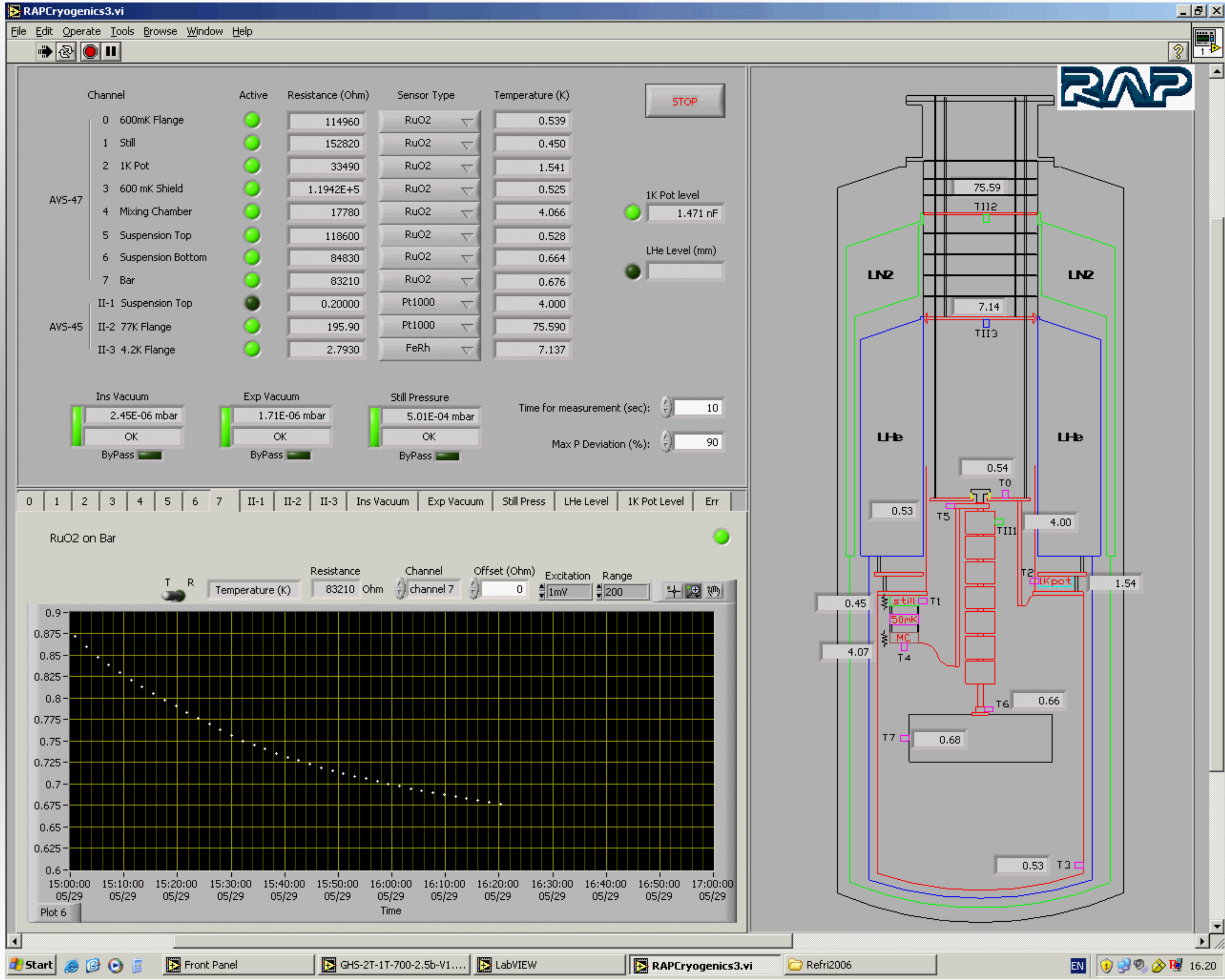

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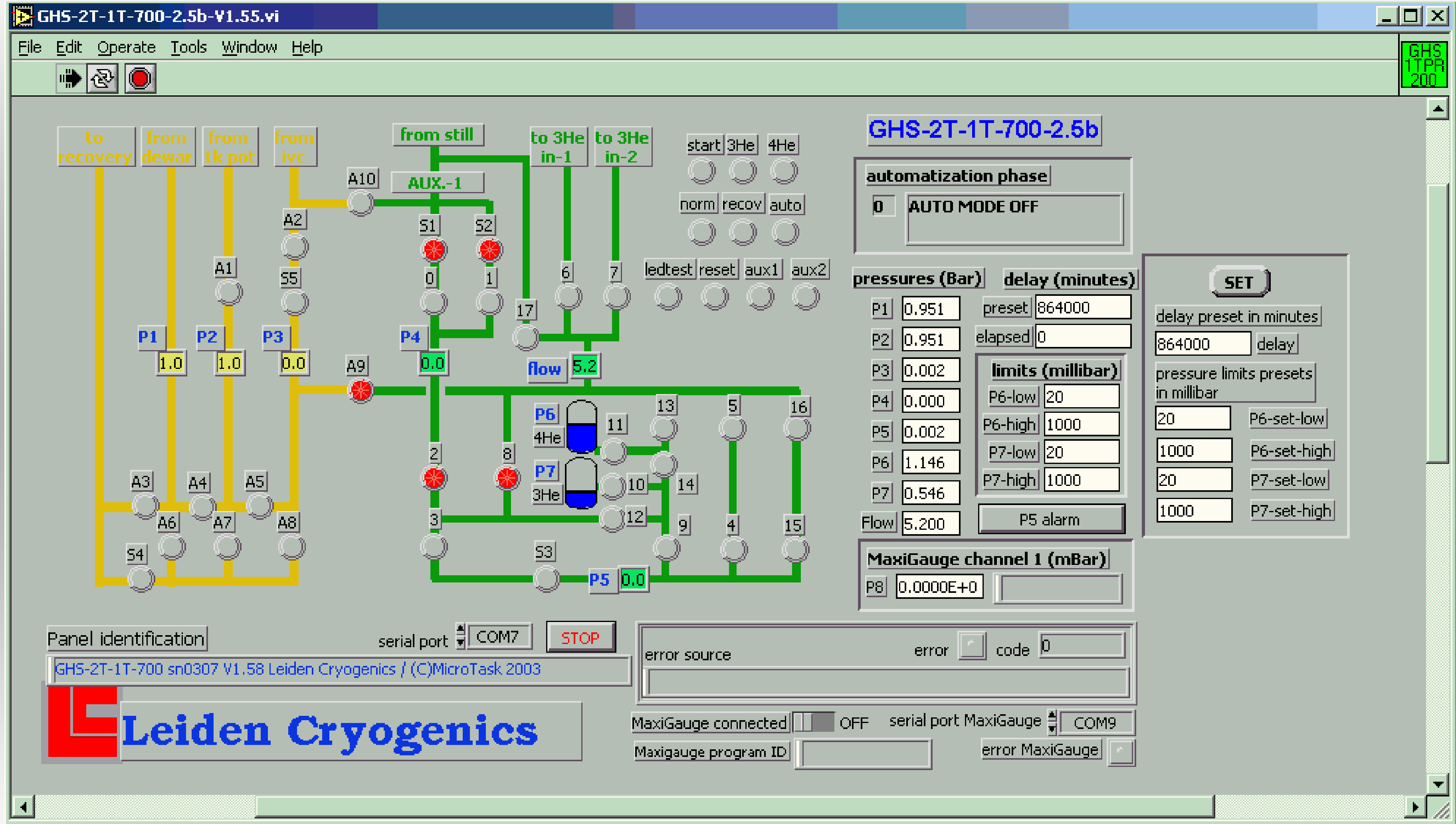


