NPL Thermal Measurement Awareness Network

Institute of Physics Low Temperature Group

British Cryogenics Council

Low Temperature Thermometry

Thursday 24th November 2005
St. Hugh’s College
St Margaret's Road, Oxford, OX2 6LE

Cryogenics is an important enabling technology for a wide variety of activities and processes in industry, medicine and scientific research. Good thermometry is essential to the successful production and exploitation of low temperatures, through liquid nitrogen to liquid helium and ultra low temperatures. The object of the meeting is to review recent developments in low temperature thermometry and anticipate new requirements for cryogenic temperature measurement.

Registration Deadline: 15 November 2005

Provisional Programme

09.30	Registration and coffee
0955	Welcome, (Graham Machin, NPL)
10.00	Overview: industrial perspective on cryogenics in the UK (Nanna Heiberg, Danfysik)
10.25	Scales and international thermometry. (Stephan Schoettl, NPL).
10.50	Cryogenic sensors: performance and applications at Oxford Instruments (Vladimir Datskov, Oxford Instruments Superconductivity)
11.15	New development in cryogenic sensors (Joe Yeager, LakeShore Cryotronics)
11.40	Temperature measurements in high magnetic fields (David Taylor, Durham University)
12.00	Discussion
12.30	LUNCH: posters and exhibition
14.00	Bolometry using high sensitivity NTD germanium thermometers (Adam Woodcraft, Cardiff University)
14.20	Thermometry down to 300 mK for space instrumentation (David Smith and Anne-Sophie Goizel, RAL)
14.40	A noise thermometer for ultra-low temperatures (Chris Lusher, Royal Holloway University of London)
15.00	Coulomb blockade thermometry (Matthias Meschke, Helsinki University of Technology)
15.30	New processing for semiconductor resistance thermometers and Hall probes (Paul McDonald, University of Southampton, Institute of Cryogenics)
15.50	Concluding discussion

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THERMAL MEASUREMENT AWARENESS NETWORK:

Low Temperature Thermometry; 24 November 2005

Registration Deadline: 15 November 2005

Please Register me for this meeting at a cost of £50* ☐

Name --

Position --

Company --

Address --

Telephone --

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To facilitate any workshops, are there any specific issues or questions relating to Low Temperature Thermometry that you would like to see addressed at this meeting?

☐ Tick here if you do not wish to become a member of the Thermal Awareness Measurement Network and receive details of future meetings.

☐ Tick here if you would like further information about being an exhibitor at this meeting.

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Overview: Industrial Cryogenics; Thermometry needs

Nanna Heiberg
British Cryogenics Council &
Oxford Danfysik Beamlines Ltd

Abstract ⇒ Agenda

- ➢ Cryogenics for bulk storage of gases and the use of those gases
- ➢ Refrigeration applications using Cryogens
- ➢ Temperature maintenance/stability using Cryogens
- ❖ Industries and specific applications
- ❖ Thermometry needs for each application

Cryogenics Bulk Storage; why?

- Transportation cost savings
- Storage space savings
- Controlled temperature take-off
- Controlled gas purity
- Controlled storage of flammable gases
- These days cryogenic storage is commonly used because the low temperature aspect of it is routine

Some uses of gases stored cryogenically: Inerting

- Oil and chemical industry
  - Vessel blanketing
  - Purging vessels and pipe lines
  - Propellant gas to move inventory
- Milling and grinding
  - Dust explosion prevention
- High precision electronics
  - High purity gas supply for cleanliness

Thermometry requirements

- Ensure temperature of gas supplied to application
- High or low temperatures may cause process faults
- Sensor environment benign
- Mechanical robustness required

- ✓ Low cost
- ✓ Reliability
- ✓ Stability over time
- ✓ Robustness
- o Absolute accuracy
- o Temperature range limited

Some uses of gases stored cryogenically: Feedstock

- Food packaging and beverages
  - Oxidation retardation
  - Carbon Dioxide (large scale)
- Oxygen to power stations and steel mills
- Breathing air for divers
- Gases for hospitals

Thermometry requirements

- Ensure temperature of gas supplied to application
- High or low temperatures may cause process faults and/or be fatal
- Sensor environment benign
- Mechanical robustness required

- ☐ Low cost
- ✓ Reliability
- ✓ Stability over time
- ✓ Robustness
- ☐ Absolute accuracy
- o Temperature range limited

Cryogens for Refrigeration

➢ Mechanical grinding

- Rubber and plastics
- Aromatics (e.g. spices)
- Fatty substances

Cryogens for Refrigeration

- Food freezing
- Largely going mechanical for large scale, such as burgers
- Still a requirement where quick, at source freezing is needed e.g. peas and raspberries.
- Seasonal variations, such as turkeys, can be alleviated by boosting mechanical freezing with cryogenics

Cryogens for Refrigeration

- Civil Engineering
- Largely going mechanical.
- Still used for smaller projects.
- Sometimes brought to the rescue of other techniques

Cryogens for Refrigeration

- Cryo-preservation
- Used very widely for many (small) tissue batches
- Quick freezing important
- Long term reliable storage often required

Thermometry requirements

- Ensure temperature of liquid/gas supplied to application
- High temperatures may cause process faults
- Sensor environment benign
- Mechanical robustness required

- ✓ Low cost
- ✓ Reliability
- ✓ Stability over time
- ✓ Robustness
- ☐ Absolute accuracy
- ☐ Temperature range to 77K

Cryogens for Refrigeration

- Solvent/VOC Recovery
  - Recovering a volatile component from a gas stream; e.g. Acetone from a Nitrogen stream.
  - The volatile component is liquefied and recovered in liquid form by gravity, while the gas stream is vented to atmosphere
  - Multi-component streams can be treated.

Cryogens for Refrigeration

- Reaction Cooling
- Used in Pharmaceutical rather than chemical plants
- Reagents are cooled prior to an endothermic reaction.
- Once the reaction takes place the heat of reaction is removed
- 3 methods of removing the heat; direct, semi-direct and indirect.

Thermometry requirements

- Ensure temperature of liquid supplied to application
- High temperatures may cause process faults
- Sensor environment NOT benign
- Mechanical robustness required

- ✓ Low cost
- ✓ Reliability
- ✓ Stability over time
- ✓ Robustness
- ✓ Absolute accuracy
- ✓ Temperatures to 77K

Cryogens for Temperature Maintenance

- ➢ MRI and other Superconducting magnet applications
- MRI for body scanners (4.2K)
- MRI with pumped Helium ciruits
- Research magnets (NMR)
- Power storage
- HTc magnet systems

Thermometry requirements

- Ensure temperature of cooled components
- Magnetic fields will affect the thermometer
- Sensor environment affects performance
- Mechanical robustness not so critical

- ☐ Low cost
- ✓ Reliability
- ✓ Stability over time
- ☐ Robustness / packaging
- ✓ Stability / performance in magnetic fields
- ✓ Absolute accuracy for some applications
- ✓ 4K or lower

Cryogens for Temperature Stability

- Removing heat from critical components during operation.
- Test stations for mechanical components
- Climate control for testing circuit boards
- Observatory platforms
- High energy particle physics experiments

Thermometry requirements

- Intimate contact with element being cooled
- Sensor environment NOT benign
- Inaccessible locations

- ☐ Low cost
- ✓ Reliability
- ✓ Stability over time
- ☐ Robustness / packaging
- ✓ Stability in magnetic fields/X-rays etc
- ☐ Absolute accuracy for some applications
- ✓ Wide temperature range

Summary of Thermometry requirements

- ✓ Low cost
- ✓ Reliability
- ✓ Stability over time
- ✓ Robustness
- ✓ Stability in magnetic fields/X-rays etc
- ✓ Absolute accuracy for some applications
- ✓ Wide temperature range
- ✓ Range of ‘packaging’

British Cryogenics Council

- ✓ An umbrellas organisation for cryogenics in all areas of work
- ✓ Provides a network for those working in cryogenics
- ✓ Provides a first port of call for those needing advice on cryogenics

British Cryogenics Council

- ✓ Has several publications in the area of cryogenics
    - ✓ Safety Manual
    - ✓ Data Handbook
    - ✓ Storage and handling of Cryogens
    - ✓ History of Cryogenics
- ✓ Provides a quarterly newsletter to members

British Cryogenics Council

- ✓ Recently relaunched website provides better communication and easier membership
- ✓ Corporate pages
- ✓ www.bcryo.org.uk

Thank you!

National Physical Laboratory

Temperature Scales and International Thermometry

Stephan Schöttl

Low Temperature Thermometry meeting
St. Hugh’s College, Oxford, 24 November 2005

Temperature: Units and Scales (1)

- Definition
  - Potential for heat transfer
- Units
  - Kelvin (water triple point)
  - Degree Celsius (Kelvin)
  - others (historic, specialist)

Temperature: Units and Scales (2)

- Thermodynamic temperature:
  ideal gas, Planck law, noise, …
- Temperature Scales
  - From ambient to colder temperatures
    ITS-90 and predecessors
  - Independent low temperature scales
    Vapour pressures
    ^{3}He melting pressure
- Define procedures for approximating thermodynamic *T* measurements using practical thermometers

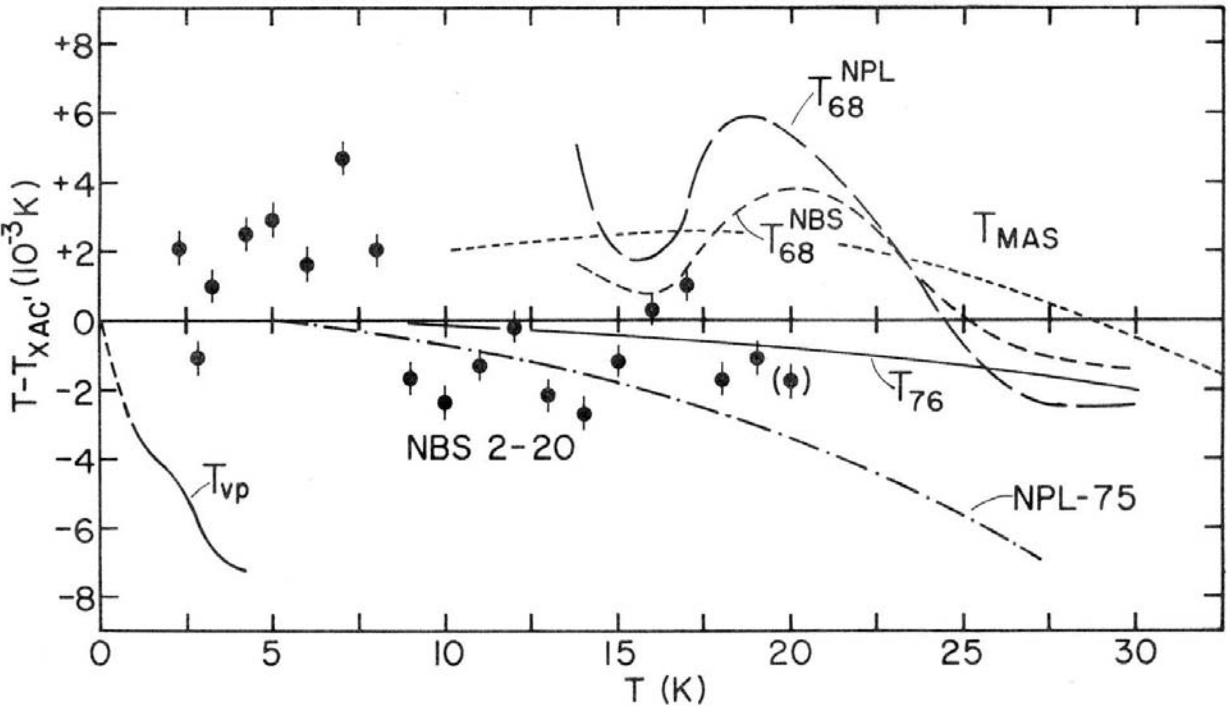
ITS-90 History (1)

- IPTS-68
  - based on scales from NBS & Penn State U, NPL, PRMI (USSR)
  - first international low temperature scale below 90 K
  - down to 13.81 K
- ^{3}He and ^{4}He vapour pressure scales
  - 1958 (^{4}He) and 1962 (^{3}He)
  - up to 5.2 K

ITS-90 History (2)

- EPT-76
  - provisional low temperature scale
  - combine IPTS-68 and vapour pressure
  - corrections to VP scales
  - unresolved thermodynamic inconsistencies
  - smooth interpolation
  - 0.5 K to 30 K

ITS-90 History (3)



- $T_{XAC'}$: magnetic (Iowa State Univ. 1974)
- T_{76}: EPT-76 ($T_{XAC'}$ minus quadratic)
- T_{NPL-75}: CVGT (NPL, ≈ T_{abs})
- T_{68}: IPTS-68 as realised at NPL and NBS
- T_{MAS}: magnetic (Iowa State / NML Australia 1975)
- $T_{NBS\ 2-20}$: acoustic (NBS 1965)
- T_{VP}: vapour pressures

- scales maintained on GRTs and RIRTs (NPL)

ITS-90 (1) — General

- Replaces IPTS-68 and EPT-76
  - improved practical thermometers
    - stability, sensitivity
    - RIRT vs. GRT
  - removes known deviations from thermodynamic *T*
  - new thermodynamic measurements
    - gas thermometry (CVGT, acoustic, ε)
- Down to 0.65 K
- Uncertainty: 0.5 mK below 27 K, up to 1.5 mK above (1σ)

ITS-90 (2) — Details

- Triple points:
  - – H_2, Ne, O_2, Ar, Hg, H_2O
  - – 13.8 K to 273 K
- Boiling points:
  - – H_2 (333 hPa and 1013 hPa)
  - – 17.0 K and 20.3 K
- Vapour pressure:
  - – ^{3}He and ^{4}He
  - – 0.65 K to 3.2 K and 1.25 K to 5 K

ITS-90 (3) — Interpolation

- Interpolating gas thermometer
  - 3.0 K to 24.6 K
- Platinum resistance thermometer
  - down to 13.8 K
  - defined “ideal” temperature dependence of *W*
  - defined deviation function
  - determination of coefficients by calibration at fixed point temperatures

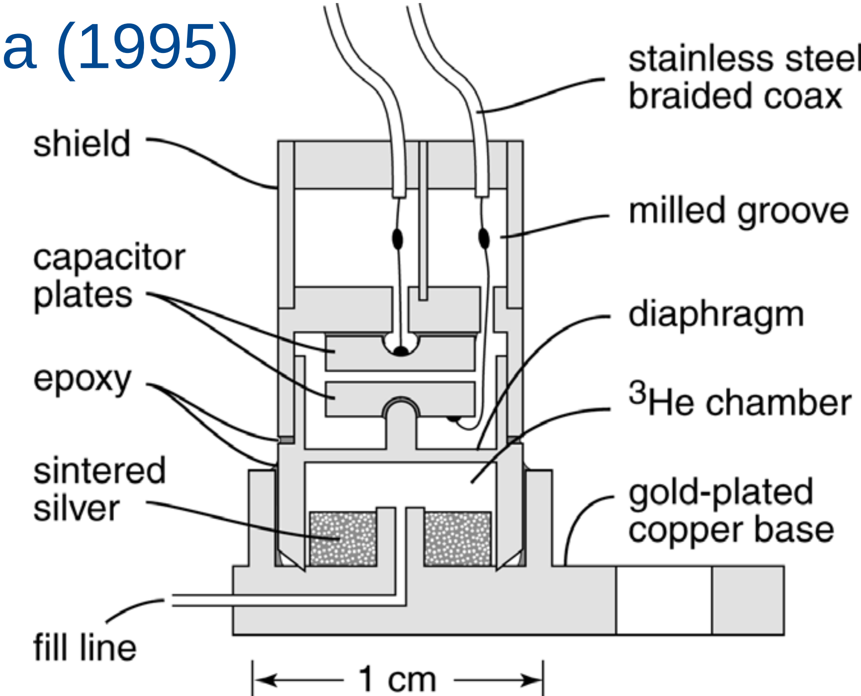
Photo: Tinsley

ULT Scales (1)

- Thermodynamic *T* measurements:
  - magnetic susceptibility (T_{x1} at NPL down to 500 mK)
  - Johnson noise
  - nuclear orientation
  - nmr
  - new: Coulomb blockade
- ^{3}He melting pressure curve:
  - high sensitivity, high sample purity, “simple” equipment
  - self-calibrating at feature temperatures
  - measure thermodynamic *T* and absolute pressure

ULT Scales (2) — ^{3}He melting curve

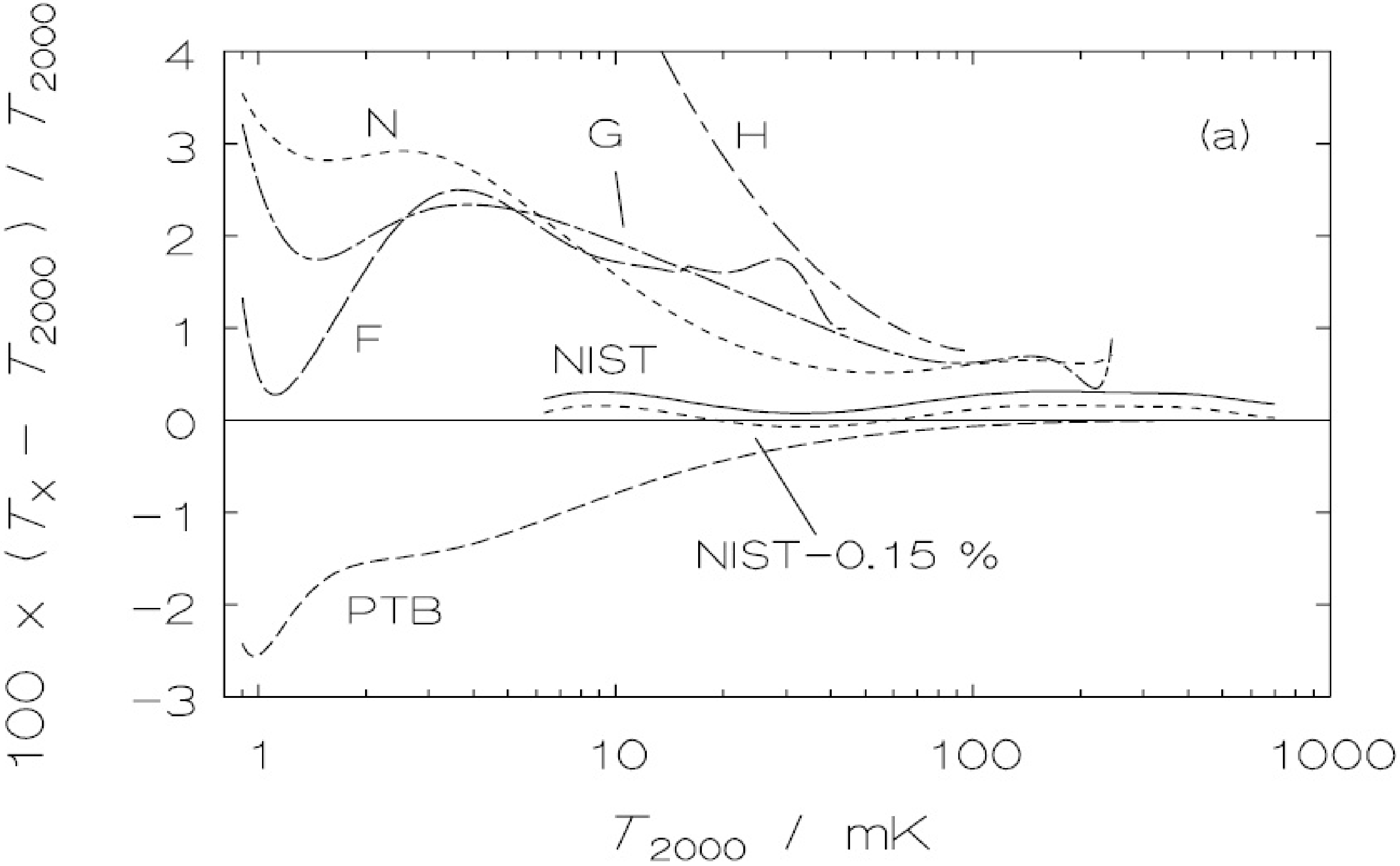
- Suggested 1970 (Scribner & Adams, Univ. of Florida)
- Laboratory scales
  - Greywall & Busch, Bell Labs (1982 & 1986)
  - Fogle et al., NIST (1992 & 1998)
  - Adams et al., Univ. of Florida (1995)
  - Schuster et al., PTB (1996)



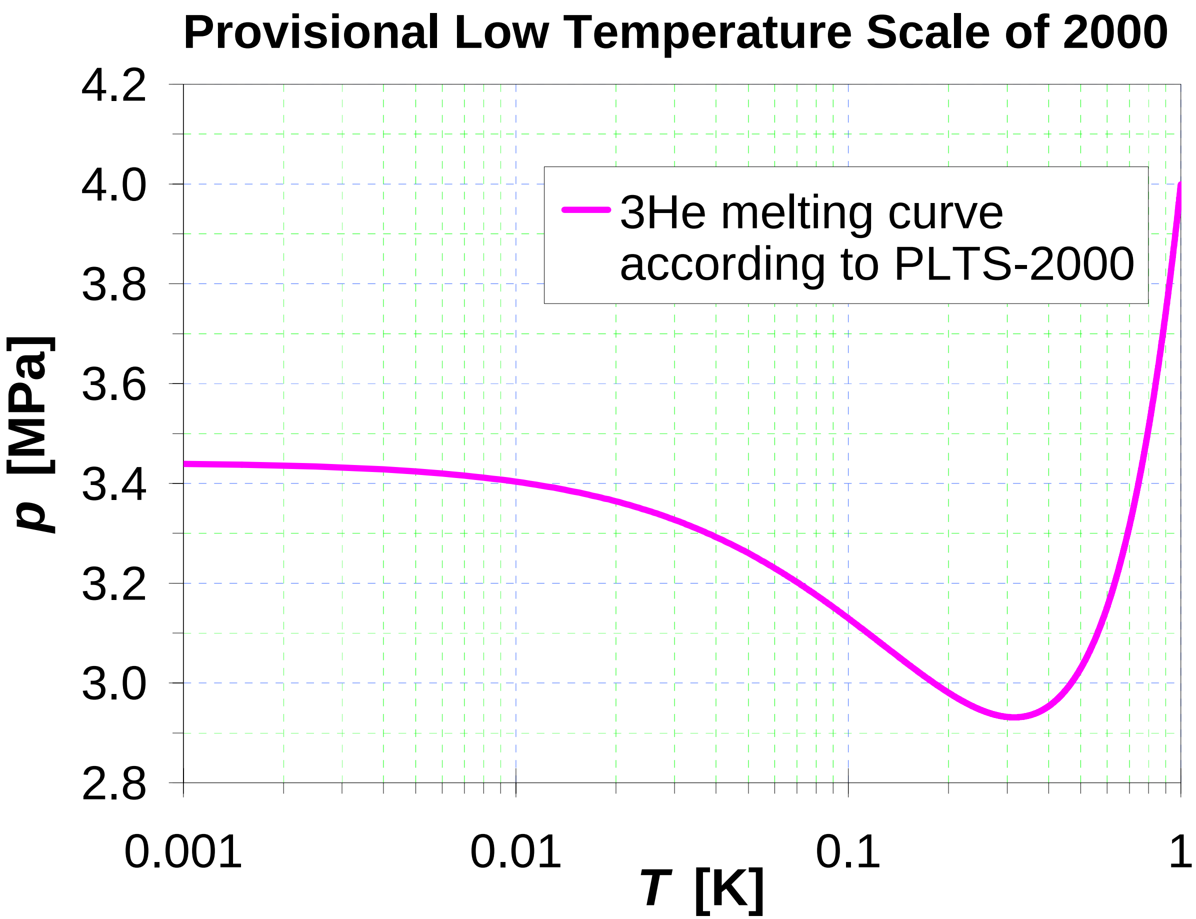
ULT Scales (3) — PLTS-2000

- PLTS-2000
  - provisional
  - remaining discrepancies

H: Halperin
N: U. Florida
G: Greywall
F: Fukuyama



ULT Scales (4) — PLTS-2000



Point	***p*/MPa**	**T_{2000}/mK**
minimum	2.93113	315.24
A	3.43407	2.444
A-B	3.43609	1.896
Néel	3.43934	0.902

Maintenance and Usage (1)

- Devices for scale maintenance:
  - fixed point (triple point) cells
  - resistance thermometers:
    - ♦ capsule type
    - ♦ RIRT, PRT
  - superconductive transitions:
    - ♦ used in EPT-76
    - ♦ SRM-767, -768
    - ♦ SRD-1000
  - ^{4}He lambda point
  - multicells

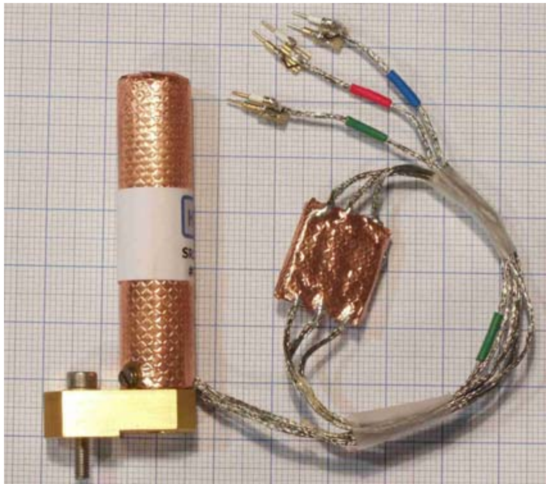


Photo: HDL Hightech
Development Leiden

Maintenance and Usage (2)

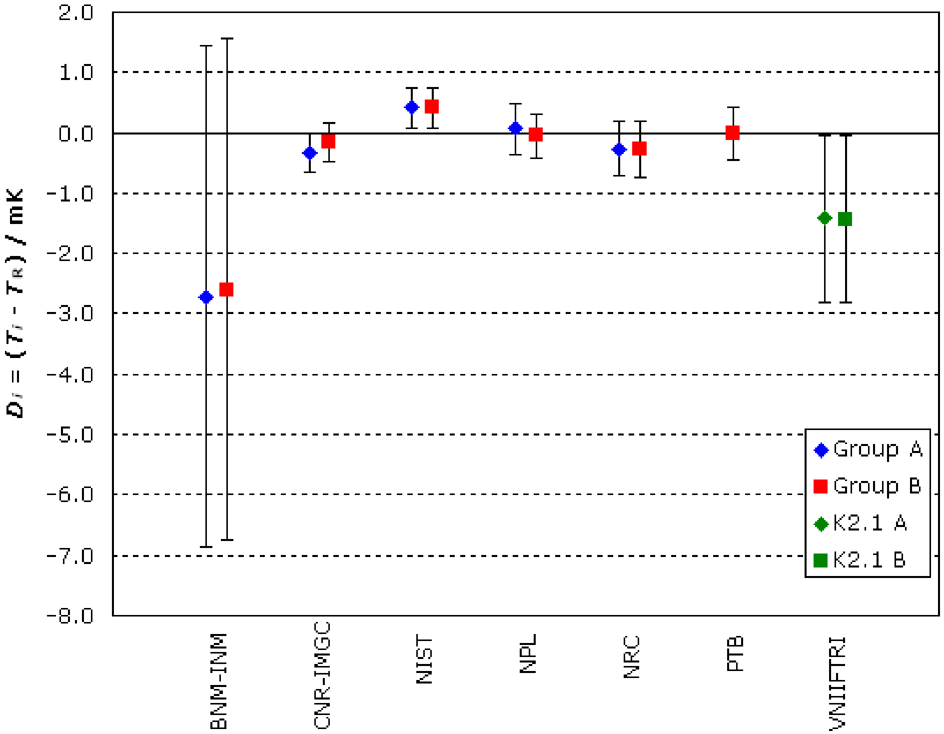
- Calibration:
  - fixed point cells
  - comparison to calibrated thermometers
- Traceability:
  - reference to national standards
  - unbroken chain of comparisons
  - propagation of uncertainties

International: Metre Convention

- Established 1875, now 51 countries
- CGPM (Conférence Générale des Poids et Mesures)
- CIPM (Comité International des Poids et Mesures)
  - BIPM (Bureau International des Poids et Mesures)
  - CCT (Consultative Committee for Thermometry)
- Mutual Recognition Arrangement 1999
  - degree of equivalence of national standards
  - mutual recognition of calibrations

BIPM KCDB

- Key comparison database at BIPM
  - – results of comparisons of national standards
  - – list of “Calibration and Measurements Capabilities”
- Example:
  PRTs at H_2 triple point



International Metrology

- EUROMET
    - collaboration of NMIs
    - EU, EFTA and accession states (+ EU commission)
    - similar organisations in other regions
- iMERA
    - EU FP6 & EUROMET
    - increase impact of metrology investment
    - collaborative projects & shared facilities
    - coordinating existing national programmes
- Accreditation
- Legal metrology

National Physical Laboratory

The End — Thank you!

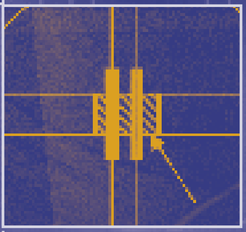
Temperature Scales and International Thermometry

Stephan Schöttl

Low Temperature Thermometry meeting
St. Hugh’s College, Oxford, 24 November 2005

Thermometry

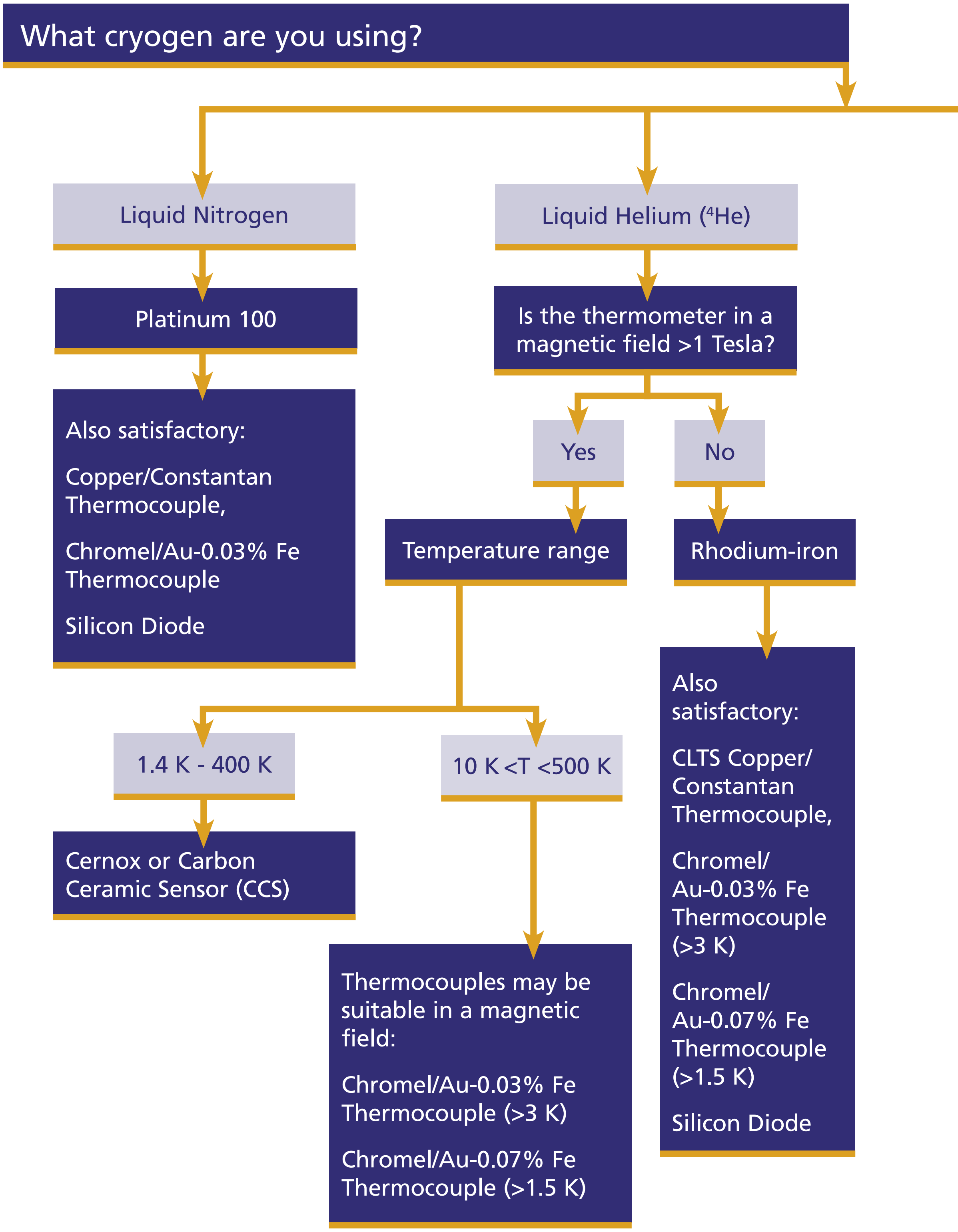
- CCS and Cernox sensors for 1.4 K – 400 K and low sensitivity to magnetic fields
- Nuclear orientation thermometry for ULT applications (<50 mK)
- Capacitance sensors for low sensitivity to magnetic fields
- Rhodium-Iron sensor for 1.4 K to 900 K
- Thermocouples for high temperatures
- Silicon diodes and CLTS for accurate calibration over a wider range



Oxford Instruments provides a comprehensive range of temperature sensors enabling precision measurement and control from 300 K down to 3 mK. We are pleased to introduce several new sensors: the economical Carbon Ceramic chip enables measurements from 1.4 to 300 K in the presence of high magnetic fields, with superior stability; the $_{60}$Co source, together with our nuclear orientation electronics enables measurement in the 3 – 50 mK range, crucial for dilution refrigerators, complementing our R_uO_2 sensor, optimal for temperatures from 50 mK to 4.2 K.

Standard sensors such as Cernox, Rhodium-Iron, CLTS, capacitance sensors and thermocouples provide a variety of temperature ranges and sensitivities, optimal for your experimental conditions. All of the above are compatible with our ITC series of temperature controllers without requiring customization or special ordering. We provide calibration options appropriate to your experimental needs and budget.

Guide to Sensor Selection



What cryogen are you using?

Liquid Nitrogen

Platinum 100

Also satisfactory:

Copper/Constantan Thermocouple,

Chromel/Au-0.03% Fe Thermocouple

Silicon Diode

Liquid Helium (^{4}He)

Is the thermometer in a magnetic field >1 Tesla?

Yes

Temperature range

1.4 K - 400 K

Cernox or Carbon Ceramic Sensor (CCS)

10 K <T <500 K

Thermocouples may be suitable in a magnetic field:

Chromel/Au-0.03% Fe Thermocouple (>3 K)

Chromel/Au-0.07% Fe Thermocouple (>1.5 K)

No

Rhodium-iron

Also satisfactory:

CLTS Copper/ Constantan Thermocouple,

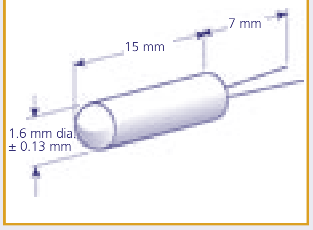
Chromel/ Au-0.03% Fe Thermocouple (>3 K)

Chromel/ Au-0.07% Fe Thermocouple (>1.5 K)

Silicon Diode

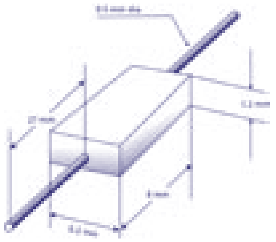
Platinum 100 Ω

Temperature range: 70 to 900 K



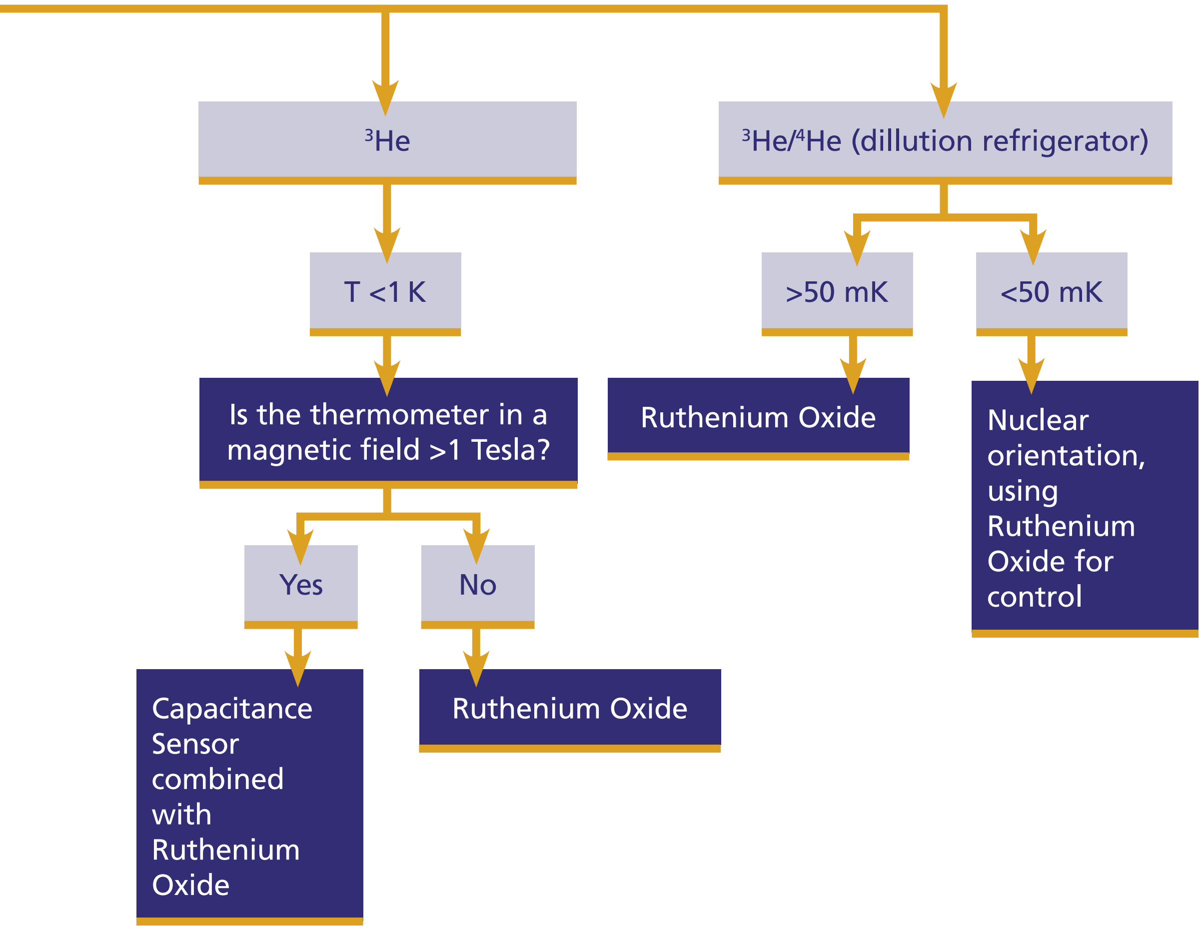
CCS

Temperature range: 1.4 to 373 K



Cernox

Temperature range: 1.4 to 420 K



^{3}He

^{3}He/^{4}He (dillution refrigerator)

T <1 K

Is the thermometer in a magnetic field >1 Tesla?

Yes

Capacitance Sensor combined with Ruthenium Oxide

No

Ruthenium Oxide

>50 mK

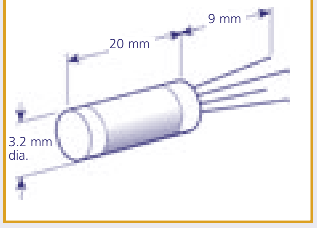
Ruthenium Oxide

<50 mK

Nuclear orientation, using Ruthenium Oxide for control

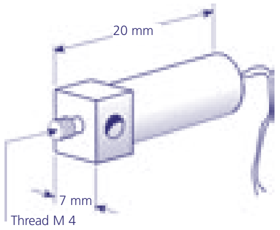
Rhodium-Iron

Temperature range: 1.4 to 800 K



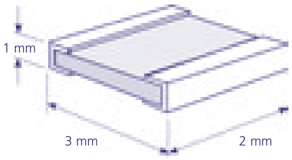
Ruthenium Oxide

Temperature: Max 4.2 K



Capacitance Sensor

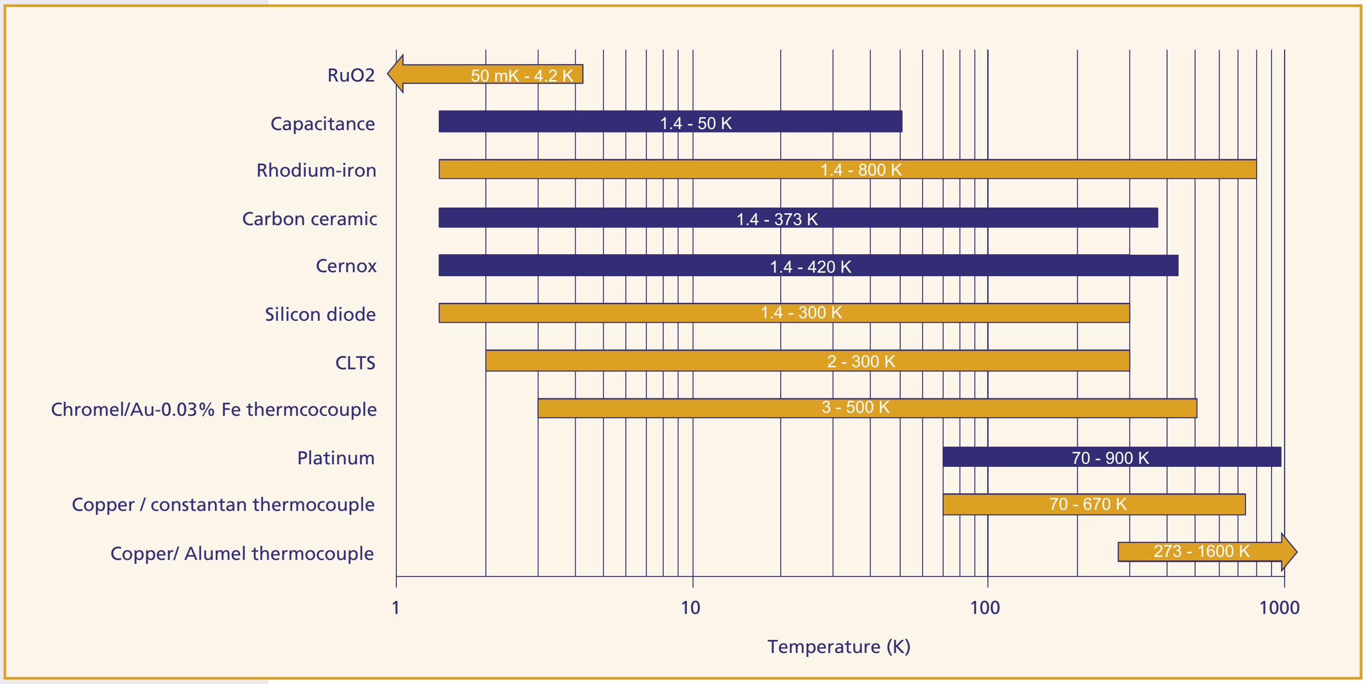
Temperature range: 1.4 to 50 K

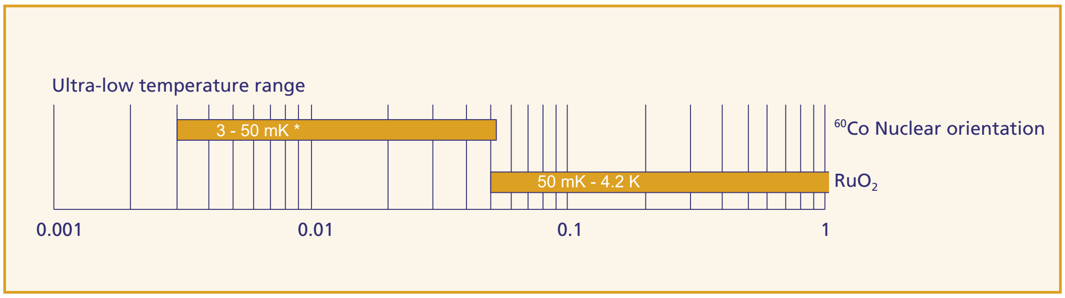


Miniature Silicon Diode

Temperature range 1.4 K to 300 K

Recommended Sensor Temperature Ranges





Notes

* Nuclear orientation thermometry is sensitive to external magnetic fields, and the source can be damaged by high fields. See sensor page for details.

🟦 Suitable for use in magnetic fields

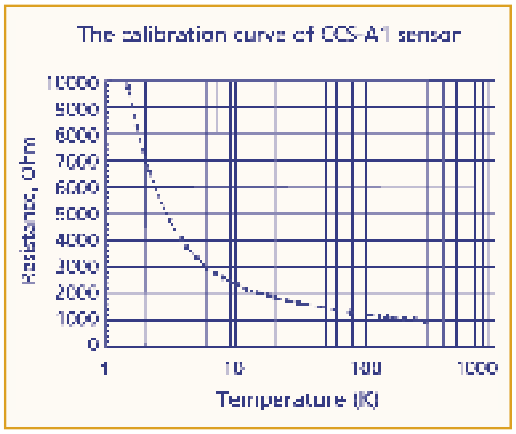
🟧 **Not** Suitable for use in magnetic fields

Carbon Ceramic Sensor - Temperature Range: 1.4 to 300 K

Oxford Instruments introduces a new sensor, suitable for use in high fields. Performance is similar or superior to the Cernox sensor in most respects. The carbon ceramic sensor (CCS) is a 2-leads device for 4-wire measurement, possessing high sensitivity, excellent stability and robustness. Its long-term stability is better than 15 mK at 4.2 K after 15 years. It is recommended for accurate temperature measurement in industrial and in high neutron irradiation environments. An excitation current of 100 µA is used over a temperature range of 77.4 K to 300 K and 10 µA is typical over 1.4 K to 77.4 K.

Two groups of calibrated sensors with different sensitivities at 4.2 K are available. Versions are available with 3-point calibration for temperature range 3 K-110 K and with 24–point calibration (1.4 K, 2.5 K and 4.2 K to 300 K) for applications requiring higher degree of accuracy.

The upper calibration temperature could be extended up to 373 K. Calibrated sensor is supplied with data, polynomial curve fit and table of the fit.



Properties at 4.2 K:

- magnetic field error ~1 % at B ≤6 T;
- heat capacity 1.3*10^{-4} J/gK;
- time response ~1 ms;
- weight 0.075 g

1. Sensor Accuracy for 24 point calibration

Temperature	1.4 K	4.2 K	77 K	273 K
Accuracy	10 mK	10 mK	40 mK	0.1K

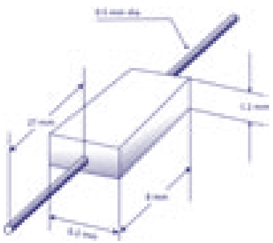
2. Sensor Accuracy for 3 point calibration

Temperature	3K	10K	30K	110K
Accuracy	25 mK	70 mK	0.5K	2K

Catalogue Numbers by Sensitivity and Temperature Range				
Sensitivity at 4.2K (Ω/K)	24-point calibration A - (1.4 – 300 K)	24-point calibration B - (2.5 – 300 K)	24-point calibration C - (4.2 – 300 K)	3-point calibration D - (3 - 110 K)
(1) 800 - 1200	T2-101	T2-111	T2-121	T2-131
(2) 500 - 800	T2-102	T2-112	T2-122	T2-132

CCS

Temperature range: 1.4 to 373 K



Cernox

Temperature range: 1.4 to 420 K

Canister

Hermetic

Cernox™ Resistance Sensor - Temperature Range 1.4 K to 420 K

The Cernox 1050 resistance sensor is the standard sensor for use in magnetic fields up to and in excess of 20 Tesla as it has a very small magnetic field dependence.

The Cernox is available in two packages: the canister package and the hermetic package.

The canister package is somewhat more robust and is convenient for insertion in a hole. It has four colour-coded leads, 15 cm long.

The hermetic package is advisable in situations where reduced size or a fast thermal response time is necessary. The hermetic package is slightly magnetic. This may have an effect on some very sensitive magnetic measurements, but since the total mass of ferromagnetic material is only a small fraction of the total sensor mass (itself only 40 mg), the effect will be negligible in most cases.

Any Oxford Instruments 500 series temperature controller (ITC 501, 502, or 503) can be used.

