
Photo:
Reidar Hahn

# Diagnostics and measurements

Special thanks to D. Reschke (DESY)


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# Vertical tests


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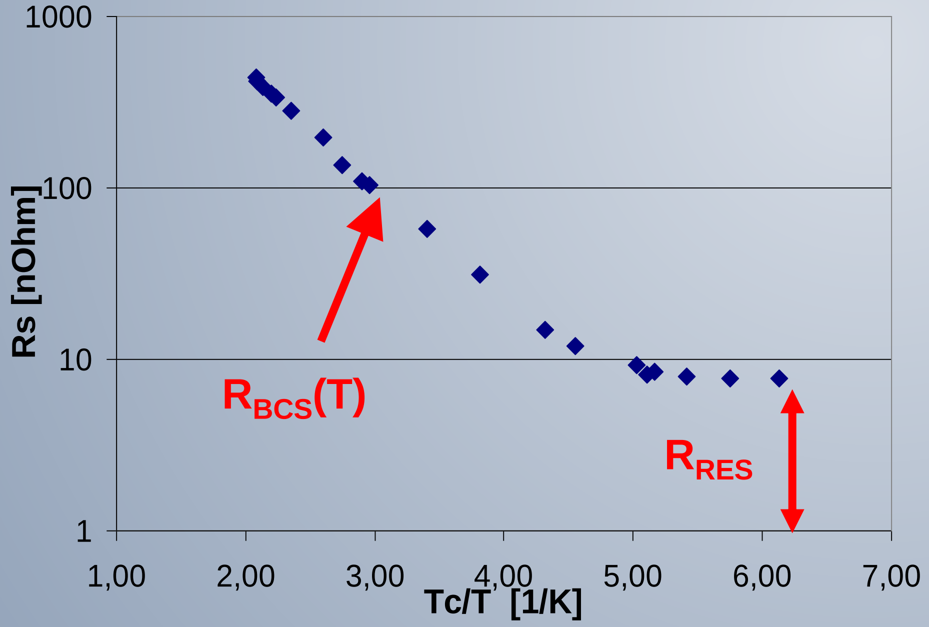
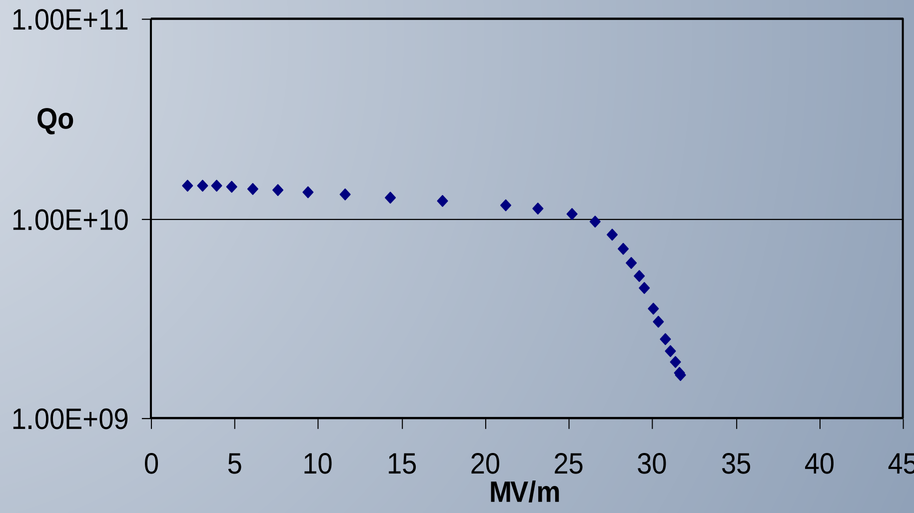
# Vertical test of SRF cavity

- Acceptance test of the cavity received from industry
- Check of a special treatment
- Goals: Determine $Q_0$ vs. $E_{acc}$ and $Q_0$ vs. $T$.
- Operation in CW or with long pulses.



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# Vertical test preparation

- Cavity ready (after cleanroom work),
- Evacuated, leak-checked to $< 10^{-10}\ \mathrm{mbar} \cdot \mathrm{l/s}$, RGA (residual gas analysis) checked,
- Mechanical assembly to the test insert,
- Vacuum connection, pumping, leak check + RGA,
- Connection of rf-cables incl. checks (short circuit, time-domain reflectometer measurement),
- Assembly + check of diagnostics (Second sound, temperature mapping, x-ray sensors, …),
- Transport to vertical cryostat
- Preparation and test of interlock systems
- Cool-down to $4.5\ \mathrm{K}$ or $2\ \mathrm{K}$, (maybe with holding at $100\ \mathrm{K}$)

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# Vertical test insert

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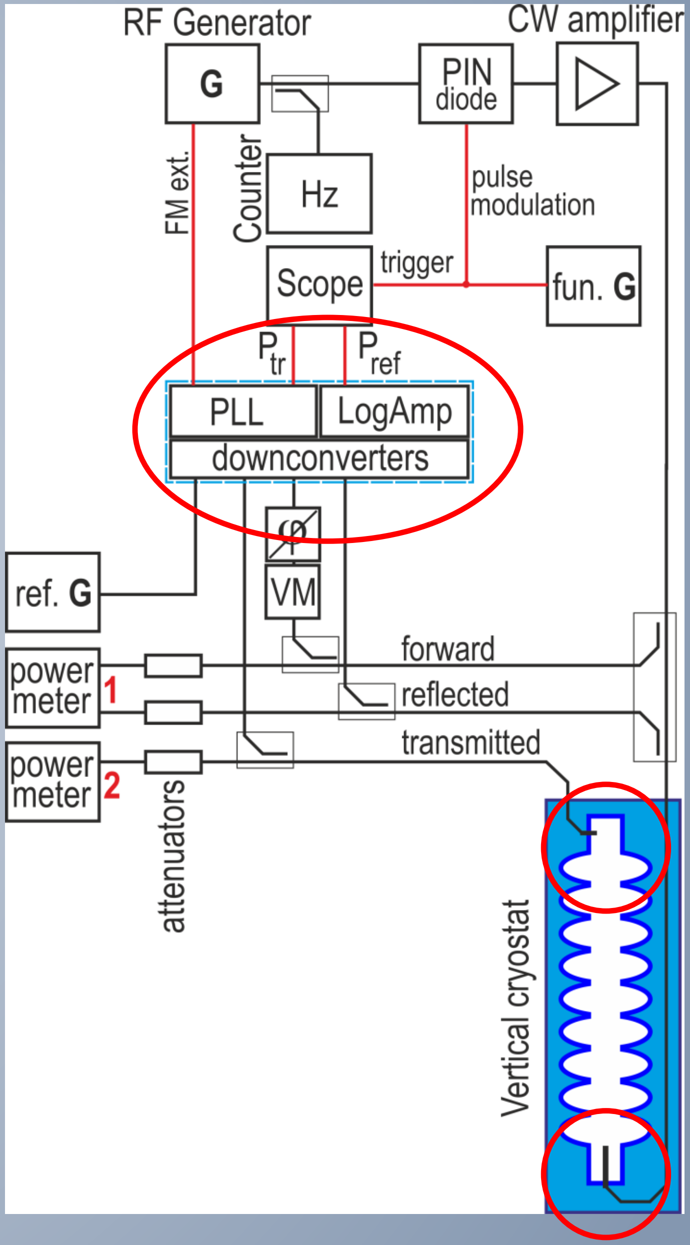
# RF Set-up for vertical test I

- Cavity is coupled to RF with
  - input antenna, matched or adjustable to expected $Q_0$
  - pick-up probe for transmitted power with weak coupling ($Q_{trans} \approx 10^2 \dots 10^3\ Q_0$)
  - for simplification, other ports (HOM) ignored here.
- Directly measurable:
  - Eigenfrequency $f_0$.
  - Decay time $\tau$.
  - Forward power $P_f$, reflected power $P_r$, transmitted power $P_t$ (in pulsed also emptying power $P_e$)
- Sharp resonance (FWHM can be $< 1$ Hz!) requires PLL
  - PLL: fraction of $P_t$ and $P_f$ are mixed and down-converted, their phased difference is used to control $f$. $\Delta\varphi = 0 \Leftrightarrow$ cavity on resonance.