# Experimental Setup

<u>Devices systematic accuracy: uncertainties</u>

- Beam monitor: 3%
- PZ24: 6%

$\left.\right\}$ Total = 7%

## <u>PZ24 Auto-Calibration</u>

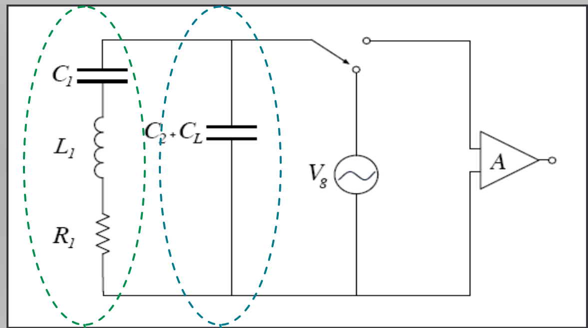
*Pallottino-Pizzella, Nuovo Cim. B **45**, 275 (1978)*

$$B_{mis}[m] = \frac{V}{\lambda}$$

signal from the beam : $V \approx 10^{-6}\ V$

$$\lambda = \sqrt{\frac{2\pi\ f_0 M V_0}{(C_2 + C_L) V_g \Delta t}}$$

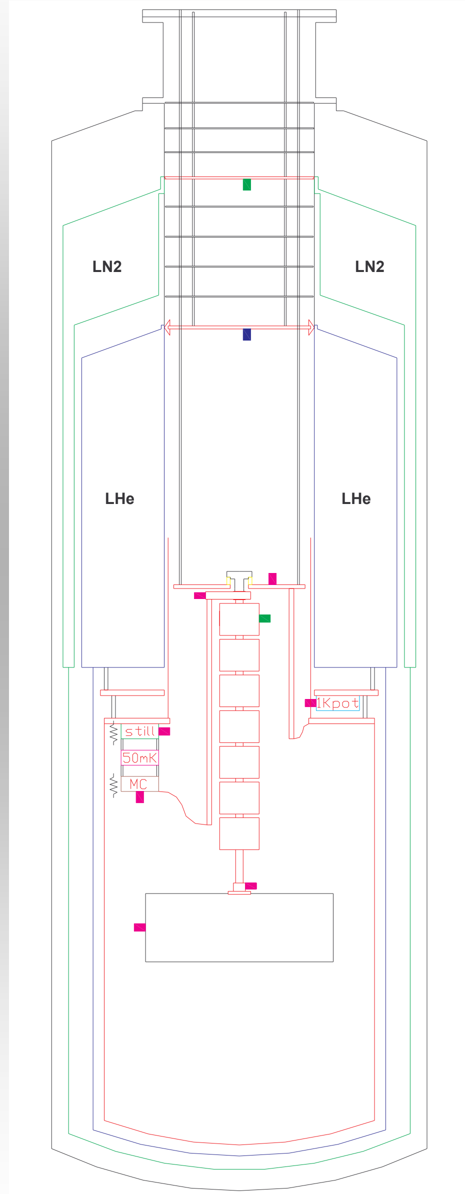
$$\text{typical } \lambda \approx \begin{cases} 10^6\ Vm^{-1}\ \text{(Nb)} \\ 10^7\ Vm^{-1}\ \text{(Al5056)} \end{cases}$$



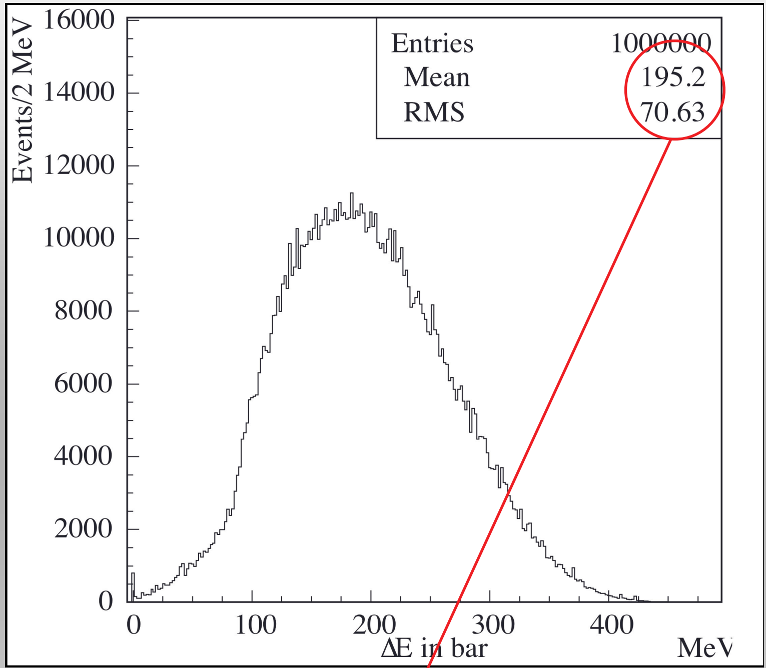

PZ + bar

amp + wires

- the auto-calibration method shows good agreement with a calibrated accelerometer
- calibrations have been done frequently during the runs

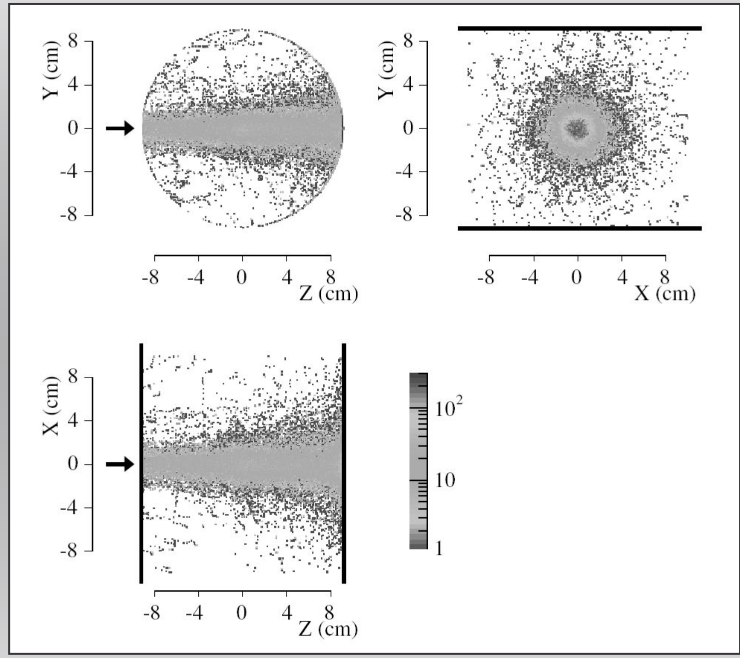


# Beam Interaction Simulations




Mean energy released by one electron for a simulation of 100 shots of $10^4$ **510 *MeV*** particles impinging the Al5056 antenna.
The same simulation for the Nb antenna gives a value of 453 ± 39 *MeV*