Calibration

A calibration, if purchased, includes:

- Certificate of calibration. This states that the calibration conforms to the International Temperature Scale (1990), and is traceable to NIST
- Measured calibration data (hard copy and floppy disk)
- A fit to the data based on Chebychev polynomials, with deviations (hard copy and floppy disk)
- An interpolation table (hard copy and floppy disk)
- With proper calibration, sensor operates to 420° K

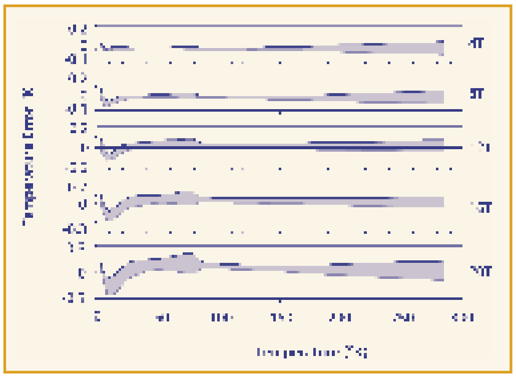
The magnetic field dependence has been described in detail in fields up to 32 T between 2 and 286 K (see graphs and reference below).

Specifications

Canister package	Hermetic package	
Thermal response	0.4 sec at 4.2 K	15 msec at 4.2 K
Temperature limit	325 K	325 K
Long-term stability	±25 mK in the range 1 K to 100 K 0.05% of temperature in the range 100 K to 325 K	

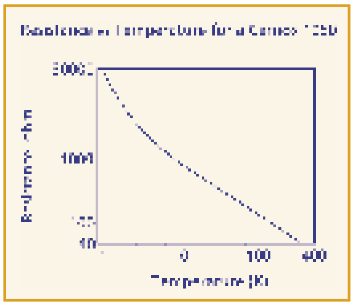
Temperature error due to magnetic field, K

The error in measured temperature due to magnetic field is likely to lie between the upper and lower lines in each graph. (Canisters mounted with long axis parallel to magnetic field)



Reference

Low temperature thermometry in high magnetic fields VII. Cernox sensors to 32 T, B.L. Brandt *et al,* Rev. Sci. Instrum., vol 70, No 1, 1999, pp 104-110.



Ordering information

	Uncalibrated	Calibrated (1.4 – 300 K)	Calibrated (1.4 – 420 K)	Mounting clamp
Canister	T1-107	T1-108	T1-111	-
Hermetic	T1-109	T1-110	T1-112	A6-106 (with 2.1 mm hole for fixing screw)

27 Ω Rhodium-Iron - Temperature Range 1.4 K to 800 K

The Rhodium-Iron 27 Ω sensor is a 4-wire device possessing excellent stability. An excitation current of 1 mA is typical. The resulting change in temperature due to self-heating is less than 1 mK over the range 1.4 to 300 K, provided the sensor is properly installed.

Two standard versions of the sensor are available: three-point calibration and full calibration. The full calibration is made between 1.4 and 300 K. When a three-point calibration is used, two of the reference points can be used to adjust the span and zero of a standard curve stored in the temperature controller. A generic calibration curve is available over the full range 1.4 – 800 K. At present calibration data for individual sensors is not available above 300 K.

A full calibration, if purchased, includes:

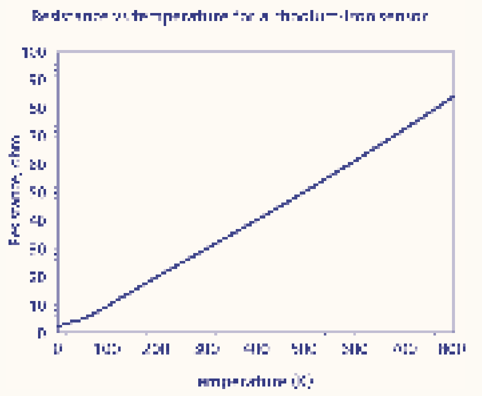
- Certificate of calibration. This states that the calibration conforms to the International Temperature Scale (1990), and is traceable to NIST
- Measured calibration data (hard copy and floppy disk)
- A fit to the data based on Chebychev polynomials, with deviations (hard copy and floppy disk)
- An interpolation table (hard copy and floppy disk)

The table below shows the percentage relative error when rhodium-iron resistance sensors are used in magnetic fields. The use of these sensors at temperatures less than 80 K is not recommended in the presence of magnetic fields.

Rhodium-Iron resistance laboratory standards are also available. Please contact your Oxford Instruments representative for further information.

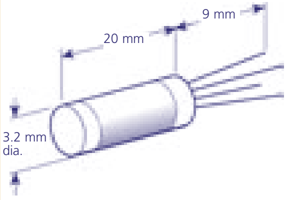
Magnetic field dependence of rhodium-iron sensors

|ΔT|/T (%) in magnetic field B				
T	B			
	2.5 T	8 T	14 T	19T
4.2 K	11	40 (6 T)	–	–
40 K	1.5	12	30	40
87 K	0.2	1.5	4	6
300 K	0.01	0.1	0.4	–



Rhodium-Iron

Temperature range: 1.4 to 800 K



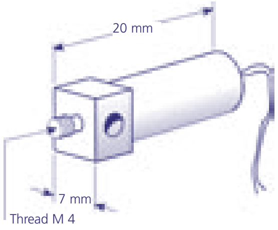
Ordering Information

	Sensor	Mounting block	Temperature controller/monitor
Three-point calibrated sensor	T1-102	A6-101	ITC 501, 502, 503, or 601 (standard curve already stored)
Fully calibrated sensor	T1-103	A6-101	ITC 501, 502, or 503

Ruthenium Oxide Temperature Sensors

- Temperature Range 50 mK - 4.2 K

Ruthenium oxide
Temperature: Max 4.2 K



The thick film RuO_2 chip sensor has been mounted in a gold-plated copper holder. The holder is designed to give a good thermal contact between the sensor and the object of interest while also minimising the mechanical strain on the sensor. Such a strain can cause the calibration to change after thermal cycling. The sensor is wired using four 0.2 mm diameter (36 SWG) polyester enamel coated copper wires, a pair each for the excitation current and measured voltage.

The thermometers have a nominal resistance of 2210 Ω at room temperature, and about 25000 Ω at 50 mK. The sensor has a thread which may be screwed into an ISO metric M4 tapped hole. It also has a clearance hole so that it can be fixed with an M3 bolt.

Ruthenium oxide sensors have relatively small magneto-resistance. For information, see "Magnetoresistance of RuO2-based resistance thermometers below 0.3 K", by Watanabe *et al*, Cryogenics, vol 41, p 143 (2001).

Ordering Information	
30-point (Roth1) calibrated sensor	T1-201
Generic (Roth2) Calibration	T1-202

Calibration

Ruthenium oxide sensors are available with two forms of calibration:

Type "Roth1": A full individual calibration. At temperatures below 650 mK the Provisional Low Temperature Scale PLTS-2000 was applied using a ^{3}He melting curve thermometer. At temperatures above 650 mK the ITS-90 was applied using calibrated germanium resistance thermometers traceable to the US-NIST with the atmospheric boiling point of ^{4}He being used as a fixed point. Checks were made using a CMN paramagnetic susceptibility thermometer and a superconducting fixed-point device.

The accuracy of the Type 1 calibration is

50 mK	<	T ≤150 mK	± 5 mK
150 mK	<	T ≤1.5 K	± 10 mK
1.5 K	<	T ≤4.2 K	± 30 mK

Type "Roth2": A 'generic' calibration. These sensors come from the same production batch as the Type 1 sensors and are mounted on the same type of support. They are thermally cycled to create reproducible resistance versus temperature characteristics. They are supplied with calibration based on the average of a representative sample of Type 1 sensors.

The accuracy of the Type 2 calibration is

50 mK	<	T ≤150 mK	± 19 mK
150 mK	<	T ≤1.5 K	± 70 mK
1.5 K	<	T ≤4.2 K	± 200 mK

The International Temperature Scale (ITS-90) and the Provisional Low Temperature Scale (PLTS-2000) have been used.

Both calibrations are accompanied by a document giving advice on sensor mounting and temperature measurement.

Temperature range

The range of calibration (both types) is 25 mK - 4.2 K.

Below 50 mK the sensor does not give accurate results. It can, however, be be used for temperature control purposes in the range 20 – 50 mK in conjunction with another thermometry system (eg nuclear orientation).

Measurement equipment

Above 240 mK, an Oxford Instruments ITC 501, 502, 503 can be used (see Electronics).

Below 240 mK, an AC bridge or IGH with Femtopower card must be used (see Electronics section).

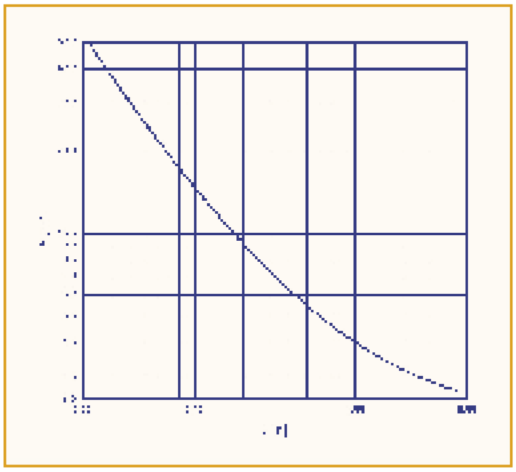
The thermal time constant of the sensor (determined by its heat capacity and thermal resistance to the holder) increases as the temperature drops, and may be several minutes at the lowest temperatures.

Self heating and radio frequency heating

It is important to ensure that the heat dissipated in the sensor is not sufficient to raise its temperature above that of the experimental apparatus. This heat can come from a variety of sources, but in resistance thermometry the most common source of problems is a high excitation current. In general, heat dissipation of the order of one picowatt (10^{-12} W) is acceptable in the milli-kelvin range.

Currents can also be induced by radio frequency (R.F.) interference. These problems can be reduced by screening the cables and using low pass electrical filters on all wires going into the cryostat.

The Oxford Instruments Femtopower system supplied with dilution refrigerators performs a pseudo DC measurement which has been optimised to measure RuO_2 sensors and allows filtering of the measurement lines down to very low frequencies. The Femtopower system can also be fitted to an ITC503.



Typical resistance against temperature curve for a 2210 Ω ruthenium oxide sensor.

Miniature Silicon Diode - Temperature Range 1.4 K to 300 K

Miniature Silicon Diode

Temperature range 1.4 K to 300 K

This fast responding sensor is useful where space is a restriction and a wide temperature range is required.

The sensor may be mounted on a flat surface by applying GE varnish to the back surface and very carefully pressing it down onto its mating surface. Great care must be taken not to damage the 25 µm gold wire bonded to the diode.

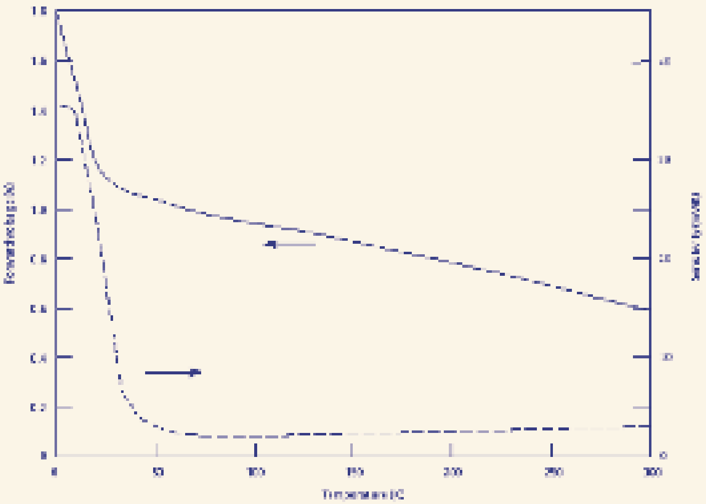
A typical sensor conforms to the standard voltage versus temperature relationship to within ± 0.1 K at 4.2 K and ± 0.5 K at 77 K. Individual calibrations are not supplied.

Magnetic Field Dependence Of Silicon Diode Sensors

	IΔTI/T (%) in magnetic field B	
T	(B = 1 T)	
	Junction parallel to field	Junction parallel to field
4.2 K	43	5
77 K	0.2	0.3

Silicon diodes exhibit strong orientational dependence when used in magnetic fields.

Silicon diode voltage (solid line) and sensitivity (dashed line) as a function of temperature (typical curves)



Catalogue Number	Temperature Controller/Monitor
T1-104	ITC 501, 502, 503, or 601 (standard curve already stored)

CLTS Temperature Sensor - Temperature Range 2 to 300 K

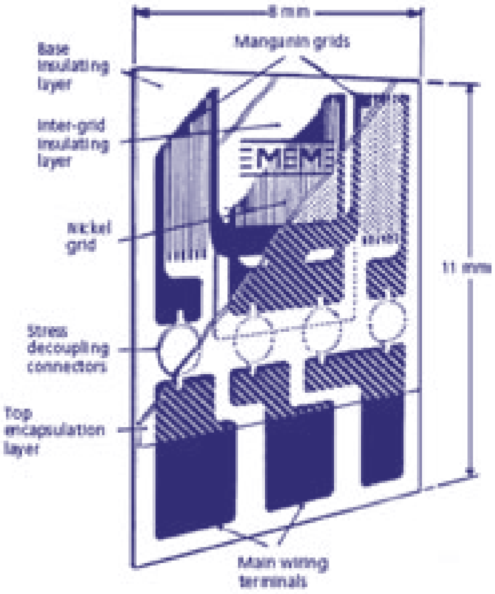
The Cryogenic Linear Temperature Sensor (CLTS) is a flat flexible sensor, incorporating manganin and nickel foil sensing grids, designed to have equal and opposite non-linearities. It is the only available sensor with a nearly linear dependence of resistance with temperature.

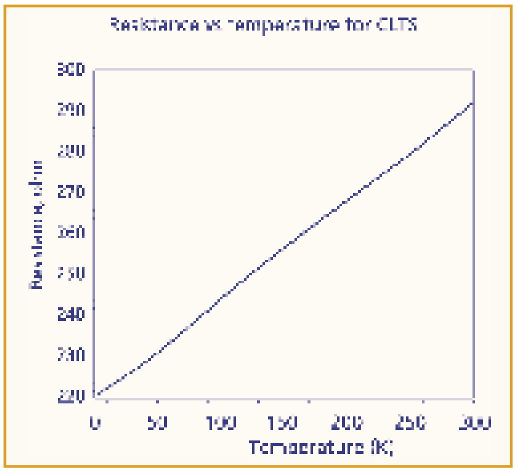
Because of its low mass and thin construction (only 0.1 mm thick, mass 0.02 g), the CLTS responds to temperature changes accurately and quickly. Special design features protect the sensor from damage due to thermal shock, even during plunges from room temperature directly into liquid nitrogen or liquid helium.

The CLTS is not recommended for use in strong magnetic fields.

It can be mounted using M-Bond 600 epoxy-phenolic adhesive (Vishay Measurements Group), or another suitable low viscosity adhesive, ensuring that the glue layer is as thin as possible. The sensor should be clamped in position while the adhesive cures. It can be mounted on flat or curved surfaces. The bonding surface is chemically and mechanically treated for proper bonding.

The CLTS is slightly sensitive to strain caused by differential contraction. As with any sensor, it is recommended that the resistance at the boiling point of helium is checked after installation.

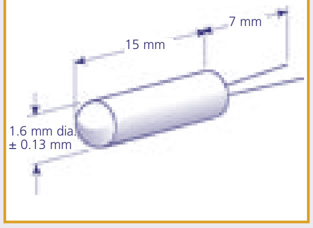




Catalogue number	Temperature Controller/Monitor
T1-105	ITC 501, 502, 503 (standard curve already stored)

Platinum 100 Ω

Temperature range: 70 to 900 K



Platinum 100 Ω Resistance Thermometer

- Temperature Range 70 K to 900 K

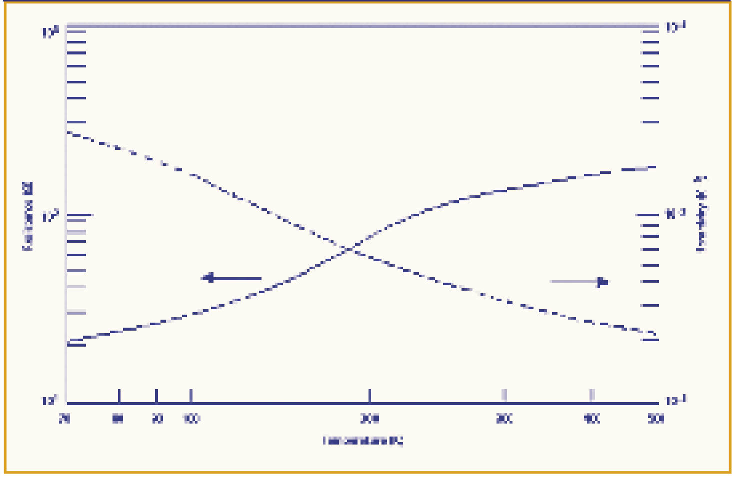
Each sensor conforms to BS 1904/1984 Class A, Band 4 and is supplied with a temperature resistance ratio chart. It is not available with individual calibration.

Platinum resistance sensors may be used in magnetic fields. The table on the right shows the percentage relative temperature error in magnetic fields to 19 Tesla.

Valves for long axis of sensor parallel to field

|ΔT|/T (%) in magnetic field B				
T	B			
	2.5 T	8 T	14 T	19T
87 K	0.04	0.4	1	2
300 K	0.01	0.02	0.07	0.13

Resistance (solid line) and sensitivity (dashed line) as a function of temperature for the platinum 100 Ω sensor (typical curves)



Ordering information

Sensor	Mounting block	Temperature controller/monitor
T1-101	A6-102	ITC 501, 502, 503, or 601 (standard curve already stored)

Thermocouples

Fast response time and a small physical measuring junction size make thermocouples a useful choice of sensor where accuracy is not an important consideration.

Every thermocouple needs a reference junction or junctions at a known temperature. For cryogenic applications it is best to put the reference junction in liquid nitrogen in a small dewar or foam bucket (see Cryogen Handling).

Room Temperature compensation (with the reference junction at room temperature) is suitable for high temperature applications but not recommended for cryogenic work. There are two reasons for this:

a) Thermocouple sensitivity tends to fall at low temperatures so a small room temperature error will cause a larger low temperature error.

b) The actual thermocouple wires must be taken all the way from the cryostat to the controller, since no compensating cable is available for common cryogenic thermocouples.

Type	Temperature range	Temperature controller or monitor
Copper / Constantan	70 - 670 K	ITC 501, 502, or 503
Chromel / Alumel	273 - 1600 K	ITC 501, 502, or 503
Chromel / Au-0.03%Fe	3 - 500 K	ITC 501, 502, or 503
Chromel / Au-0.07%Fe	1.5 - 500 K	ITC 501, 502, 503, or 601

Order information for single wire is shown in top right table. Other thermocouple materials and diameters are available on request.

Order information for twisted pairs of wires is shown in the middle table on the right.

Thermocouple wires			
Wires	**Dia. (mm)**	**Insulation**	**Catalogue Number**
Copper	0.2	Polyester	T4-101
Constantan	0.2	Polyester	T4-102
Chromel	0.3	Trimel	T4-103
Chromel	0.2	Polyester	T4-104
Alumel	0.2	Uninsulated	T4-105
Gold - 0.03% Iron	0.3	Polyester	T4-106
Gold - 0.07% Iron	0.2	Polyester	T4-107

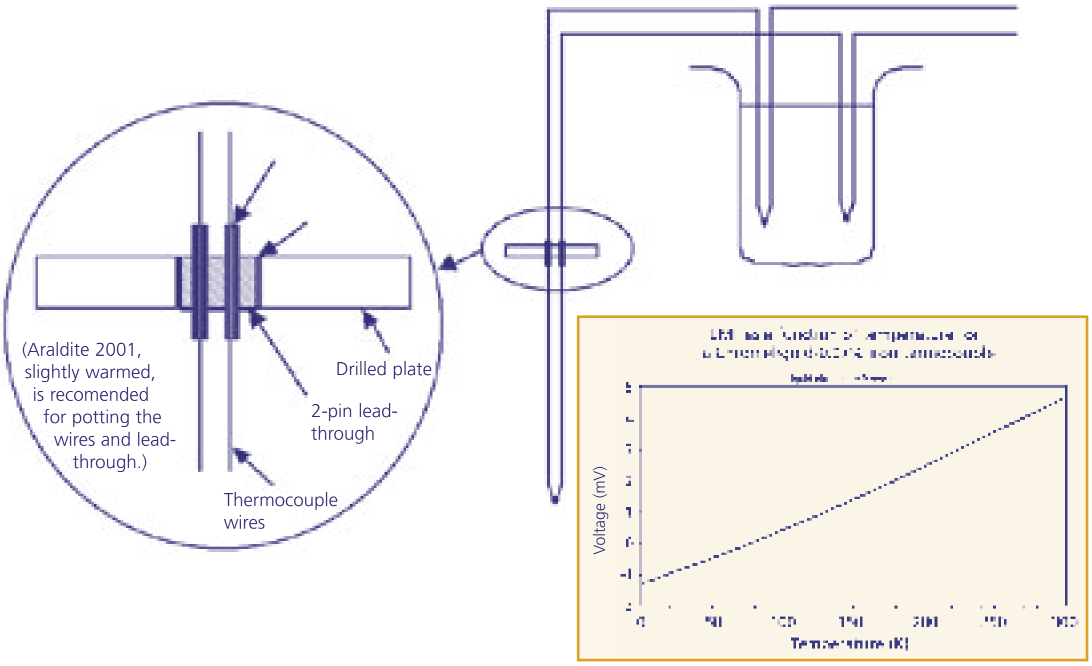
Thermocouple twisted pairs		
Twisted Pairs	**Insulation**	**Catalogue Number**
Copper/Constantan (Type T)	PTE Insulated	T4-108
Chromel/Alumel (Type K)	PTE Insulated	T4-109

Thermocouple wiring and accessories

A thermocouple can be wired in a number of different ways. An example is shown on the next page.

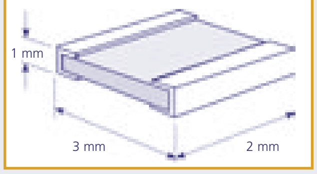
Accessories (see Cryogenic Accessories for details)	Catalogue Number
Thermocouple mounting clamps	A6-104
Hermetic feedthrough assembly for an existing O.I. hermetic wiring port:	
Feedthrough plate using either	
Blanking plate drilled to accept one leadthrough + 2-pin leadthrough (hollow)	A1-122 + A1-120
OR	
3 x 2-pin seal (hollow)	A1-129
Shroud	A1-105
Flexible cable clamp	A1-104

Thermocouples continued



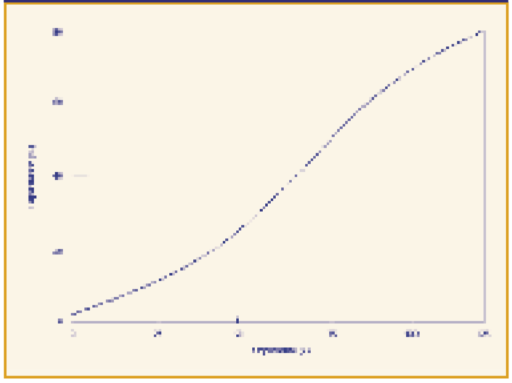
Capacitance Sensor - Temperature Range 1.4 K to 50 K

Capacitance sensor
Temperature range: 1.4 to 50 K



Unlike other cryogenic temperature sensors, capacitance sensors are virtually unaffected by magnetic fields. They are ideal sensors for temperature control in fields up to 20 T and above. However, since they exhibit drift due to aging and thermal cycling, they are not suitable for absolute temperature measurement. The ITC502 and 503 temperature controllers can be fitted with a capacitance range card for temperature measurement with this sensor. When used in conjunction with a temperature controller, it is recommended that a sensor with good long term stability (e.g. rhodium-iron) be used to establish the desired temperature in zero magnetic field. Control is switched to the capacitance sensor to maintain temperature stability while the magnetic field is applied.

Capacitance as a function of temperature for a capacitance sensor



Catalogue Number	Temperature Controller/Monitor
T1-301	ITC 501, 502, 503 with capacitance range card

Nuclear Orientation Thermometry

- Temperature Range 3 mK to 50 mK

The principle of the Nuclear Orientation Thermometer (NO Thermometer) is based on the measurement of the nuclear magnetic polarization of radioactive nuclei (single crystal of Co with ^{60}Co impurities) by detecting a spatial anisotropy of the emitted γ-rays.

The temperature range: 1 mK to 100 mK. Use is commonly limited to a maximum ~ 50 mK because of the long integration periods necessary at higher temperatures). This is the primary technique used by Oxford Instruments at millikelvin temperatures. Nuclear orientation thermometry may be used to calibrate much faster thermometers, like Pt-NMR, PdFe susceptibility, carbon or RuO_2 resistor thermometers.

Accuracy: 0.1% - 0.5% (between 3 mK to 50 mK)

The main advantages of the NO thermometer are:

- It is a primary thermometer and measures absolute temperature
- It is simple to mount on the object and does not require wiring

Practical issues to be considered:

- It is slightly radioactive and requires special precautions (typically ≤5 µCurie)
- It requires certain time to measure temperature (typically few hundreds of seconds)
- **It is sensitive to the external magnetic field and crystal can be damaged in high magnetic field**

Due to the radioactivity of the source (approximately 5 µCu), Oxford Instruments requires evidence of regulatory compliance when ordering, such as a site license for handling radioactive materials.

Detection technique

Oxford Instruments supplies a nuclear multi-channel analyser (MCA) with following specifications:

- MCA including high voltage amplifier, Wilkinson-ADC and microcomputer integrated in a NaI(Tl) detector socket
- 4 hours battery powered with internal rechargeable NiMH batteries
- Low weight: 450 g without battery 550 g with batteries
- Dimensions: diameter 62 mm x 125 mm high
- The MCA is directly attached to the NaI detector socket. The advantage is that no HV and signal cable are needed
- Serial data transfer to a notebook or a computer via RS-232 cable (up to 38,4 k baud, cable included)
- Stand-alone measurement possible without PC/notebook
- Power supply to operate the nanoSPEC and/or charge the internal batteries
- Standard Windows MCA software winTMCA in English
- Complete documentation manuals in English

We provide a choice of NaI (Tl) scintillation detectors with integral line structure and magnetic shielding:

- Type: 51 B 51/2, 2” x 2” thick, energy resolution: ≤7,5 % at 662 keV(Cs137)
- Type: 76 B 76/2, 3” x 3” thick, energy resolution: ≤8 % at 662 keV(Cs137)

Product	Catalogue Number
^{60}Co Source	T3-101
Multichannel Analyser	T3-102
NaI Scintillation Detector, type 51B	T3-103
NaI Scintillation Detector, type 76B	T3-104

Suggested references:

Nuclear Orientation Thermometry, H. Marshak, Journal of Research of the National Bureau of Standards, 88, 175-217, 1983

R. J. Soulen, H. Marshak, Cryogenics, 20, 408, 1980

Nuclear Orientation Thermometry (H. Marshak) in Low Temperature Nuclear Orientation, N. J. Stone, H. Postma (eds), North Holland, 1986

Matter and Methods at Low Temperatures 2nd edition by F. Pobell page 296. Nuclear Orientation Thermometry

How to Choose A Sensor

Sensitivity, stability and accuracy data is given for guidance only, and is not guaranteed.

1. Stability

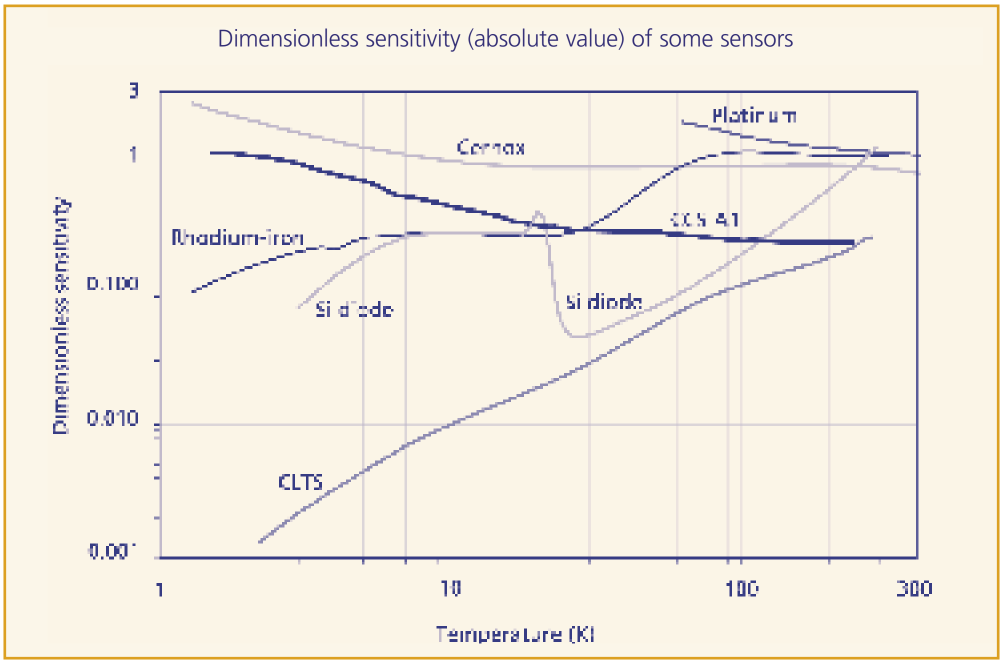
Since most sensors are rarely if ever recalibrated after being installed, stability is the most important factor affecting the measurement accuracy. The table shows the long-term stability of some sensors.

Sensor stability

Sensor type	Stability (mK/year)		
	at 4.2 K	at 77 K	at 300 K
Rhodium-iron	10	10	10
Platinum	-	100	100
Silicon diode	30	30	30
CLTS	500	500	500
Capacitance	>1000	>1000	>1000
Cernox	25	25	150
Carbon ceramic sensor	15 mK in 15 years	data not available	

2. Sensitivity

If a sensor exhibits high sensitivity then less precision is required in the measuring system to achieve a given level of accuracy. High sensitivity sensors usually have a narrow useful temperature range. The figure shows the dimensionless sensitivity of some of the resistance sensors. The figure illustrates the exceptionally high sensitivity of the Cernox at low temperatures.


Dimensionless sensitivity (absolute value) of some sensors

Dimensionless sensitivity $\frac{dR}{dT}\frac{T}{R}$ or $\frac{dV}{dT}\frac{T}{V}$, where T = absolute temperature, R is resistance and V is voltage.

3. Magnetic field

All sensors, except capacitance sensors, exhibit a dependence of their resistance or voltage on magnetic field. Some show a strong or unpredictable effect making them unsuitable for use in a magnetic field. Others show a weaker, quite predictable dependence. Capacitance sensors exhibit virtually no magnetic field effect and may be used for temperature control. They are not suitable for absolute temperature measurement.

4. Size

Listed in order of increasing size the sensors are: thermocouples, silicon diode, Cernox (hermetic package), platinum, rhodium-iron, Cernox (canister), mounted ruthenium oxide.

Application Notes

Sensor installation

Measurements undertaken with accurately calibrated thermometers are of little use unless attention is given to sensor mounting. When mounting sensors, consideration must be given to thermal contact, temperature range, strain effects and unwanted heat loads.

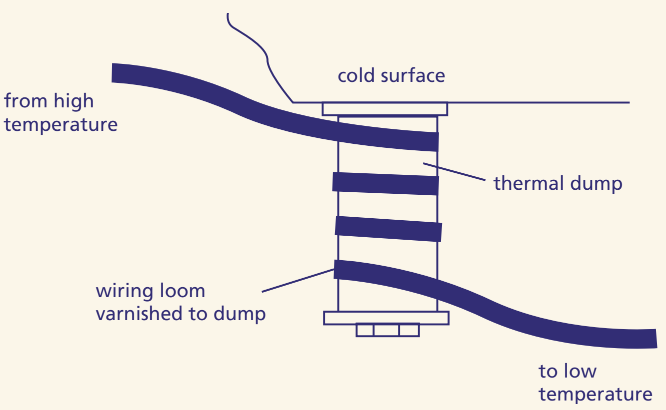
Cylindrical sensors are best mounted in a hole in the object to be measured, with a radial clearance of at most 0.1 mm. For temperature environments not exceeding 300 K, a thermally conductive grease (Type ‘N’ grease, A4-902) is recommended. For applications above 300 K, a high temperature sensor cement (C4-105) should be used. See Laboratory Essentials for specified consumables.

Thermocouples are usually brought into contact with the object to be measured using a clamp. Enhanced thermal contact is achieved by wrapping the junction in either indium (to 300 K), lead (to 500 K), or aluminium or copper tape.

Silicon diodes are very delicate and must be handled with care. The top face of the sensor must not be touched as this could result in damage to the diode chip or the 25 μm gold wire. The sensor may be mounted on a surface using GE low-temperature varnish (C5-101).

Sensors should never be mounted on a surface exposed to thermal radiation from room temperature. If necessary a covered mounting bracket should be fabricated. It is extremely important to ensure that the wiring for the sensor does not introduce unwanted heat loads. This is accomplished by thermally anchoring the leads on to the object to be measured. Additionally, wires should be anchored to intermediate stages in the cryostat to reduce conducted heat loads from room temperature. The simplest way is to wrap them around a copper post which is held at a known temperature. GE varnish is used to make sure that they are in good thermal contact with the post. Although its thermal conductivity is poor, it gives a large area of contact. See Figure below.

Thermal anchoring of leads



The same techniques can be applied to systems working at millikelvin temperatures. A heat load of 0.1 μW is enough to produce noticeable warming at these temperatures.

In a dilution refrigerator the wiring is typically fixed at the following temperatures:

- 4.2 K, cooled by the liquid helium bath, where the majority of the heat is absorbed
- 1.2 K, on the 1 K pot
- 0.6 K, on the still
- 50 mK, on the cold plate
- on the mixing chamber, to cool the wires to the same temperature as the experiment

If the wires are in gas or liquid – for example, if the experiment is carried out in liquid helium or helium gas in a variable temperature insert, the gas flows over the wires before it leaves the cryostat. This cools them effectively, and it is only necessary to make sure that sufficient length of wire is in contact with the cold gas. Allow the wires to spiral around some convenient mechanical support, such as a pumping line or support leg.

If it is important that the capacitance between the wires and ground is very low (for example, less than 100 pF), alternative methods of heat sinking have to be considered. One method is to clamp the wires firmly, and another is to encapsulate them in epoxy resin.

Sensor mounting at milli-kelvin temperatures

When measuring milli-kelvin temperatures it is essential that the sensor is in intimate thermal contact with the part of the apparatus whose temperature is to be measured. It is not always sufficient to attach the sensor to the refrigerator itself because there may be a significant temperature difference between the sample and the cold point of the refrigerator, especially when the experimental heat load is high. It is also possible that there will be significant temperature differences across the sample itself. The important parameter is the effectiveness of the heat transfer from the sample to the sensor.

In general good thermal contact (to a solid thermometer or holder) is obtained by face to face contact between two clean copper surfaces. Gold-plating the copper surfaces will improve thermal contact. The surfaces should be pressed together using a screw thread (or similar clamping method), so that there is a large force between them. It is important to avoid the presence of any superconducting materials in the thermal path because they are very good thermal insulators. Many solders become superconducting at milli-kelvin temperatures. In some cases it may be acceptable to suppress the superconductivity using a small magnetic field (<0.1 T). Superconducting transitions of a few common materials are listed in the Cryogenic Reference section. Non-superconducting solder is available.

At very low temperatures there is a large thermal resistance (“Kapitza resistance”) between liquid helium and any solid. When even a small amount of heat is supplied to the sample, its temperature quickly rises to a value much higher than that of the ^{3}He/^{4}He mixture. The most effective way to ensure good thermal contact between the sample and the mixture is to mount the sample directly onto a mixing chamber that has been designed with a very large surface area to make good thermal contact with the mixture.

Twisted pairs

Electrical noise is often picked up by an electrical circuit, and if sensitive measurements are being made the noise may make it difficult to detect a signal. The noise can also contribute to radio frequency heating of the sensor in ultra low temperature systems. One way of reducing the electrical noise pick up is to arrange the wires in twisted pairs. The wires are twisted together for their whole length, so that the currents induced by flux passing between the wires in each twist is cancelled by that in the next twist.

Thermo-electric voltages

If two dissimilar metals are joined together they act as a thermocouple, and small voltages (typically microvolts) can be generated. If very low voltage signals are being measured steps have to be taken to reduce the thermal voltages, so that they do not affect the readings. This is especially important at temperatures below 4 K, when very small excitation currents are required to prevent self-heating. As there are always some joints, it is important to ensure that the joints in all the wires are at exactly the same temperature. The dependence on temperature (near room temperature) of thermoelectric voltage with respect to copper (relative thermopower) is given in the table. These figures should be treated with caution, as the thermolectric properties of copper are very sensitive to purity.

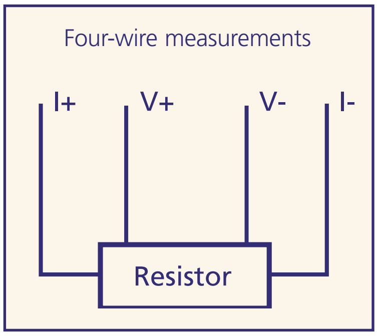
Thermoelectic voltage coefficient with respect to copper

Metal	µV/K
Copper	<0.3
Constantan (copper-nickel)	40
Gold	0.5
Silver	0.5
Brass	3
Beryllium Copper	5
Aluminum	5
Kovar or Alloy 42	40
Silicon	500
Copper-Oxide	1000
Cadmium-Tin Solder	0.2
Tin-Lead Solder	5

Four wire measurements

Cryogenic resistance thermometry requires the use of the four-wire technique. Using this technique a sensor with a resistance of a few ohms can be measured accurately through leads with a resistances of several hundred ohms. Two wires are used to supply the excitation current. The other two wires are used to measure the voltage across the sensor. Since there is almost no current flowing in these wires the voltage drop along them is tiny, and their resistance can also be neglected.

All Oxford Instruments temperature controllers and monitors use the four-wire technique.



Ultra-High Vacuum (UHV) systems

While some sensors in bare chip form or hermetic packages are reported to be suitable for use in UHV, it is always advisable to mount the sensor and wiring outside the UHV space if possible. Mounting sensors and thermally anchoring the wires is made much easier by use of greases, adhesives, varnish, insulating sleeving and fishing line, none of which are advisable in UHV.

Accuracy in temperature measurement

The Oxford Instruments ITC500 series of temperature controllers and monitors has designated excitation currents for each sensor offered which ensure negligible self-heating over the recommended temperature range.

Semiconductor resistance sensors have a resistance which rises rapidly with decreasing temperature. In the ITC500 series the sensor current is measured at constant voltage for these sensors. This reduces the risk of self-heating since the current is automatically reduced with decreasing temperature.

The tables below summarise the capabilities of the ITC500 series temperature controllers and monitors when used with fully calibrated sensors.

Sensor	Rhodium-Iron	Cernox
Temperature range for which these figures have been estimated	1.4 – 300 K	1.4 – 300 K
Display resolution	0.1 K	0.1 K
Accuracy	0.1 K	0.1 K

Accuracy of measurement for sensors used with the ITC501 monitor or the ITC502 controller

Sensor	Rhodium-Iron	Cernox
Temperature range	1.4 – 300 K	1.4 – 300 K
Display resolution		
T≤19.99K 20 K≤T≤199.99 K T≥200 K	1 mK 10 mK 100 mK	1 mK 10 mK 100 mK
Accuracy		
T≤19.99K 20 K≤T≤199.99 K T≥200 K	30 mK 30 mK 100 mK	30 mK 30 mK 100 mK

Accuracy of measurement for sensors used with the ITC503 temperature controller

References
"Cryogenic Thermometry: A Review of Recent Progress ", L. G. Rubin, Cryogenics, Vol 10, 14-20, (1970).
"Cryogenic Thermometry: A Review of Progress Since 1970", L. G. Rubin, B.L. Brandt and H.H. Sample, Cryogenics, Vol 22, 491 (1982).
"Cryogenic Thermometry: A Review of Progress Since 1982", L. G. Rubin, Cryogenics, Vol 37, 341-356, (1997).

reference

www.lakeshore.com

New Developments in Cryogenic Sensors at Lake Shore

Joe Yeager

LakeShore

mK *and* km
Developing new sensors

There are two new sensor developments at Lake Shore. The first is to provide sensors and calibrations to 10 mK, and the second is to multiplex hundreds of sensors over long distances. These two applications are beyond the present boundaries of commercial sensors.

There are two paths for developing a new sensor line

We are trying to expand the boundaries of conventional, commercial temperature sensors.

This boundary is set by the scientists and engineers doing new work, who are going colder, faster, farther, and bigger. Their work has progressed faster and farther than the existing tools allow.

Lake Shore is, fundamentally, a tool manufacturer. Specifically, thermometry tools. It is more efficient for a manufacturer if everybody wants the the same thing, but this field doesn't allow that. Working at the boundaries requires new tools.

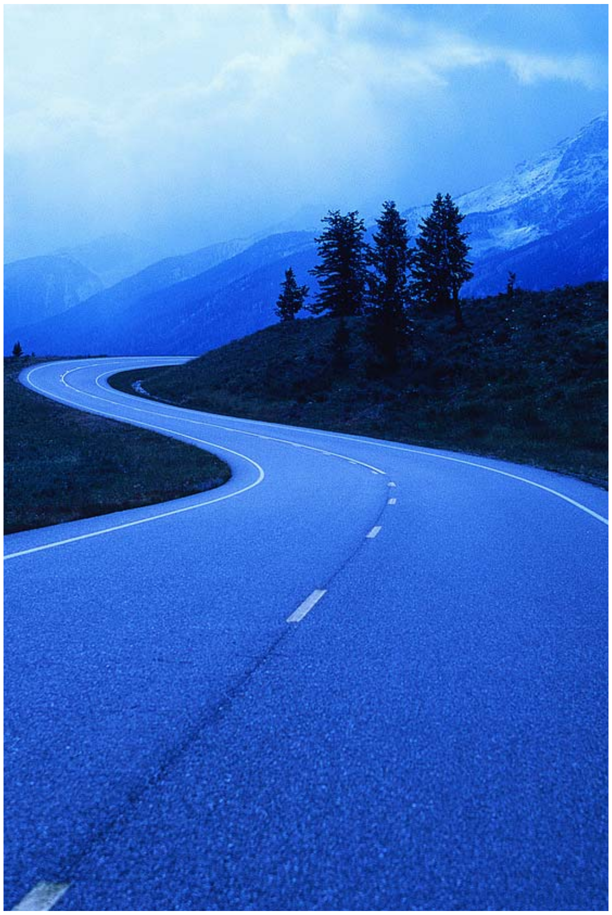
Now, one person can solve an immediate problem more quickly and cheaply than a company can. If there is no available commercial solutions, and it is a critically important problem, then "good" is just "good enough". It is necessary because there are no nicely packaged answers for these unique problems.

The difficulty lies in the fact that there are multiple people solving multiple problems. When someone else needs this tool at another university, how to you transfer a "good enough" process? How do you transfer the technology from small-scale to large-scale?

I see two paths:

1) Extend the current process/platform as far as it can go
2) Find a new platform

These two paths exist in work we are doing at Lake Shore. The first is an extension of RTDs to 10 mK or lower. The other to apply fiber optic sensors to cryogenic applications.



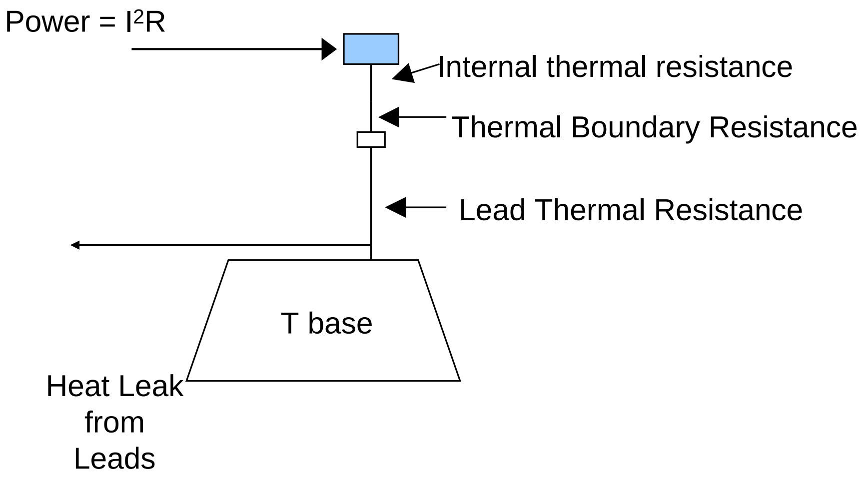
Method 1: Continue on the existing path

How cold can you really take a resistance thermometer before you give up and find a new method? Can it work to 10 mK or even lower? And if so, can it be reproducible so the whole community can benefit?

The advantage of staying with RTDs is that they are easy to use. The process doesn't change. Mount the sensor, measure resistance, convert to temperature.

The problem to overcome is thermal, and the difficulty this puts on packaging and instrumentation.

The sensor environment makes resistive thermometry very difficult



Power = I^2R

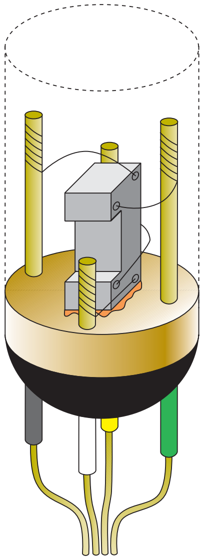
Internal thermal resistance

Thermal Boundary Resistance

Lead Thermal Resistance

T base

Heat Leak
from
Leads



We want to measure the environment temperature without changing the environment. Its connection to the environment is dominated by the thermal boundary resistance; this goes as T^{-3}.

This simple joule heated sensor model shows the thermal path to the base temperature. This could be between the sensor and its world. Too much heat in, and it creates a self-heating offset.

The germanium sensor cutaway shows leads coming into a hermitically sealed can. They go to anchoring posts where gold wire is bonded to the germanium crystal. The thermal contact is at the base of the crystal and the gold leads.

Thermal boundary resistance puts limits on amount of joule heating

Temperature gradient can be empirically determined.

$\Delta T = R_{TH} P$

$R_{TH} \sim T^{-3}$ *[K⁴/(W/cm²)]* *thermal resistance*

$P = I^2 R$ *joule heating*

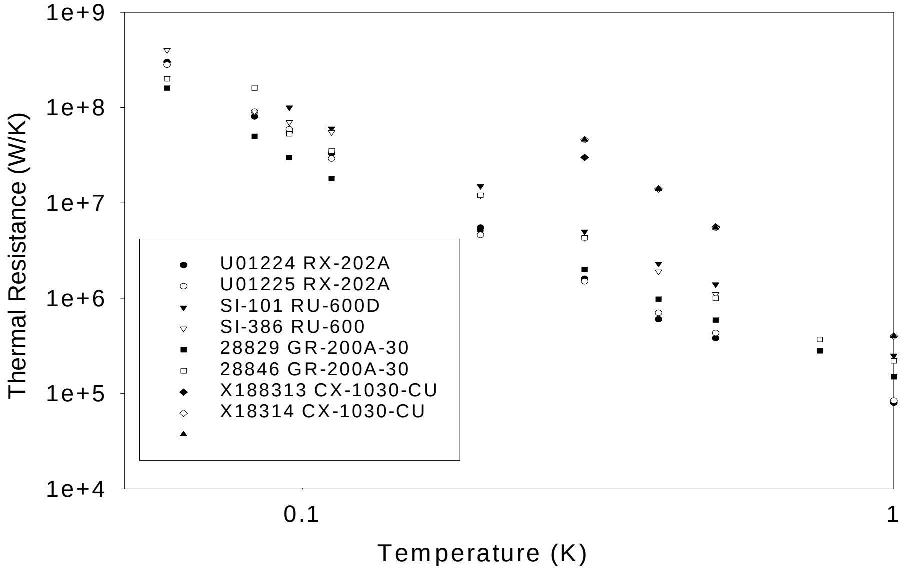
Setting at $\Delta T/T = 1\%$ and rewriting in term of allowable exicitation

$I_{MAX} = ((0.01T)/(RR_{TH}))^{0.5}$: $(I_{MAX} \sim T^3)$

1 nA at 100mK; then 1 pA at 10mK !

The thermal resistance can be determined empirically and the self-heating offset can be estimated. It typically goes at T^{-3}. It is the sum of all thermal mechanisms: sensor mounting, sensor construction, thermal boundary resistance, sensor materials, cooling history, and lead conduction.

