The RAP Experiment:

Acoustic Detection of Particles in Cryogenic Niobium and Aluminium Bars

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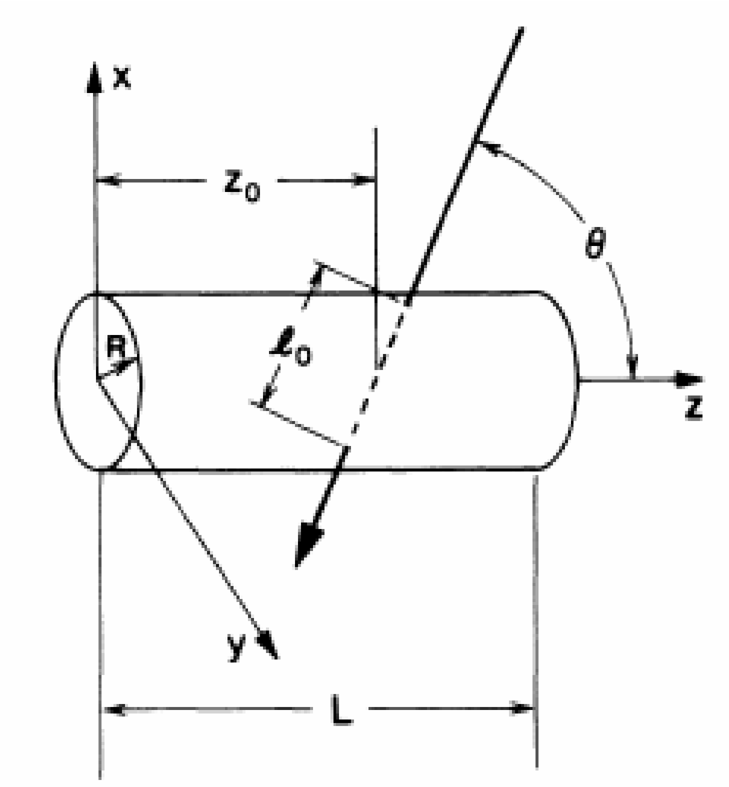
Thermo-acoustic Model
(Grassi Strini, Strini, Tagliaferri; 1979)



Relates the energy lost by the particle to the energy installed in the various normal modes of vibration of the cylindric bar:

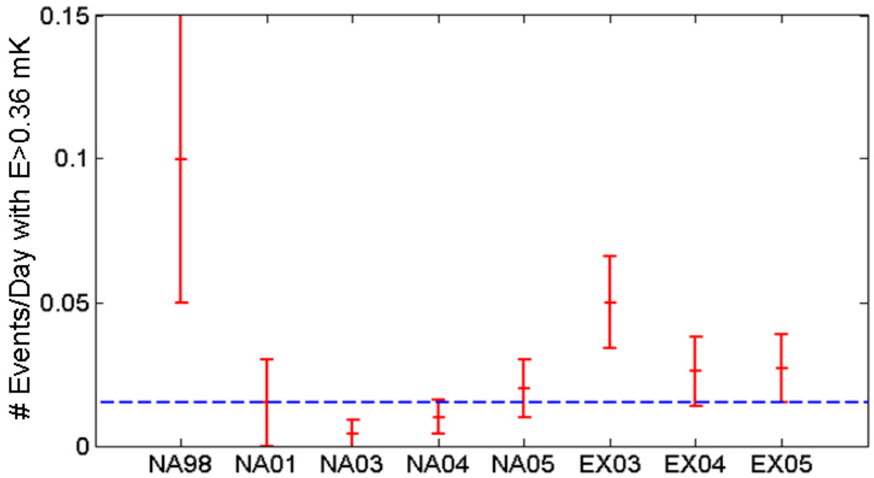
$$E_n \propto \left(\frac{\alpha}{C_V}\right)^2 \cdot \left(\frac{dE}{dx}\right)^2 \cdot F_n^2(L,R)$$

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

The quantity α/C_V (proportional to the Grüneisen parameter γ) is practically constant between 10-300 K;

What happens in the superconducting state?

