Instrumentation

Juan Casas

CERN – TE/CRG Group

Technical Training: Cryogenic Engineering for Helium Superconducting devices
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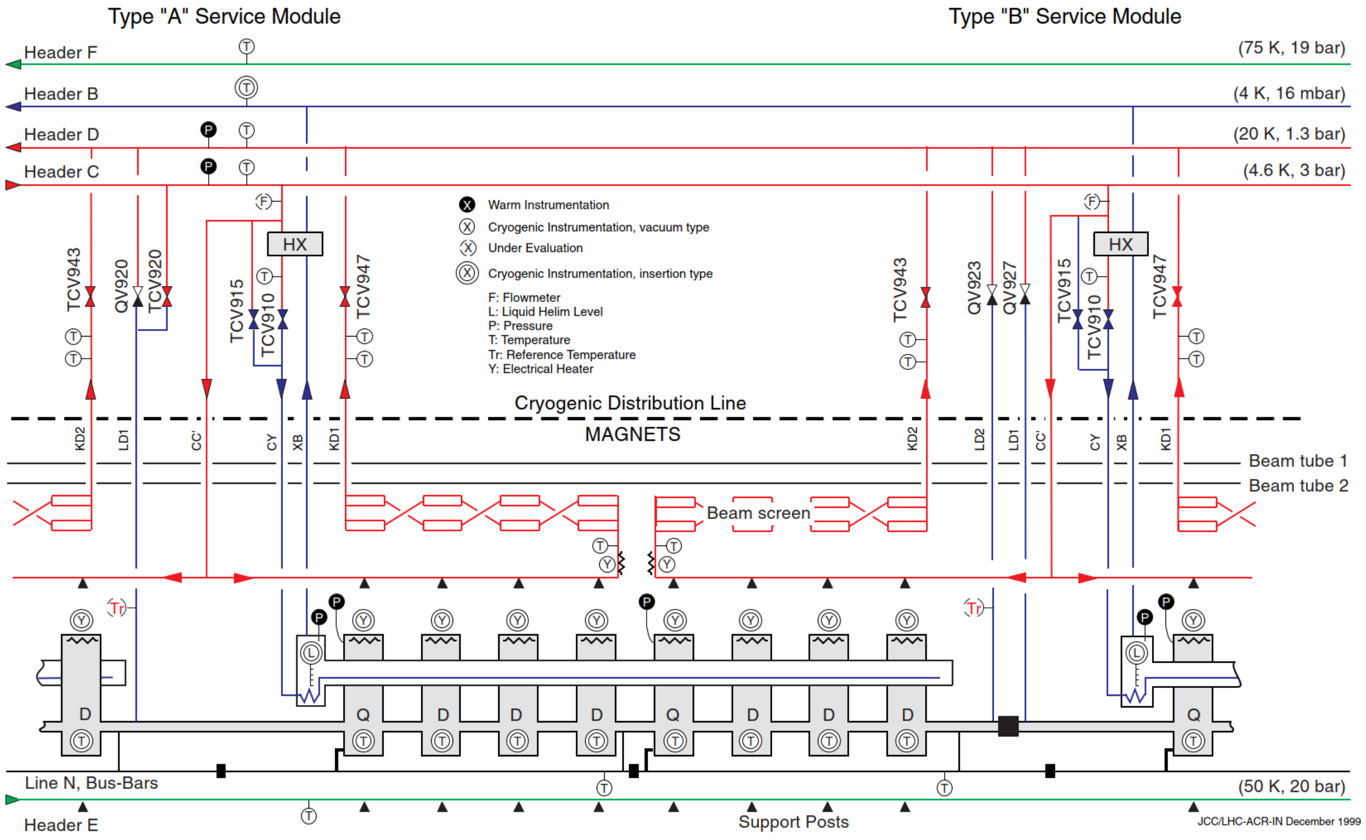
Instrumentation: what is it for?

The instrumentation is “one” of the set of apparatuses that permit the operation, optimization and diagnostics of, in this case, a large scale cryogenic facility.
The components are sensors & actuators with its ancillary equipment.
The instrumentation is shown on a P&ID (example: LHC cell 1999 version).



Instrumentation: Requirements then Selection

The ideal workflow is:

- Design engineer provides a set of requirements
  - Quantity including criticality (redundancy)
  - Measurement uncertainty
  - Environmental conditions
- Instrumentation specialist selects appropriate candidates
  - Final selection include qualification for non-standard (commercial) environments
  - Acquisition chain is critical and shall be part of the cost optimization

LHC: selected requirements

Table 11.12: Cryogenic instrumentation inventory

Sensor type	Quantity	Redundancy	RadTol quantity
Temperature CX	4,500	1,153	3,347
Temperature Pt100	2,400		450
Pressure Low	230		230
Pressure Mod/High	900		900
Level Gauges	300		300
Electrical Heater	2,500		2,000

Table 11.13: Measurement uncertainty requirements versus temperature.

Temperature Range	1.6-2.2 K	2.2-4 K	4-6 K	6-25 K	20-300 K
Uncertainty [K]	± 0.01	± 0.02	± 0.03	± 1	± 5

Type of Sensor	Range	Accuracy	Availability	Location	Approximate Quantities
Temperature	1.6 - 40 (300) K	Fct (T)	Allen Bradley, Carbon thin-film, TVO, Cernox	QRL, cold-mass	4400
Temperature > 50K	50 - 300 K	Class B	Platinum thermometer	QRL, cold-mass, DFB	900
Liquid He level meter	Various ranges	5%	Commercial	SSS, DFB, cavities	300
Pressure (warm)	0 – 70 mbar	0.1 % FS	Commercial	SSS	530
Pressure (warm)	0 – 20 bar	1% FS	Commercial	QRL	455
Pressure (warm)	0 – 4 bar	1% FS	Commercial	QRL, DFB	264
Differential pressure (warm)	0 – 20 mbar	1% FS	Commercial	Cavities	16
Flow meter @ 2.2K	0 – 10 g/s	10% FS	Prototypes under test	QRL	280
Flow meter (warm)	Various ranges	3%	Commercial	Gas return lines	20
Cryoheater @ 2 K	0 – 100 W	2%	Commercial	Cold-mass, DFB, cavities	2700

LHC: preliminary analysis

Instrumentation: Metrology

Measurement is the process of obtaining experimental values attributed to a quantity or property.

Measurement of fundamental properties shall be reproducible worldwide.

National standard laboratories compare their measurement standards to provide consistent reproducibility of measurements worldwide and over time.

Major standard laboratories (non exhaustive) are:

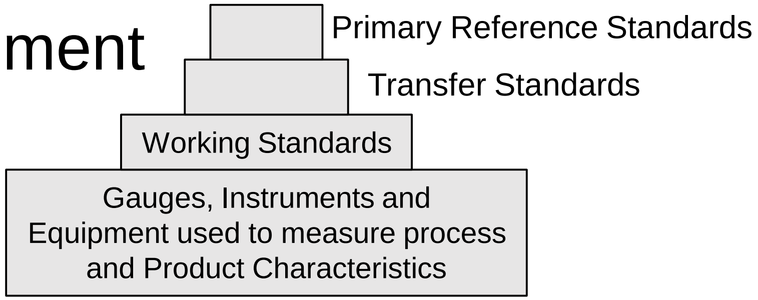
- National Physical Laboratory (UK)
- Physikalisch-Technische Bundesanstalt – *PTB* (GE)
- Laboratoire National de métrologie et d'Essais – LNE (FR)
- Istituto Nazionale di Ricerca Metrologica – INRIM (IT)
- National Institute of Standards and Technology – NIST (USA)
- ….

International organization responsible for worldwide coordination:

- Bureau International des Poids et Mesures – BIPM (located in Sèvres, France)

Instrumentation: Metrology

The metrological traceability is a property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations.



Uncertainty defined by the GUM (Guide to the expression of Uncertainty in Measurement):

- Uncertainty: quantification of the doubt about a measurement result
  - width of the margin (+/-) and confidence level (%)
- Random errors Type A, systematic Type B

Practical measurements rarely use the formality stated in the GUM.
The GUM requires:

- A mathematical model of the measurement process
- Type A & B evaluation of standard uncertainty <= statistical analysis

Instrumentation: Metrology (Technical)

Objective of a measurement is to determine a value of the measurand, in other words, to sample one value out of a universe of possible values.

Accuracy: agreement of measurement with respect to the true value

Precision: spread of measurements (not related to true value, ~ repeatability)

Reproducibility: results can be attained by a different research team, using the same methods.

Bias: total systematic error as contrasted to random error

Trueness: closeness between the test results and an accepted reference value. The measure of trueness is normally expressed in terms of bias.

Inaccurate & imprecise (unrepeatable)

Precise but inaccurate (repeatable)

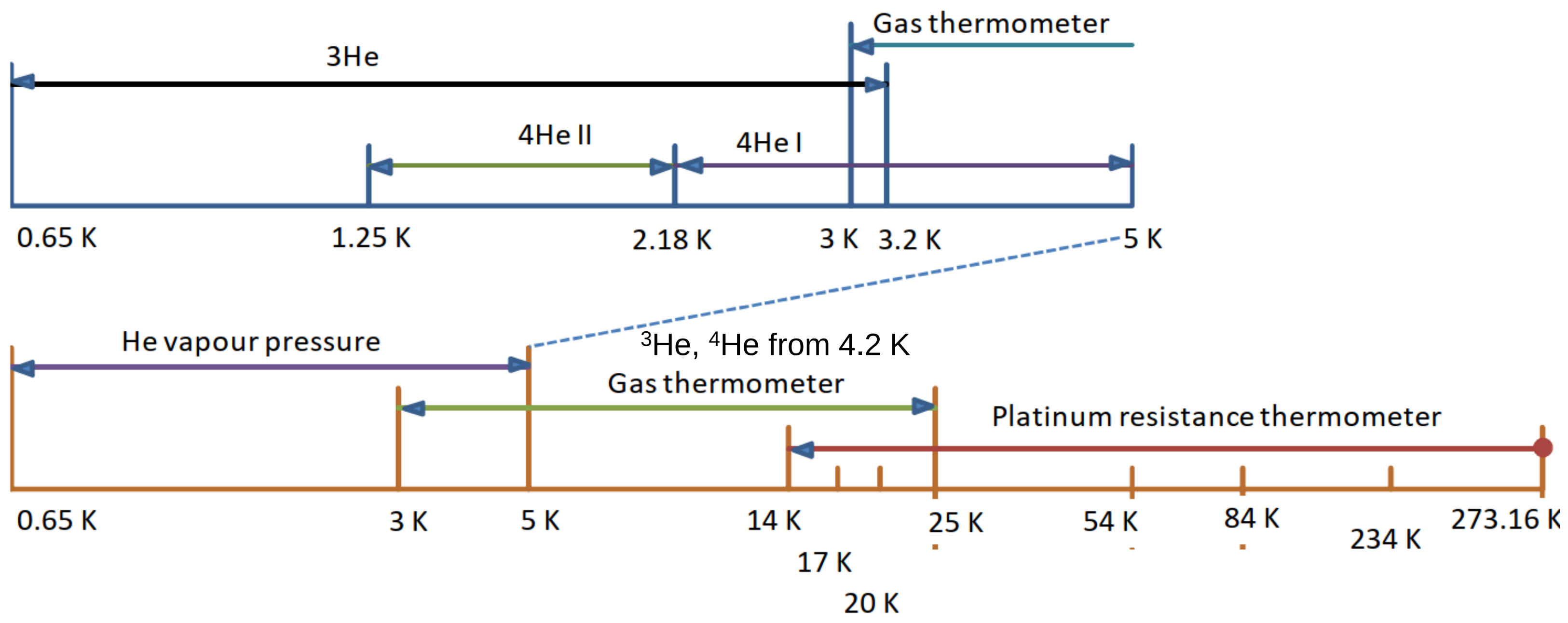
Accurate but imprecise

Accurate & precise

Figures from a poster made by NPL

Absolute Temperature Scale (ITS 90)

Temperature (as pressure) is an intensive quantity and its measurement is done via the use of a transducer that measures a temperature dependent quantity.
An intensive property does not depend on size or mass.
The International Temperature Scale of 1990 extends upwards from 0.65 K.
Between 0.9 mK & 1 K it exists a provisional temperature scale (PLTS2000)

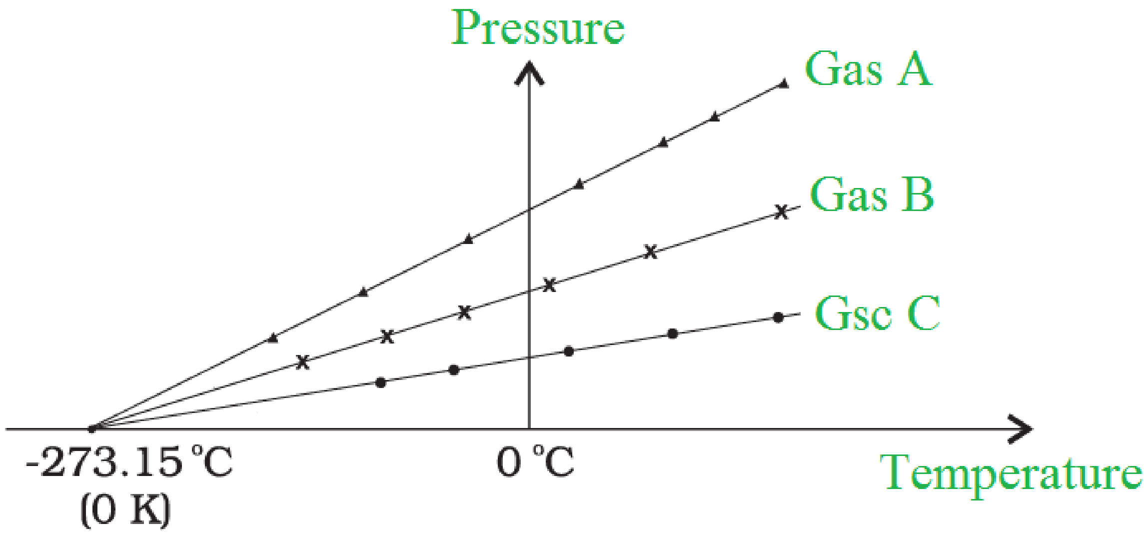


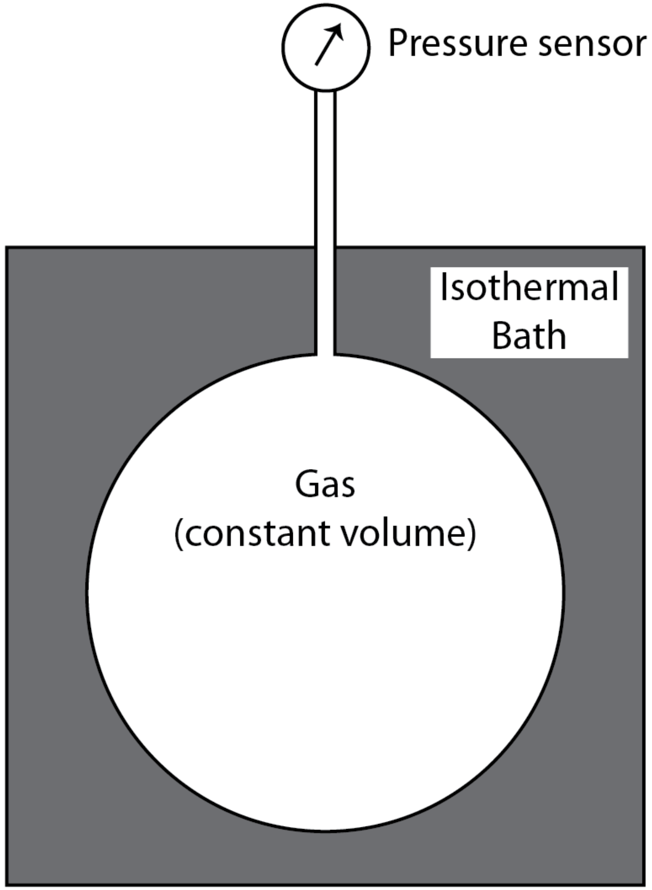
T [K]	Substance
13.8033	e-H_2 (T)
17	e-H_2 (V)
20.3	e-H_2 (V)
24.5561	Ne (T)
54.3584	O_2 (T)
83.8058	Ar (T)
234.3156	Hg (T)
273.16	H_2O (T)

Absolute Temperature Scale

The origin for the value of the lowest attainable temperature is related with:

- Freezing (ice point) temperature of water (0 °C)
- Boiling temperature of water (100 ºC)
- Law of perfect gases & constant volume gas thermometer
  - Temperature % Pressure
- Vanishing pressure ⬄ lowest temperature
- The SI unit for temperature is K (Kelvin)
  - 0 ºC = 273.15 K



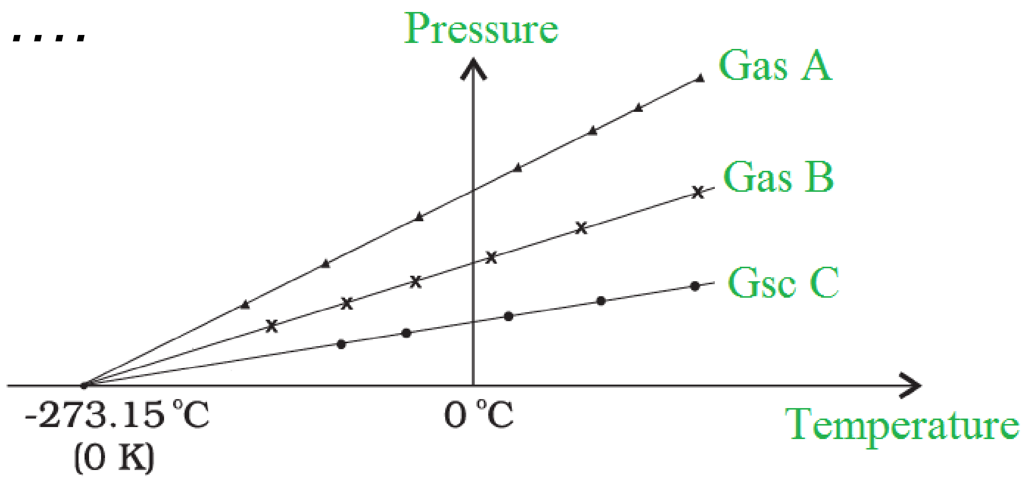


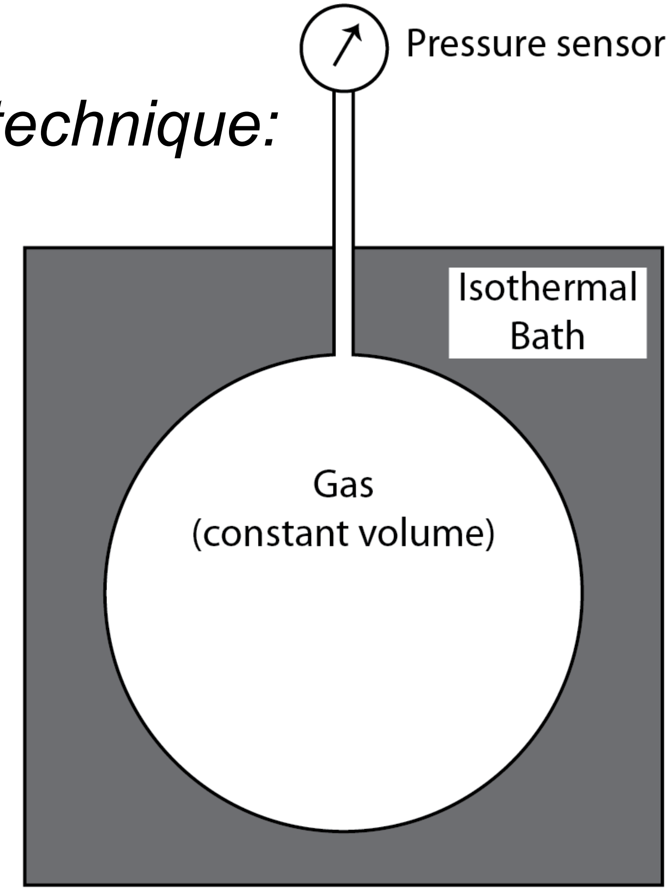
Absolute Temperature Scale

Constant volume gas thermometer: $p \, . \, V = n \, . \, R \, . \, T \quad => \quad p \, \% \, T$

- Stop working when reaching the gas liquefaction temperature
- Virial expansion required to model non ideal gas behavior
  $p \, . \, V = n \, . \, R \, . \, T \, (1 + B(T) \, . \, (n/V) + C(T) \, . \, (n/V)^2 + \ldots)$

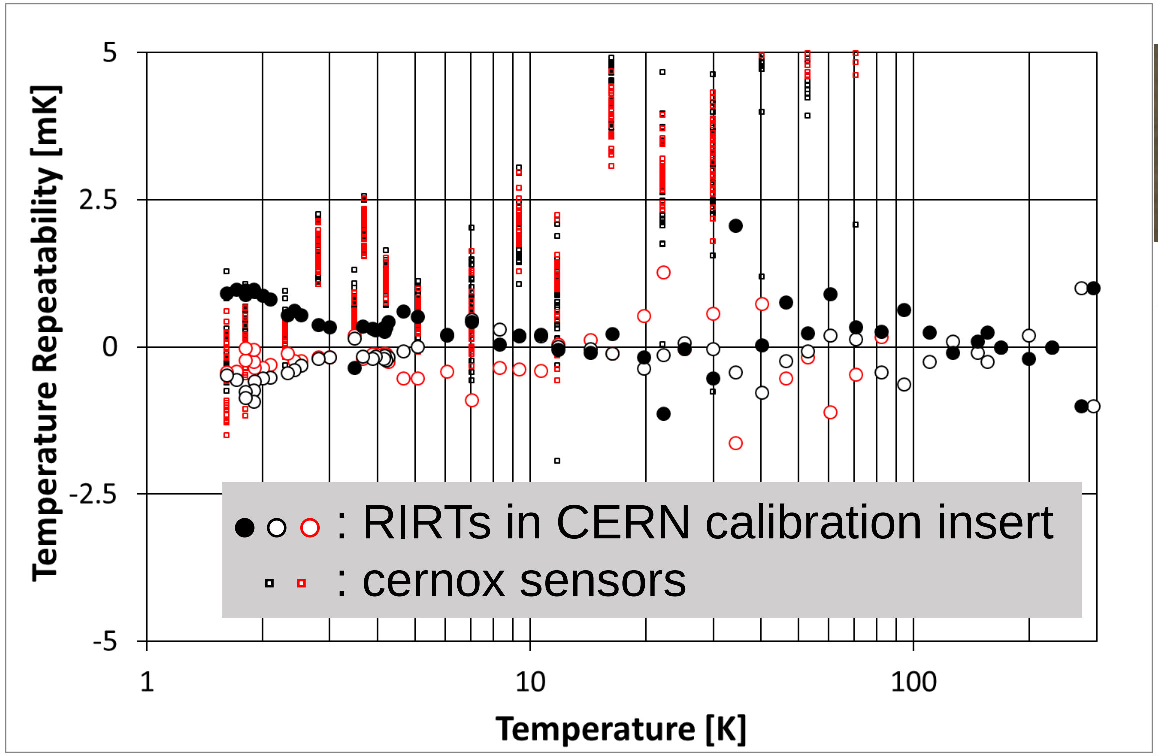
- *Not as easy to use as it looks, it is an "approximation" technique:*
  - *Real gas is not an ideal gas*
  - *Temperature gradient along capillary*
  - *Accuracy of pressure sensor*
  - *……*





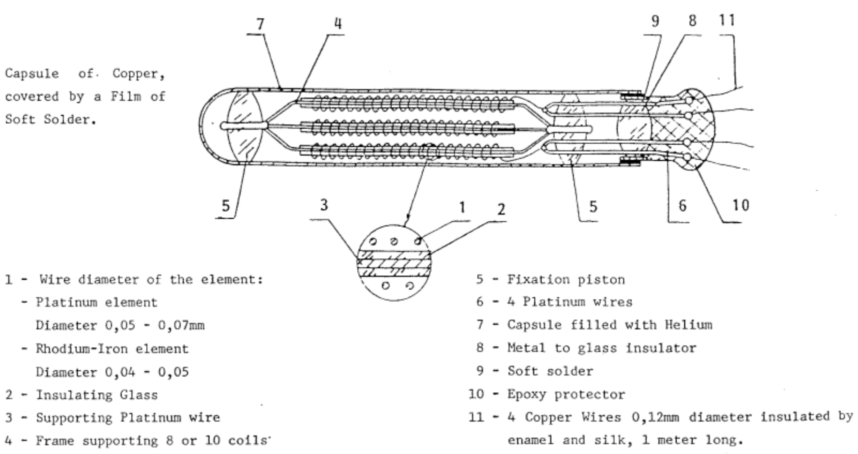
Absolute Temperature Scale: CERN standards

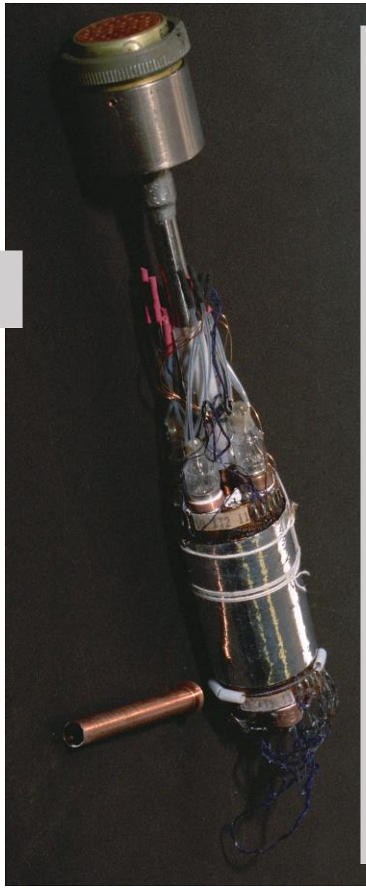
Rhodium IRon Thermometers (RIRT): used as secondary & working standards.
2^{ary} standards are compared to primary standards by a reference laboratory.
Working standards are installed in the series calibration insert & compared from time to time (yearly basis) to the secondary standards (in a separate insert).



RIRT standard made by Tinsley (UK)

RIRT standard made by VNIIFTRI (RUS)





VNIIFTRI standard comparison insert

Standards/Calibration Certificates

The LHC requirements for the measurements below 4 K are very tight
Not far off from the national standards laboratories results:

Working & secondary standards are not required for:

- Pressure
- Voltage
- Current
- etc.

industrial calibration certificates of apparatuses is sufficient; these are:

- DMM
- Portable calibrators
- Bench instruments
- …..

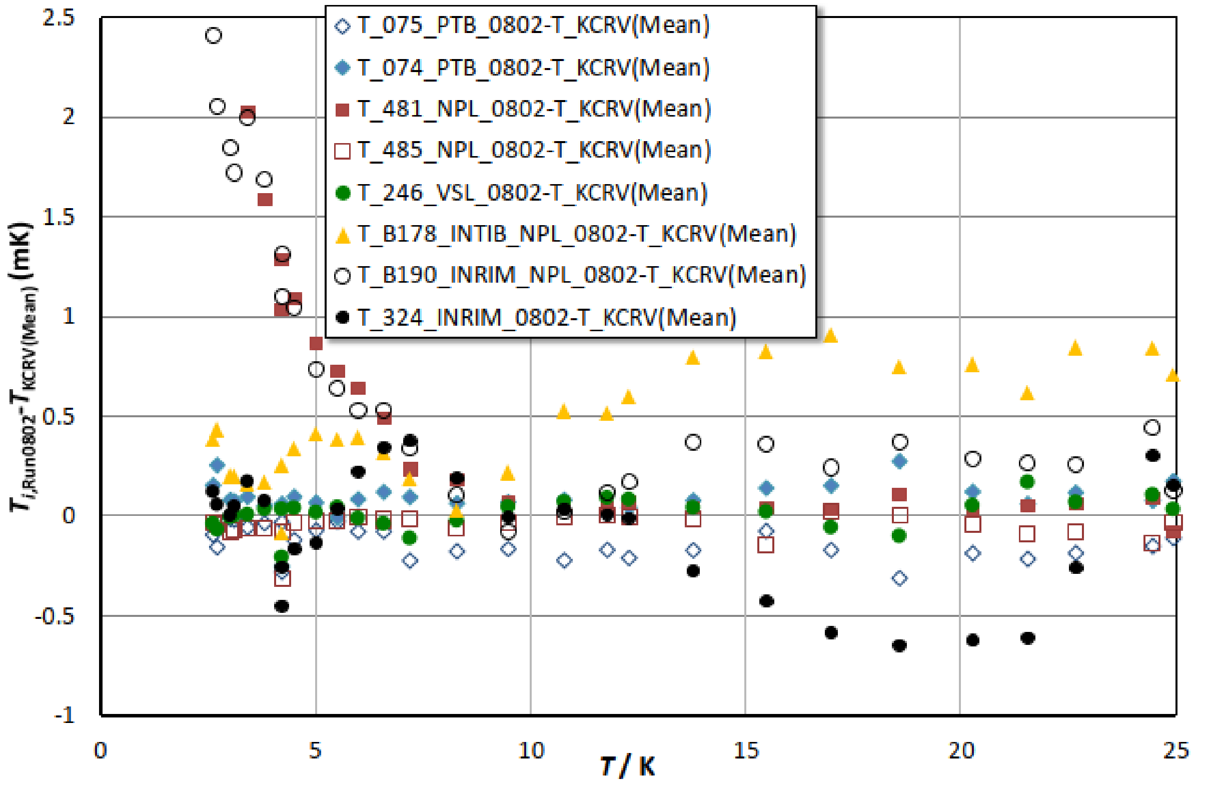


Figure 5: Deviations of the readings of 8 RIRTs from the KCRVs obtained in the main comparison run No. 0802.

From <<EURAMET Key Comparison No. EURAMET.T-K1>> (2016)

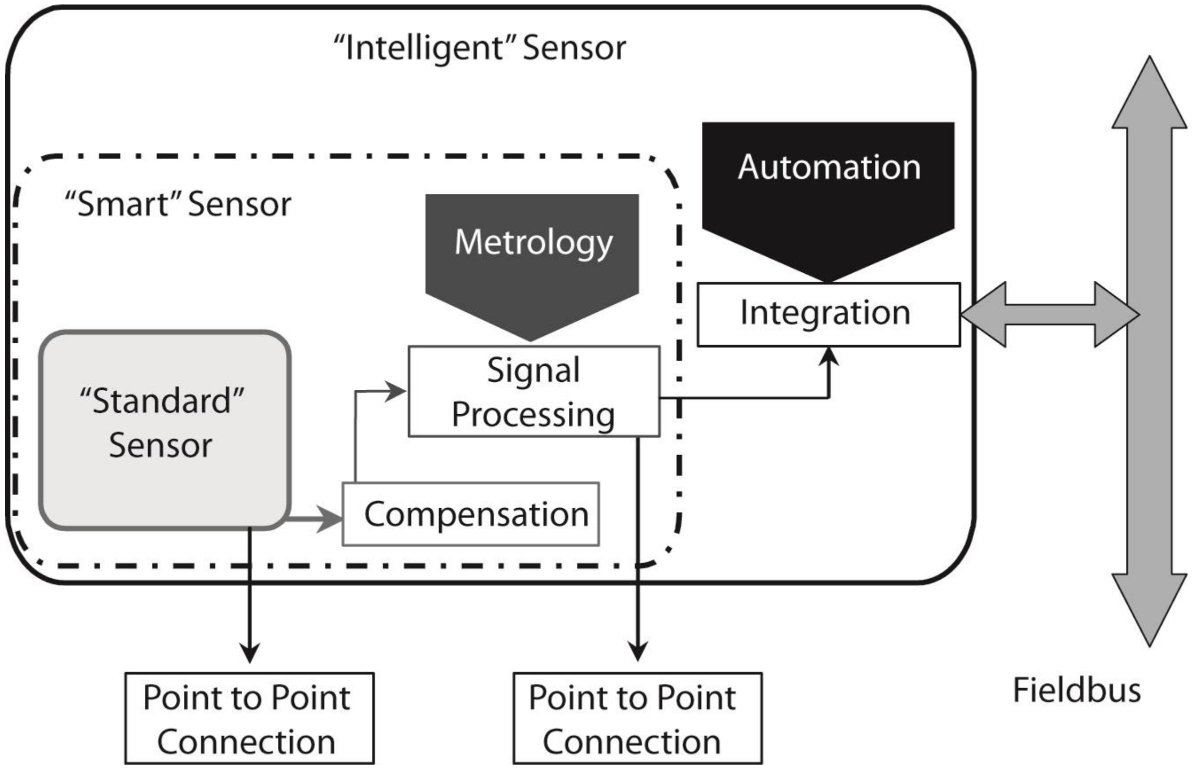
Instrumentation Chain: “Sensor” View

The market for sensors is moving towards more complex sensors that include all possible linearizations/compensations.
“Smart” commercial instrumentation for cryogenics is usable only @ warm.
Accelerators usually impose passive (dumb) sensors:

- Too low temperature
- Exposure to ionizing radiation

Many “smart” sensor are presently being used in test areas and are connected via fieldbuses:

- Pressure
- Flow
- Valve actuators
- …



Instrumentation Chain: Particle Accelerator

Particle accelerator usually involve environmental radiation

⇒ More challenging than a typical industrial installation

⇒ Equipment need to be qualified by the end user

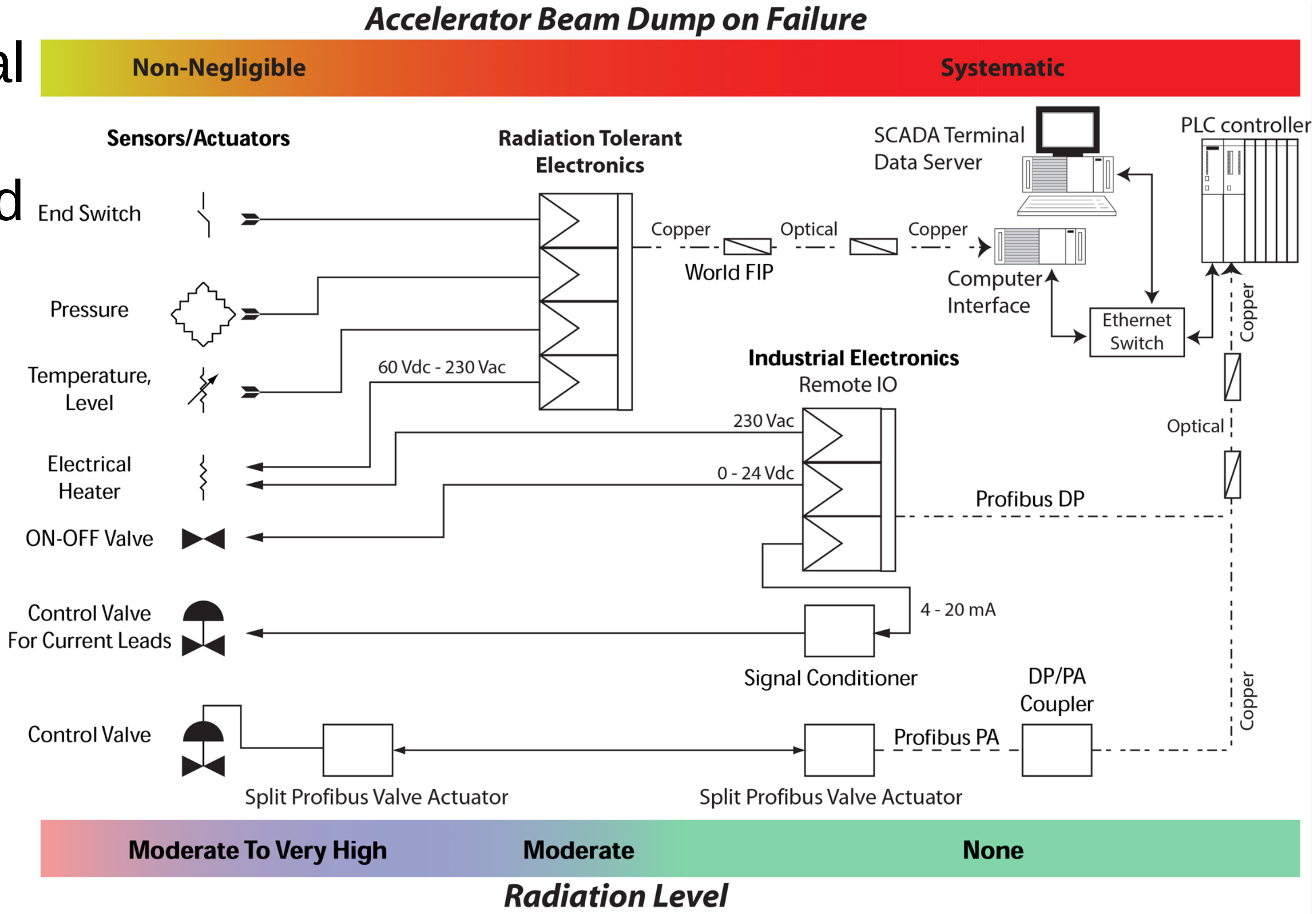
⇒ Critical equipment need to be located appropriately or provide adequate redundancy

⇒ Long distance require mechanisms to cope with EMI

⇒ 20+ year operation design

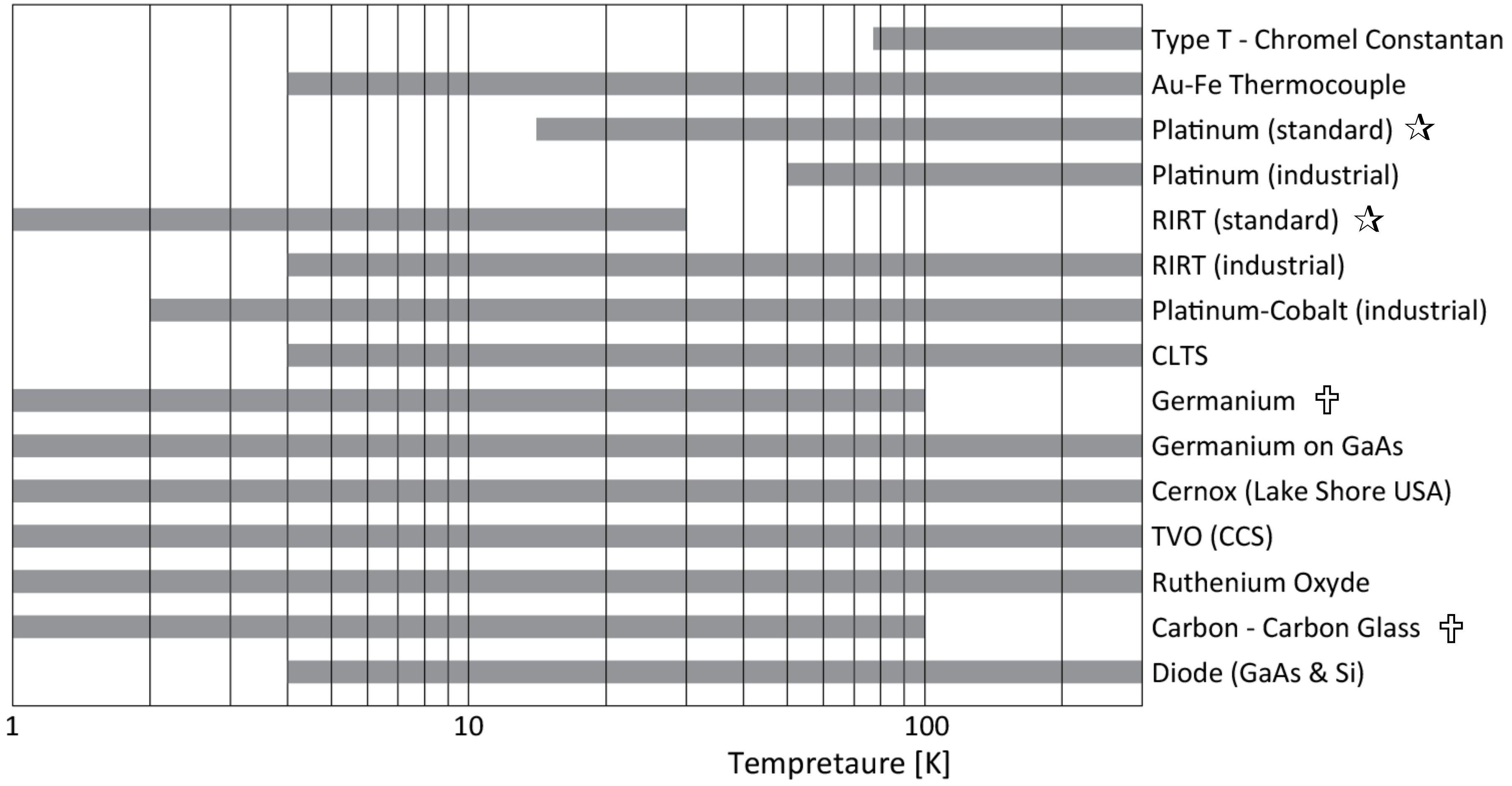
⇒ ¡ obsolescence !