Thermal boundary resistance vs. Temperature

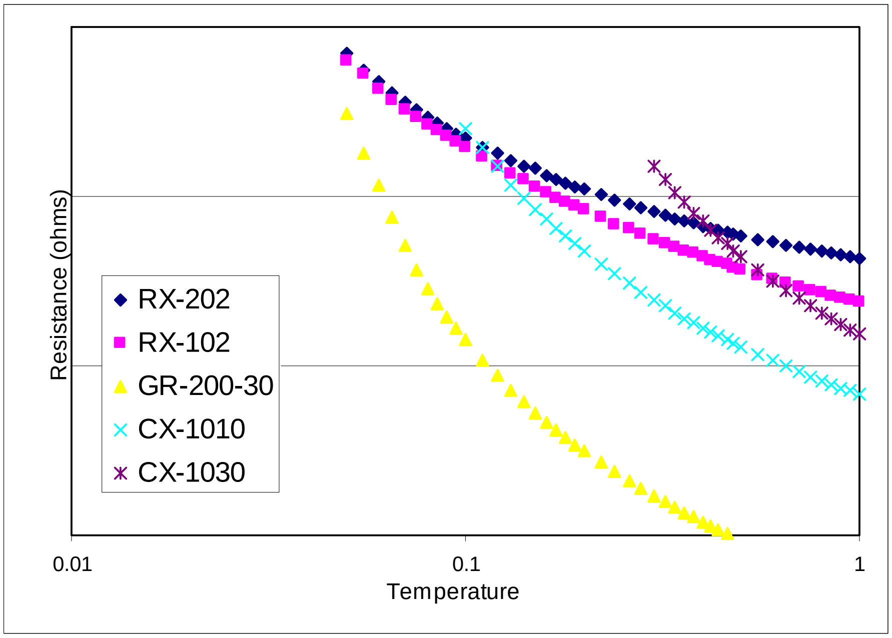


Thermal boundary resistance is shown down to 50 mK.

The germanium and ruthenium oxide are about the same and go as T^{-3}.

The Cernox™, a thin film resistor, goes as T^{-4} and is higher in magnitude.

We also need to find the right resistance range



Another design item is to find the right resistance range

Resistance	10,000 to 100,000 οημ
Sensitivity	At least Sd ~2 (able to measure µK resolution)

Some likely candidates include the GRT 50 and the RX-102. The Cernox is too high resistance and more sensitive to self-heating.

The high sensitivity works in our advantage

Temperature resolution is ratio of instrument resolution to sensitivity.

$$\Delta T = \Delta R / (dR/dT)$$

$$= (\Delta V/I)/(dR/dT) ;$$

If Imax goes as T-3 and V stays constant then all that left is dR/dT….

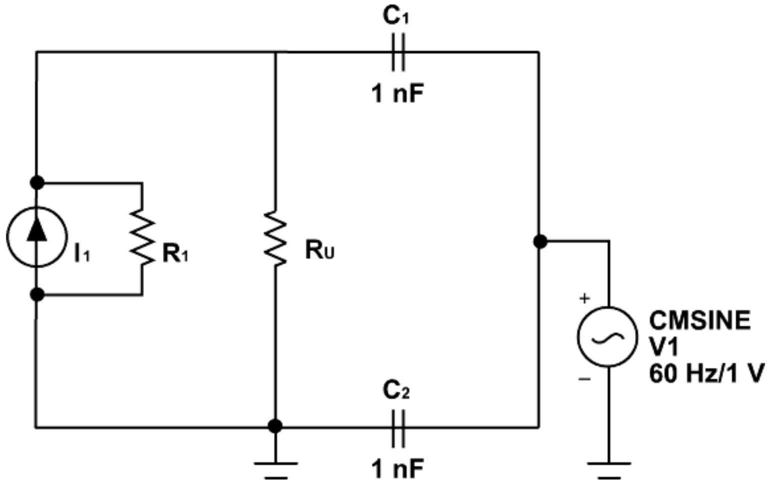
If it gets bigger faster than T-3 then resolution improves at lower temperature even as the excitation decreases.

Since the sensitivity increases faster at lower temperature, it is possible to make high temperature resolution measurements even while the resistance resolution is decreasing.

This works within limits. There can be rf-noise on the leads.

There is also current noise, or DC leakage current, that adds to the AC excitation. This puts an absolute limit on the lowest excitation, i.e., around 3 pA.

Rf-coupled noise adds to the problem

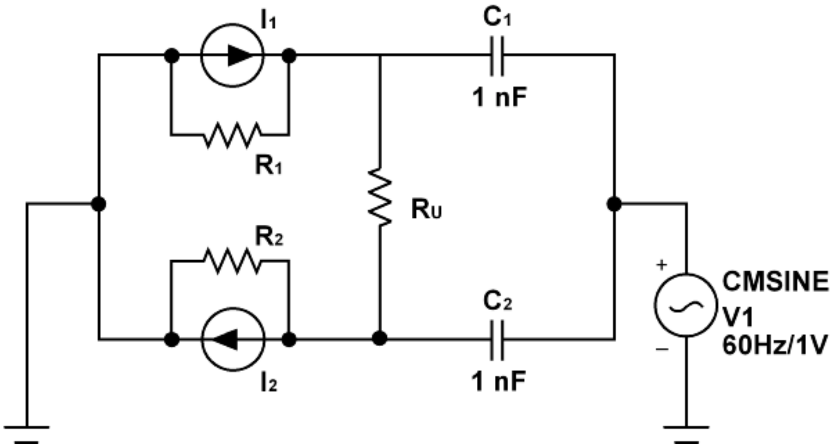


Discussion of noise reduction using a matched impedance current source begins by looking at a single ended current source. When common mode noise couples into the current leads as modeled here, it “sees” two different impedances on the leads. A very low impedance on the ground lead shunts the noise source and causes no problems. The noise source coupled to the second lead will cause current to flow through the sensor R_u. This is effectively how common mode noise is converted into normal mode noise. The noise amplitude is not important at high temperatures but at low temperatures the current created will self heat the sensor. Filtering and differential input amplifiers cannot eliminate the self heating.

RF-noise couples to one side and sees a low impedance path to ground

RF-noise couples to other side and goes through sensor to ground

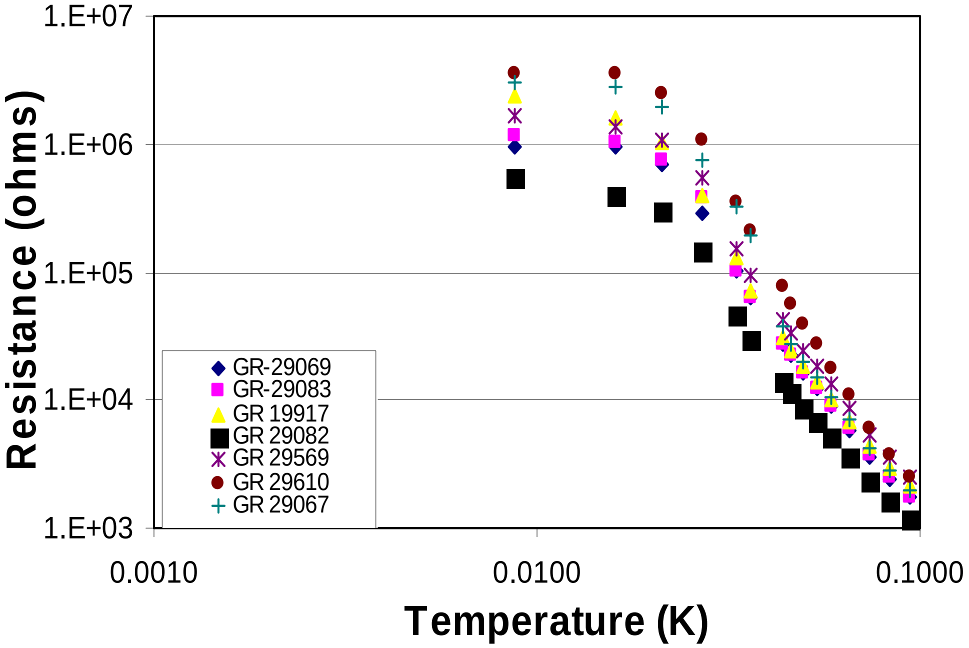
Matched impedance current source minimizes rf-noise



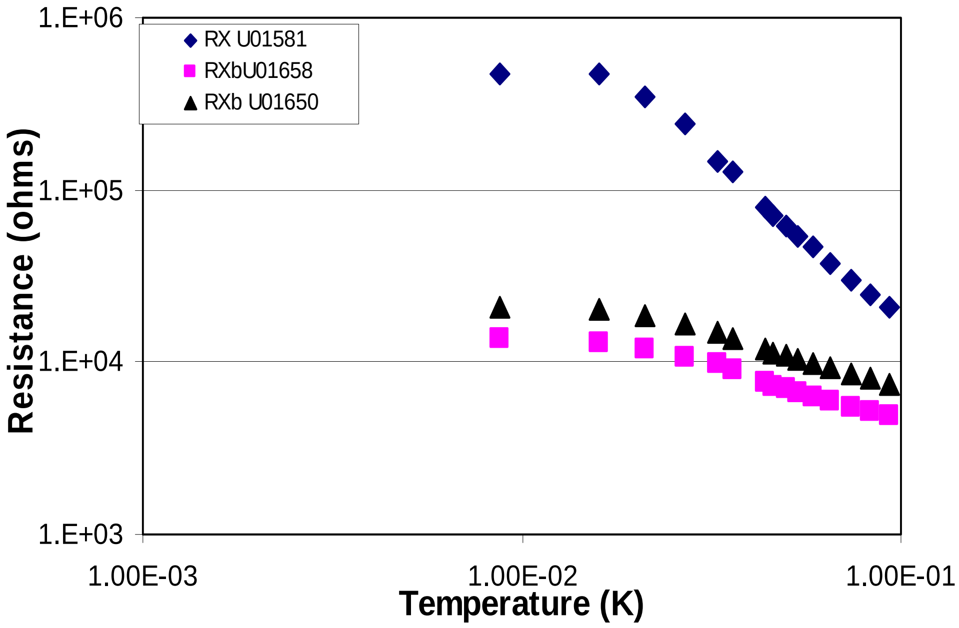
RF-noise (common mode noise) coupled onto leads “sees” the same impedance on both leads.

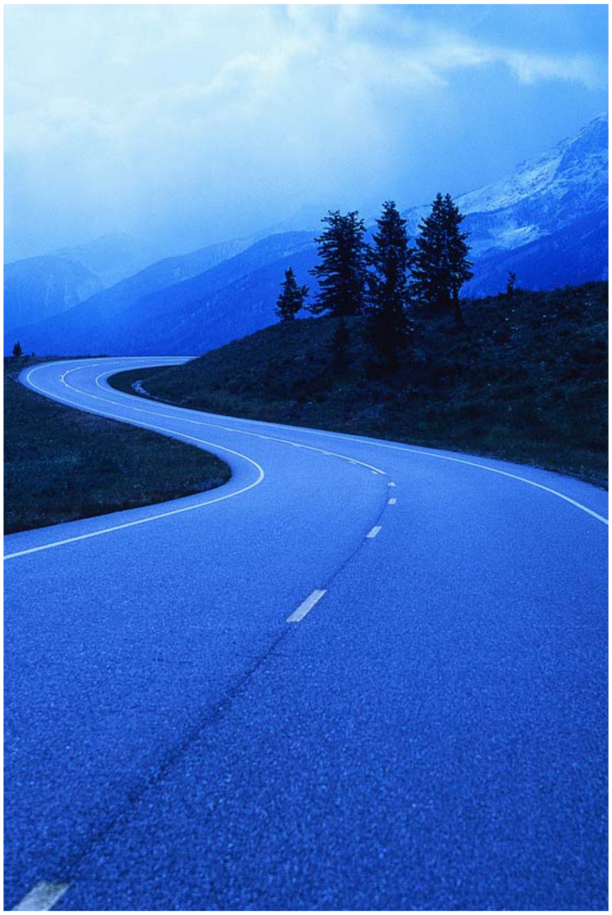
There is no path to ground and no noise current through the sensor.

Germanium RTD tested down to 9 mK



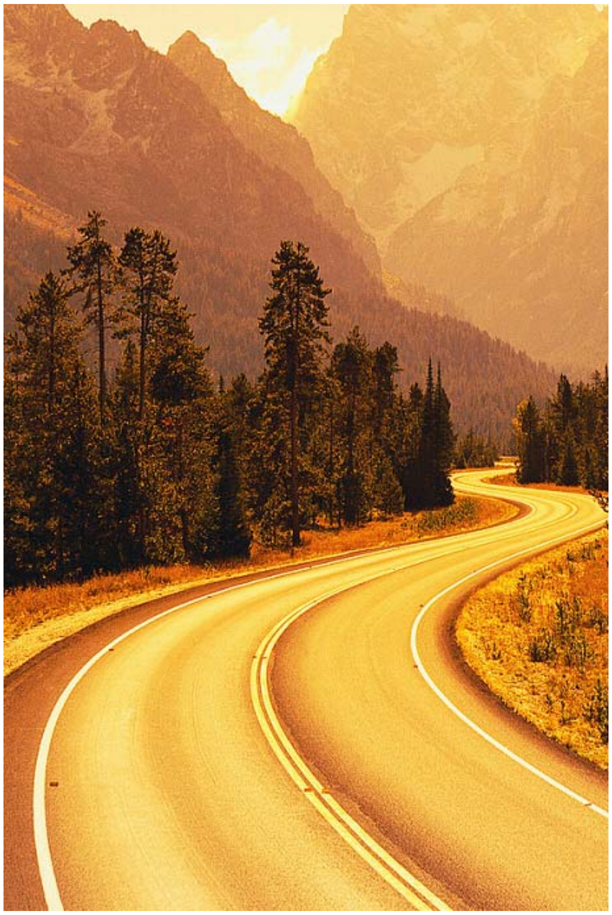
Ruthenium Oxide RTD tested to 9 mK





Method 1: Existing method optimistic but still challenges ahead

Method 2: develop a completely new process



Now we are moving away from low temperature and going up to 10 K to 20 K, in other words, taking the 10 mK and turning it into 10 km.

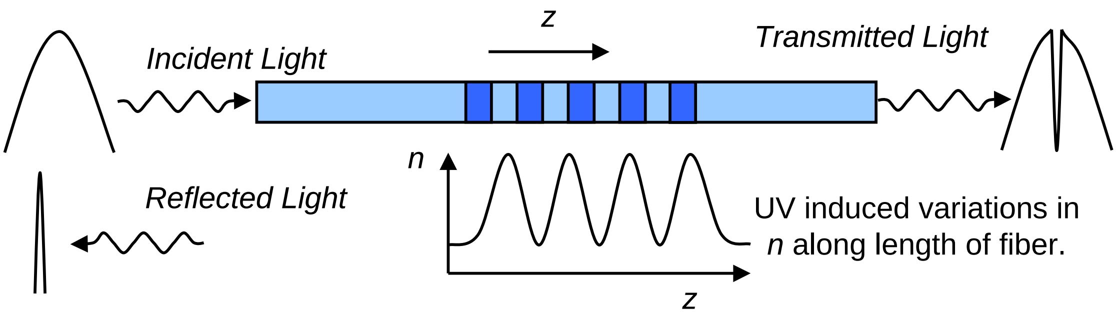
The new challenge is to get hundreds of sensors and have them extend a few meters to a few kilometers.

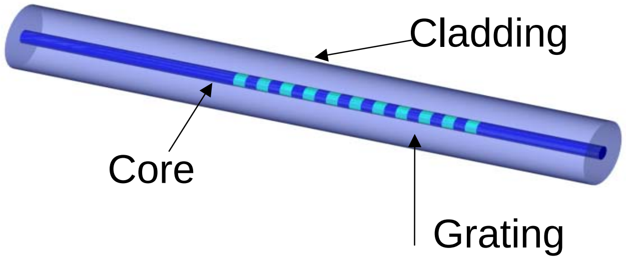
The measurements one can imagine are cryogenic fuel tanks (on-ground and on-orbit) and high T_c superconducting power applications.

There is a new platform of fiber optic sensors, specifically fiber Bragg gratings, that are being used for similar scale high temperature applications. These sensors are immune from harsh environments and EMI, and can multiplex hundreds of sensors and work over long distances. Down-hole oil, power line transformers, and civil structures like bridges all can be monitored with fiber optic sensors.

The nice thing about fiber is that it doesn't measure only temperature: strain, pressure, level and many other parameters can be measured with similar tools.

How a fiber Bragg grating (FBG) sensors works





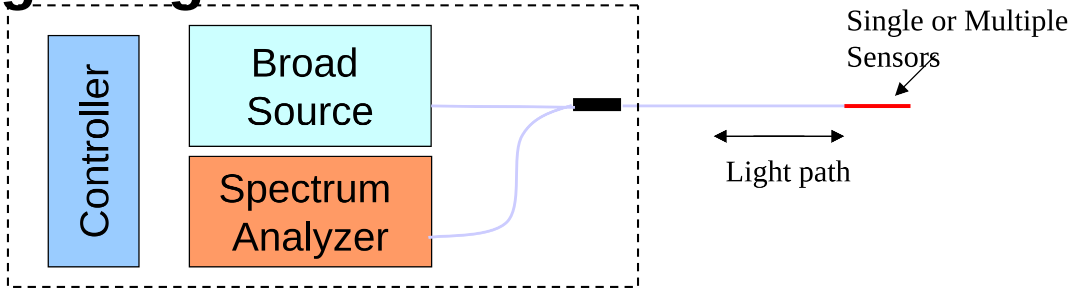
A fiber Bragg grating is made by a UV laser writing a periodic change in the index of refraction in the core of a fiber optic. This makes a partial mirror that reflects light at a certain wavelength.

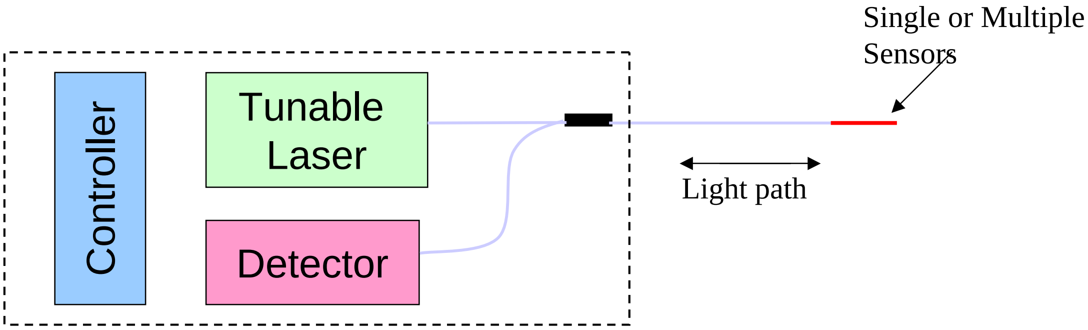
The fiber being used is all communication band fiber, which is about 1550 nm.

How is it a sensor? The reflection peak is dependent on strain. Stain is dependent on temperature. Find the right stain-free mount and it will measure the temperature-induced strain of the glass cladding.

How can it be multiplexed? Different gratings that have different peak reflection wavelengths can be written into the same fiber. This allows for wavelength division multiplexing of multiple sensors.

How to instrument a fiber Bragg grating: broad-band or laser


Controller
Broad Source
Spectrum Analyzer
Single or Multiple Sensors
Light path


Controller
Tunable Laser
Detector
Single or Multiple Sensors
Light path

To read out the sensor there are two options.

The first is to put in a broad-spectrum of light and then use a spectrum analyzer.

The other method is to use a tunable laser and sweep through the fiber Bragg grating range. The laser has a large signal to noise advantage since all the power is in the narrow band.

The spectrum analyzer method has lower signal to noise but also lower costs.

We can do it colder, but there are some design problems

Teflon

PMMA

Metals: lead, zinc, aluminum

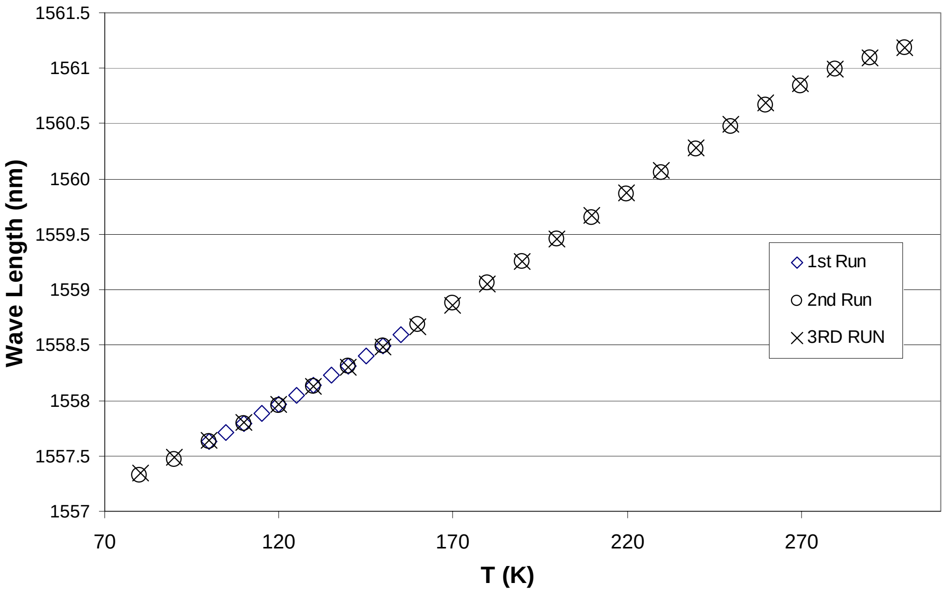
Polypropylene

For a cryogenic sensor, we need to coat the sensor with a material that has a high coefficient of expansion.

Some possibilities… Teflon®, PMMA, metals, etc.

We are still trying to get some results with Teflon, and other groups have had results with zinc and lead. We wanted to avoid metals for the intended high voltage applications. We have had the best success to date with PMMA and polypropylene.

Calibration results for PMMA recoated FBG

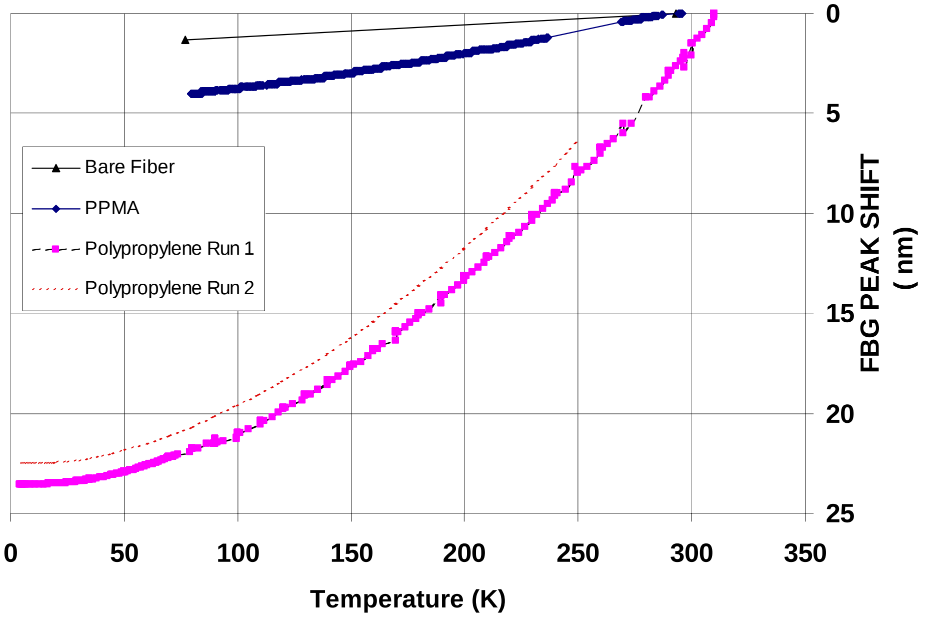


Approximately 20 pm/K over 70 K < T < 300 K

~ 0.2 K at 1 pm resolution; 2 K at 10 pm resolution

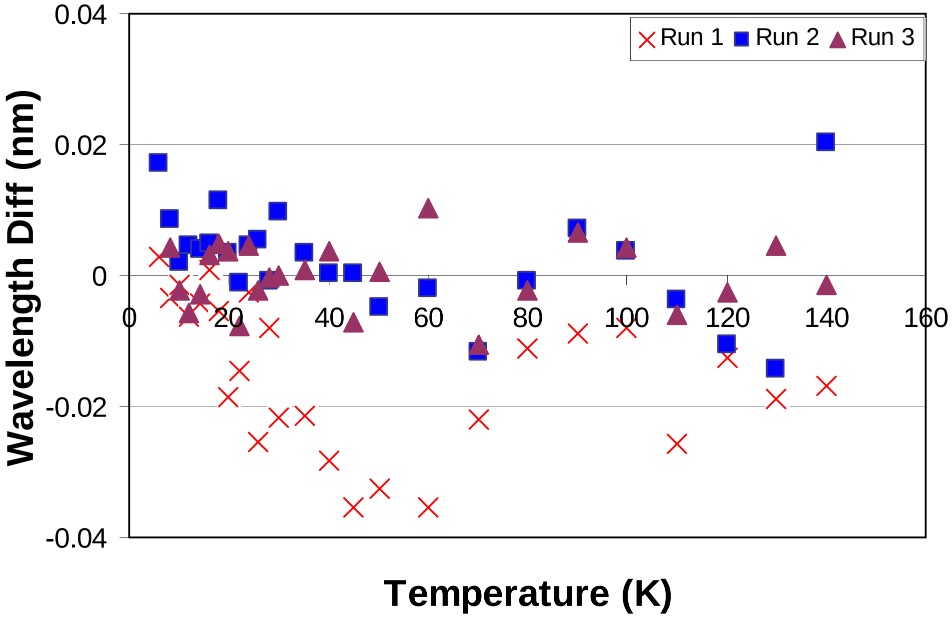
Not sensitive below 50 K

Calibration results for bare, PMMA, and Polypropylene



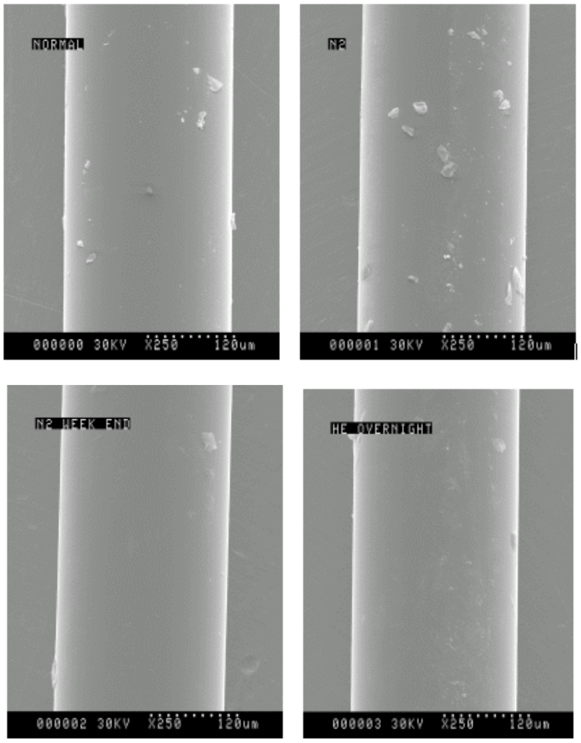
- PP coating compared to bare and acrylate
  - Sen > 40 pm/K at 77 K
  - Sen ~ 7 pm/K at 20 K
- With 10 pm instrument wavelength resolution, this translates into a ±1.5 K
- Shows hysteric behavior

Reproducibility Results for PP



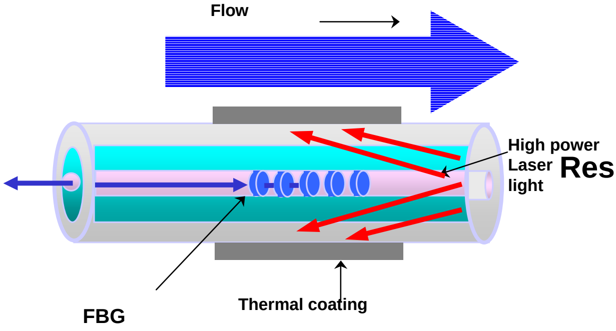
The temperature equivalent sensitivity is about ±2 K.

Does thermal cycling deteriorate the coatings? No

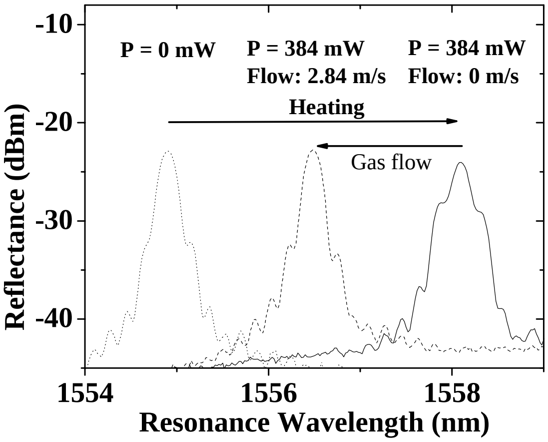


Views of Corning SMF-28 fiber from the side after various times in liquid nitrogen and liquid helium. No delamination is evident

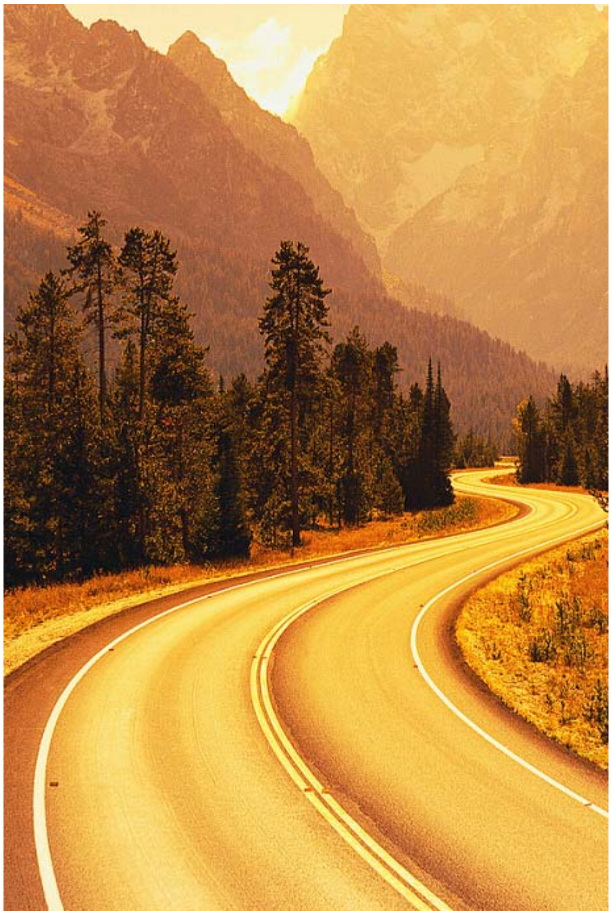
Active FBG gas flow sensor



Resonance frequency shifts by N2



Method 2: beginning of the road

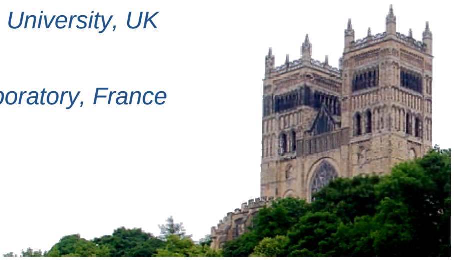


This is the beginning of the road, really. There is good promise, and think we can all get the kinks out for reproducible gratings. The resolution is only 1 K, maybe better, but for the applications this is what is needed. Fiber is going into places where conventional sensors cannot get to.

We are getting closer

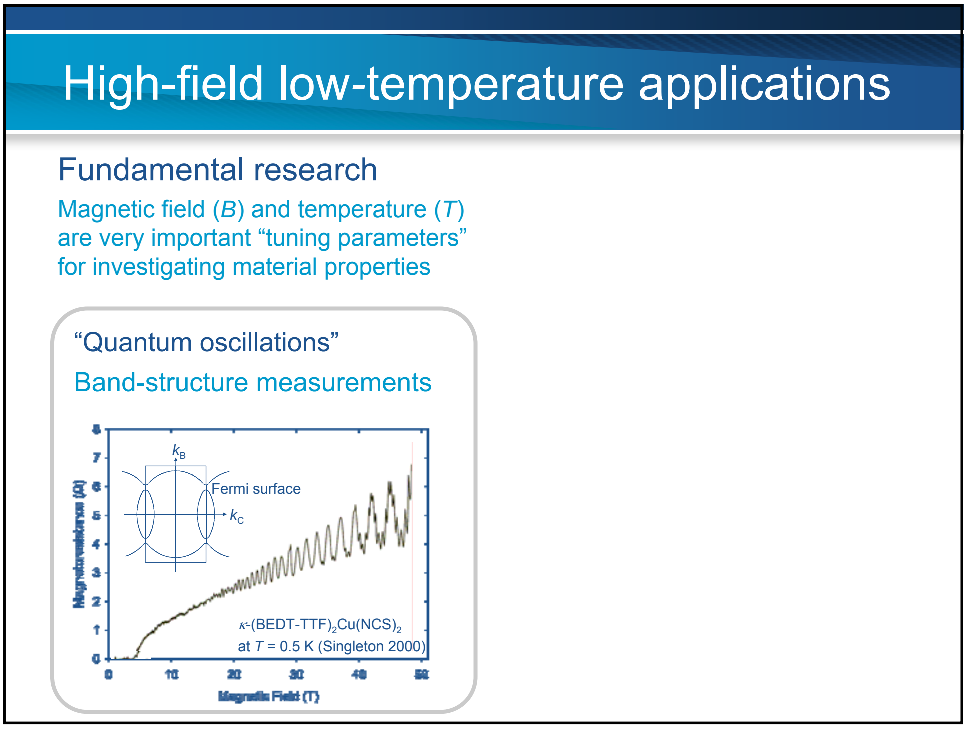
Temperature Measurement in High Magnetic Fields

David Taylor, Damian Hampshire
Superconductivity Group, Durham University, UK
Eric Mossang
Grenoble High Magnetic Field Laboratory, France



Overview

1. Introduction – high-field low-temperature applications; thermometry issues
2. Overview of thermometer performance as a function of field and temperature
3. Details of various state-of-the-art high-field low-temperature thermometers
4. Case study – superconductor critical current measurements



High-field low-temperature applications

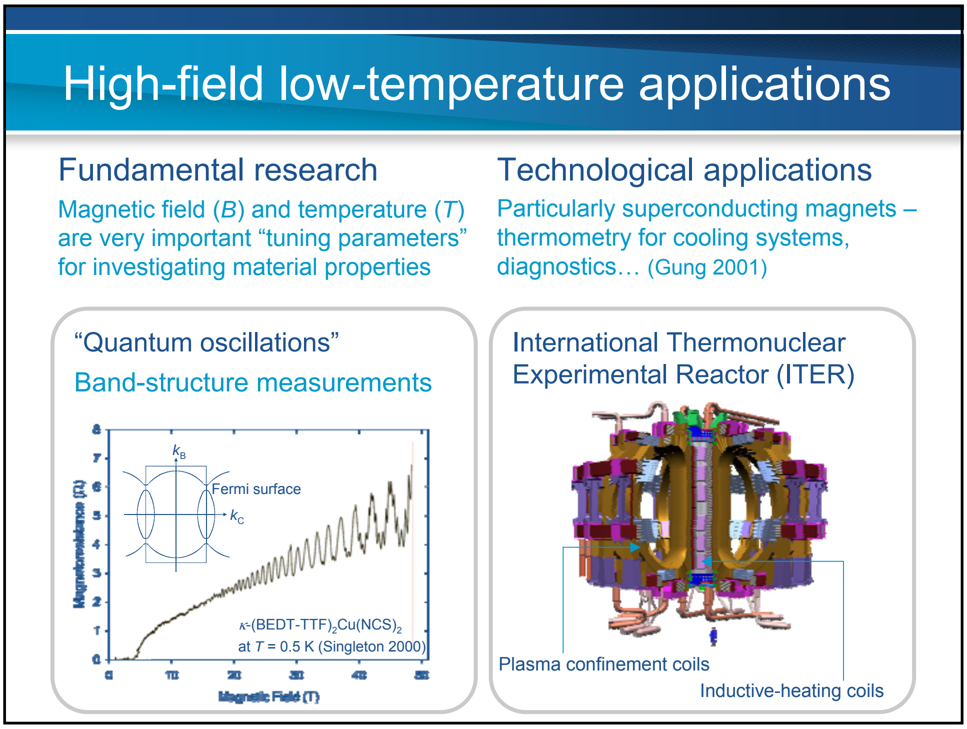
Fundamental research

Magnetic field (B) and temperature (T) are very important “tuning parameters” for investigating material properties

“Quantum oscillations”

Band-structure measurements

κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ at T = 0.5 K (Singleton 2000)



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Technological applications

Particularly superconducting magnets – thermometry for cooling systems, diagnostics… (Gung 2001)

International Thermonuclear Experimental Reactor (ITER)

Plasma confinement coils

Inductive-heating coils

High-field thermometry – issues

Use of a **compensating coil** or superconducting screen? → ~zero-field region for the thermometer (*spatially separated from sample*)

High-field thermometry – issues

Use of a **compensating coil** or superconducting screen? → ~zero-field region for the thermometer (*spatially separated from sample*)

Wiring from sensor to instrumentation – twisted pairs, rigidly tied down – to reduce noise voltages induced by the magnetic field

High-field thermometry – issues

Use of a **compensating coil** or superconducting screen? → ~zero-field region for the thermometer (*spatially separated from sample*)

Wiring from sensor to instrumentation – twisted pairs, rigidly tied down – to reduce noise voltages induced by the magnetic field

Choice of **thermometer**: (Rubin 1997)
– Most thermometers exhibit a magnetic field response (e.g. magnetoresistance $\Delta R/R_0$) → temperature error ($\Delta T/T_0$):

$$\Delta R/R_0 = \frac{R(B,T)-R(0,T)}{R(0,T)} \qquad \Delta T/T_0 \cong \frac{\Delta R/R_0}{d\log R_0/d\log T}$$

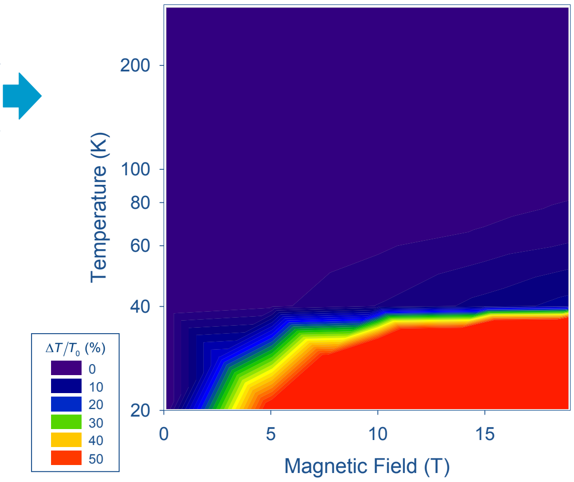
– **If** the response is small and reproducible, it can be accurately corrected..

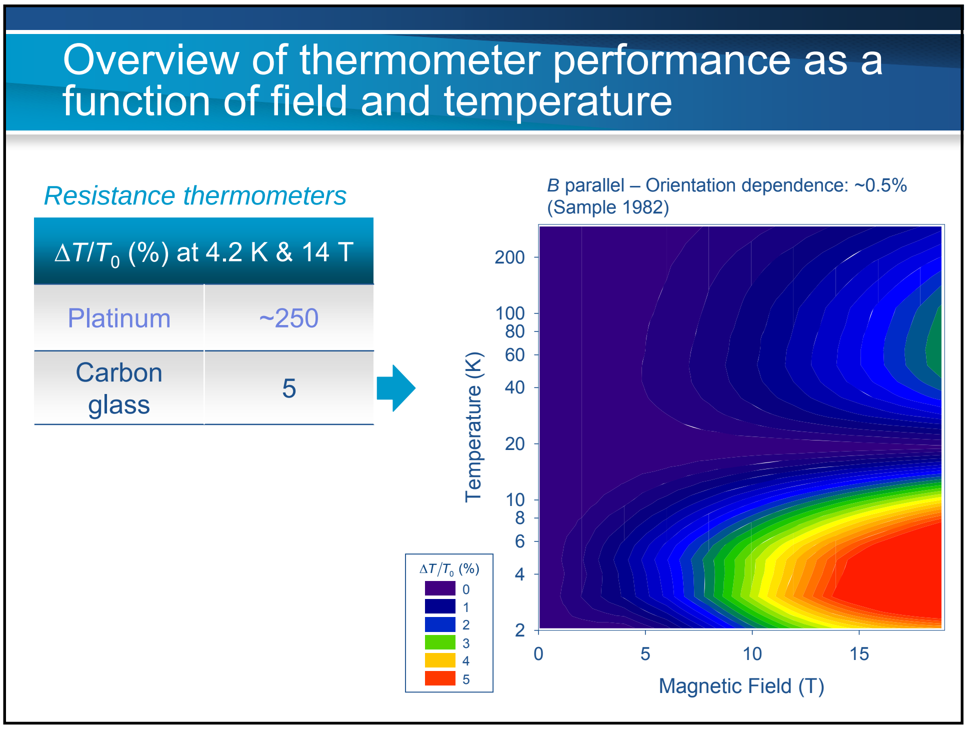
Overview of thermometer performance as a function of field and temperature

Resistance thermometers

$\Delta T/T_0$ (%) at 4.2 K & 14 T	
Platinum	~250

B parallel – Orientation dependence: ~20%
(Brandt 1988)



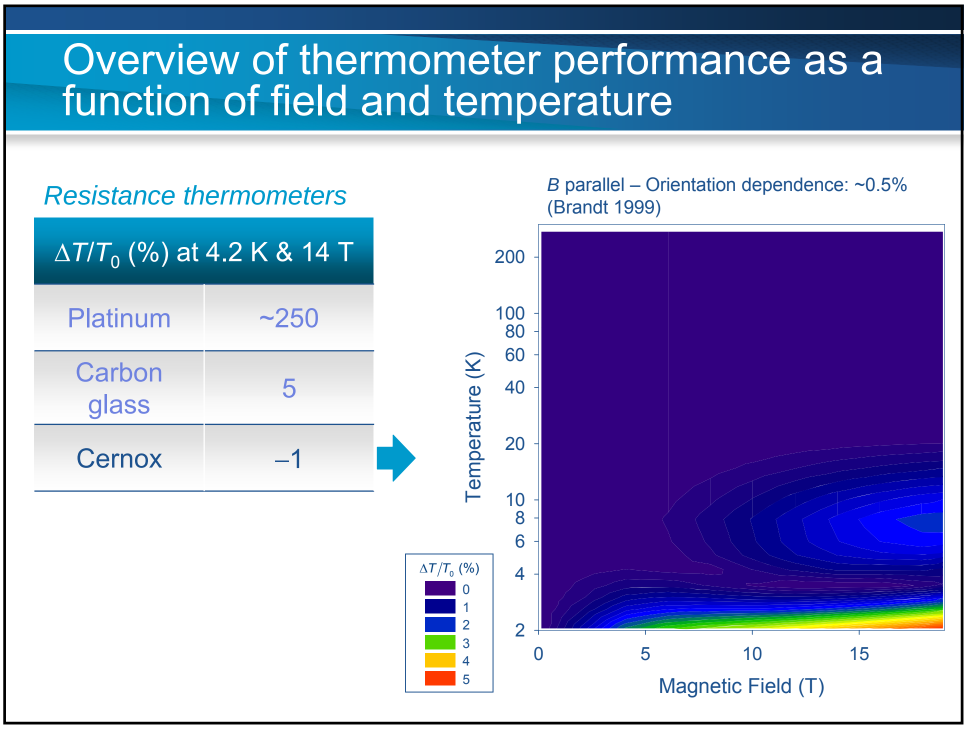


Overview of thermometer performance as a function of field and temperature

Resistance thermometers

$\Delta T/T_0$ (%) at 4.2 K & 14 T	
Platinum	~250
Carbon glass	5

B parallel – Orientation dependence: ~0.5%
(Sample 1982)

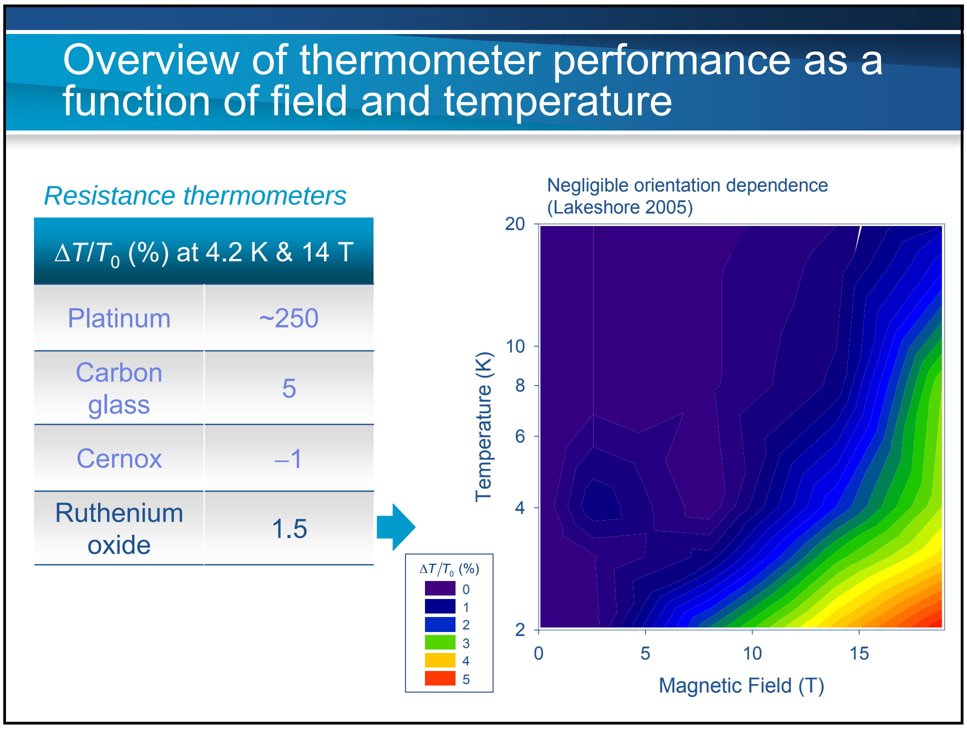


Overview of thermometer performance as a function of field and temperature

Resistance thermometers

$\Delta T/T_0$ (%) at 4.2 K & 14 T	
Platinum	~250
Carbon glass	5
Cernox	–1

B parallel – Orientation dependence: ~0.5%
(Brandt 1999)



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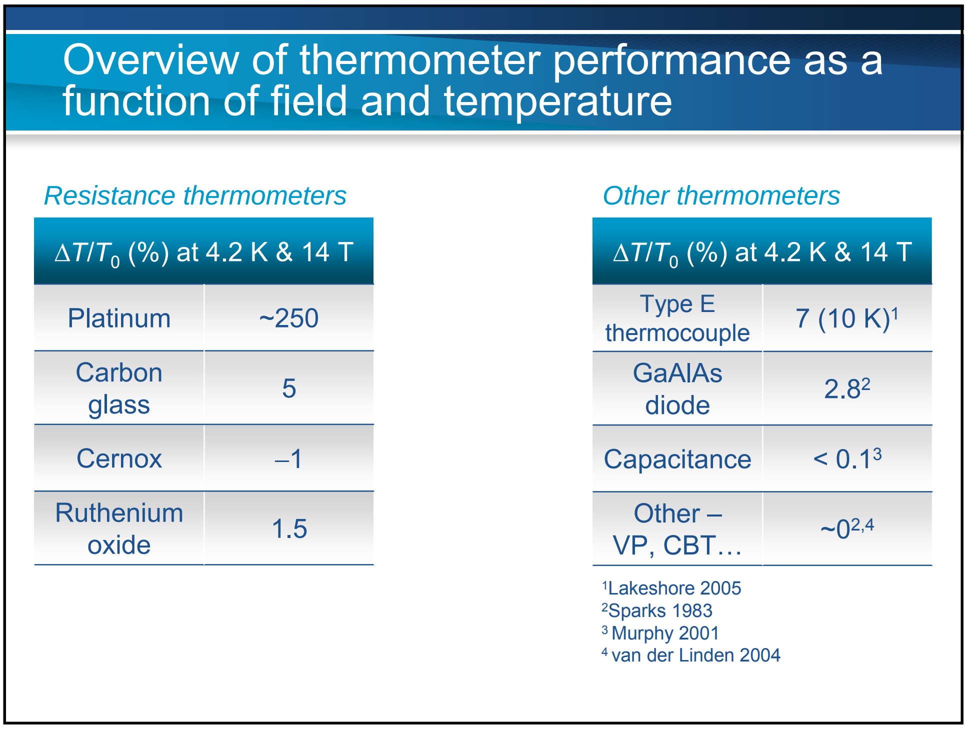
Ruthenium oxide	1.5

Negligible orientation dependence (Lakeshore 2005)



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Other thermometers

$\Delta T/T_0$ (%) at 4.2 K & 14 T	
Type E thermocouple	7 (10 K)[1]
GaAlAs diode	2.8[2]
Capacitance	< 0.1[3]
Other – VP, CBT…	~0[2,4]

[1] Lakeshore 2005
[2] Sparks 1983
[3] Murphy 2001
[4] van der Linden 2004

Overview of thermometer performance as a function of field and temperature

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Workhorses of high-field, low-temperature thermometry

Other thermometers

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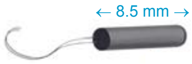
Capacitance thermometers

Temperature range: ~1.4–300 K

Sensitivity (4.2 K): ~30 pF/K

Thermal response time: minutes

(Lakeshore 2005)



Negligible field-induced errors $\Delta T/T_0$ < 0.1% (Murphy 2001)

Variations in the capacitance–temperature calibration curve occur on thermal cycling

Capacitance thermometers

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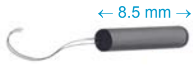
Sensitivity (4.2 K): ~30 pF/K

Thermal response time: minutes

(Lakeshore 2005)



Negligible field-induced errors $\Delta T/T_0 < 0.1\%$ (Murphy 2001)

Variations in the capacitance–temperature calibration curve occur on thermal cycling

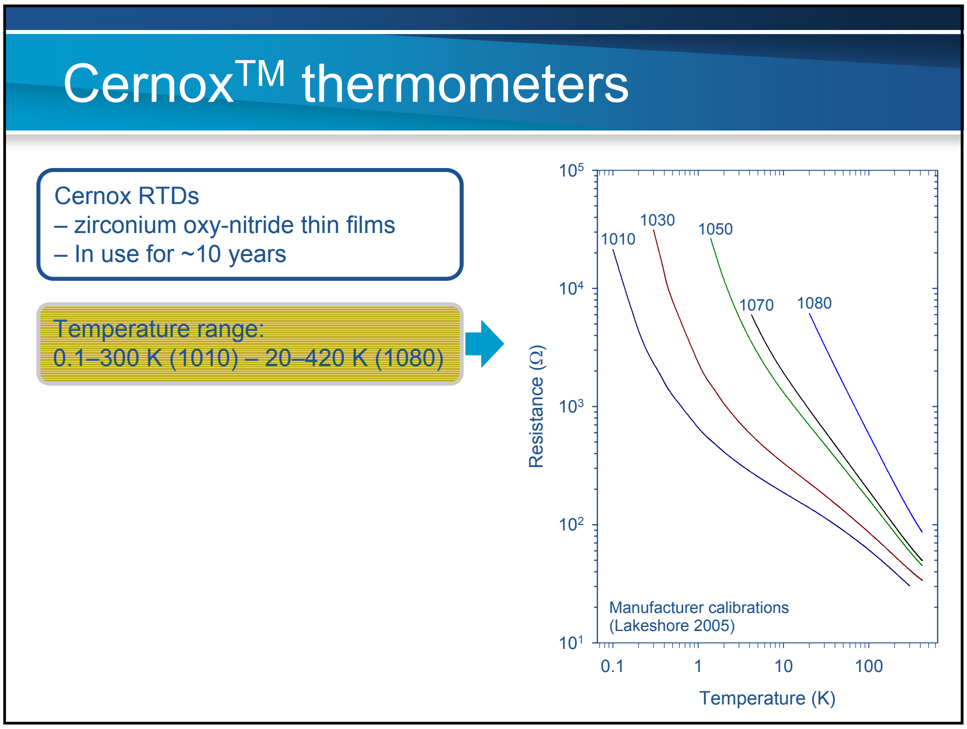
Predominantly used as a **control element**:

1. Temperature in zero magnetic field is set using a 2nd standard thermometer.
2. Capacitance (→ temperature) kept constant as the field is changed.