***Monte Carlo simulations***



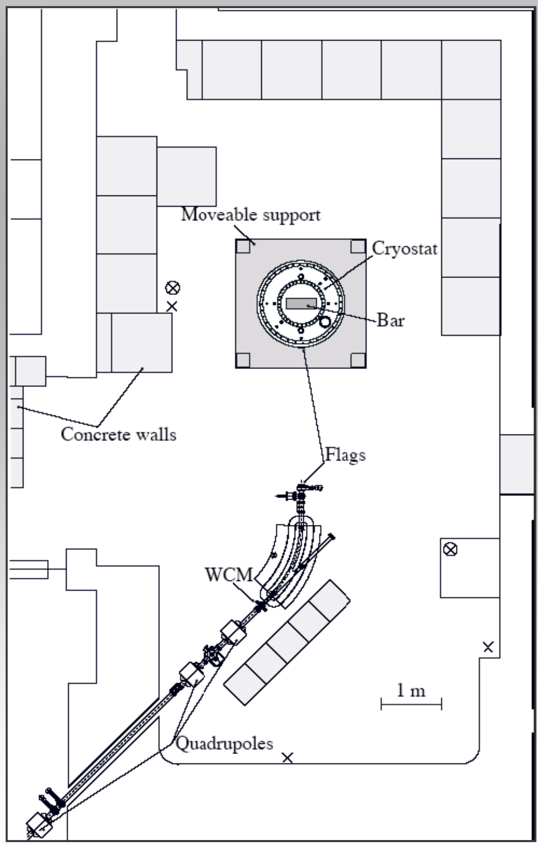

Secondary particle distribution for a 510 *MeV* primary e⁻

- In Al5056: 2*R* ~ 2 radiation lengths
- In Nb: 2*R* ~ 9 radiation lengths

# DAΦNE BTF Runs

All the measurements have been done in the *DAΦNE Beam Test Facility*, using pulses of electrons

- pulse duration = 1 ÷ 10 *ns*
- $n_e = 10^8 \div 10^9\ e^-$
- *E* = 510 *MeV*
- spot size ≈ 2 *cm*
- Beam Current Monitor sensitivity ≈ 1.4 $10^7\ e^-$



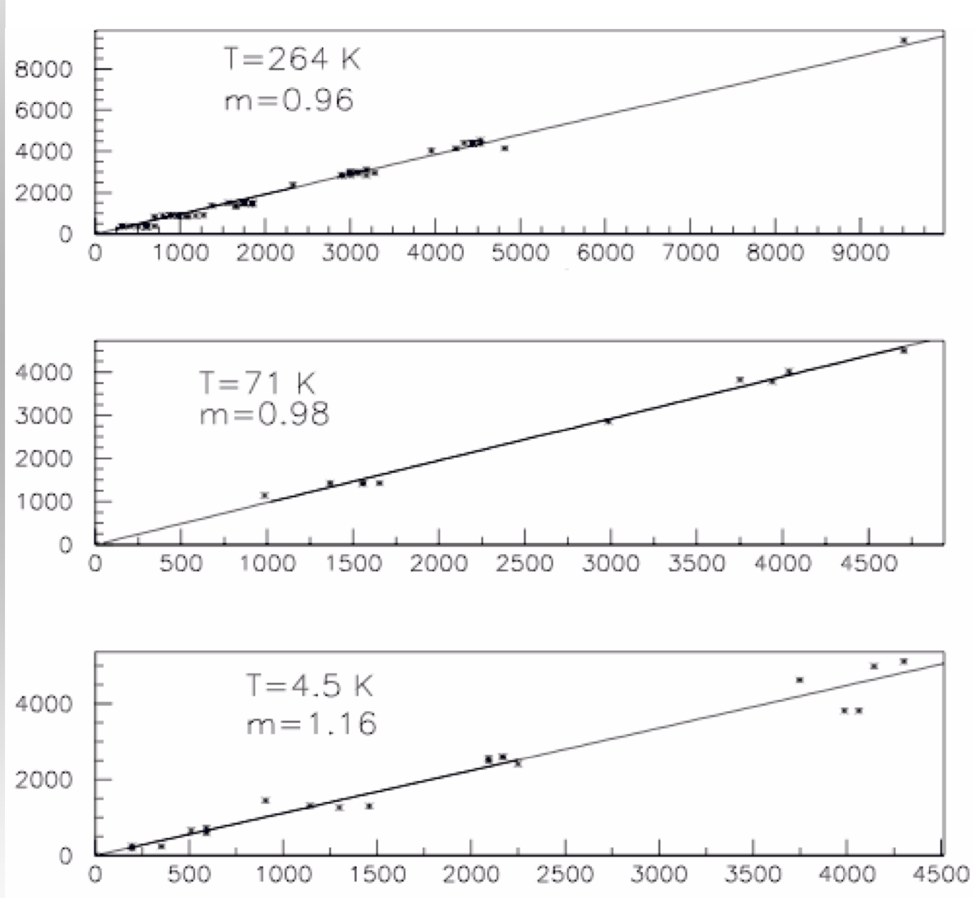

# Al5056 Measurement Results

## - normal state -

AstroParticle Physics **24**, 65-74 (2005)