Scientific Motivation



- Calculated rates in blue
- Measured rates (in red) using the TAM with Monte Carlo simulation for particle energy loss

Gravitational Wave Antenna Nautilus has observed the passage of cosmic rays

The process of energy conversion from particle energy loss into normal modes of oscillation is explained by the Thermo-acoustic Model

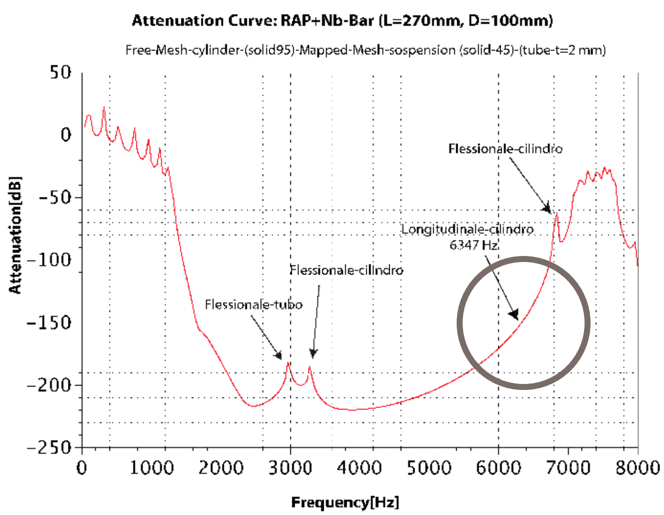
This model is confirmed in the normal conducting state, but in the superconducting state (NA98) large signals are seen too often

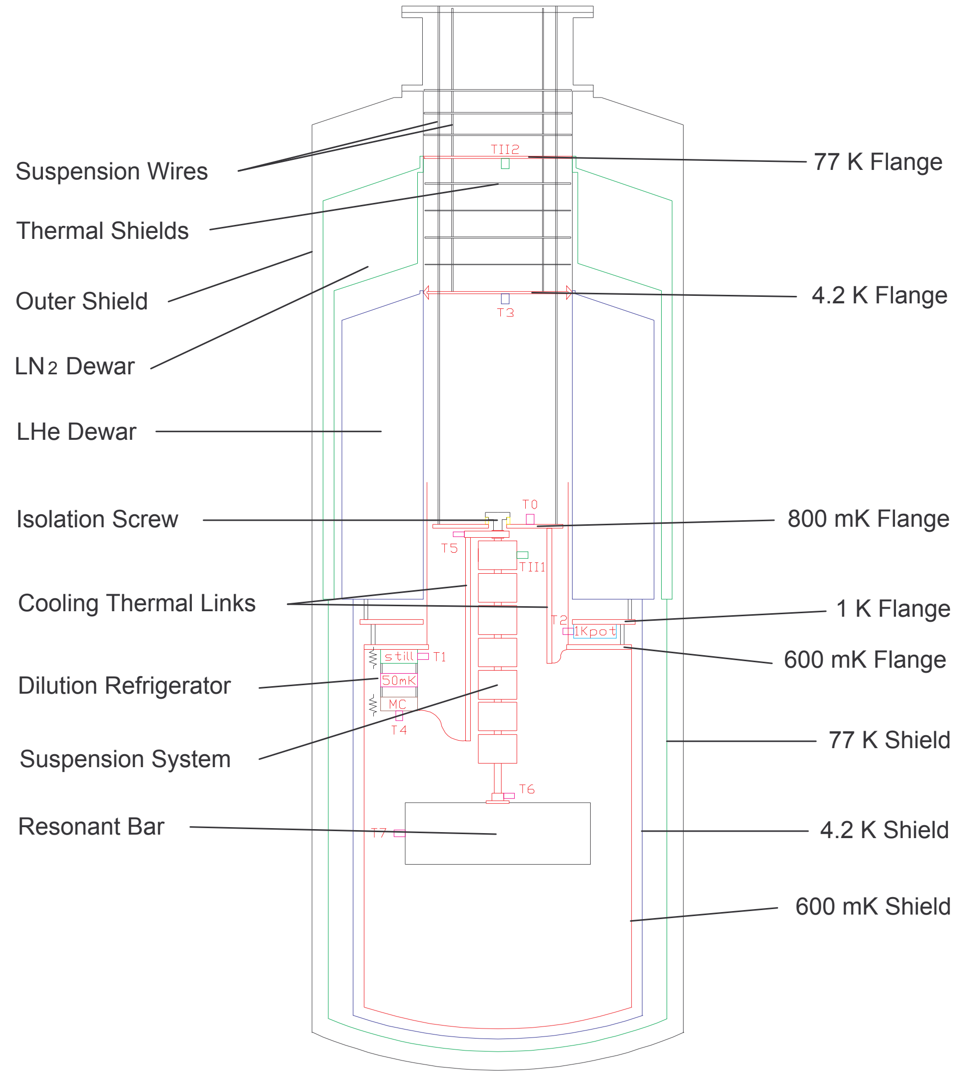
Different mechanism of energy conversion in the SC state? → RAP