In-field calibrations of resistance thermometers

Cernox^{TM} thermometers

Cernox RTDs
– zirconium oxy-nitride thin films
– In use for ~10 years



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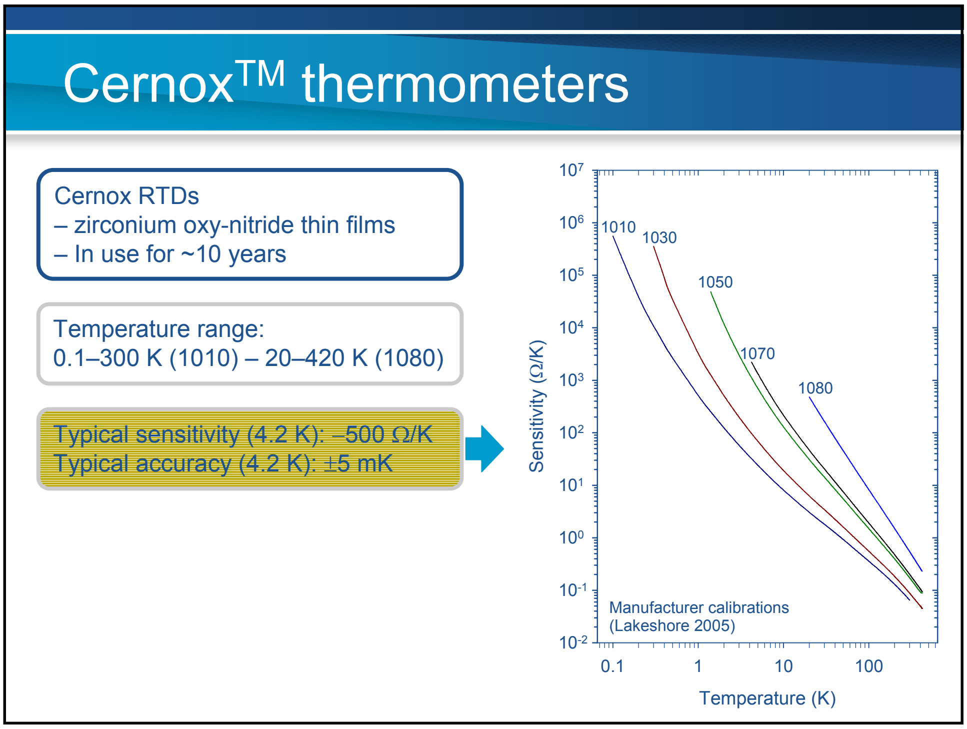
0.1–300 K (1010) – 20–420 K (1080)



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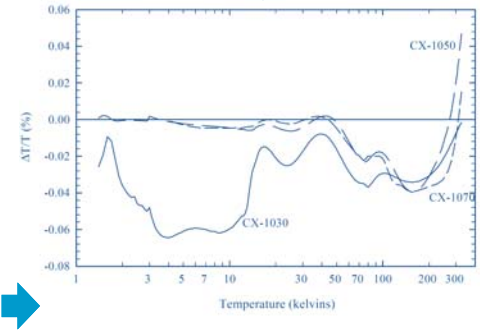
Long-term reproducibility:
<0.07% after 4.4 years

Calibration shift at 4.4 years (Courts 2000)



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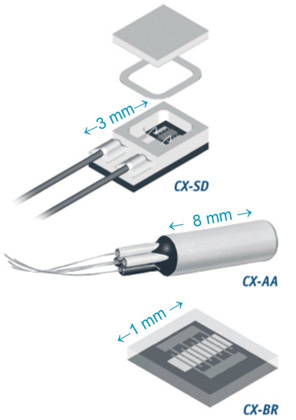
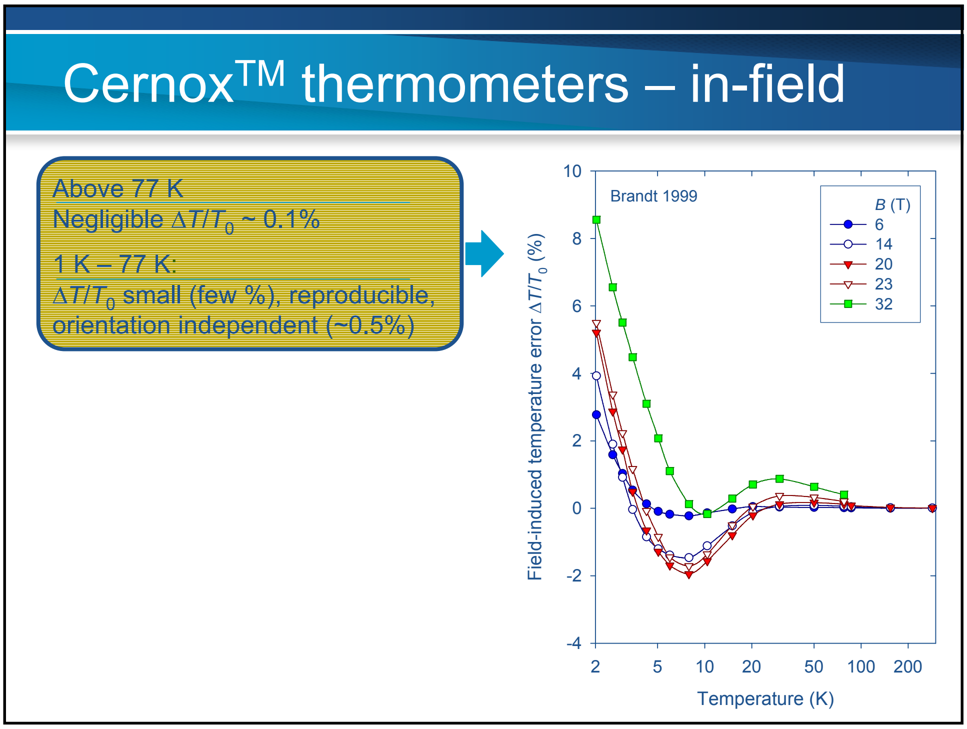
Thermal response time (4.2 K):
1.5 ms (BR), 15 ms (SD), 0.4 s (AA)



(Lakeshore 2005)



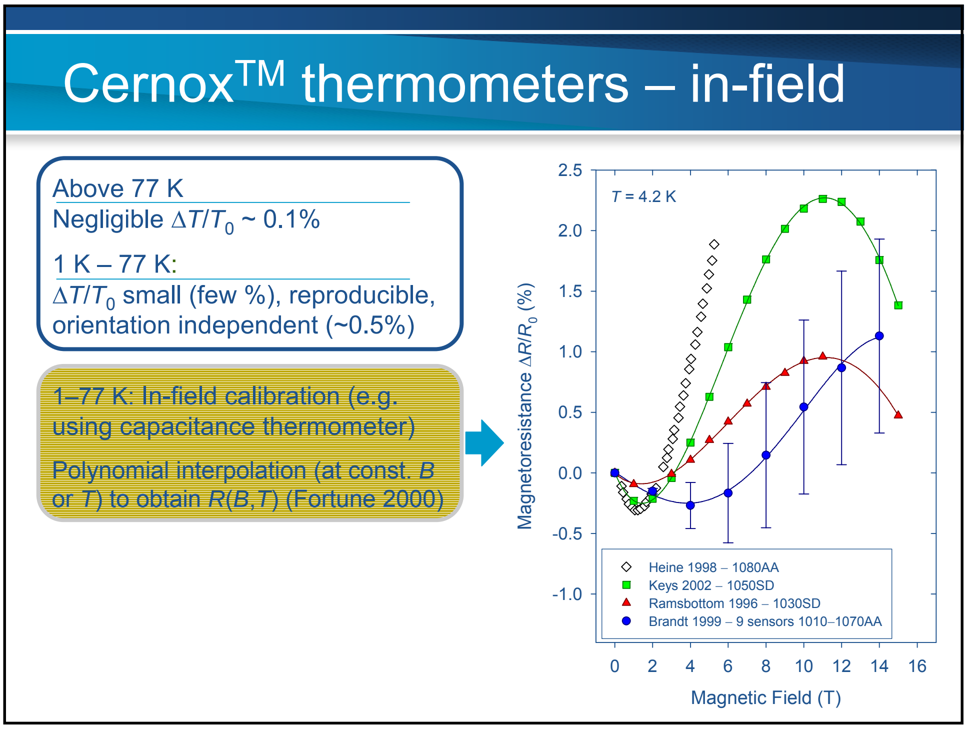
Cernox^{TM} thermometers – in-field

Above 77 K

Negligible $\Delta T/T_0$ ~ 0.1%

1 K – 77 K:

$\Delta T/T_0$ small (few %), reproducible, orientation independent (~0.5%)



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Polynomial interpolation (at const. *B* or *T*) to obtain *R*(*B*,*T*) (Fortune 2000)

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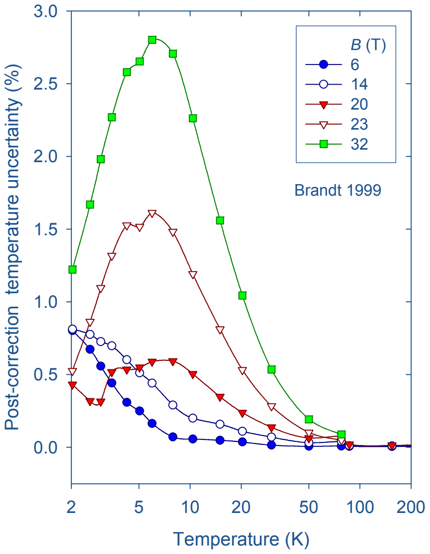
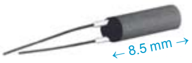
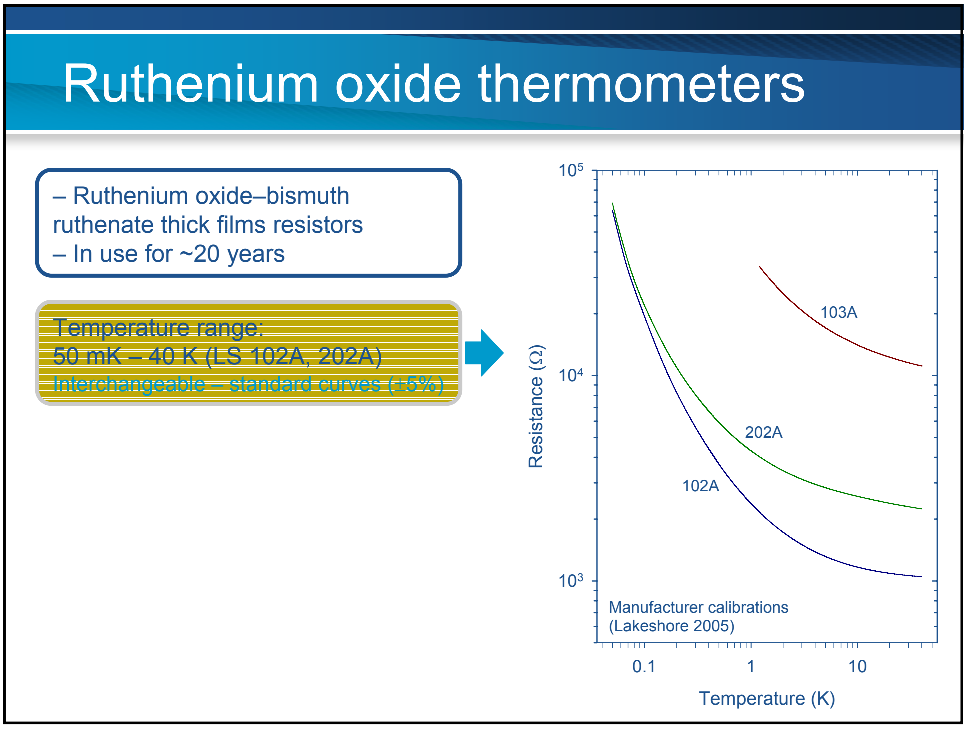
Using data tabulated in Brandt (1999) for an off-the-shelf sensor → estimated <0.5% temperature uncertainty at 20 T



Ruthenium oxide thermometers

– Ruthenium oxide–bismuth ruthenate thick films resistors
– In use for ~20 years





Ruthenium oxide thermometers

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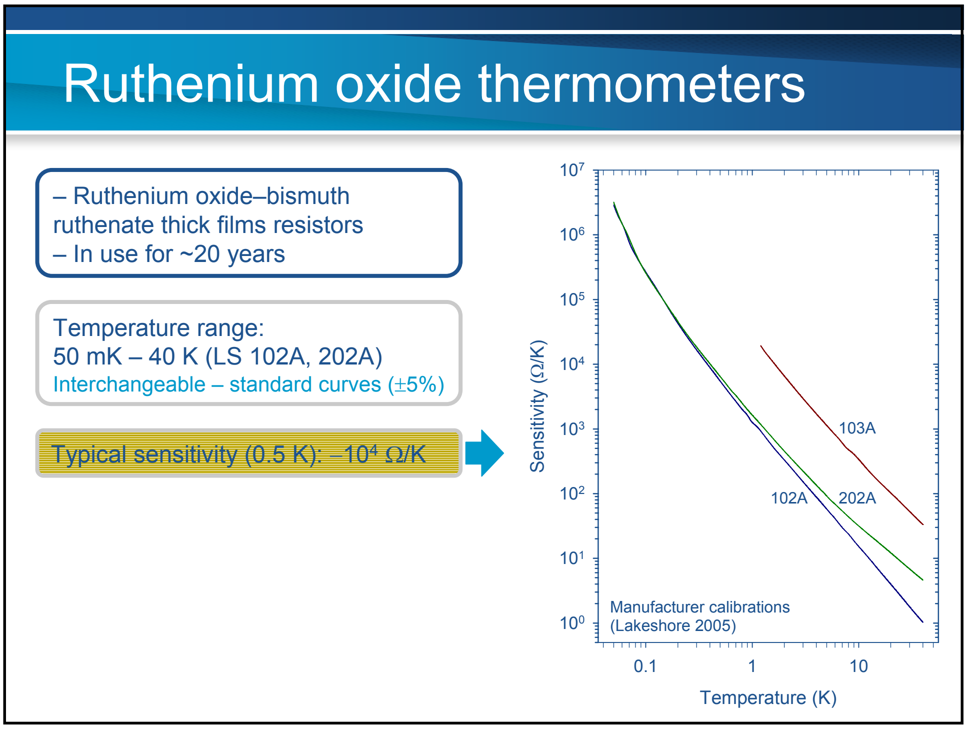
Temperature range:
50 mK – 40 K (LS 102A, 202A)
Interchangeable – standard curves (±5%)

Manufacturer calibrations (Lakeshore 2005)



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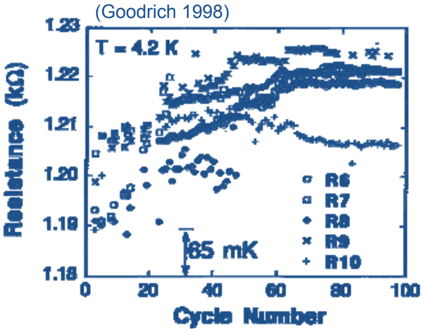
$= \left[(\text{calibration uncertainty})^2 + (\text{reproducibility})^2 \right]^{1/2}$

Thermal cycling: 300 ↔ 4.2 K
(Goodrich 1998)



Lakeshore Rox^{TM} 202A
Reproducibility at 50 mK
(thermal shocking): **±5 mK**

(Lakeshore 2005)

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Thermal response time (4.2 K): 0.5 s

(Lakeshore 2005)

Ruthenium oxide – in-field

Recommended for high-field use between ~50 mK and ~1 K.

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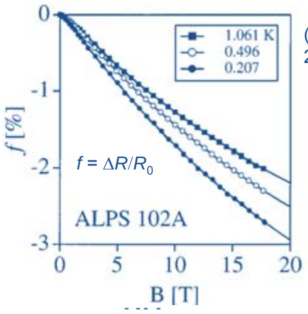
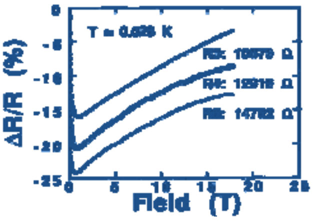
Recommended for high-field use between ~50 mK and ~1 K.

Require in-field calibration (e.g. using a compensation coil or capacitance thermometer)

$\Delta R/R_0$ (and hence $\Delta T/T_0$) typically a few percent, orientation independent, reproducible



(Fortune 2000)



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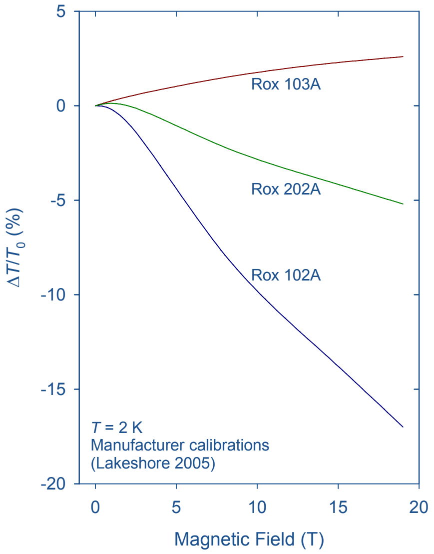
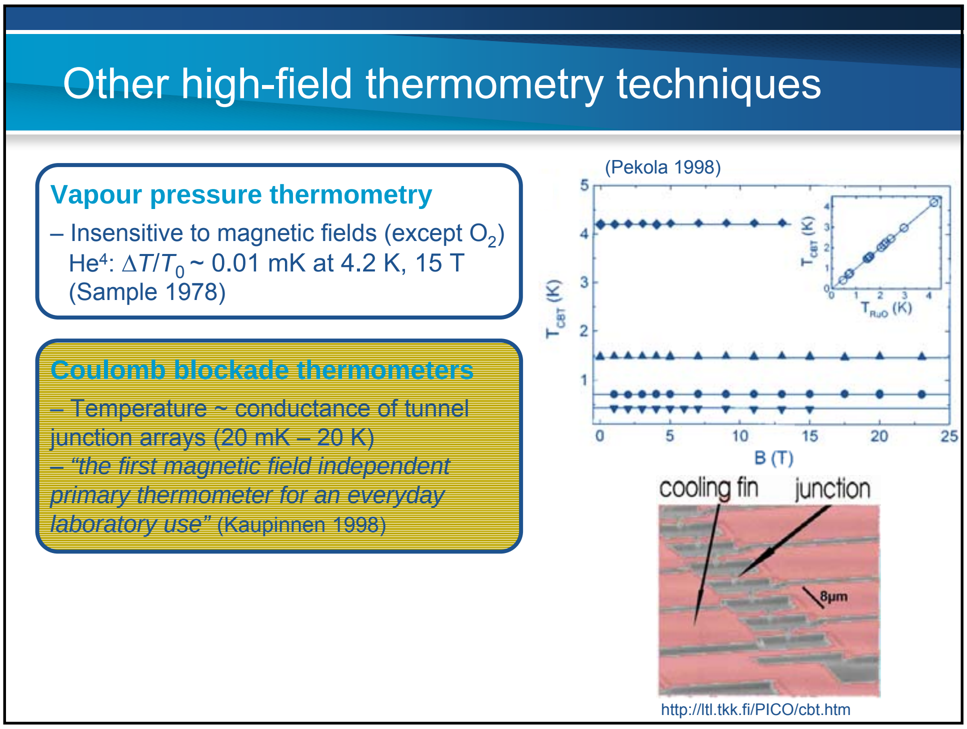
Significant differences in $\Delta T/T_0$ between different sensor types



Other high-field thermometry techniques

Vapour pressure thermometry

– Insensitive to magnetic fields (except O_2)
He⁴: $\Delta T/T_0$ ~ 0.01 mK at 4.2 K, 15 T
(Sample 1978)



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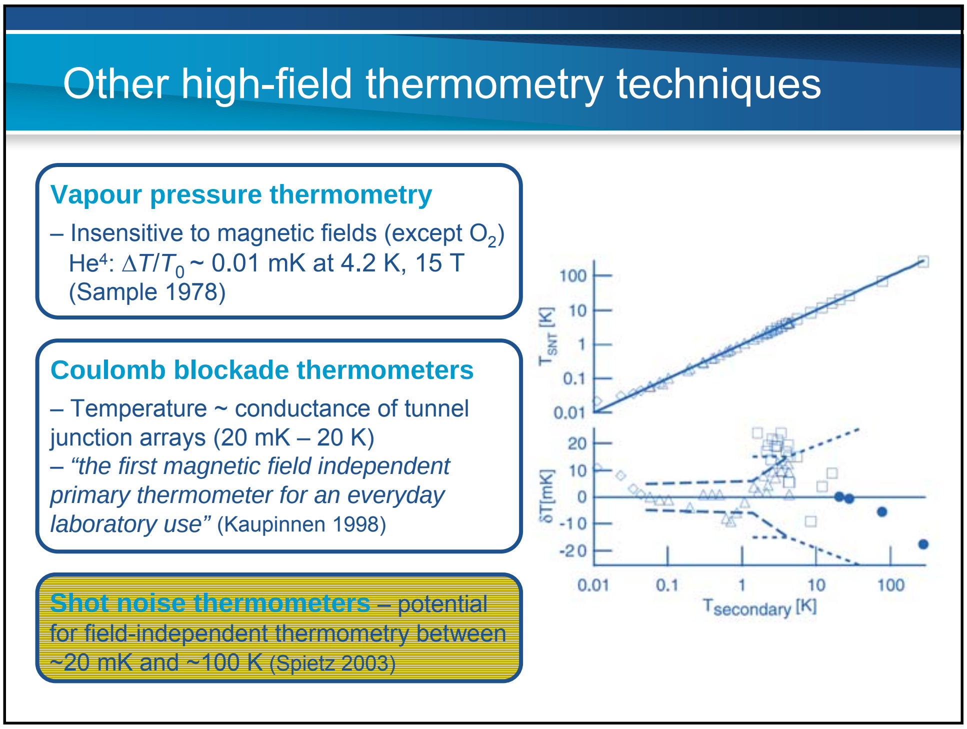
Coulomb blockade thermometers

– Temperature ~ conductance of tunnel junction arrays (20 mK – 20 K)
– *"the first magnetic field independent primary thermometer for an everyday laboratory use"* (Kaupinnen 1998)

(Pekola 1998)

http://ltl.tkk.fi/PICO/cbt.htm



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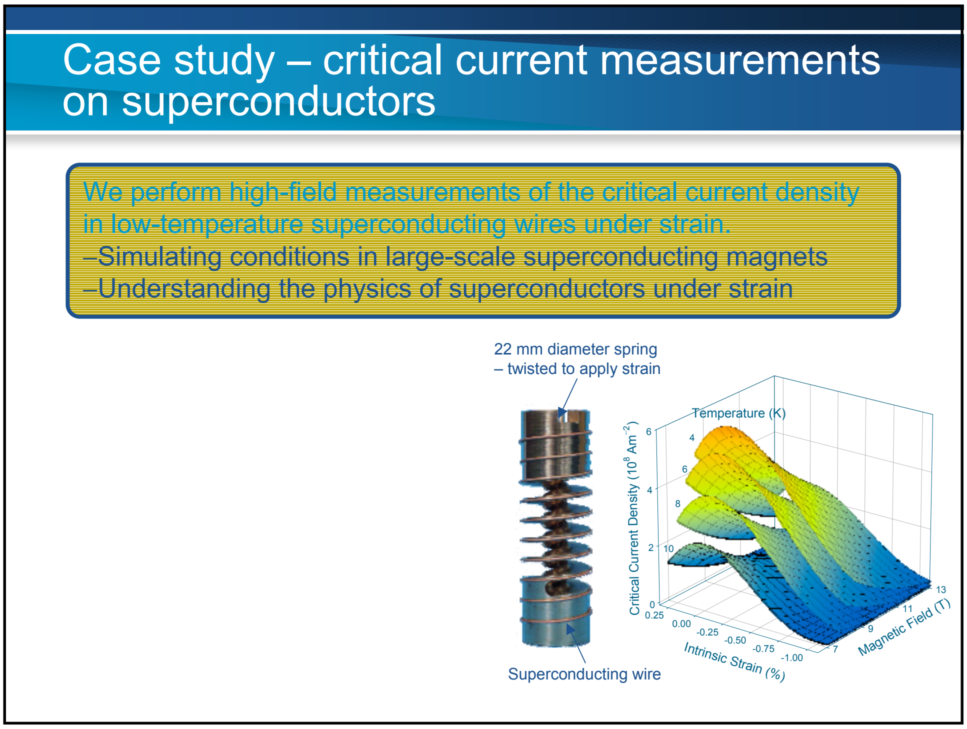
Shot noise thermometers – potential for field-independent thermometry between ~20 mK and ~100 K (Spietz 2003)

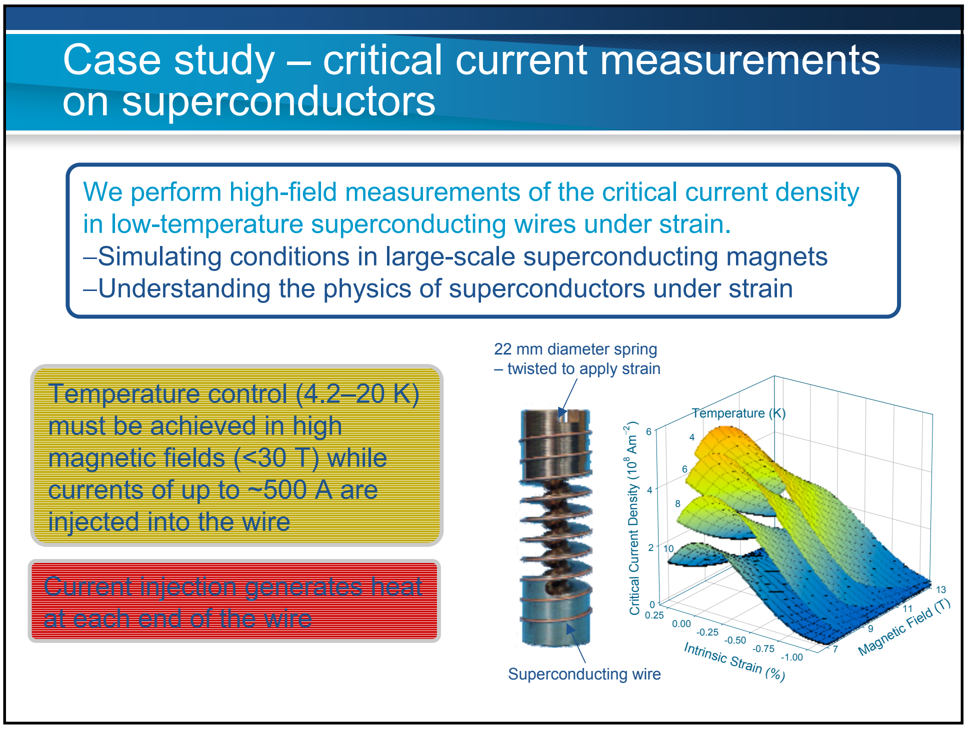


Case study – critical current measurements on superconductors

We perform high-field measurements of the critical current density in low-temperature superconducting wires under strain.
–Simulating conditions in large-scale superconducting magnets
–Understanding the physics of superconductors under strain

22 mm diameter spring – twisted to apply strain

Superconducting wire



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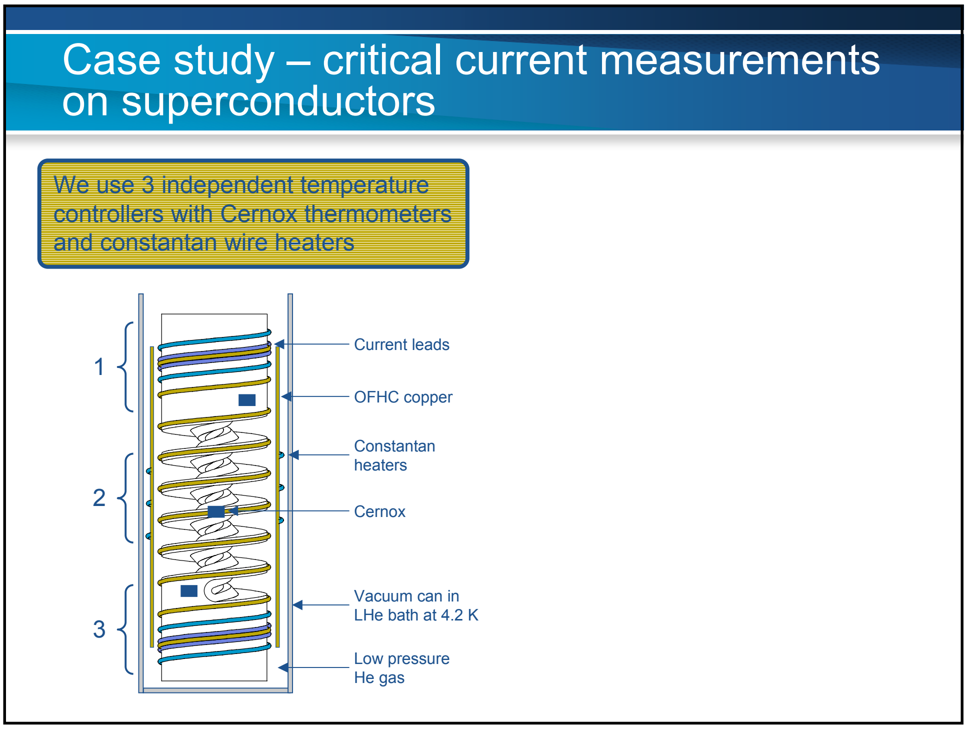
–Simulating conditions in large-scale superconducting magnets
–Understanding the physics of superconductors under strain

Temperature control (4.2–20 K) must be achieved in high magnetic fields (<30 T) while currents of up to ~500 A are injected into the wire

Current injection generates heat at each end of the wire

22 mm diameter spring – twisted to apply strain

Superconducting wire



Case study – critical current measurements on superconductors

We use 3 independent temperature controllers with Cernox thermometers and constantan wire heaters

Current leads

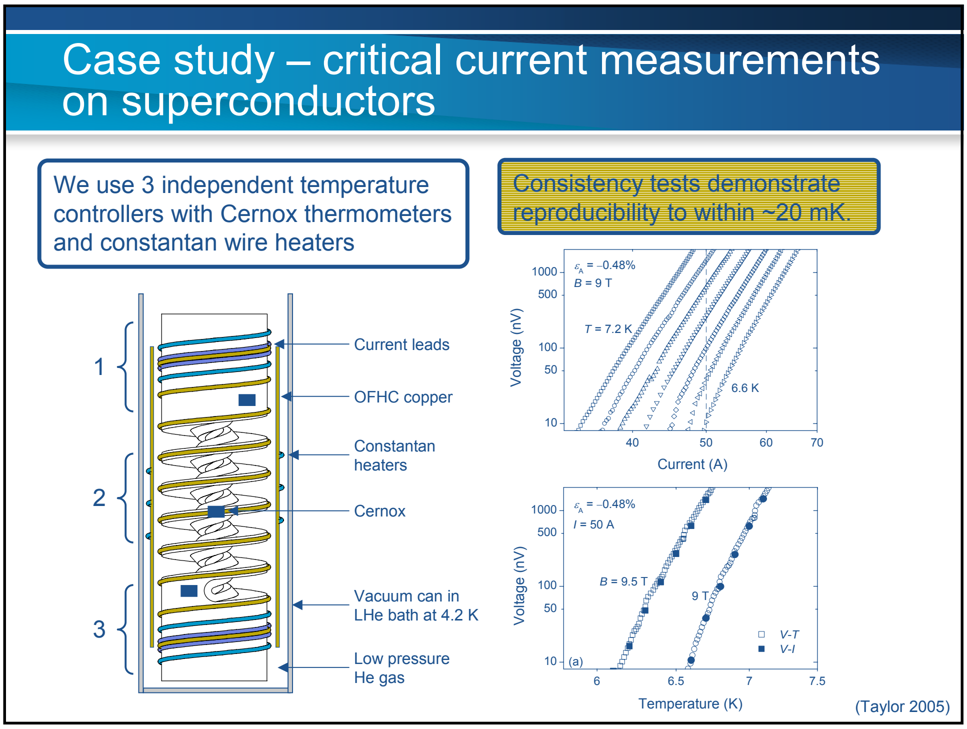
OFHC copper

Constantan heaters

Cernox

Vacuum can in LHe bath at 4.2 K

Low pressure He gas



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Consistency tests demonstrate reproducibility to within ~20 mK.

(Taylor 2005)

Conclusions

- Due to their scientific and technological importance, considerable effort has been directed at developing accurate low-temperature high-field thermometers.
- The state-of-art commercial thermometers are Cernox (above 1 K) and ruthenium-oxide (down to 50 mK) RTDs.
- These must generally be calibrated to correct for their magnetoresistance (e.g. using a capacitance thermometer).
- The development of new high-field thermometers continues today.
- In the example of critical current measurements on superconductors up to ~500 Amps, temperature reproducibility of ~20 mK was achieved using 3 independent temperature controllers with Cernox thermometers.

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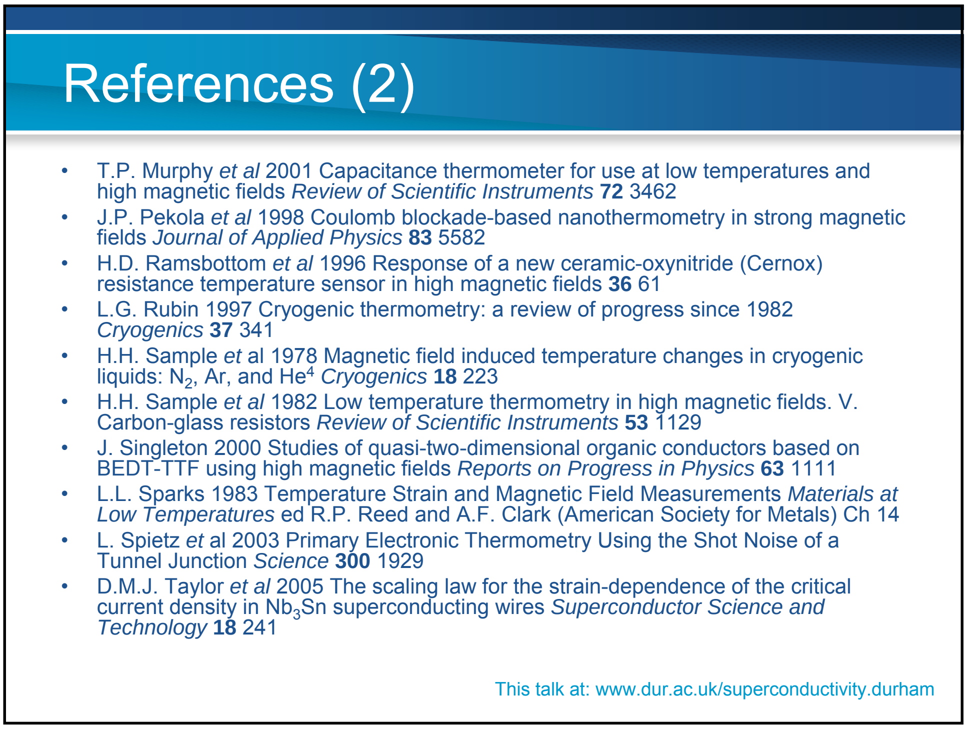

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This talk at: www.dur.ac.uk/superconductivity.durham

Bolometry using high sensitivity NTD germanium thermometers

Adam Woodcraft
Astronomical Instrumentation Group
School of Physics and Astronomy,Cardiff University
http://woodcraft.lowtemp.org/

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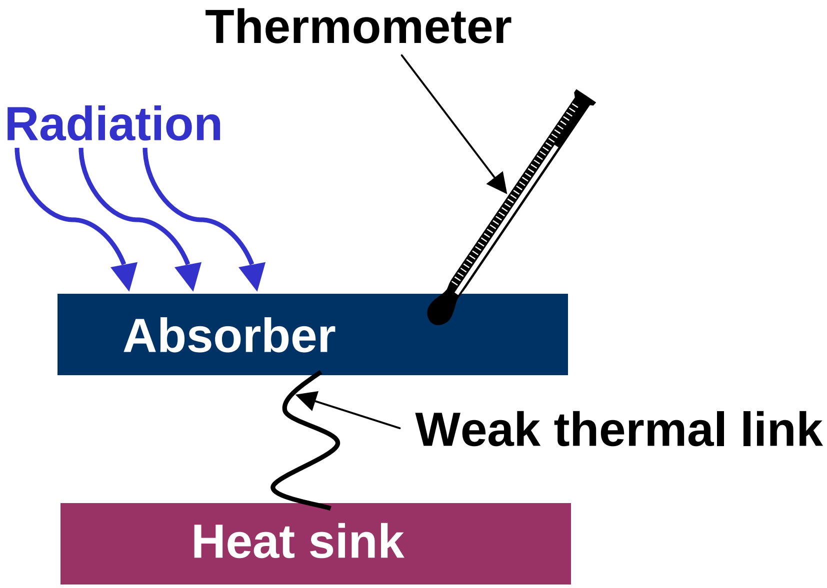
Introduction

Bolometers

A bolometer is conceptually very simple



Absorber temperature is a function of "optical" power

Nearly flat spectral response over wide bandwidth:

- Can define bandwidth using filters/waveguides

Can use simple read-out scheme

Practical to calibrate

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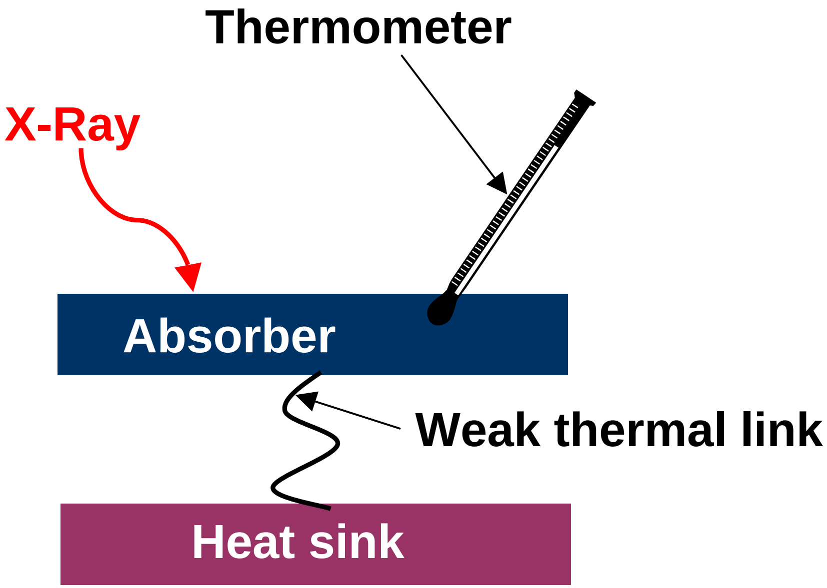
Calorimeters

Measure temperature as a function of time and you have a calorimeter



Thermometer

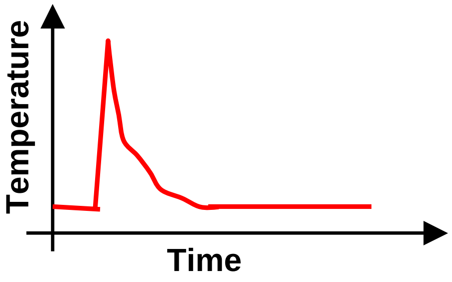
X-Ray

Absorber

Weak thermal link

Heat sink

Uses include:
- Detecting:
  - X-rays
  - Dark matter
  - Double beta decay
- Mass spectroscopy



Sub-mm astronomy

Astronomy at wavelengths of a few hundred μm
Typically around 450 and 850 μm

Bolometers are the best detectors for continuum ("broadband") measurements

James Clerk Maxwell Telescope, Mauna Kea, Hawaii

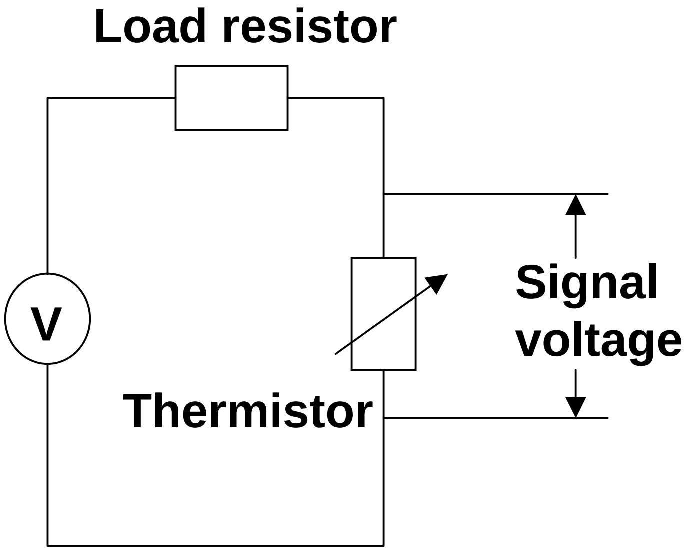
Bolometers for sub-mm astronomy

“Classical” design for sub-mm:
Metal-coated dielectric as absorber
Semiconductor resistance thermometer

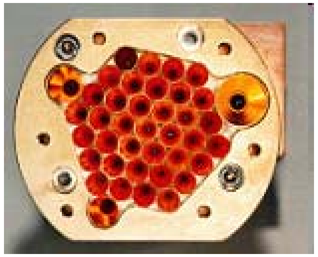
Each pixel illuminated by a feedhorn

Build up focal plane by stacking individual pixels together, each with independent readout

Readout circuit



Operate at 100 mK or 300 mK



NTD Germanium

Neutron transmutation doping

NTD relies on elements having mix of isotopes; some transmute to acceptor and donor elements in neutron flux

Since isotope distribution is homogenous, doping is uniform and random down to the atomic level

NTD silicon ~ 5% of silicon semiconductor market
Used mainly for power transistors

NTD Ge: made in much smaller quantities; applications more limited – available commercially from Haller-Beeman Associates (http://www.haller-beeman.com/)

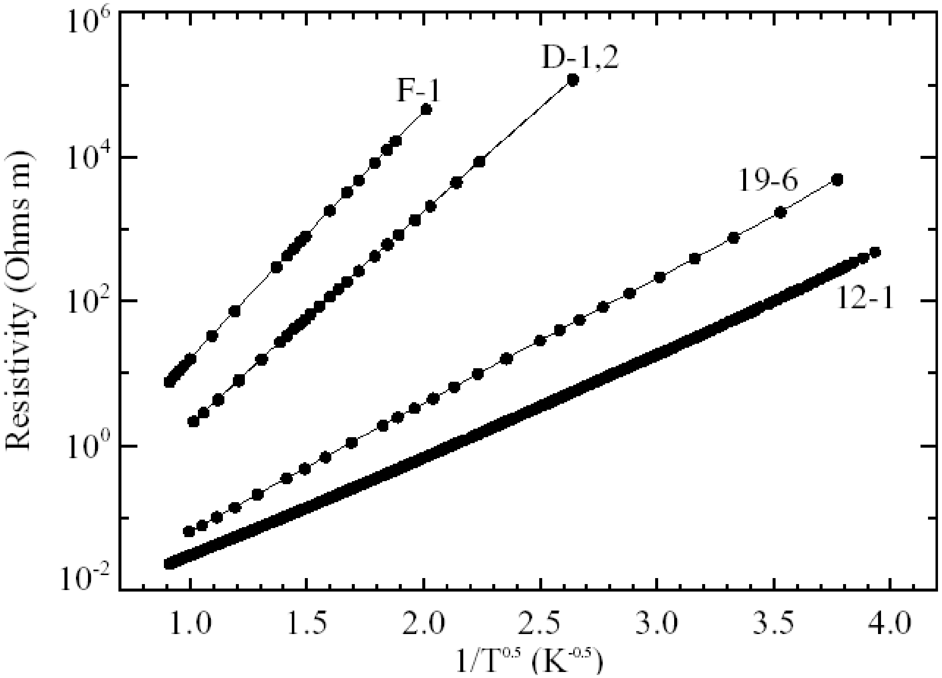
NTD Germanium

Neutron transmutation doping converts ^{70}Ge to ^{71}Ga (acceptor) and ^{74}Ge to ^{75}As (donor)

Doping level depends on neutron flux

Compensation ratio can be changed by altering isotope ratios

Very simple R(T) relation – no Chebychev polynomials!