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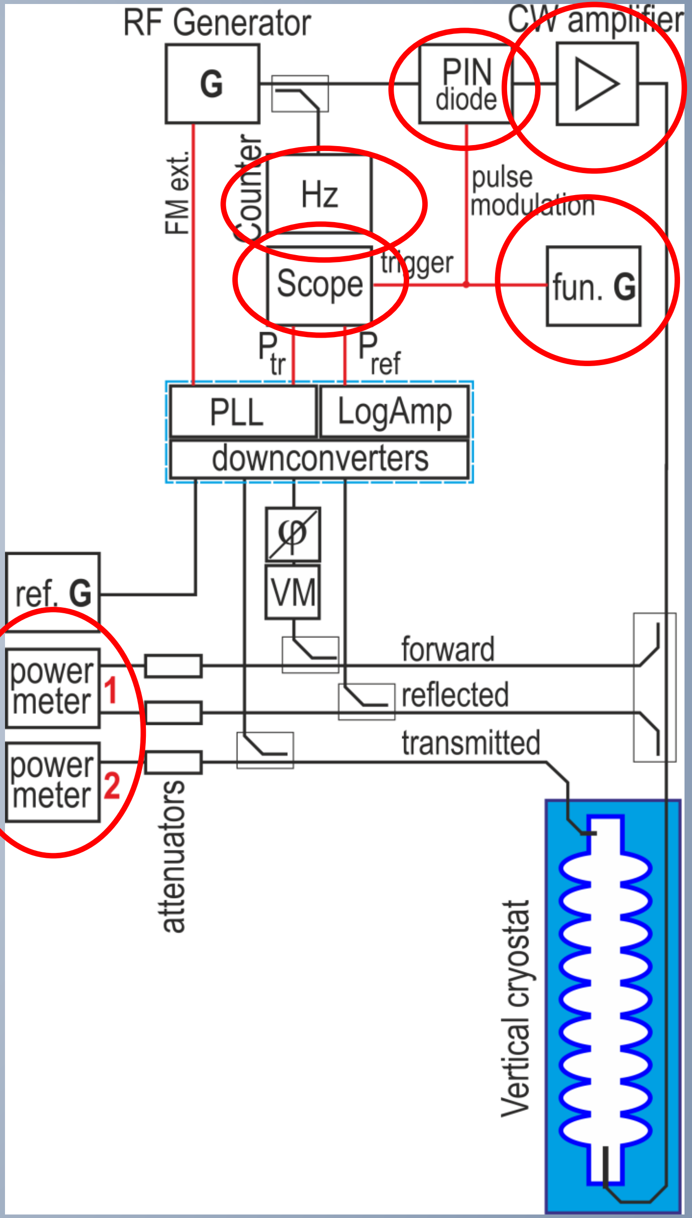
# RF Set-up for vertical test II

- Frequency counter
- PIN diode & function generator
  - fast switching of the RF signal,
  - typically a rectangular pulse by the function generator.
- CW amplifier
  - typically up to 1 kW
  - Solid-state is state-of-the-art
  - Water- or air cooled
  - Important: Circulator
- Power measurement in steady state
  - Power meter
- Power measurement for pulses
  - Scope with crystal detectors or logarithmic amplifiers
  - ADCs
- Passive components: directional couplers, attenuators, cables.



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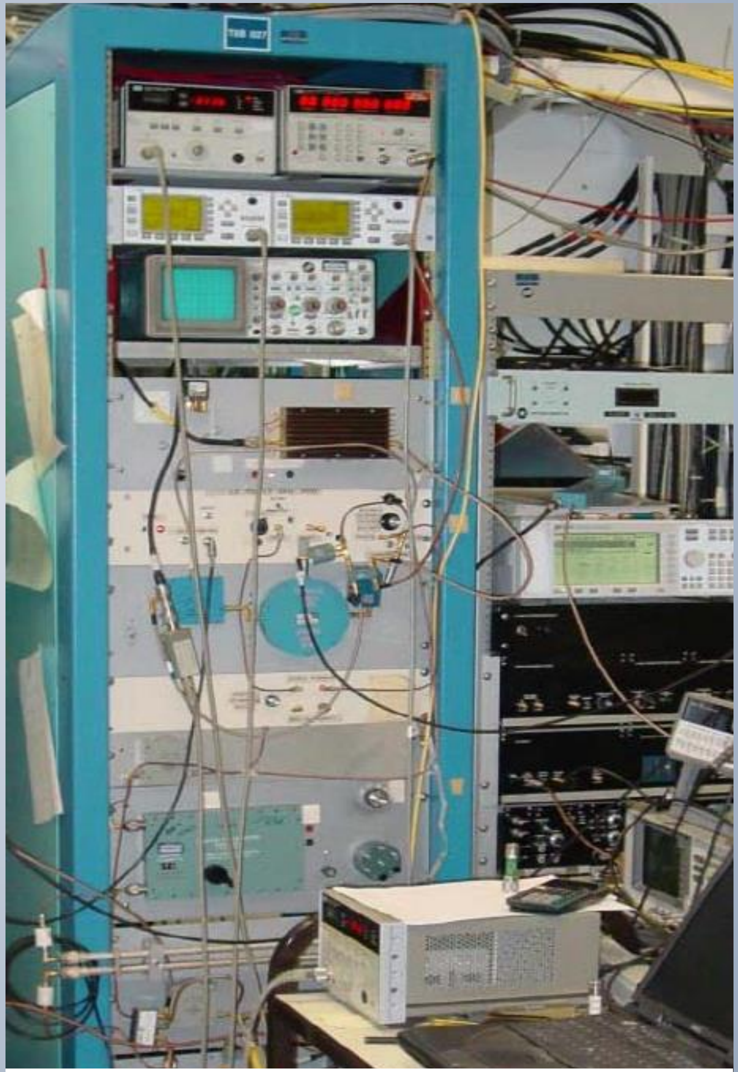
# RF set-ups

AMTF DESY 1.3GHz for XFEL cavities



JLAB 0.5-3GHz VCO PLL system for R&D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# Interlocks

- SRF cavities can “produce” significant amounts of hazardous x-rays with comparatively low RF power!
- RF measurements direct at the cryostat require exact rules and limits depending on your local test situation.
- For high gradient measurements an appropriate shielding and operational interlock system is mandatory.

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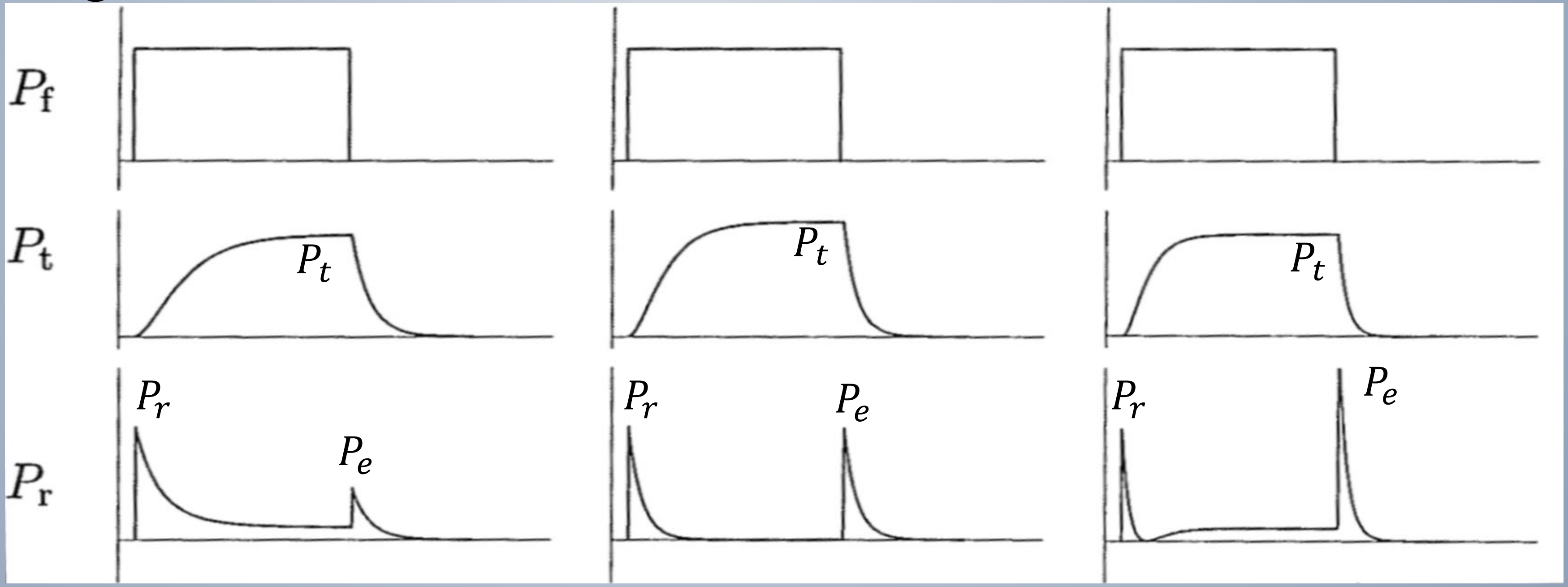
# Measurement of $Q_0$ and $E_{acc}$ (1 of 2)