LHC example



Temperature Measurement: Electrical Sensors

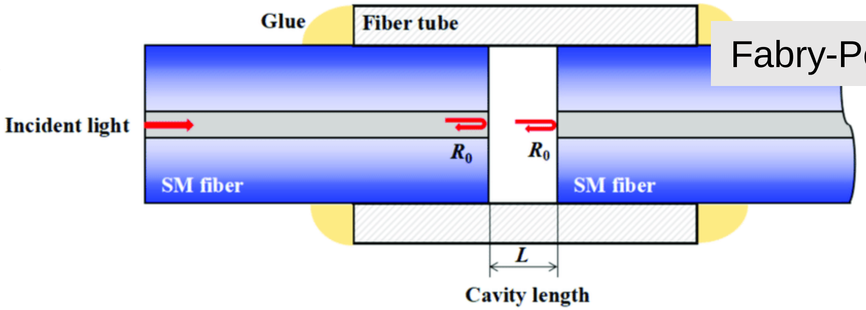
Most of the temperature measurements are based in electrical sensors.
Wide variety makes difficult to find a single one fitting all applications.
All are several decades old and some are becoming obsolete ♰ or difficult to obtain ☆.



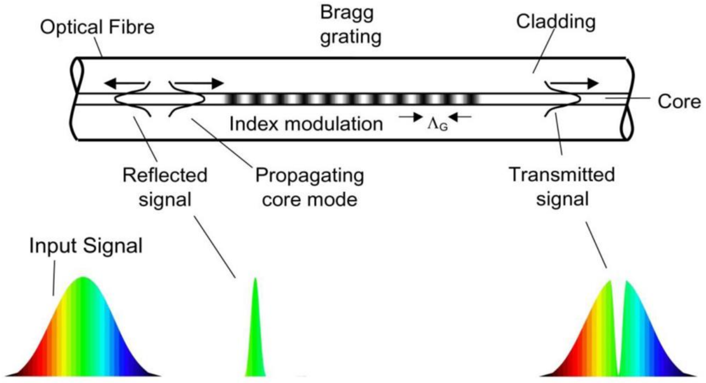
Temperature Measurement: Optical Sensors

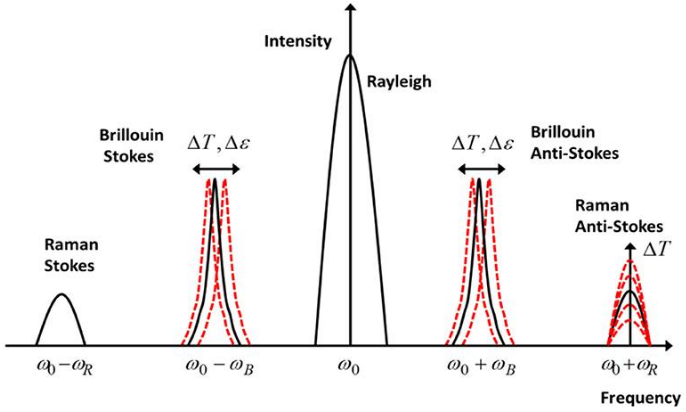
"Bare" optical Fiber Sensing (OFS) technologies have a lower measurement temperature of about 50-80 K.

Distributed optical sensors is a mature technology used to measure stress and temperature in civil engineering, oil & gas, marine, etc.



Fabry-Perot





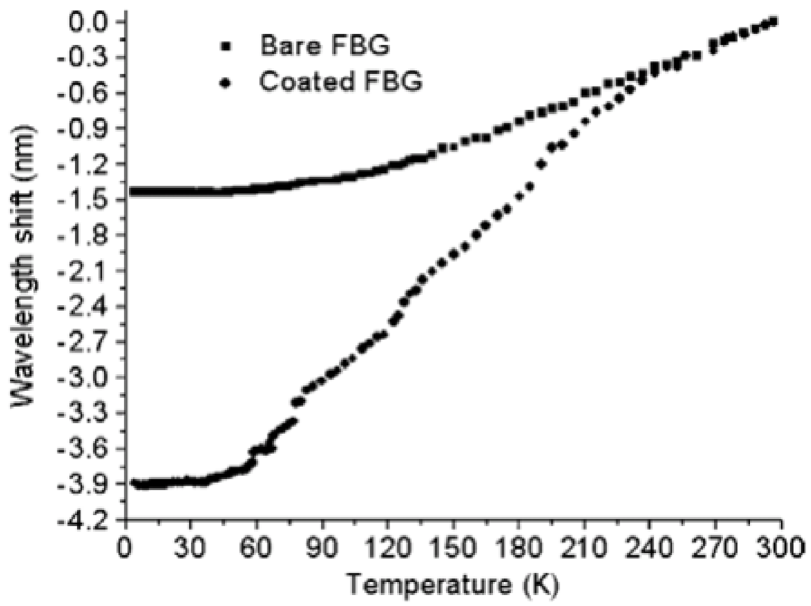
Technology	Distributed?	Based on	Temperature/stress discrimination
Fabry-Perot (FP)	multi-point	boundary scattering	No
Fibre Bragg Grating (FBG)	multi-point	grating scattering	No
Raman	Distributed	optical phonons scattering	n.a.
Brilloiun	Distributed	accoustic phonon scattering	Yes
Rayleigh	Distributed	nanometer scale defects scattering	Yes

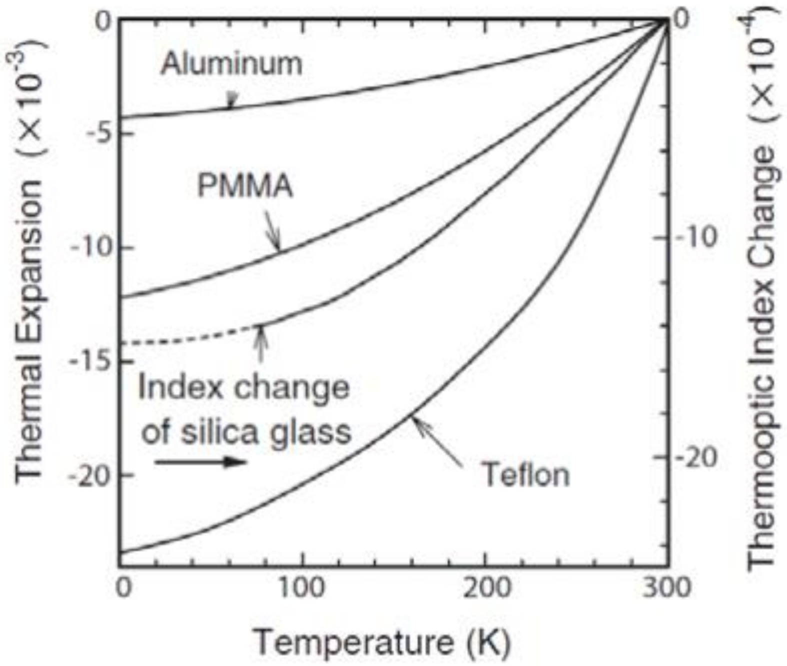
Temperature Measurement: Optical Sensors

The lower temperature measurement range can be extended by coating the fibre with appropriate cladding materials, the coating shall provide a significant thermal contraction well below 80 K.

Temperature is therefore measured through thermally-induced strain in the optical fiber => stress and temperature cannot be differentiated when using such technique.

No impact on Raman scattering as it is only temperature dependent.





Temperature Measurement: Optical Fiber Sensors (OFS)

OFS cryogenic applications are indeed being developed.

For instance ITER intend to deploy OFS to measure stress (FBG), displacement (FBG & FP) and temperature (FBG).

Some published data indicate measurement of temperature down to LHe temperatures, although the associated uncertainty is difficult to understand.

As for any temperature sensor, they require to be appropriately anchored and are affected by thermal cycles.

Main advantages are distributed measurements over long distances (several km), immunity to electro-magnetic noise, high voltage insulation, etc.

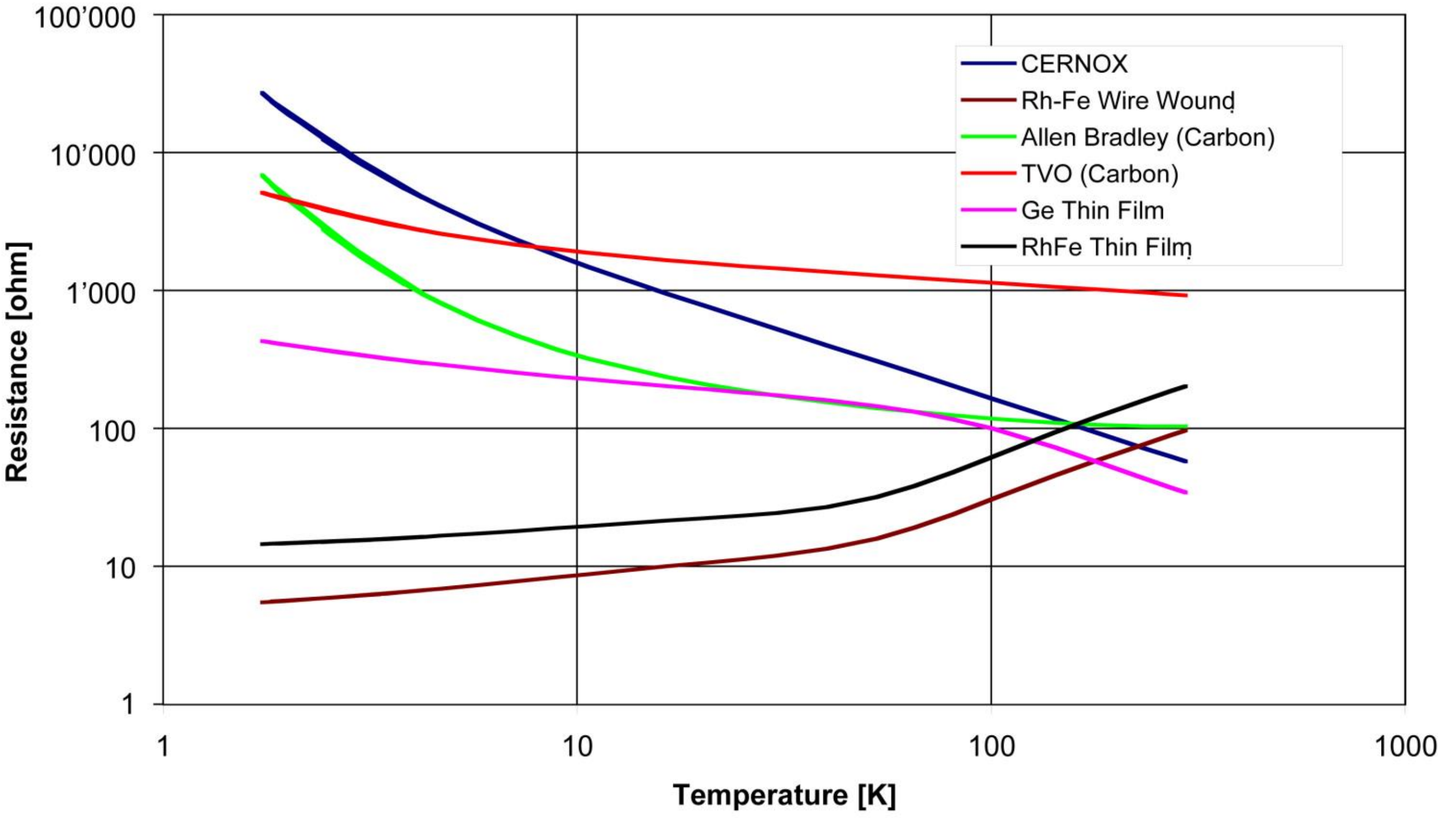
Measurements require a reading unit that provides the optical signal (laser) and process the reflected and/or transmitted light.

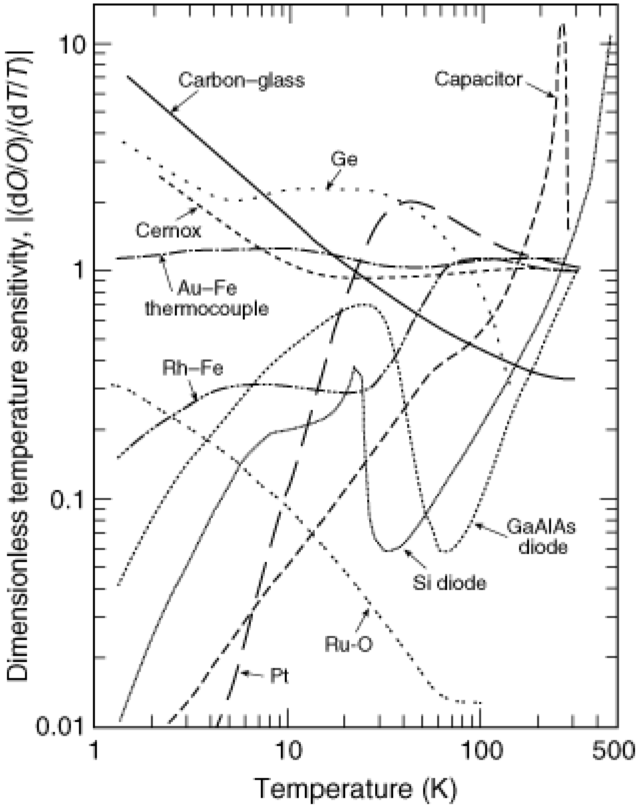
Temperature Measurement: Electronic <-> Sensor Matching (LHC)

The LHC temperature requirement:

Temperature Range	1.6-2.2 K	2.2-4 K	4-6 K	6-25 K	20-300 K
Uncertainty [K]	± 0.01	± 0.02	± 0.03	± 1	± 5

The TYPICAL resistance versus temperature of the LHC candidates had both positive (RhFe & Pt 100) and negative (cernox, Allen-Bradley, TVO, Ge) dR/dT





Temperature Measurement: Electronic <-> Sensor Matching (LHC)

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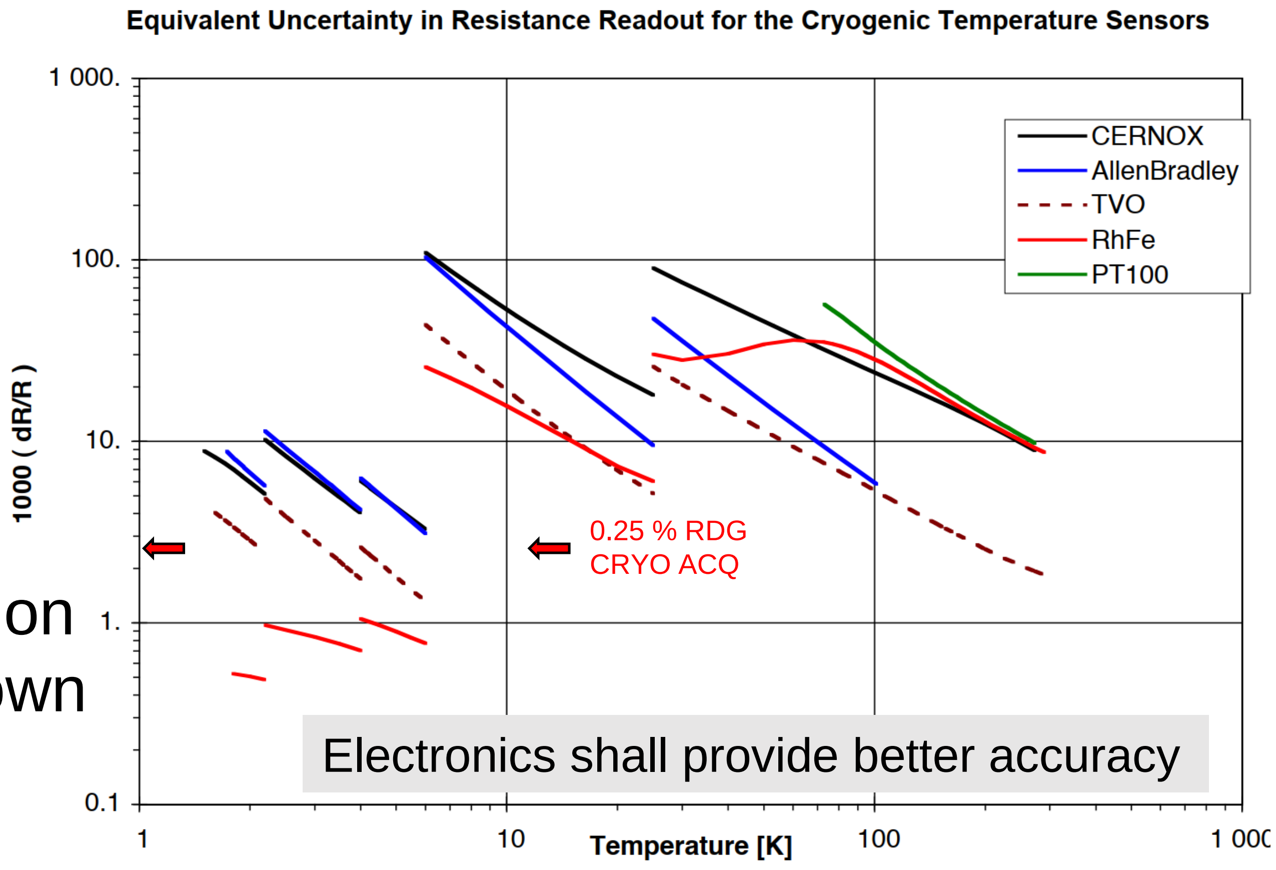
Temperature Range	1.6-2.2 K	2.2-4 K	4-6 K	6-25 K	20-300 K
Uncertainty [K]	± 0.01	± 0.02	± 0.03	± 1	± 5

The precision budget was shared in equal parts between the sensor & electronics.
Requirements are tough below 6 K.

RhFe: demanding signal conditioning
Very small sensitivity

All sensors are slightly different:

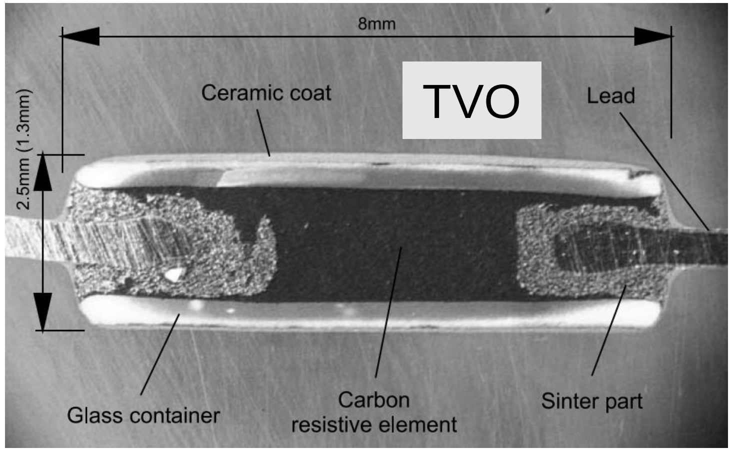
- QA system to track sensor installation
- Sensor <-> location need to be known



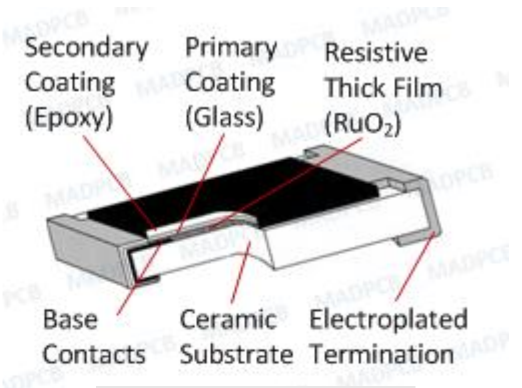
Temperature Measurement: packaging for electrical sensors

- Commercial resistors

TVO, Allen Bradley, Ruthenium oxide
Anchoring via wires & body
Robust package



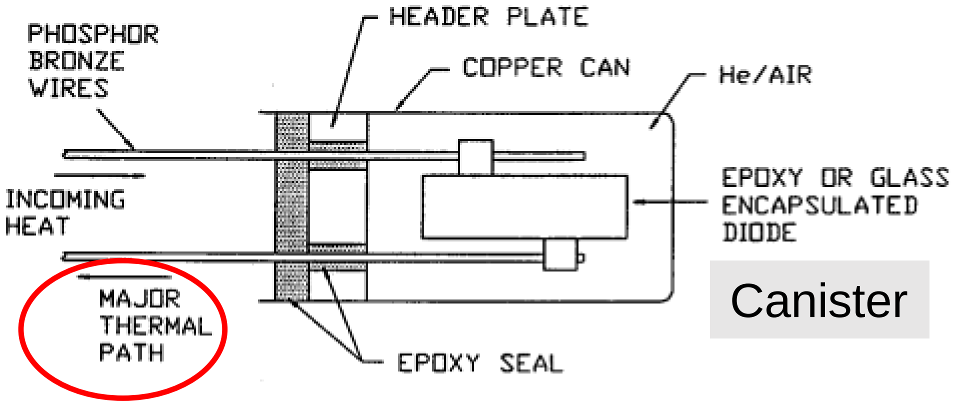
TVO



RuO2 (SMD)

- Canister mounting

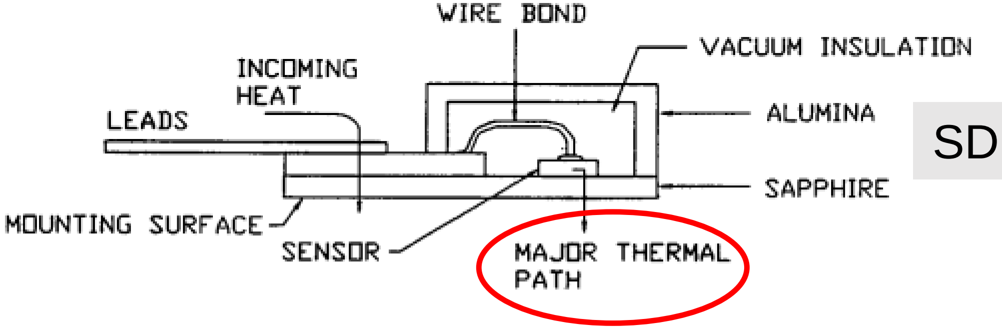
Ge, carbon glass, cernox, ..
Anchoring via wires
Canister anchoring quite useless ⬄ vacuum
Fragile package:
epoxy seal damage
=> sensor damaged if not passivated



Canister

- Specific mounting (SD Lake Shore)

Cernox, diode, etc
Anchoring via wires (& body)
Robust package but wires (leads) are fragile.



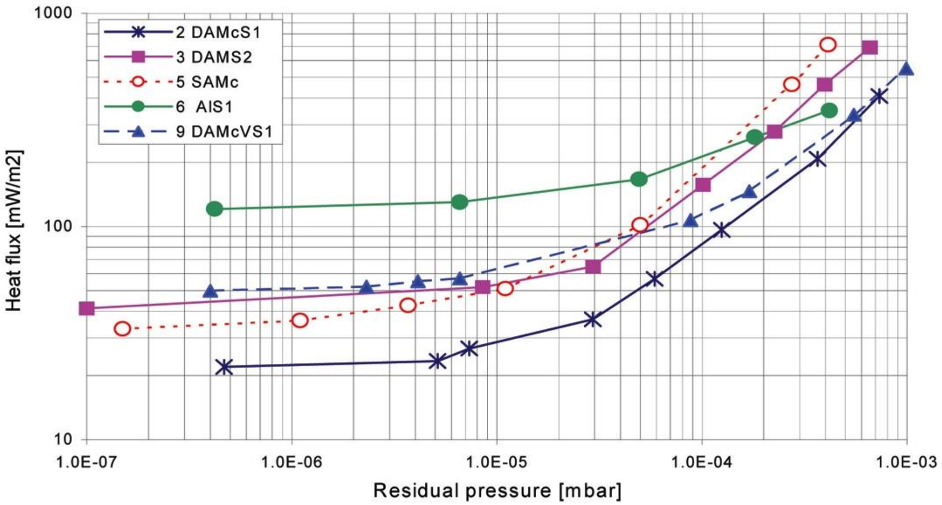
SD

Temperature Measurement: Thermal Anchoring under vacuum

Need to cope with photon radiation, heat transfer through solids & Joule effect.

Radiated Heat Flux In Vacuum envelope

PARAMETER: Type of Superinsulation



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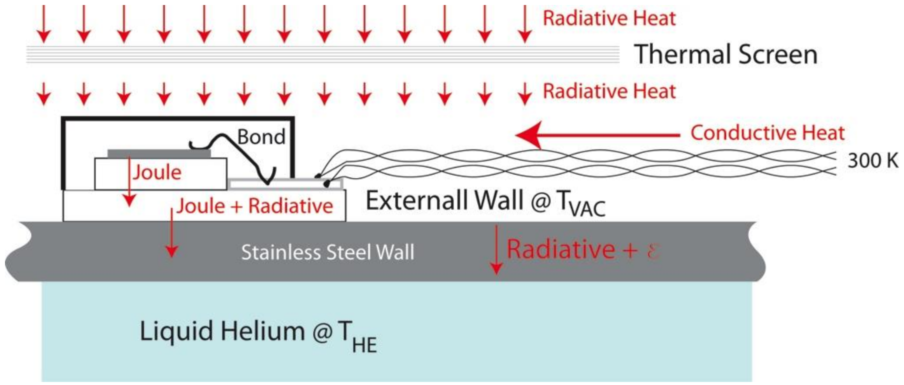
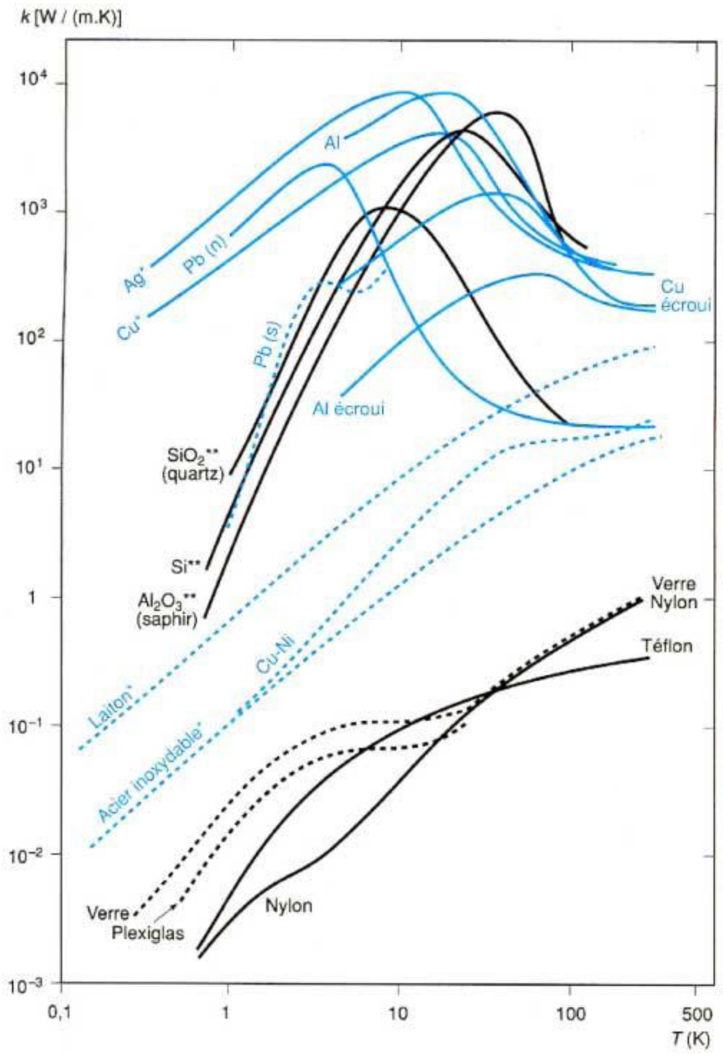
Measurement



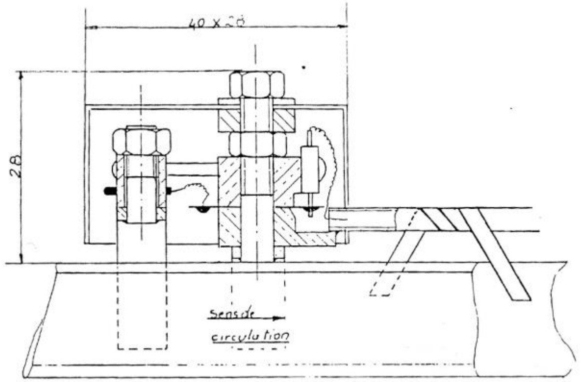
Thermal Conductance

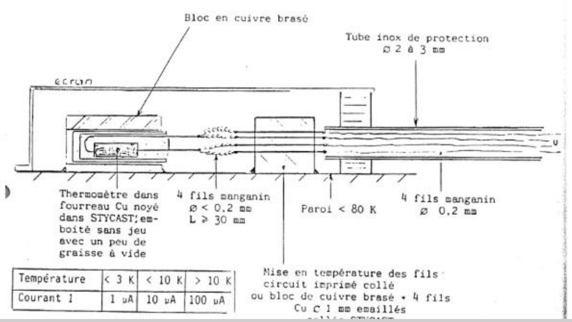


Temperature Measurement: Thermal Anchoring under vacuum

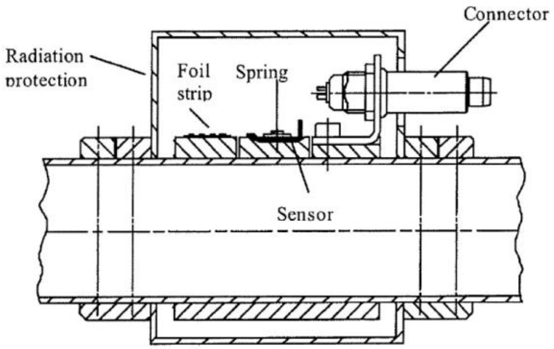
Existing industrial approaches, both examples rely on two anchoring “islands”:

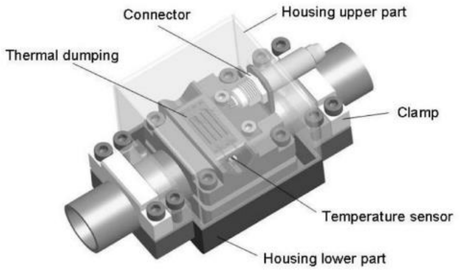
- 1st island anchors the incoming wires to reduce the heat reaching the sensor
- 2nd island anchors the sensor body and wire





CEA – 1998
Independent thermal anchor for sensor & wires
Brazed assembly





KFK - 2010
Independent thermal anchor for sensor & wires
Clamped assembly

Temperature Measurement: Thermal Anchoring under vacuum

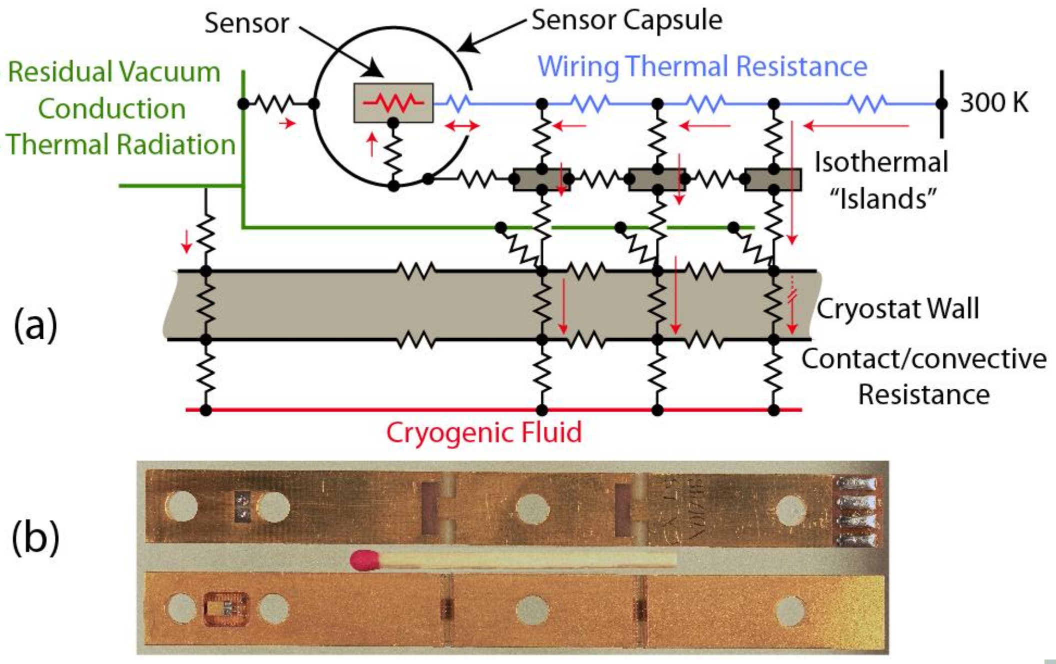
LHC vacuum thermometer based on a triple anchoring support

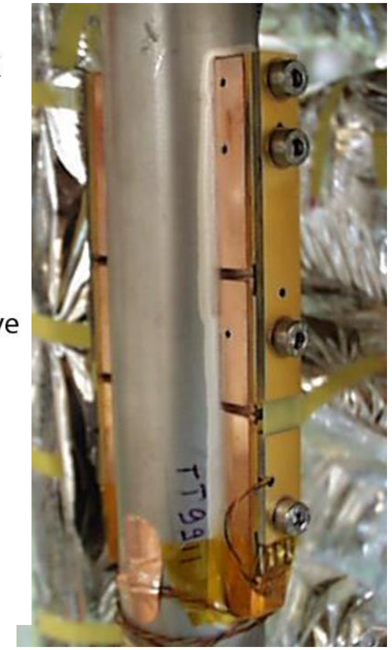
increases robustness in case one anchor “island” is loose

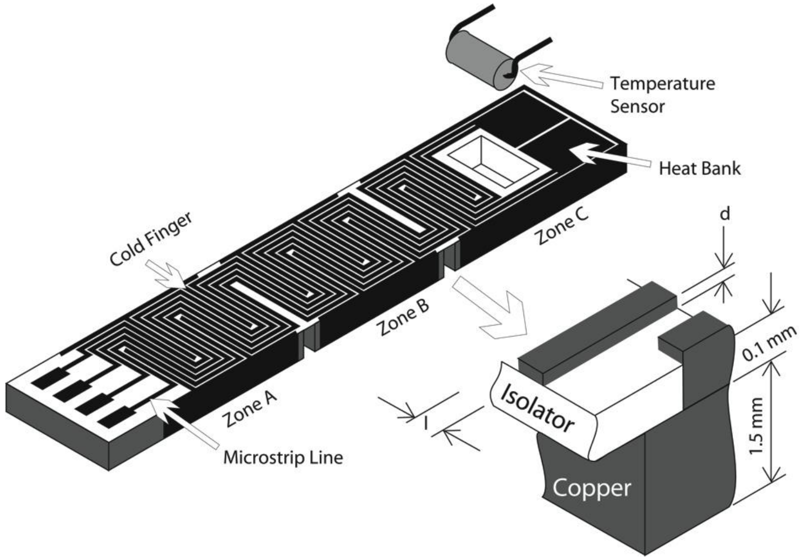
“islands” are thermally decoupled ⇔ do not short on copper support

Reduce heat from warm feedthrough => long & resistive (non-copper) wires

Calibration performed on full assembly before screwing in final position



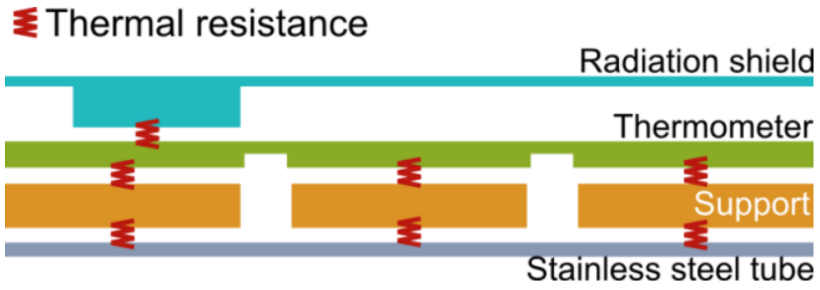


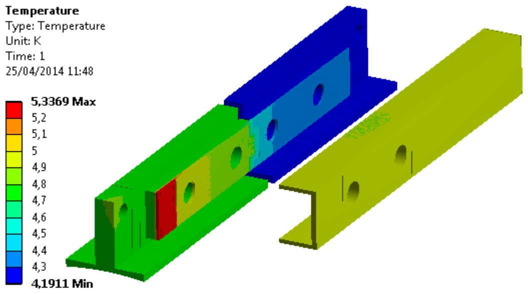


Temperature Measurement: Thermal Anchoring under vacuum

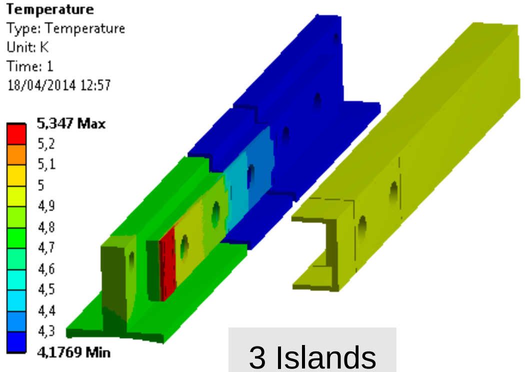
ITER-CEA has adopted the LHC long thermometer block for vacuum applications.
CEA used finite element model to simulate 2 & 3 island configurations:

- 3 islands provides better accuracy
- confirms CERN's (much) simpler calculations
- Main contributors to external wall temperature increase:
  - Thickness of stainless steel wall
  - Photon radiance
  - Thermal transport through wires <= ~~copper~~
- Measurand = external wall temperature

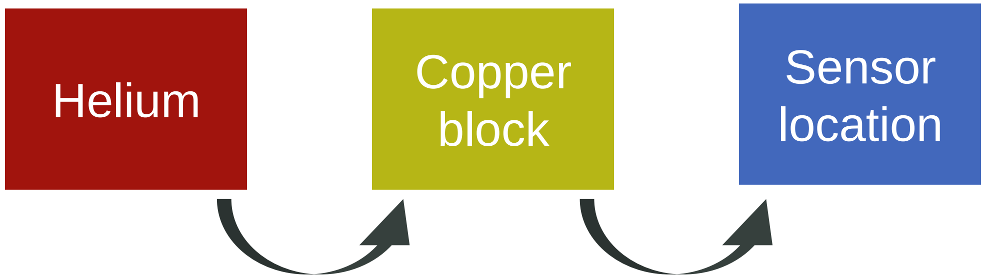




2 Islands



3 Islands



3 islands -> ΔT = 15 mK ΔT = 2 mK
2 islands -> ΔT = 43 mK ΔT = 8 mK

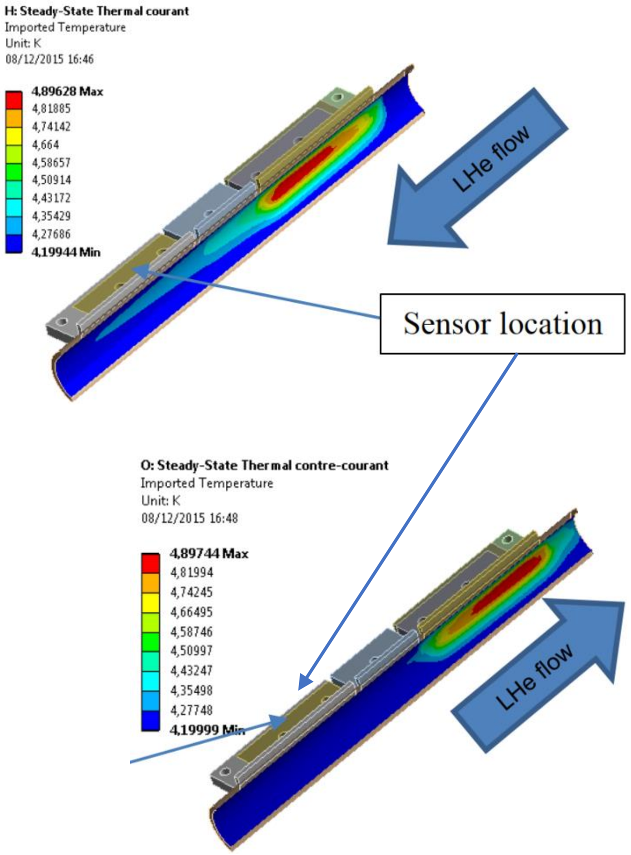
Temperature Measurement: Thermal Anchoring under vacuum