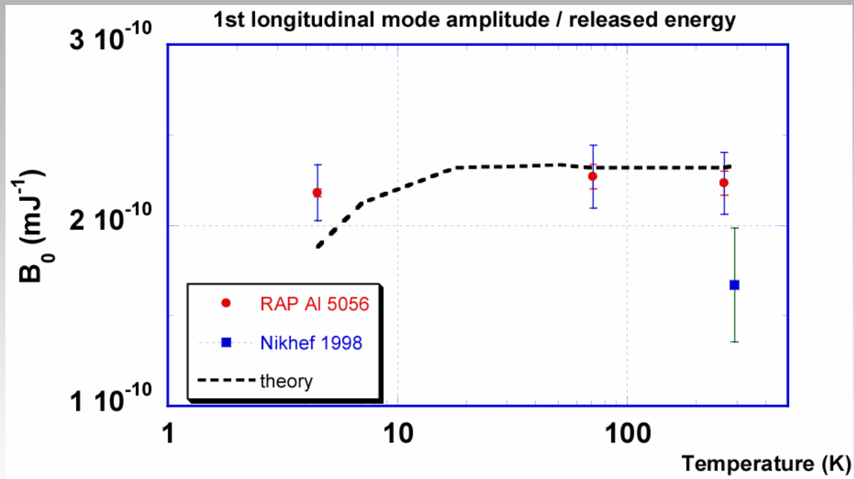
$$B_{MEAS} = mB_{TH}$$

measured vs calculated 1st longitudinal mode amplitude




$B_{MIS}$ vs $B_{TH}$ ($10^{-16}$ m)

| T [K] | $B_{TH}$ [$10^{-10}$ m/J] | m | Δm |
|---|---|---|---|
| 264 | 2.32 | 0.96 | 0.01 |
| 71 | 2.32 | 0.98 | 0.03 |
| 4.5 | 1.88 | 1.16 | 0.03 |



# Al5056 Measurement Results

## - normal state -

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$$B_{MEAS} = mB_{TH}$$

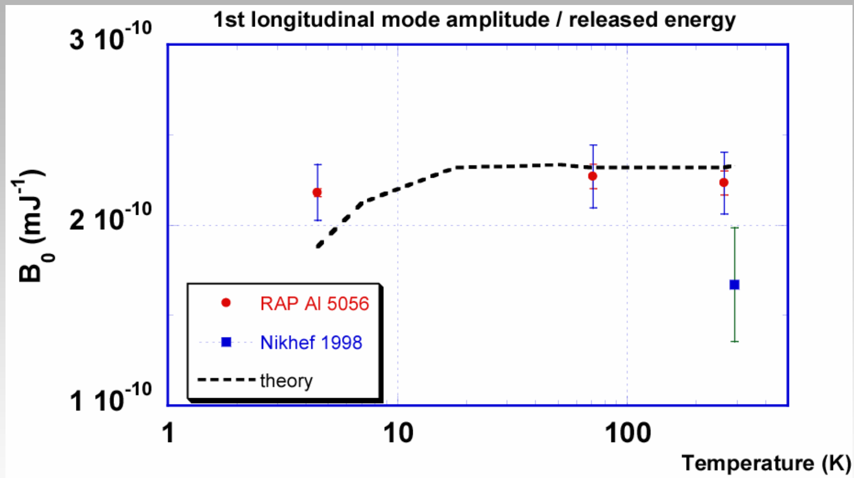
| $T$ [K] | $B_{TH}$ [$10^{-10}$ m/J] | $m$ | $\Delta m$ |
|---|---|---|---|
| 264 | 2.32 | 0.96 | 0.01 |
| 71 | 2.32 | 0.98 | 0.03 |
| 4.5 | 1.88 | 1.16 | 0.03 |

✓better agreement with the model with respect to the previous measurements

✓first assessment of the model at cryogenic temperatures

✓small disagreement at liquid helium temperature, probably due to the lack of knowledge of the thermophysical parameters ($\alpha$ e $C_V$) at low $T$

✓linearity of the response with the energy released by the beam



# Niobium Measurement Results

## - normal state -

Europhys. Lett. **76**, 987-993 (2006)

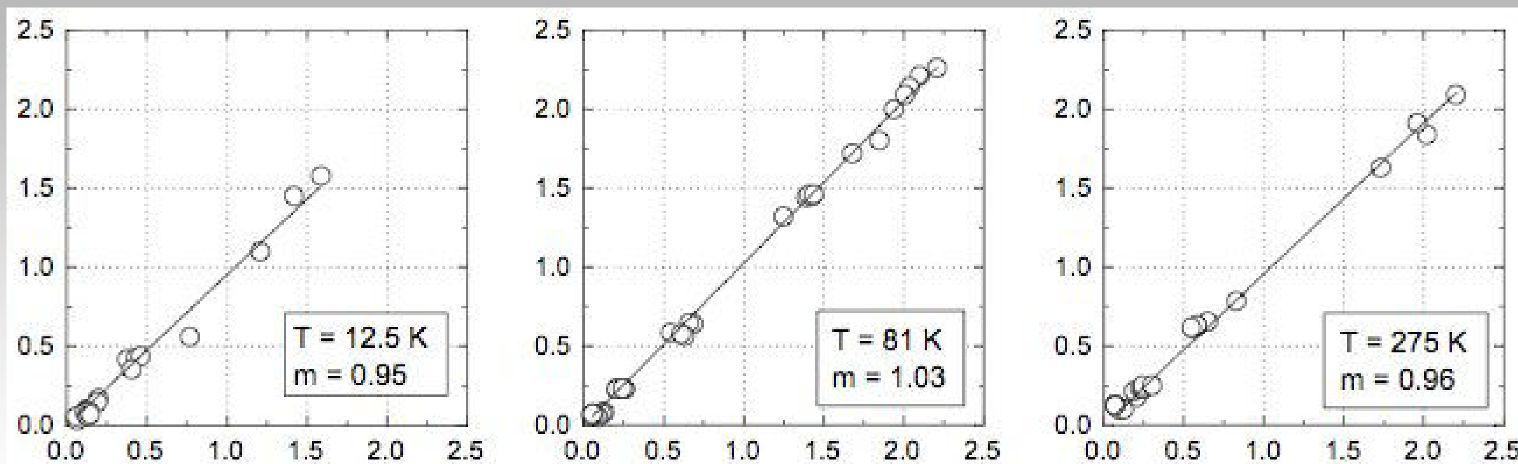
$$B_{MEAS} = mB_{TH}$$

| *T* [K] | $B_{TH}$ [$10^{-10}$ *m/J*] | *m* | *Δm* |
|---|---|---|---|
| 275 | 2.31 | 0.96 | 0.01 |
| 81 | 2.30 | 1.03 | 0.01 |
| 12.5 | 1.55 | 0.95 | 0.02 |

✓very good agreement with the model also due to the very well known thermophysical parameters of the pure Niobium as a function of the temperature

✓linearity of the response with the energy released by the beam

measured vs calculated 1st longitudinal mode amplitude

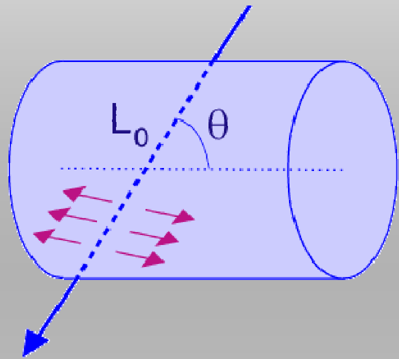



$B_{MIS}$ vs $B_{TH}$ ($10^{-11}$ m)

# What happens in SC state?...

Two possible approaches:

- The beam <u>does NOT cause any transition</u> in the material
  → the material gets warm same as in the normal-conducting state and the process should be described by the *Thermo-Acoustic model* using the thermophysical parameters of the material in the <u>superconductive state</u> (basically $\alpha$ and $C_V$)




- The beam <u>causes local transitions</u> in the material
  → two different processes contribute in the energy release in the material:
  (*Allega-Cabibbo – Lett. N. Cimento **38**, 263 (1983)*
  *Bernard et al. – Nucl. Phys. B **242**, 93 (1984)*)

  1) the energy released by a particle interacting with the bulk determines a s-n local transition, which causes a pressure pulse in the material

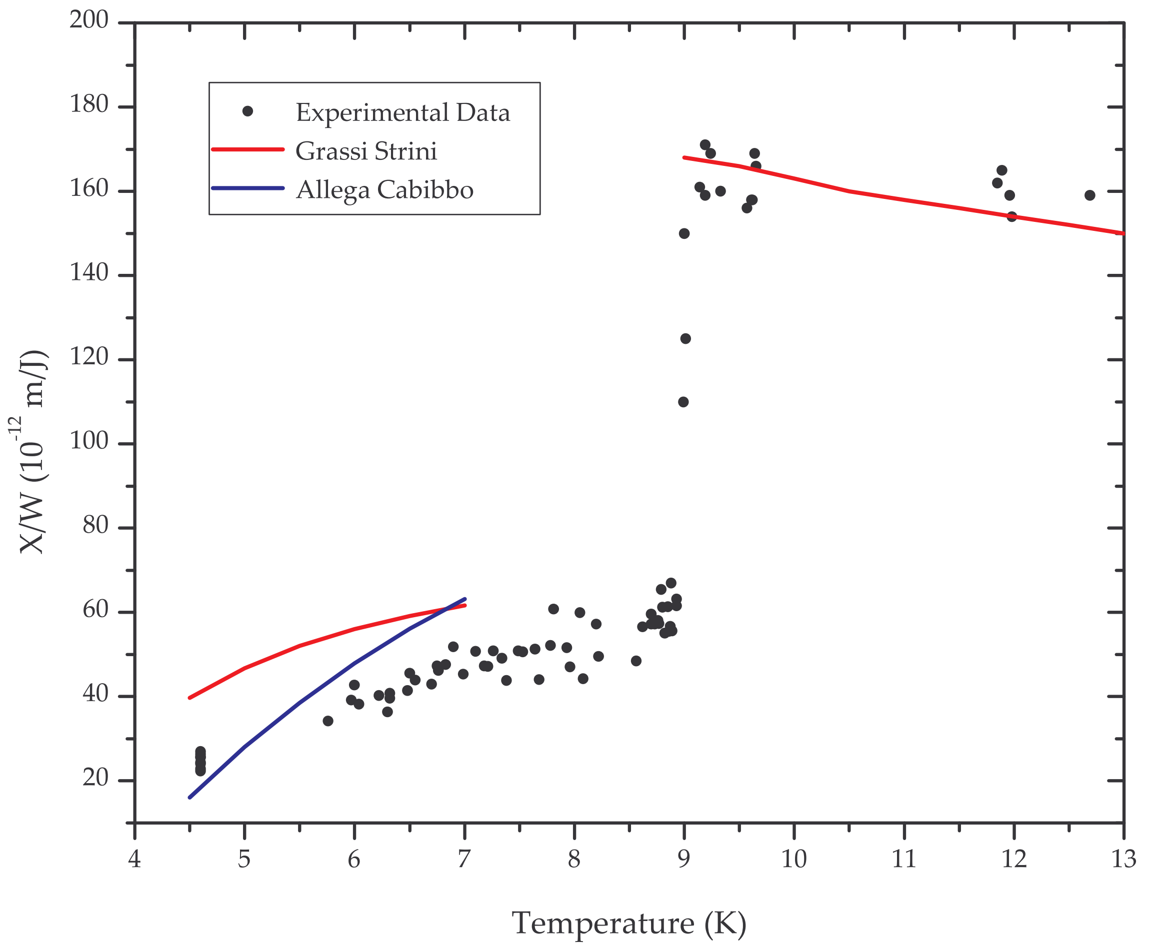
  2) so the heating of the material should be treated with the Thermo-Acoustic model at $T < T_C$, but using the thermophysical parameters of the material in the <u>normal-conducting state</u>

# Niobium Measurement Results

## - superconducting state -

Europhys. Lett. **76**, 987-993 (2006)