RAP Experimental Setup

Experimental Setup

- Test masses:
  - Al 5056 bar
  - Nb bar
- Multi-stage OFHC Copper suspension
- 3 m high, 1 m diameter, LN_2 shielded, LHe Cryostat
- Continuous flow dilution refrigerator for Al bar cooling

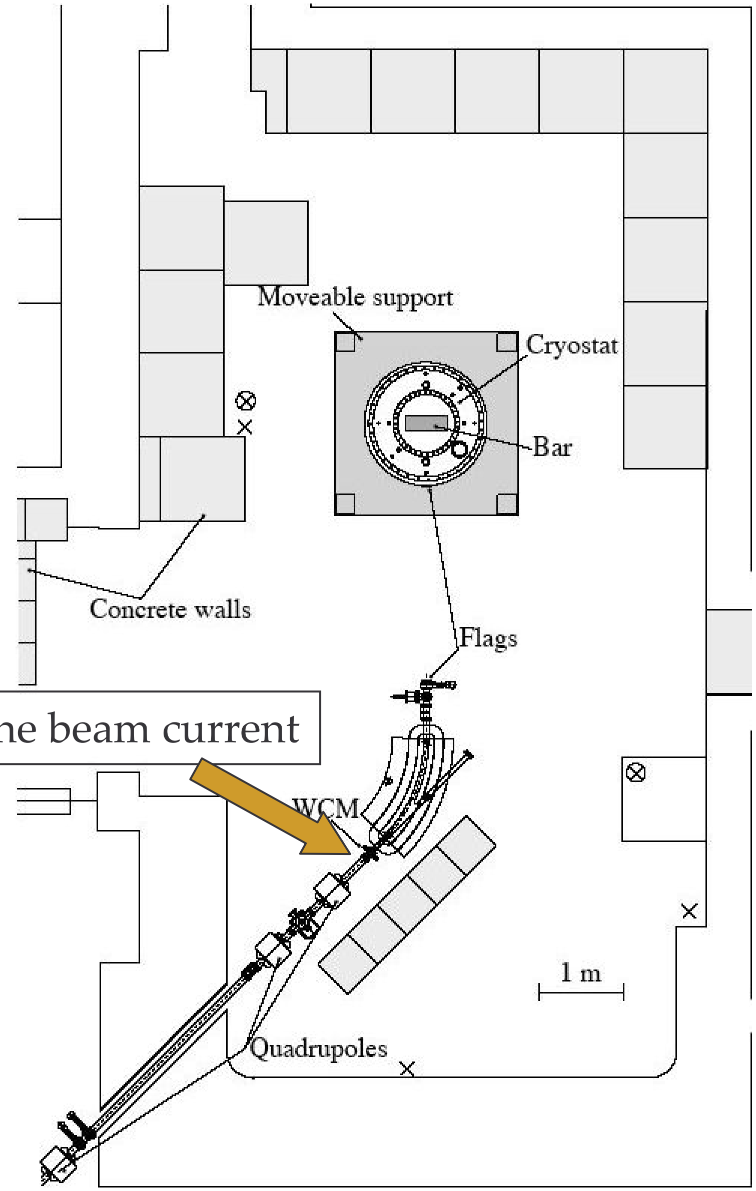




Electron Beam

The electron beam used for the experiment is provided by the DAΦNE Beam Test Facility (BTF):

- electron energy of 510 MeV
- pulse duration of 1 or 10 ns, with a fairly uniform distribution
- intensity of $10^7 - 10^9$ particles per bunch
- Single impulses are used, spaced by about 3 τ (Al5056 @ 0.8 K, τ = 120 s)



GEANT simulations for the energy loss of a single electron give:

$$\Delta E_{Al} = 195 \pm 70\text{MeV}$$

$$\Delta E_{Nb} = 450 \pm 40\text{MeV}$$

$$W = N\Delta E \pm \sqrt{N}\sigma_{\Delta E}$$

Allega-Cabibbo Model (Allega, Cabibbo; 1984)