- Step 1: measure $P_f$ and $P_r$ in steady state and determine $\beta = \dfrac{1 \pm \sqrt{P_r/P_f}}{1 \mp \sqrt{P_r/P_f}}$
- Step2: measure $P_f$, $P_r$, $P_t$ and $P_e$ with rectangular RF pulse to determine the sign above.



undercoupled ($\beta < 1$)    critically coupled ($\beta = 1$)    overcoupled ($\beta > 1$)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# Measurement of $Q_0$ and $E_{acc}$ (2 of 2)

- Step 3: Calculation of dissipated power

$$P_{loss} = \frac{4\,\beta P_f}{(1+\beta)^2} - P_t$$

- Step 4: Measurement of $\tau$ and determination of $Q_L$ (pulse measurement)
- Step 5: Calculation of $Q_0$:

$$Q_0 = Q_L\left(1+\beta\left(1+\frac{P_t}{P_{\text{loss}}}\right)+\frac{P_t}{P_{\text{loss}}}\right)$$

- Step 6: Calculation of $E_{acc}$:

$$E_{acc} = \frac{\sqrt{R/Q \cdot Q_0\,P_{\text{loss}}}}{l \cdot n}$$


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# Temperature mapping

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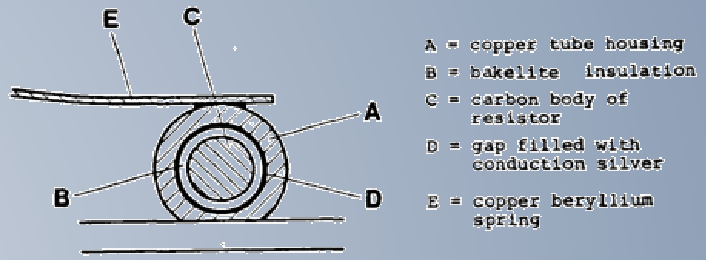
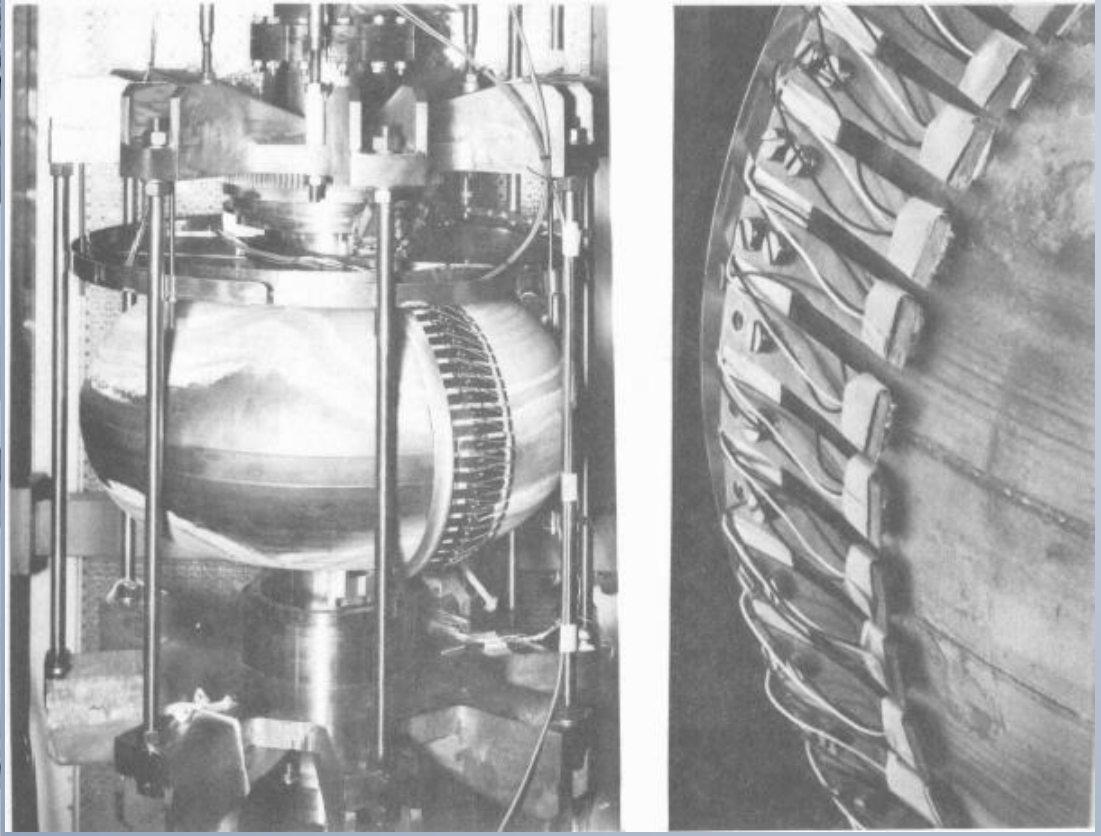
# Temperature Mapping

- Measure the temperature on the He-side to detect losses on the RF-side
- Developed in the 1970es at Stanford + CERN for normal-fluid / sub-cooled helium



Cross section of the carbon thermometer



Rotating thermometry system used at CERN for 352 MHz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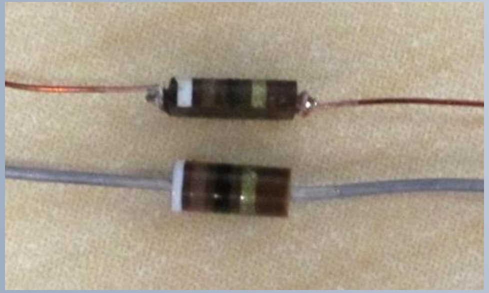
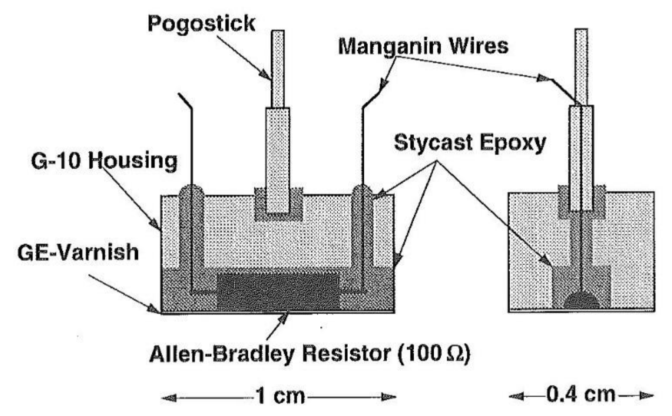
# Temperature Mapping in superfluid He

- In superfluid He (necessary for high gradients at $f_0 > 1\ \mathrm{GHz}$):
  - **+** BCS losses are suppressed
  - **+** spatial resolution is increased
  - **-** "efficiency" of thermometers is reduced due to extremely good cooling
    for fixed thermometers: 20-40% with strong variations
    for movable thermometers: < 3%
- Basic component is a heat sensitive element with a strong characteristic line at low temperatures: mostly carbon resistors