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VRH

The low temperature conduction method is variable range hopping (VRH). This requires an amorphous structure.

For NTD Ge, the crystal is uniform but the dopant atom positions are random (compare with NbSi which is an amorphous alloy)

Need extremely uniform doping for reproducible behaviour. Other doping methods cannot achieve this

Bolometers

NTD Ge meets all the requirements for cryogenic bolometers and calorimeters:

High sensitivity to temperature – can be tuned for operating temperature from < 20 mK to 4 K

Very good reproducibility (so instruments remain calibrated)

Low “excess” noise

Good (metallic) electrical contacts can be made readily

Can be made very small (-> low heat capacity)

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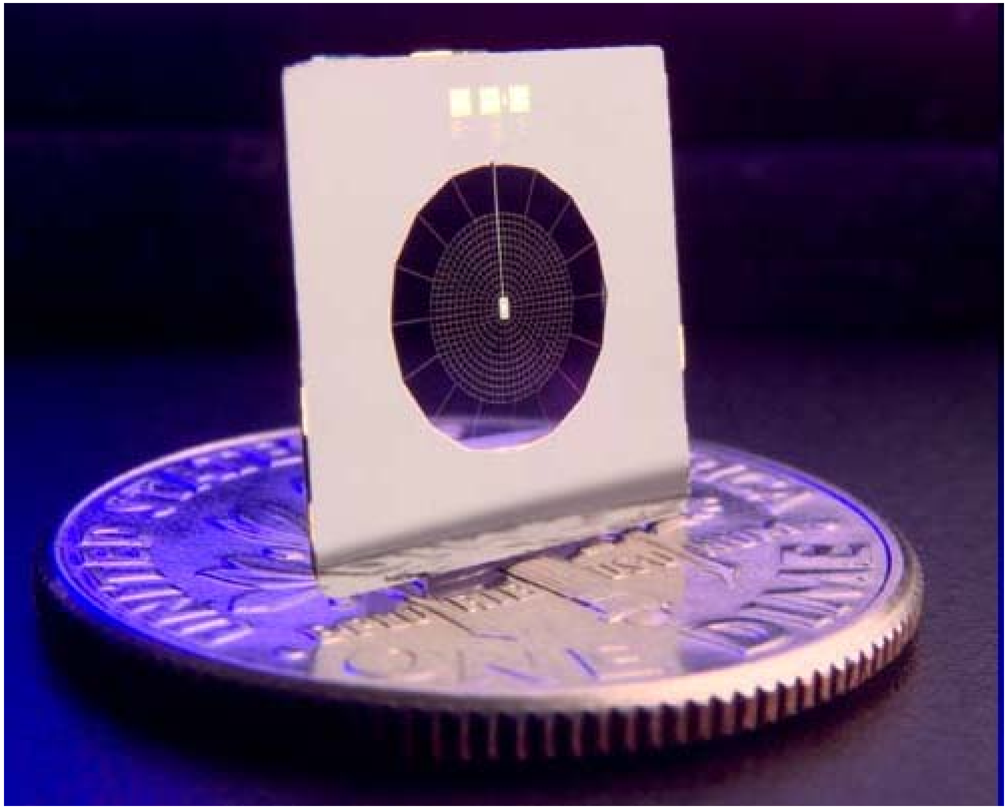
Spiderweb bolometer

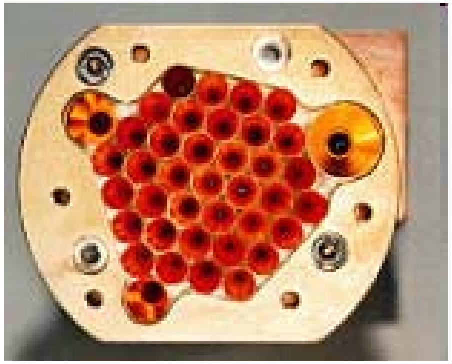
Developed at Caltech
Thermistor sits at centre of silicon nitride mesh spiderweb absorber



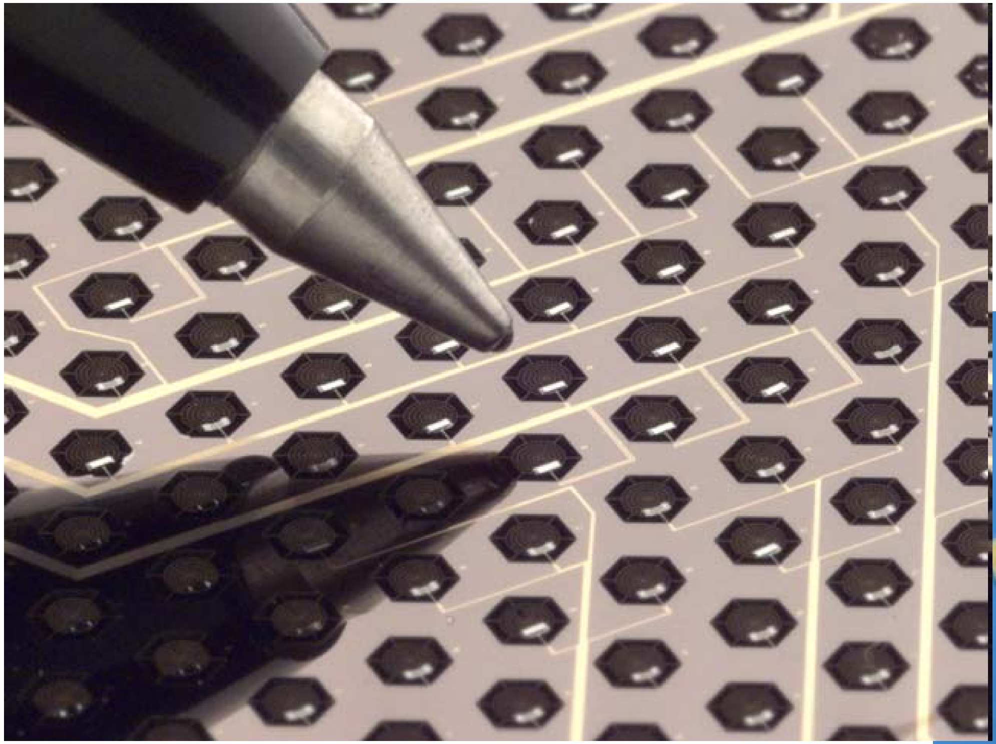
Array made of individual pixels

JPL NTD germanium spiderweb bolometer module with Cardiff feedhorn and metal mesh filter (HFI)

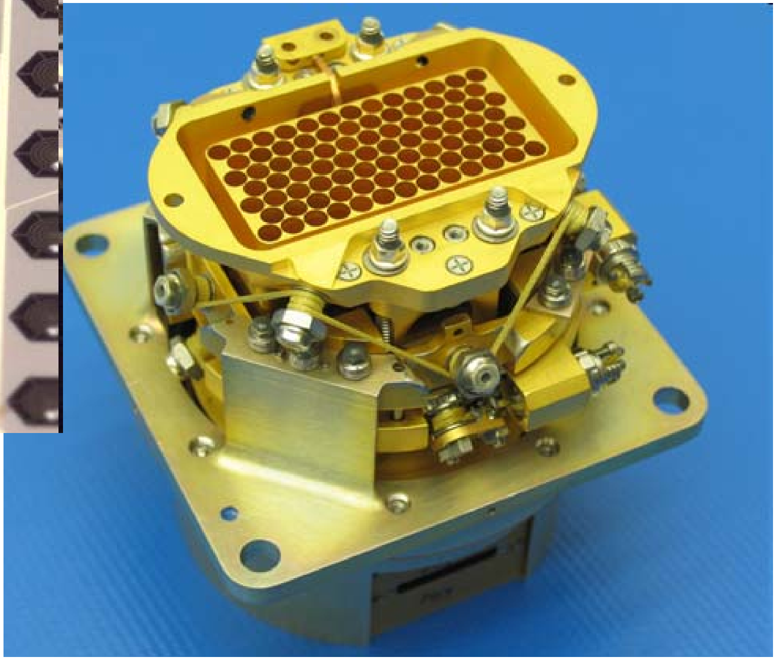
SCUBA bolometer array



Many pixels on single wafer



Wafer for SPIRE bolometer array



SPIRE bolometer array

Ge chips stuck on by hand

Some instruments using NTD Ge

Astronomy
SCUBA
HFI
SPIRE
Boomerang
Bolocam

Dark matter
Eidelweiss
CDMS

Double beta decay
CUORE

Competing technologies

Ion implanted silicon

+ Similar properties to NTD Ge – very uniform doping
+ Easier to make arrays (no manual steps)
– Traditionally 1/f noise has been a severe problem
    Mitigated by increasing doping thickness
– Not usually used for thermometry

Transition edge sensors

+ Easier to make arrays, multiplexing is practical
+ Better sensitivity
– Stop working completely if optical signal too large
– Read-out much more complex
– Sensitive to magnetic fields
– Don't make good thermometers!

History of ground based sub-mm bolometer arrays

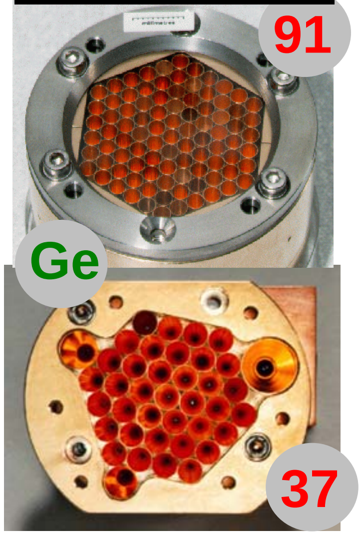
JCMT-UKT14
350μm-2mm

1986-1996

CSO-SHARC
350 μm array

1996-

JCMT-SCUBA
350/450 &
750/850μm



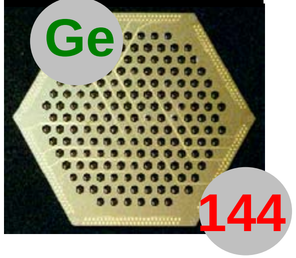
1997-

Also 19 pixel 2 mm array at 0.1 K

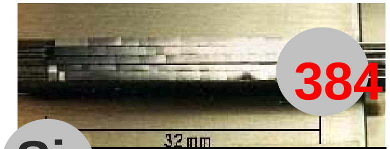
IRAM- MPIfR
1.3mm array

1998-

LMT-BOLOCAM
1.1mm



2001-



CSO-SHARC-II
350/450

2004-

91 Number of pixels

Ge Material

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R(T) expressions

VRH

Use NTD Ge on the insulator side of the metal-insulator transition

Conduction is via variable range hopping (VRH) – electrons hop to sites with small ΔE rather than nearest neighbour

For NTD Ge, people normally assume

$$R = R^* \exp\sqrt{\frac{T_g}{T}}$$

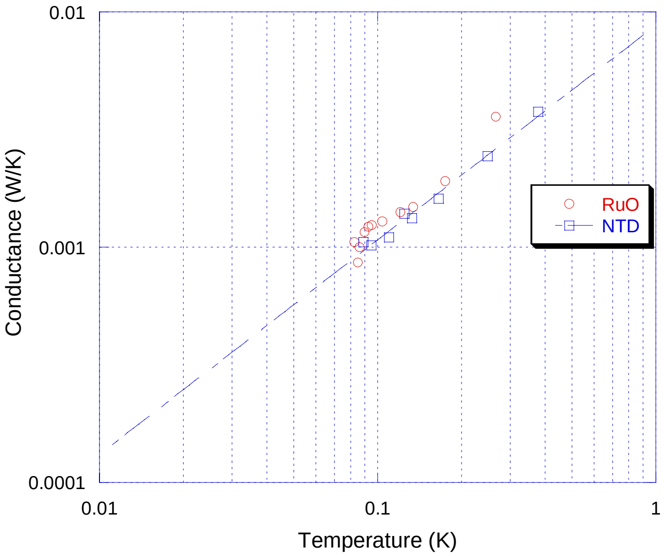
R: resistance
T: temperature
R^*, T_g: constants

Analytical expressions

Why is a simple analytical expression so useful?

Convenience: don’t have to fit complex empirical functions (e.g. Chebychev polynomials)

Improves calibration accuracy – structure in residuals for empirical fits cause systematic errors, especially when measuring very small temperature differences.



Thermal conductance calculated from small temperature differences using NTD Ge (□) and RuO (o) thermometers

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Analytical expressions

Why is a simple analytical expression so useful?

Need fewer points for calibration

Makes measurement errors more obvious – if you depart from the fit, perhaps something is wrong

Makes bolometer models simpler and enables analytical expressions to be written down for properties such as responsivity

Can even extrapolate fits outside range used for calibration with some degree of confidence, especially if using several thermometers from the same batch

VRH

But:

If you use the wrong expression, you make things worse!

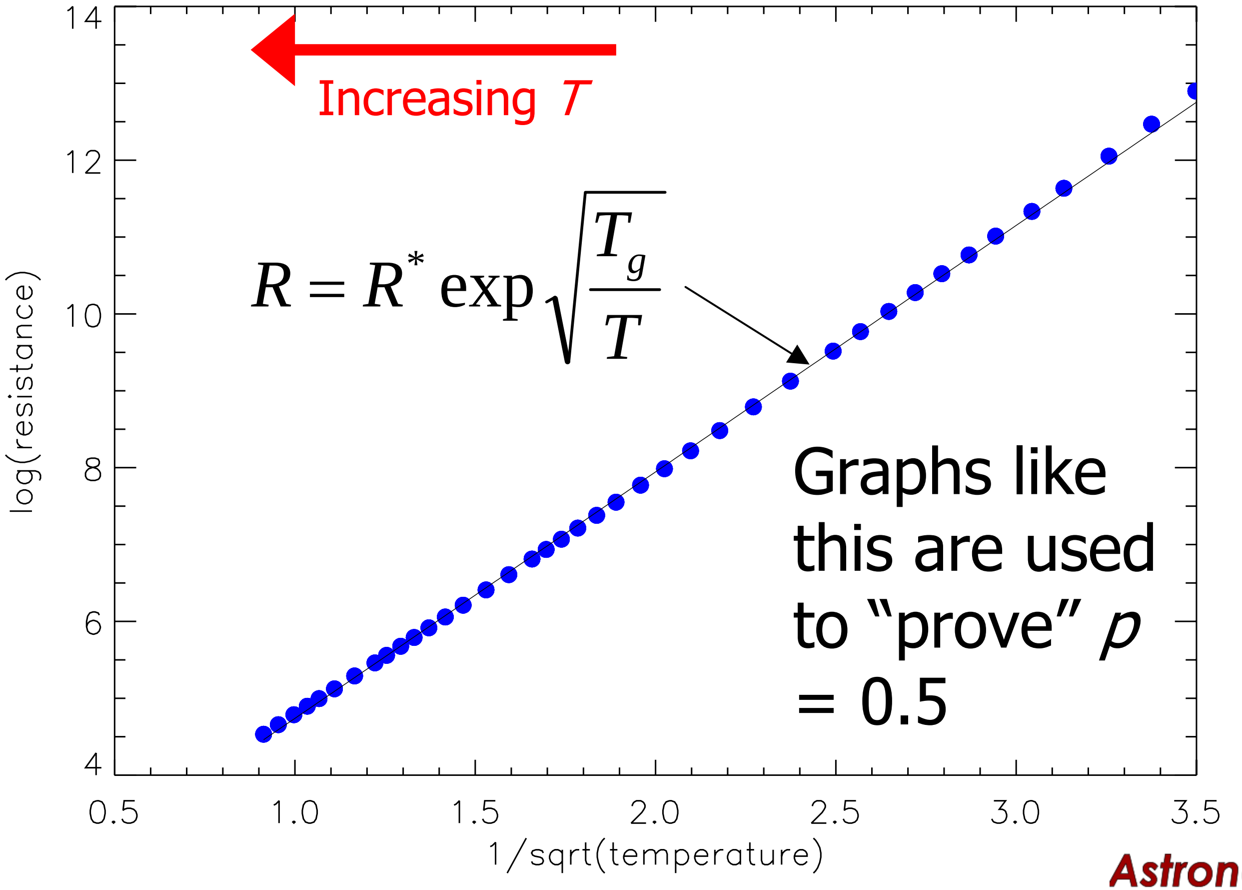
In fact, theory suggests $$R = R^{*}\exp\left(\frac{T_g}{T}\right)^{p}$$ $p \sim 0.5$

Or rather $$R = R^{*}T^{q}\exp\left(\frac{T_g}{T}\right)^{p}$$ $q = ???$

But we shall ignore q because experimentally it can generally be absorbed into the p term

Measurements

Reasonable fit with p=0.5 to data for a 100 mK thermometer…

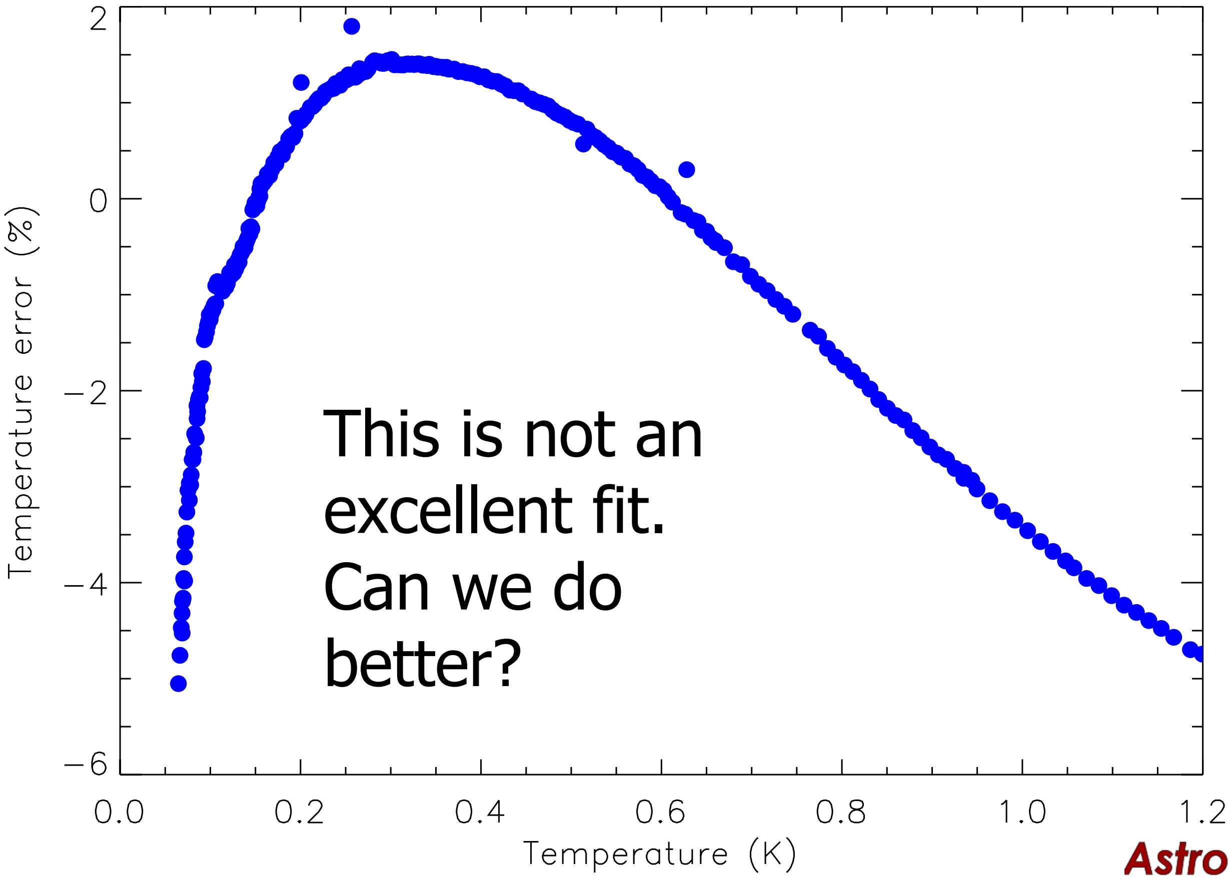


$$R = R^{*} \exp\sqrt{\frac{T_g}{T}}$$

Graphs like this are used to “prove” *p* = 0.5

Measurements

…but look at residuals.
(And you should always look at residuals!)



This is not an excellent fit. Can we do better?

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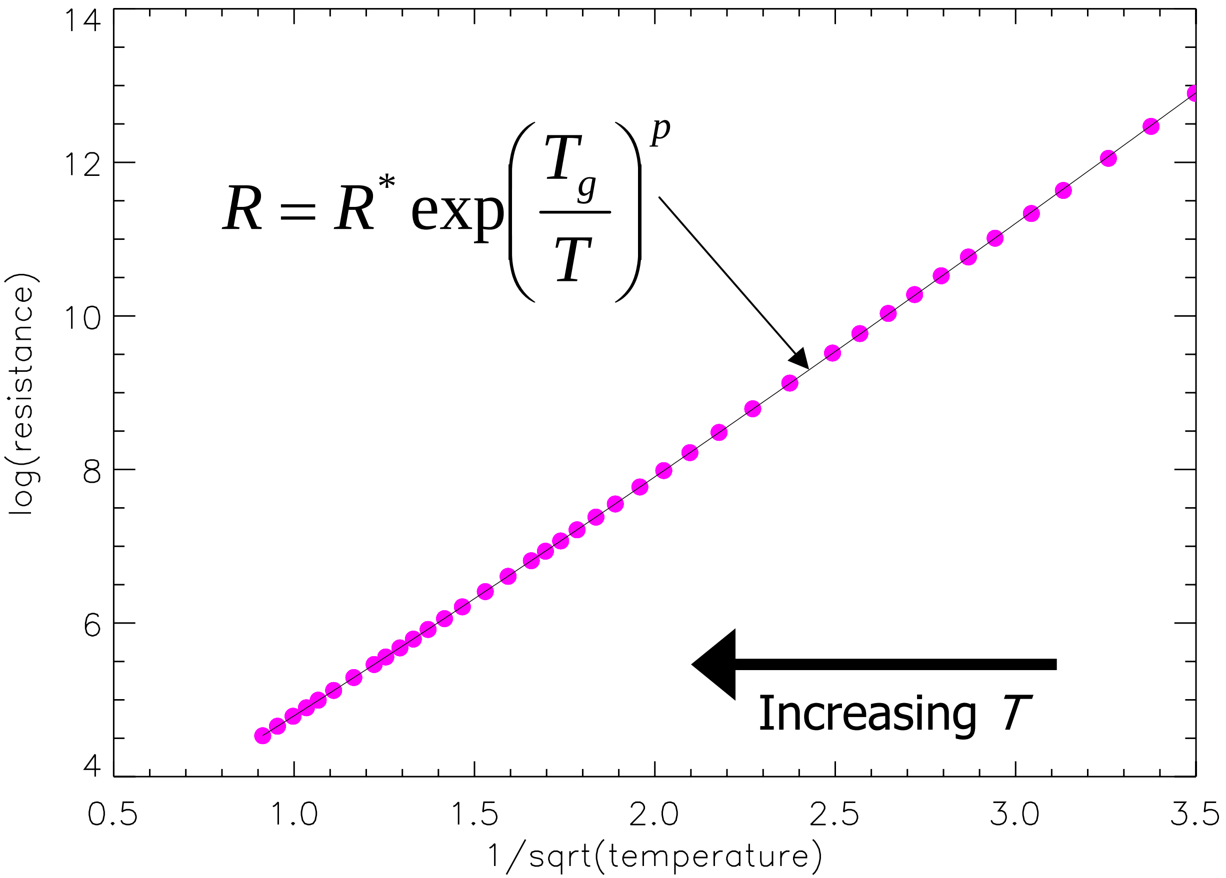
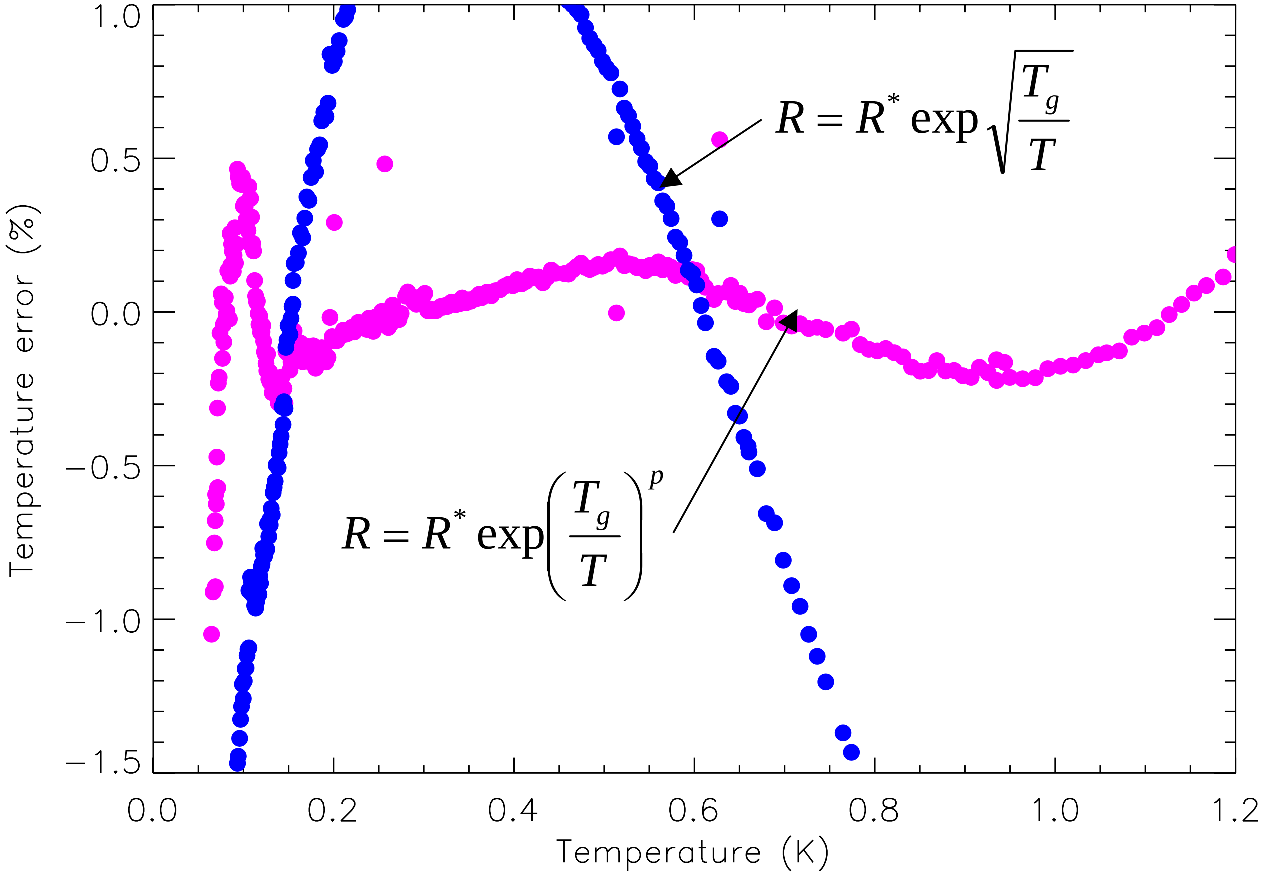
Measurements

With *p* as adjustable parameter:
$p = 0.5611 \pm 0.004$



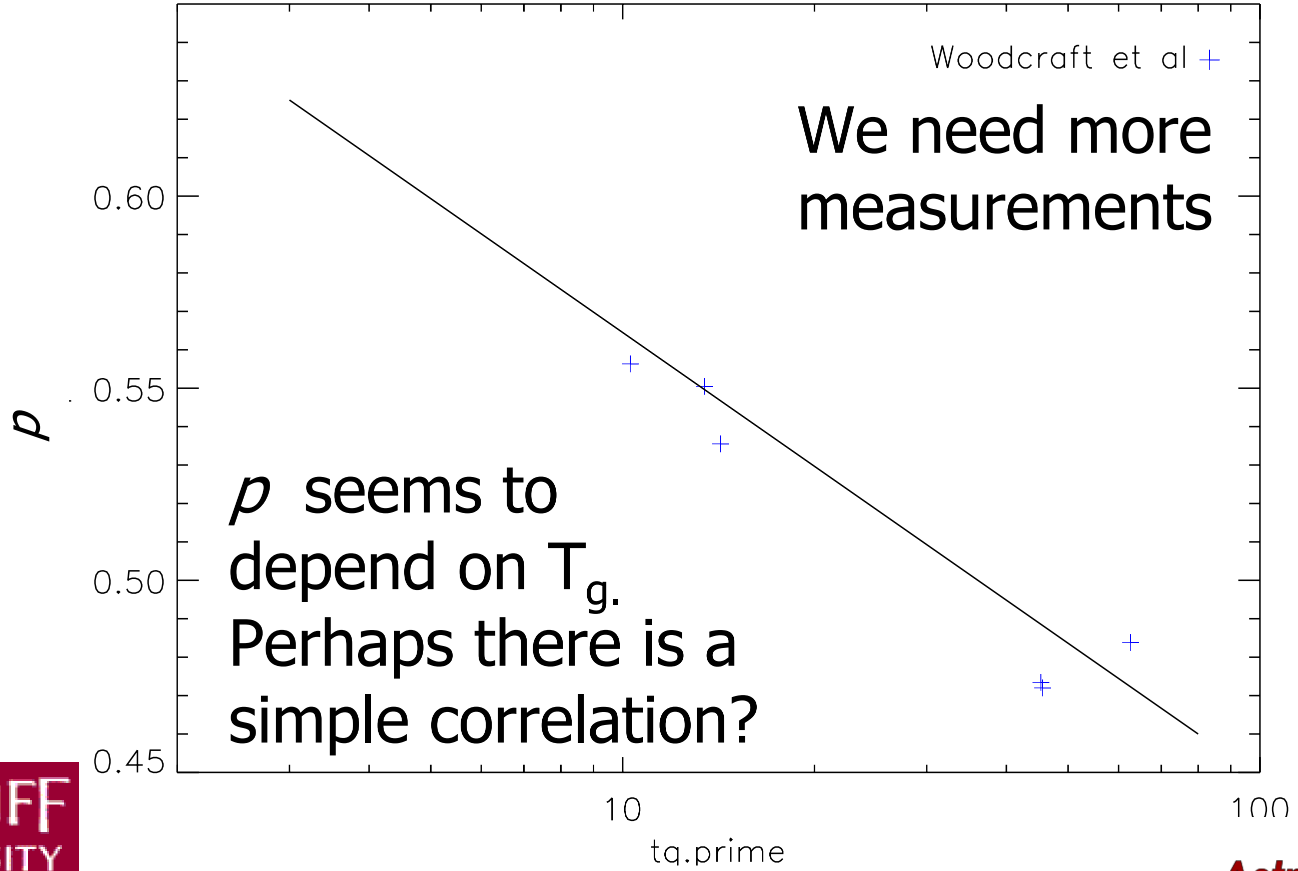
Measurements

Fit is now accurate to better than 0.5% in temperature over almost entire range



More measurements

Get similar results from examining other thermometers: but get different values of *p*



We need more measurements

p seems to depend on T_g. Perhaps there is a simple correlation?

Woodcraft et al. Journal of Low Temperature Physics 134 (3) 925-944 (2004)

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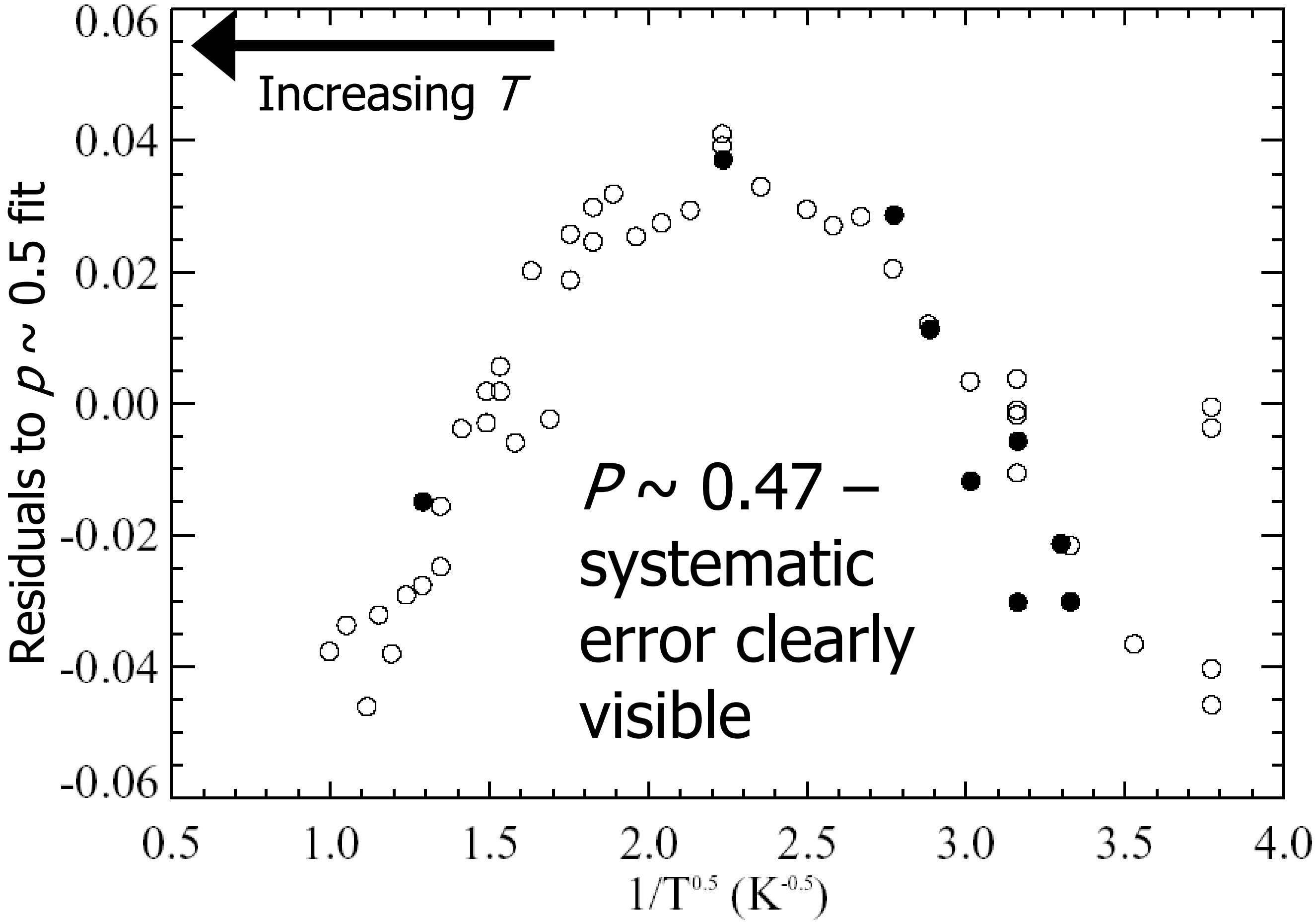
Check

Same thermistor measured in two entirely independent systems (on two different continents)

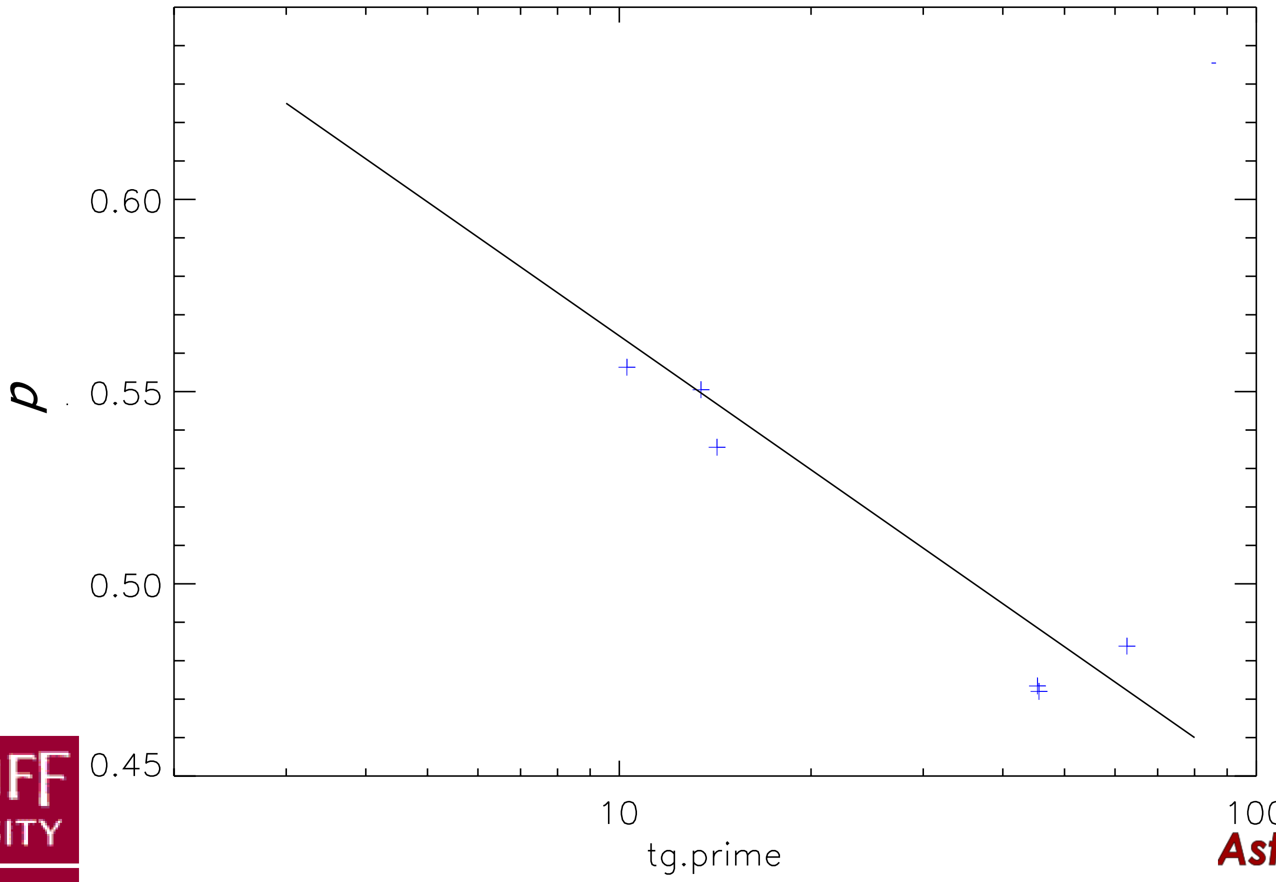
Other checks confirm results and suggest we really are measuring power-laws (difficult)



P ~ 0.47 – systematic error clearly visible

$p(T_g)$

New measurements at lower T_g fall on this line!



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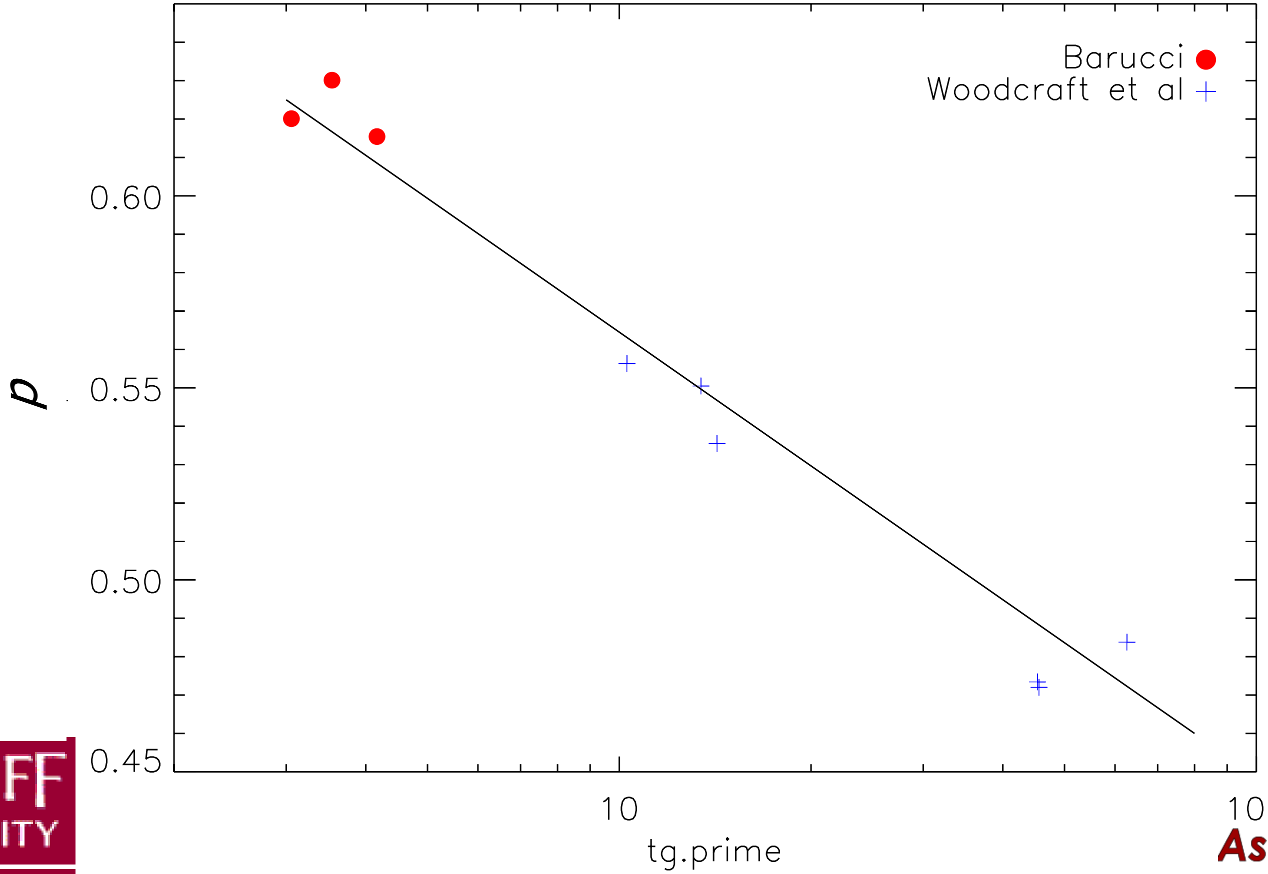
$p(T_g)$

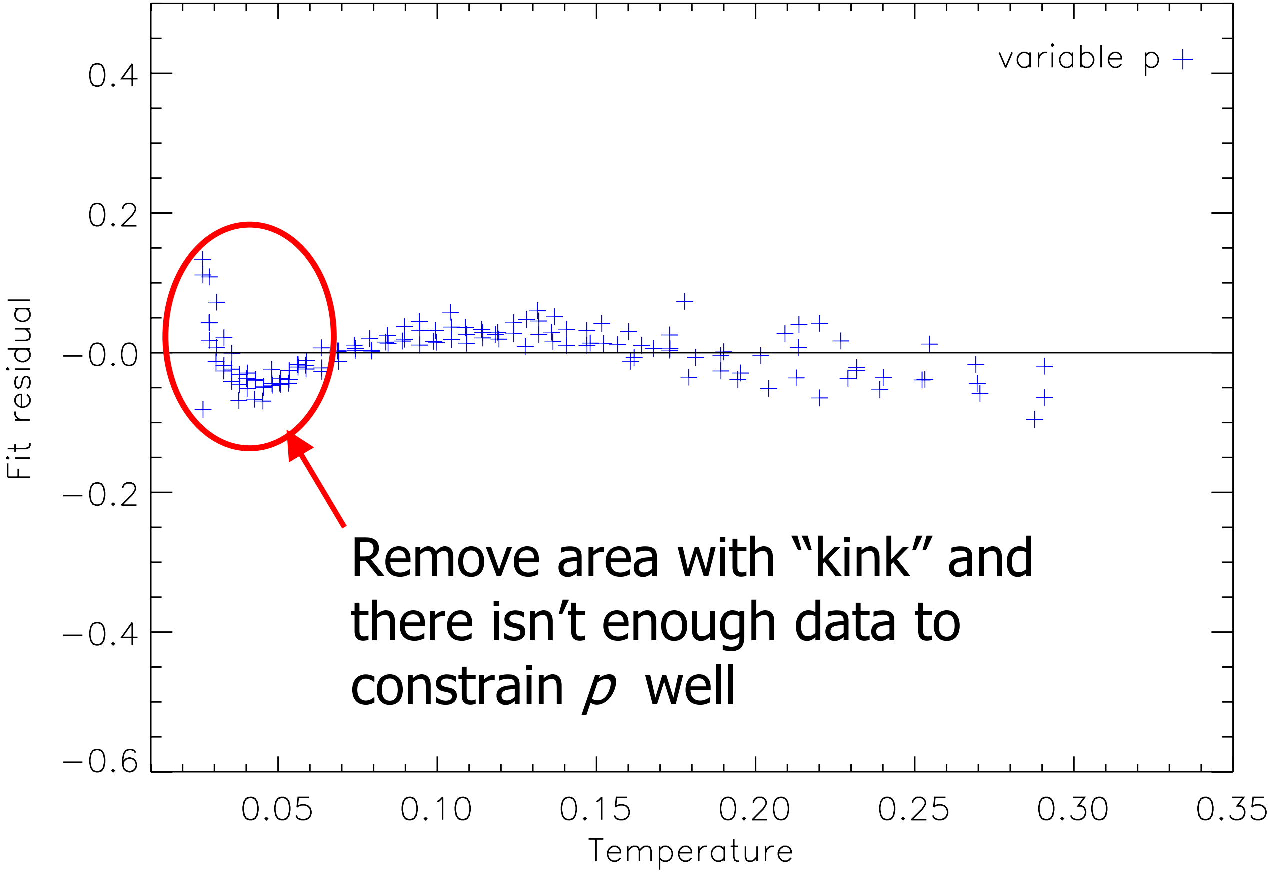
New measurements at lower T_g fall on this line!