- Same predictions as the Grassi Strini TAM model for the normal state
- In the superconducting state two effects create the oscillations:
  - ***Magneto-acoustic effect*** due to phase transition along the particle path: the 2 states have different specific volumes and the transition creates a shock-wave
  - ***Thermo-acoustic effect*** due to local heating along the particle trajectory in the now normal state material

$$B_0^{trans} = \frac{2\varrho W L}{3\pi M}\frac{\Delta V/V}{\Delta \mathcal{H}/V}$$

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

Experimental runs

Conducted experiments in the normal & superconducting state:

- **Niobium bar (0.274 m long, 0.1 m in diameter, mass 18.44 kg)**
- **Al5056 bar (0.5 m long, 0.182 m in diameter, mass of 34.1 kg)**

Model predictions:

- Normal state:
  - Thermo-acoustic model in the normal state
- Superconducting state
  - Grassi Strini TA model, using thermodynamic parameters in the sc state

$$X_{GS} = \frac{2}{\pi}\frac{\alpha_{SC} W L}{C_V^{SC} M}(1+\varepsilon)$$

  - AC model, combined effect of phase transition and thermal effect with normal state thermodynamic parameters

$$X_{AC} = \left[\frac{2\varrho W L}{3\pi M}\frac{\Delta V/V}{\Delta\mathcal{H}/V} + \frac{2}{\pi}\frac{\alpha_N W L}{C_V^N M}\right](1+\varepsilon)$$

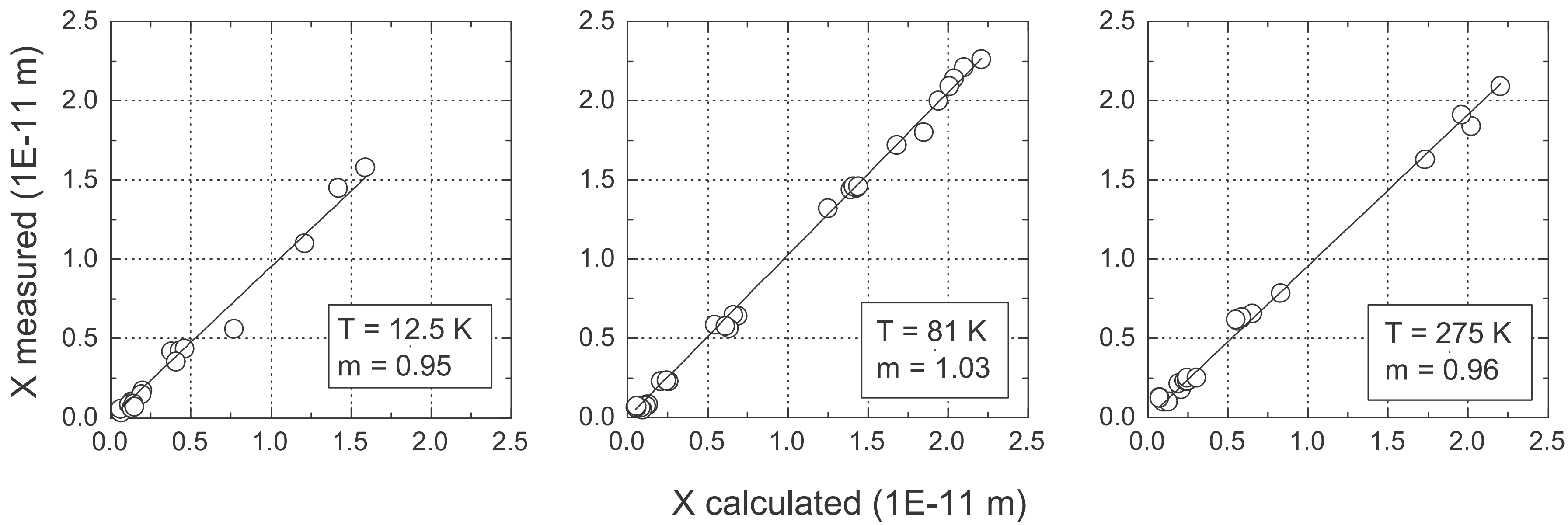
Niobium bar – Normal state

Europhys. Lett., 76 (6), pp. 987-993 (2006)

- 0.274 m long, 0.1 m in diameter, mass of 18.44 kg
- Critical temperature around 9 K