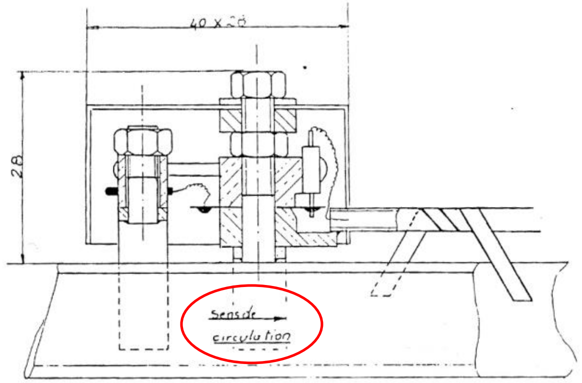
As confirmed by finite element modelling the sensor should be upstream

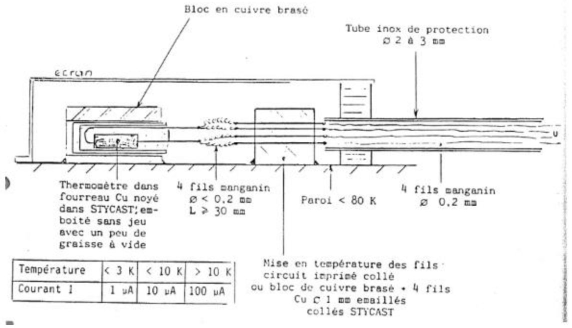
see light blue temperature propagation with flow

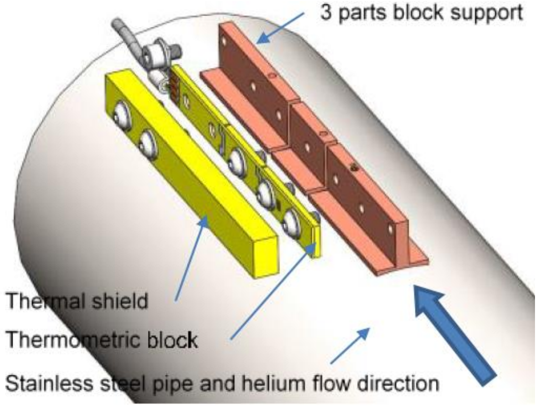
CERN design is asymmetrical => support structure shall be properly orientated

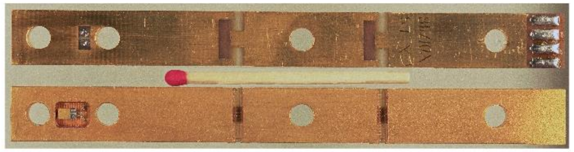
CEA design is symmetric => orientation has to be checked on assembly or repair









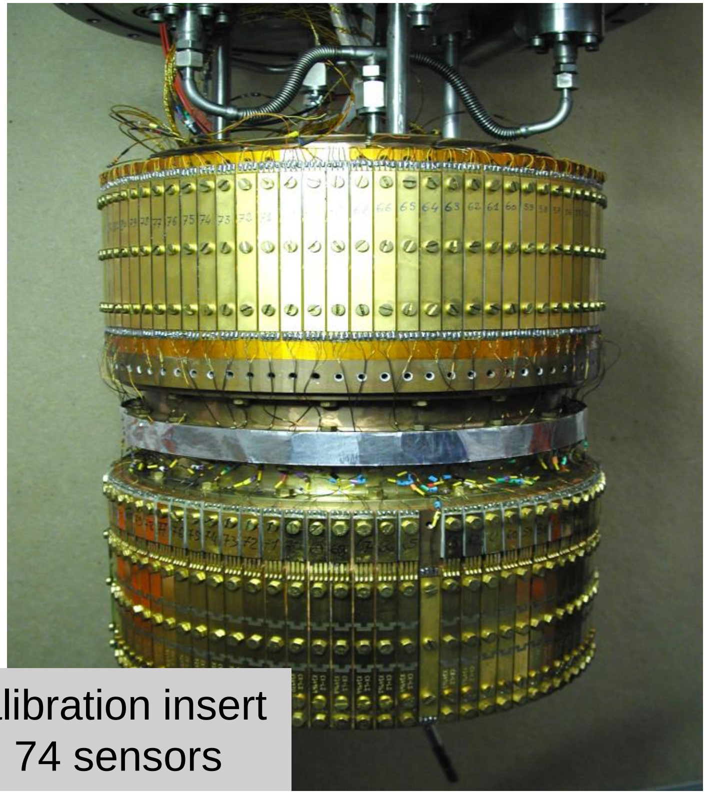


Temperature Measurement: Thermal Anchoring under vacuum

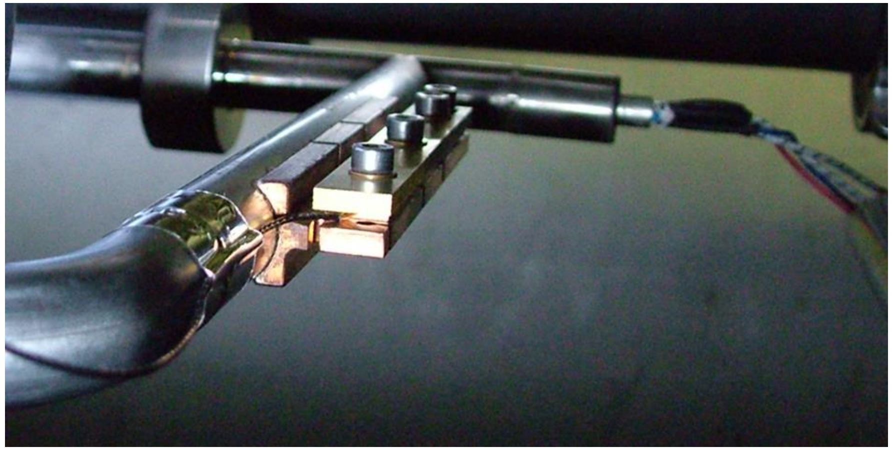
Calibration performed under vacuum with sensors on final holder:

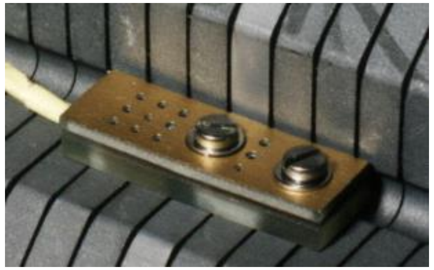
- Long block for vacuum applications
- Short block for immersion in LHe
- Bare sensor for insertion thermometry

} <= Sensor not manipulated after calibration



Series calibration insert
Capacity: 74 sensors





Temperature Measurement: Insertion thermometry

Through wall thermometry (vacuum) for low pressure gaseous helium complicated due to poor heat exchange between helium and inner pipe walls.

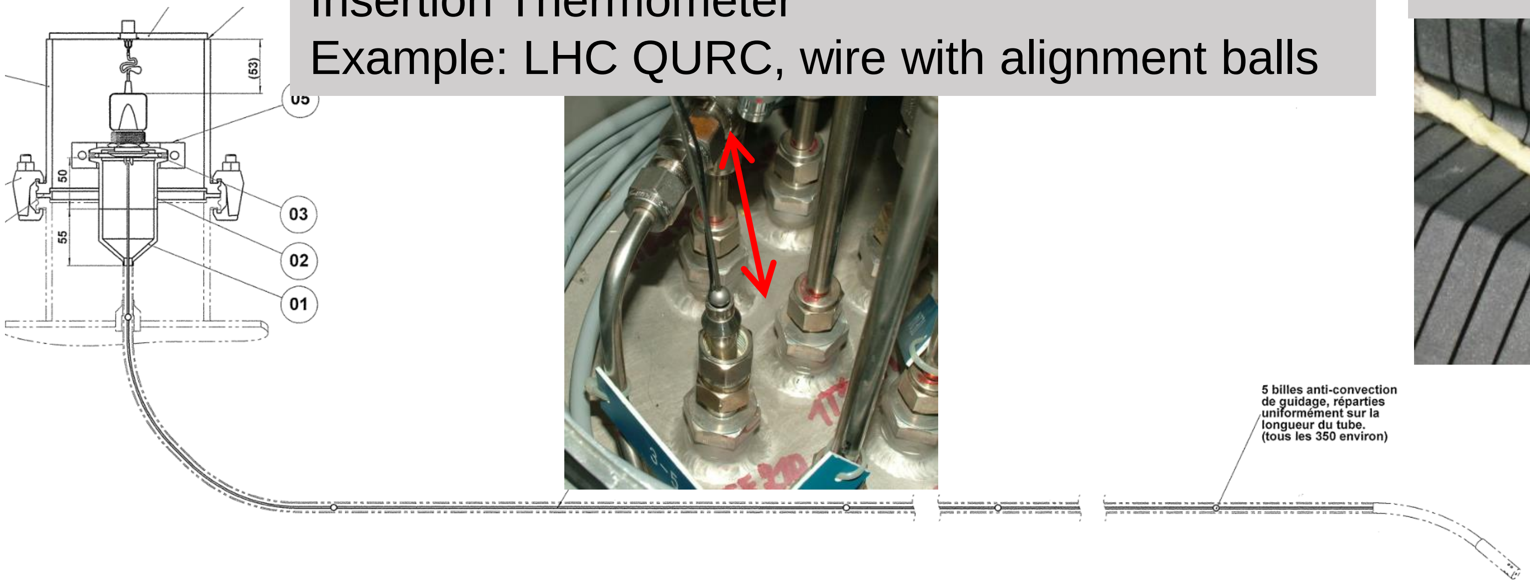
Low pressure gaseous helium => insertion thermometers:

- Added advantage: exchangeability

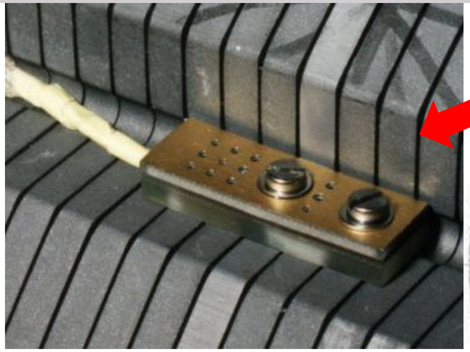
Liquid helium thermometers have their cables anchored at the fluid temperature

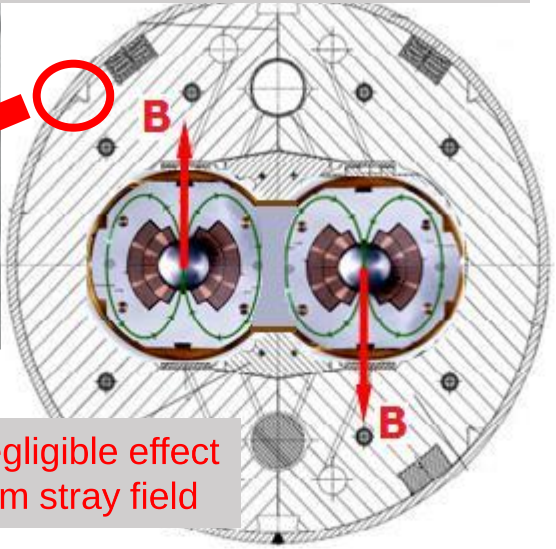
- Possible problem is sensor mechanical protection during fast flow transients
- Wires thermalized by LHe ⇔ wires bring heat.

Insertion Thermometer
Example: LHC QURC, wire with alignment balls



LHC cold mass thermometer.
Mechanical protection for cable and fast flow

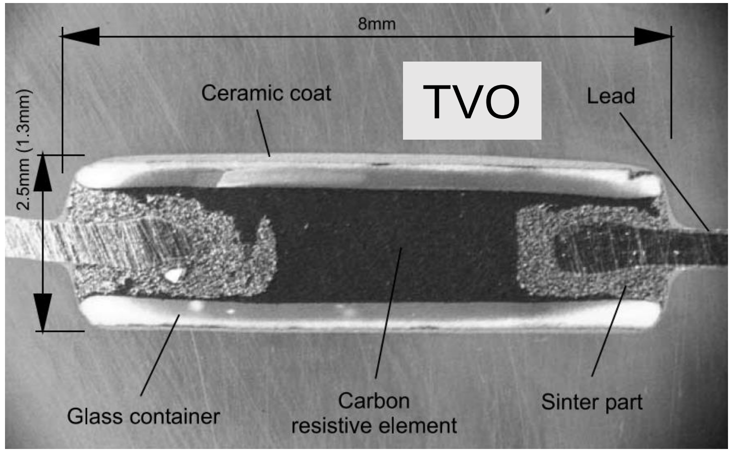


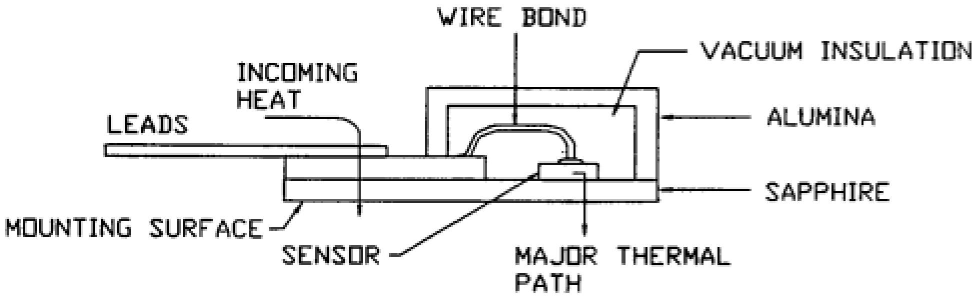


Temperature Measurement: Electrical Perturbances – Joule self-heating

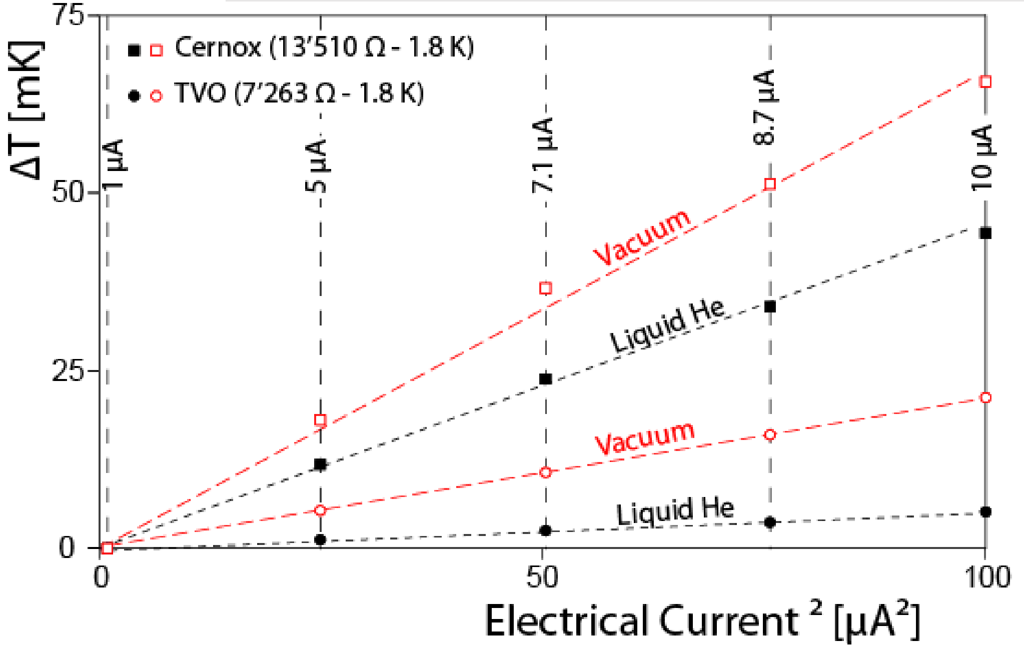
Resistance measurements using a DMM will result in a too high temperature:
- 100 µA (or higher) is common for portable and benchtop DMMs

Measurements below 5 K require:
- a low current source and a volt-meter.
- bipolar excitation current to compensate thermoelectric effects.





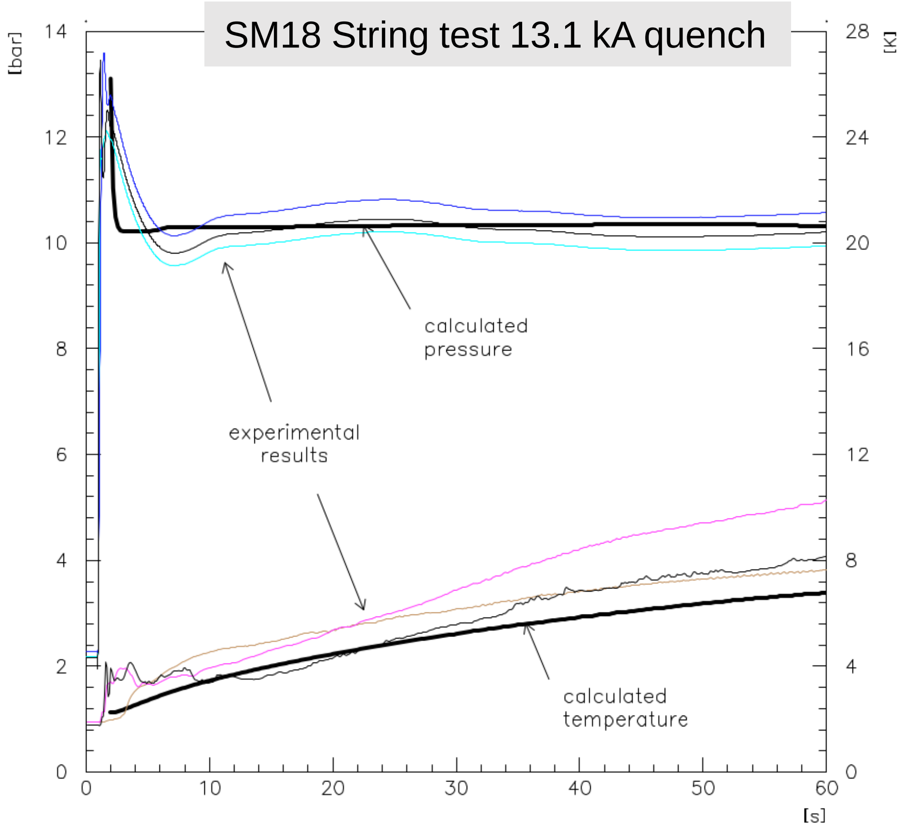
CERN data for sensors:
- vacuum: thermalization only through wires
- LHe: immersion of sensor & wires

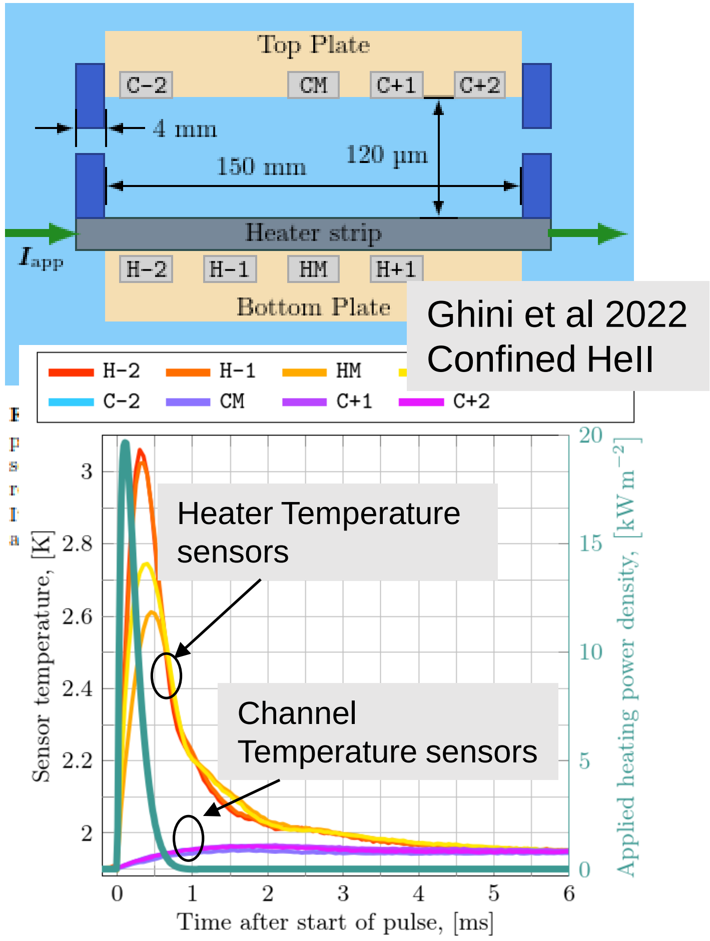


Temperature Measurement: time response

Examples of fast temperature transients can be found in:

- LHC string test that at the time had a variety of sensors (20 Hz BW)
- Heat transfer in confined He II using bare-chip cernox sensors (10 kHz BW)





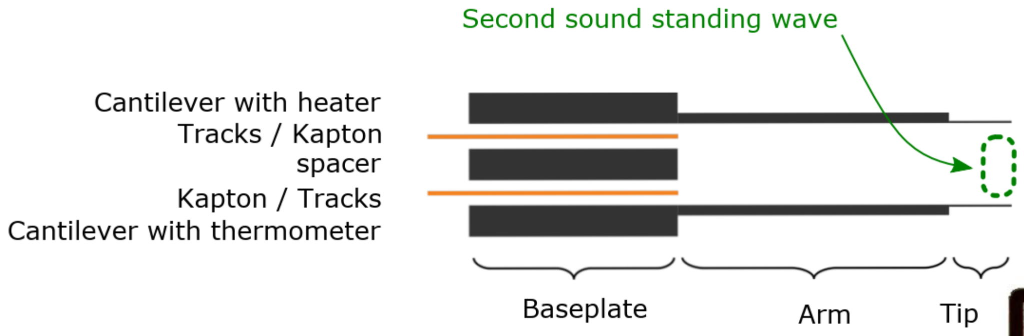
(a) Focus on heater sensors during the first 6 ms of the test.

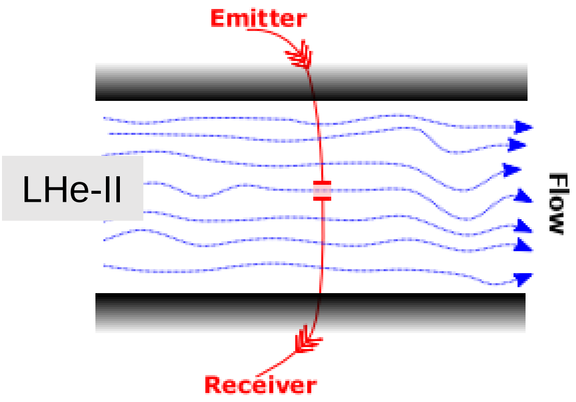
Temperature Measurement: time response (courtesy Ph. Roche)

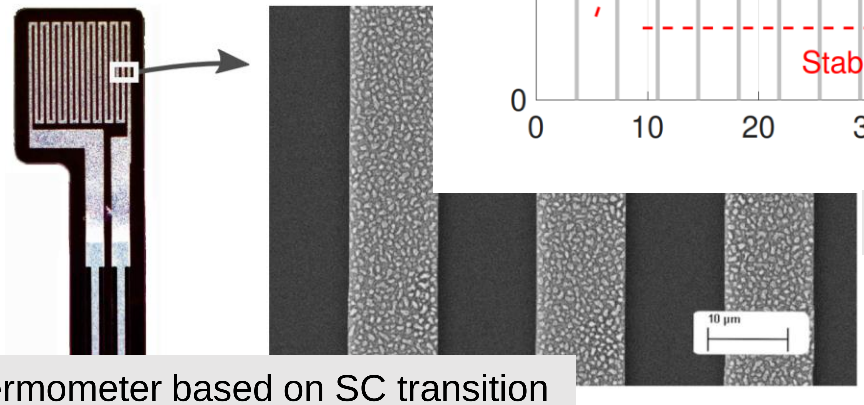
Within the framework of EUHIT (European High-performance Infrastructures in Turbulence) fast thermometers (> 70 kHz) were developed:

very low mass & adequate resistance to cope with stray capacitance.

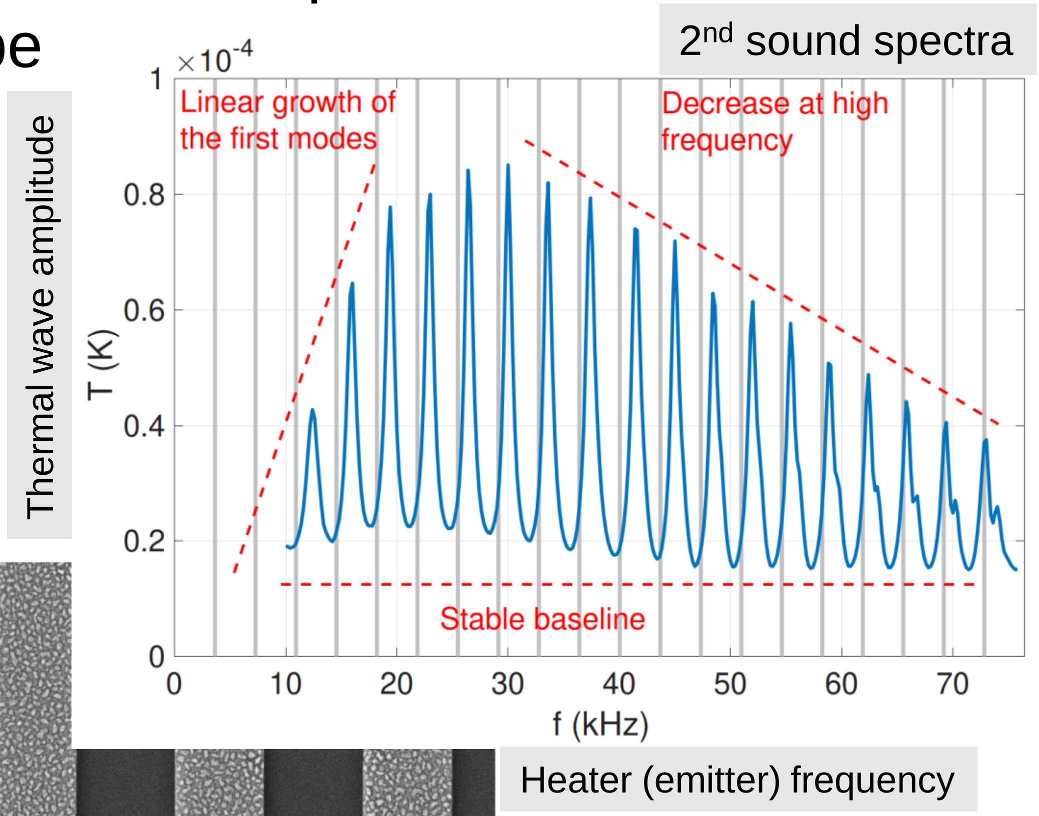
Low heat capacity is crucial!







Heater or AuSn thermometer based on SC transition
AuSn thermometer deposited on 20 µm thick Si



Temperature Measurement: time response

Reported time response vary from author to author and it is often difficult to understand how the stated value is obtained.

However some authors do provide experimental data:

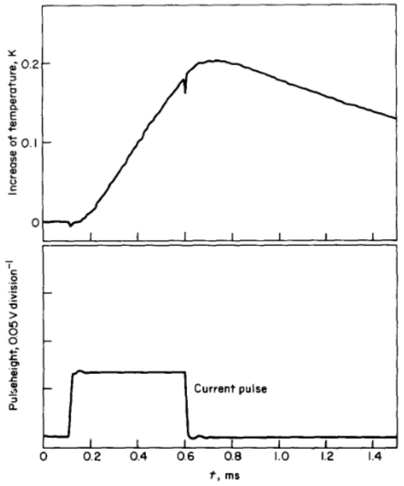
- Bloem: sensor attached to Cu under vacuum
- Louie: thermo-acoustic temperature oscillations

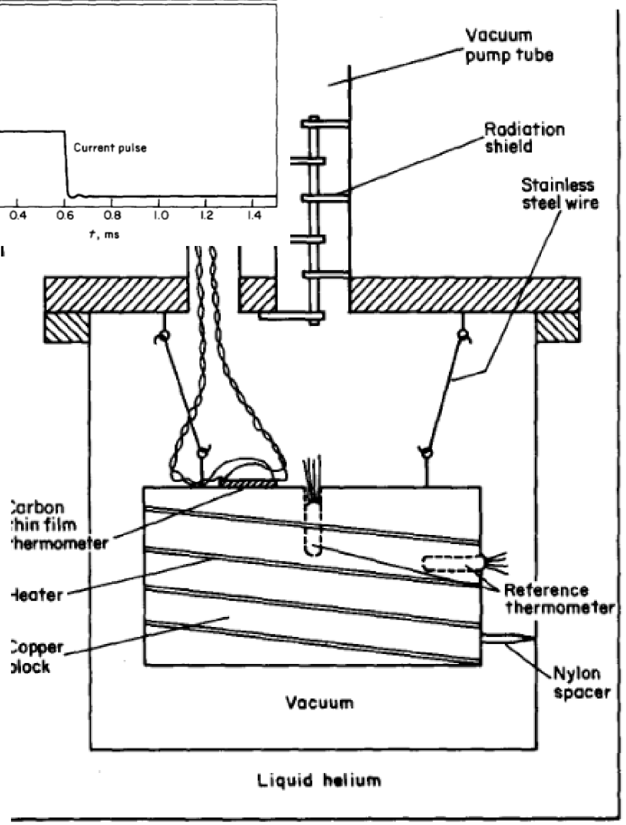
In most cases the temperature response time is dominated by the specific heat of the part under test.

Lower heat capacity (mass) ⬄ faster thermometer

Author	Sensor Type	Response Time[s]
Datskov et al 2013	TVO	0.001
Datskov et al 2013	Cernox	0.015
Kar et al 2007	Cernox	0.002
Bloem 1984	Carbon thin film	< 0.001
Louie et al 1986	Film on sapphire	10 n

Bloem 1984





Louie 1986

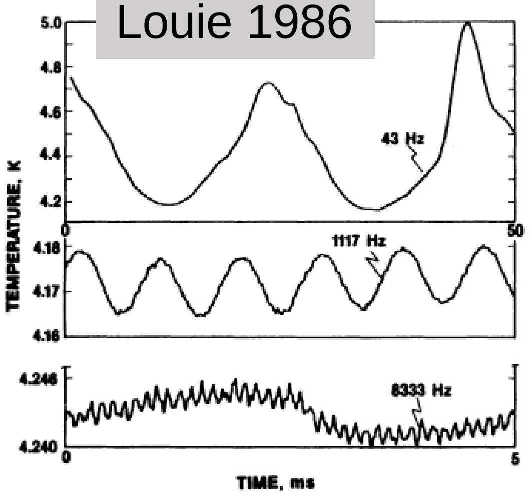


Fig. 11. Acoustic oscillations at temperature and frequencies indicated.

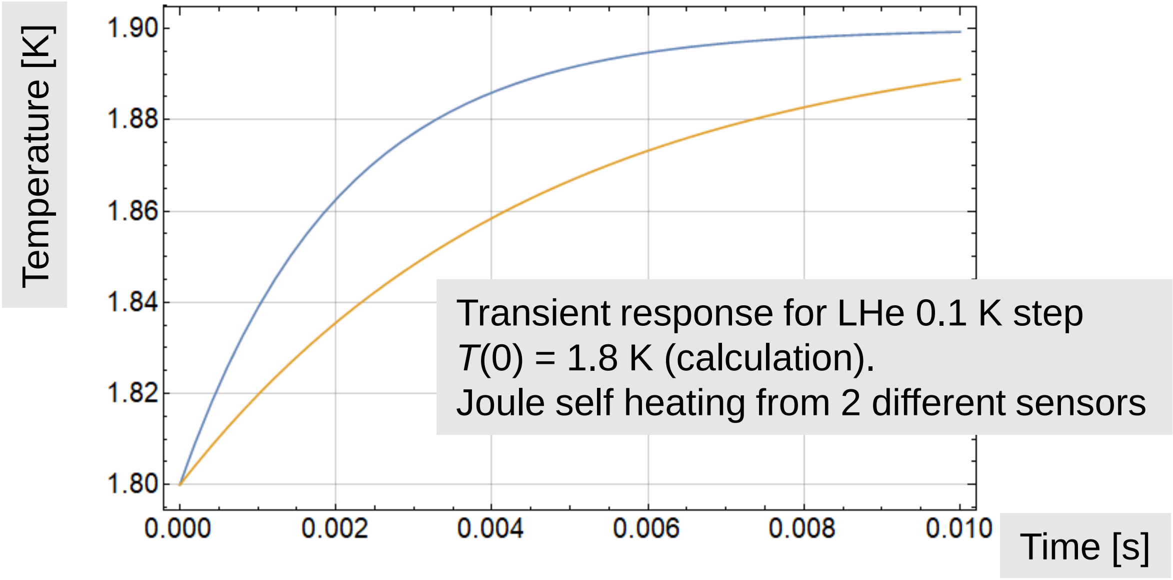
Temperature Measurement: time response estimation for cernox

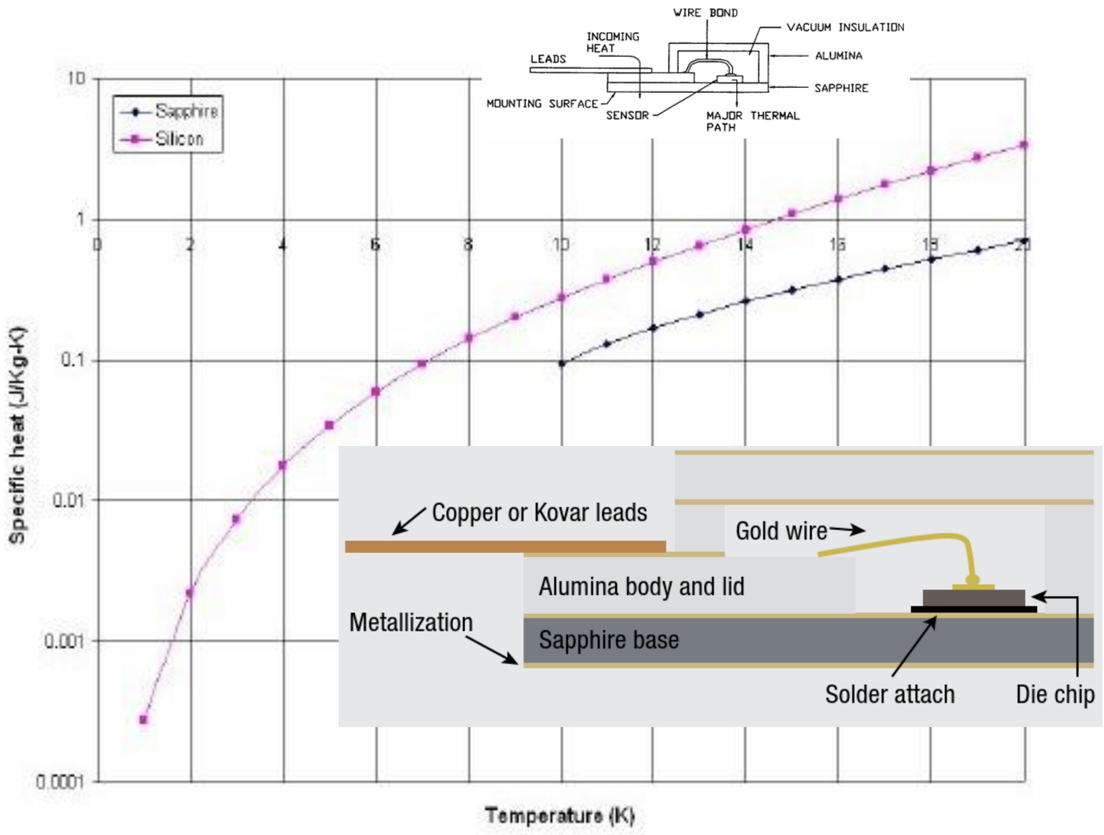
From the Joule self-heating (current vs ΔT figure), sapphire density (3980 kg/m3), C_p specific heat (2.3x10-3 J/(kg.K) @ 1.8 K) and assuming (overestimation) that it is a cube of sapphire (3.175 mm x 1.905 mm x 1.08 mm) the temperature evolution can be estimated by solving:

$$\frac{dT(t)}{dt} = (T_b - T(t)) \times \frac{R \times i^2}{\Delta T_{joule}} \times \frac{1}{C_p \times mass}$$

Response time: a few ms

Cernox chip: 40 less mass & better contact



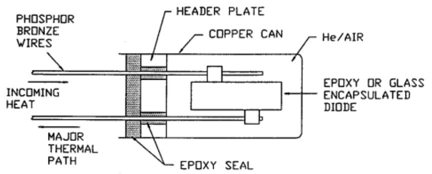


Temperature Measurement: Environmental Perturbances – magnetic field

Variable temperature resistance sensors exhibit magnetoresistance

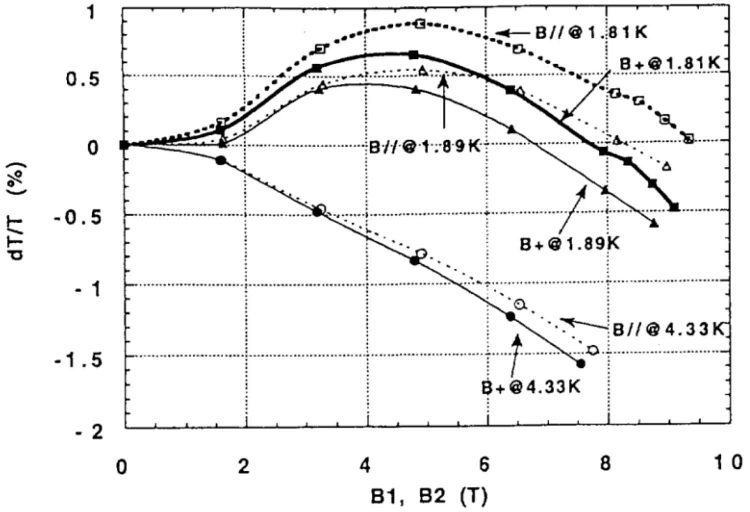
Capacitance, gas, … thermometers are insensitive to magnetic field

However are less practical thermometers



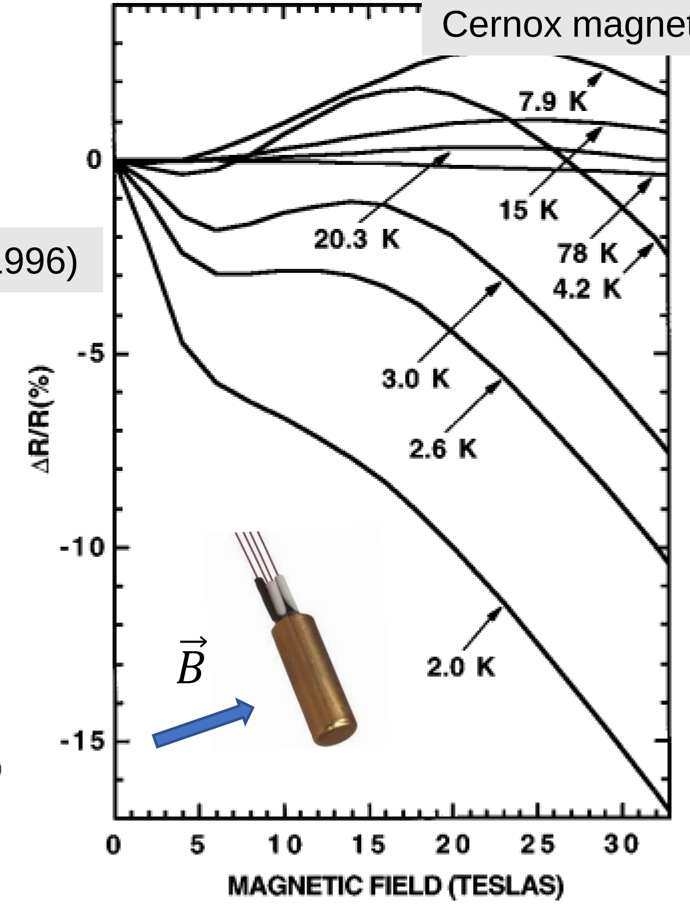
$\vec{B}$ versus ΔT in principle repeatable.