Barucci et al. Physica B 368 (2005) 139-142



But…

However, need to treat these values of *p* with some caution



Remove area with "kink" and there isn't enough data to constrain *p* well

Alternative expression

We can get good fits by letting *p* vary

McCammon finds this method does *not* work for ion implanted silicon, and suggests a modified equation with no new free parameters: ("Wouter" function)

$$R = R^{*} \exp\sqrt{\frac{T_g}{T}} + R^{*'} \exp\sqrt{\frac{T_g{}'}{T}}$$

$$R^{*'} = R^{*} \exp\left(2.522 T_g{}^{(-0.25)} - 8.733\right)$$

$$T_g{}' = 2.7148 T_g + 1.2328$$

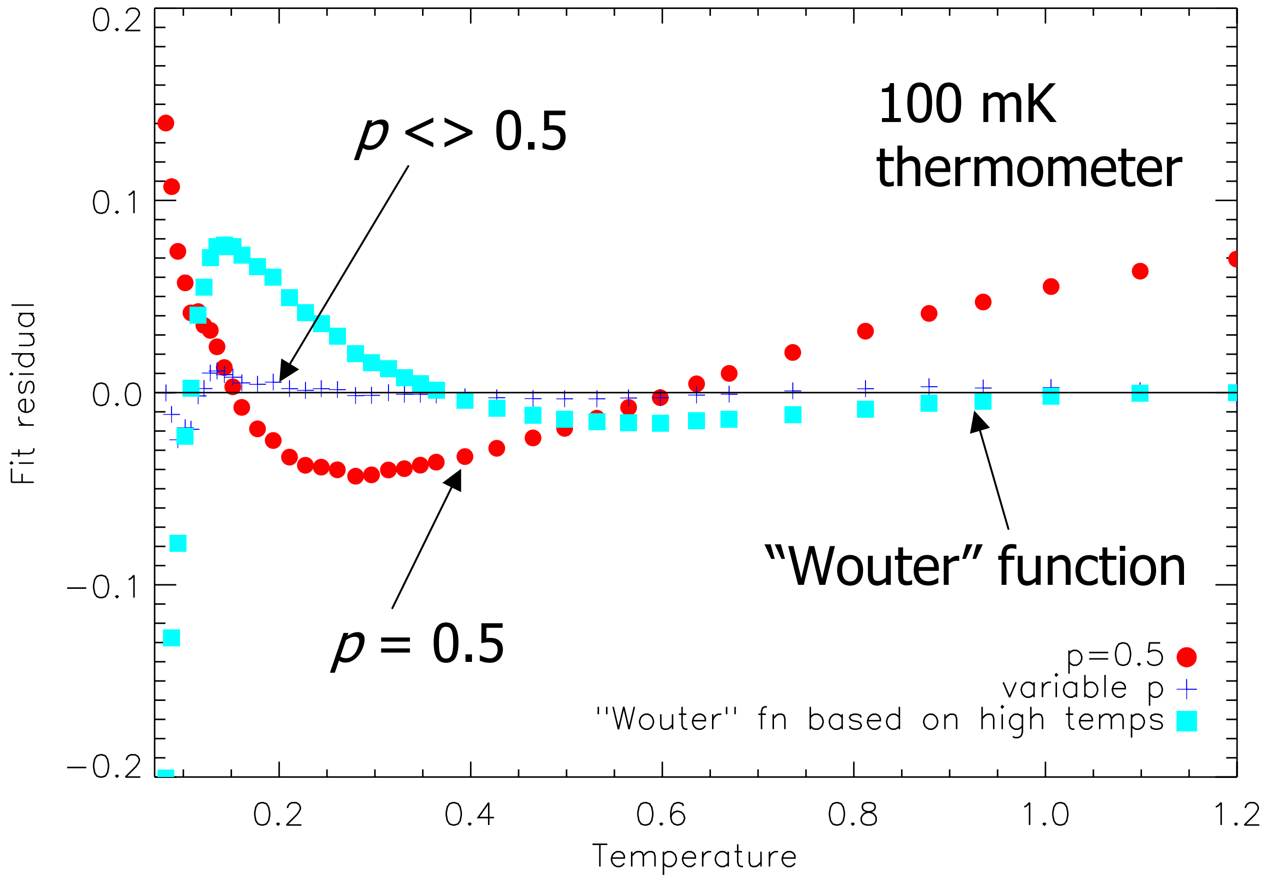
D. McCammon, in Cryogenic Particle Detection, Ed. Enss, Springer 2005

D. McCammon, http://arxiv.org/abs/physics/0503086

He also finds this works well for an NTD Ge sample

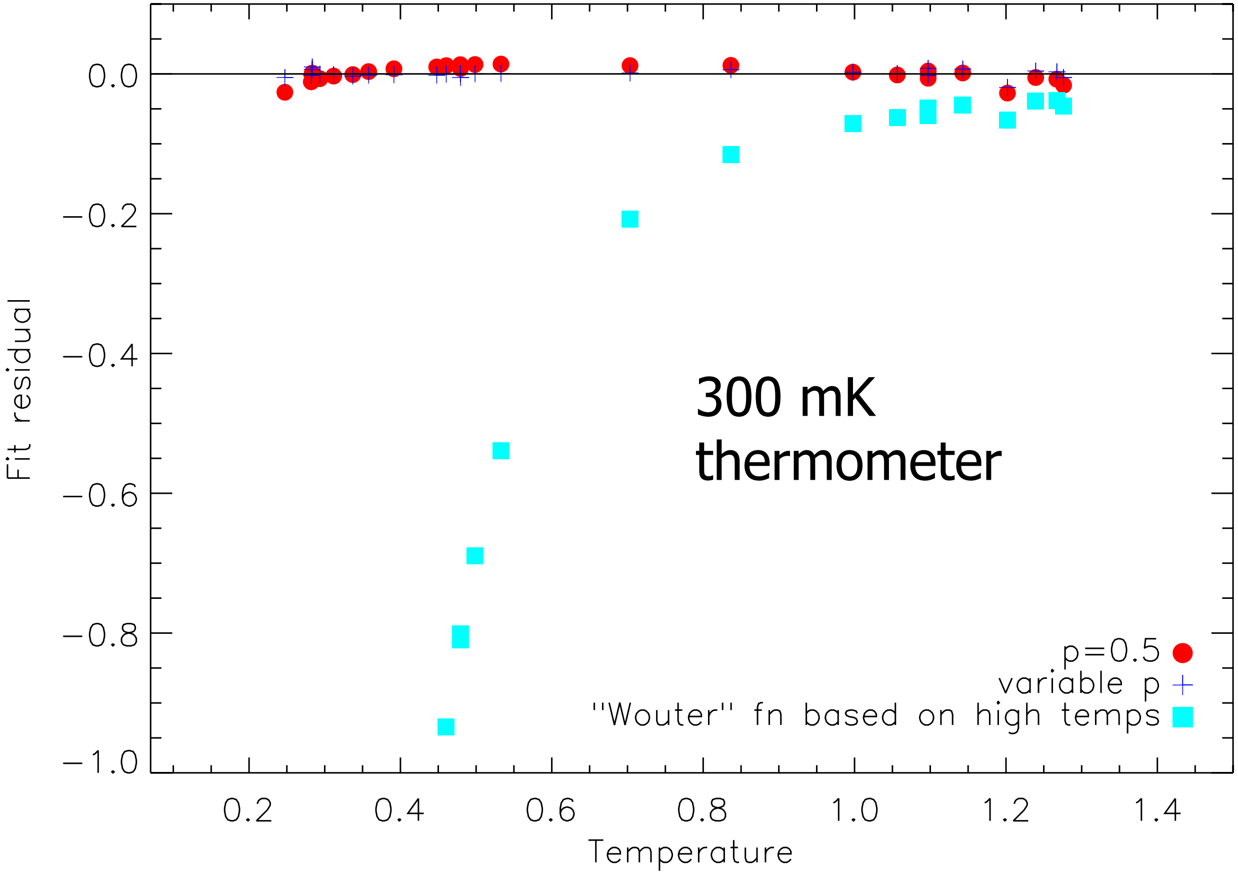
Trying alternative expression

Doesn’t work well for 100 mK thermometer measurements



Trying alternative expression

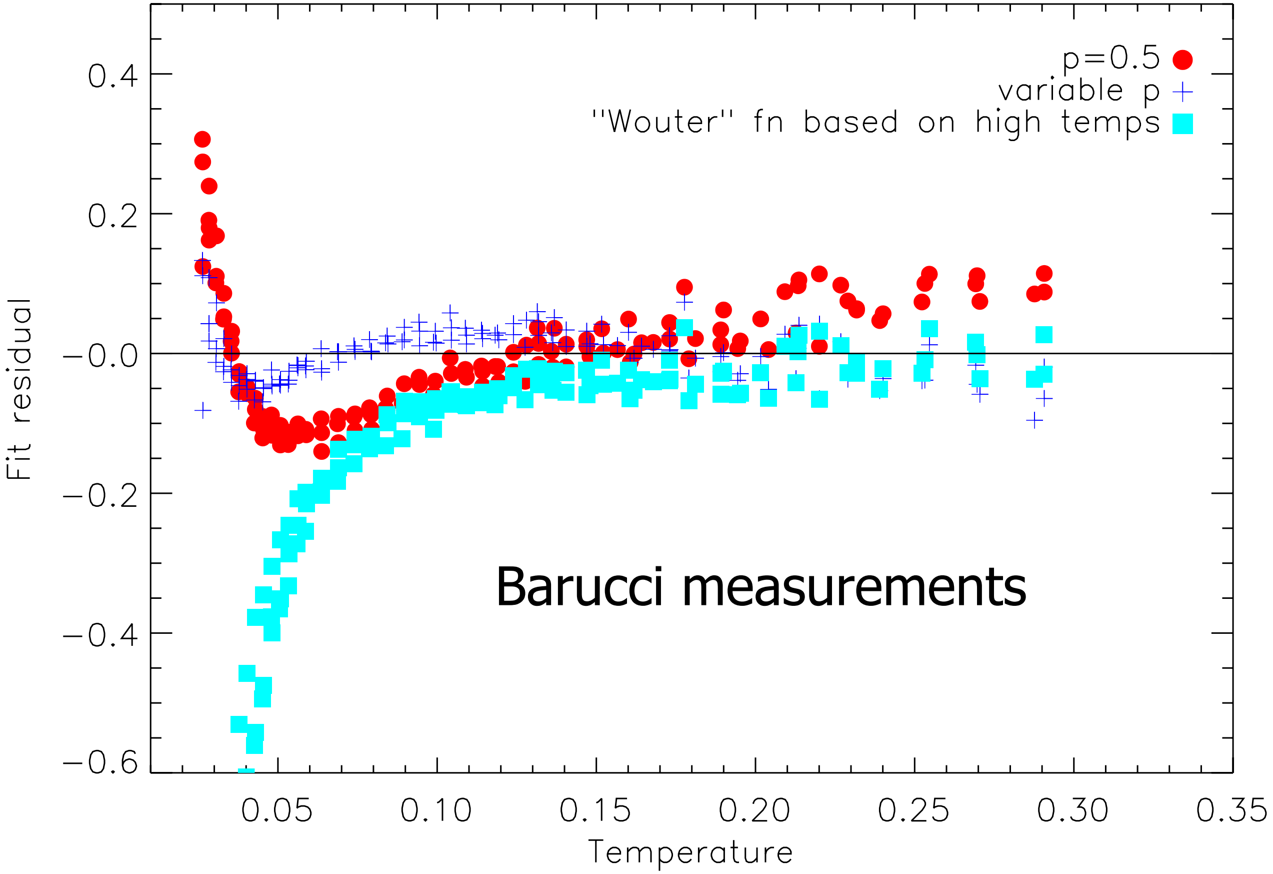
…or for 300 mK thermometers



300 mK thermometer

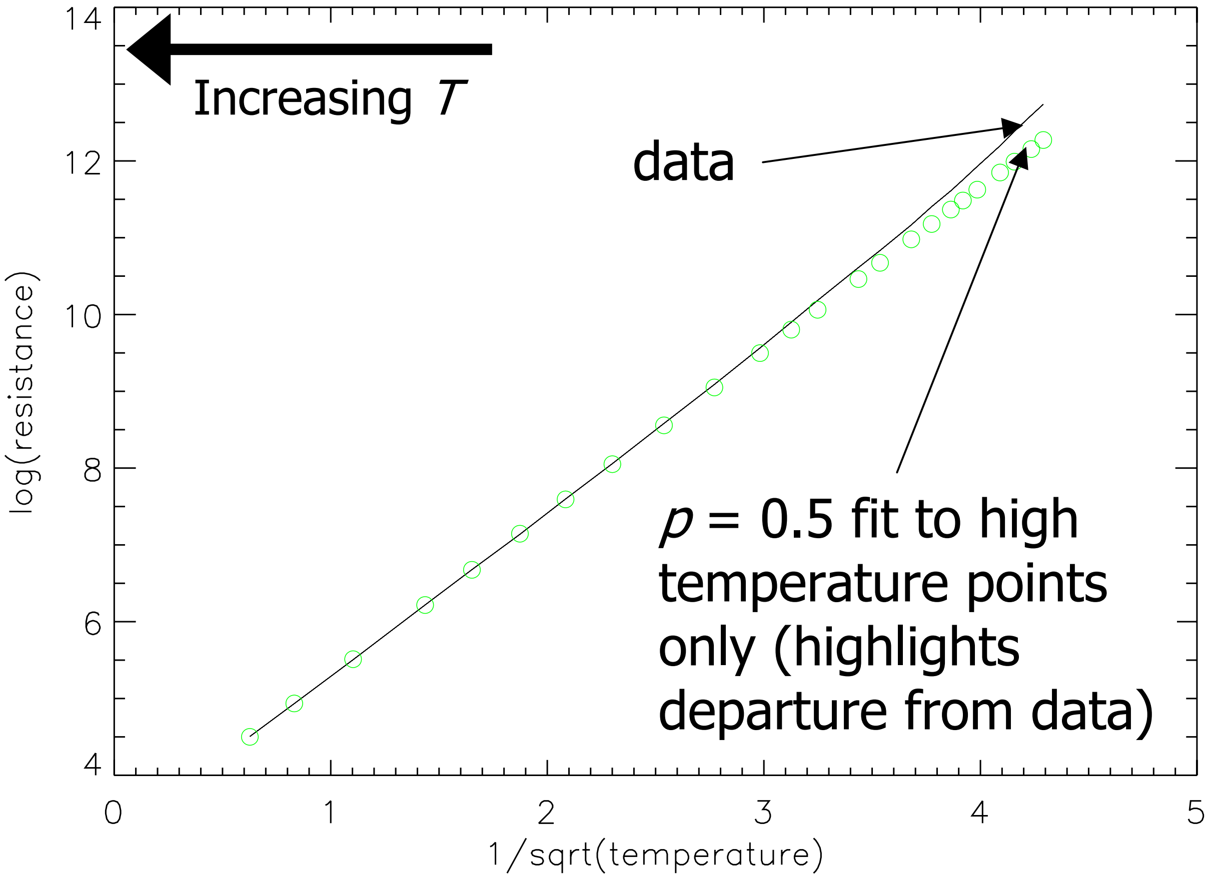
Trying alternative expression

…or for measurements in Barucci et al 2005



Trying alternative expression

NTD Ge sample from McCammon 2005



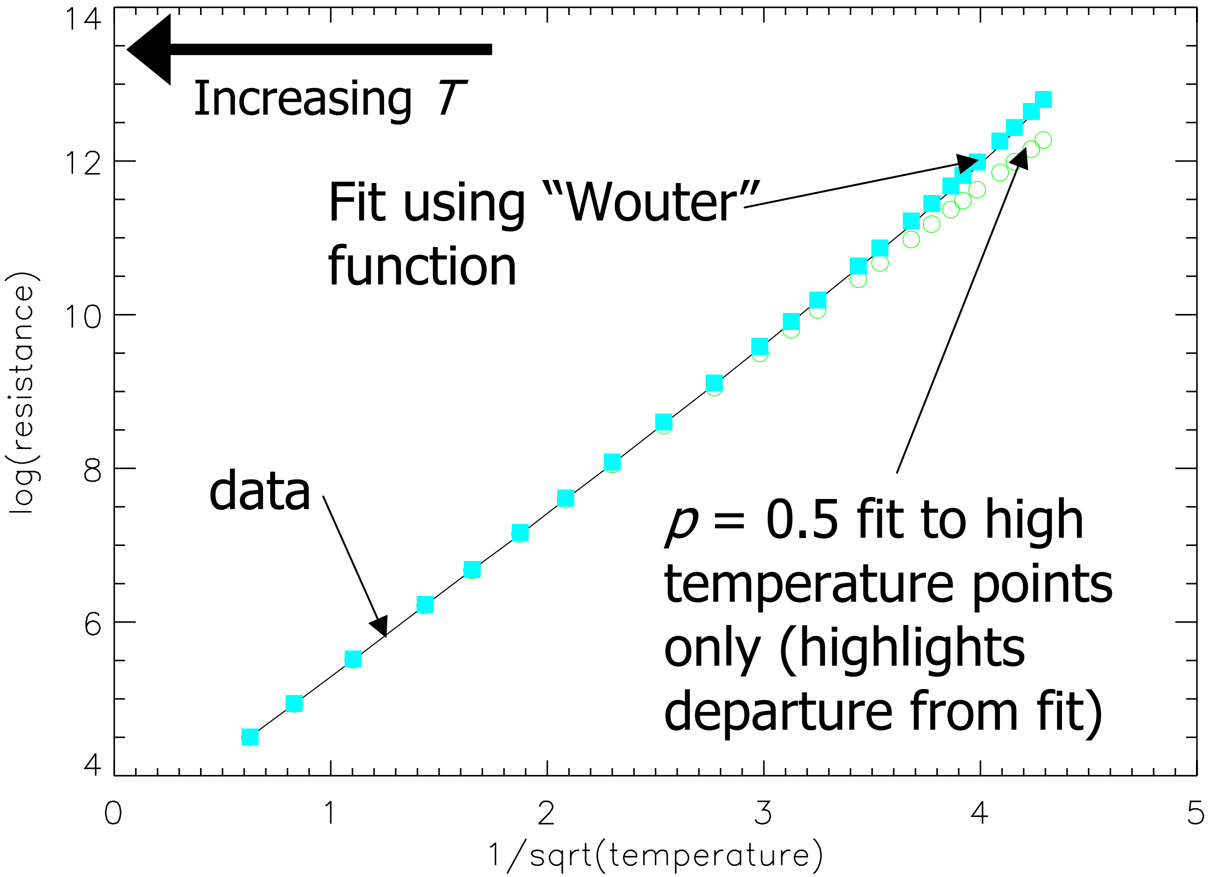
Increasing *T*

data

p = 0.5 fit to high temperature points only (highlights departure from data)

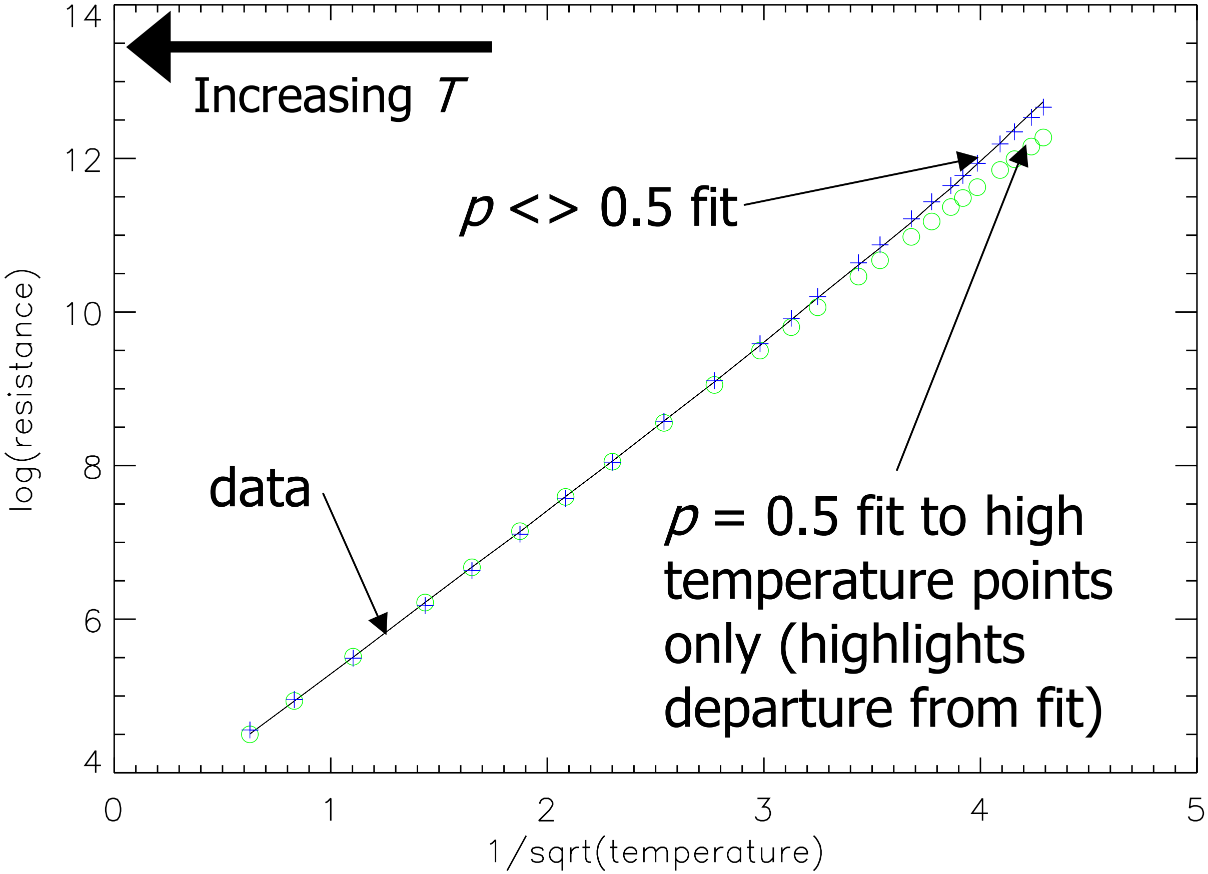
Trying alternative expression

"Wouter" function fits the data well



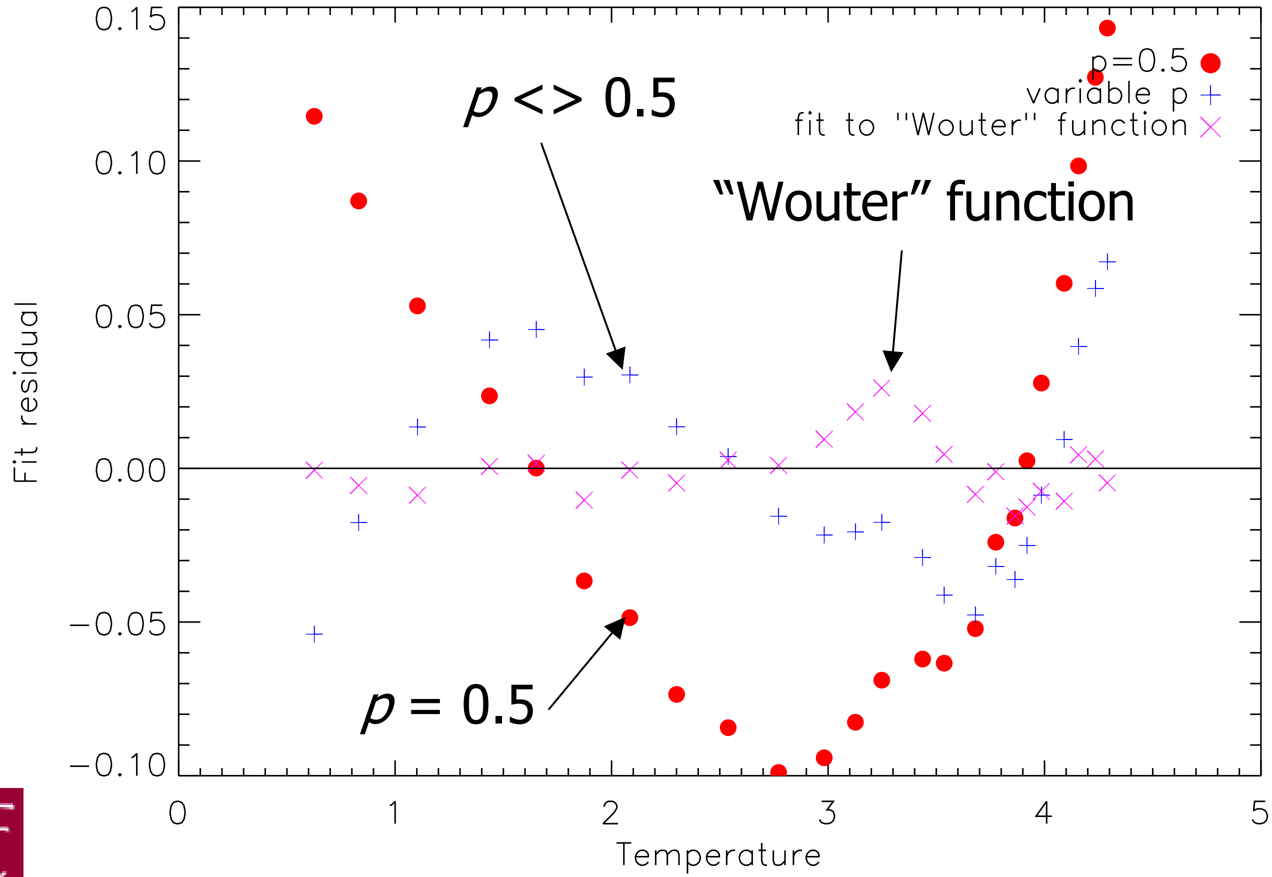
Trying alternative expression

But variable *p* fit is also good (at the expense of an extra free parameter)



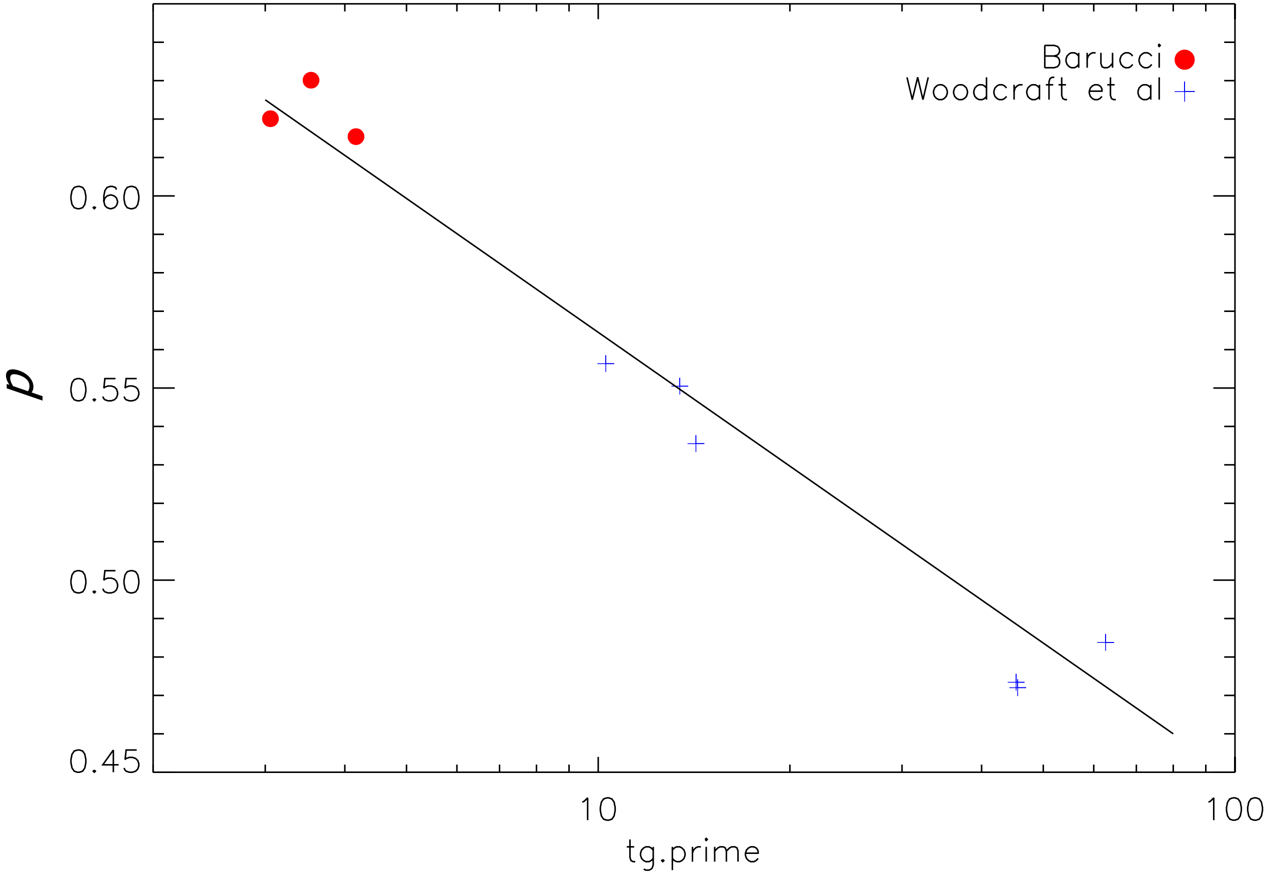
Alternative expression

"Wouter" function seems to do a somewhat better job, but variable *p* fit is not bad



$p(T_g)$

Return to p as a function of T_g



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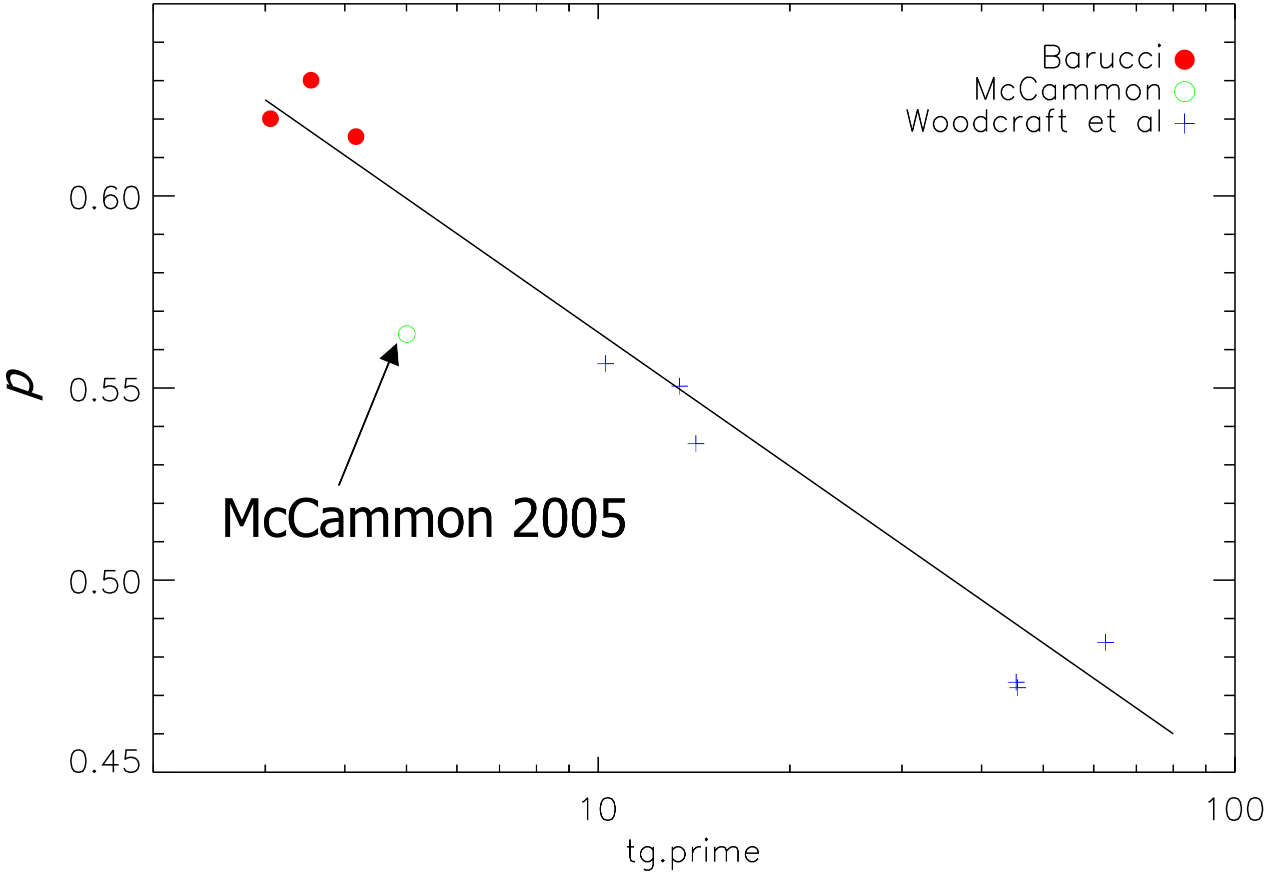
$p(T_g)$

Result from McCammon sample not wildly in disagreement.
Hard to put error bar on – depends on systematic effects

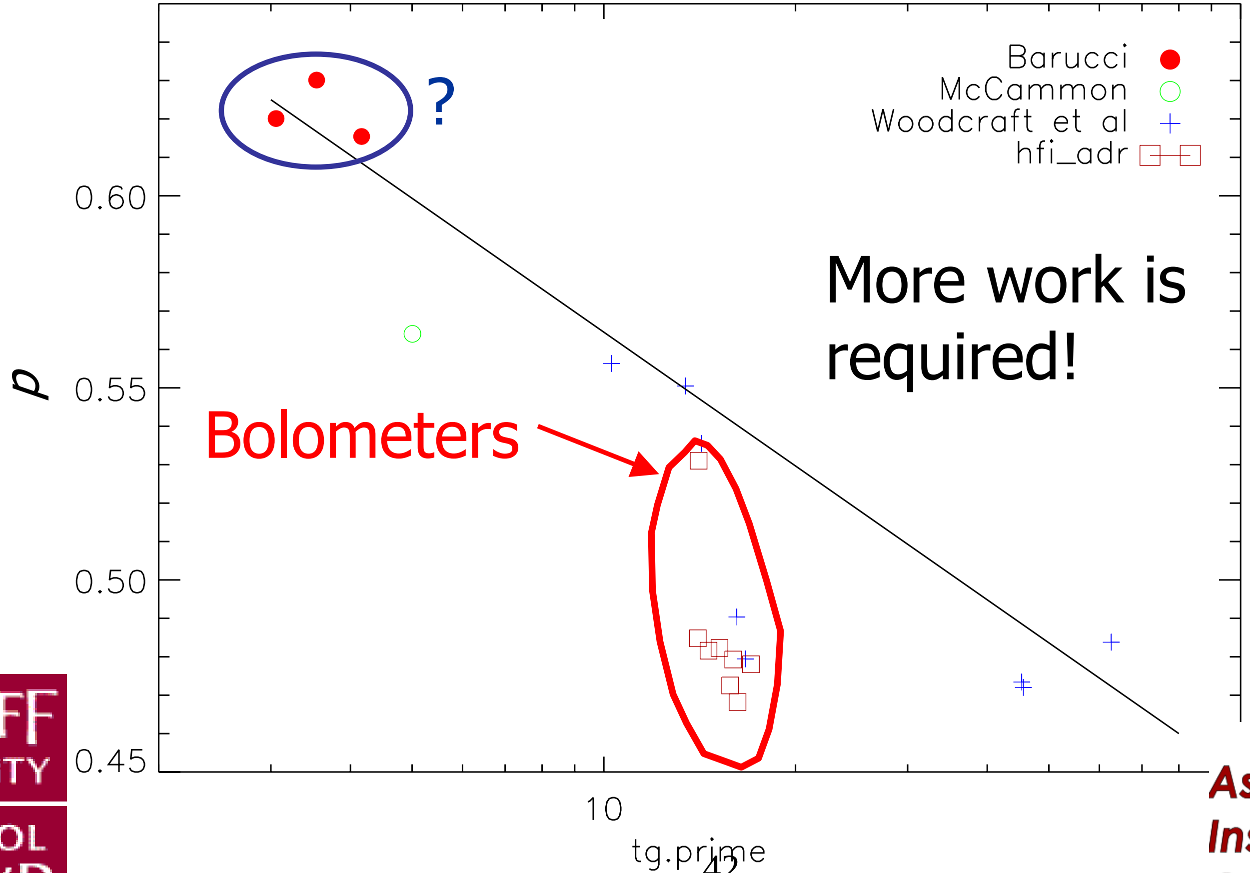


$p(T_g)$

But: measurements on *bolometers* do not agree with the fit!

Mounting in a bolometer shouldn’t make a difference

Only significant difference is geometry: contacts on one face not opposite sides – could this make a difference?



Bolometers

More work is required!

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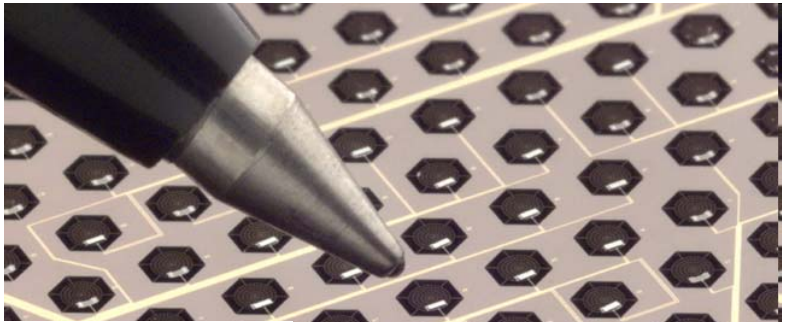
Conclusions

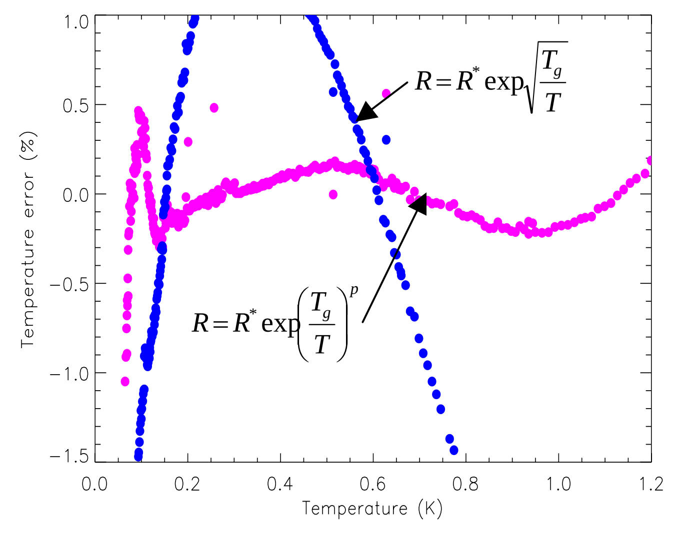
Neutron transmutation doped germanium can be used to make sensitive and reproducible thermometers with a very simple calibration.

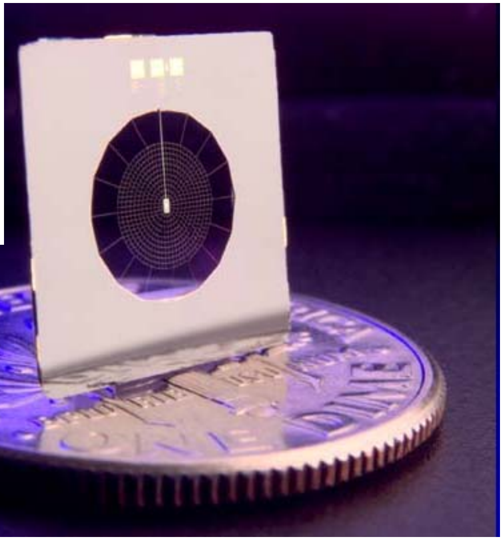
This makes them ideal for use in bolometers and calorimeters

The commonly used calibration expression is often wrong, but adding one more parameter (*p*) produces good fits for all thermistors examined. There *may* be a correlation between *p* and T_g – more work is required!

The calibration expression proposed by McCammon based on work on silicon thermistors does *not* appear to be generally appropriate for NTD Ge.







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More information: *Woodcraft et al. Journal of Low Temp. Physics 134 925-944 (2004)* *http://reference.lowtemp.org/woodcraft_ntd.pdf*

NPL Thermal Measurement Awareness Network

Low Temperature Thermometry – Status and Future Requirements

Thermometry Down To 300mK For Space Instrumentation

Anneso Goizel & David Smith

Space Science Technology Department

Rutherford Appleton Laboratory, Oxfordshire, UK

Content

- ✓ Space Instrumentation at RAL
- ✓ Example: SPIRE Instrument
- ✓ Applications of Thermometry for Space Projects
- ✓ Thermometry Performances and Issues
- ✓ Future Projects

Space Instrumentation at RAL

- With significant involvement in over 50 space missions in recent years, the Space Science and Technology Department (SSTD) is on the forefront of UK space research.
- The Space Science and Technology Department is based at the Rutherford Appleton Laboratory near Didcot in Oxfordshire.
- http://www.sstd.rl.ac.uk/

Current Cryogenic Projects at RAL SSTD

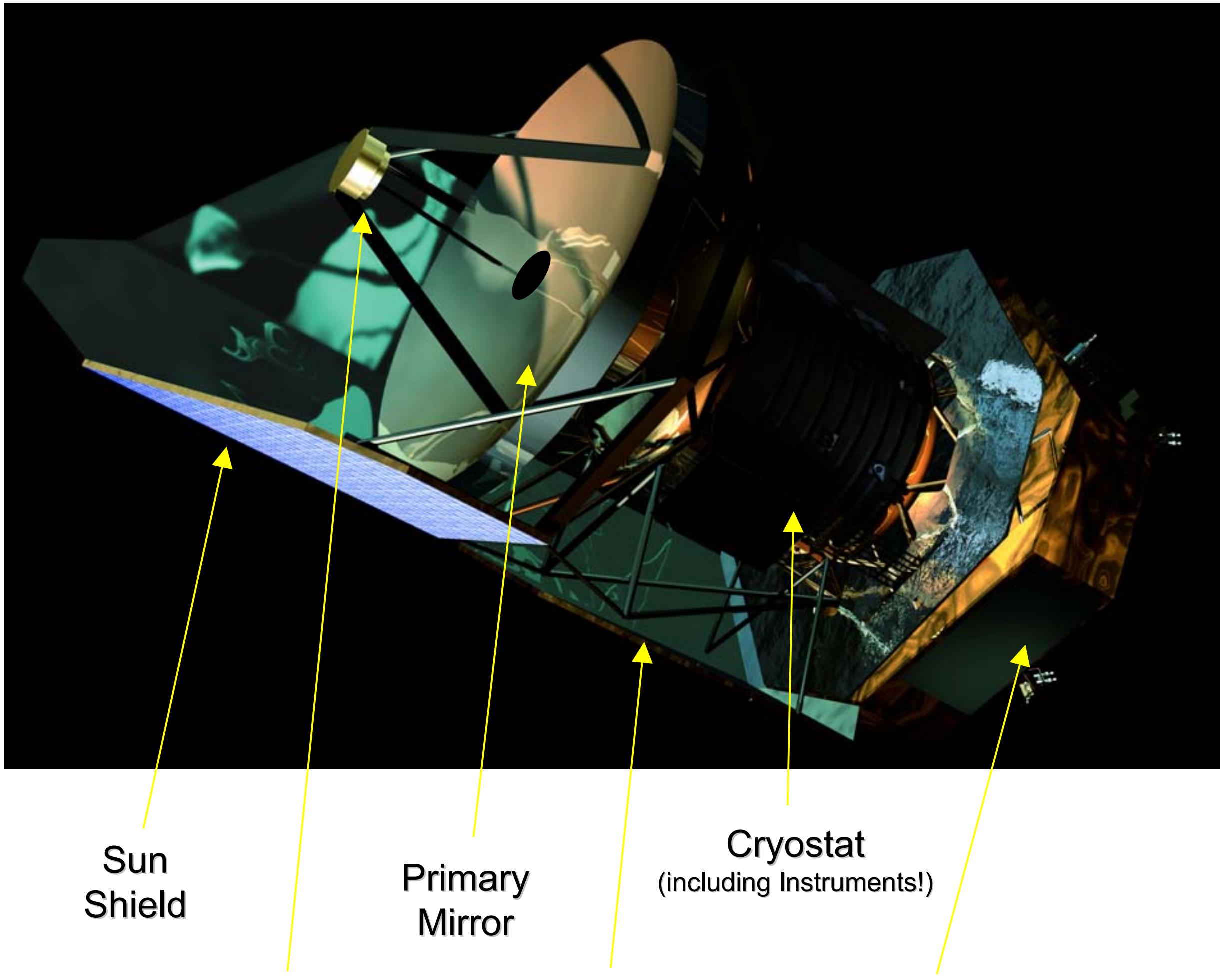
- Space Instruments:
  - **SPIRE** – **S**pectrographic and **P**hotometric **I**nfra**r**ed **E**xperiment
    - For Herschel Space Telescope – to be launched 2007
    - Instrument Main and Detector Enclosures cooled by Herschel cryostat at 4K and 1.7K respectively while Detectors passively cooled at 300mK using He3 sorption Cooler.

  - **MIRI** – Mid Infrared Instrument for James Webb Space Telescope (JWST)
    - 6.5m IR telescope at L2 to be launched 2013 (Replacement for HST)
    - Optical Module at 15K with Detectors at ~5-7K using a two stage cooler.

- Ground-Based Telescopes:
  - **VISTA** – Visible and Infrared Telescope for Astronomy
    - 4m wide field survey telescope
    - CCD Array controlled at 70K

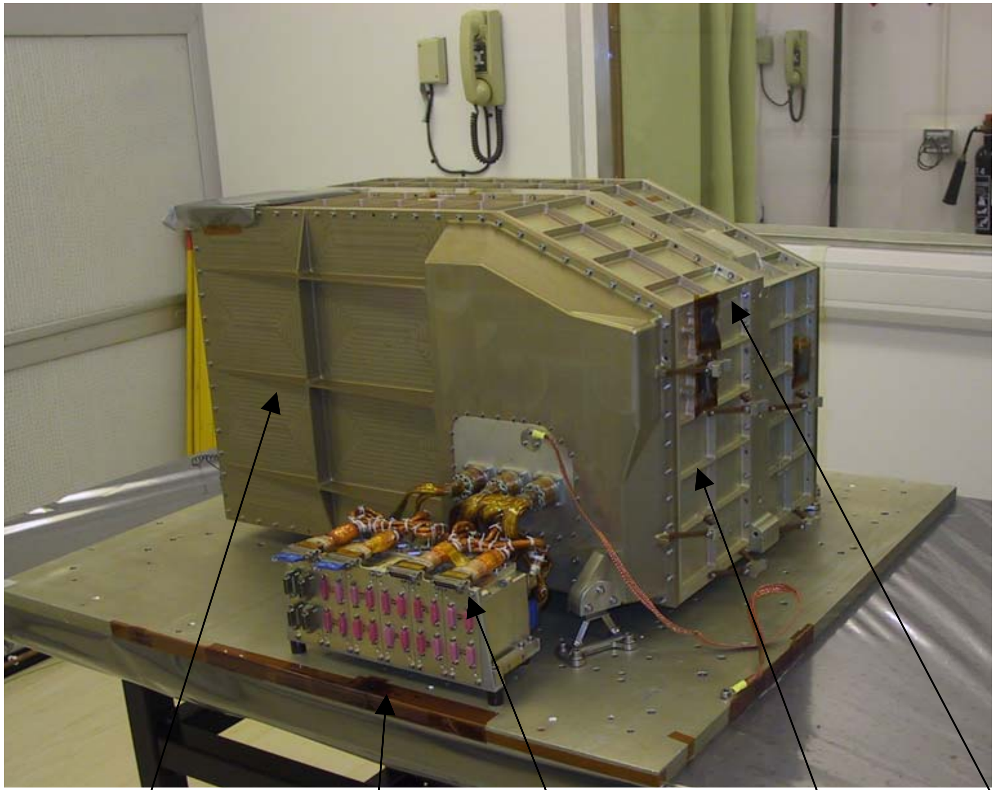
  - **FMOS** – Mirrors and enclosure Detectors actively controlled at 70K for IR measurement.

The Herschel Space Observatory



- ESA Cornerstone Mission
- Launch Ariane 5, 2007
- Mission duration: 3 years nominal
- Orbit: L2, 1.5million km away from the Earth
- Height: 9000mm
- Diameter: 4500mm
- Mass: 3500kg
- Primary Mirror: Ø3500mm, Silicon Carbide. T_{M1}=80K
- Instruments: SPIRE, PACS and HIFI
- Instrument accommodation: Super-fluid ^{2}He Cryostat with 1.7K, 3.5K and 10K cooling stages
- Wavelength range: λ=60-760μm

What is SPIRE?