Allen-Bradley carbon
resistor 100 Ω, 1/8 W
4.2K: ≈ 1 kΩ
1.8K: > 10 kΩ



"Pogostick" Thermometer (Cornell)

Cernox® resistors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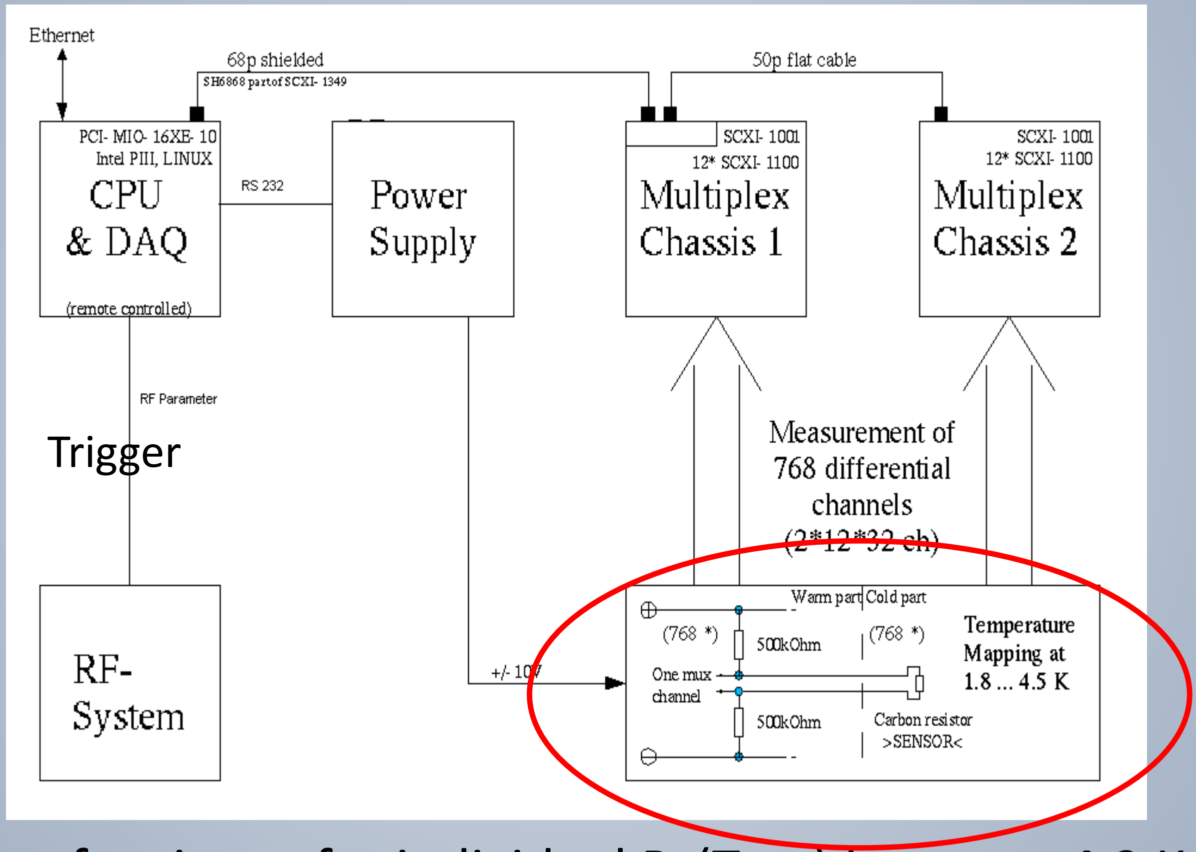
# Temperature Mapping: Layout

- General layout of T-mapping system (DESY):



- Calibration of resistors for individual $R_i$ ($T_{bath}$) between 4.2 K and 1.8 K.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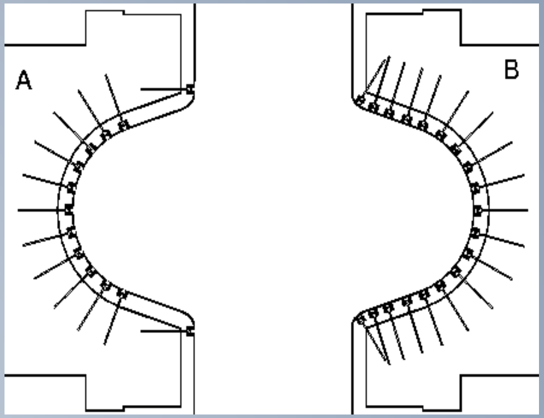
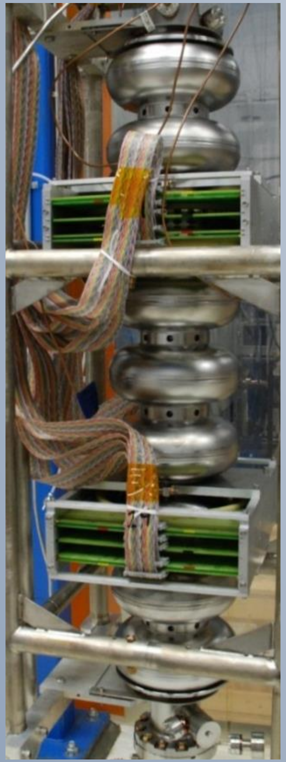
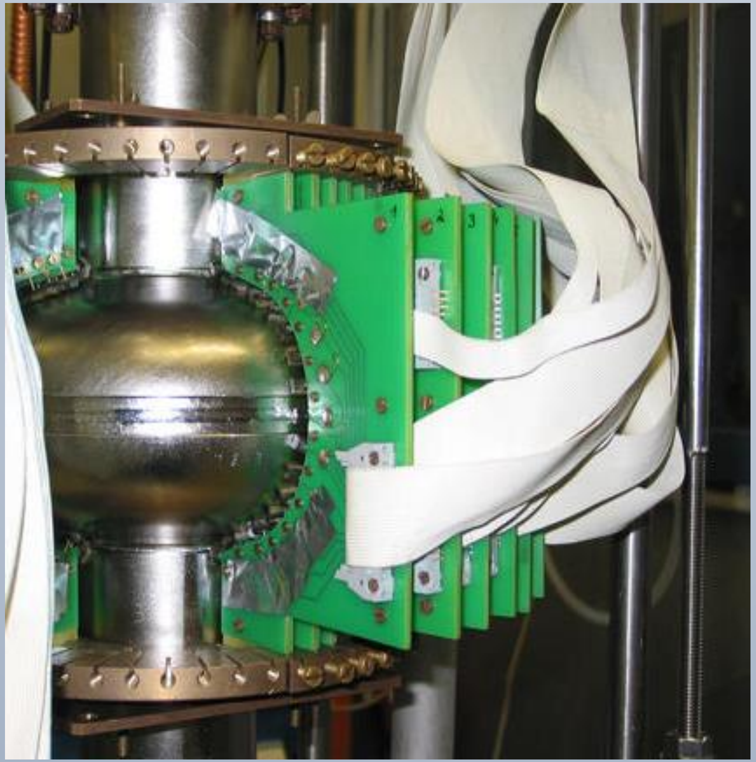
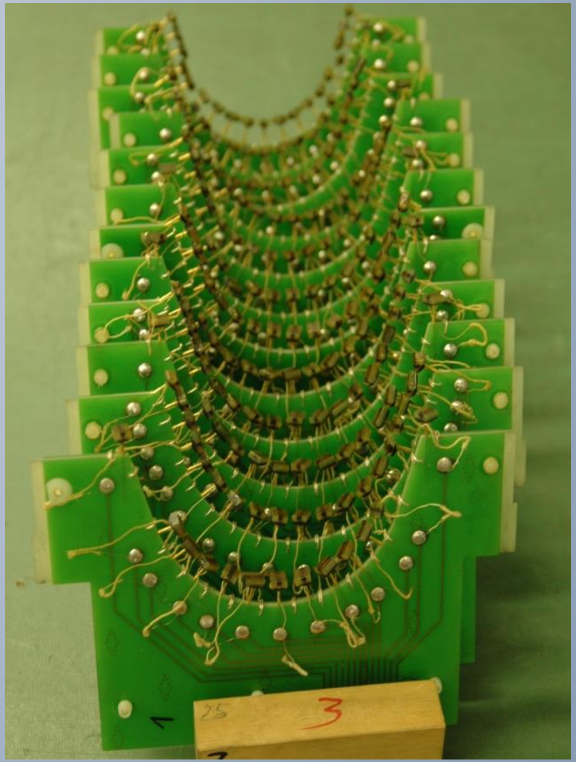
# Temperature Mapping: Fixed Systems I