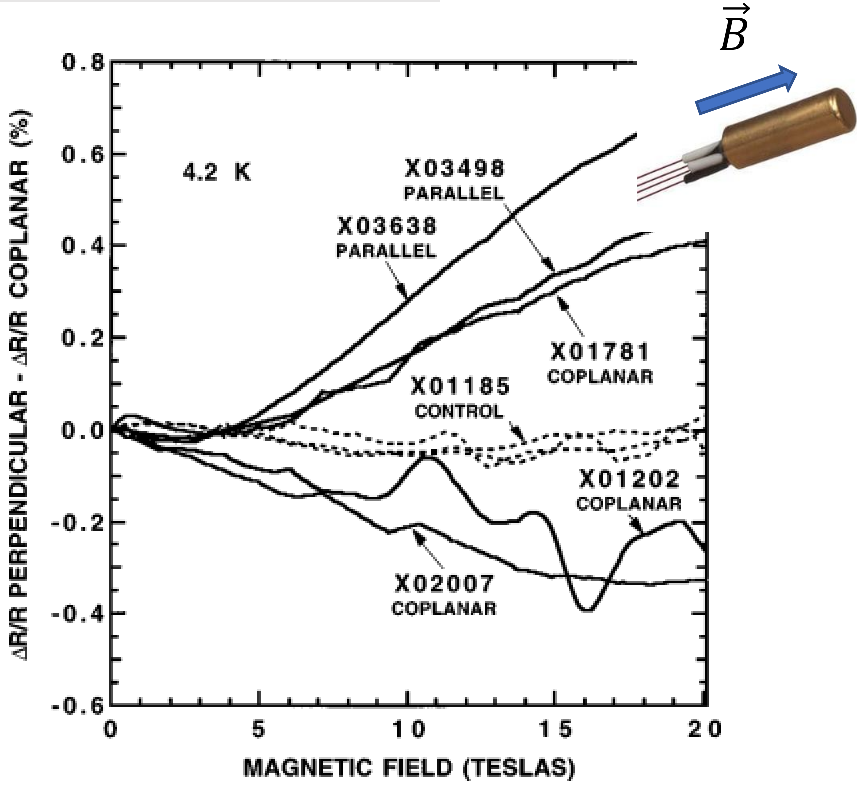
Ge magnetoresistance, Haruyama et al (1996)



= & ǂ orientations

Cernox magnetoristance, Brandt et al (1999)





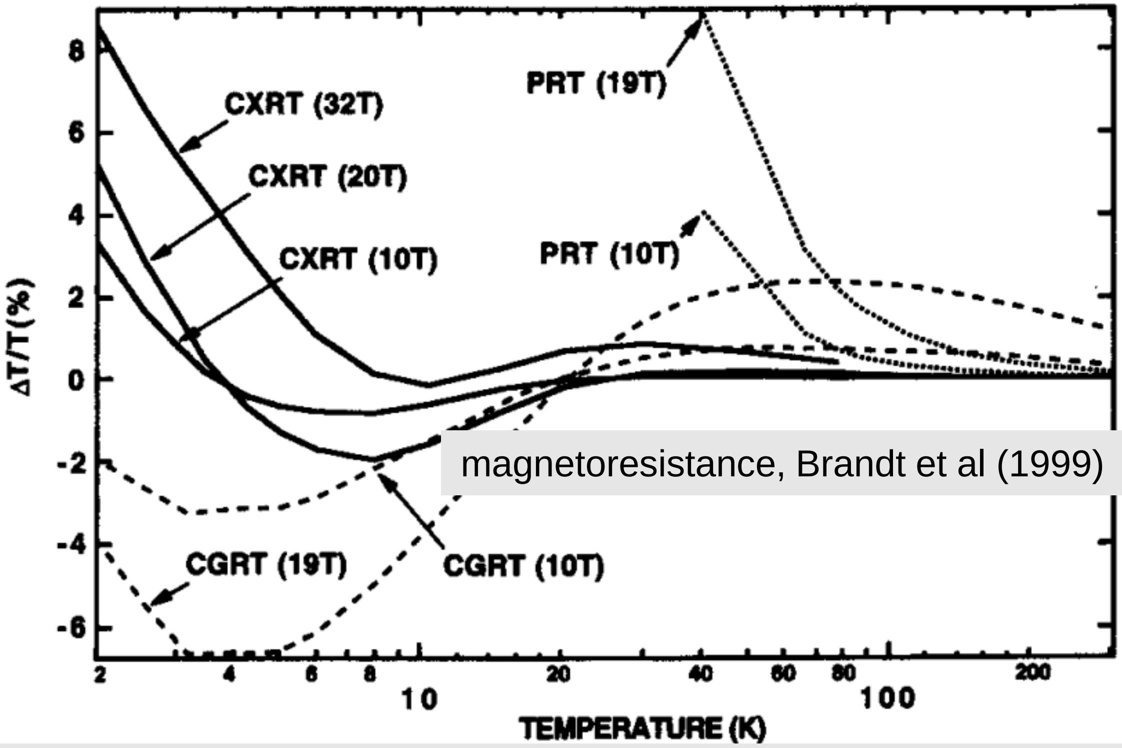
Temperature Measurement: Environmental Perturbances – magnetic field

If the magnetic field is known the temperature reading can be corrected

An individual sensor correction is preferable

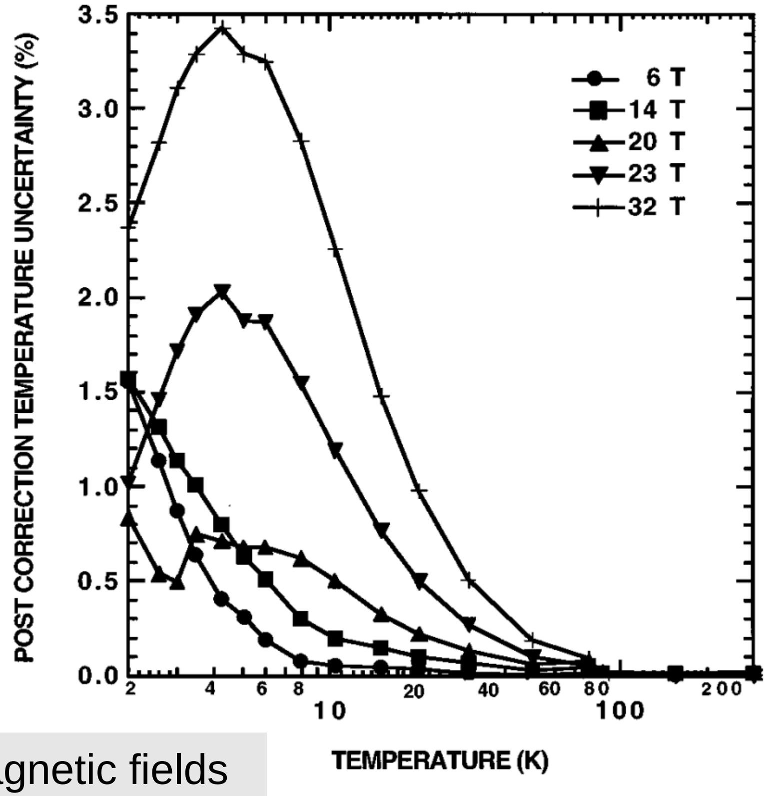
LHC stray fields are low and no effects are seen on the temperature reading.

High magnetic stray fields may exist in high current lines & magnets



magnetoresistance, Brandt et al (1999)

Error for cernox single B correction, Brandt et al (1999)



It is assumed that for other measurements the sensors can be moved away from magnetic fields

Most sensors will exhibit magnetic induced deviations

Temperature Measurement: Environmental Perturbances – Radiation

Radiation affects in a non predictable way the characteristics of any sensor.
Pre-LHC radiation qualification, several sensors were reported for radiation resistance effects; they were TVO, Allen-Bradley, Ge on GaAs, cernox…
LHC specific radiation tests were carried to understand effects from heavier and more energetic particles and thermal annealing when irradiating @ superfluid helium

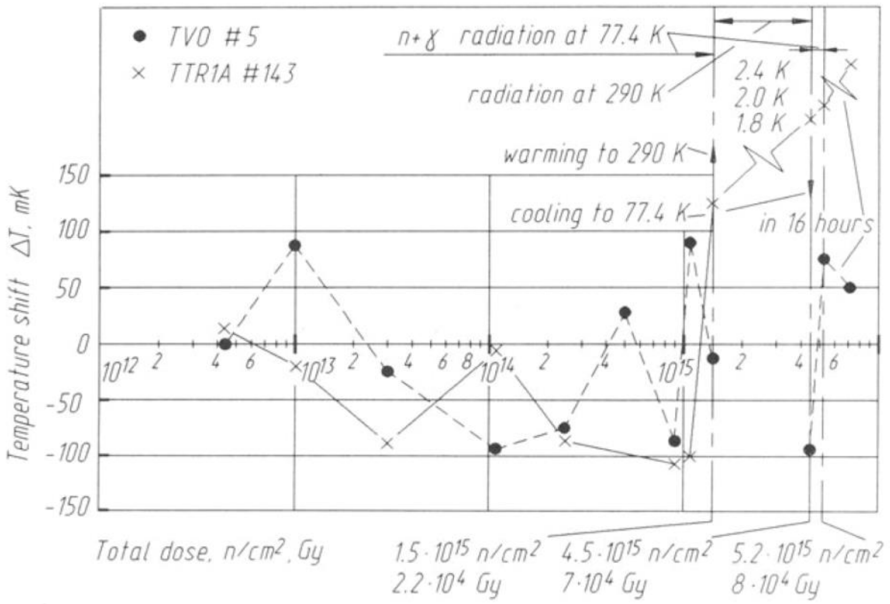


Figure 1. Temperature shift at 77.4 K due to neutron plus gamma irradiation ($7.5 \cdot 10^9$ n/cm²/s + 0.11 Gy/s) versus total dose for TVO and TTR thermometers.

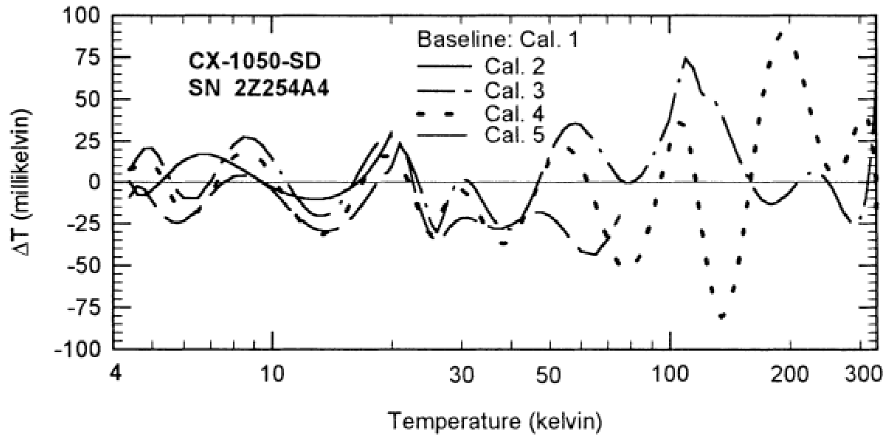


Figure 8. Calibration shift after irradiation for CX-1050-SD Cernox™ RTD, SN 2Z254A4, irradiated at 4.2 K at a flux of 7.41×10^7 n/cm2/s to a total fluence of 2×10^{12} n/cm² in a nuclear pool reactor.

Temperature Measurement: Environmental Perturbances –Radiation

Radiation tests are very demanding on resources.
Furthermore health hazards need to be tackled carefully.
Ideally radiation tests shall be done in the nominal operating conditions:

For LHC cryogenic temperature sensors it means between 1.8 & 300 K.

In the early LHC design days the radiation background was well known for the arcs.
The guidelines were:

- Arc TID x 10 = TID for DS
- Arc TID x 100 = TID for IT

Sensor shall be located according to radiation maps:

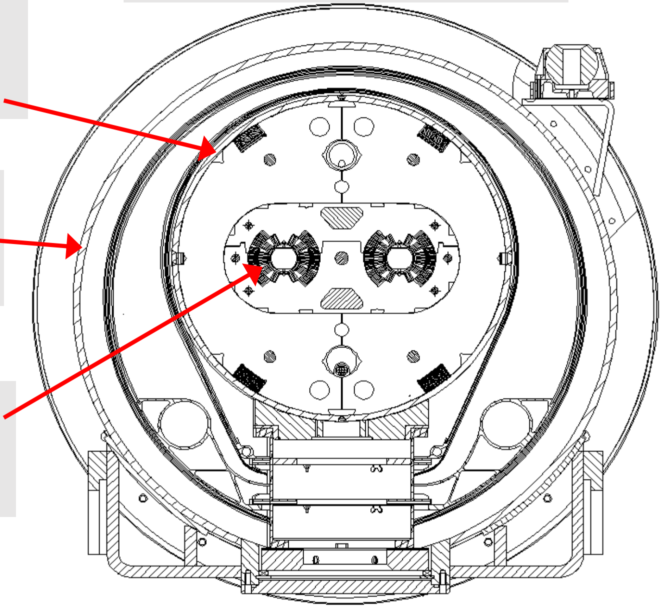
- yoke used to attenuate de TID
- Avoid areas with gaps respect to the radiation source

LHC annual dose (ARC)

300 Gy @ 25 cm
1,5 10^{13} n.cm^{-2}

60 Gy @ 45 cm
3 10^{12} n.cm^{-2}

10.000 Gy @ 6 cm
5 10^{14} n.cm^{-2}

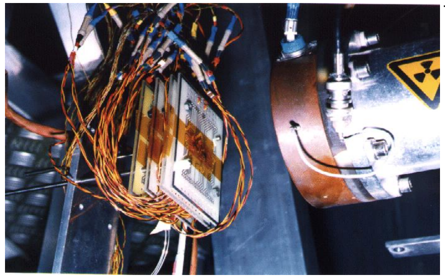


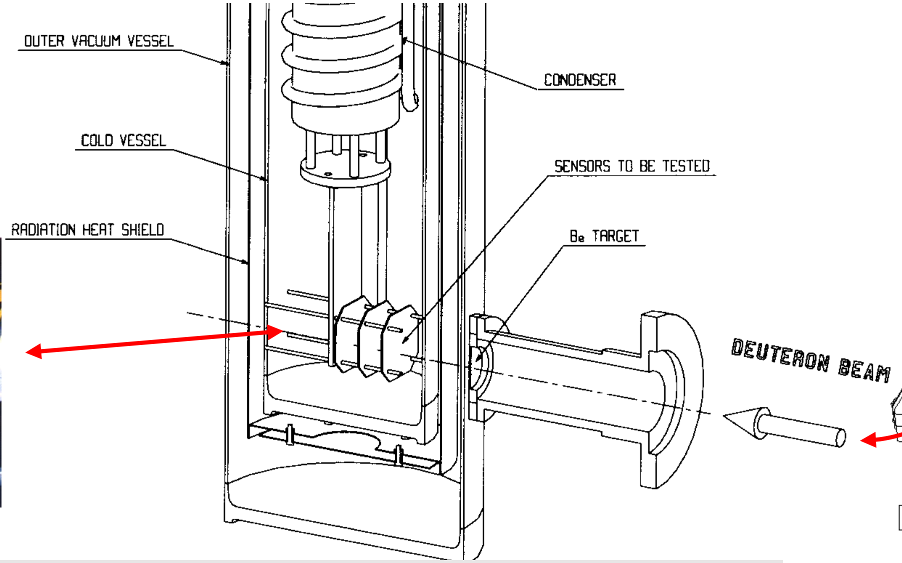
Temperature Measurement: Environmental Perturbances –Radiation

The LHC radiation qualification was performed in the SARA and CERI cyclotrons.
The test cryostat was shared between ATLAS (LAr) & CERN/tunnel (LHe).
To reduce the thermal budget the cryostat was made of aluminum

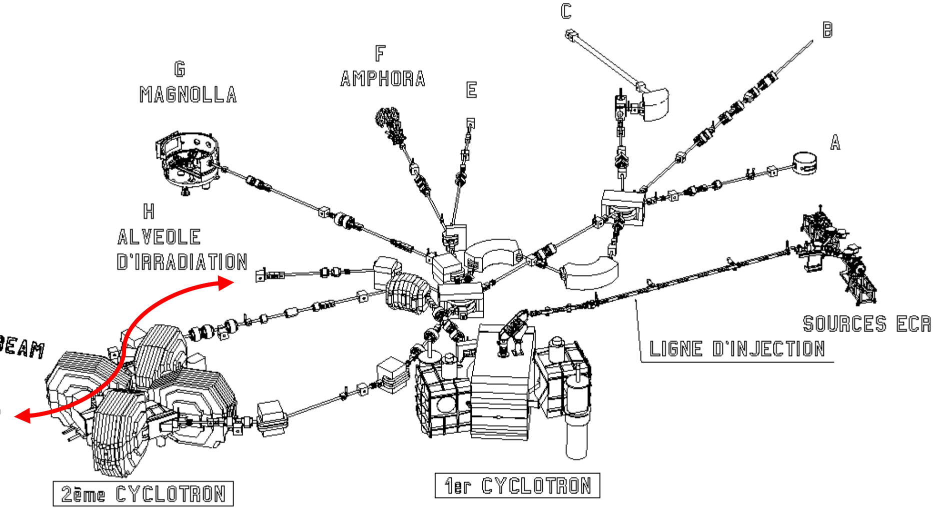
- Density much lower when compared with stainless steel
- Absorbed radiation % mass => produce heat

Operating temperature between 1.6 and 4.2 K.





LHC temperature sensors radiation qualification set-up



Cyclotrons: SARA (Grenoble) or CERI (Orleans)

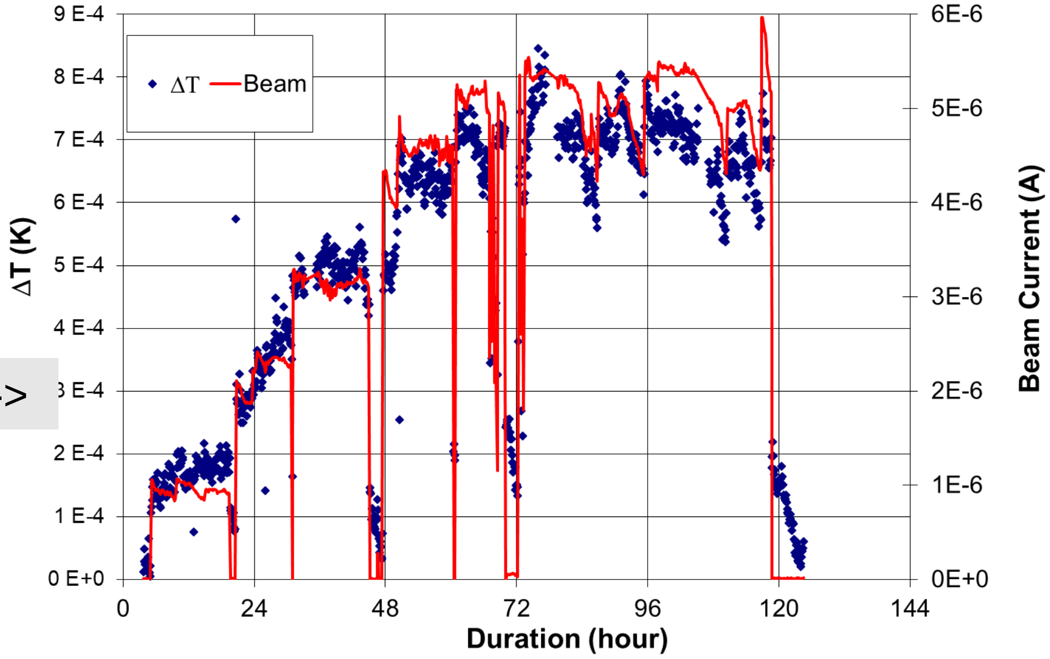
Temperature Measurement: Environmental Perturbances –Radiation

The radiation dose rate induces an additional sensor heating -> temperature rise

- Similar for a given sensor type (% mass, cross section & thermal contact)
- Can be compensated on the condition that the dose rate is known
- LHC radiation dose rate is comparatively extremely low
  - => no observable heating due to radiation

Radiation dose heating for a TVO sensor

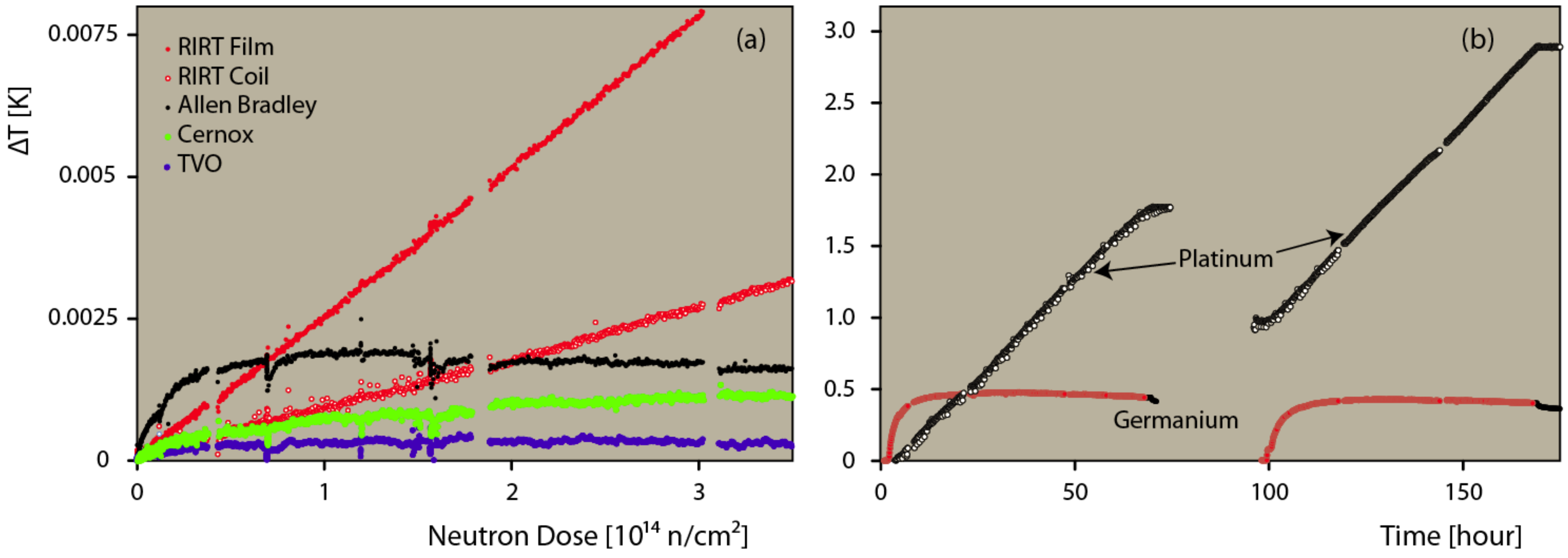
Yearly LHC radiation dose accumulated in a few hours ->



Temperature Measurement: Environmental Perturbances – Radiation

Neutron irradiation expected to cause larger damage to ordered structures:

- RIRT and platinum performance improves with stress free structure
  => neutron damage probably causes additional stress
- Allen Bradley, TVO and cernox are amorphous materials



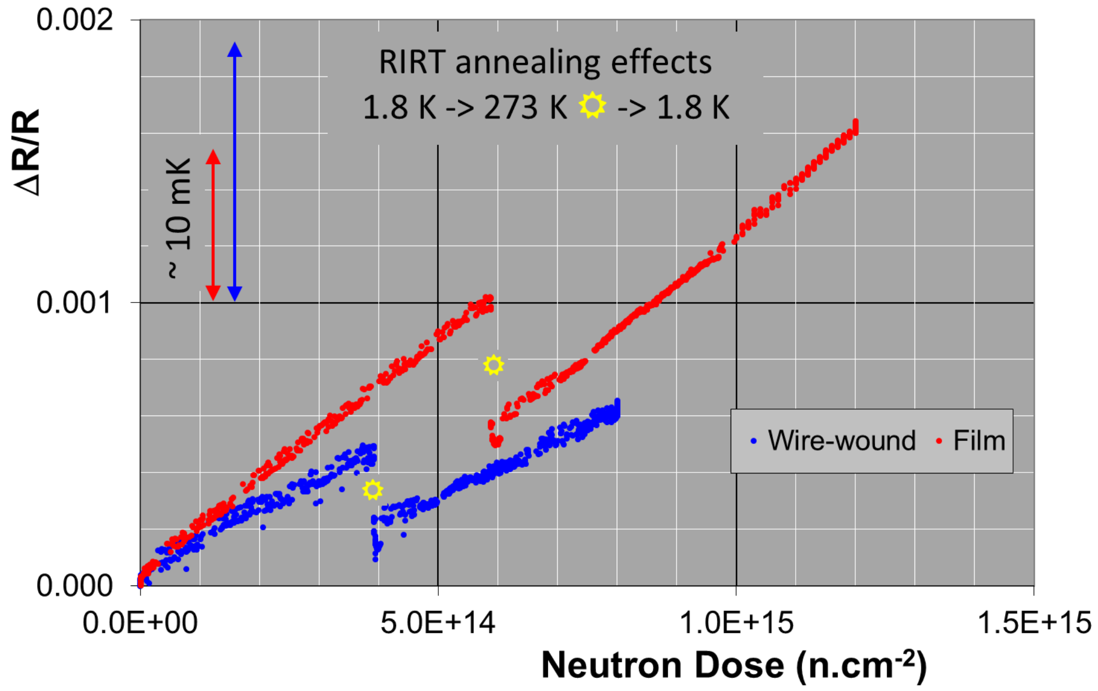
Temperature Measurement: Environmental Perturbances – Radiation

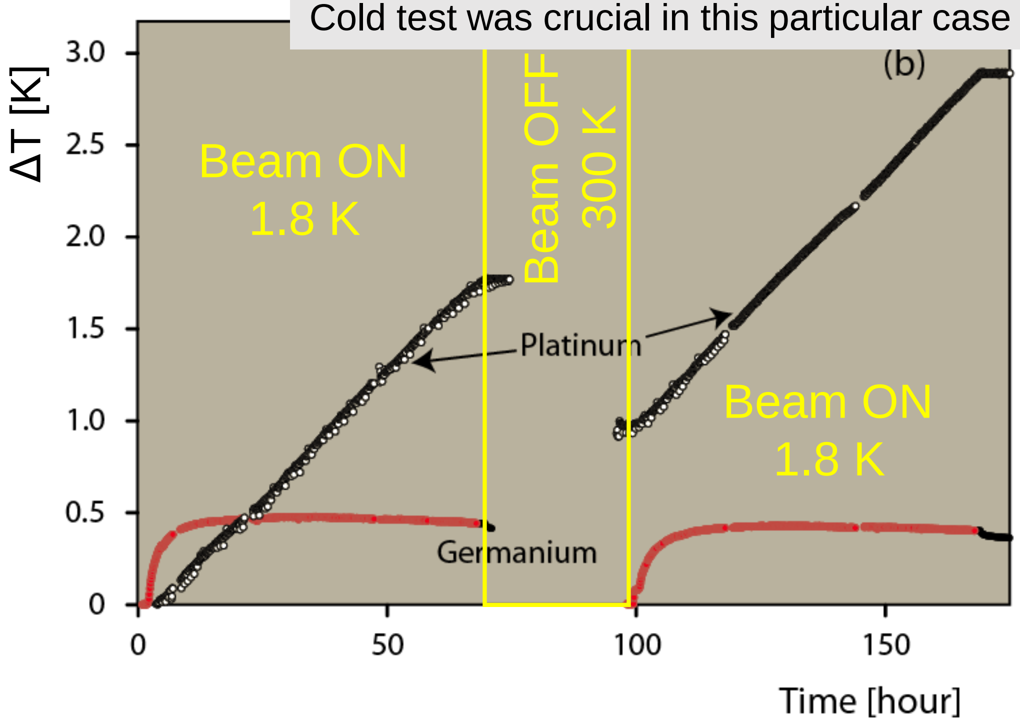
Sensor damage/drift not only depends on the Total Integrated Dose (TID)
But also in its history => Thermal annealing of defects

- Ge on GaAs (Germanium) was reported @ LN2 to be radhard; BUT
  - 1.8 K neutron irradiation provokes a very fast drift of its resistance
  - 4.2 K to 273 K completely restores initial characteristics

Thermal annealing not observed for cernox & TVO.

Ge on GaAs could have been adopted for the LHC
Cold test was crucial in this particular case





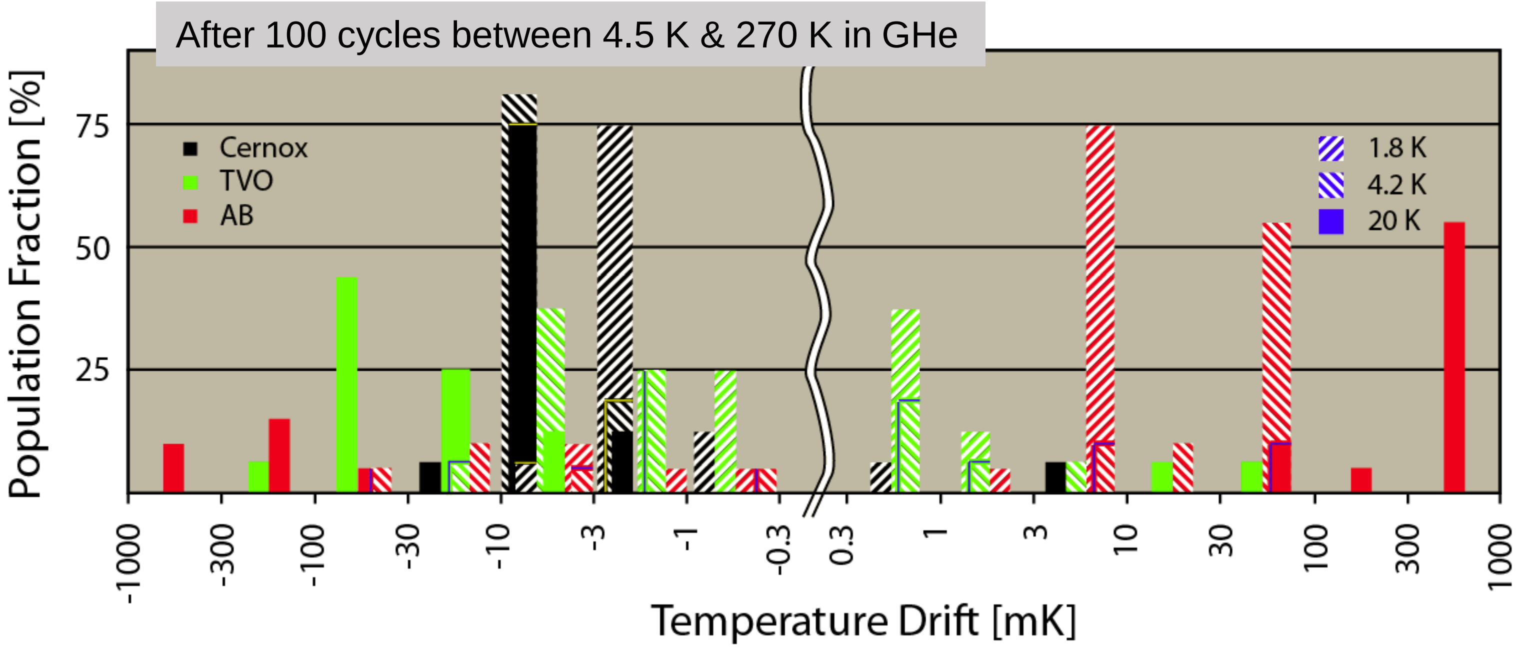
Temperature Measurement: Sensor ageing (resistive type)

Cryogenic temperature sensors may change their characteristics over time

- Historical data is very important for standard laboratories
- Thermal cycles is the accepted method for accelerated ageing
  - Shall be within the expected range of operation
- Moisture is a concern in particular for non sealed sensors
- Drift for industrial Pt100 sensor is not a concern, the standard curve (ie sensor interchangeability) is adequate for most applications.

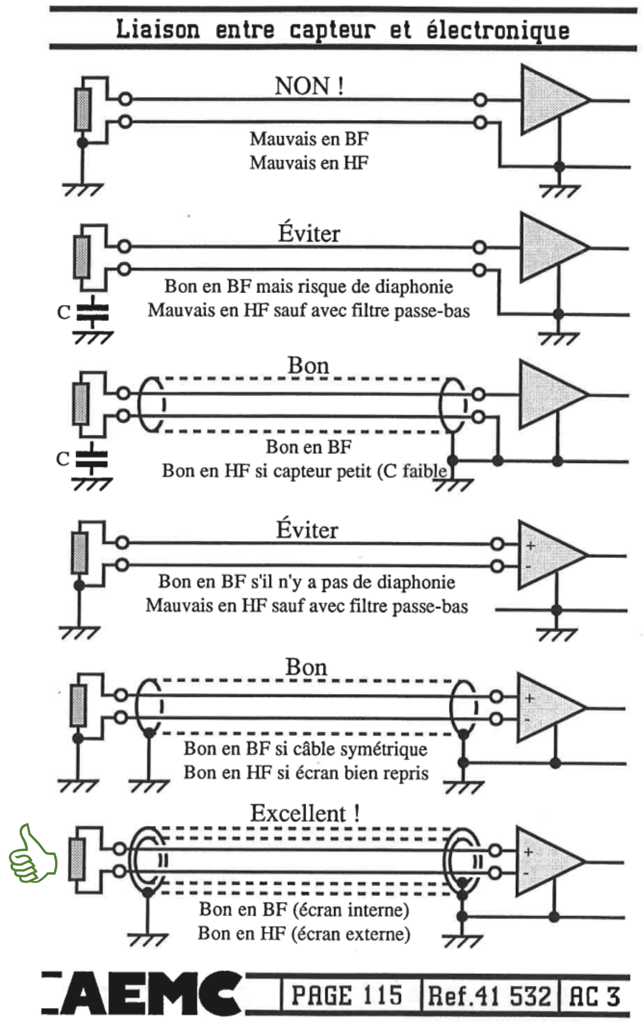
Cernox exhibits better stability with increasing temperature.

AB “improved” packaging no observable improvement.



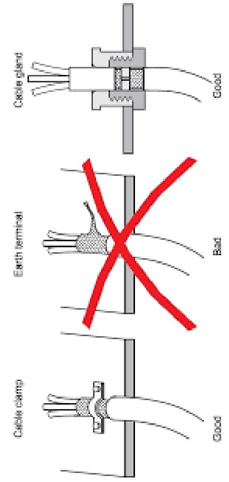
Temperature Measurement: Protection of low level signals

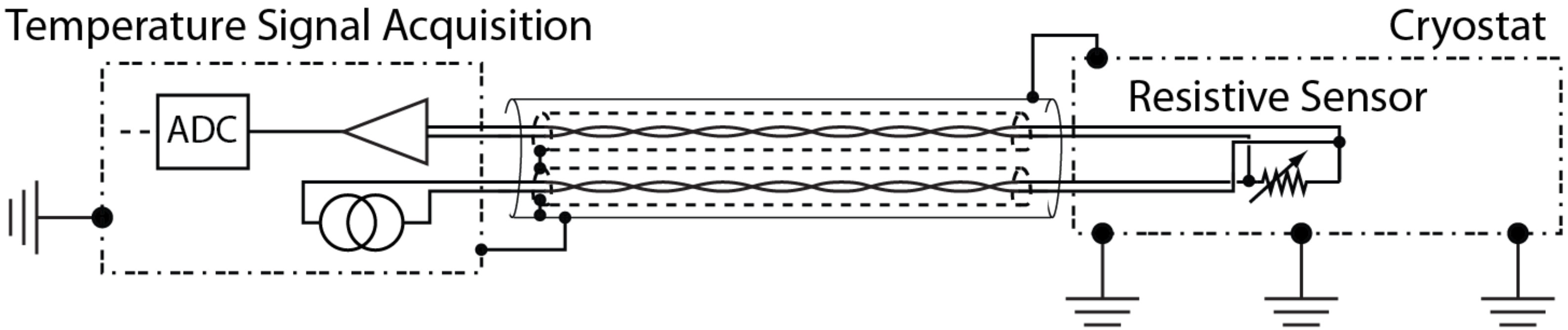
Temperature measurement: very low amplitude & usually low frequency



Electrical signals require EMC emission protection:

- Cables shielded (double shielded ideally)
  - External shield GND on both sides (HF)
    - shield taken on full circumference
    - No pigtails, it degrades immunity
  - Internal shields GND on <u>only</u> electronic side (LF)
- Twisted signal pairs
- Cryostat is a Faraday cage ⬄ no need for shields
  - Check neighbors for noise emission





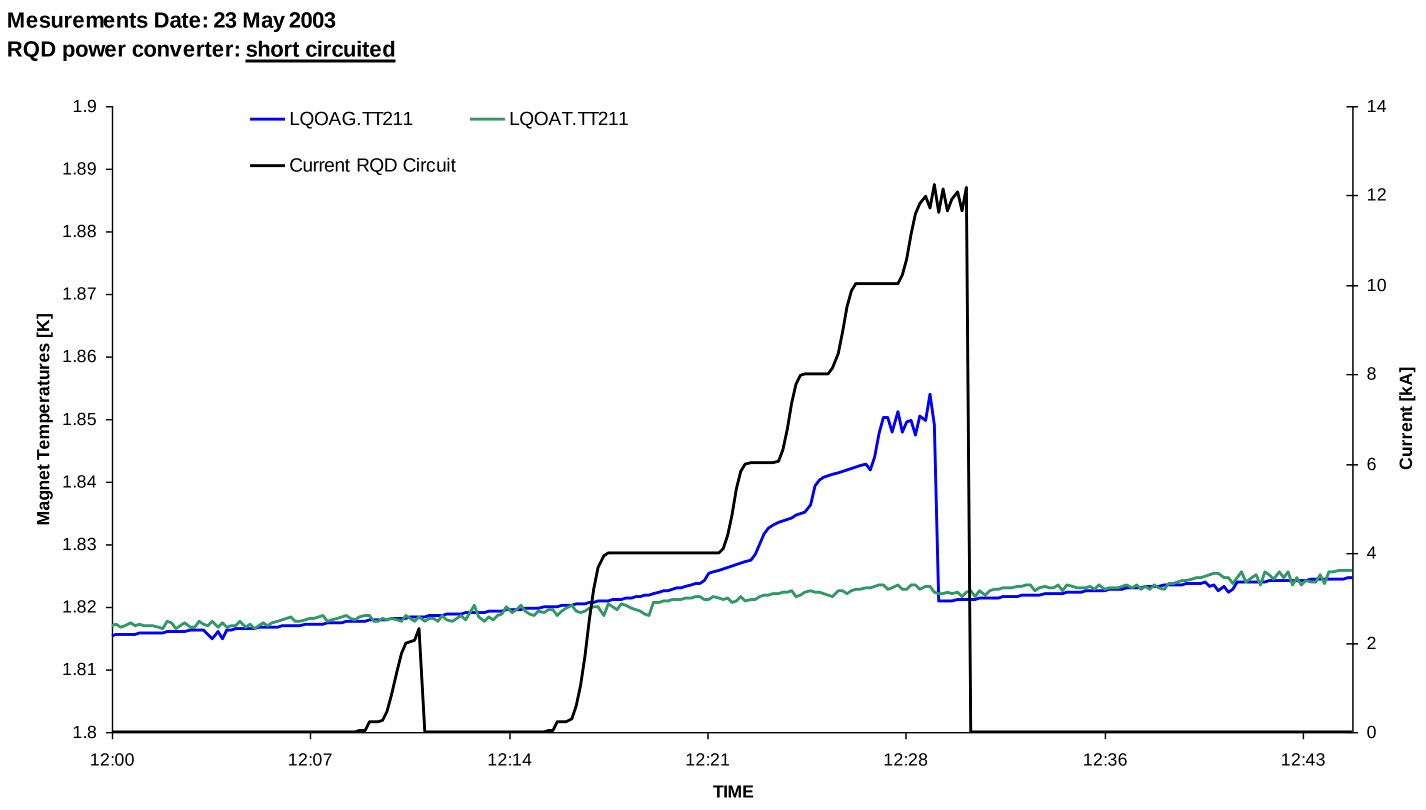
Temperature Measurement: Environmental Perturbances - EMI

SM18 – String test (2006)

Cross talk from magnets current => erroneous 30 mK temperature increase

Solution: power converter filter circuit modified

Most probably cross-talk happens inside the LHe magnet vessel

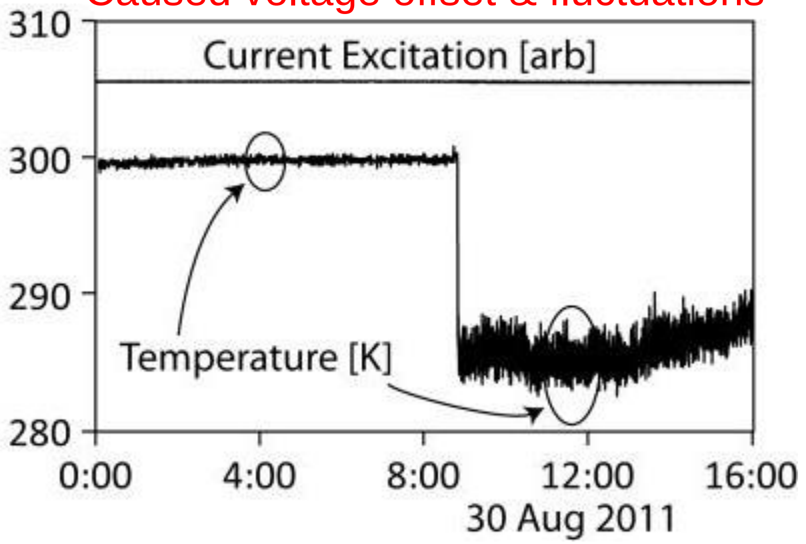


Temperature Measurement: Environmental Perturbances

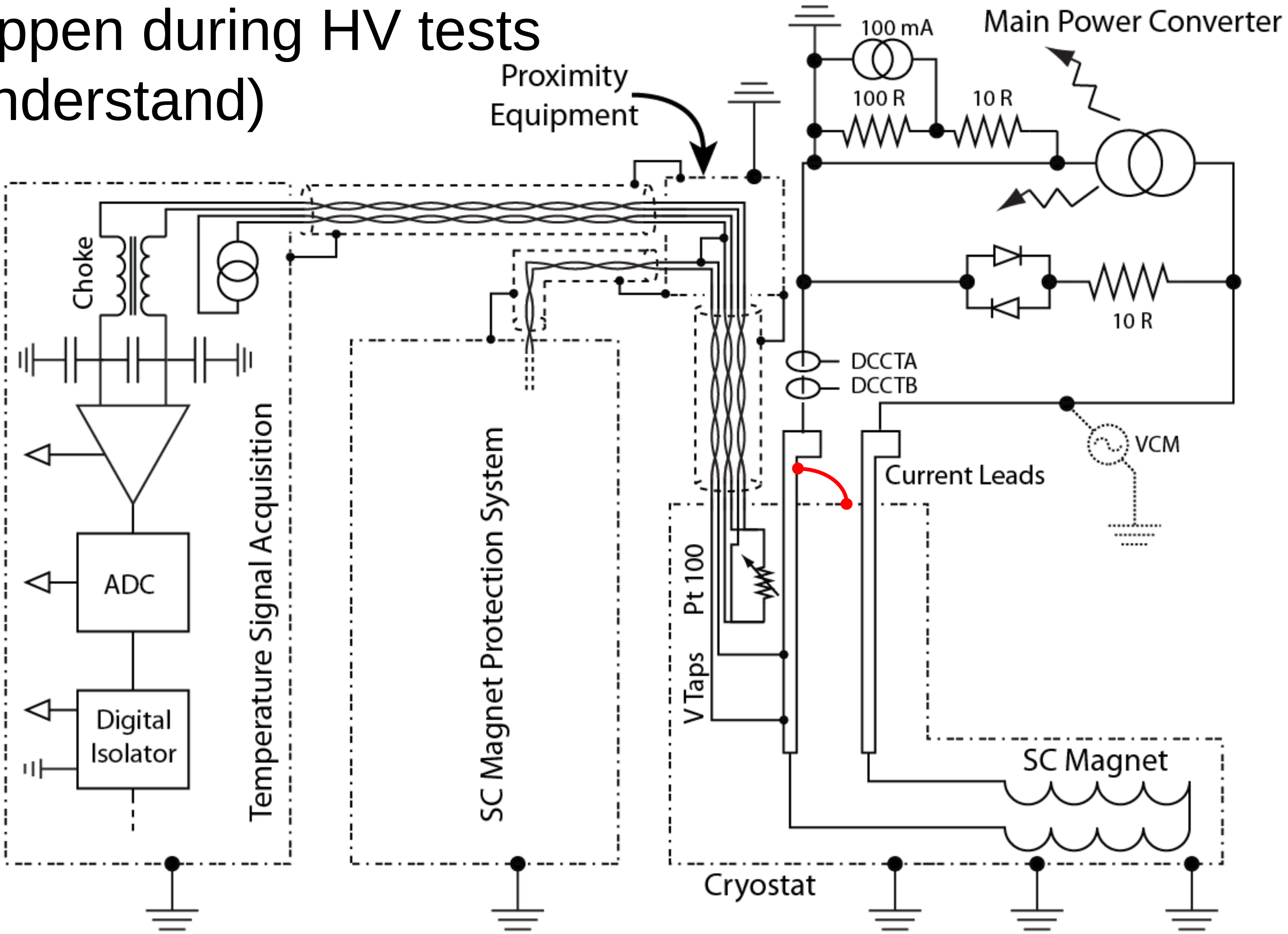
LHC case: shared grounds with power converter and quench protection

- May result in collateral damage (sensor, electronics, ..)
  - Dielectric breakdown can happen during HV tests
- Can result in noise (difficult to understand)
- May require additional filtering

Temporary GND connection
Caused voltage offset & fluctuations



a.c. noise => non-linearity => d.c. offset!