Outer Cover of Photometer

JFET rack

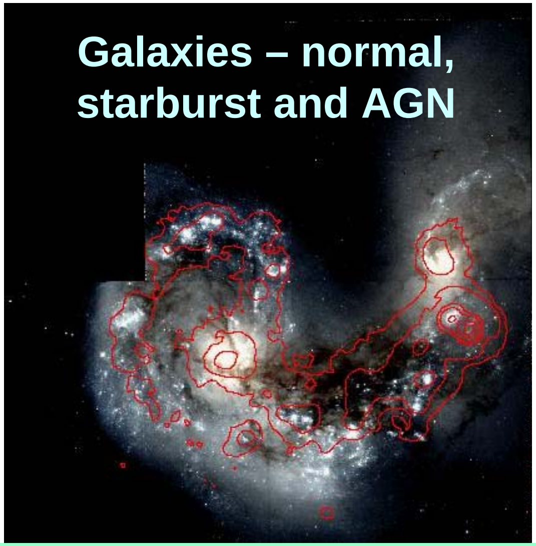
Detector Harnesses

Cryostat thermal Interfaces

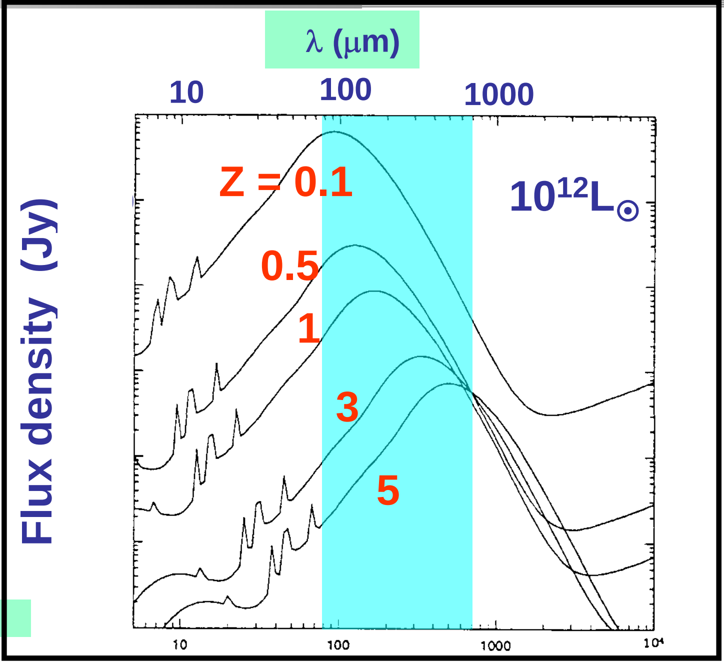
Spectrometer Outer cover

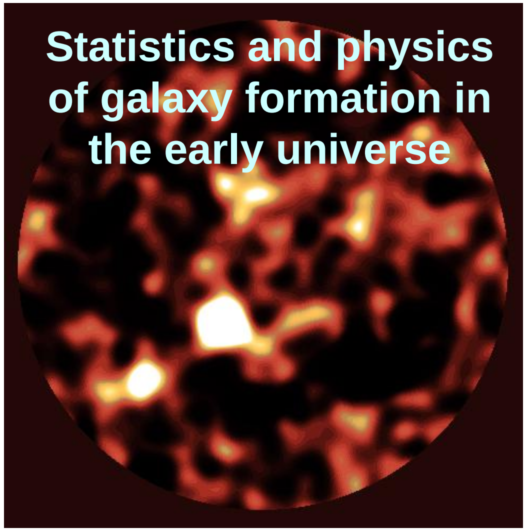
- **Spectrographic and Photometric Infrared Experiment**
- **Photometer simultaneously images three bands: 250, 360 and 520µm**
- **Spectrometer images in two bands: 200-325 µm and 315-670 µm**
- **Instrument Field of View: 4’x8’**
- **Optimised to map large swathes of the sky in three bands (colours)**
- **Follow up sources at higher photometric or spectrographic sensitivities**

SPIRE Scientific Goals

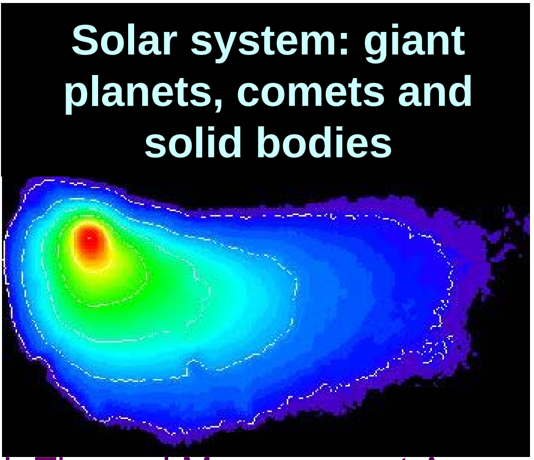


Galaxies – normal, starburst and AGN

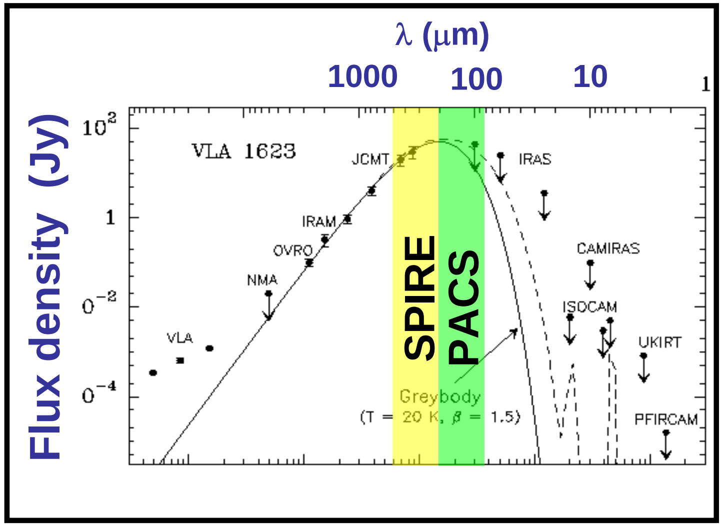


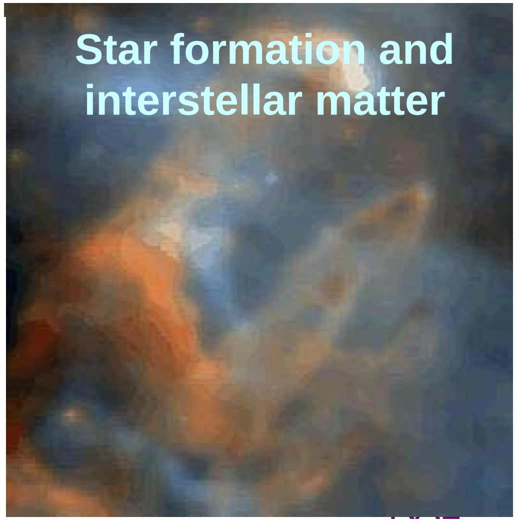


Statistics and physics of galaxy formation in the early universe



Solar system: giant planets, comets and solid bodies



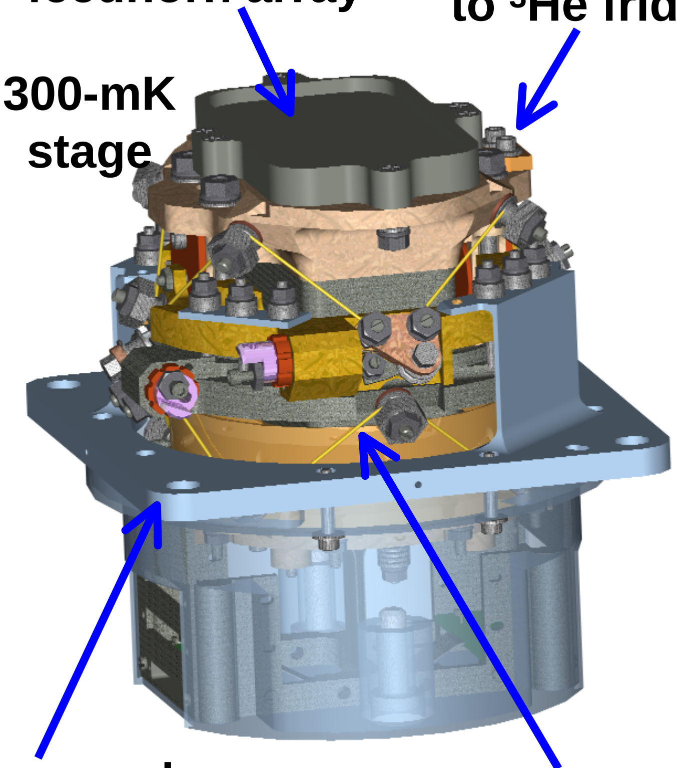


Star formation and interstellar matter

Engineering Challenges

- Electrical design:
  - The performance is noise limited and much work is required to maintain the system design requirements
- Thermo-mechanical design
  - Thermal and mechanical designs are **always** competing
  - The appropriate tradeoffs had to be made
- Management / Systems Engineering
  - Very large consortium
  - Subsystem interfaces and spacecraft interfaces
  - Tight schedule
  - Budget limited
- AIV and calibration
  - Need to reproduce space environment on the ground
  - Very complex cryostat and OGSE/EGSE/MGSE

Bolometer Array Module



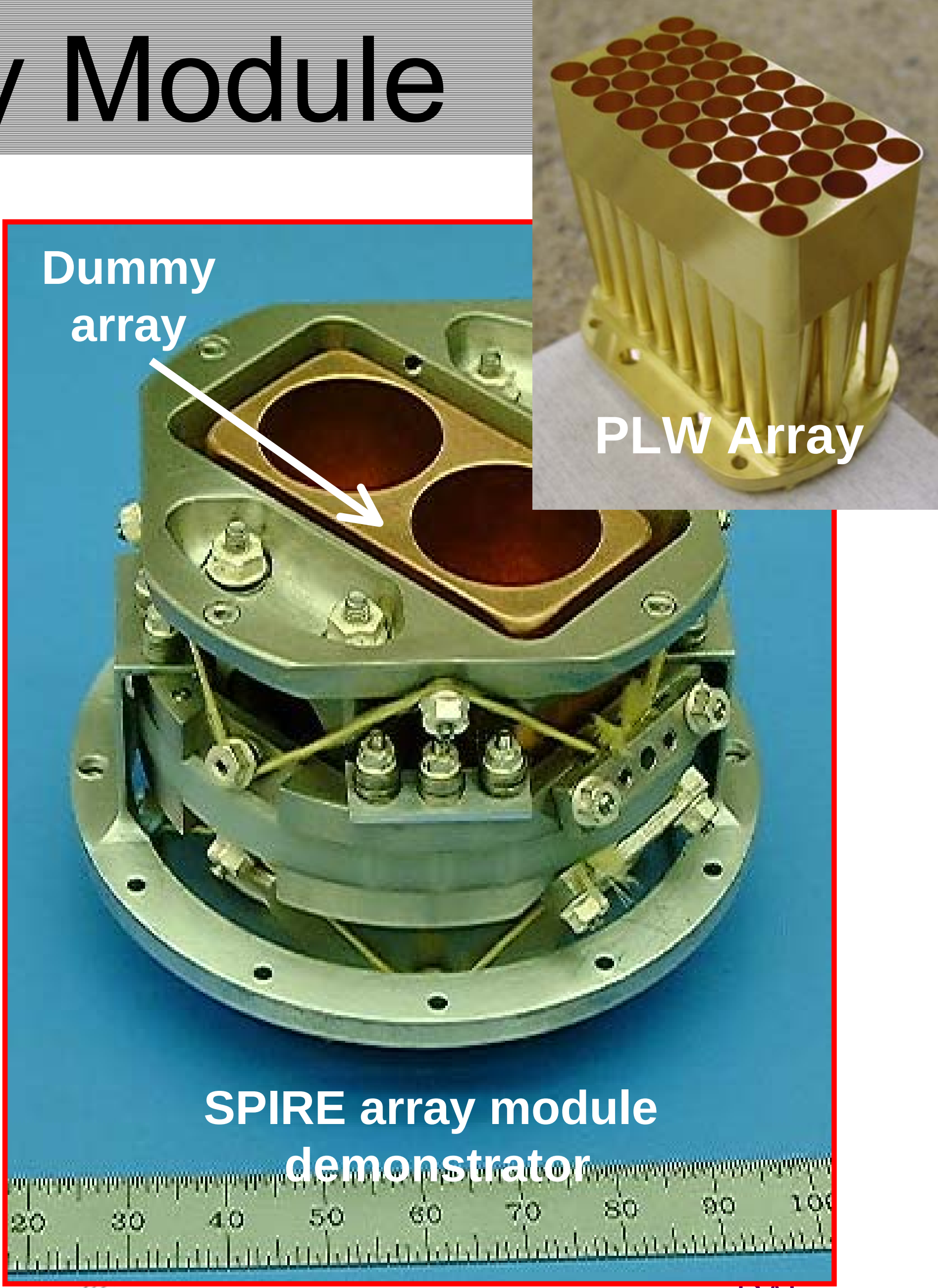
Filter covering feedhorn array

Connection to ^{3}He fridge

300-mK stage

2-K stage and interface to SPIRE 2-K box

Kevlar suspension



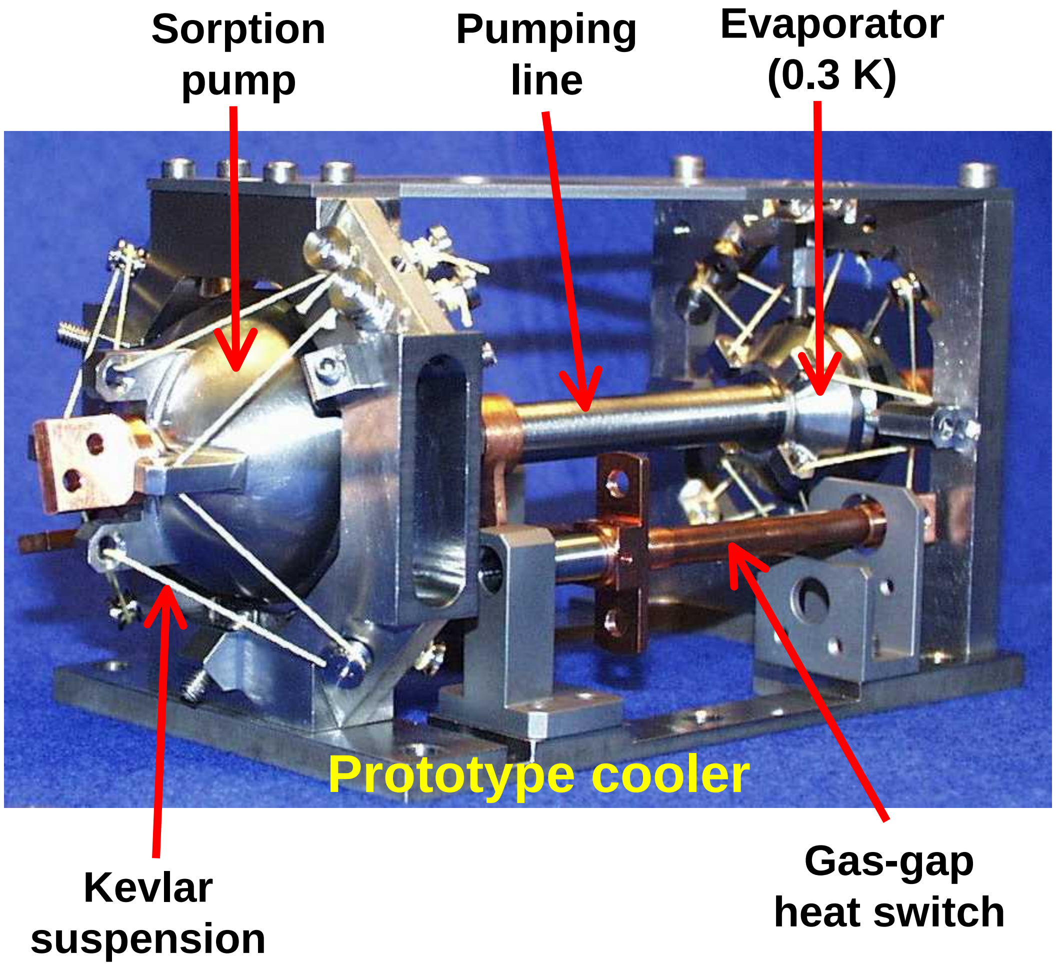
Dummy array

PLW Array

SPIRE array module demonstrator

^{3}He Cooler

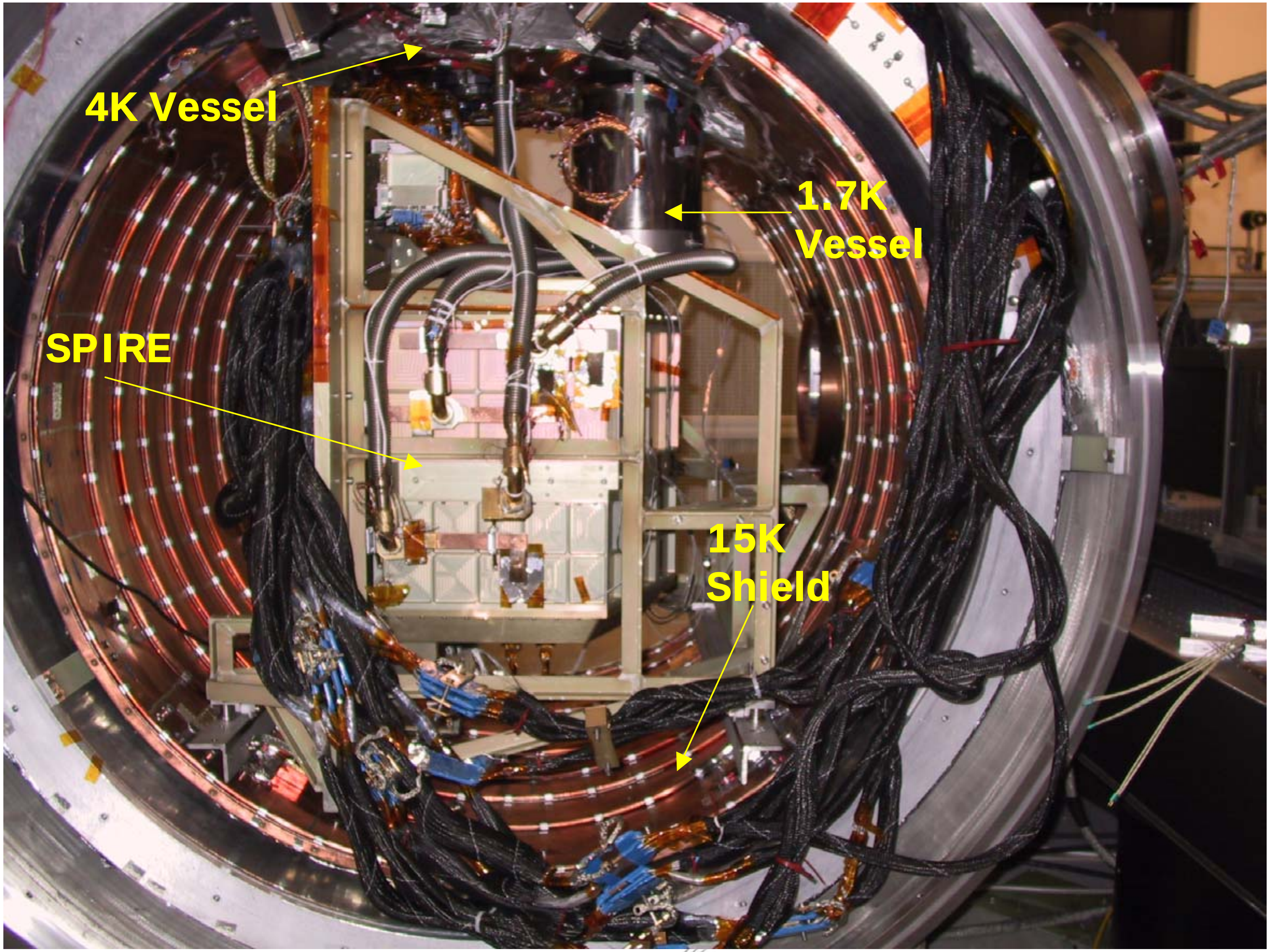
- Cold stage temp. < 280 mK
- Hold time > 46 hrs
- Cycle time < 2 hrs
- Average load on ^{4}He tank < 3 mW
- Heat lift provided to detector arrays > 10 μW
- Gas-gap heat switches (no moving parts)



SPIRE Test Facility

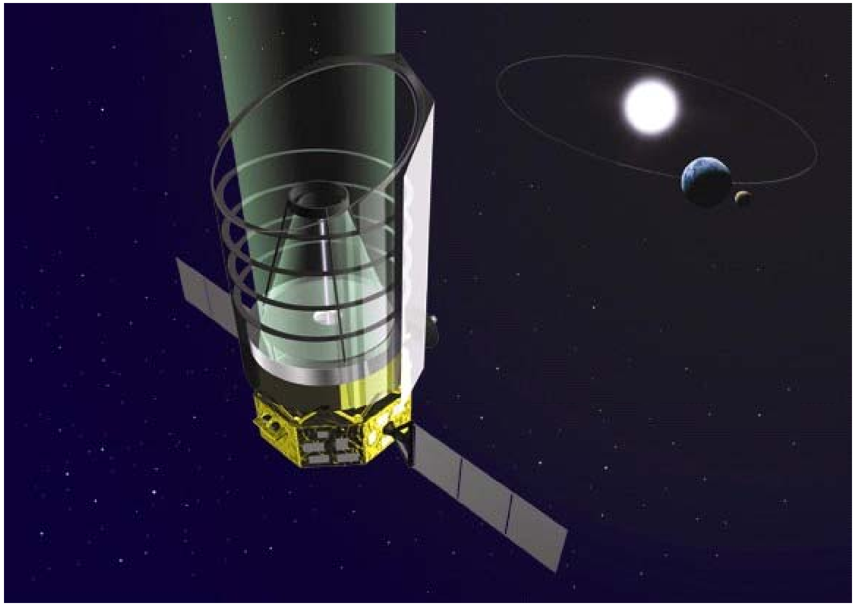
- Class 1000 clean room
- Dedicated Liquid Helium Cryostat
  - 10K radiation shield
  - 100litre 4K main helium vessel
  - 16litre 1.7K vessel
- Cryogenic Blackbody Source
- FIR Laser
  - 100-700um lines
- Fourier Transform Spectrometer
  - 1200K broadband source
- Electrical Ground Support Equipment
- Control Room

Cryostat



Future Projects

- SPICA
  - currently being proposed by ISAS (the Institute of Space and Astronautical Science)
  - Infrared Space Observatory
  - 3500mm diameter primary mirror
  - Telescope cooled to ~5K by cascaded cryocoolers
  - Launch date is stated as 2012 but a slip of a few years is very likely
  - Core wavelength coverage: 5um - 200um
  - Operational orbit: L2
  - Launcher: H-IIA



Applications of Thermometry for Space Projects

- In flight instrument monitoring
    - Health check
    - Calibration sources
    - Active control of subsystems
        - Photometer thermal control
        - Cooler recycling

- On-ground instrument qualification and characterisation
    - Thermal design qualification/verification
        - Thermal model correlation
        - Thermal strap characterisation (conductance, interfaces etc…)
    - Pre-Launch calibration testing
        - Cold blackbody
        - Cryostat test facility monitoring

Requirements for Thermometry

- Instrumentation used for spacecraft testing must be calibrated against traceable standards
  - Prerequisite for all testing

- Sensors used for flight have strict reliability requirements
  - Long term stability
  - Radiation hardened
  - Need to withstand test/space environment
    - Vibration, thermal cycling, bake out
  - Materials used must not be a source of contamination

- Required absolute accuracy is dependent on the project needs but:
  - The current needs (SPIRE, MIRI) are in the order of 5mK for a 1.7K-5K temperature range.

Overview of Thermal Verification (1)

- Thermometry is crucial for the instrument thermal performances verification

- The primary goal of the thermal verification is to measure and confirm that the instrument heat loads onto the Herschel Cryostat are in specifications as this has a direct impact on the mission lifetime.

- The heat loads verification requires an accurate measurement of a temperature drop/increase along thermal straps of known conductance

- So the accuracy of the two temperature sensors used for this measurement is driving the accuracy with which the heat loads will be measured.

Overview of Thermal Verification (2)

1.7K Thermal Strap for detector box

Detector Box I/F

Interface to Spacecraft

- The instrument thermal design requires that:
  - High conductance thermal straps be used to interface the instrument with the cryostat for optimal performances (~ 0.15W/K).
  - The heat load to the cryostat be as low as possible (~ 1mW) to maximise the cryostat and mission lifetime.
  - => the temperature drop along the strap is very small (~ 7mK)
  - To obtain a measurement with an error of less than 10% would require a sensor accuracy of 0.7mK.

Overview of Thermal Verification (3)

- Integrating temperature sensors on these thermal straps is another challenge because of:
  - The limited amount of flat area to mount sensors
  - The limited space and scope for an efficient heat sinking of the sensors leads

- Achieving such an accuracy below 4K is quite challenging as the sensor interface resistance increases as the environment temperature decreases.

- Self heating can become as much as the temperature drops being measured across interfaces.

Summary of Test Results (1)

- The temperatures measured during the first instrument test campaign were somehow confusing: with the temperature sensors on the instrument reading colder than the cryostat.

- Calibration of the cryostat temperature sensors were initially thought to be at fault and were replaced for second test campaign.

- An identical behaviour was observed however during the second test campaign which led us to carry out more investigation.

- A full characterisation of the instrument and ground support temperature sensors provided an interesting insight as to what was taking place. The following aspects were analysed:
  - Sensors self-heating
  - Sensor DC offset
  - Calibration Error

Summary of Test Results (2)

Sensor Name **1.7K** **4K**	**Sensor Interface Resistance**	**Temperature Self-Heating Error**	**DC Offset Error**	
	K/W	**mK**	**Ohms**	**mK**
Cooler Pump	42107	3.5	0.7	1.9
Cooler Shunt	58306	10.1	7.6	6.2
Cooler Evaporator	43819	8.5	**11.6**	10.0
Cooler Pump Heat Switch (sieve)	20846	1.9	4.2	14.6
Photometer Level 0 Enclosure	54135	10.0	8.8	6.5
Spectrometer Level 0 Enclosure	54275	9.0	**14.9**	12.8
HSFPU Harness Filter Bracket	33550	1.5	5.7	84.4
M3,5,7 Optical Sub Bench	21880	1.1	5.2	64.2
Input Baffle	13154	0.9	5.6	49.3
BSM/SOB I/F (SOB side)	**286506**	18.1	5.3	48.3

Issues

- Wires very fragile and therefore difficult to handle
  - Risk of damaging sensors/wiring if handled too frequently

- Restricted access for sensor integration
  - Once in they are often difficult to remove
      - Hence permanent installation results

  - Project constraints
    - Tight timescales
      - Very short windows of availability for recalibration
      - Need for local calibration service for quick response

    - Little flexibility to change design at late stage
      - Requirements need to be fully thought through
      - permanent and/or temporary sensor integration

- Limited scope of cryogenic thermometers suitable for flight use

Noise Thermometry

Physics Department
Royal Holloway
University of London

Low Temperature Thermometry – status and future requirements

Oxford Nov 24th

Royal Holloway

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Oxford Instruments Superconductivity

V. Mikheev
A. Adams
P. Noonan

Work supported by EPSRC, Oxford Instruments, the Royal Society and the European Commission

Outline

1. Current Sensing Noise Thermometry using a DC SQUID preamplifier
    a)Sensitivity of DC SQUIDs
    b) Principle of the Noise Thermometer
    c) Noise Thermometry from 4.2 K down to below 1 mK
2. Self Contained ^{3}Melting Curve Thermometer
3. Future Directions

Lusher *et al.*, Meas. Sci. Technol. 12, 1 (2001)
Casey *et al.* Physica B **329-333** 1556 (2003)

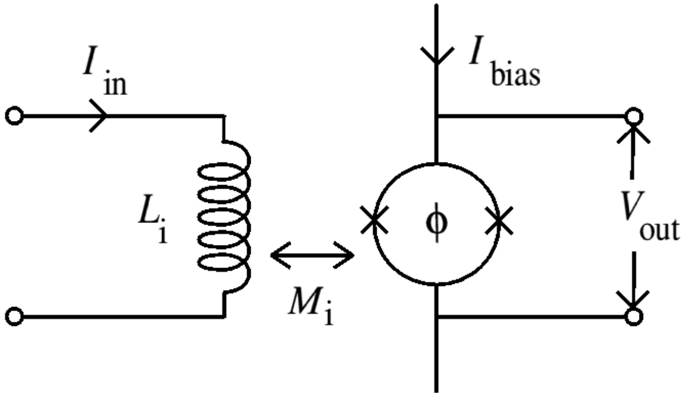
CSNT

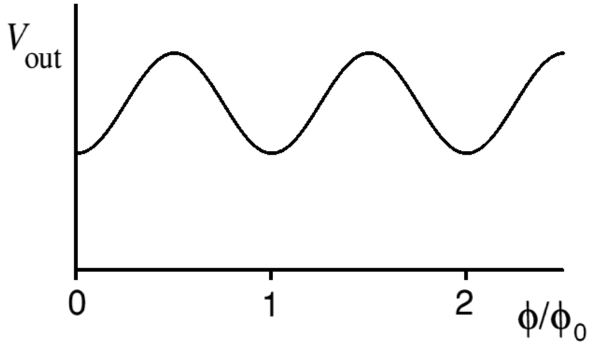
Shvarts *et al.*, Physica **329-333** 1566 (2003)
Shvarts *et al.*, Meas. Sci. Technol. **15**, 131 (2004)

SCMCT

Development of both thermometers supported by EU Framework 5 contract G6RD-CT-1999-00119 “Dissemination of the European Ultra Low Temperature Scale” – coordinated by NPL

Sensitivity of DC SQUIDs





- DC SQUIDs are extremely sensitive flux to voltage converters
- Coupled energy sensitivity, ε_{c} - Energy equivalent of minimum detectable current in input coil

$$\varepsilon_{\text{c}} = \frac{1}{2} L_{\text{i}} \frac{\langle \phi_{\text{N}}^{2} \rangle}{M_{\text{i}}^{2}}$$ where $\langle \phi_{\text{N}}^{2} \rangle^{1/2}$ is SQUID flux noise

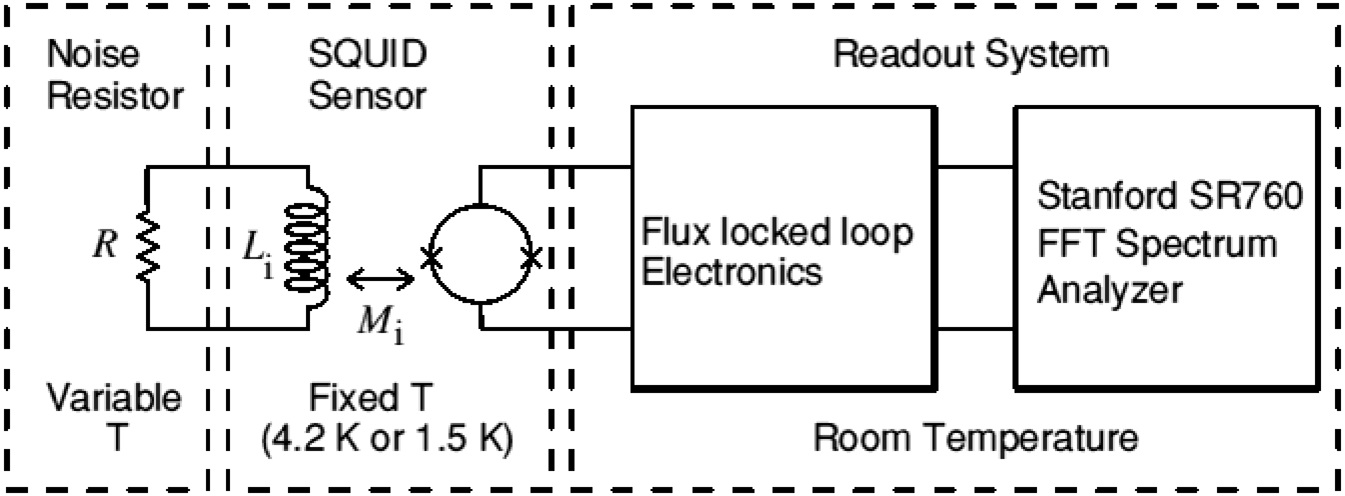
Important contribution to noise from Johnson noise in resistive shunts across Josephson Junctions

- We are using a low T_c DC SQUID (QuantumDesign) Flux-locked loop bandwidth 50 kHz

$L_{\text{i}} = 1.9\ \mu\text{H}$, $M_{\text{i}} = 10.4\ \text{nH}$, $\langle\phi_{\text{N}}^{2}\rangle^{1/2} = 3\ \mu\phi_0\ \text{Hz}^{-1/2} \Rightarrow \varepsilon_{\text{c}} = 500\ h$

- RF SQUID used in earlier work -$\varepsilon_{\text{c}} = 10^5\ h$

Current Sensing Noise Thermometer using DC SQUID Preamplifier



- Measure thermal noise currents in resistor using DC SQUID
- Mean square noise current per unit bandwidth

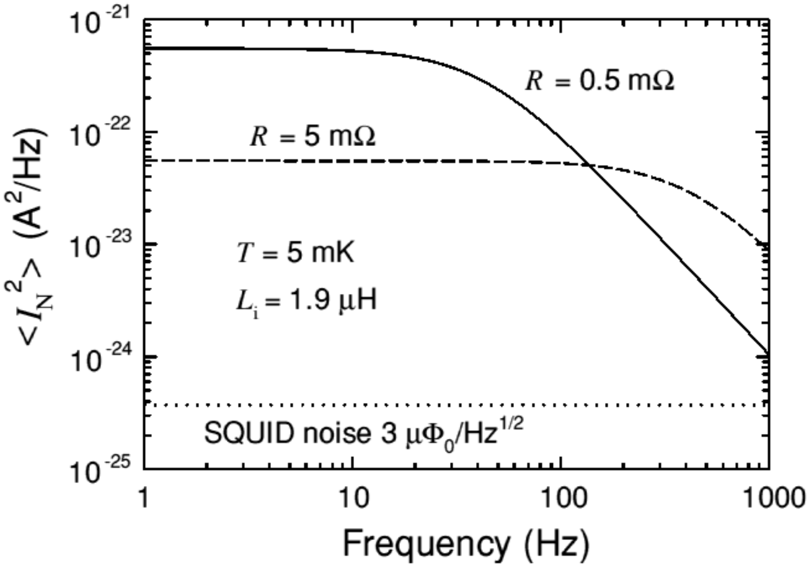
$$\left\langle i_N^2 \right\rangle = \frac{4k_B T}{R}\left(\frac{1}{1+\omega^2\tau^2}\right)$$

where $\tau = (L_i/R)$. L_i is DC SQUID input coil inductance plus any additional inductance in input circuit

- Noise resistor can be remote from SQUID with SQUID at fixed temperature
- Absolute thermometer if *R* and SQUID gain known. One fixed point required for use as secondary thermometer

Other work RF SQUID (Giffard *et al.*, Webb and Washburn, Bremer and Durieux)
DC SQUID (Roukes *et al.*, Schwab *et al.*, Meeson *et al.*, Fleischmann *et al.*)

Noise Temperature and Speed of Thermometer



- Noise temperature, T_N - temperature at which DC value of noise from resistor equals SQUID noise

$$T_N = \left(\frac{\varepsilon_c}{2k_B}\right)\left(\frac{R}{L_i}\right) = \frac{\varepsilon_c}{2k_B\tau}$$

$\varepsilon_c = 500\,h$, $L_i = 1.9\ \mu\mathrm{H}$
$R = 5\ \mathrm{m}\Omega \Rightarrow \tau = 0.38\ \mathrm{ms}$
$T_N = 32\ \mu\mathrm{K}$

- Speed also depends on (L_i/R)

$$\sigma = \frac{\Delta T}{T} \approx \left(\frac{2\tau}{t_\mathrm{meas}}\right)^{1/2} = \left(\frac{2L_i}{t_\mathrm{meas}R}\right)^{1/2}$$

$\tau = 0.38$ ms, $(\Delta T/T) = 0.01$
(1% precision)
$t_\mathrm{meas} = 7.6$ s

Figure of merit of thermometer
(Roukes *et al.*, LT17, 1984)

$$\boxed{T_N\sigma^2 t_\mathrm{meas} = \frac{\varepsilon_c}{k_B}}$$

- Percentage precision independent of temperature

Optimization of Current Sensing Noise Thermometer

- Value of resistor determined by temperature range required

$$T_N \sigma^2 t_{\text{meas}} = \frac{\varepsilon_c}{k_B}$$

Previous work using rf SQUIDs (Webb, Bremer..)

$\varepsilon_c \approx 10^5 h$

For mK range (down to 10 mK)

$T_N \sim 0.1$ mK, $\sigma \sim 1\%$,

$t_{\text{meas}} = 480$s $(R = 104\ \mu\Omega)$

For μK range (down to 100 μK)

$T_N \sim 1\ \mu$K, $\sigma \sim 1\%$,

$t_{\text{meas}} = 13$ hours $(R = 1.04\ \mu\Omega)$

This work using a DC SQUID

$\varepsilon_c \approx 500\, h$

For mK range (down to 10 mK)

$T_N \sim 0.1$ mK, $\sigma \sim 1\%$,

$t_{\text{meas}} = 2.4$ s $(R = 16\ \text{m}\Omega)$

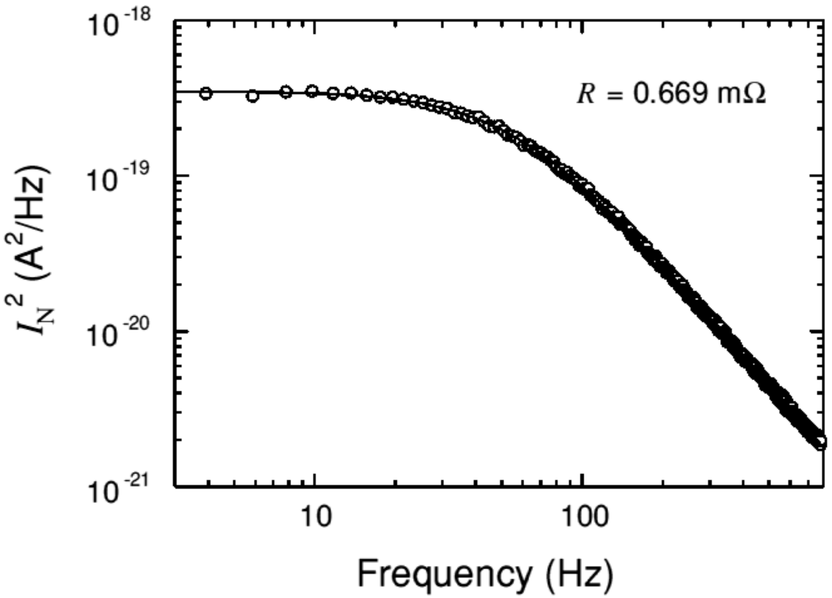
For μK range (down to 100 μK)

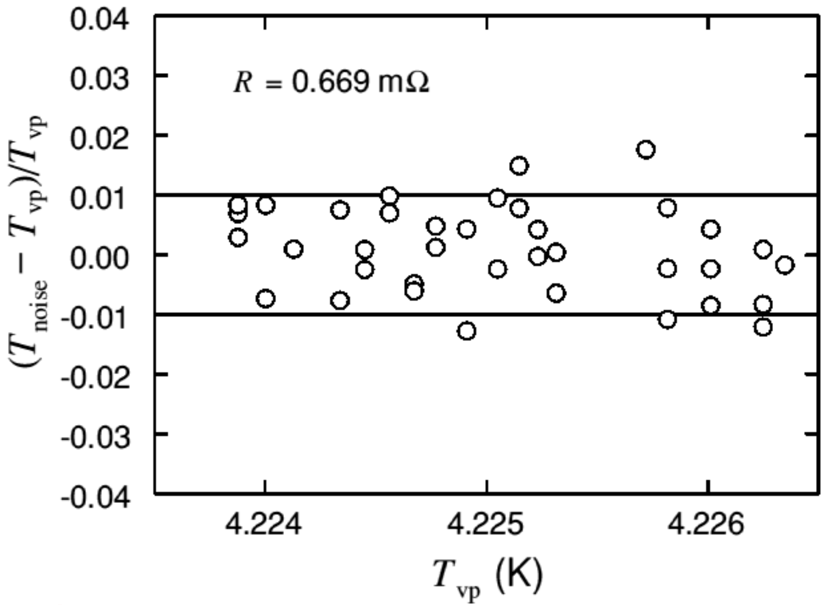
$T_N \sim 1\ \mu$K, $\sigma \sim 1\%$,

$t_{\text{meas}} = 240$ s $(R = 0.16\ \text{m}\Omega)$

- DC SQUIDs are faster

Measurement of Absolute Temperature





- Measure *R* and SQUID gain in separate experiments
- Fit to current noise to extract temperature and τ

(a) Initial Measurement in transport dewar

- Compare with ITS-90 using helium vapour pressure-good agreement

Parameters

$R = 0.669$ mΩ, $\varepsilon_c = 500\ h$, $L_i = 1.9$ μH, $t_{\rm meas} = 160$ s. Standard deviation 0.7 %

Accurate to ~ 0.1%

(b) Measurement on UTL Cryostat

0.2 mΩ sensor. Agreement with PLTS-2000 to better than 1% down to 5 mK

$T_N = 1.3\ \mu$K - limited by SQUID noise

Hot Electron Effects

- At low temperatures in presence of small heat leak electron temperature T_e higher than phonon temperature T_p

$$P = \Sigma\Omega(T_e^5 - T_p^5)$$

where Ω is sample volume (10 mm × 5 mm × 25 μm)

$\Sigma = 1.8 \times 10^9\ \mathrm{W\,m^{-3}\,K^{-5}}$ for Cu film (Roukes *et al.*)

Minimum achievable electron temperature

$$T_{\min} = \left(\frac{P}{\Sigma\Omega}\right)^{1/5}$$

Gives $T_{\min} = 3.8$ mK for $P = 1$ pW

Solution (Junyun. Li, European Patent Application 99306845.1)

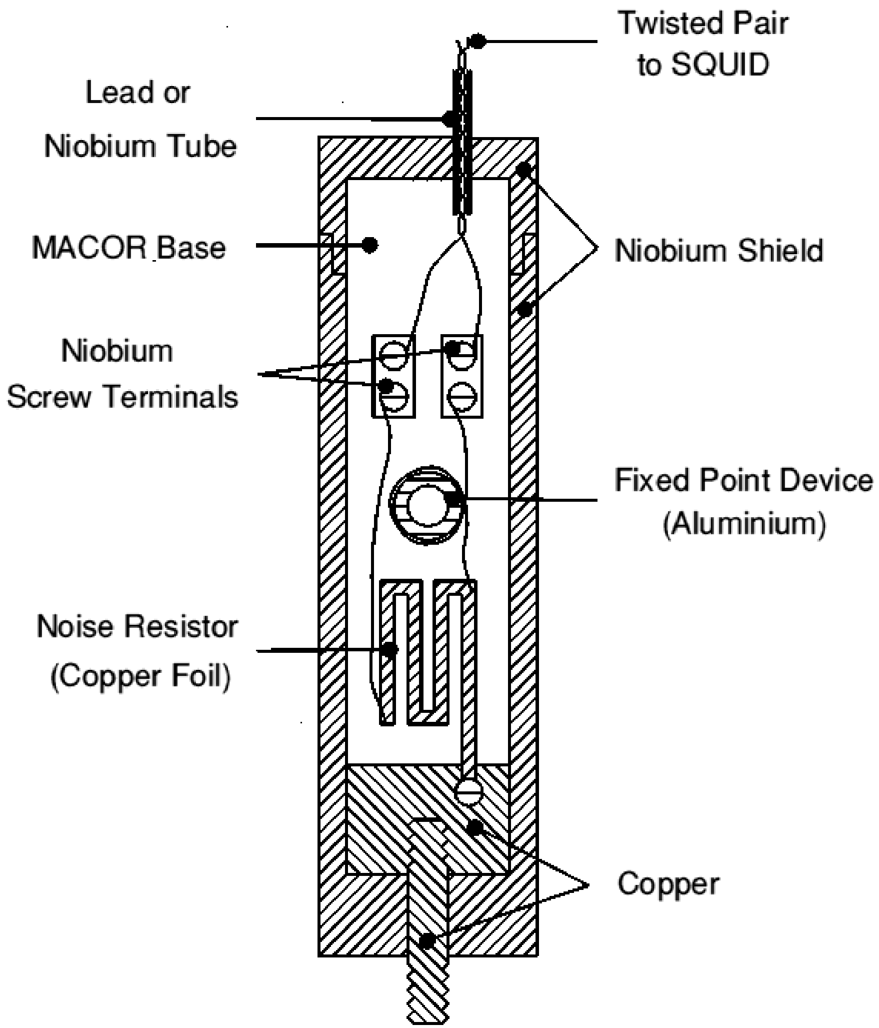
Electrically ground one end of resistor to large volume copper plate

- Ensures adequate cooling of electron system

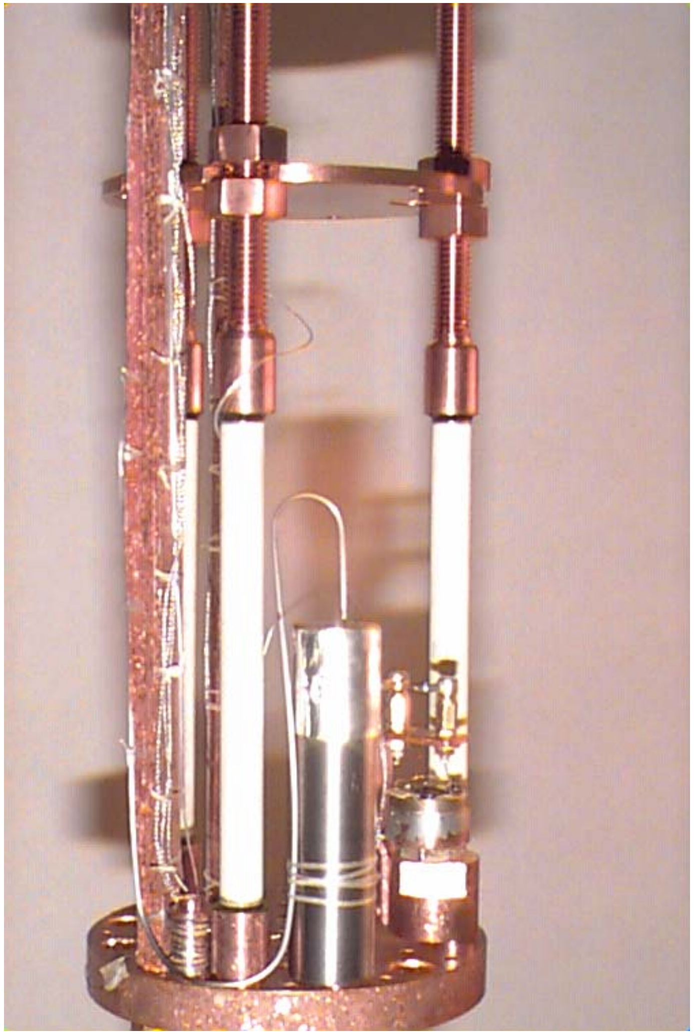
ULT Cryostat

- ULT cryostat for SQUID NMR and Noise Thermometry
- Oxford Instruments dilution unit
- Nuclear stage diffusion bonded in Moscow (Nyeki, Dmitriev)
- ^{3}He melting curve thermometer (MCT)
- Platinum NMR thermometer
- Extensive space for mounting experiments
- High level of access for experimental services, including SQUID amplifier systems

Sensor for Low Temperatures

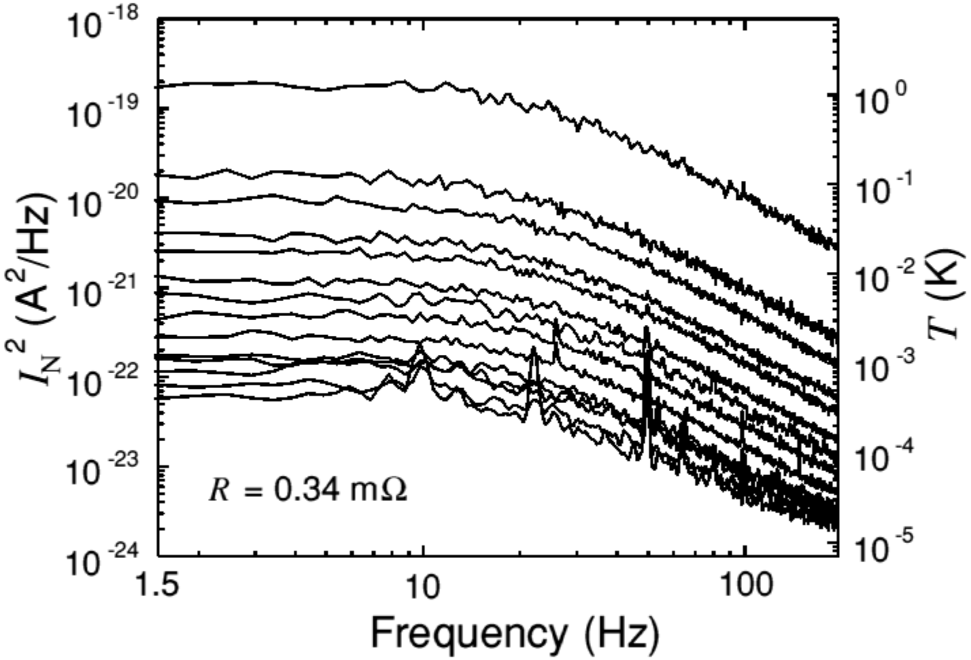


Sensor resistor - Copper foil
25 μm thick 99.9% purity



Noise Thermometer and MCT mounted on nuclear stage

Performance down to below 1mK

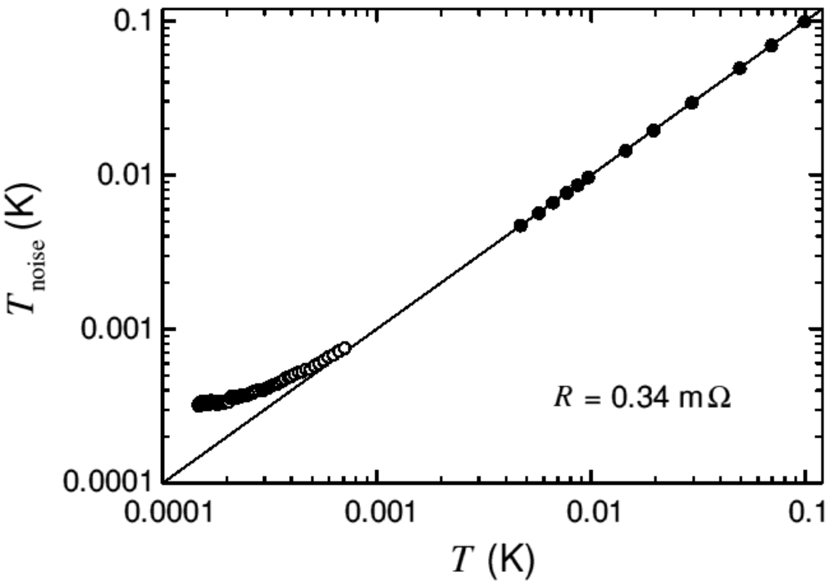


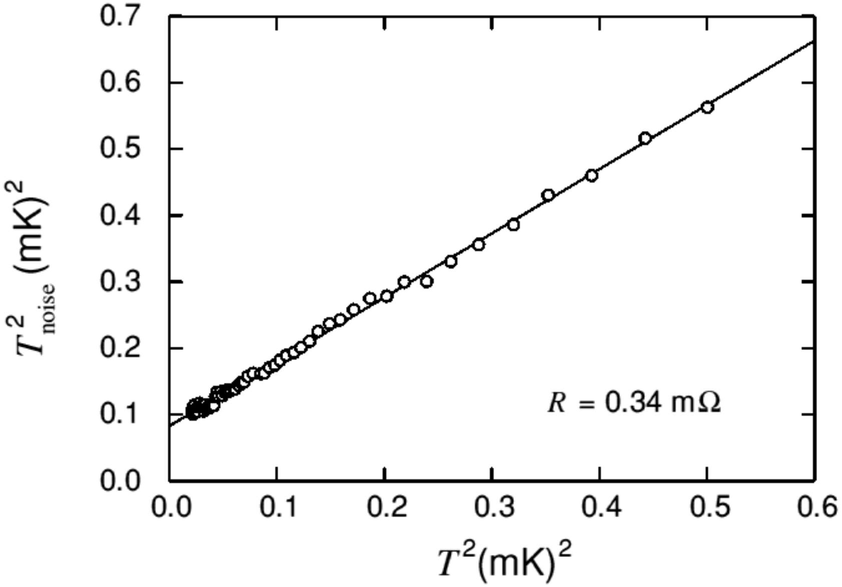
- Current sensing noise thermometer used as secondary thermometer.
- Gain calibrated against ^{3}He melting curve thermometer (MCT) at 100 mK using the Provisional Low Temperature Scale PLTS-2000 (Rusby *et al.*)

- Comparison with MCT made down to 4.7 mK using temperature stabilization

- Comparison with a Platinum NMR thermometer calibrated against the MCT using PLTS-2000.
- Data taken whilst slowly warming (over 4 days) following demagnetization.