T [K]	m	Δm
275	0.96	0.01
81	1.03	0.01
12.5	0.95	0.02

$$X_{\text{measured}} = m X_{\text{calculated}}$$



Superconducting Niobium bar

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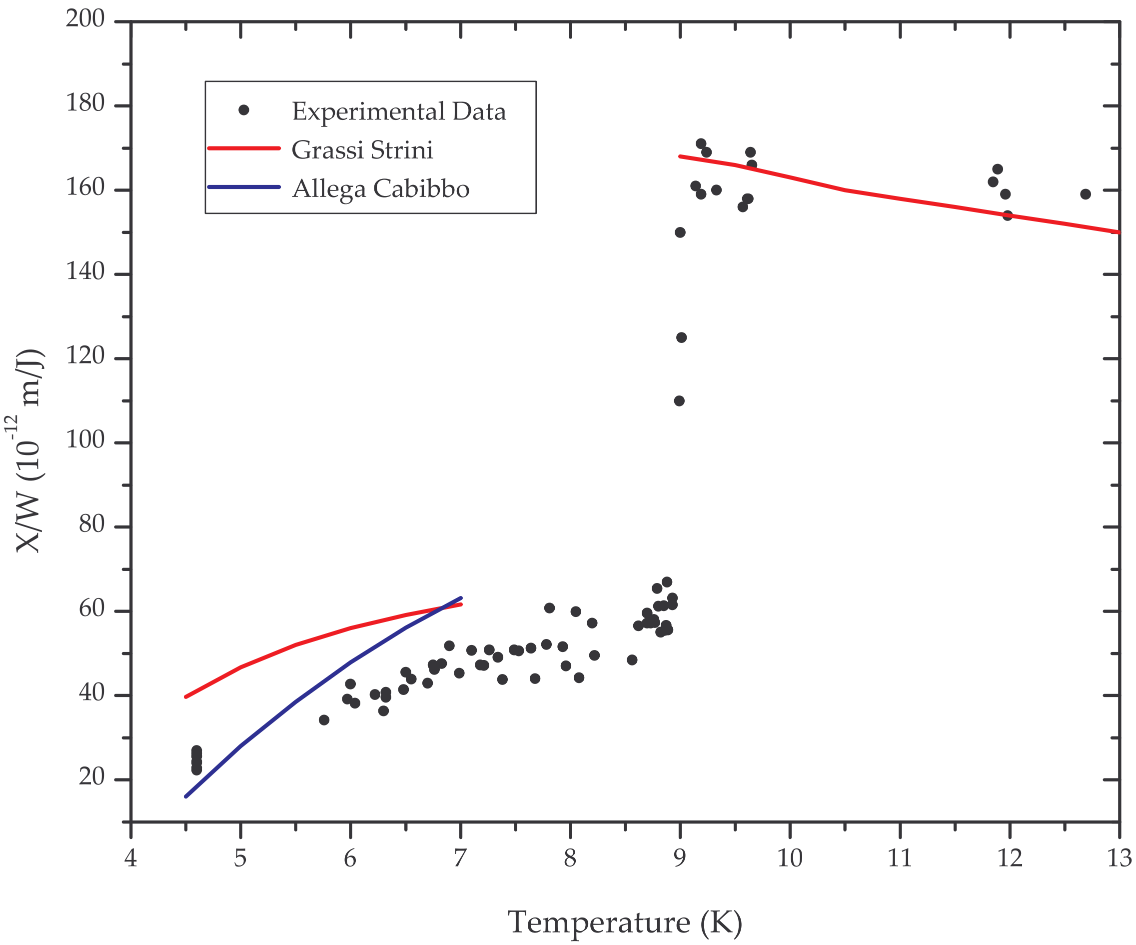