- Fixed systems with several hundreds of resistors
  - **+** Fast read-out (≈ sec)
  - **+** Sensitive: ΔT ≈ 0,1 mK can be detected
  - **-** Sensitive cabling
  - **-** Intensive maintenance necessary







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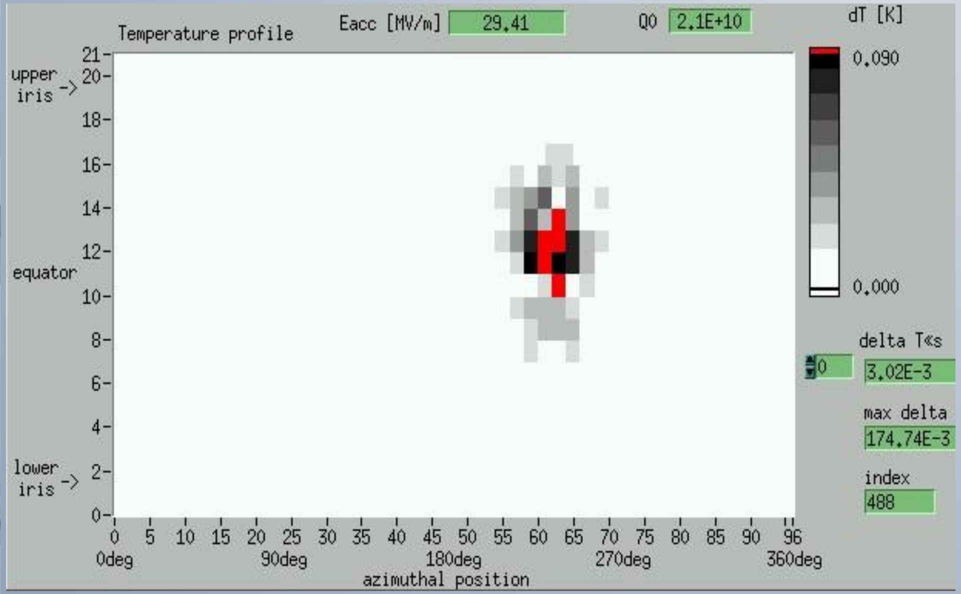
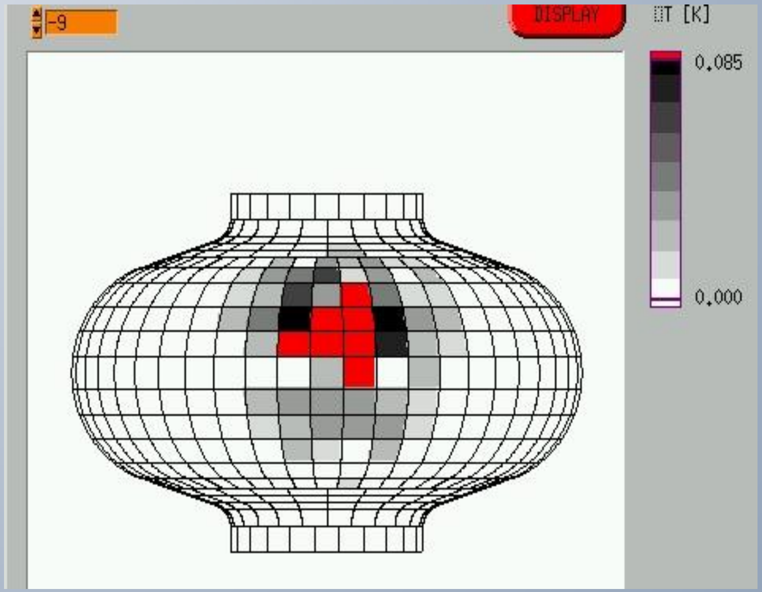
# Temperature Mapping: Fixed Systems II

- Fixed systems are most complex, but most powerful:
  - 1) Qualitative analysis → quench location (easy)
  - 2) Semi-quantitative analysis → $\Delta T$ vs. $E_{acc}$
  - 3) Quantitative analysis → $R_{s,calc}$ from $\Delta T$ (requires additional calibration)
  - 4) time resolved measurements → temperature (quench) evolution
- Example 1: Locating the quench and the temperature distribution


Eacc [MV/m] 29.41
Q0 2.1E+10
delta T«s 3.02E-3
max delta 174.74E-3
index 488



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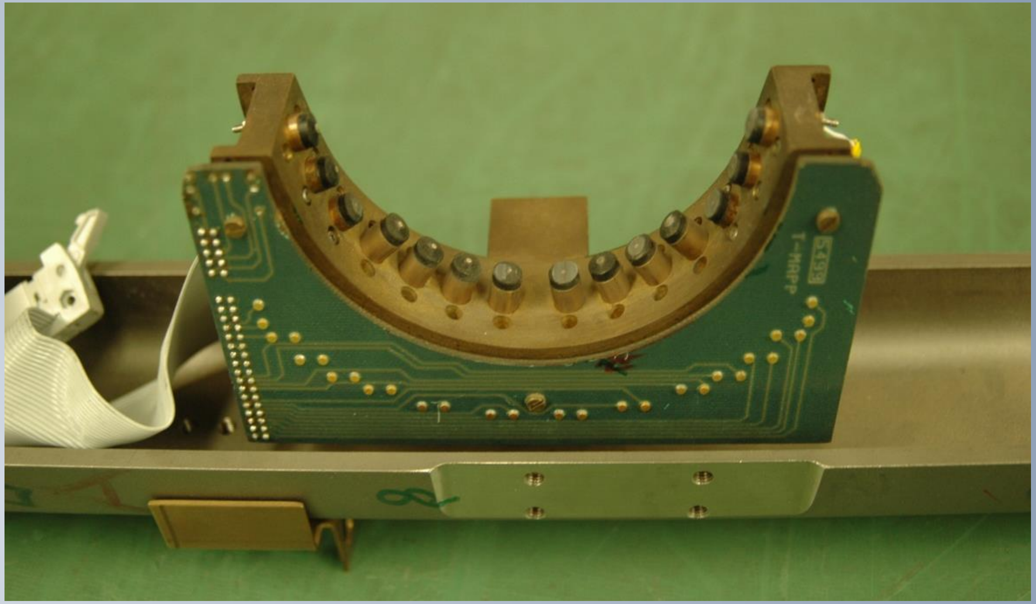
# $T$ mapping – rotating systems



- Quench detection + time-resolved measurements
- Less thermometers for multi-cell cavities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# Second sound