measured 1st longitudinal mode amplitude / released energy vs *T*



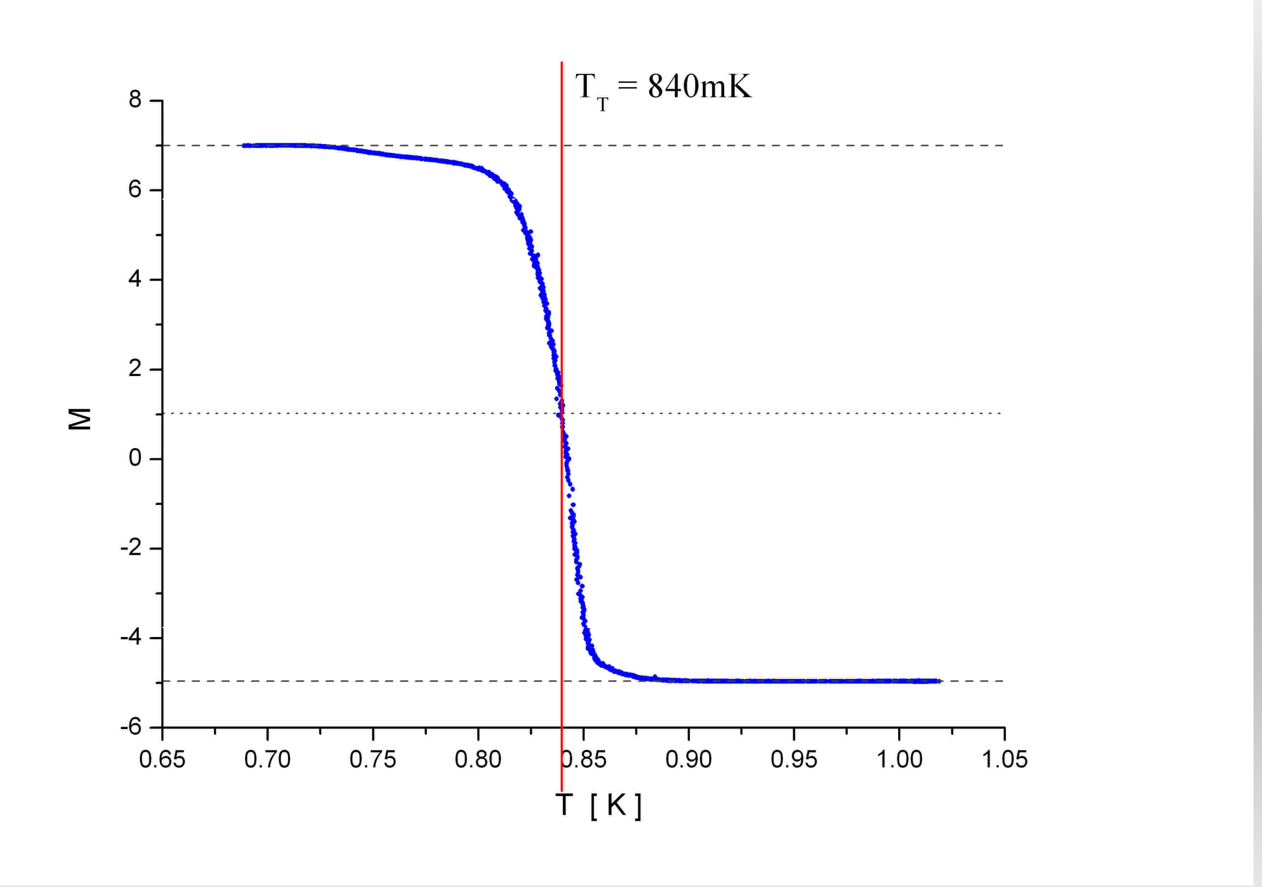

✓ For the first time has been experimentally verified that the amplitude of the longitudinal oscillation of a bar, when hit by a ionizing particle, depends on the conduction state of the material

✓ A possible agreement of the data with the predictions of the ACB model is found

✓ The direct extension of the application of the GS model to the SC state seems to fail

# Al5056 Measurement Results

## - superconducting state -




A transition temperature determination of a Al5056 sample made by INFN-Florence group in 2007, using a mutual-inductance method. The transition width is ~ 100 *mK*.
Note: the pure Al transition temperature is 1.14 *K*. The difference is basically due to a 0.1% contents of Manganese in the alloy.

# Al5056 Measurement Results

## - superconducting state -

Due to the very low transition temperature of the Al5056 alloy, it is necessary a refrigerator to cool it. In the last months of 2006 a dilution refrigerator has been installed in the cryostat and during the 2007 we tried to characterize it. Unfortunately, a leak in the hydraulic circuit didn't allow to correctly use the refrigerator.

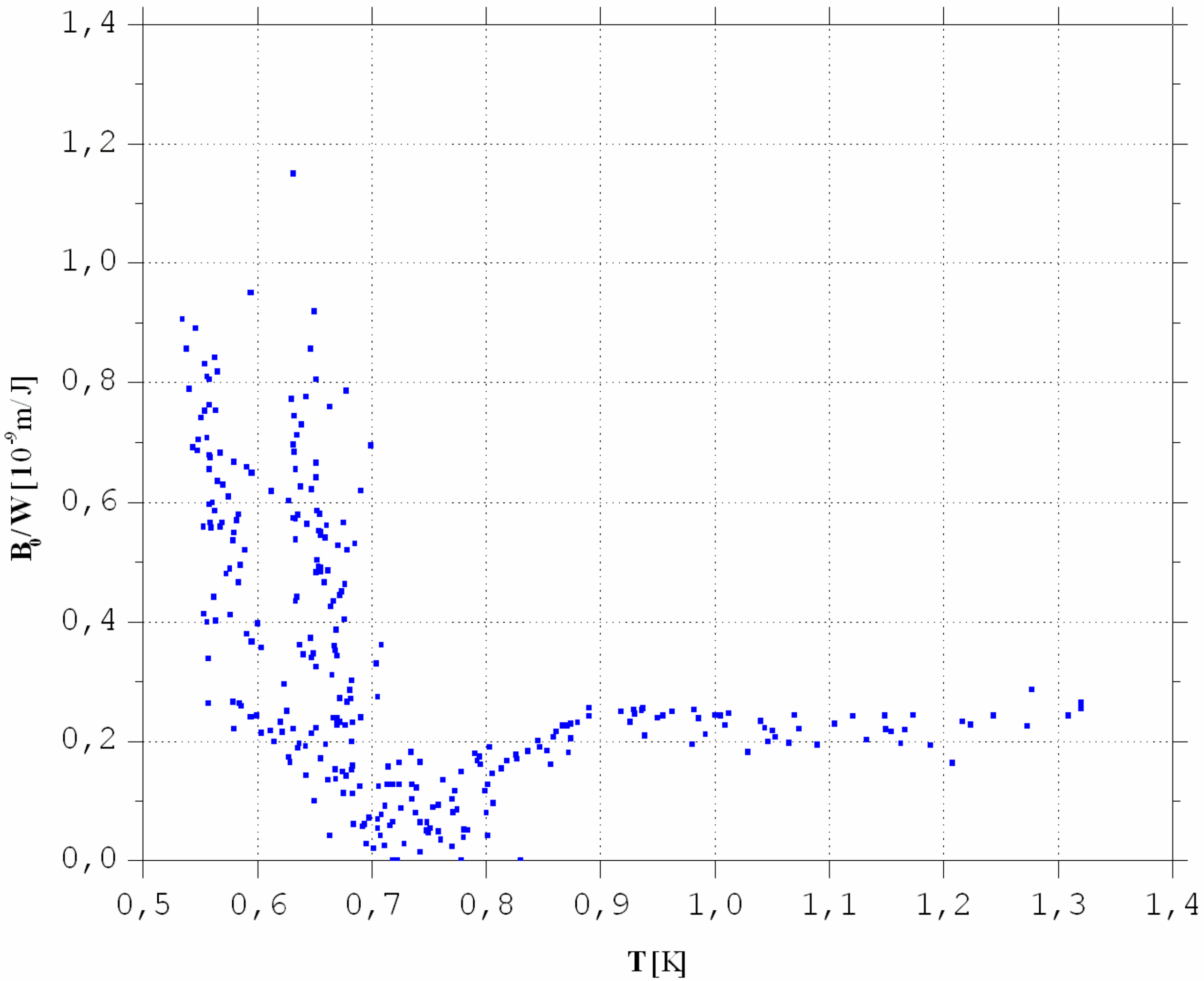
Waiting for the problem fixing, we temporarily found a (partial) solution using the refrigerator as a $^3$He evaporator fridge, keeping the coldest side in the Still. In this way, we was able to cool the bar down to about 530 *mK*.
A measurement campaign has been done in spring 2007 in the DAΦNE BTF

Note: differently from the Nb case, the theoretical models in Al5056 predict an increase of the longitudinal vibration amplitude of the bar, when cooled in superconducting state, with respect to the normal state values.