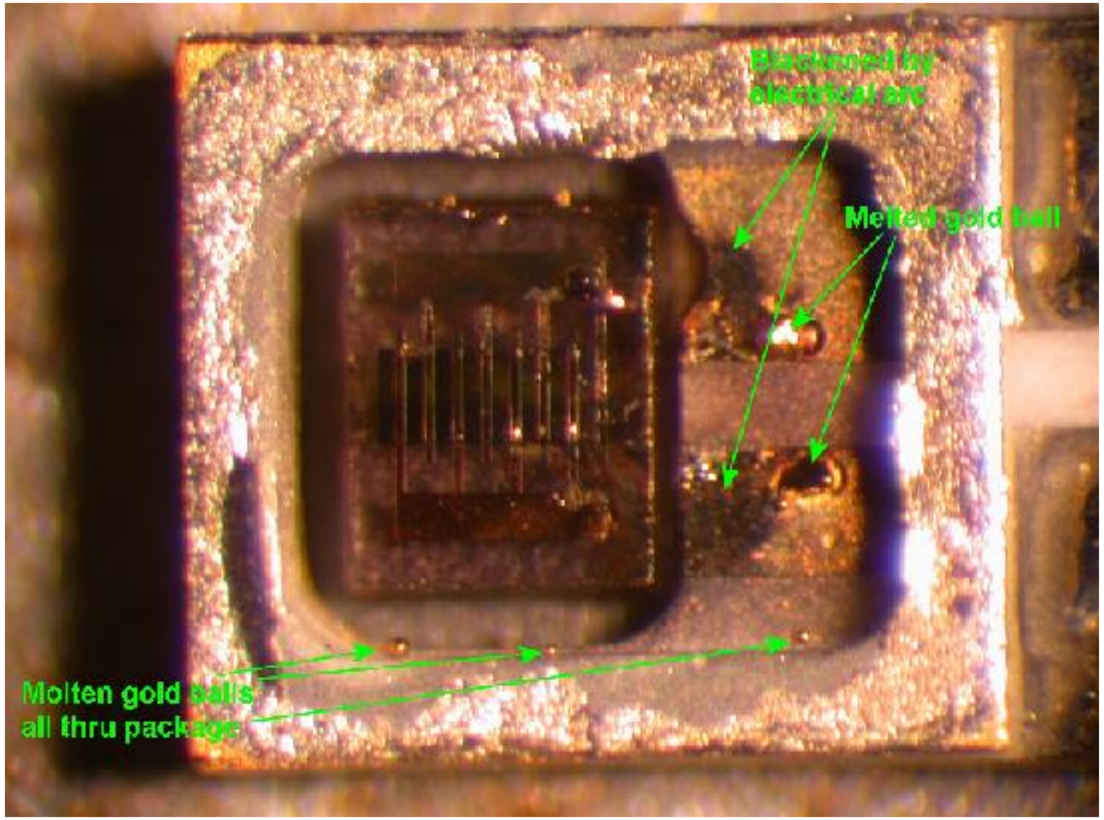


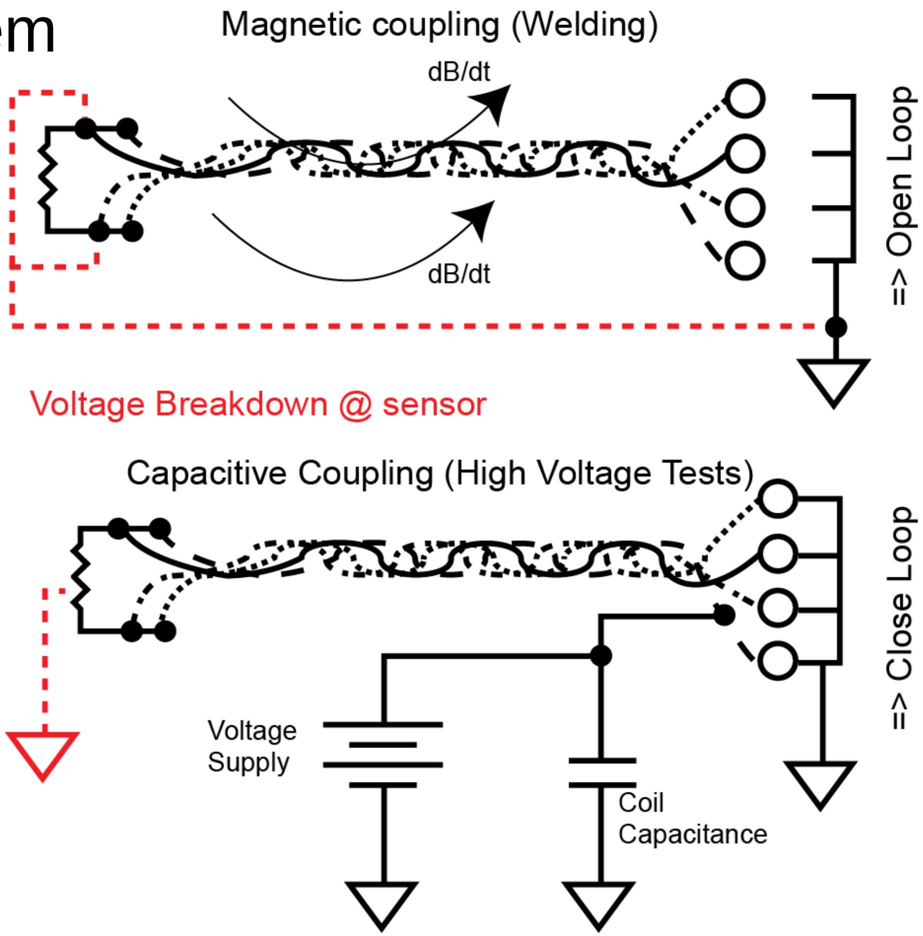
Temperature Measurement: Catastrophic Events

During the assembly of the LHC magnets, sensors were destroyed during:

- LHe vessel longitudinal welding (magnetic coupling)
- HV coil tests (capacitive coupling)

=> Appropriate procedure mitigated the problem



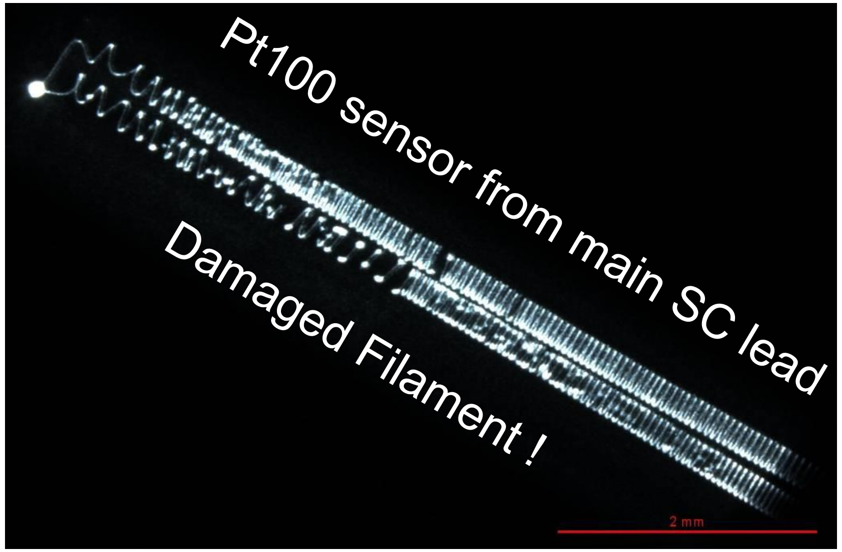


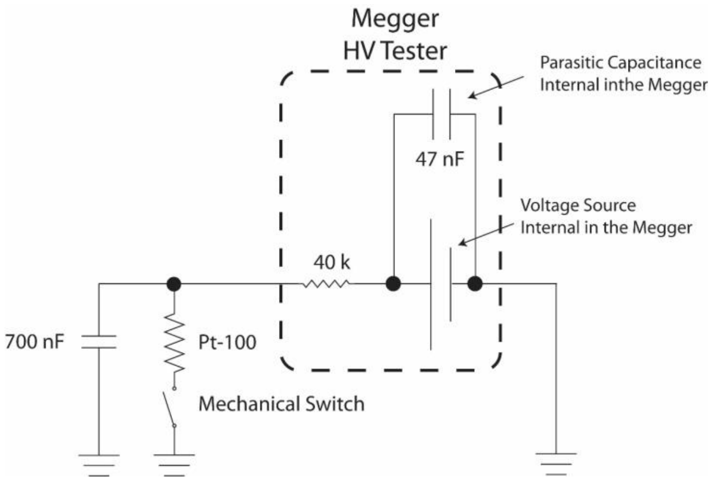
Temperature Measurement: Catastrophic Events

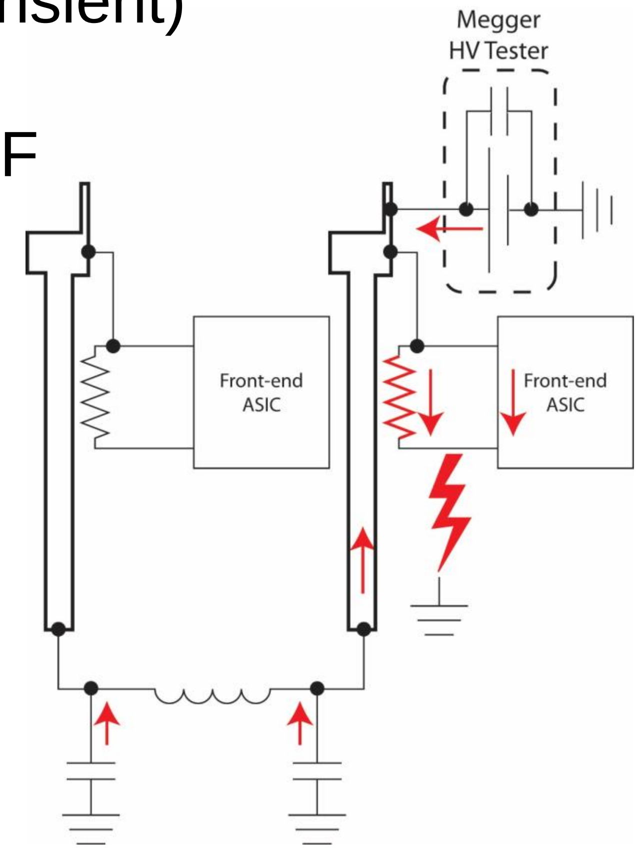
Routine high voltage tests on LHC circuits may destroy a temperature sensor:

- Platinum filament is about 2 µgr
- 2041 K is the melting temperature of platinum
    - => 0.45 J to melt 2 µgr in adiabatic conditions (fast transient)
    - Verified experimentally in the lab with 700 nF
    - Magnetic circuits stray capacitance: 700 nF up to 50 µF

=> “HOT” lines shall provide adequate voltage insulation



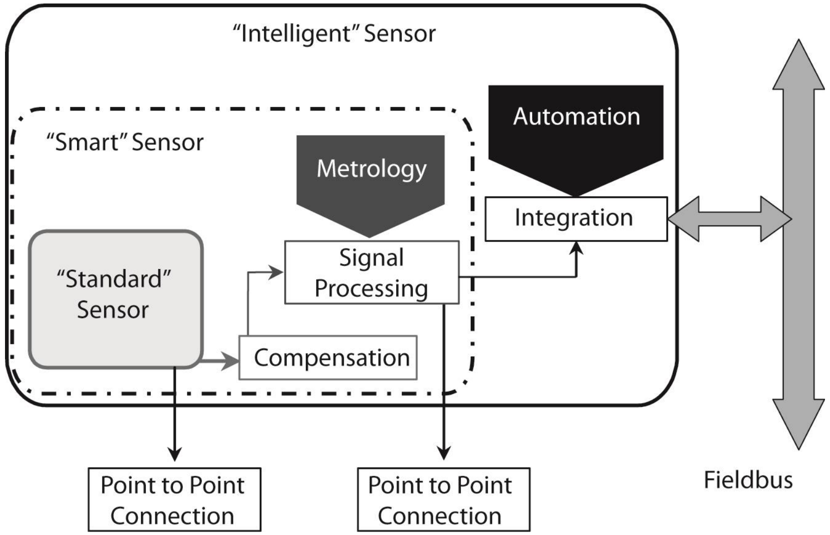




Temperature Measurement: Signal Conditioning

Resistance based temperature sensors electronics & processing:

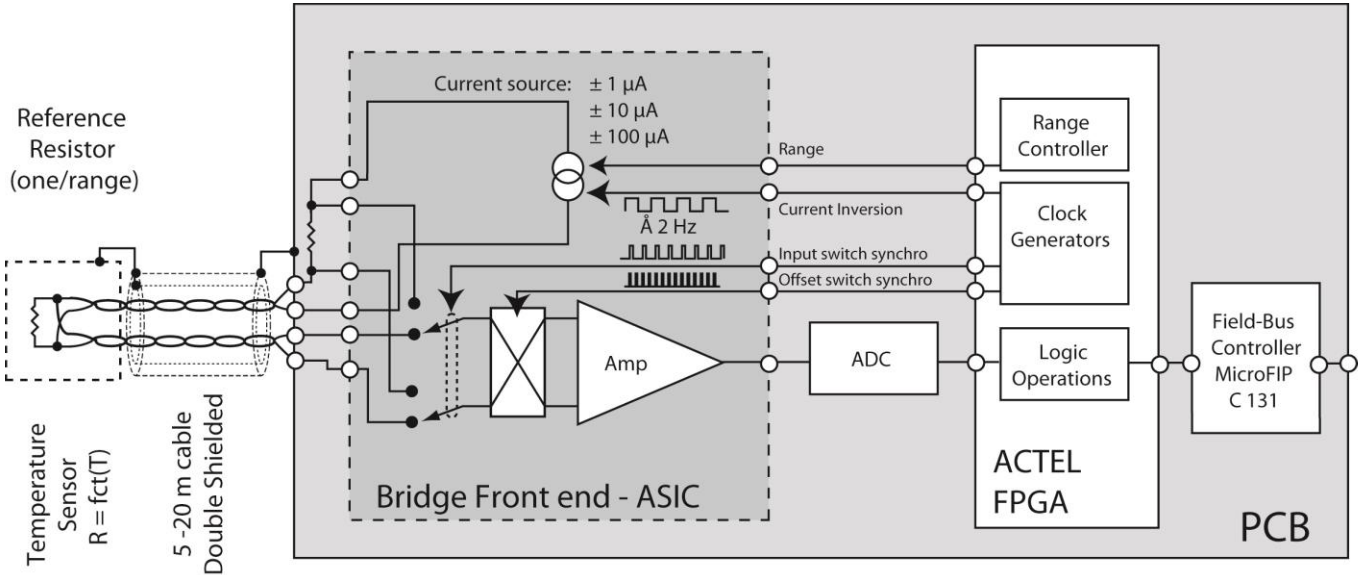
- Thermo-voltage compensation (variable excitation current)
  - It can be in the range of tens of µV
- Low excitation current (otherwise sensor self-heating need compensation)
  - Repeatable self-heating temperature increase (varies slightly from sensor to sensor)
- Low noise amplifier
- Typically some analog to digital conversion (ADC, analog to time,..)
  - or analog output (4-20 mA, 0-10 Vdc, ..)
- Resistance to temperature conversion
  - CERN:
    - calibration data stored in a database
    - Calibration data automatically loaded during control system configuration

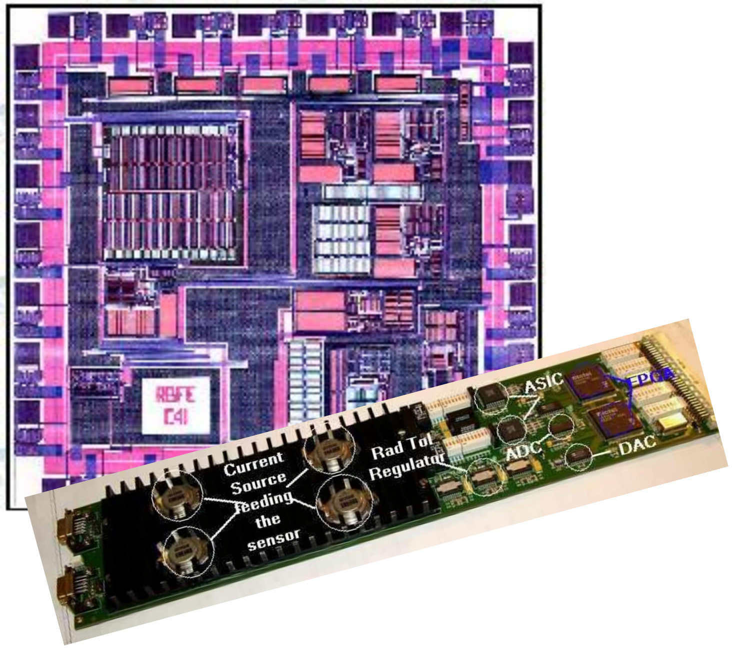


Temperature Measurement: Signal Conditioning

Measurement of resistance based temperature sensors is based on a comparison bridge:

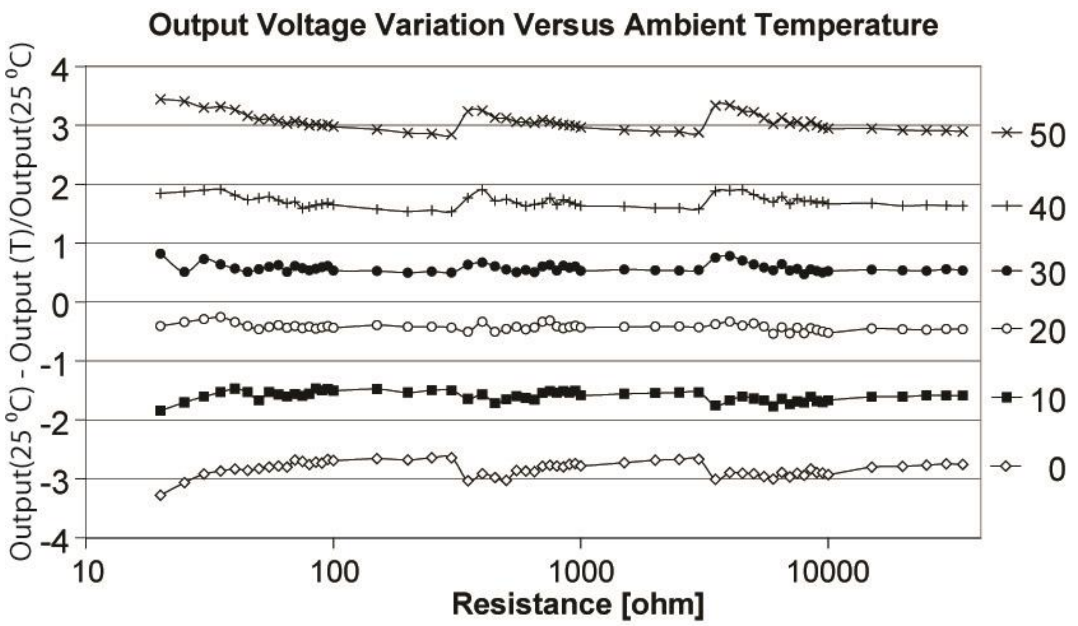
- Comparison resistor
  - low temperature drift (10 ppm/^{o}C) & RadHard
  - repeatable resistor value (< 0.1%) avoids individual adjustments
- Non linearity on amplifier or ADC cannot be compensated

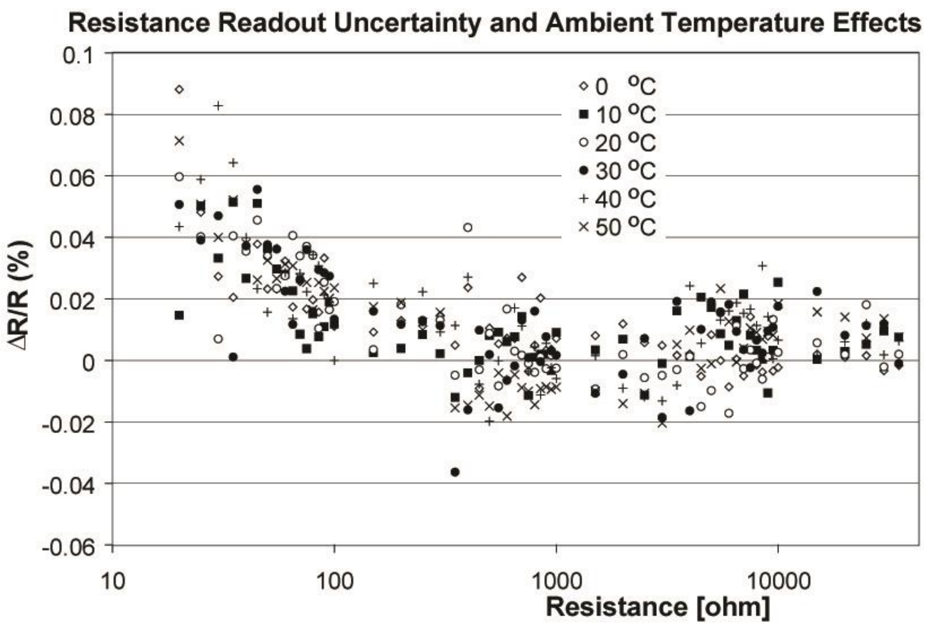




Temperature Measurement: Signal Conditioning

Electronics shall be compatible with the LHC tunnel environment (DS & ARC).
For analog circuits effects from temperature and from radiation are very similar.
Robustness of comparison bridge method permits to sample the sensor resistance within better than 0.25% in spite of gain variations exceeding +/- 3%.

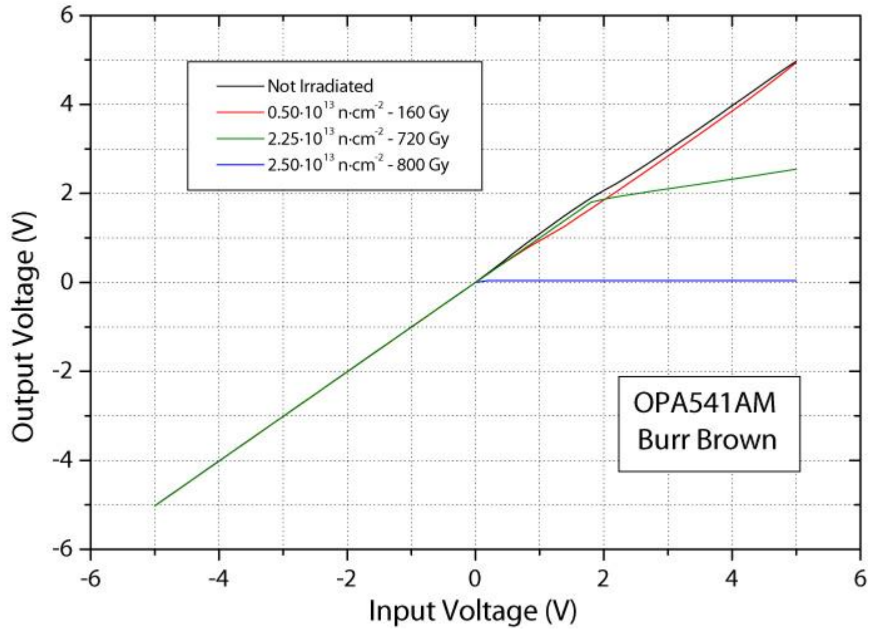


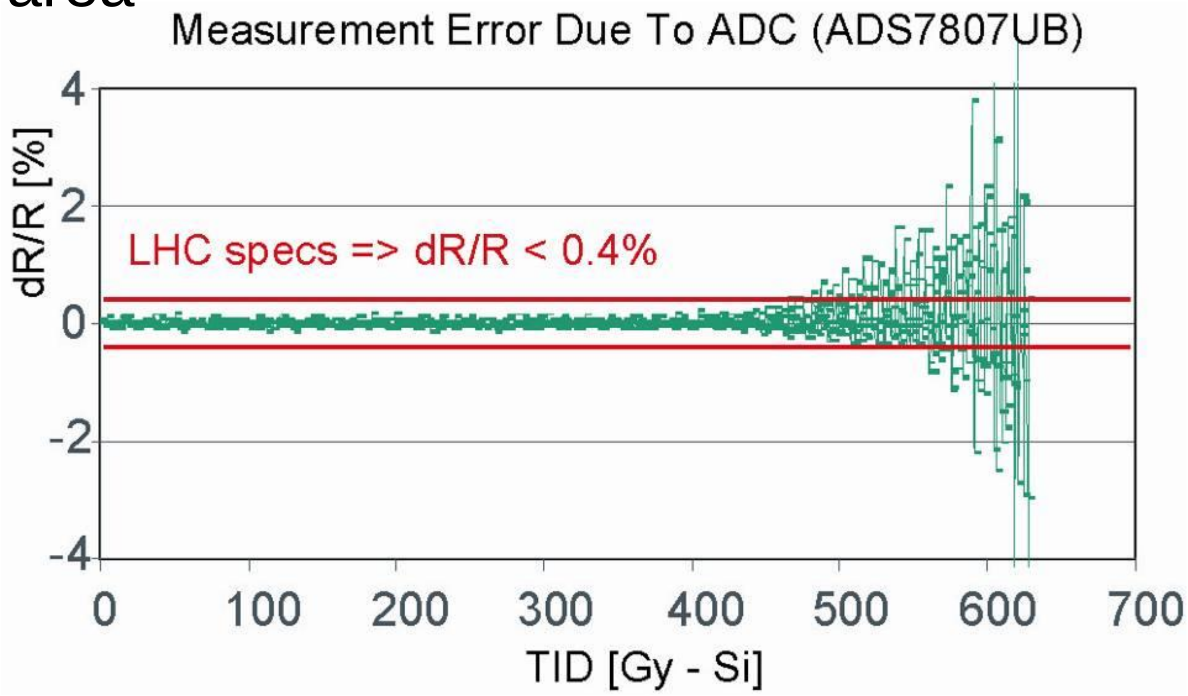


Temperature Measurement: Signal Conditioning

Radiation qualification campaign shall test every single component:

- CERN TCC2: radiation of passive components
- Radiation effects are observable on analog and mixed digital-analog integrated circuits
- 1 kGy was the target for operational accumulated radiation dose
  - Verified in the CHARM irradiation area

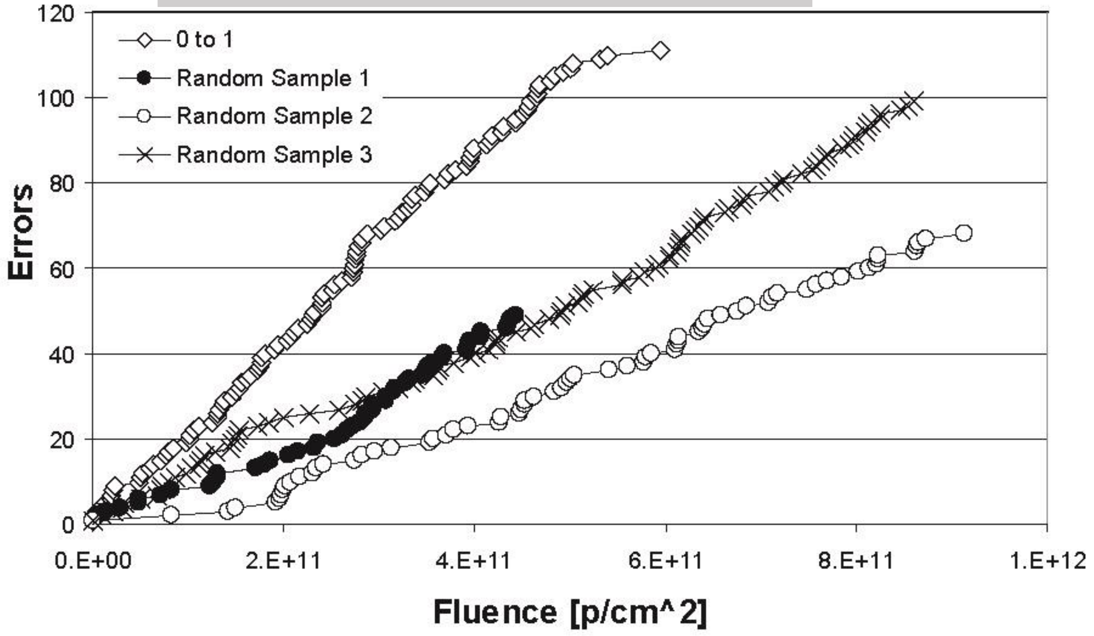


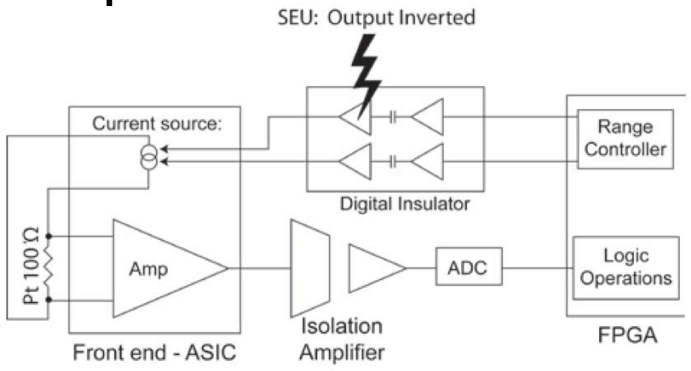


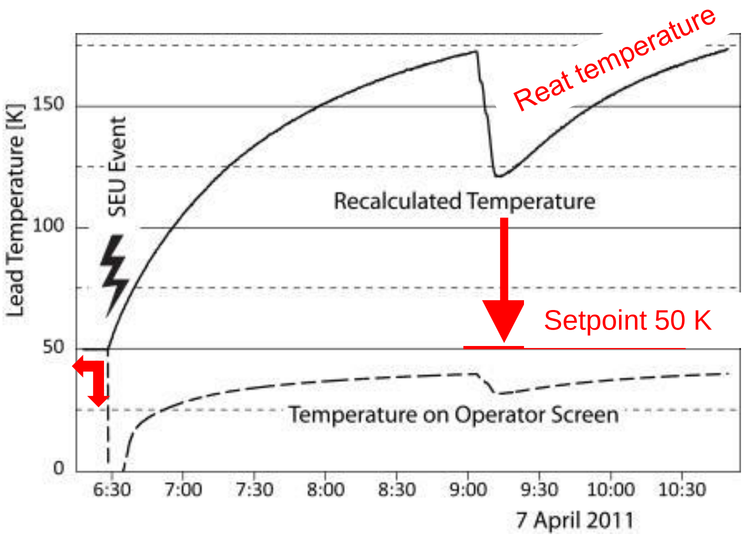
Temperature Measurement: Signal Conditioning

Single Event Effects (SEE) happen in digital circuits, may be catastrophic (mainly for power components) or produce soft errors.
Soft errors may provoke anomalous readings on the operator screens.