TAM normal state amplitudes are in agreement with experimental data 9-300 K

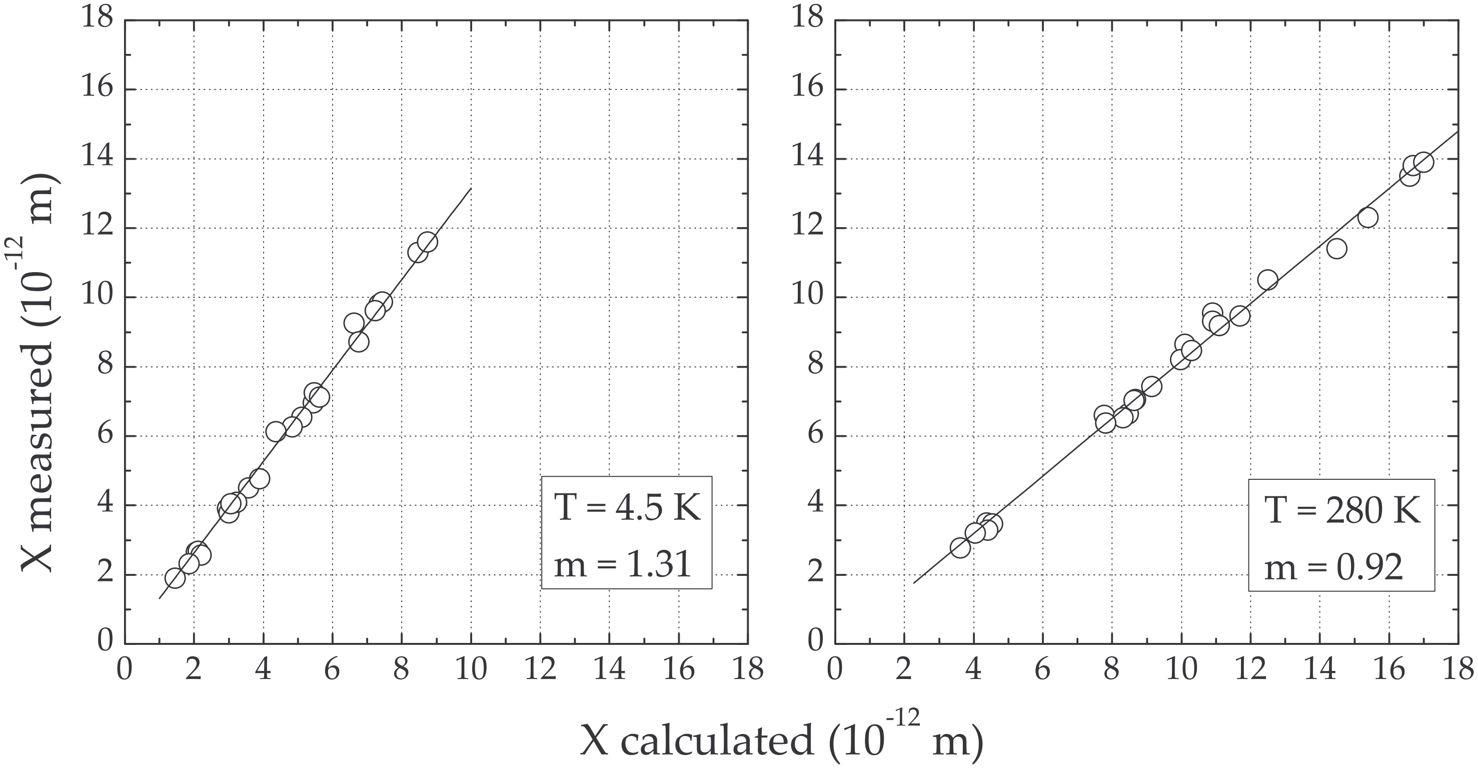
Clearly visible transition effect

AC model (blue) seems to match the experimental data better than the GS model (red) in the SC state – transition zones around single particle trajectories