# Al5056 Measurement Results

## - superconducting state -

measured 1st longitudinal mode amplitude / released energy vs *T*

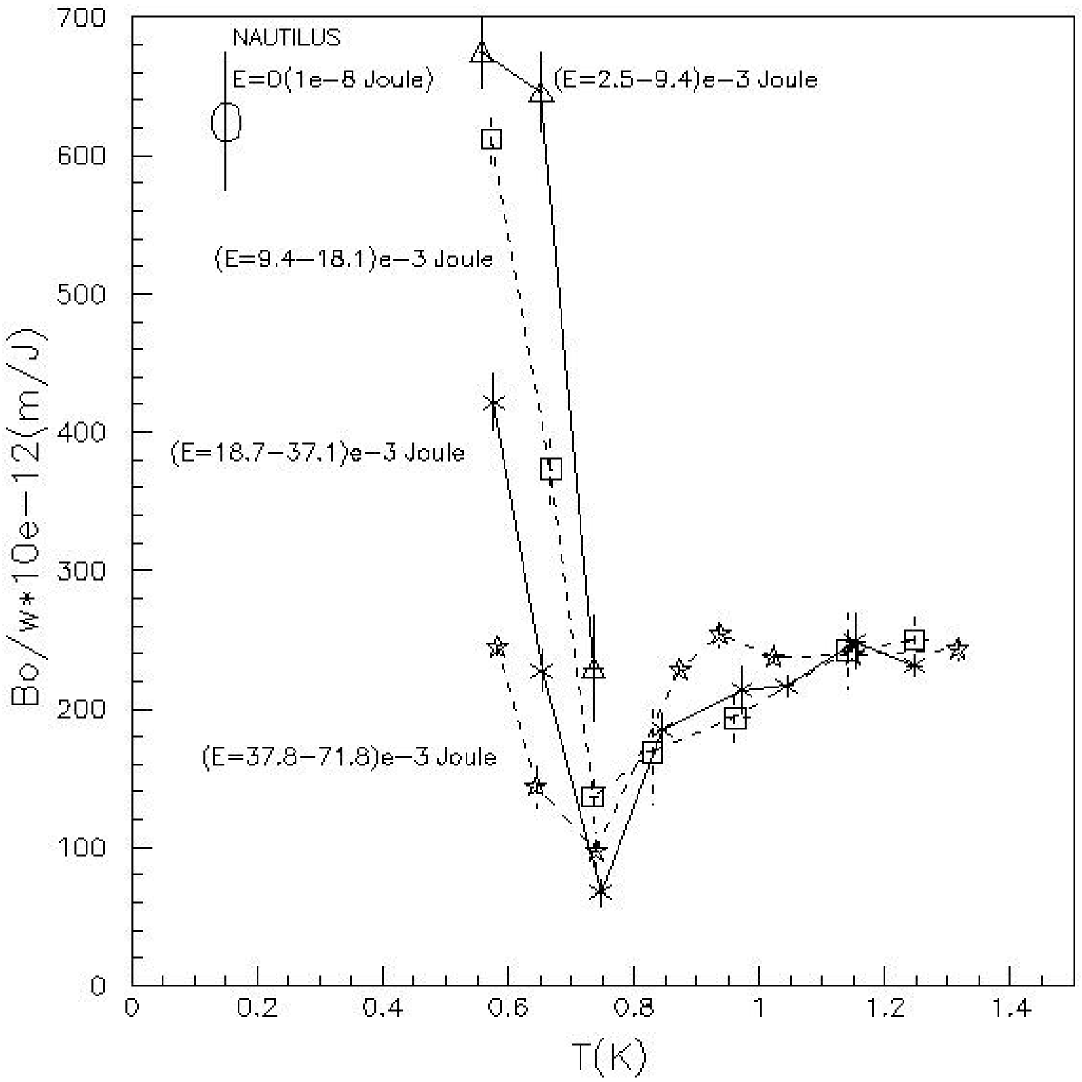



- Results from the 2007 BTF measurements campaign from 1.3 *K* down to the lowest reached T (540 *mK*)
- Has been confirmed that the amplitude of the longitudinal oscillation depends on the conduction state of the material
- As predicted, there is a trend to a raising of the bar oscillation amplitude in SC state
- However, a not explained quite complicated structure of the amplitude near the transition temperature has been observed!!

# Al5056 Measurement Results

## - superconducting state -

measured 1st long. mode amplitude / released energy vs *T*




- Comparison between the RAP measurements and the superconducting NAUTILUS data

- Single shots are grouped in different released energy ranges. In this way a released-energy-dependence has been pointed out

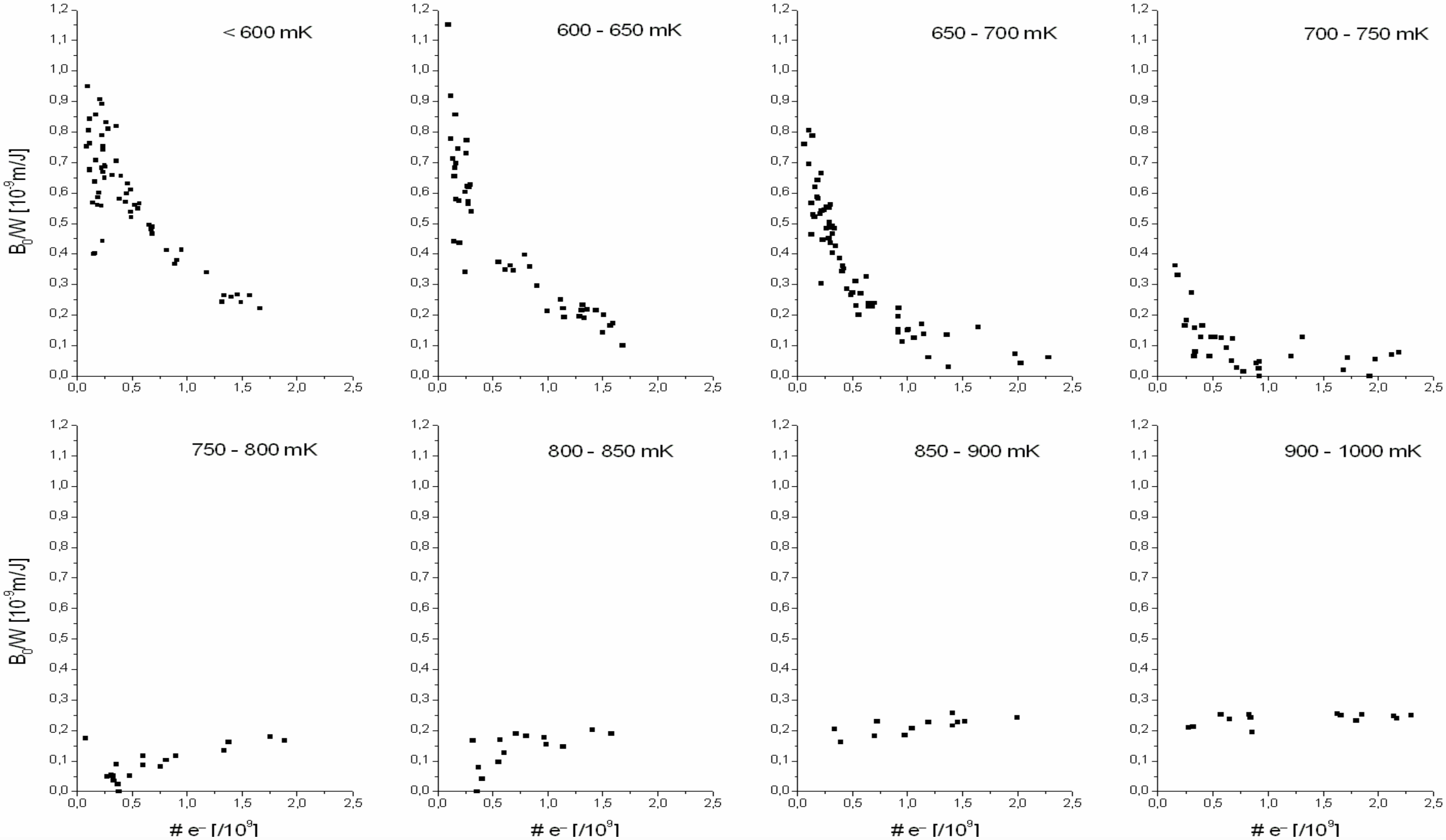
- Measurements at the lowest T seem to be compatible with the cosmic rays NAUTILUS measure