Soft errors on WFIP memory





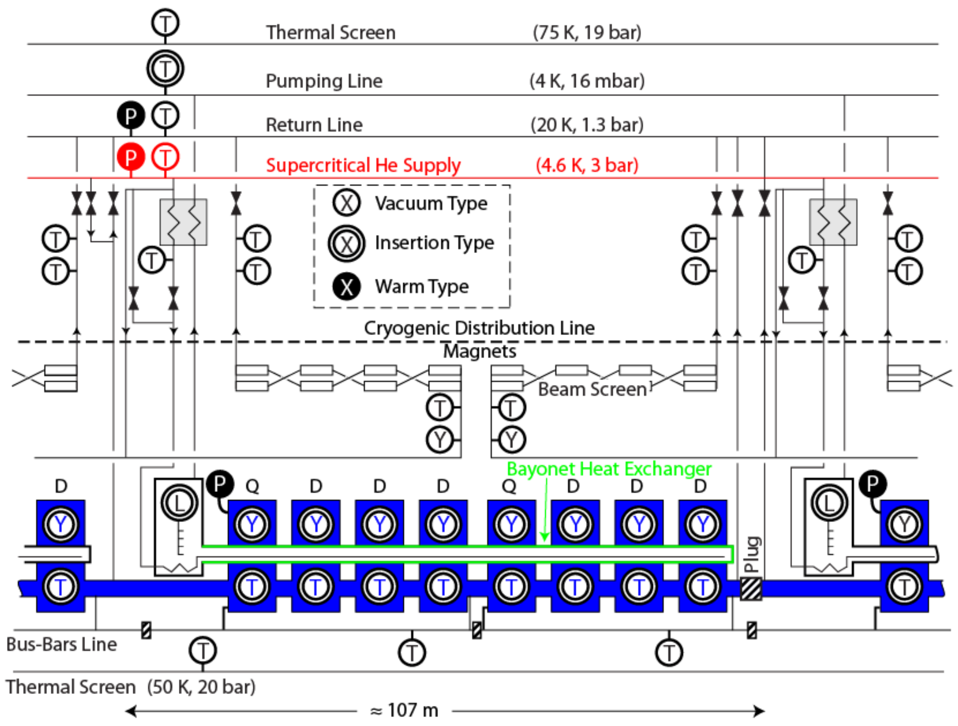


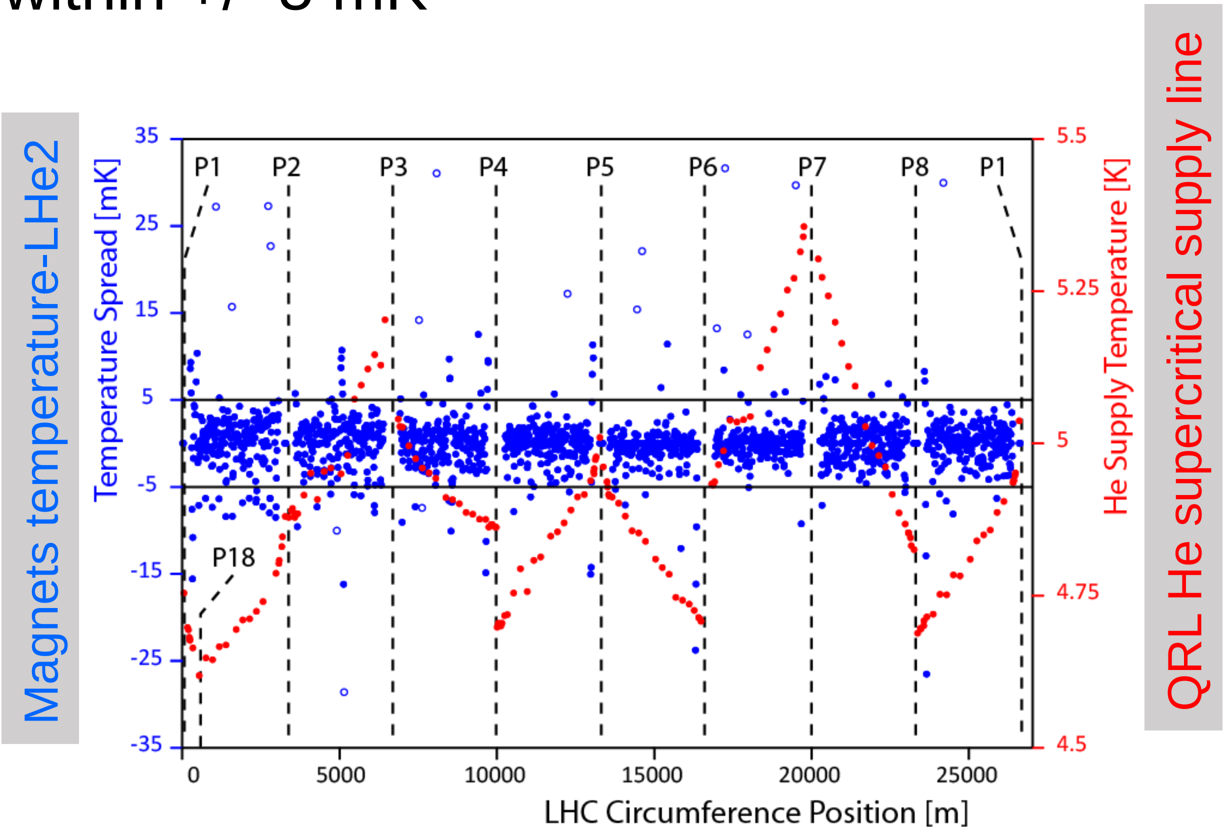
Temperature Measurement: The full picture

It is impossible to check or recalibrate the LHC sensors, however for the cold mass they are immersed in superfluid helium:

=> in between plugs the temperature is ~ isothermal

=> Most 1600 cernox sensors are within +/- 5 mK





Liquid level Measurement: Techniques

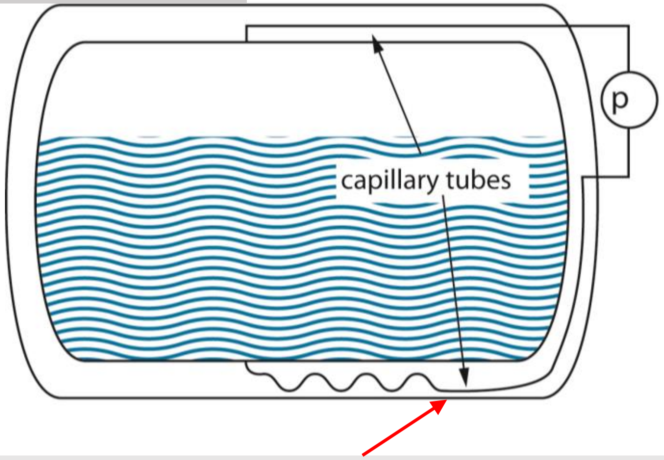
Hydrostatic head is probably the most robust method for large reservoirs:

$$\Delta p = \int_{Bottom}^{Top} \rho(h, T(h), p(h)) \cdot g \cdot dh$$

Capacitance mainly applicable to liquid nitrogen (gas & liquid He have similar ε)

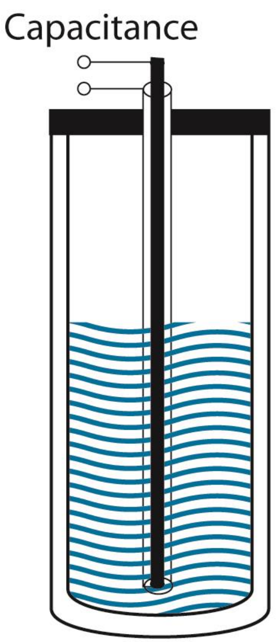
$$C = C_L + C_V = 2 \cdot \pi \cdot \varepsilon_0 \cdot \frac{\varepsilon_{rL} \cdot h_L + \varepsilon_{rV} \cdot h_V}{\ln\left(r_1 / r_2 \right)}$$

LHe: 👍 LN2: 👍

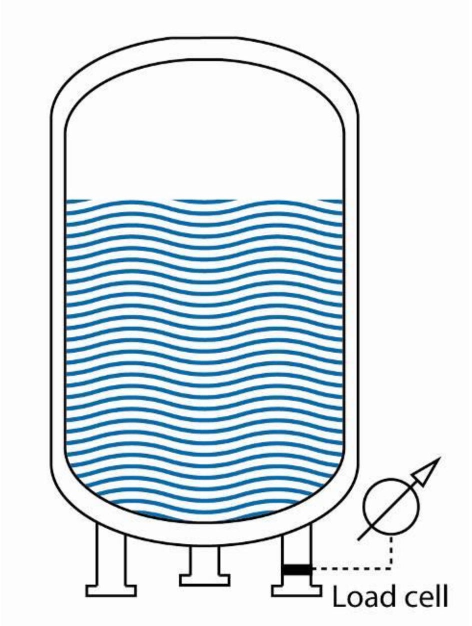


Liquid shall no go up the bottom capillary!
Design not so trivial.
Assumes density vapor << liquid

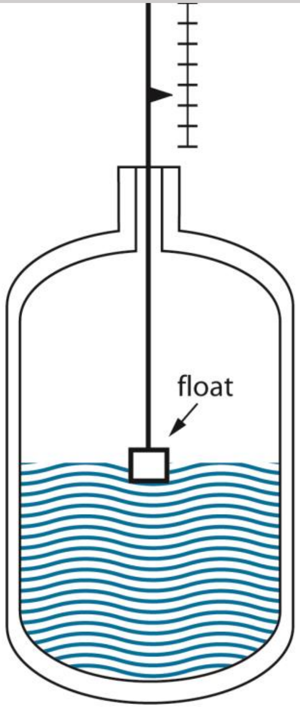
LHe: ? LN2: 👍



LHe: ? LN2: 👍



LHe: 👎 LN2: 👍



LHe level Measurement: Techniques

For a depth exceeding 1 m the best is to use the hydrostatic head.

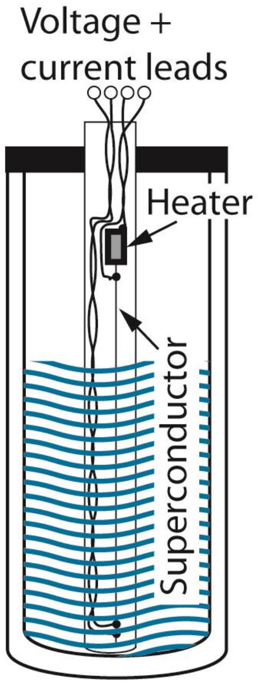
Superconducting level gauges are widely used

- They work as a variable resistor

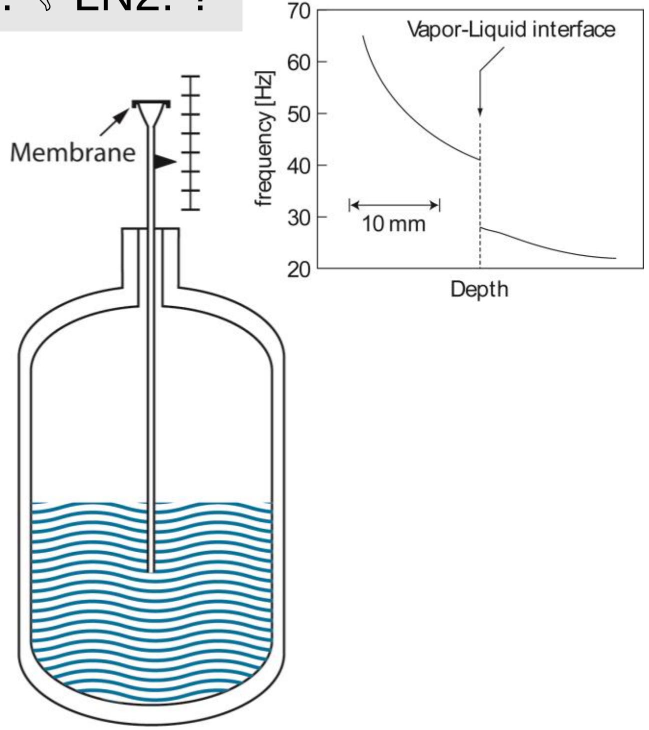
Membrane based level gauges are a cryogenic laboratory curiosity

- Based on thermo-acoustic oscillations
- Audible sound pitch change suddenly on gas-liquid interface
- Among the sole applications where thermo-acoustics are welcomed!

LHe: 👍 LN2: 👎



LHe: 👎 LN2: ?



LHe level Measurement: superconducting wire

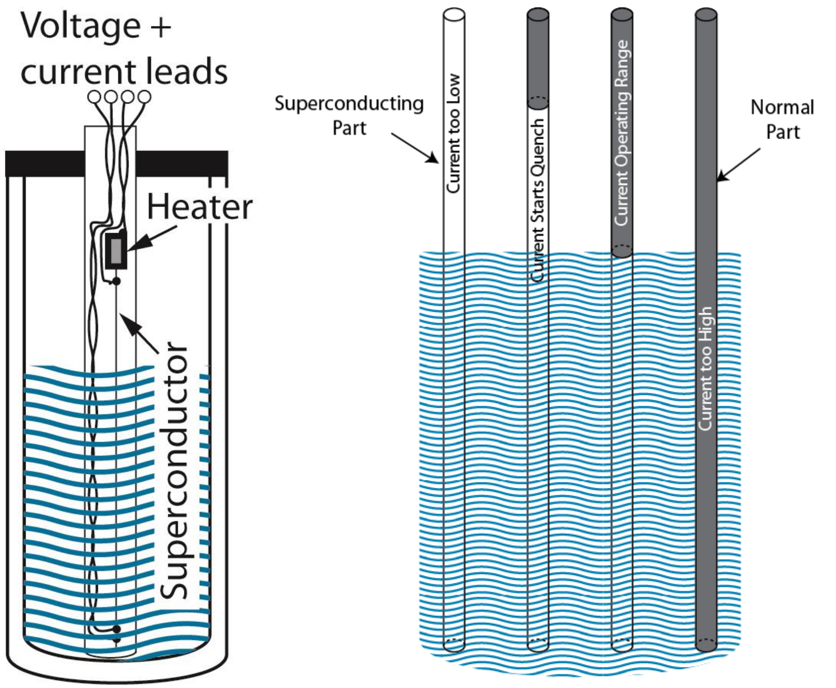
Liquid helium level can be measured with a superconducting wire, it behaves as a variable resistance.

- Immersed => superconducting => R= 0 ohm
- In gas => normal wire => R= length x ohm/cm

On the gaseous part the excitation current shall be “high” enough to propagate the quench (destruction) of the superconducting state.

On the liquid part the excitation current shall be “low” enough to not propagate the quench.

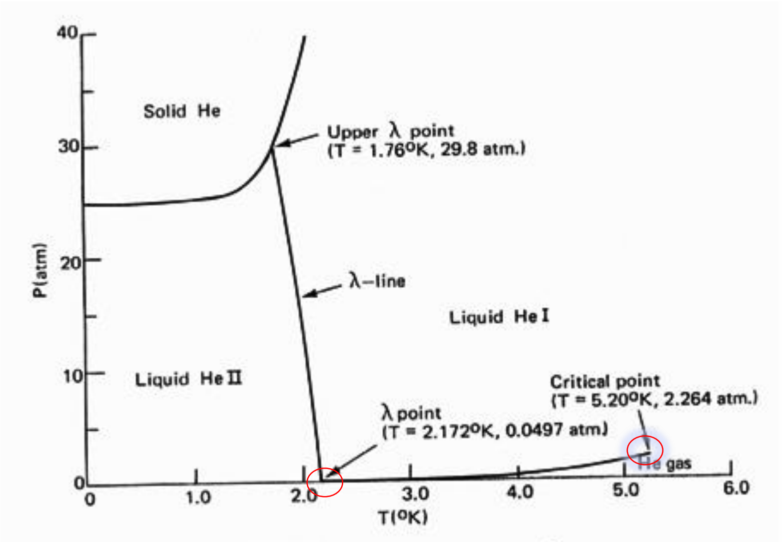
Excitation current has a narrow range of values.



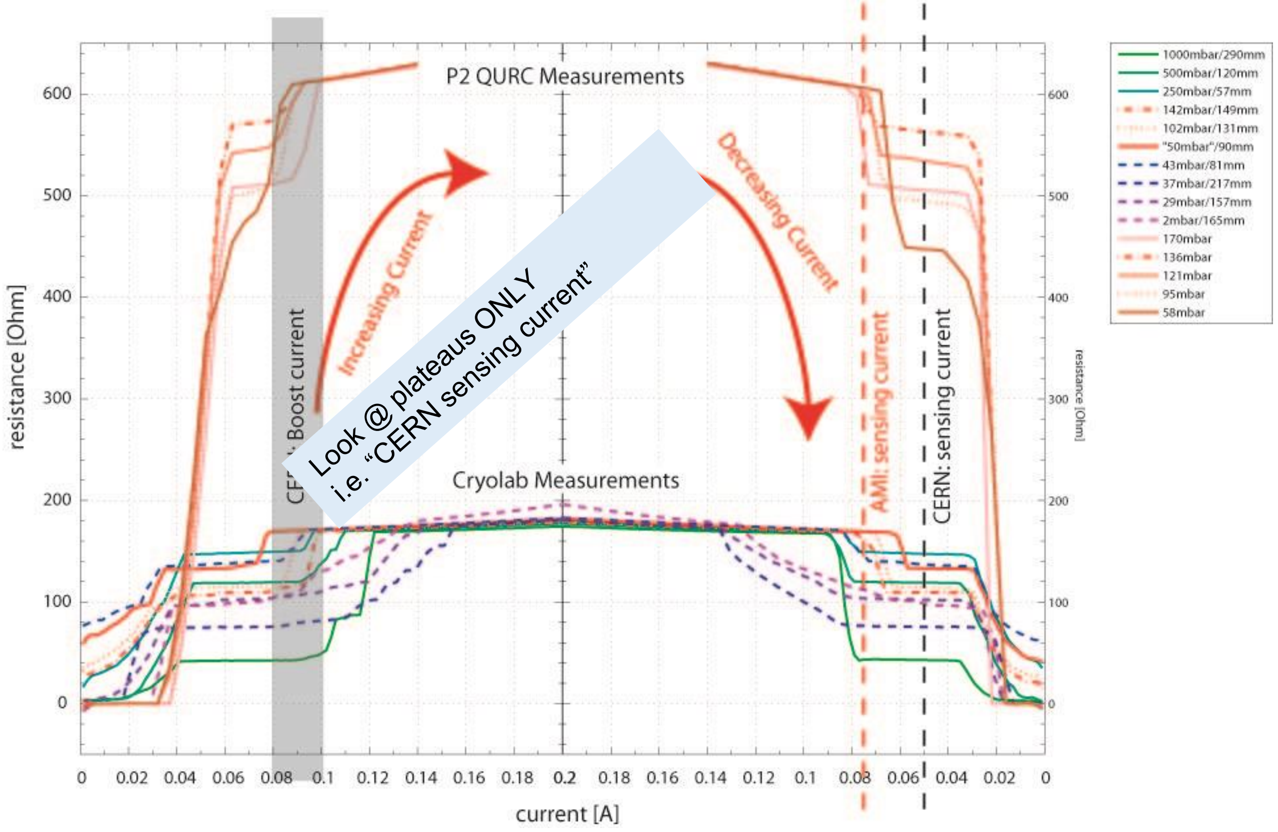
LHe level Measurement: superconducting wire

Optimal operating conditions depend on:

- the superconducting wire diameter
- the heat exchange with gaseous & liquid helium
  - !! @ 50 mbar (λ transition)
  - !! approaching critical point



The phase diagram of He^4.

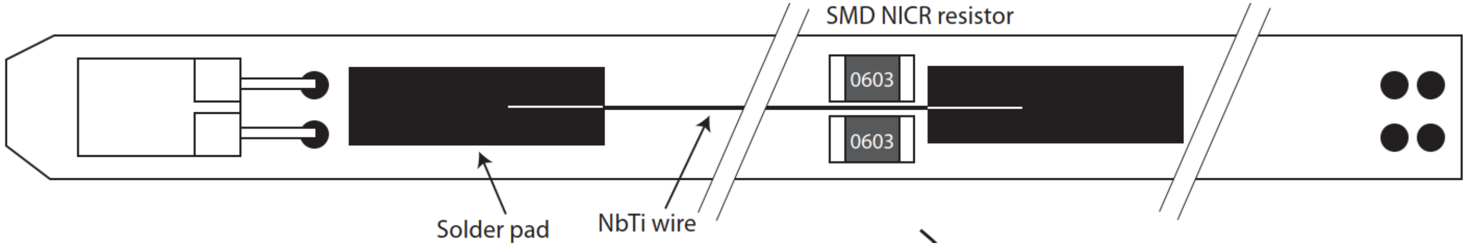


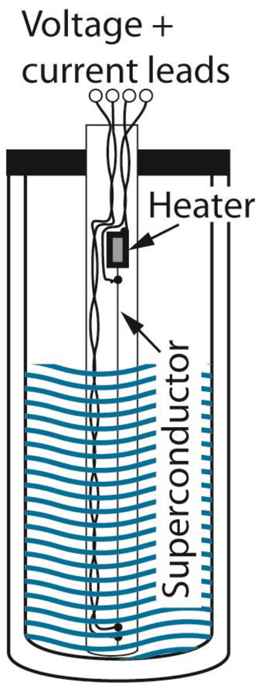
LHe level Measurement: superconducting wire

For measuring liquid helium level a NbTi SC wire is used

- Typical wire diameter: 50 µm
  - Critical field @ 4.2 K is about 8 T => current to quench 800 A!
  - Critical current density limit is about 7 A @ 3T, maybe 60 A @ 0T
- Typical measurement current is about 50 to 80 mA
  - ? How can the wire be quenched????

- Heating resistor is absolutely required
  - Need to raise temperature above 10 K (NbTi T_c)
  - Wire resistance in the normal state: typ 0.3 Ω/mm
  - Quench is propagated by exceeding a certain heat flux

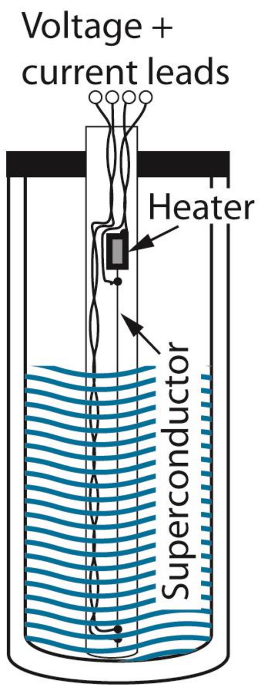


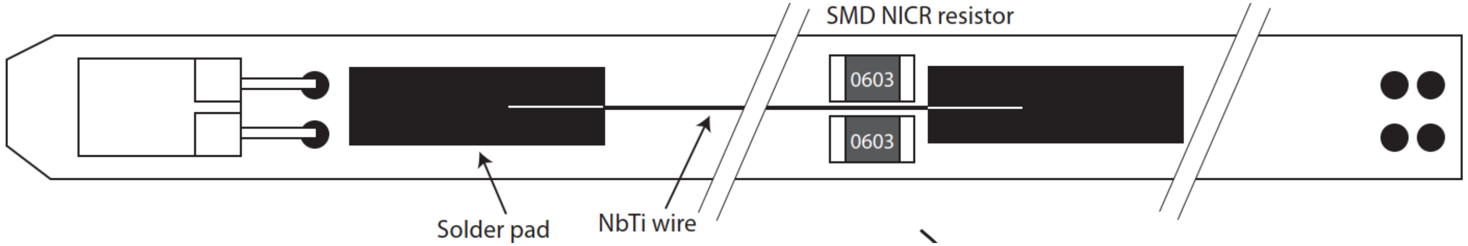


LHe level Measurement: superconducting wire

The level gauge operates as long as:

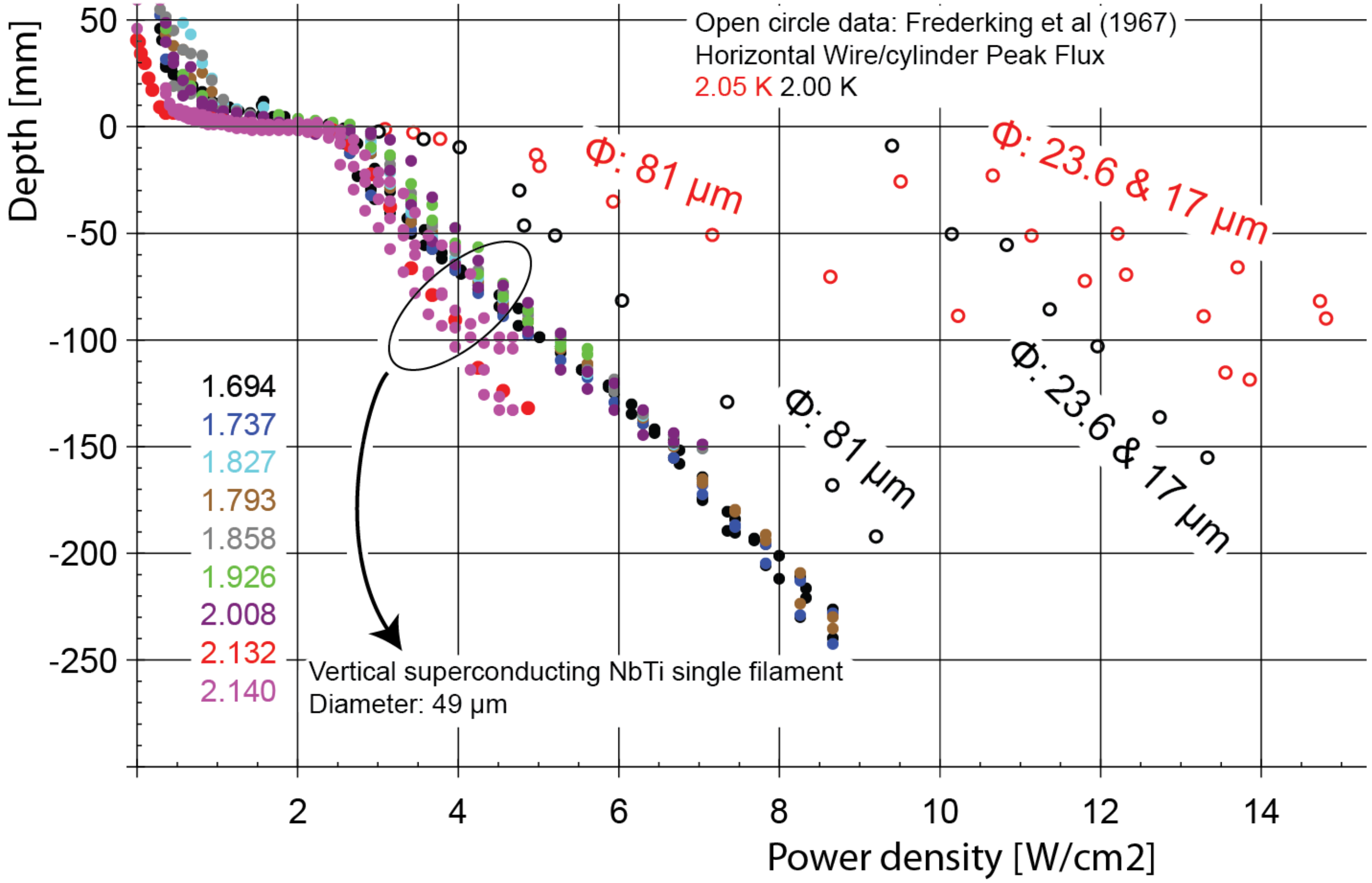
- Current is high enough to propagate the normal state in the vapor part
- Current cannot exceed the critical heat flux in the liquid
  - Critical heat flux is about 1 W/cm^2 (0.01 W/mm^2)
  - Above this heat flux a gas blanket may form along the wire
    - Careful with heaters, once the blanket appears it may cause catastrophic damage!
  - For a 50 µm diameter wire & 0.3 Ω/mm => 72 mA
    Coherent with excitation current usually being used

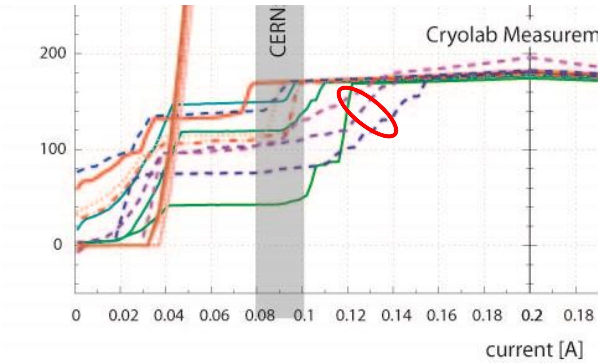


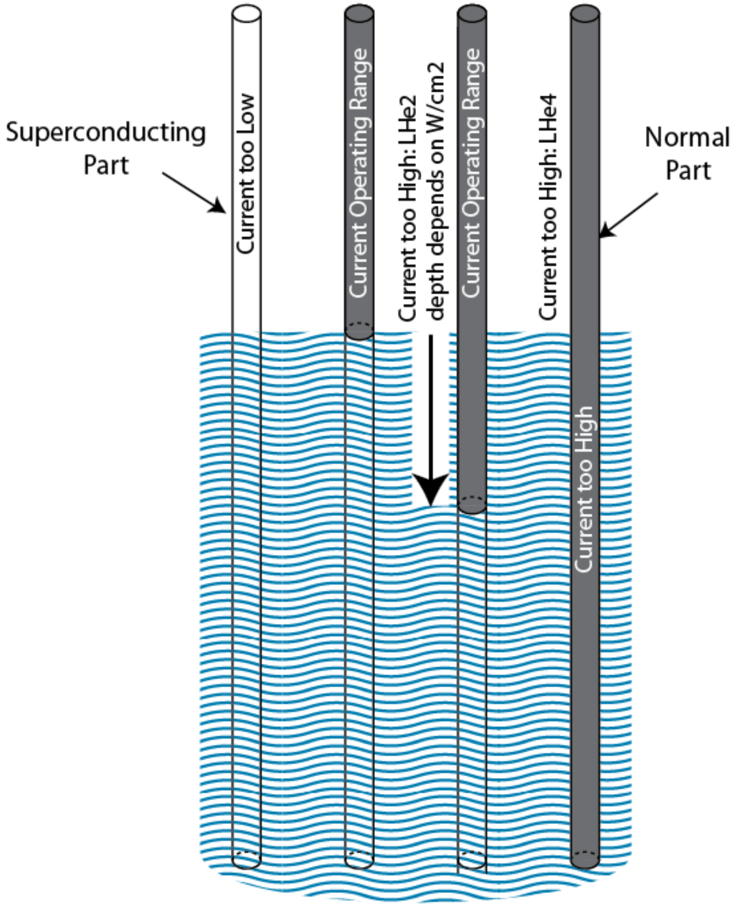


LHe level Measurement: superconducting wire

In superfluid LHe the position of the SC-normal interface depends on the power density (peak flux).
Gaseous blanket when density exceeds peak flux.

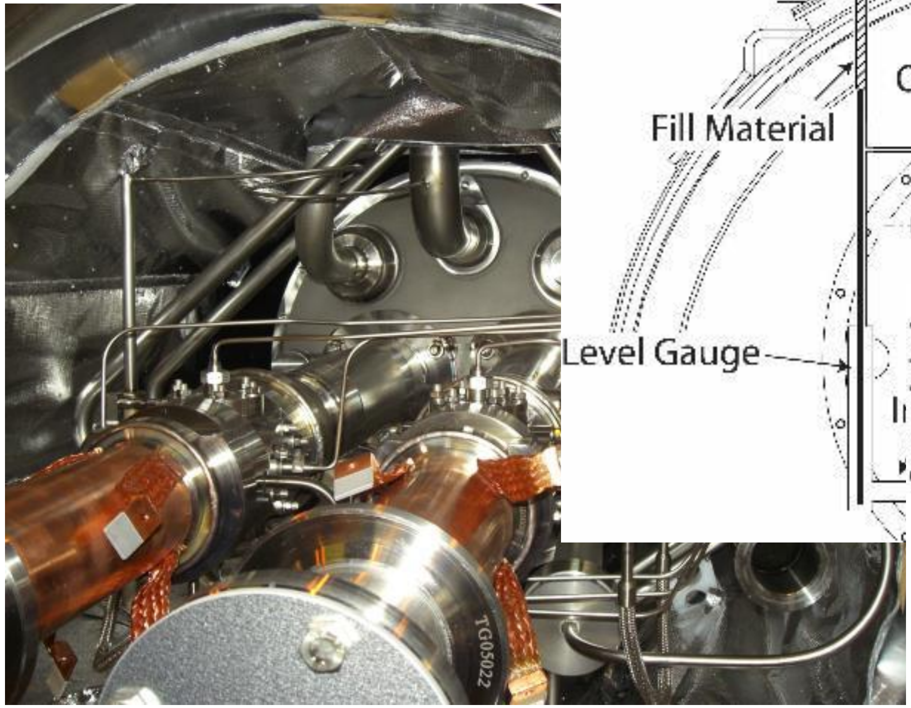


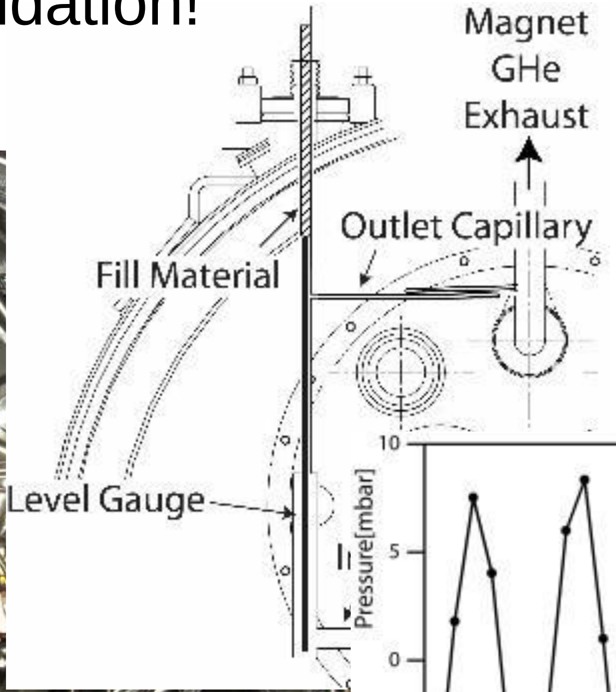


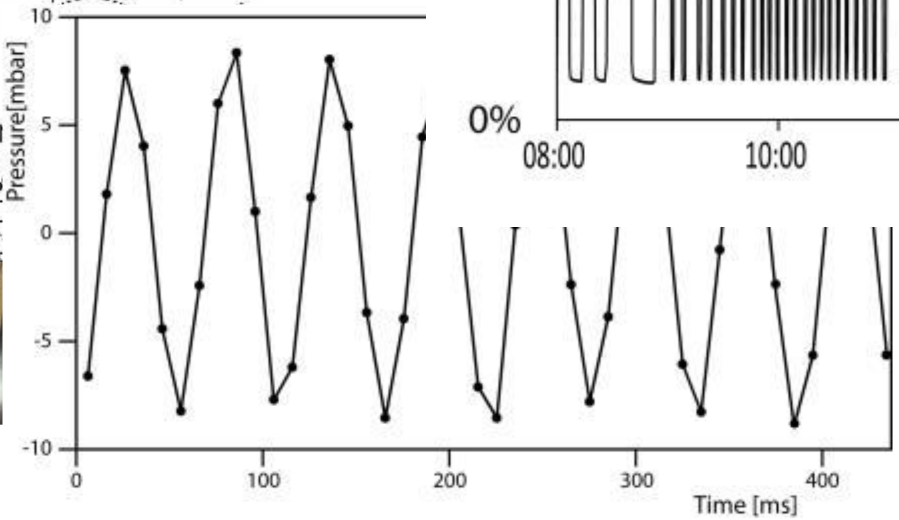


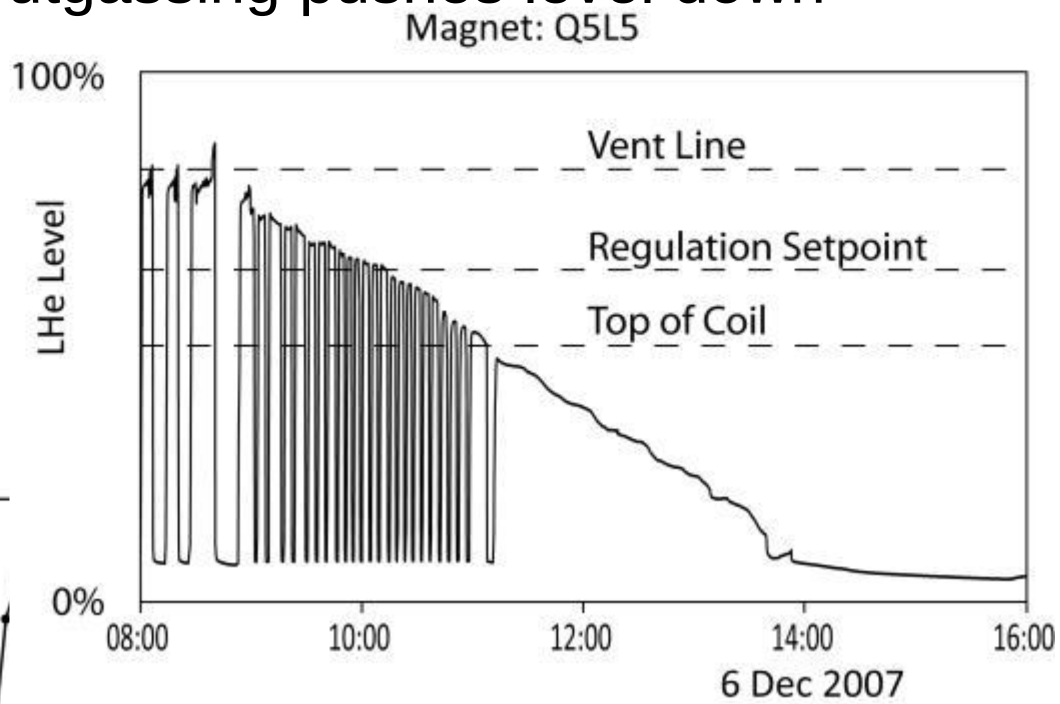
LHe level Measurement: Perturbations

Thermo-acoustic oscillations induce heat and evaporation
LHC: sensor connected @ top/bottom with pipes
TOP one too long & too narrow => low outgassing pushes level down
=> Required consolidation!







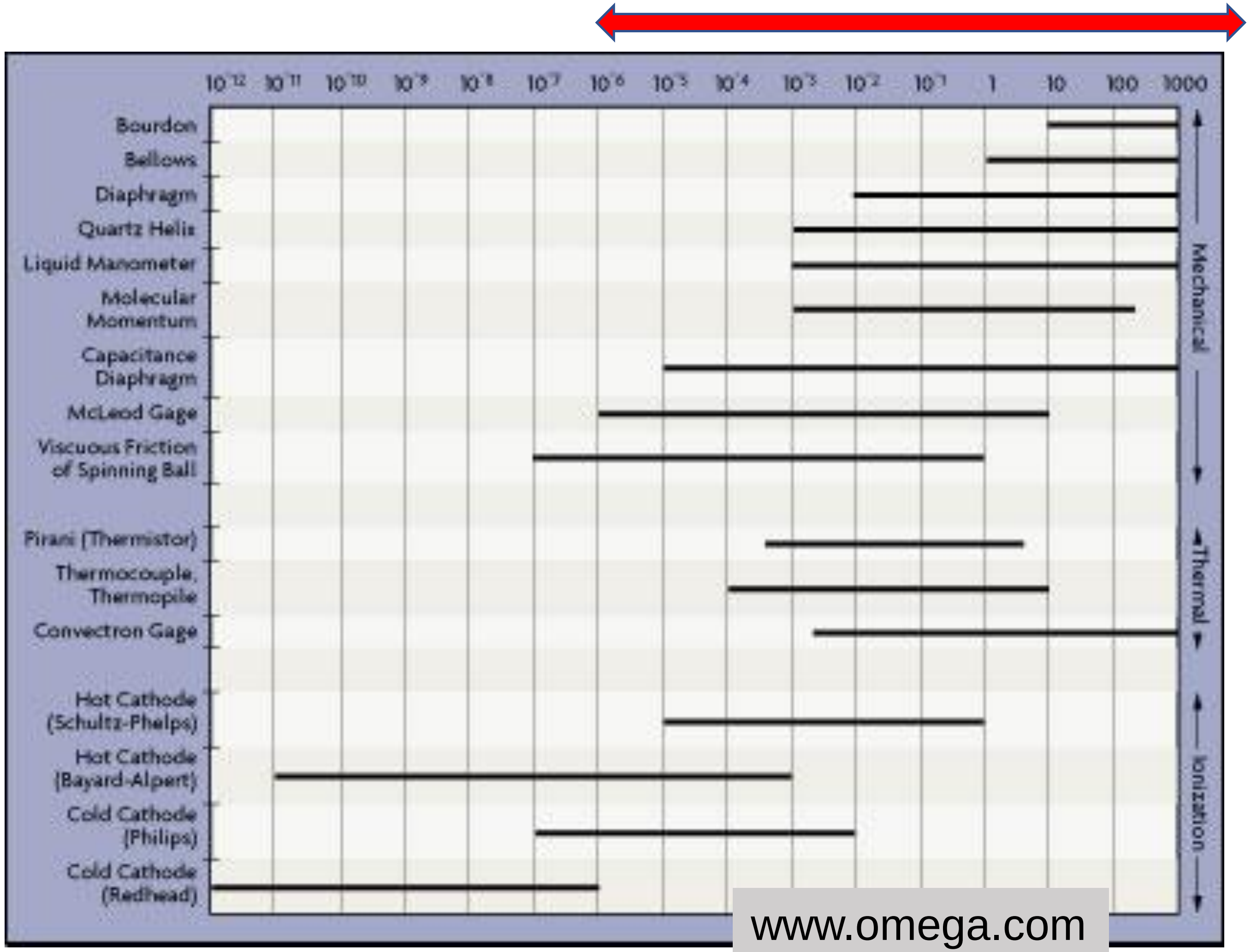


Pressure Measurement: Basics

Cryogenic facilities require to measure:

- insulation vacuum in the range 10^{-9} (ie 10^{-6} mbar) till 1 bar
  - Based mostly on thermal & ionization effects
- Cryogenic fluids in the range 0.01 till 25 bar
  - Based mostly on mechanical displacement
- Accelerator beam vacuum 10^{-9} mbar & lower
  Out of scope.