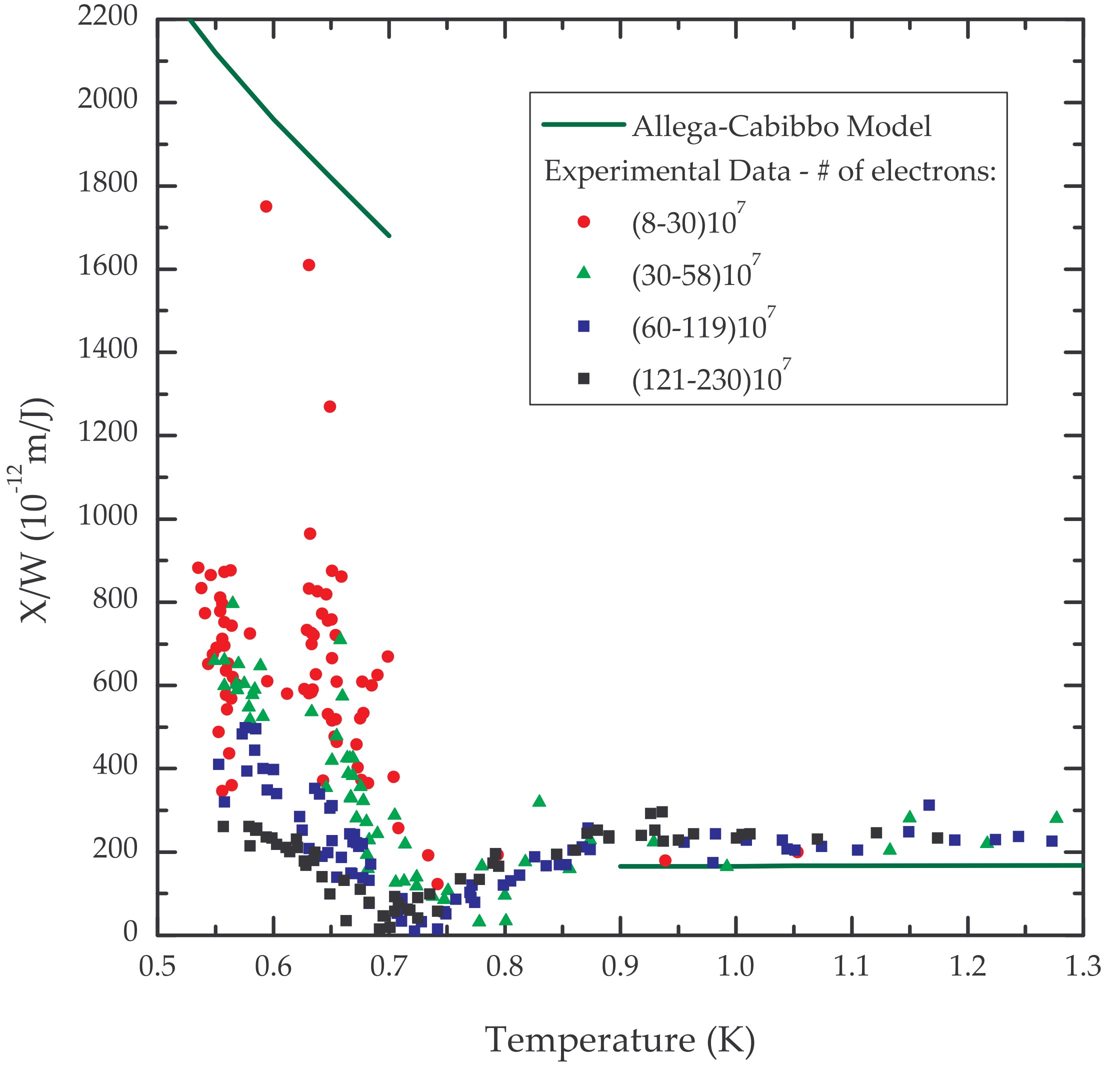
Al5056 bar – Normal state

- 0.5 m long, 0.182 m in diameter and mass of 34.1 kg
- same alloy as used for Nautilus and Explorer, containing on average about 5.2 % Mg, 0.1 % Mn and 0.1 % Cr
- Critical temperature: 840 mK