- At present the response depression in the range 0.7 *K* < T < 0.9 *K* has not yet well understood, even though it could be related to a two-components process

# Al5056 Measurement Results

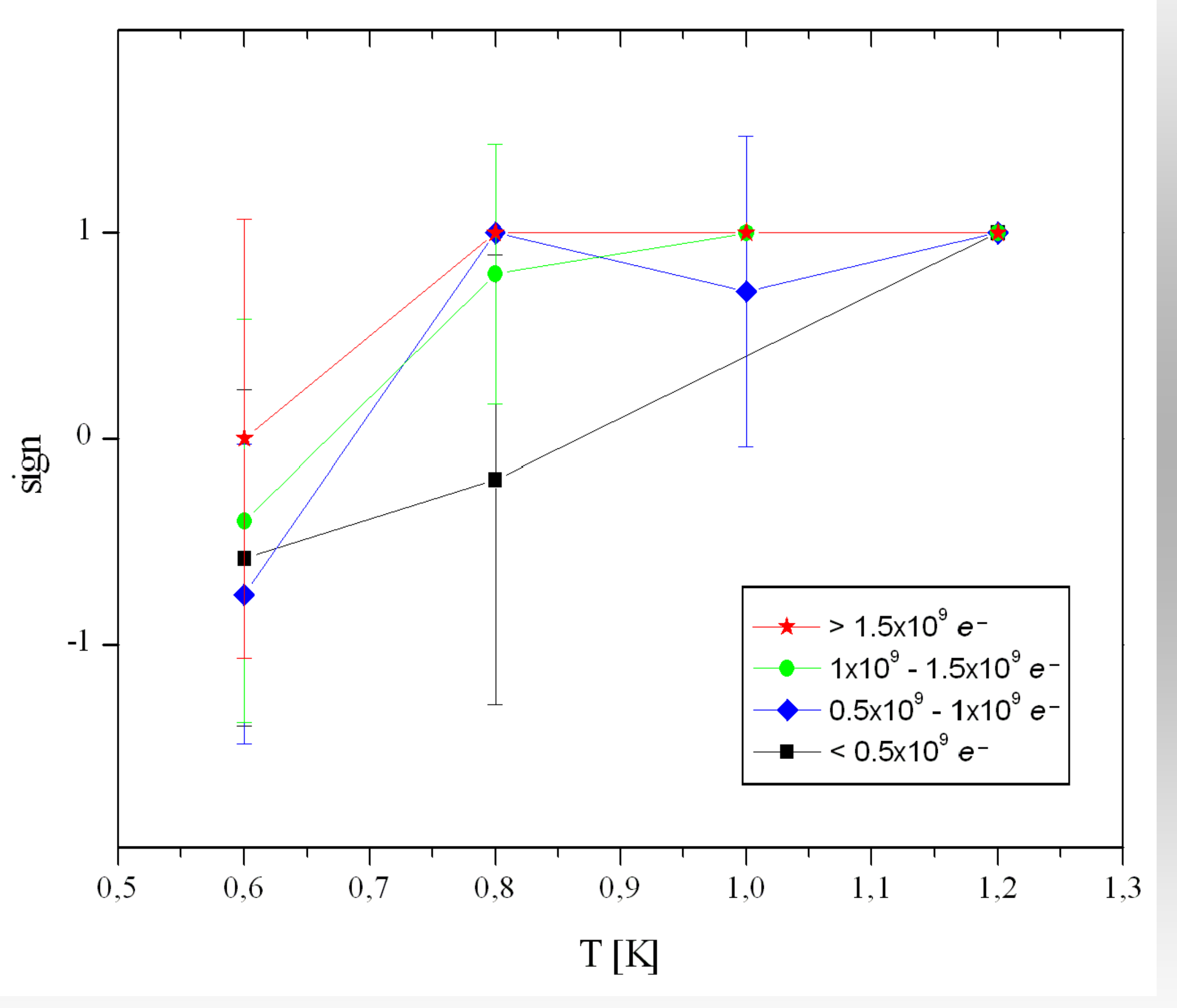
## - superconducting state -

measured 1st long. mode amplitude / released energy vs beam multiplicity for fixed ranges of *T*



# Al5056 Measurement Results

## - superconducting state -




- First half-wave sign of the bar response after the beam crossing. Averaged values in slices of temperatures are showed
- Positive sign means an initial expansion of the bar, negative one means a contraction. It is related to the sign of $\alpha$
- In NC state the bar starts almost always with an expansion. Below $T_C$ there is an evidence of a modification in its behavoiur
- It also seems to be a dependence on the beam multiplicity

# Conclusions

NAUTILUS CR 1998 detections brought us to a discussion about if is correct to extend the use of Thermo-Acoustic Model in SC materials. RAP has been proposed to verify the model.

- ✓ Measurements in NC state have verified the model within the 10% level, using both Nb and Al5056 alloy bars, <u>also at cryogenic *T*</u>
- ✓ Measurements in SC state gave us a number of information, some of them not yet completely understood:

1) The 1st longitudinal mode of oscillation amplitude definitely <u>depends</u> on the conduction state of the material
2) The Grassi-Strini Model seems to fail in the prediction in SC state. The two-components Model (Bernard) seems to be in better agreement with the data. A not good knowledge of the thermophysical parameter of the alloy does not allow to give a final result
3) Al5056 measurements at the lowest T seem to be in a qualitative agreement with the NAUTILUS data
4) The Al5056 data shows some unpredicted behaviour, such as a dependence of the oscillation amplitude from the beam multiplicity.

→ **Measurements at $T \ll T_C$ might help to improve our knowledge of the bar behaviour in SC state, and might give information about the open tasks**

# RAP on the WEB


www.lnf.infn.it/esperimenti/rap