Pressure range for cryostats

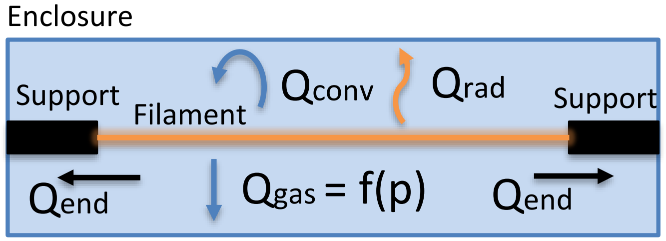


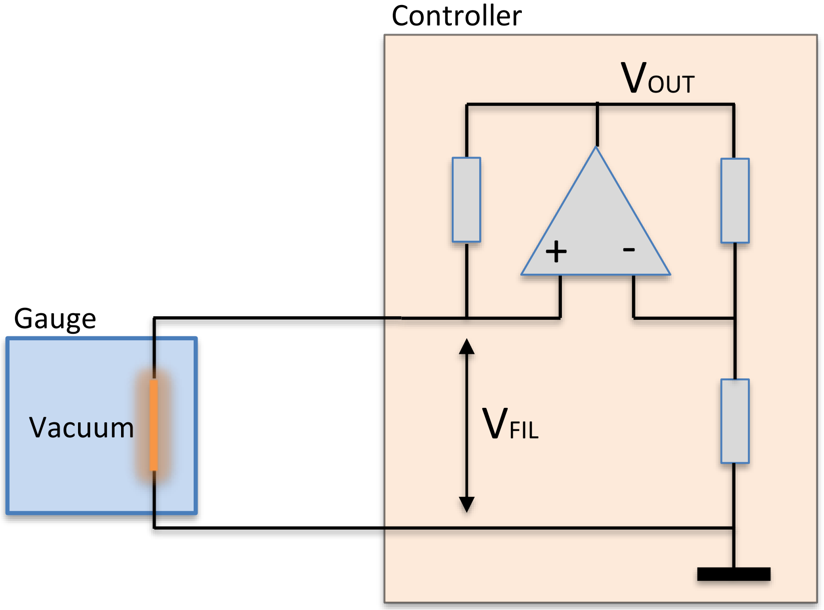
www.omega.com

Pressure Measurement: Vacuum

Pirani gauges:

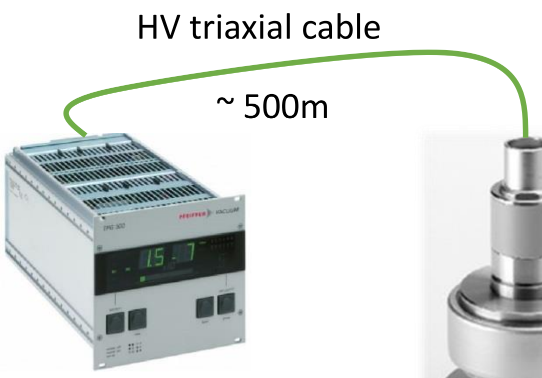
- Measurement range: 10^{-4} till 1000 mbar
- Heat loss: conduction + radiation + convection
- Filament temperature set @ 293 K
- Radiation hardness 10^7 Gy with remote electronics
- Cable is part of the sensor => calibration for lengths exceeding 20 m
- Accuracy: +/- 30 % of read value





Courtesy N. Chatzigeorgiou (CERN)

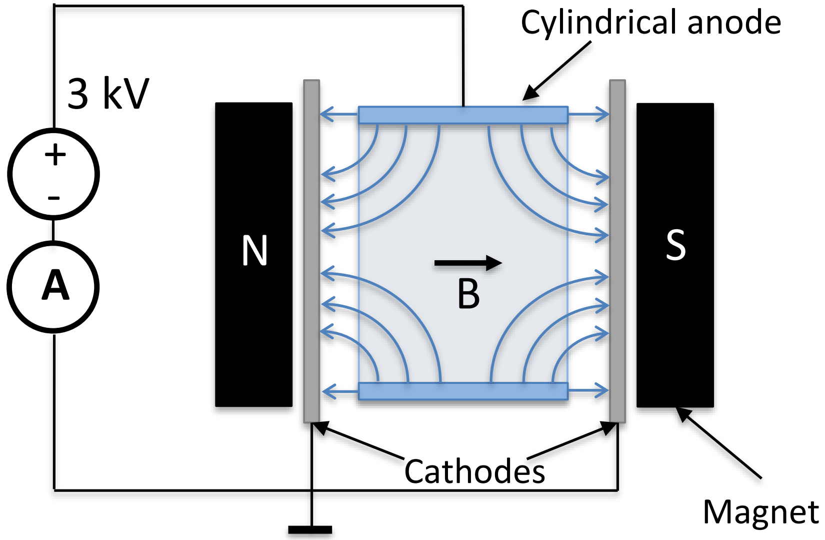
Pressure Measurement: Vacuum



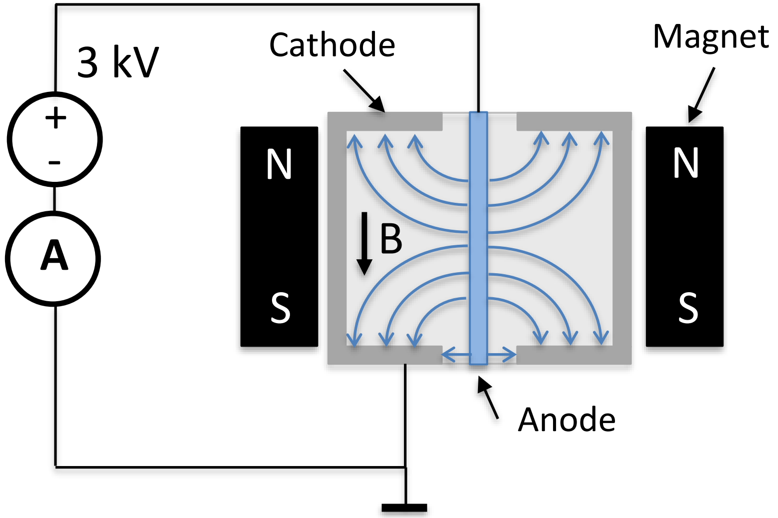
Penning gauges:

- Measurement range: 10^{-11} till 10^{-11} mbar
- Ionization of gas molecules ⬄ discharge current
- current range 10^{-6} - 10^{-12} A (impedance !)
- Cable is part of the sensor => calibration for lengths exceeding 20 m
- Accuracy: +/- 50 % of read value

Original Penning cell



Inverted magnetron (higher sensitivity)

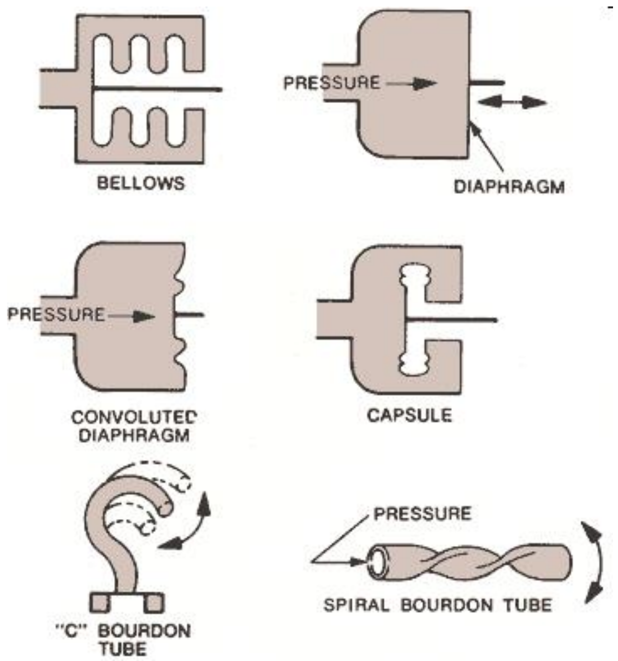


Courtesy N. Chatzigeorgiou (CERN)

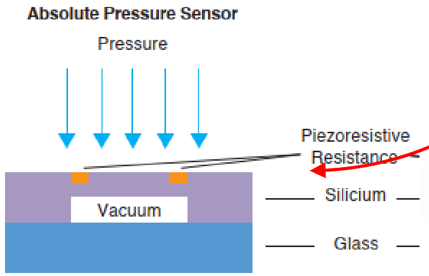
Pressure Measurement: Fluid range

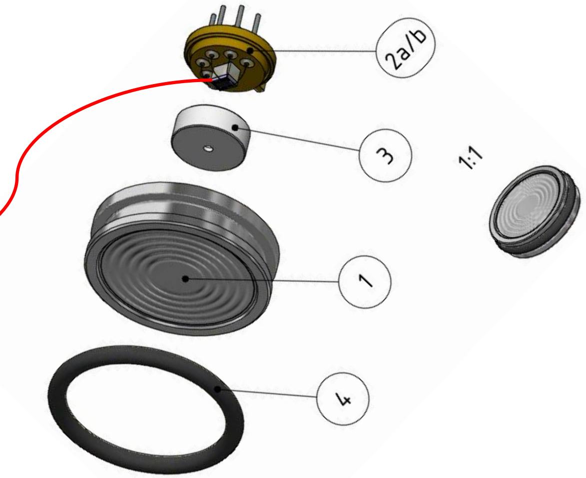
0.01 to 25 bar (or more) measurements are typically based on:

- Elastic deformation of a “thin” membrane/diaphragm
- Elastic displacement is measured through:
  - Strain gauges
  - Capacitive or inductive displacement sensors
- Excessive pressure across membrane
  - Inelastic displacement => permanent damage
  - Burst => membrane destruction => loss of containment
- “smart” industrial sensors are suitable for most applications



Sensor Type	Side 1 of membrane	Side 2 of membrane
Gauge	Process pressure	Ambient pressure
Differential	Process pressure 1	Process pressure 2
Absolute	Process pressure	Vacuum

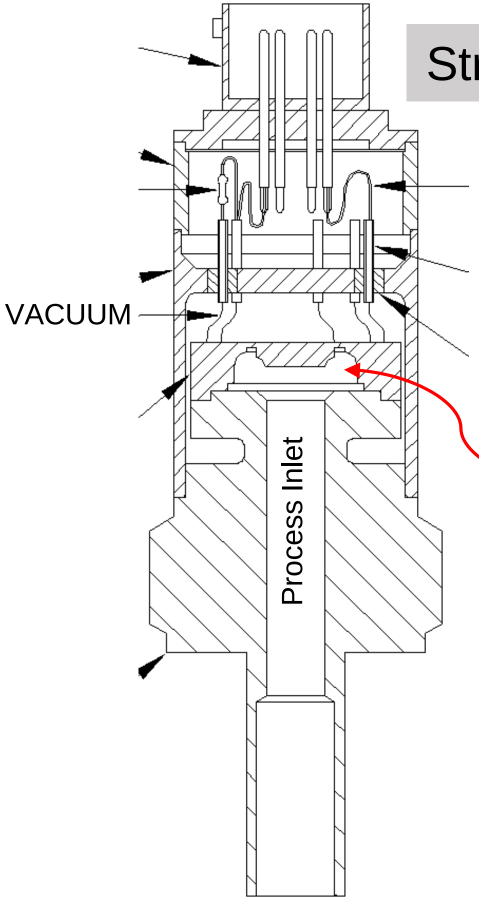




Pressure Measurement: passive types – strain gauge based

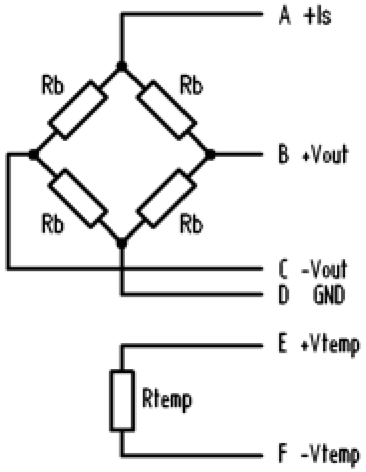
Operation in cryogenic conditions or in radiation => passive sensor.
Passive sensors are becoming a rarity, most manufacturers embed electronics.
Smart sensors embed temperature corrections to improve accuracy:

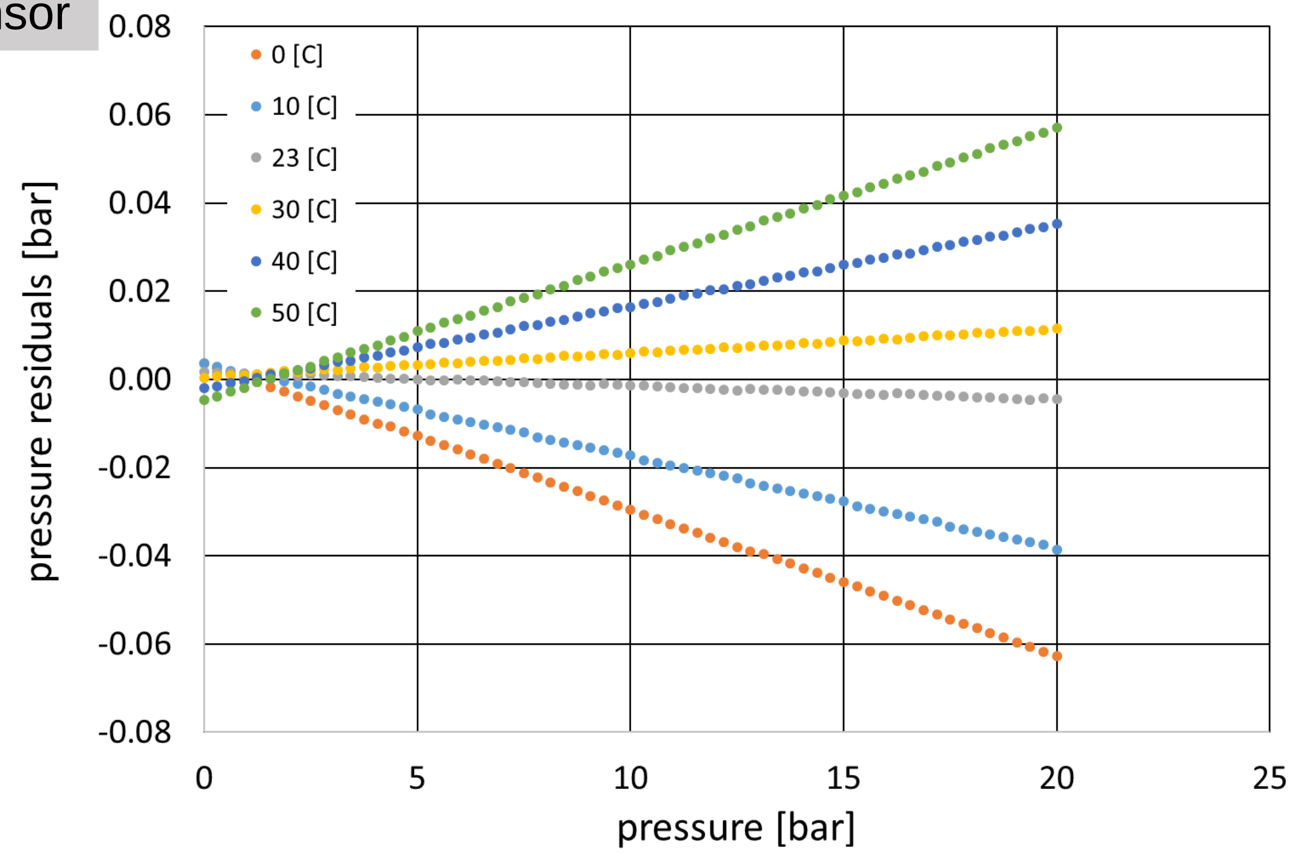
- Passive sensor + temperature + correction formulae ~ smart sensor



Strain Wheatstone bridge based sensor

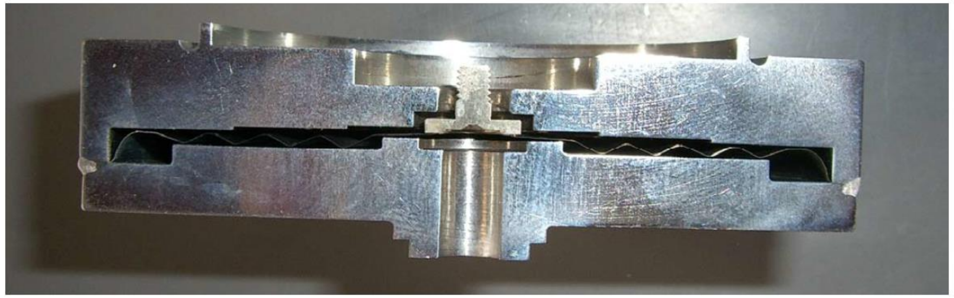
Metallic strain gauge



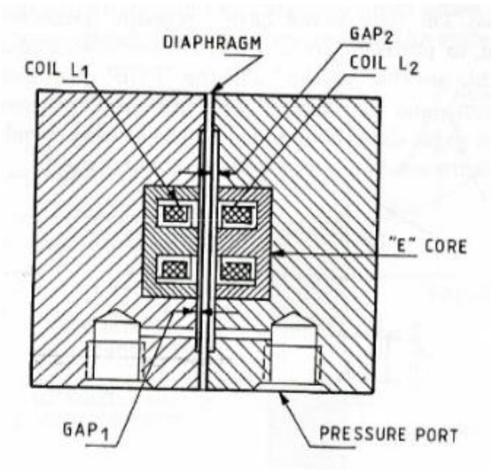


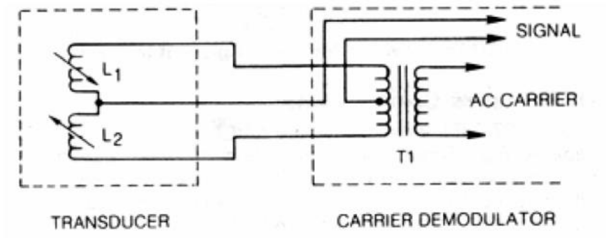
Pressure Measurement: passive types – variable reluctance

Variable reluctance sensors use comparatively larger membranes and can be a good alternative to measure saturated LHe-II pressures.
Furthermore are based on magnetic components that usually are very robust in radiation environments.
However the connecting cable is part of the sensor
⇨ calibration in-situ or with “final” cable



Sensor made by NICHE





Validyne sensors

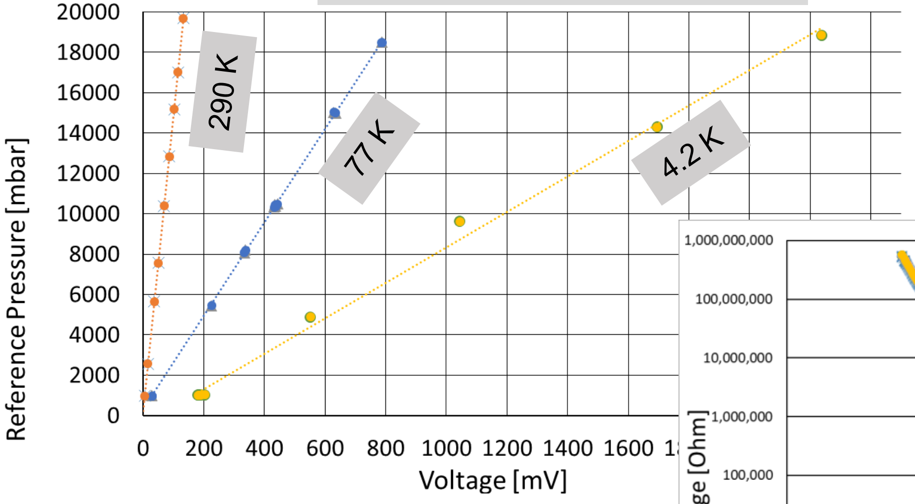
Pressure Measurement: passive types – Cryogenic conditions

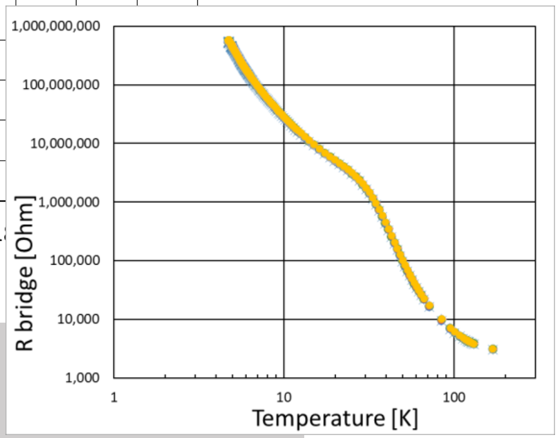
Cryogenic pressure measurements are desirable when measuring fast transitions, avoid capillary hydrostatic head and time response reduction, etc.

Resistance bridge based sensors have been reported to work properly, however they are not manufactured any more (Fujikura, Siemens, etc.).

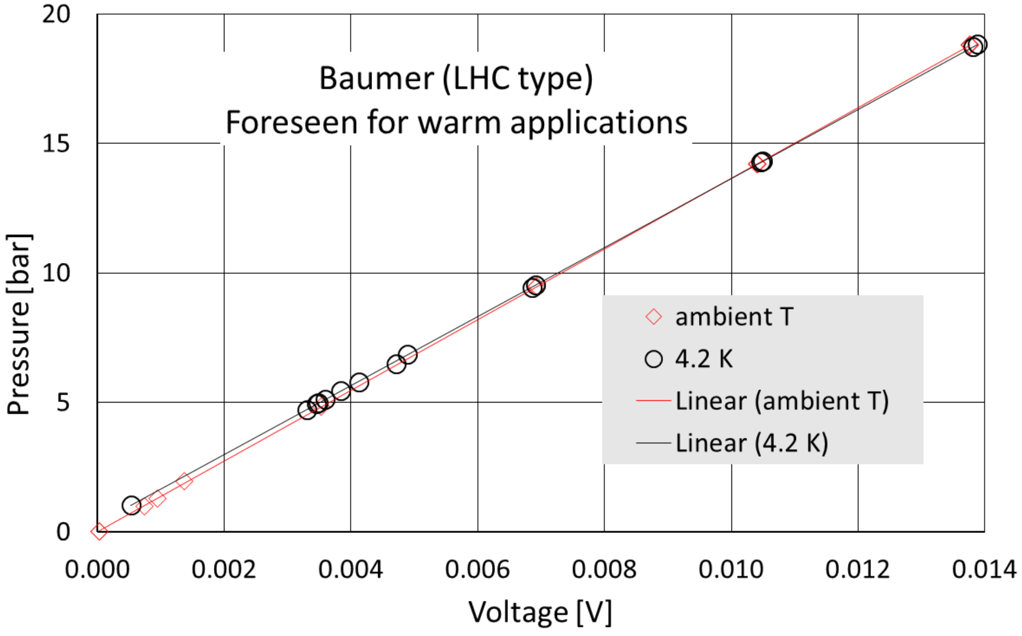
Unfortunately qualifying new sensors for cryogenic operation is very tedious.

Constant voltage excitation





Merit strain gauge based sensor
1 GΩ impedance @ 4.2 K
=> Stray capacitance limits bandwidth (1/(R.C))



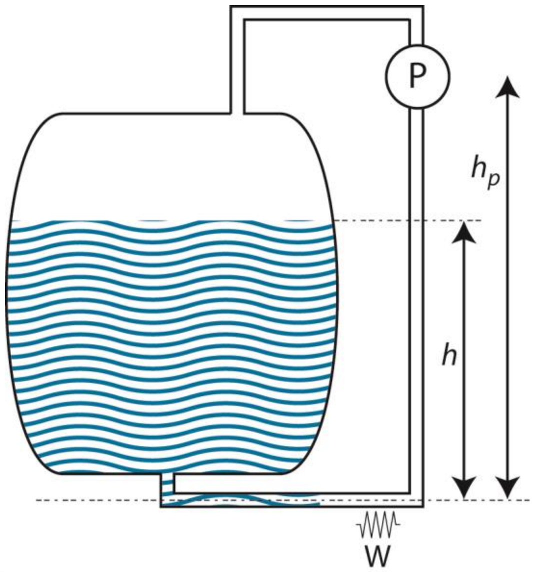
Constant current excitation

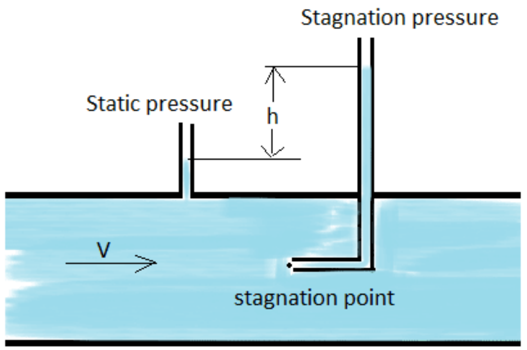
Pressure Measurement: peculiarities for cryogenic equipment

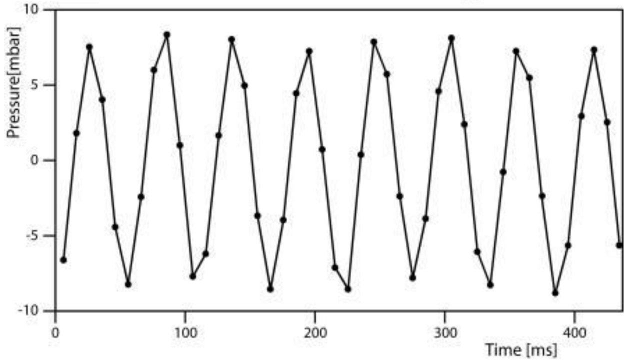
Pressure sensors require routine calibration, may fail and require replacement.
⇨most applications install warm conventional sensors and the process pressure is connected via sensing capillaries with a wide temperature gradient.

The sensing capillary introduce artifacts due to:

- Hydrostatic head (depends on temperature/density profile)
- Thermoacoustic oscillations
- Pressure drop due to fluid flow
- Additional dynamic pressure if it looks like a Pitot tube
- Limits the measurement frequency bandwidth







Mass Flow Measurement: Basics

Flow measurement is an essential tool for many industries and public utilities.
In cryogenic facilities flow metering is used for

- the assessment of cryogenic loads
- process monitoring and control
- detection of faults and wear on pumping machinery

Apart from oil contamination in the ambient temperature circuits, most of the gaseous fluids used in cryogenics are pure, clean and are well described by the ideal gas law. Oil contamination can be a problem for hot wire anemometers.
However when a fluid rate is to be measured at cryogenic temperatures care is necessary in order to avoid the presence of two-phase flow or cavitation.
The main fluid properties for gas flow rate meters are: temperature, pressure, density and viscosity

Mass Flow Measurement: Techniques

There is a variety of techniques, some suitable for cryogenic conditions (☆):

- Positive displacement (accumulated volumetric flow)
- Variable area or rotameter
- Thermal ☆
- Differential pressure ☆
- Vortex
- Coriolis ☆
- Turbine ☆
- …

Type	Ultimate accuracy	range-ability	Pressure loss	Straigh Piping	Cryogenic Service?	Helium	Cost
orifice	1 - 2 %	medium	High	10-30 D	Possible		low
venturi	1%	medium	Low	5-10 D	Possible	Cryo: Size!	high
V-cone	0.5-1 %	medium	Medium	3-5 D	Possible		medium
pitot tube	3%	medium	Low	20-30 D	Possible		low
variable area	1-10 %	medium	Medium	none	No		low
positive displacement	1%	good	High	none	No		medium
thermal mass	1%	good	Low	none	Possible		medium
turbine	0.30%	good	High	10-20 D	Possible		high
vortex	0.75%	medium	Low	15-25 D	?		medium
target	0.5-2 %	low	Medium	10-20 D	?		low
Coriolis	0.30%	good	High	none	Possible	Cryo or HP	high

Mass Flow Measurement: Basics

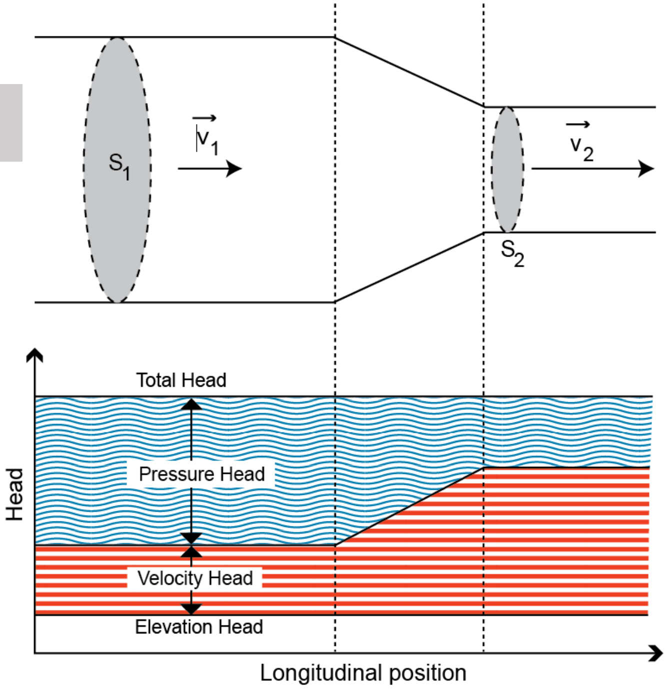
The transport of fluid through a pipe is described by the equation of continuity (1), Bernoulli's theorem (2) and the Reynolds number Re (3).

(1): $\frac{\partial \rho}{\partial t} + \nabla(\rho . \vec{v}) = 0$ non compressible => volumetric flow conservation

ρ and *v* are respectively the fluid density and velocity.

(2): $\rho \frac{v^2}{2} + p + \rho . g . z = constant$ non compressible & no viscocity

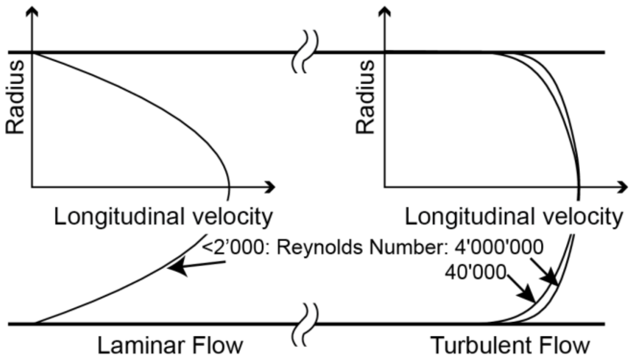
p, *g* & *z* are respectively the pressure, gravity and vertical distance



The Reynolds number R_e defines the flow regime:

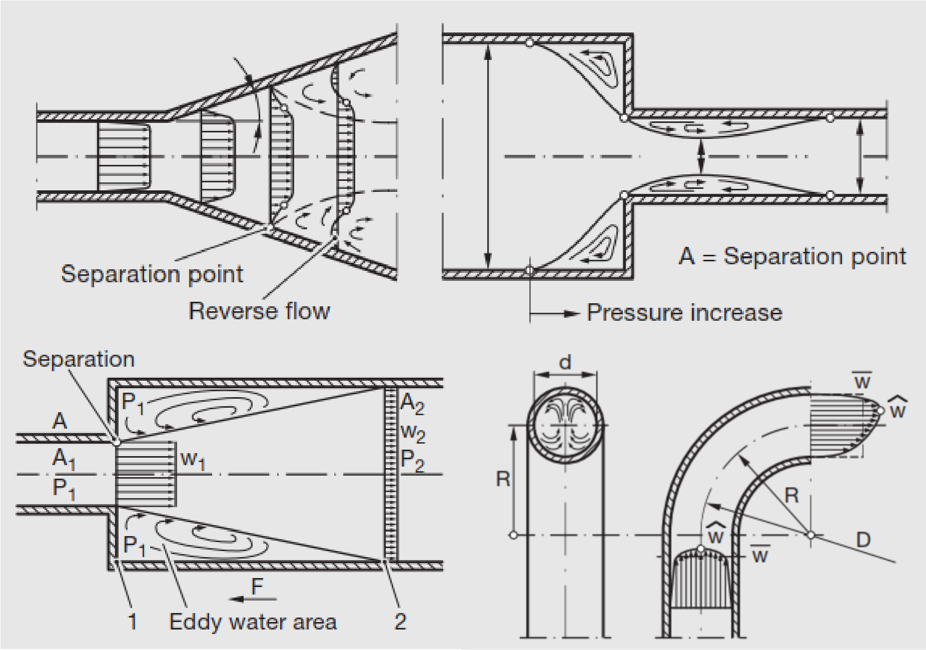
(3): $R_e = \tilde{v}.D / \nu$

D & ν are respective the pipe diameter & kinematic viscosity. Flow regimes are laminar, intermediate and turbulent.

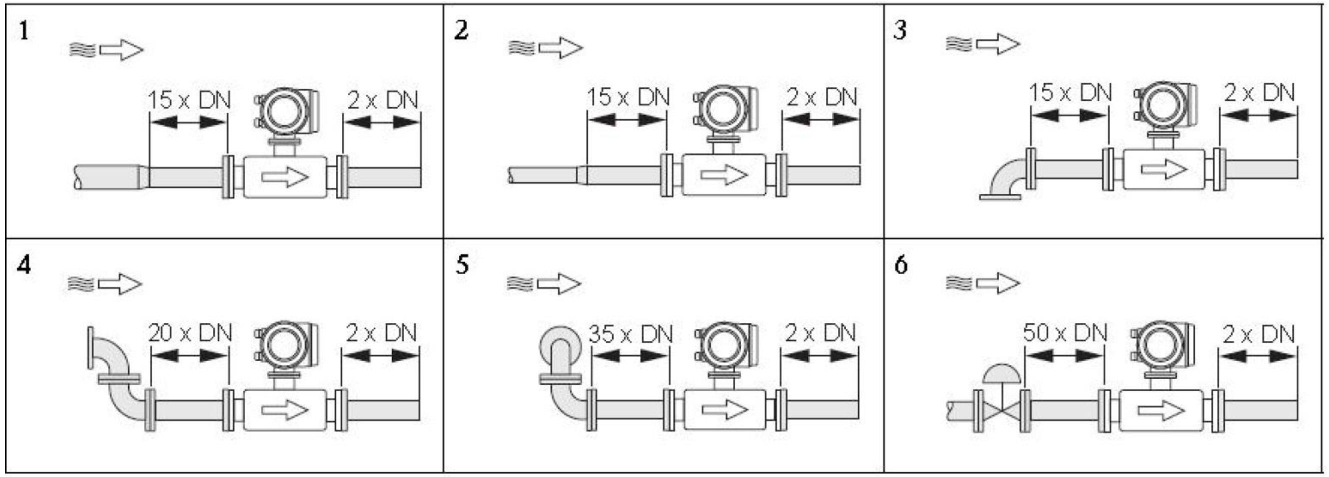


Mass Flow Measurement: Basics

Most flow measurements require non-perturbed flow
⇒ Requirement for minimum length of upstream & downstream piping
⇒ Straight piping shall be smooth (it means no valves)
⇒ Cost of piping need to be taken into account, in particular for large diameters.



From ABB: industrial flow measurement



Mass Flow Measurement: Differential pressure

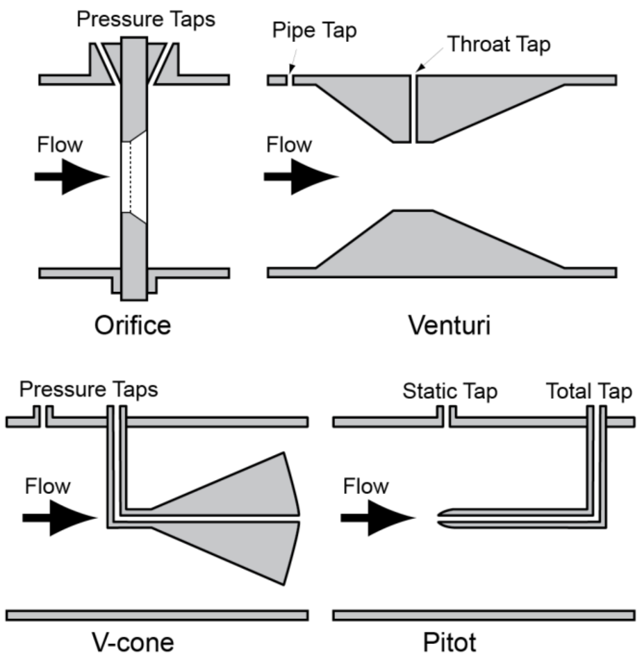
Differential pressure flow meters are widely used in both ambient and cryogenic conditions.

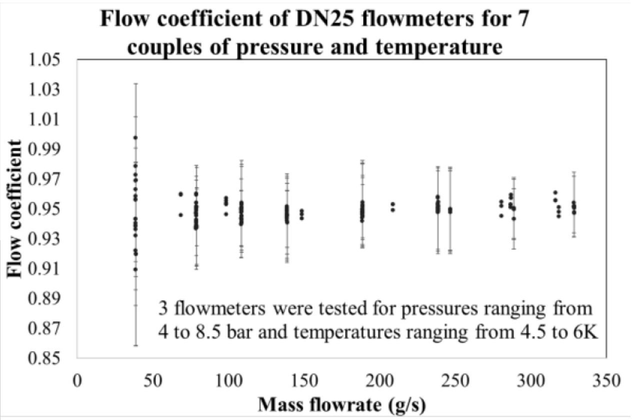
The volumetric flow is:

$$\dot{Q} = C\frac{\pi}{4}D_2^2\frac{\sqrt{2(p_1-p_2)}}{\sqrt{\delta\left[1-\left(\frac{D_1}{D_2}\right)^4\right]}}$$

The flow is overestimated because non-reversible processes are ignored.

The discharge coefficient factor *C* (it is a multiplying factor) is added to improve accuracy. It is an empirical term that corrects for friction, geometrical contraction or imperfections, etc.





ITER venturi flowmeters discharge coefficient => Varin et al (2019)

Mass Flow Measurement: Differential pressure

ITER has foreseen the use of more than 200 venturi flowmeters to measure the cold flow on the tokamak magnets, their temperature range is 4.2 to 6 K.
ISO 5167 describes the manufacturing and uncertainty calculations for venturi and orifice flowmeters.
In CERN cryogenic facilities Venturi and V-cone flowmeters read respectively the ATLAS and SM18 test benches current leads flow and many orifice meters are deployed in the refrigerators.
Venturi flowmeters for cryogenic applications require extremely tight dimensional tolerances due to their small size.

Venturi for LHe metrology.
Manufactured by Colonetti (IT)

Mass Flow Measurement: Thermal

There are two main types of thermal flowmeters:

- heat loss from a heated element (resistance wire, thermocouple, etc.) to the flow stream

$$q = \Delta T\left[k + 2\sqrt{kC_v\rho\pi dv}\right]$$

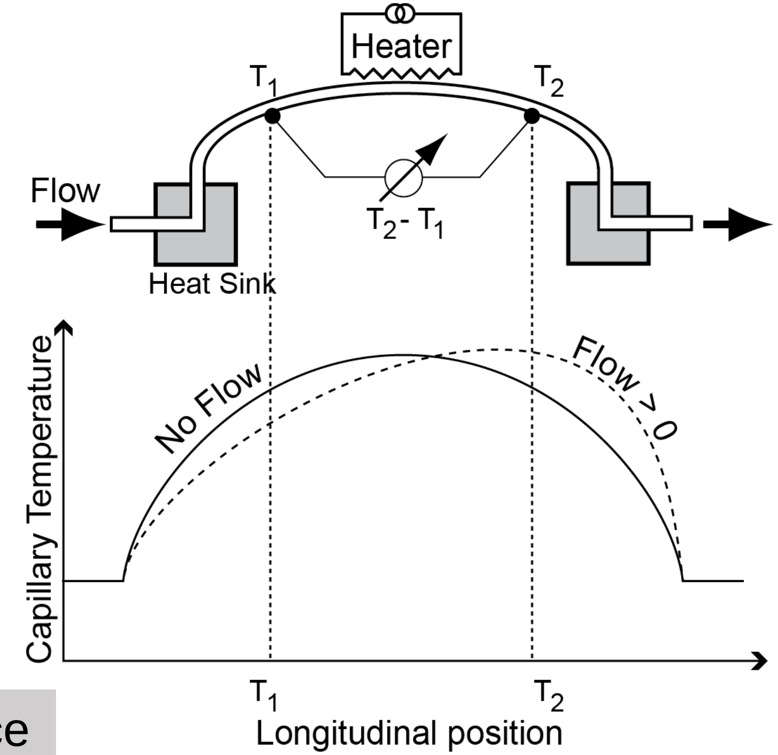
King equation

k,*d* and *v* are the fluid thermal conductivity, wire diameter and fluid average velocity

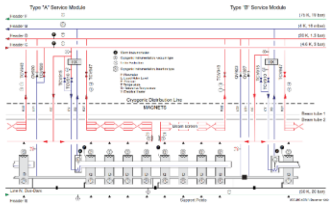
- temperature rise of a fluid passing over a heated element

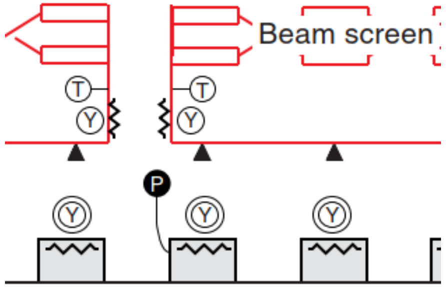
$$\dot{m} = \frac{W}{\Delta H}$$

= power / enthalpy difference



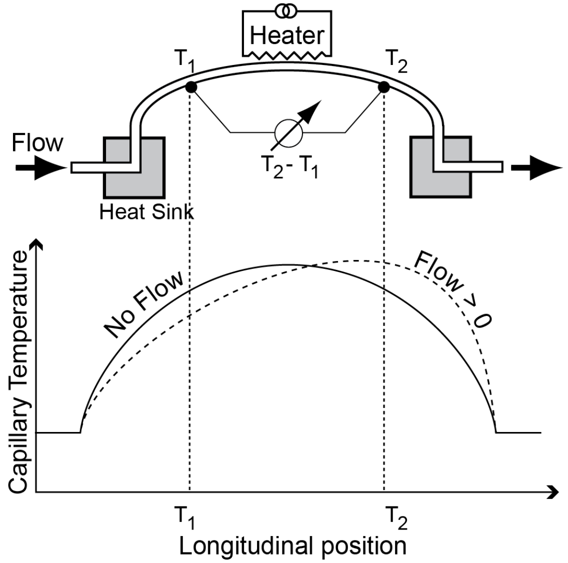
Thermal flowmeters are widely used to measure gases above 273 K.
Heaters, temperature and pressure sensors permit to estimate flow along cryogenic lines.

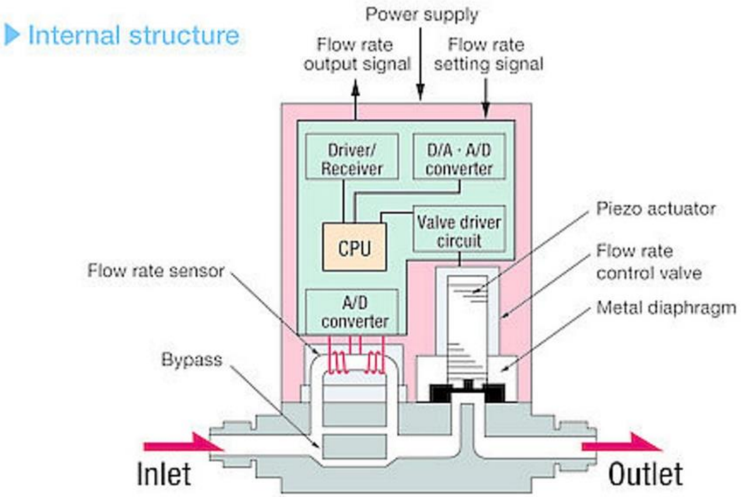




Mass Flow Measurement: Thermal

Output signal depends on gas characteristics.
For most application GN2 is an adequate surrogate calibration fluid for GHe applications.
Conversion factor depends slightly on vendor or model.
Exist also as thermal mass flow controller.
WEKA is developing a device suitable for cryogenic operation.