T [K]	m	Δm
280	0.92	0.01
4.5	1.31	0.01

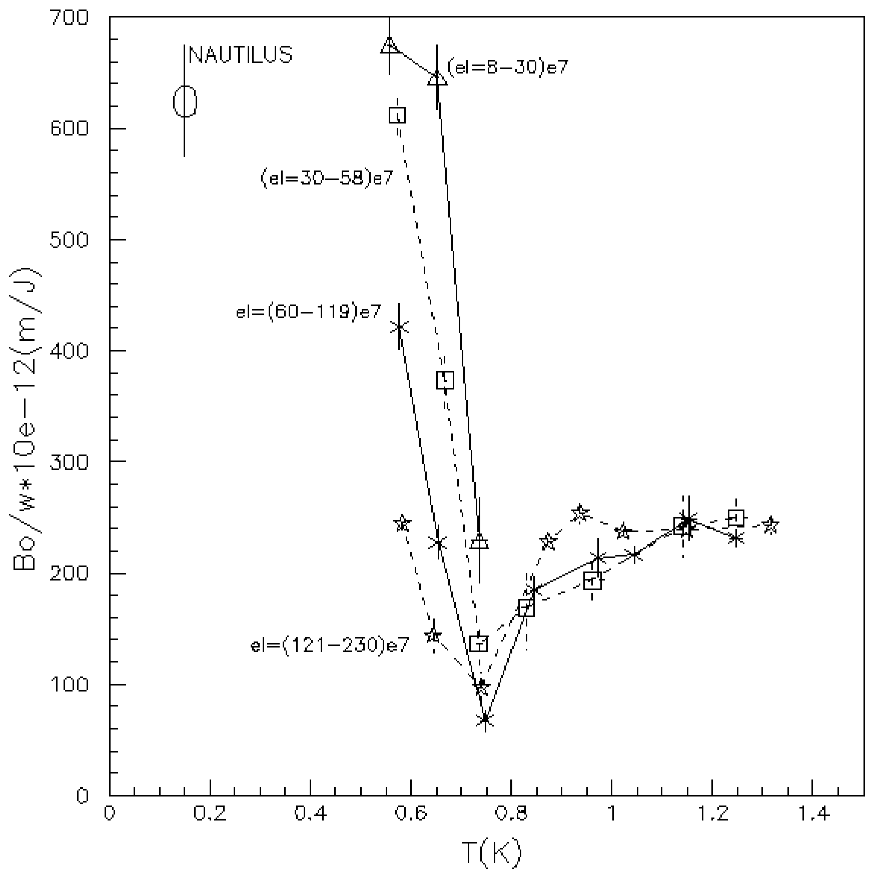


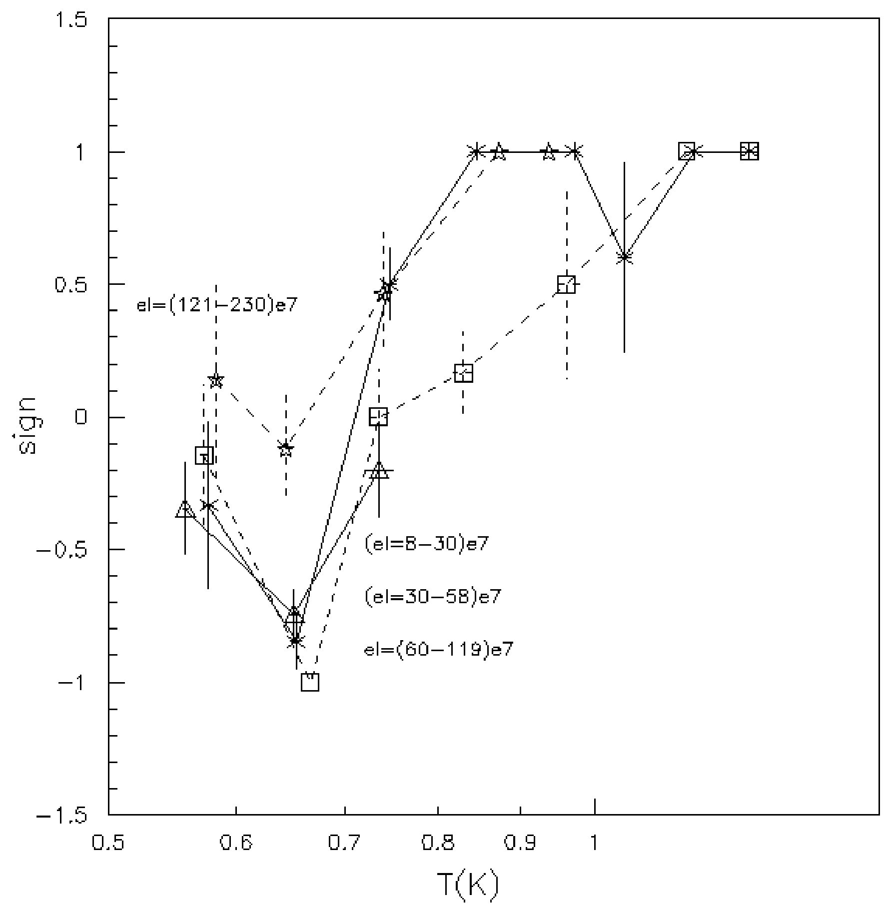
Superconducting AL5056 bar



- Points correspond to single shots
- Tc = 840 mK (measured independently)
- Linearity in electron current observed for T>Tc;
- Current non-linearity in the SC state

Al 5056 averaged results





Conclusions

- Characterization of the Al5056 alloy is in progress – lack of thermodynamic data at very low temperatures
- Thermo-acoustic model validated down to below 1K (normal state) for aluminium
- The expected amplification of signals while the bar is in the SC state has been observed, as expected from Nautilus data
- Quantifying this amplification has proven difficult:
  - As seen from the data on Nb, the region where the models can be compared to experimental data should not be too close to the transition (T/Tc below about 0.7); for Al5056 this range has not been fully investigated yet…

    → need to reach lower temperatures
  - The non-linear dependence on the number of electrons has been observed (only in the SC state!)