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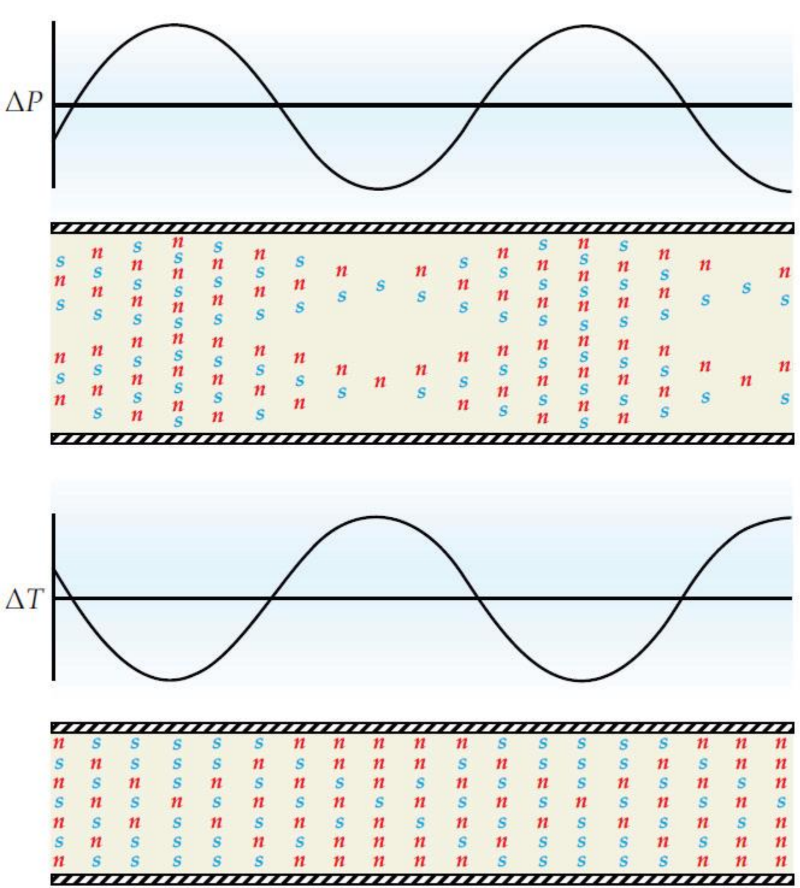
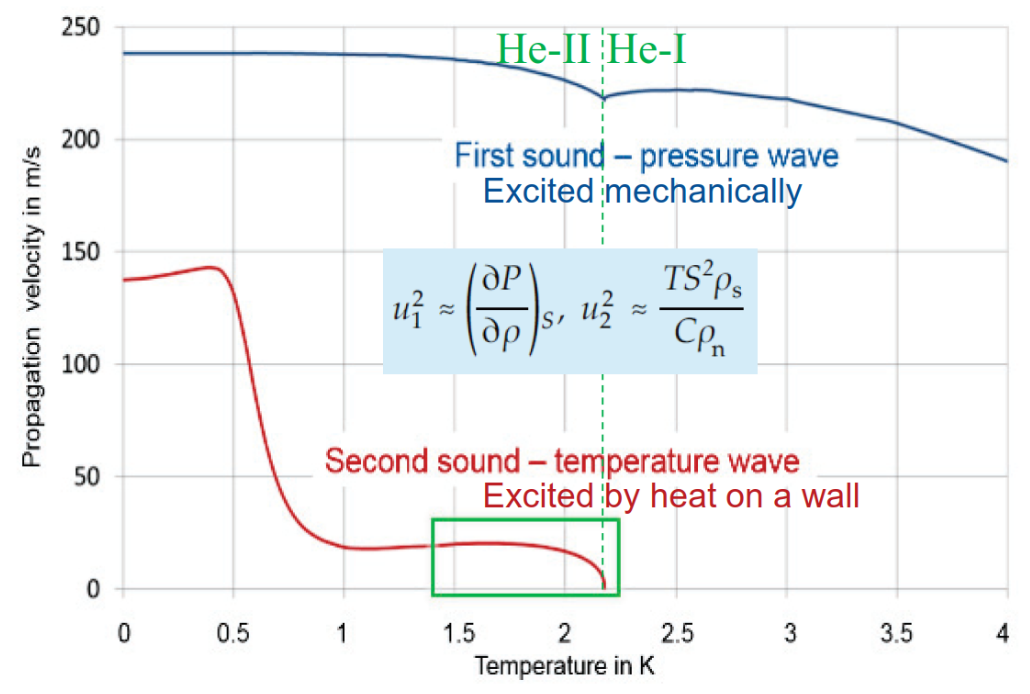
# He-II and second sound



n: normal component particles

s: superfluid component particles

Source: R. J. Donnelly "The two-fluid theory and second sound inliquid helium". Physics Today, Oct. 2009.



First sound – pressure wave
Excited mechanically

$$u_1^2 \approx \left(\frac{\partial P}{\partial \rho}\right)_S, \quad u_2^2 \approx \frac{TS^2\rho_s}{C\rho_n}$$

Second sound – temperature wave
Excited by heat on a wall

Hernan Furci: SRF2017 (THXA05)

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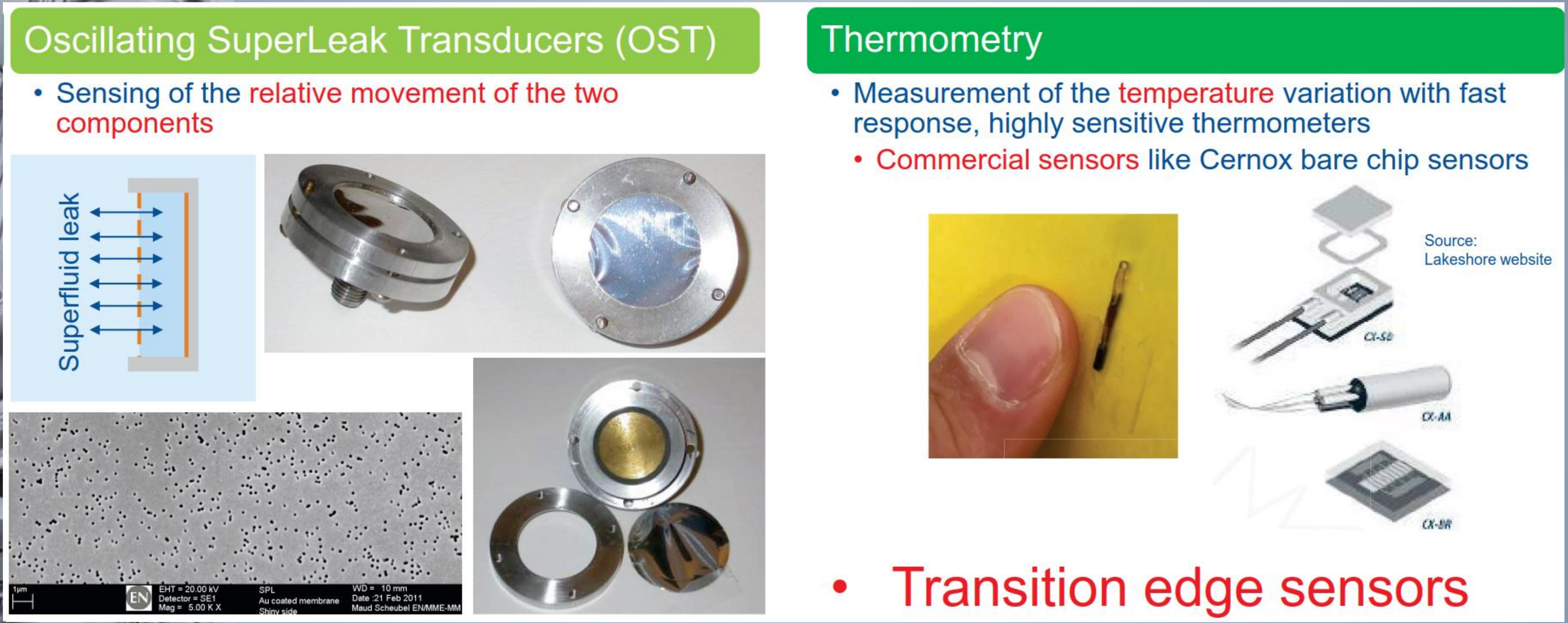
# Second sound detection



## Oscillating SuperLeak Transducers (OST)

- Sensing of the relative movement of the two components

## Thermometry

- Measurement of the temperature variation with fast response, highly sensitive thermometers
  - Commercial sensors like Cernox bare chip sensors

Source:
Lakeshore website

- Transition edge sensors

Transition edge sensors are very fast thermometers that can be tailored to be sensitive only in the transition range.