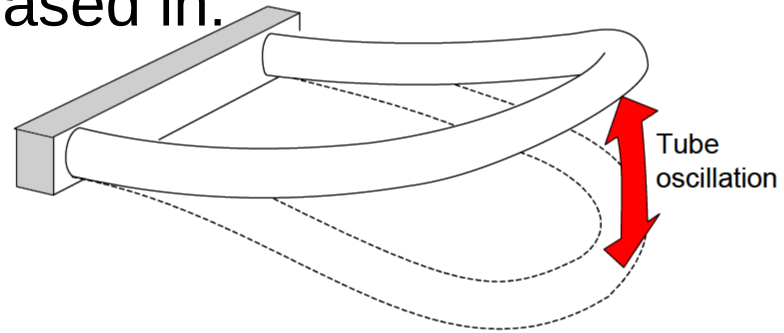
Gas Conversion Factors (N_2)		
	200 Series	300 Series
Helium	1.402	1.400
Oxygen	0.981	0.978
Carbon Dioxide	0.743	0.753
Carbon Monoxide	1.001	1.001
Methane	0.770	0.779
Ammonia	0.781	0.781
Hydrogen	1.009	1.004
Argon	1.401	1.405

From Teledyne-Hastings

Mass Flow Measurement: Coriolis

As it is indicated by its name the Coriolis flowmeters are based in:

$\overrightarrow{F_c} = -2\, m\, \vec{\omega} \times \vec{v}$ Coriolis force



ω and v are the tube angular motion and the flow velocity.

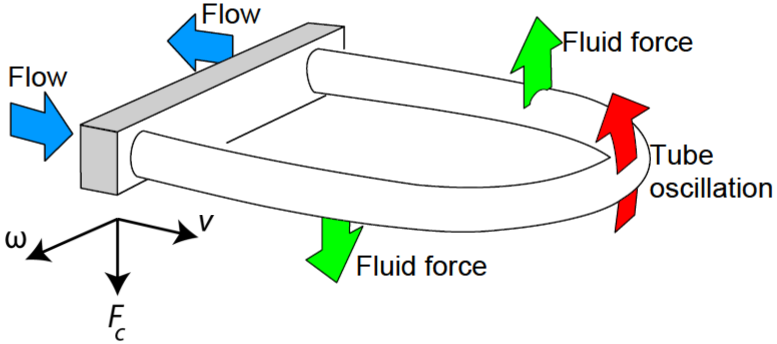
The Coriolis forces (flow) are of opposite directions

⇨arm twist amplitude depends on mass flow

Excitation coil induces vibration at natural frequency

Left and right pick-up coils measure twist

Phase shift is proportional to flow rate



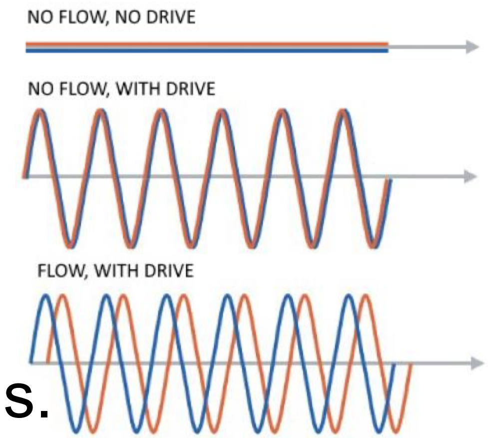
Signal conditioner (it is a computer) makes correction for:

- Changes of elasticity (Young modulus)
- Dimensional variations

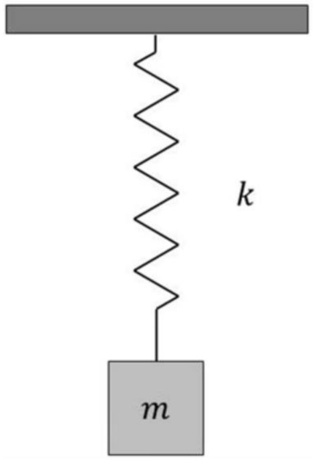
Corrections rely on a temperature sensor

⇨temperature sensor saturates @ about 70 K

⇨CRYO =>replace with “fixed” value and perform corrections.



Mass Flow Measurement: Coriolis



Mass flow rate is not affected by the tube vibration frequency.
However vibrating at the natural frequency has two advantages:

- Least amount of energy to keep the tube vibrating (as a tuning fork)
- Natural frequency depends on the mass contained within the tube
  - Fluid density *ρ* can be measured

$$Natural\ Frequency \propto 1 \Big/ \sqrt{M_{tube} + \rho . Volume}$$

$$\omega_n = \sqrt{\frac{k}{m}}$$

Coriolis flowmeters are best suited for dense fluids, they measure the mass flow rate directly and have a turn down ration better than 100 x.
For warm helium service Coriolis flowmeters are limited to high pressure (> 100 bar) applications due to the relatively large pressure drop.

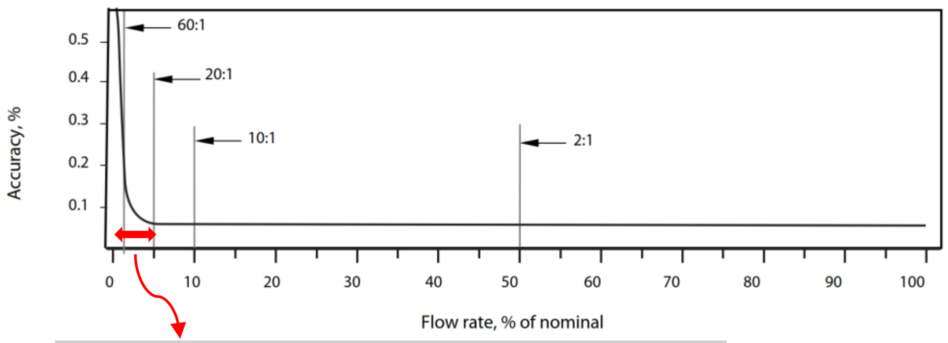
Mass Flow Measurement: Coriolis

Coriolis flowmeters can be used for liquid and supercritical helium.
Calibration is performed with water as surrogate fluid.
Cryo applications require remote electronics:

- 10, 300, 700 or 1’000m cable length have been shown to not affect the reading
- Suitable for accelerator applications => deployed in the LHC
  - Flow measurements on some beam screen circuits and QURCs

CMF 010 used in the LHC beam screen circuits
- Range 27 g/s
- LHC cryogenic range 1.5 g/s

Accuracy is limited by stability of ZERO



Cryogenic range due to pressure drop

Adding Heat: Electrical Resistors

Electrical heaters used to evaporate liquid helium, perform calorimetry tests, etc.

For precise heating measurements it is preferable to assume that heat is only transferred from the heater body; however:

- Wires are required and they do transfer heat:
  - Cross section as small as possible to reduce conduction heat transfer

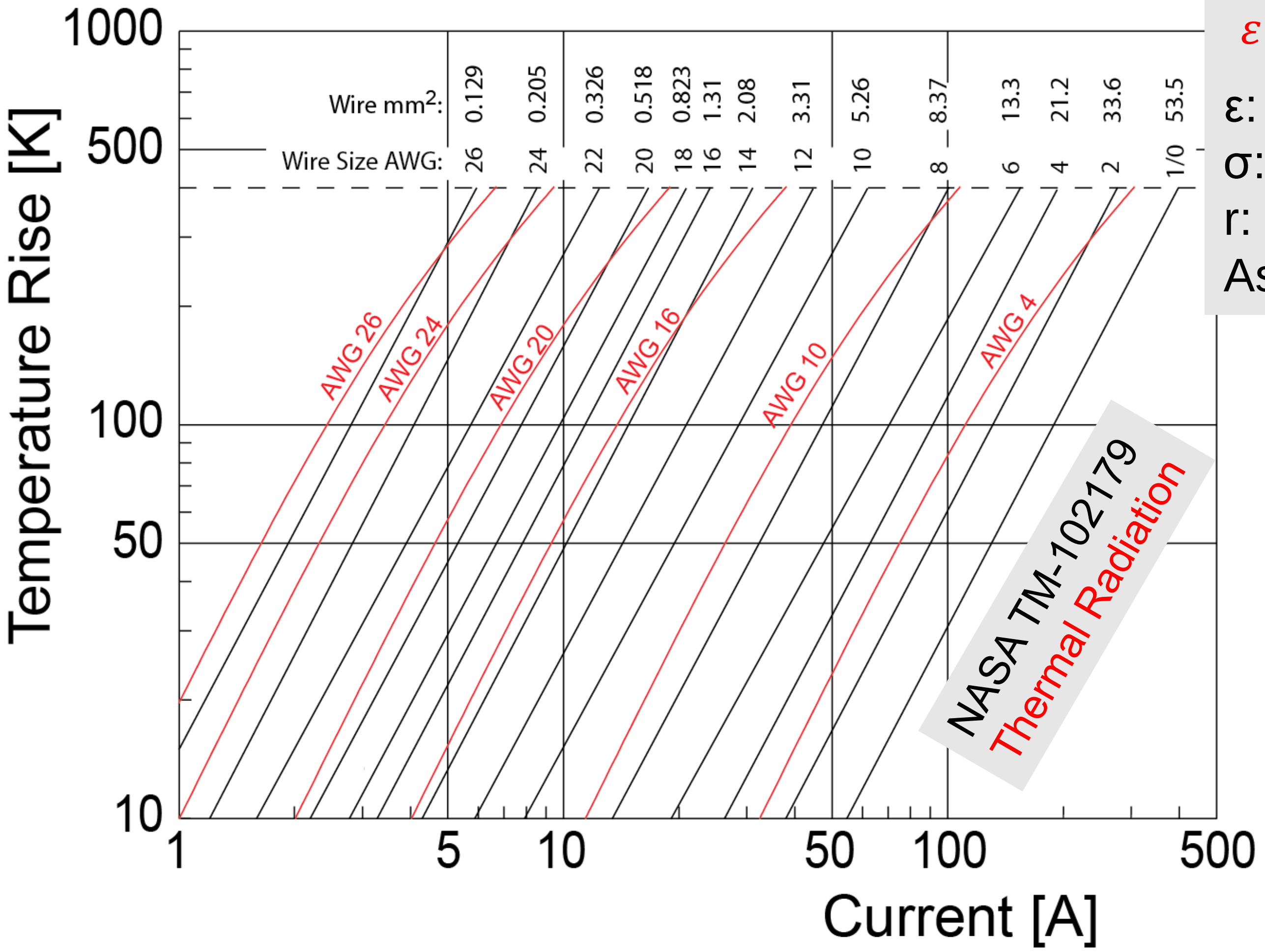
$$\vec{q} = -k(T) \cdot grad(T)$$

  - Cross section large enough to avoid burn-out due to Joule heating
  - 4-wire power measurement if you are able to estimate previous 2 terms

The current-carrying capacity of a wire is the amount of current the wire can carry in its operating environment without causing the insulation temperature to exceed its rating (usually never higher than 200 ^oC).

Adding Heat: Electrical Resistors – Wire Current Capacity

Wire temperature increase from 22 °C depending on wire size and current in vacuum:



$$\varepsilon.\sigma.\left(T_{wire}^4 - T_{backgnd}^4\right) = \frac{\rho(T_{wire}).i^2}{2.\pi^2.r^3}$$

ε: emissivity (0.9)

σ: $5.67\ 10^{-8}$ [W/(m² K⁴)]

r: wire diameter

Assume infinite long wire

DRUFLON INTERNATIONAL

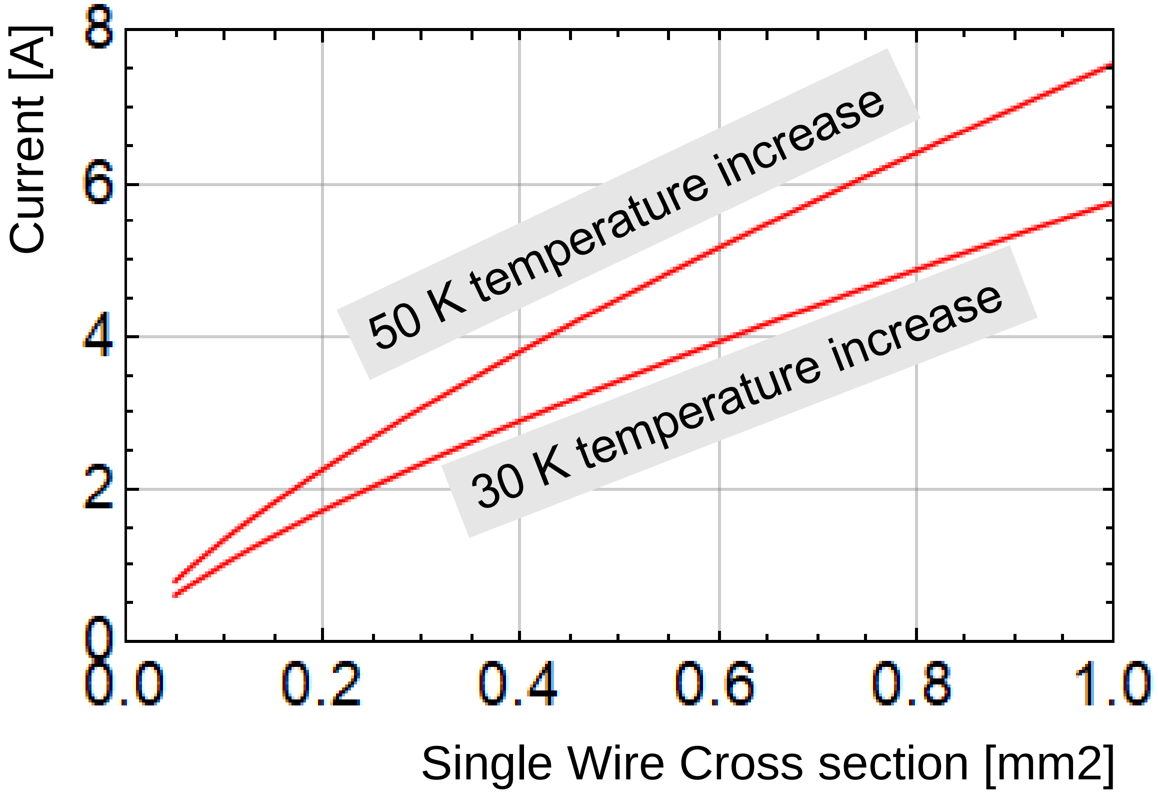
Properties of PTFE and other Insulating & Jacketing Compounds

Properties	PTFE	CR PTFE	FEP	Polyimide Kapton	Polyurethane Elastomer	PVC Elastomer
	<----------------------		TYPICAL VALUES			---------------------->
Physical and Thermal						
Continuous Use Temperature (degC)	260	180	200	200	95	105
10 Minute Endurance Temperature (degC)	325	325	280	500	105	150
Melt Temperature (degC)	327	327	285	None	140	175

Adding Heat: Electrical Resistors – Wire Current Capacity

Electrical wiring is mostly used in bundles.
Bundles reduce the current carrying capacity => derate by at least 30%
Overheating is catastrophic:

- Sputters plastic or metal
- Damages turbo-molecular pumps,..



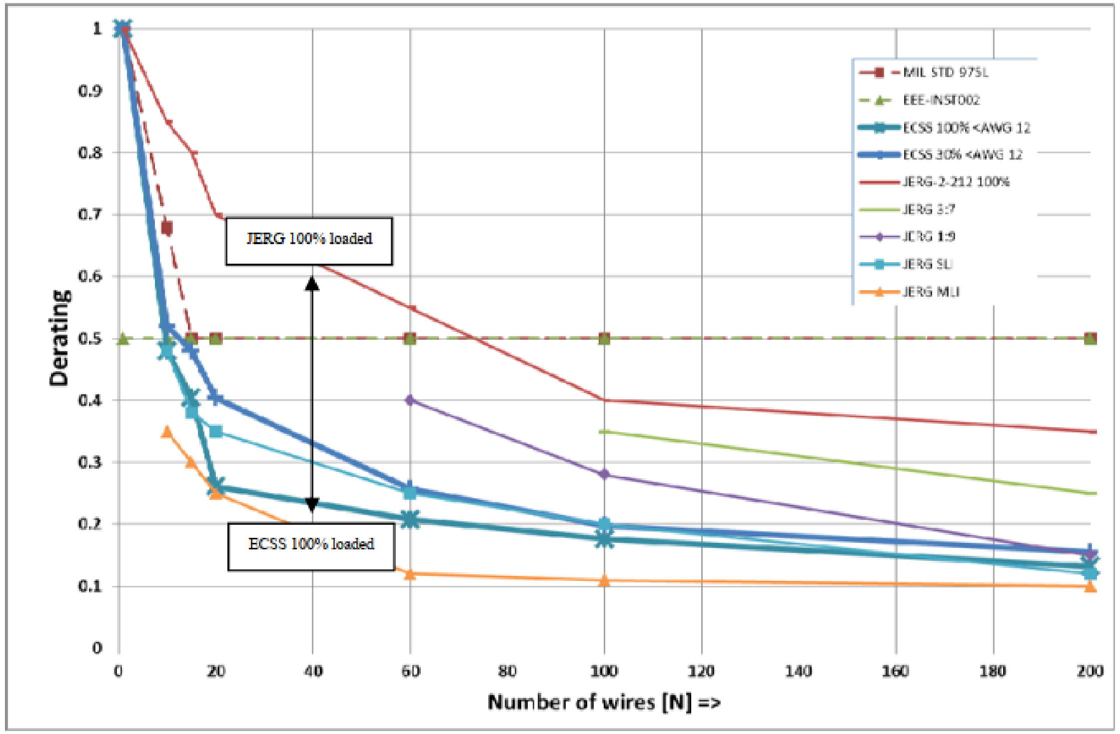


Figure 3 Comparison of the bundle derating versus number of wires (N) for several standards. JERG[5] derating is less severe (~0.3-0.4) for 100% loaded bundles compared with ECSS[1] except for bundles wrapped in MLI.

From: "Derating Standards and Thermal Modelling Tools for Space Harness Designs" ICES-2015-59

Adding Heat: Electrical Resistors – Voltage rating

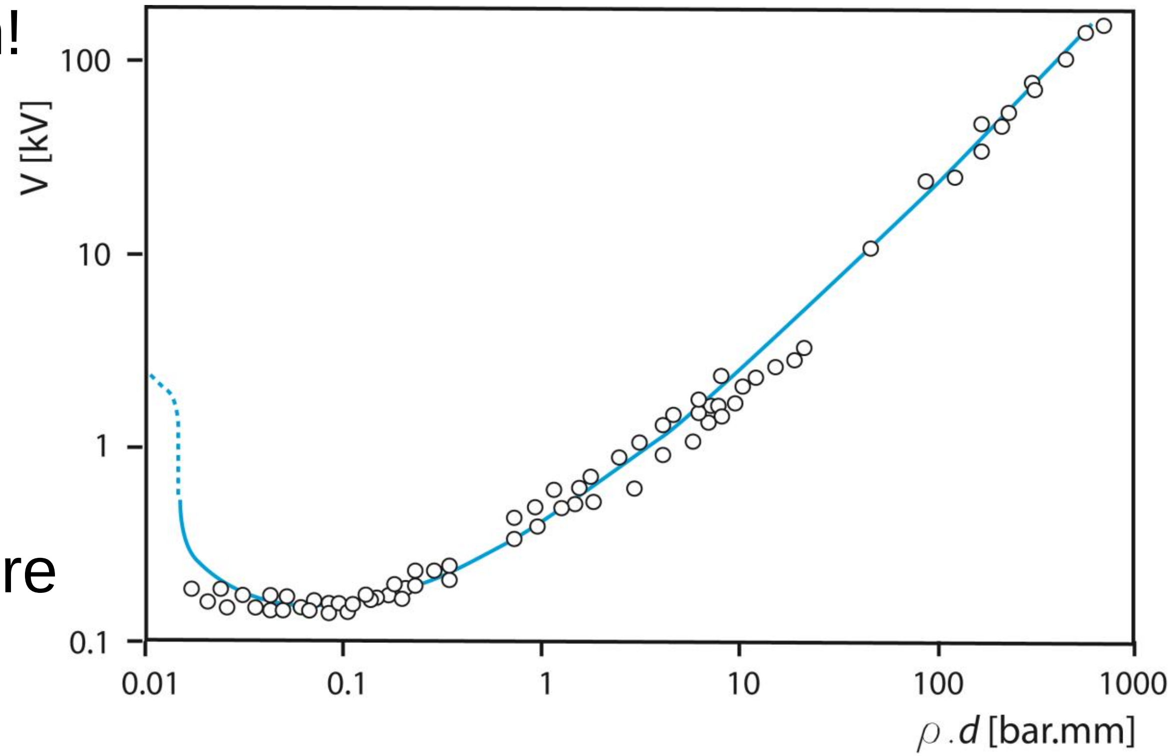
Vacuum and liquid helium environments have good dielectric characteristics.

However gaseous helium need care in order not to exceed the dielectric breakdown voltage!

- Depends on closest distance between bare conductors
  Check warm electrical feedthrough!
- Gaseous helium pressure

Best is to not exceed 100 V
Remember 100 Vac =>141 Vdc p-p
GHe will catch the peak!

Dielectric breakdown protection require extremely fast fuses.



(Winkelnkemper et al)

Adding Heat: Electrical Resistors – Heat Transfer Density

Transfer of heat to liquid is done through (increasing heat flux density):

- Convective heat transfer
- Nucleate pool boiling
- Film boiling

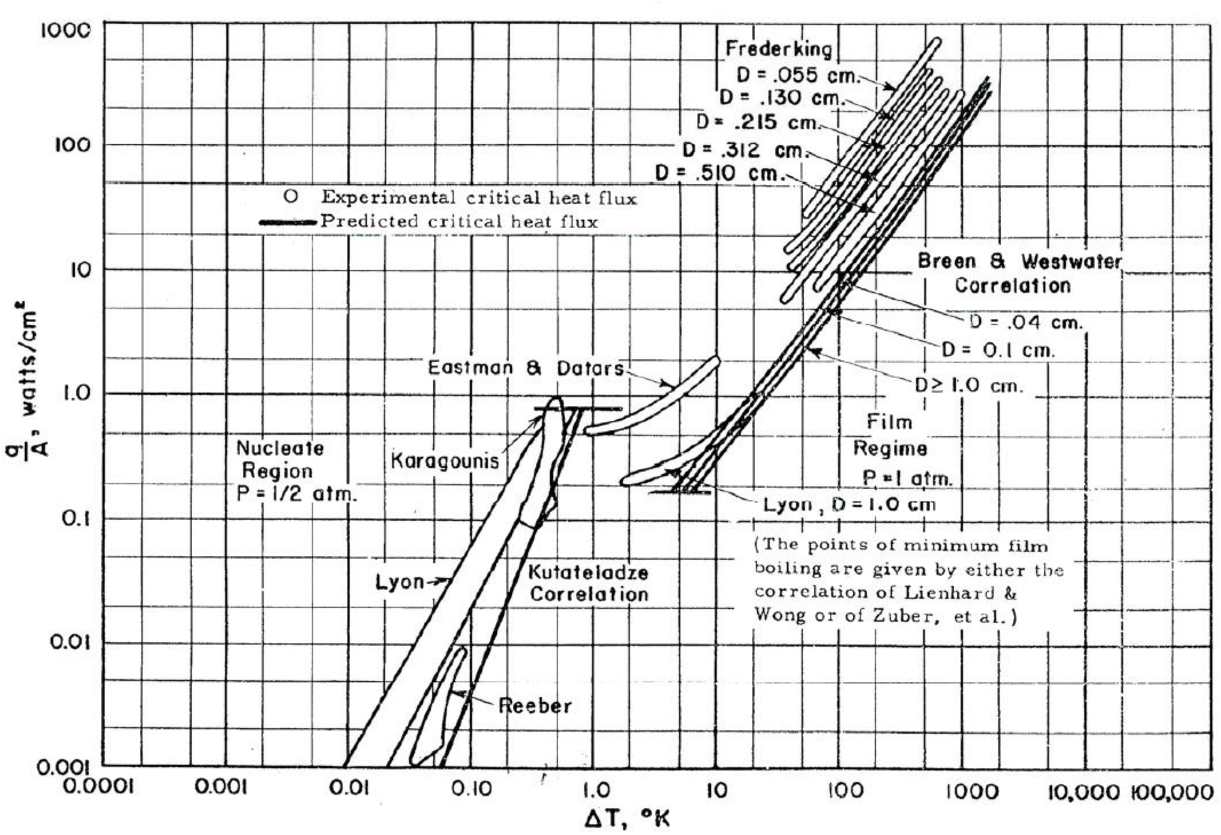
Heat will always be extracted:

$\Rightarrow$ Heater too small

$\Rightarrow$ Very large temperature rise

$\Rightarrow$ burnout

For immersed heater in LHe do not exceed the heat density of 1 W /cm^2.



Actuators: Regulating valves

The flow coefficient (K_v) describe the relationship between the pressure drop and the corresponding flow rate (IEC 60534)

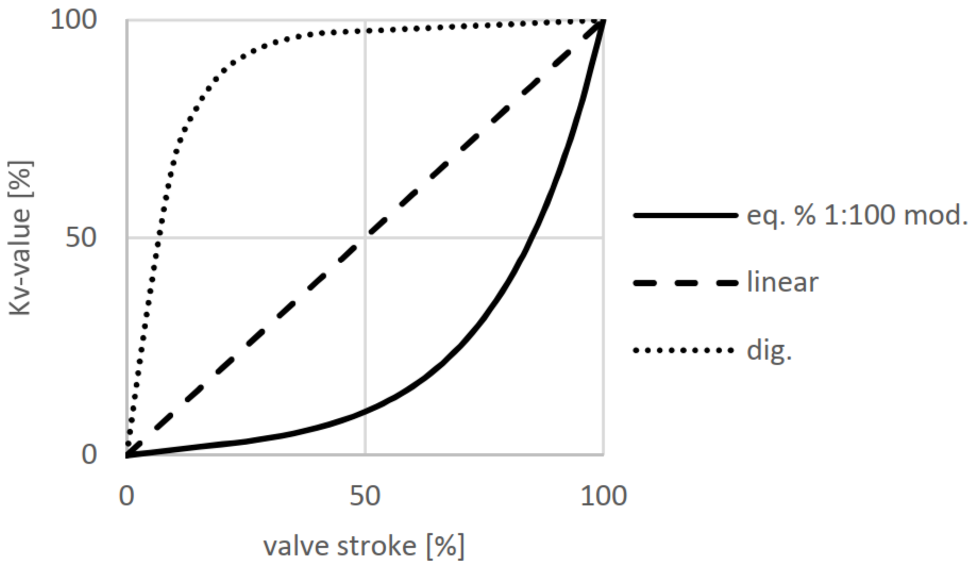
K_v is the m3/h of H_2O at 5-40 °C flowing at Δp = 1 bar

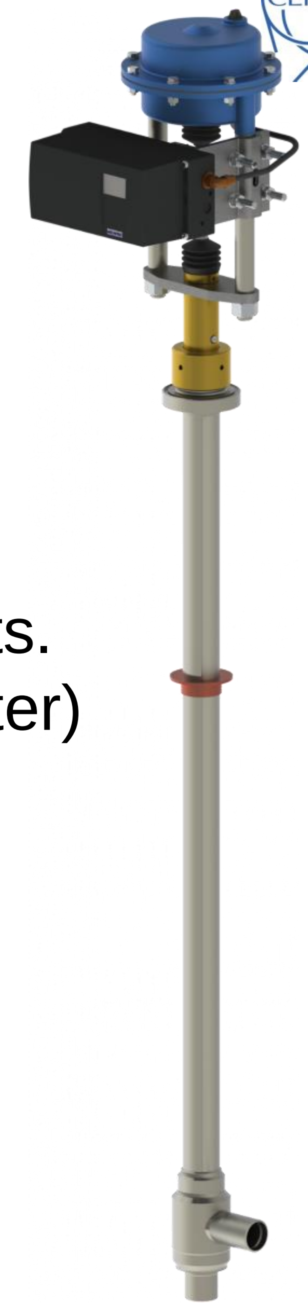
Non-compressible volumetric flow though a valve:

$$Q = K_v \sqrt{\Delta p . \rho_{water} / \rho_{fluid}}$$

Cryogenic valves are characterized by long stems with thermal intercepts.

Knowledge of fluid parameters permit to recalculate flow (virtual flowmeter)

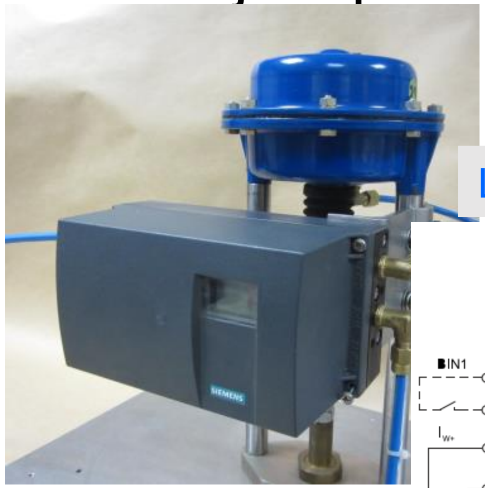




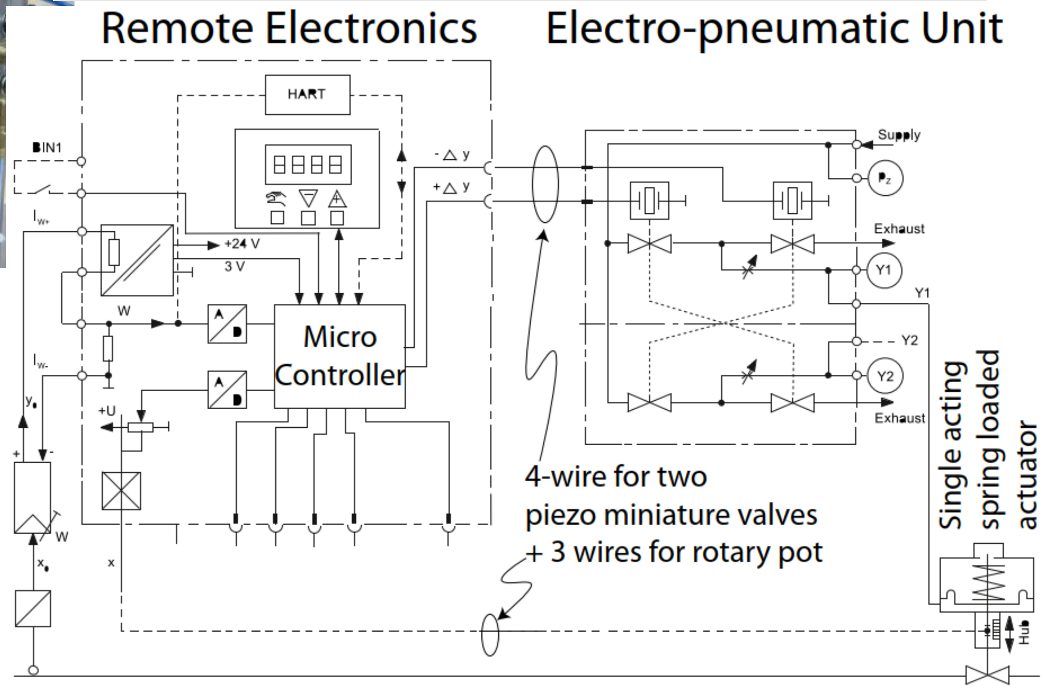
Actuators: intelligent valve actuators

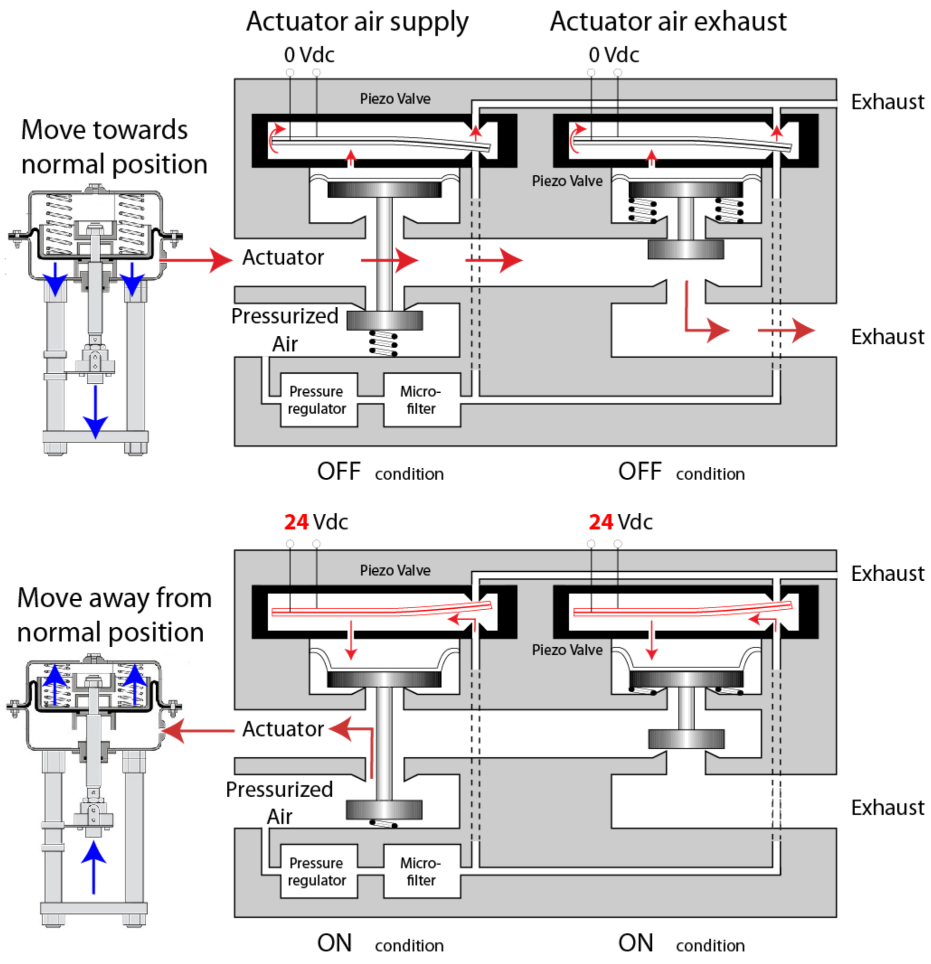
CERN cryogenic facilities are using SIPART intelligent valve positioners:

- Reduce air consumption
- Provide fail safe operation & diagnostics
- Adjust position according to potentiometer



LHC version: split design to cope with radiation





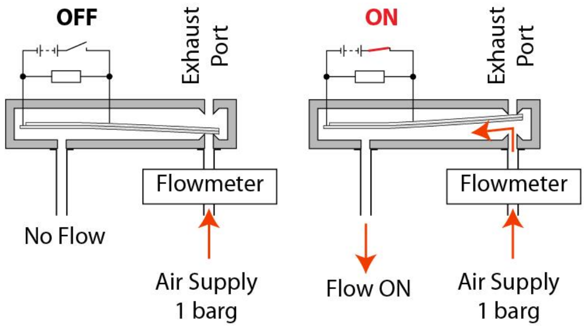
Actuators: intelligent valve actuators

LHC split SIPART intelligent valve positioners:

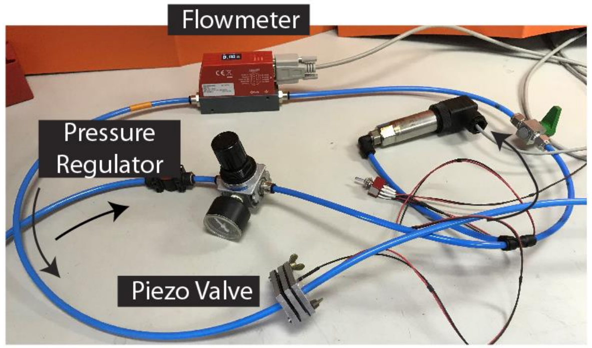
- Electronics in radiation free area
- Piezo actuators & rotary valve potentiometer exposed to radiation
- Interconnection cable length up to about 2 km

Piezo actuators qualified to HiLumi operation

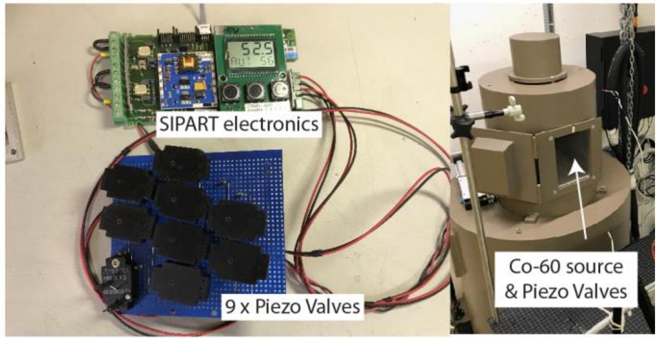
Radiation results
Tested 10 piezo actuators
“cooling” => 111 days without radiation
First failures from 137 kGy

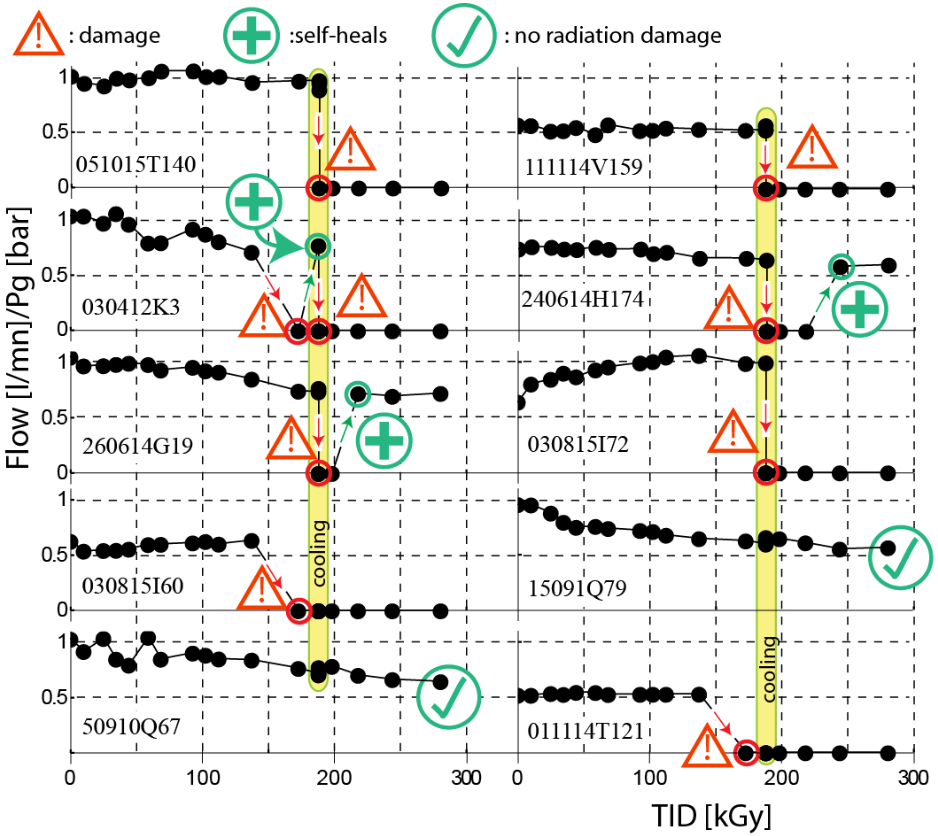


Laboratory Functional test



Radiation test





Reading Material

- J. Casas, "LHC thermometry: laboratory precision on an industrial scale in a hostile environment: tutorial 52," in IEEE Instrumentation & Measurement Magazine, vol. 17, no. 1, pp. 57-64, February 2014, doi: 10.1109/MIM.2014.6782999.
- F. Pavese, Lessons learnt in 50 years of cryogenic thermometry, Chapter in “Cryogenic Engineering: Fifty Years of Progress”, Timmerhaus and Ross eds., Springer, New York, 2006, ch.10, pp. 179-221.