Hernan Furci: SRF2017 (THXA05)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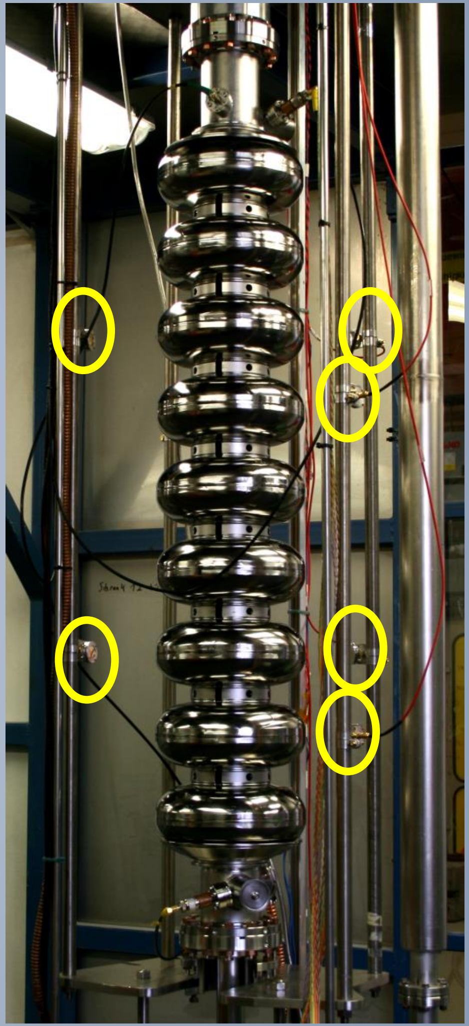
# Comparison of Second Sound and $T$-Mapping

- Temperature mapping (left)
  - Complex assembly for each test required.
- Second Sound (right)
  - Simple and one-time assembly at the cryostat insert
  - Fast measurement
  - 16 (8) sensors only

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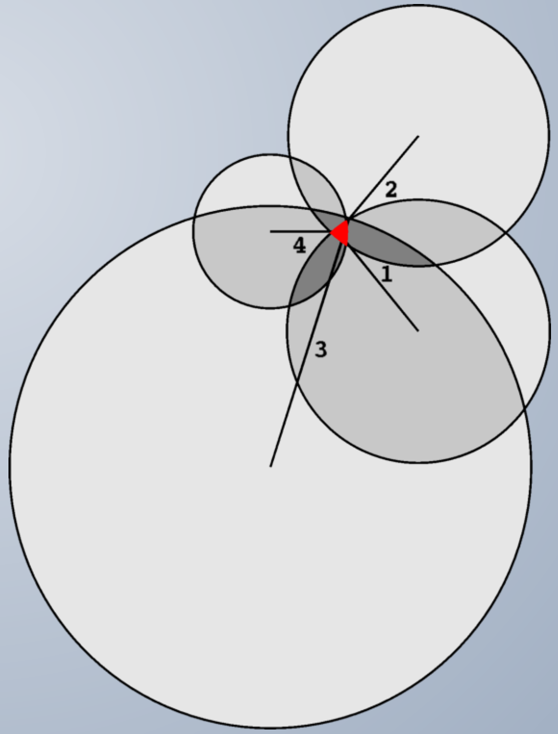
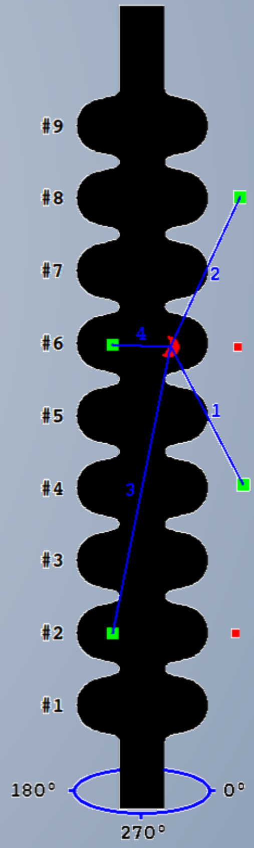
# Quench localisation with second sound

- The second sound arrives at different times at different detectors (OST or TES)
- Knowledge of the second sound velocity, the origin of the signal can be reconstructed by trilateration



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# Quench localisation Summary

- Uncertainties:
  - Size of the OSTs or TESs,
  - Heat distribution in Nb,
  - Signal analysis
- Measurement uncertainty typically $\mathcal{O}(\mathrm{cm})$.
- Comparison with T-Map:
  Agreement with uncertainty of 1-2 cm


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# Interpretation of RF signals

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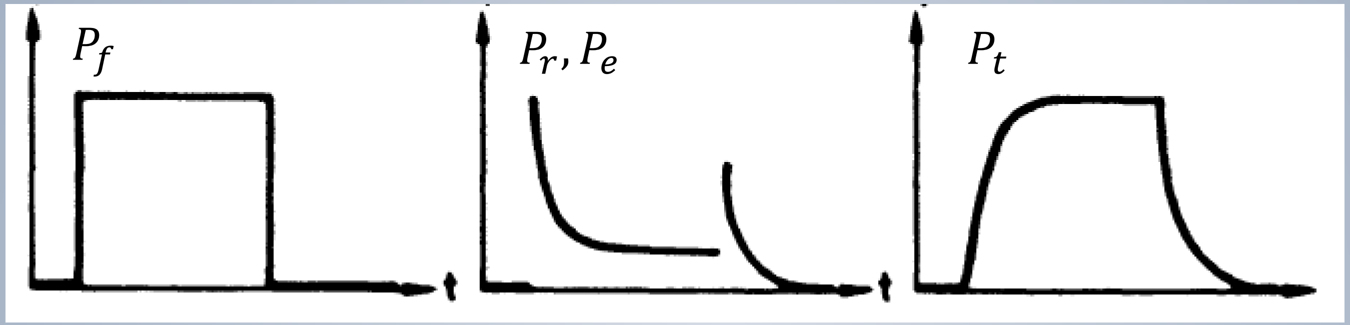
# Normal RF signals

- Response for a cavity working well:

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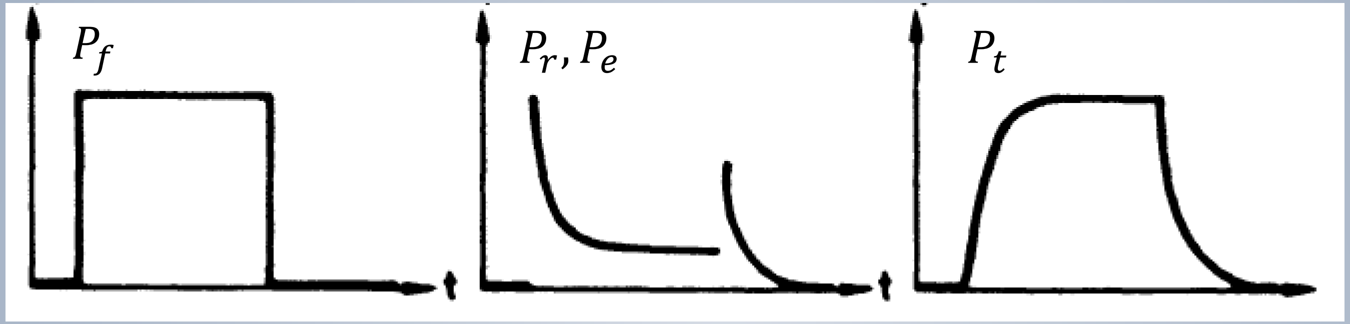
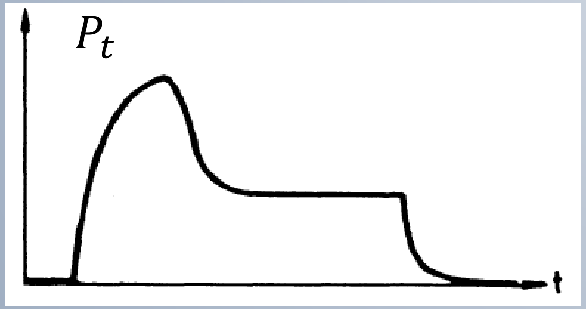
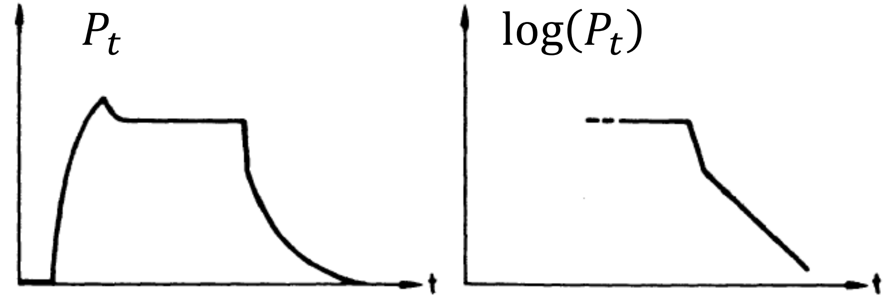
# Something is warming up

- Response for a cavity working well:



- Additional losses appear during build-up time of the field





- Sudden changes in the power may hint towards a breakdown or gas discharge in the transmission line.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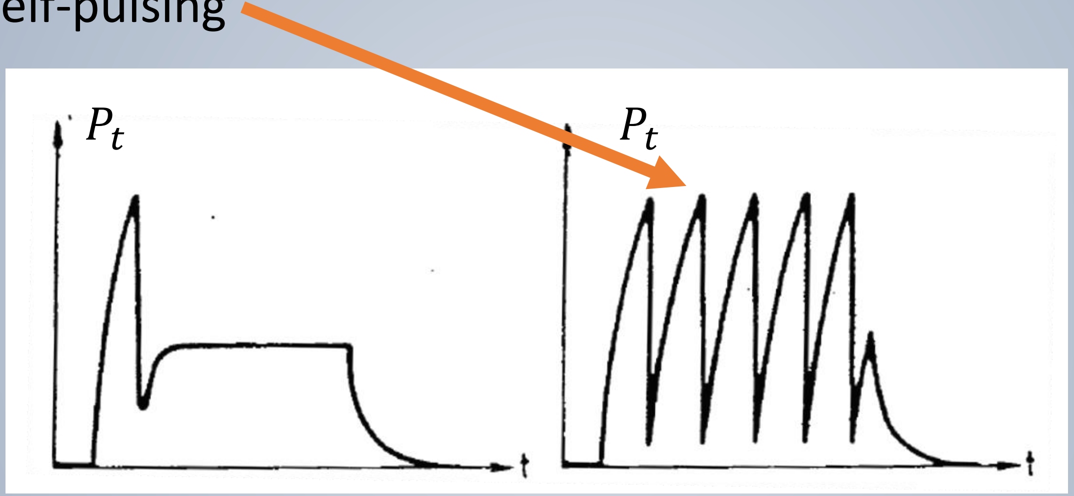
# Symptoms of a quench

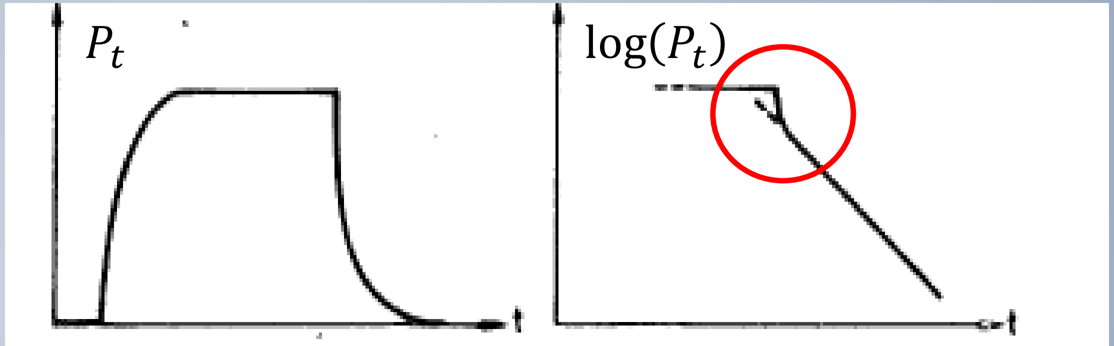
- RF signal of a thermal or magnetic breakdown (quench):
  - breakdown of transmitted power within $\approx \mathrm{ms}$ (thermal time constant)
  - often self-pulsing



… but no increase in X-rays observed, unless quench in the presence of FE or MP.

# Symptoms of Field Emission

- Change of field decay slope – reflects a change of $Q_0$.



… and simultaneously appearance of X-rays.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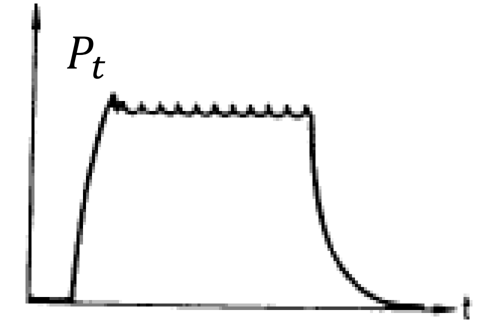
# Symptoms of Multipactor (MP)

- No increase of $P_t$ above a certain barrier, even with increased $P_f$.



- During cavity processing, these barriers slowly increase to eventually disappear.
- Often breakdowns of RF field happen during processing.
- X-ray bursts observed at the moment of breakdown with active MP.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# Cryomodule testing

Photo: Reidar Hahn

# Horizontal Cavity Tests

- Horizontal cavity tests are important in order to a cavity full equipped with its subsystems before a module integration
  - Power coupler
  - Tuner
  - Piezo-Tuners
- Check of cooling conditions + flux trapping

Horizontal cryostat at DESY for high power pulsed operation (without beam)


Photo:
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# Cryomodule testing

- Cryomodule tests for FLASH + EU-XFEL as example


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# Module Test Procedure

1. RF cables calibration
2. Technical interlocks/sensors
3. RF source / waveguides / LLRF
4. Warm input FPC conditioning
5. Cooldown to 2 K
6. Cavities spectra measurement
7. Cavities tuners test
8. Couplers $Q_L$ measurement
9. Cavities on resonance
10. Cold input FPC and cavities conditioning
11. Module performance measurement
12. Single cavities measurements
13. cryogenic system performance test

Photo:
Reidar Hahn

# Cryomodule Test Bench

Photo:
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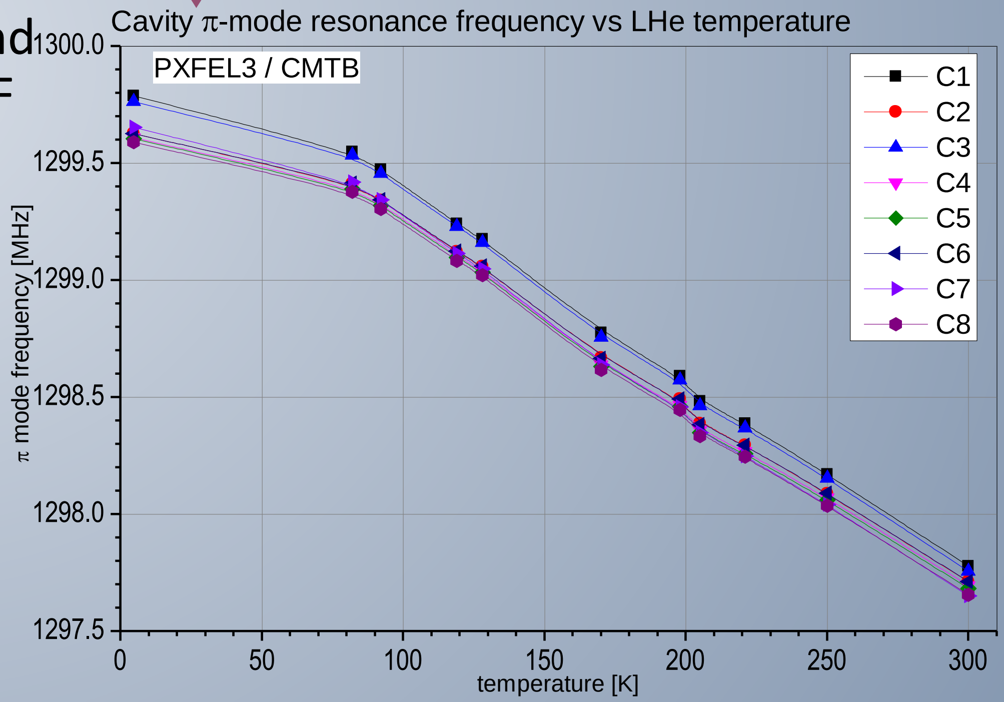
# Example: Cryosystem/cool-down test

- $T$ measurement: temperature sensors (cavities/couplers + cryogenics) data are stored.
- Cavity resonance frequency measurement during the cool-down.
- Cryogenic losses measurement based on temperature and LHe flow data: 2 K, 4 K and 70 K static (infrastructure) and dynamic (RF power) losses.
- Optional: stretch-wire based module dimensional changes measurements.

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# End of Diagnostics and measurements

Thank you very much!