Performance down to below 1mK





- Agreement with PLTS-2000 better than 1 % at 4.7 mK and above

- Evidence of heat leak at low temperature. Plot T_{noise}^{2} versus T^{2}
- Minimum electron temperature - 290 μK

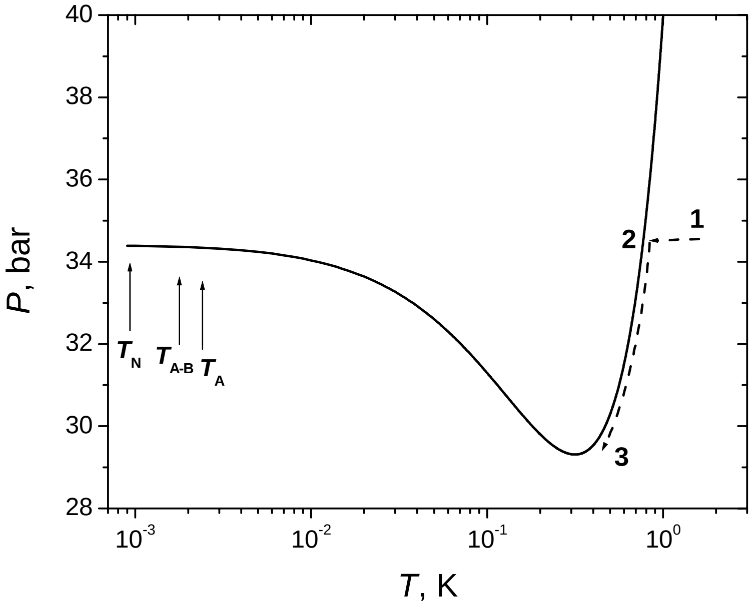
Experimental Parameters of ULT thermometer

- Quantum Design SQUID $\varepsilon_c = 500\,h$, $L_i = 1.9\ \mu\mathrm{H}$
- Sensor resistor copper foil 25 μm thick, 99.9 % purity, $R = 0.34\ \mathrm{m\Omega}$
- Measured Precision – 1.5 % in 200 secs. Measured noise temperature – $T_N = 8\ \mu\mathrm{K}$
- Minimum electron temperature - 290 μK. Given observed temperature dependence can be extrapolated to higher temperatures, thermometer should read 40 μK above true temperature at 1 mK and 8 μK hotter at 5 mK

Potential for CSNT in Metrology

- Thermometer ideally suited to check PLTS-2000 down to the solid ordering transition
- Resolve present discrepancy between the scales of NIST/University of Florida and PTB (~6% at the ordering transition)

Self Contained ^{3}He Melting Curve Thermometer



^{3}He melting curve, showing the minimum and the three other fixed points - the superfluid 'A' transition T_A, the 'A' to 'B' transition T_{A-B}, and the solid magnetic ordering transition T_N.

- Collaboration between RHUL and Oxford Instruments Superconductivity
- Offers direct access to PLTS-2000
- Much more straightforward to use than conventional set-up
- Designed to be simple to construct and can be operated in a closed cycle without user intervention
- Based on cylindrical pressure gauge
- Readout system uses tunnel diode oscillator circuit
- Gas handling system makes use of relief valves at room temperature for simple operation

Cylindrical Pressure Gauge

Mounted on mixing chamber

Schematic diagram

(Mikheev et al. Cryogenics 34 167 (1994))

Designed and Constructed at OIS

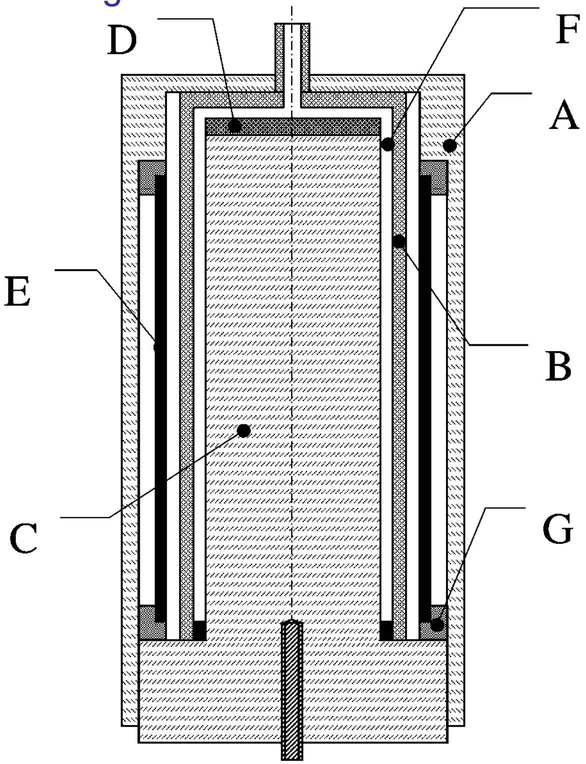


Diagram of the cylindrical pressure-gauge:

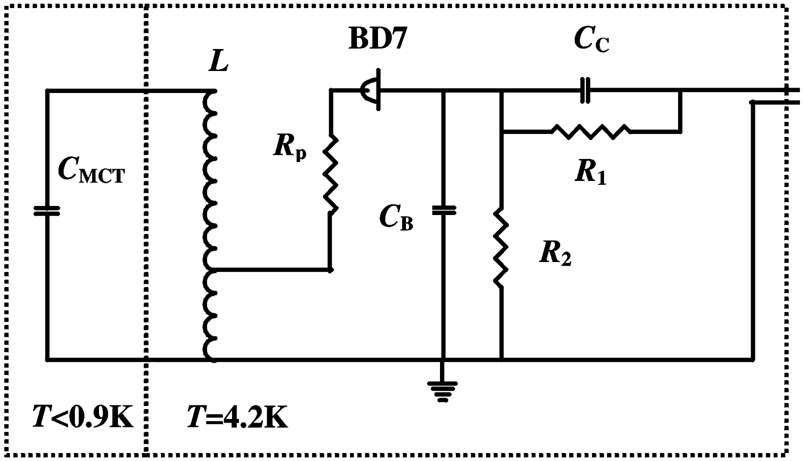
A - outer body, B - BeCu membrane (electrically grounded), C - oxygen free copper inner body, D - silver sinter heat exchanger, E - cylindrical electrode (electrically floating), F - ^{3}He cavity, G - insulating support of the electrode E.

Tunnel Diode Oscillator

Located on 4.2 K flange

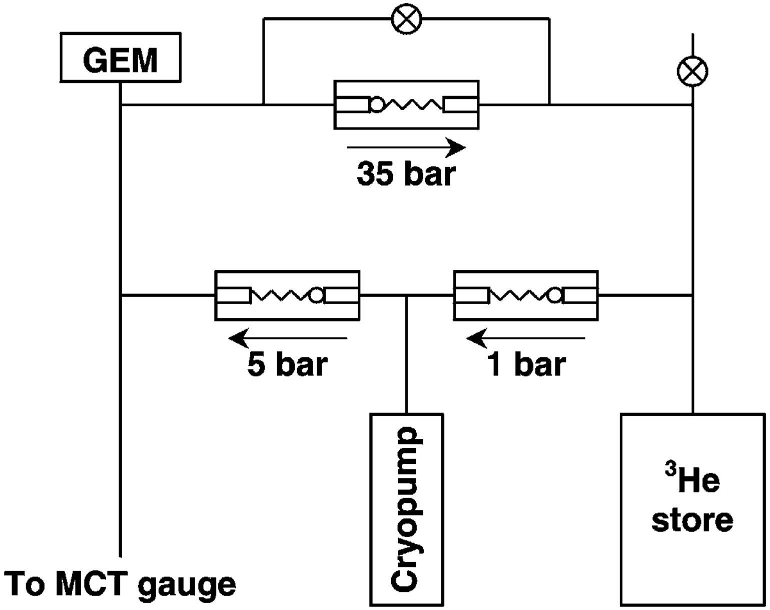
Based on a low power back diode (BD7)

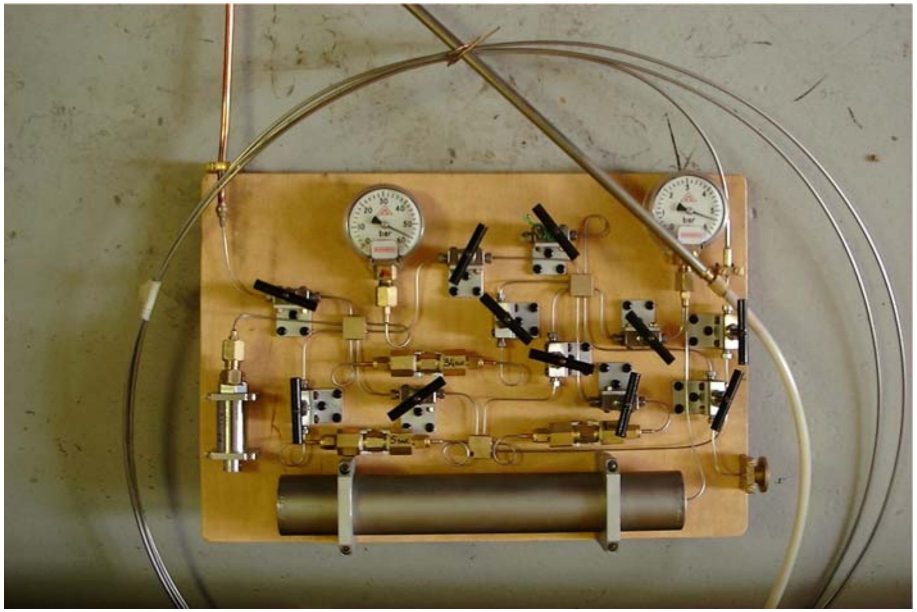
(C.T. Van Degrift Rev. Sci. Inst. 46 599 (1975))



- Gauge connected to coil via single superconducting wire
- Oscillator frequency ~ 3 MHz
- Oscillator stability ~ 35 parts in 10^9 in 5 s

Gas Handling System (Mikheev)





- Designed to allow for computer automation including automatic sensor calibration
- Uses set of relief valves and a cryopump together with an electronic pressure sensor
- Could be made compact enough to fit on top plate of refrigerator
- Prototype system has additional valves for diagnostic purposes so is larger

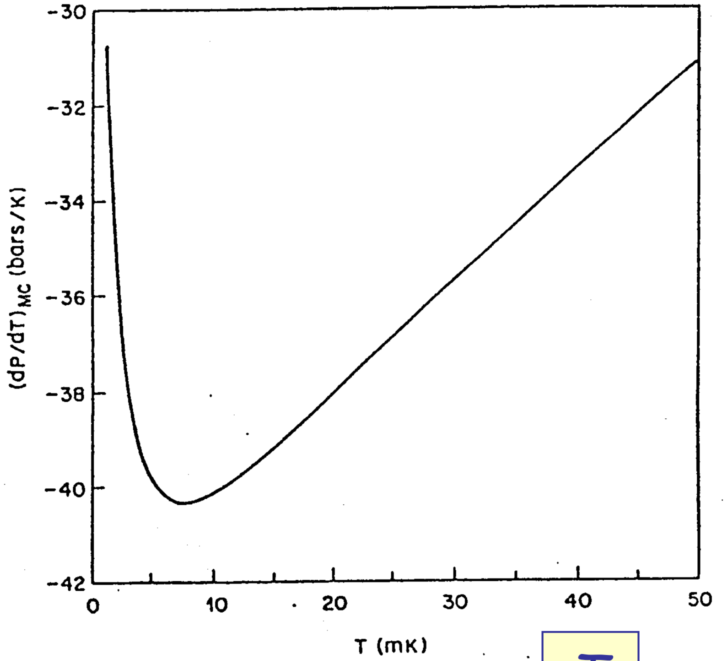
- By appropriate warming and cooling of cryopump stable pressures (within ±1 mbar) can be set for calibration purposes
- Pressure monitored by GEM 4000 series electronic pressure transducer

Self Contained ^{3}He Melting Curve Thermometer

- Compact, self-contained ^{3}He melting curve thermometer built and operation confirmed.
- Preliminary comparison against scale determined by current sensing noise thermometer made down to 20 mK showing agreement to ~1%.
- Design allows in principle for computer automation.
- Operation in High Magnetic fields possible since field dependence of melting curve well defined

Temperature Resolution and Field Sensitivity

$\frac{dp}{dT}$

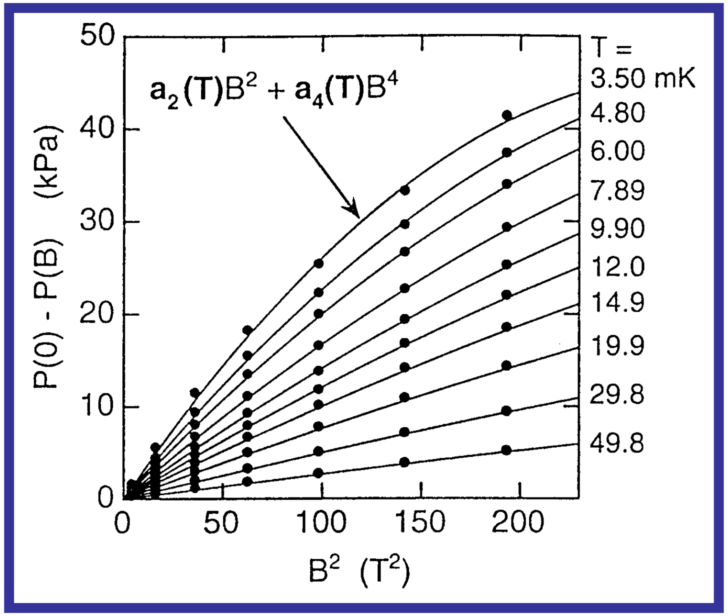


T

High temperature resolution
10 μbar ~ 0.3 μK

Small, measurable, sensitivity to magnetic fields

Pressure sensor fabricated from silver and silver alloy
Fukuyama et al. Physica B329 (2003) 1560
J Low Temp. Phys. 113 (1998) 769



Future Directions

1. Improved SQUID Sensors will increase speed of thermometer

$$T_{\mathrm{N}}\sigma^{2}t_{\mathrm{meas}} = \frac{\varepsilon_{\mathrm{c}}}{k_{\mathrm{B}}}$$

- RHUL has strong links with cryosensors laboratory at PTB (Drung, Schurig)
- Recently prototype 2-Stage SQUID current sensor tested with ε_c =50 *h*
- with
  sensor at 4.2 K. Close to quantum limited sensitivity expected for sensor at 300 mK

- Using 50 *h*, with T_N = 0.1 mK (suitable for operation to 10 mK) 1% precision should be obtained in 0.24 s
- Another factor of ten possible by operating current sensor at 300 mK

2. Establishing PLTS-2000

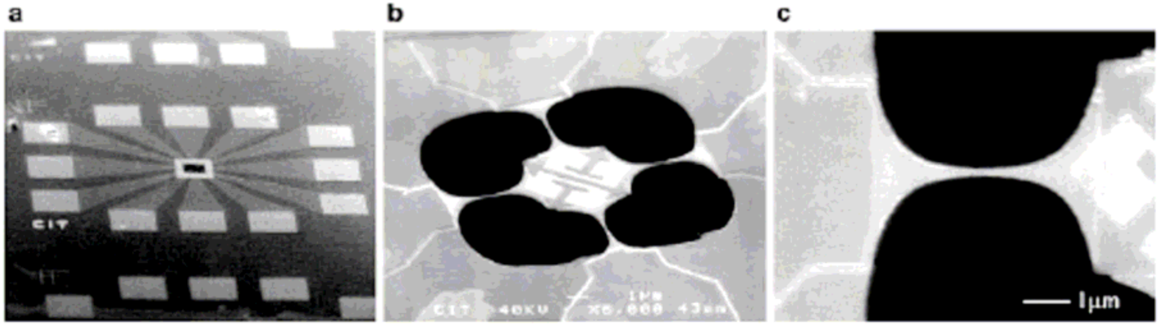
3. Application to Nanoscience

- In-situ noise thermometry “on-chip”

Measurement of Quantum of Thermal Conductance

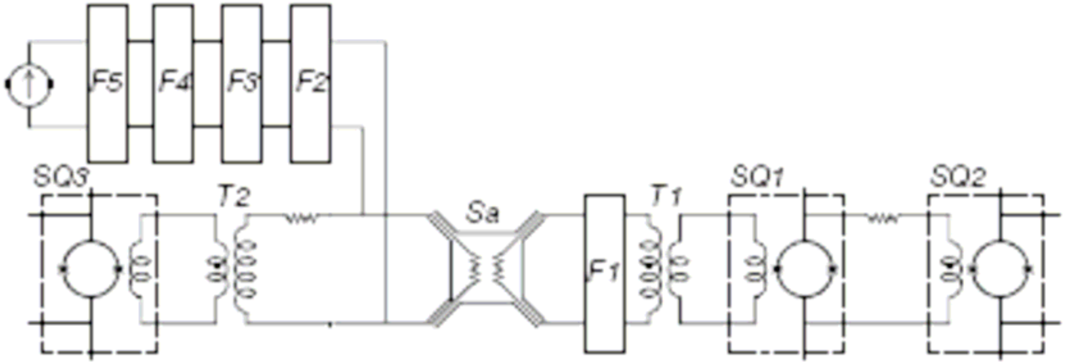
Determine temperature of suspended mesostructure from current noise of gold thin film resistor

Roukes group, Caltech, Nature 404 974 (2000)



Progressive magnifications of suspended mesostructure (narrowest region < 200 nm)

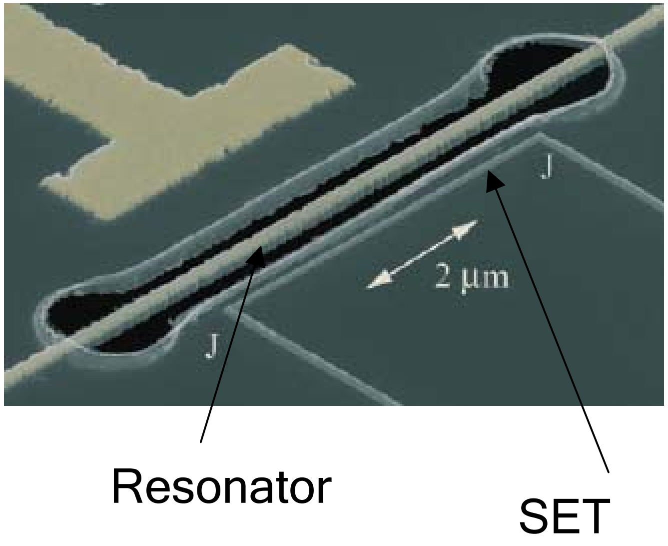
DC SQUID readout system for current sensing noise Thermometry on Au resistor (4.2 K down to 80 mK)



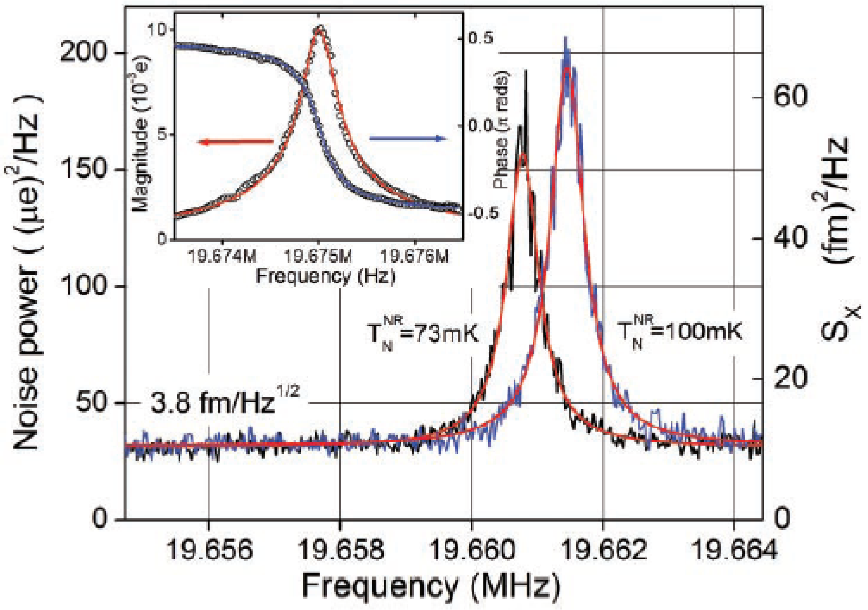
Nanomechanical Resonator Approaching Quantum Limit

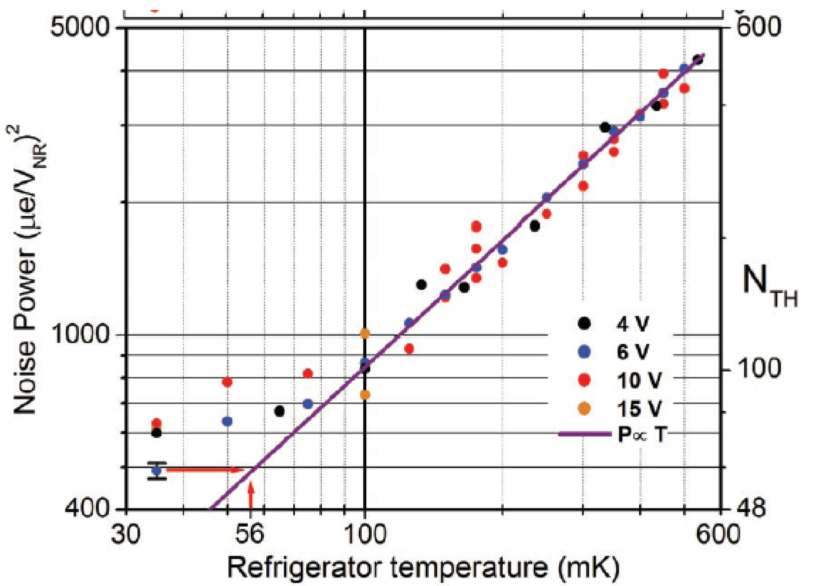
Determine temperature of nanomechanical resonator from current noise of SET around resonator frequency

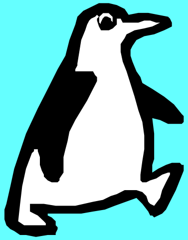
Schwab group, Maryland, Science 304 74 (2004)



Fit noise power to harmonic oscillator response: determine temperature and Q-factor



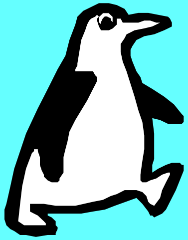




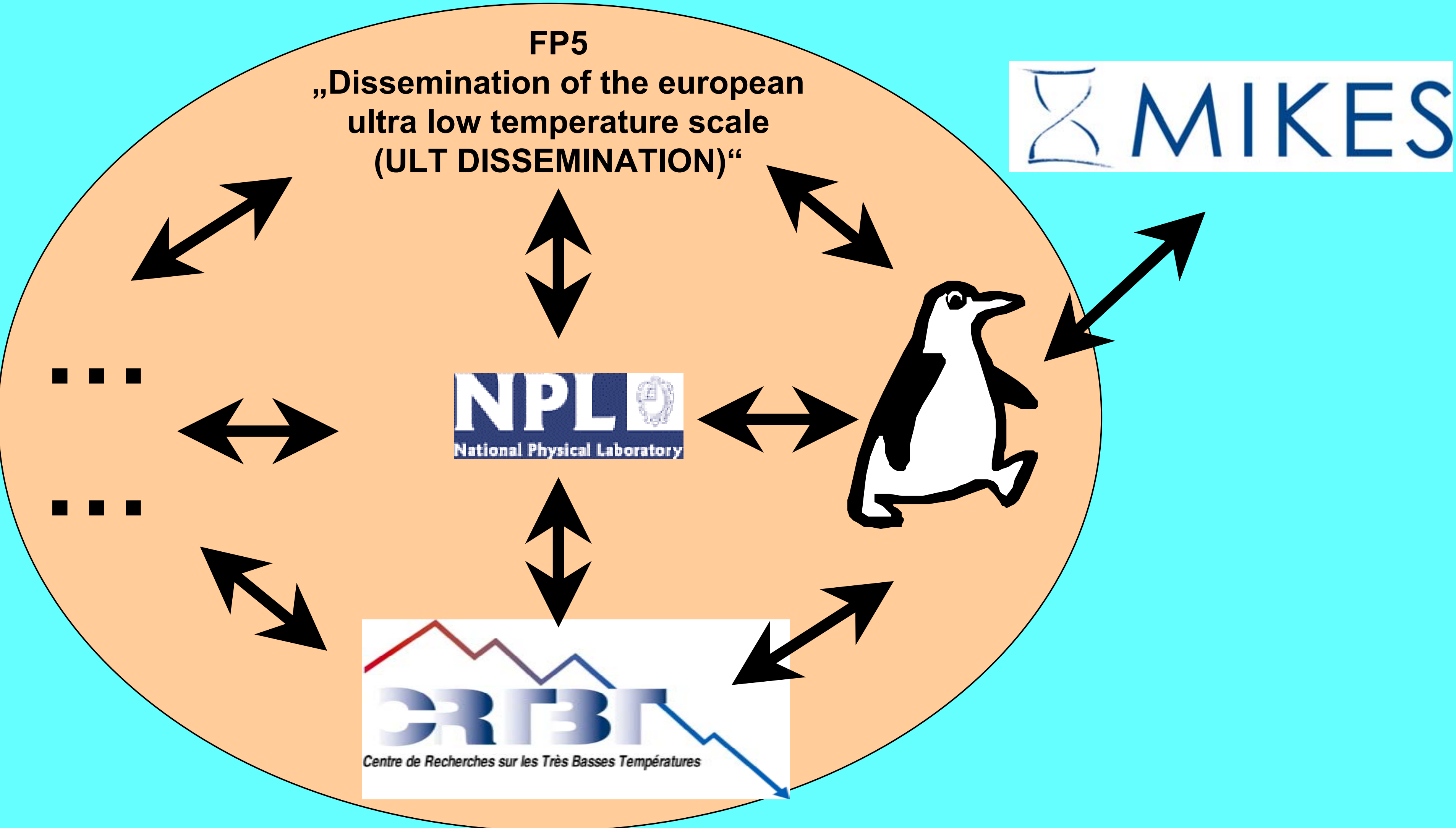
Coulomb blockade thermometry

M. Meschke and J.P. Pekola

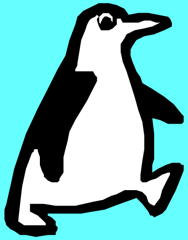
Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 2200, FIN-02015 HUT, Finland



Coulomb blockade thermometry



FP5
„Dissemination of the european ultra low temperature scale (ULT DISSEMINATION)“



Coulomb blockade thermometry

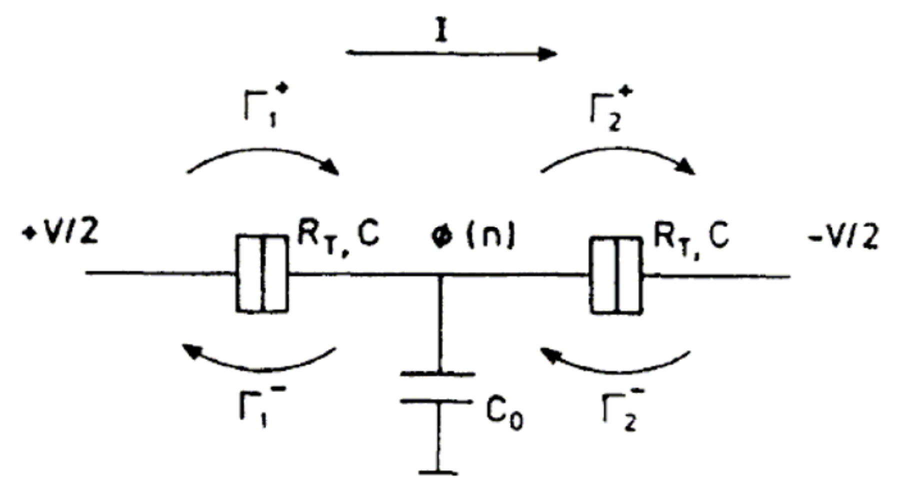
M. Meschke and J.P. Pekola

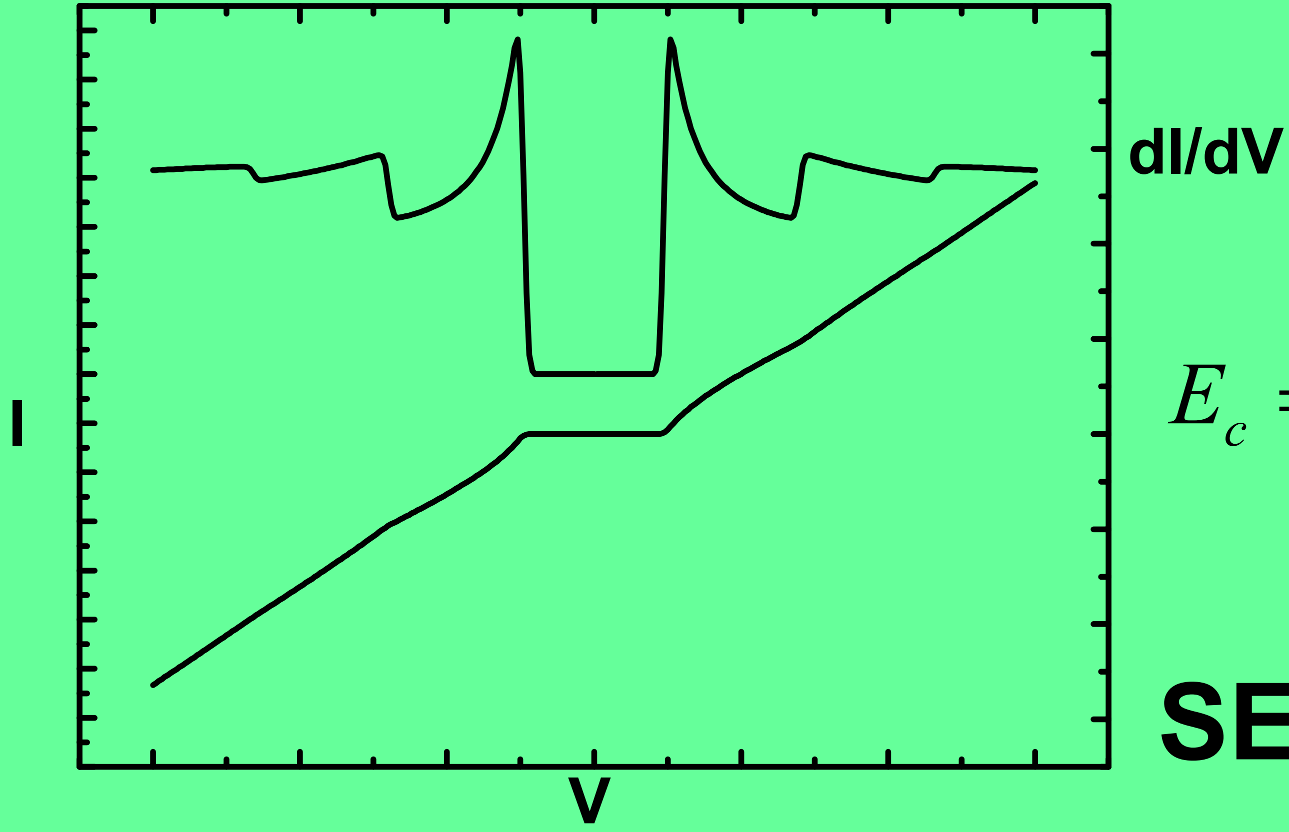
Outline

- What is a CBT?
- How does it work?
- Useful temperature range
- CBT meets MCT
- Accuracy of CBT

Single Electron Transistor SET

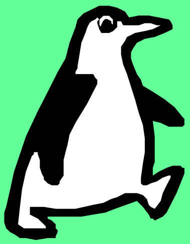
Coulomb Blockade





$$E_c = \frac{e^2}{2C} = 50 k_B T$$

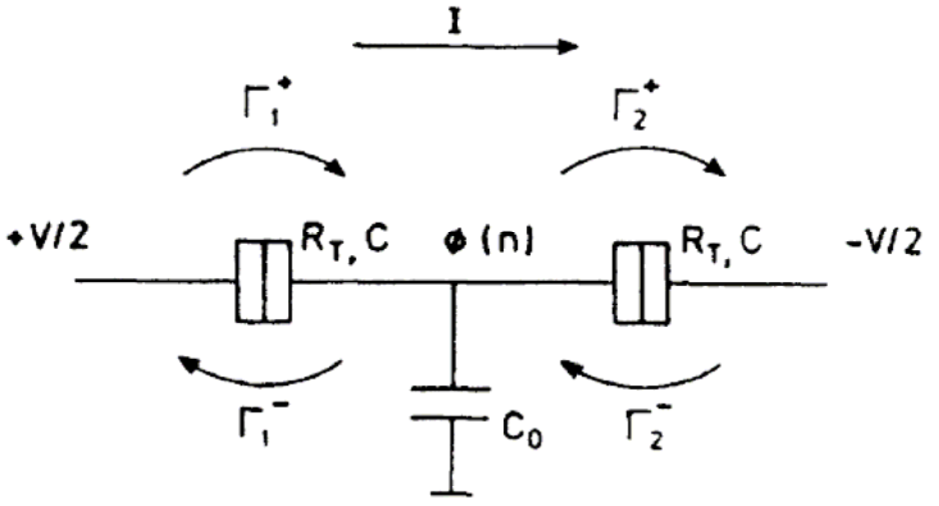
SET: $k_B T < E_c$

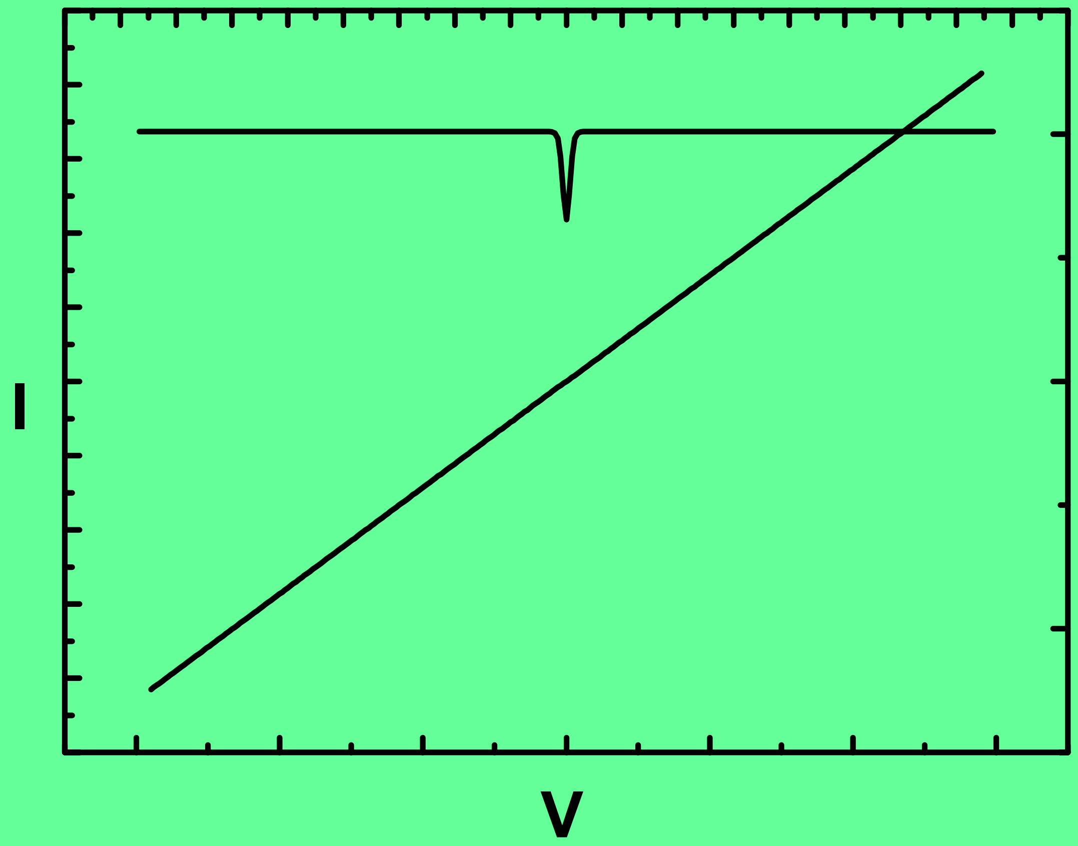


$k_BT \geq Ec$???

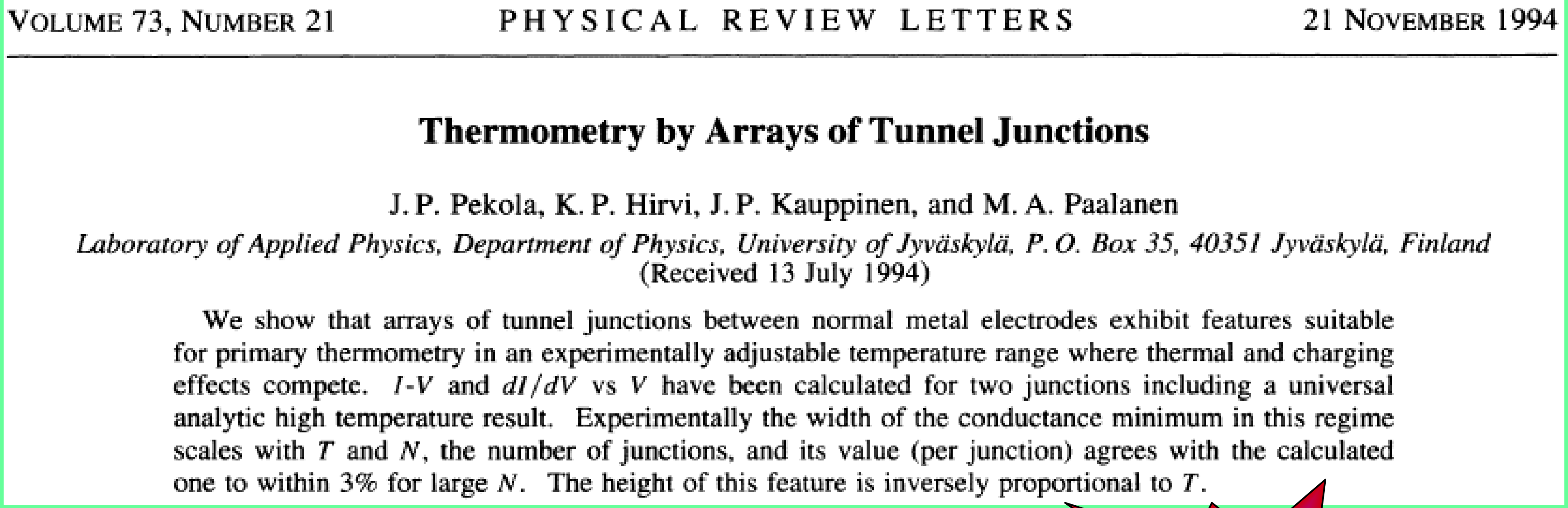
Partial

Coulomb Blockade





$$E_c = \frac{e^2}{2C} = 0.5k_BT$$



VOLUME 73, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1994

Thermometry by Arrays of Tunnel Junctions

J. P. Pekola, K. P. Hirvi, J. P. Kauppinen, and M. A. Paalanen
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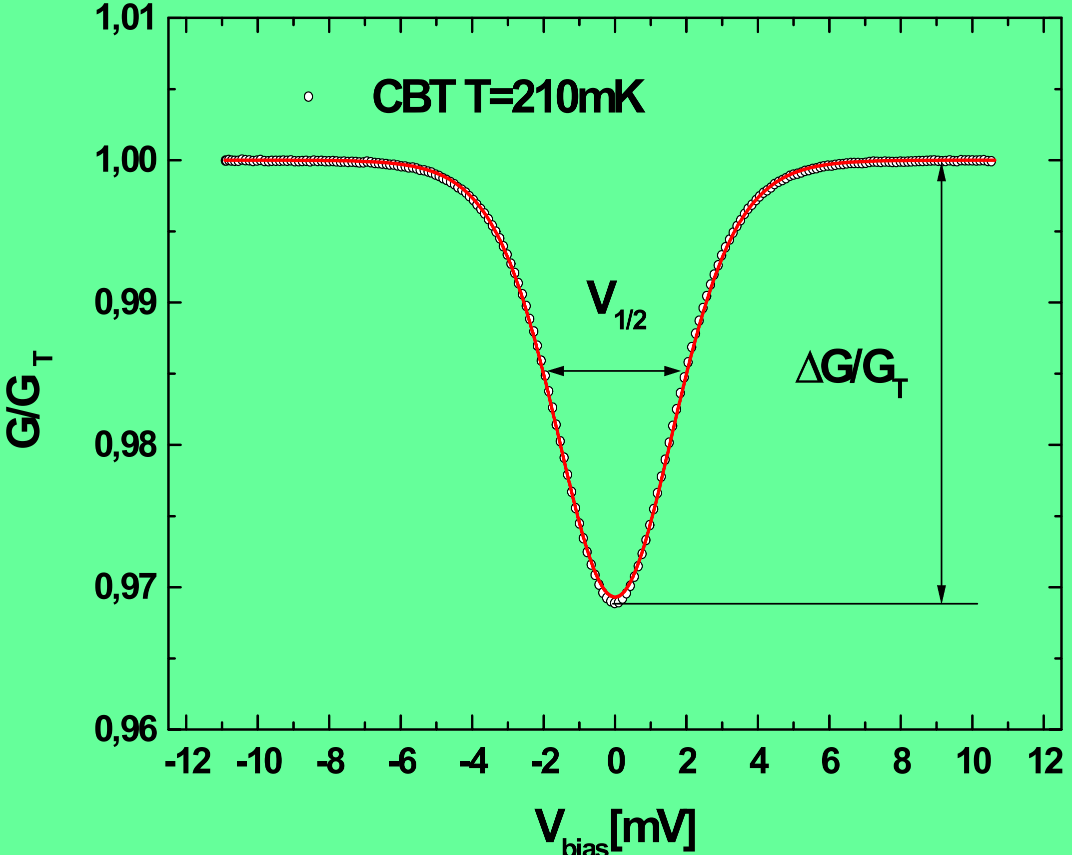
(Received 13 July 1994)

We show that arrays of tunnel junctions between normal metal electrodes exhibit features suitable for primary thermometry in an experimentally adjustable temperature range where thermal and charging effects compete. *I-V* and *dI/dV* vs *V* have been calculated for two junctions including a universal analytic high temperature result. Experimentally the width of the conductance minimum in this regime scales with *T* and *N*, the number of junctions, and its value (per junction) agrees with the calculated one to within 3% for large *N*. The height of this feature is inversely proportional to *T*.



CBT

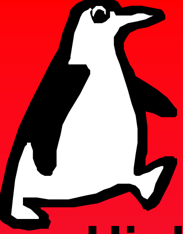
$$E_C << k_B T$$

$$V_{1/2} = 5.439 N k_B T / e$$

primary thermometer!!!

$$\Delta G/G_T = 2\frac{N-1}{N}\frac{e}{2Ck_BT}$$

secondary thermometer



Useful temperature range for CBT

High limit

•**Fabrication limit for small junctions: 100mK 1µm x 1µm**
10K 100nm x 100nm

➡**Flat background for high Voltages at high temperatures: 30Kelvin**

Useful range for one sensor:
two orders of magnitude in temperature

$$\Delta G/G_T = 2\frac{N-1}{N}\frac{e}{2Ck_BT} \propto \frac{1}{T}$$

$$\Delta G/G_T \approx 0.3\%$$

$$\Delta G/G_T \approx 30\%$$

Useful temperature range for CBT

- upper limit ~30Kelvin
- Two orders of magnitude in temperature
- Lower limit ~10mK

$$P_{el-ph} = \Sigma\Omega(T_{el}^{n\approx 5} - T_{ph}^{n\approx 5})$$

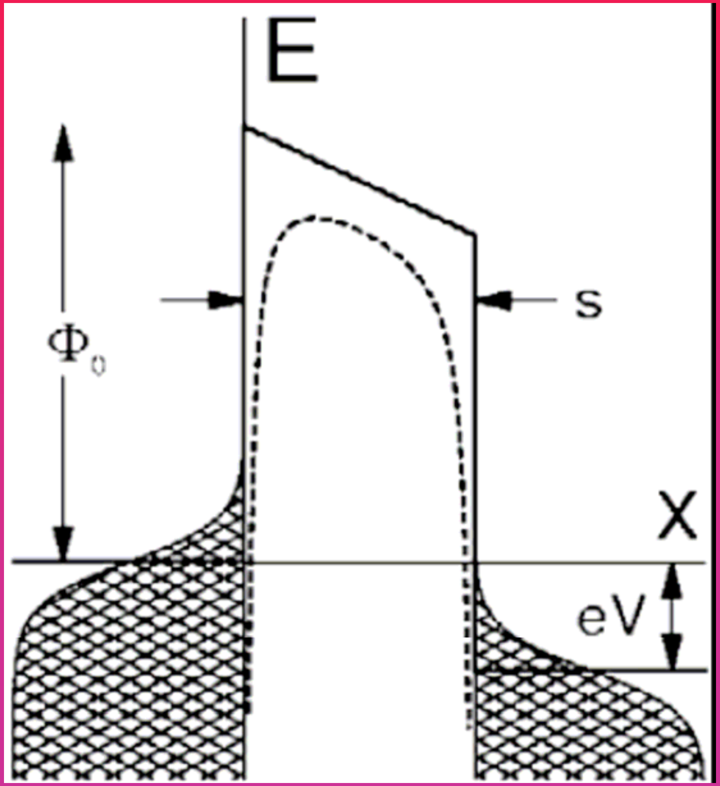
$$\Sigma = 2\cdot 10^{9} WK^{-5}m^{-3} \text{ (copper)}$$

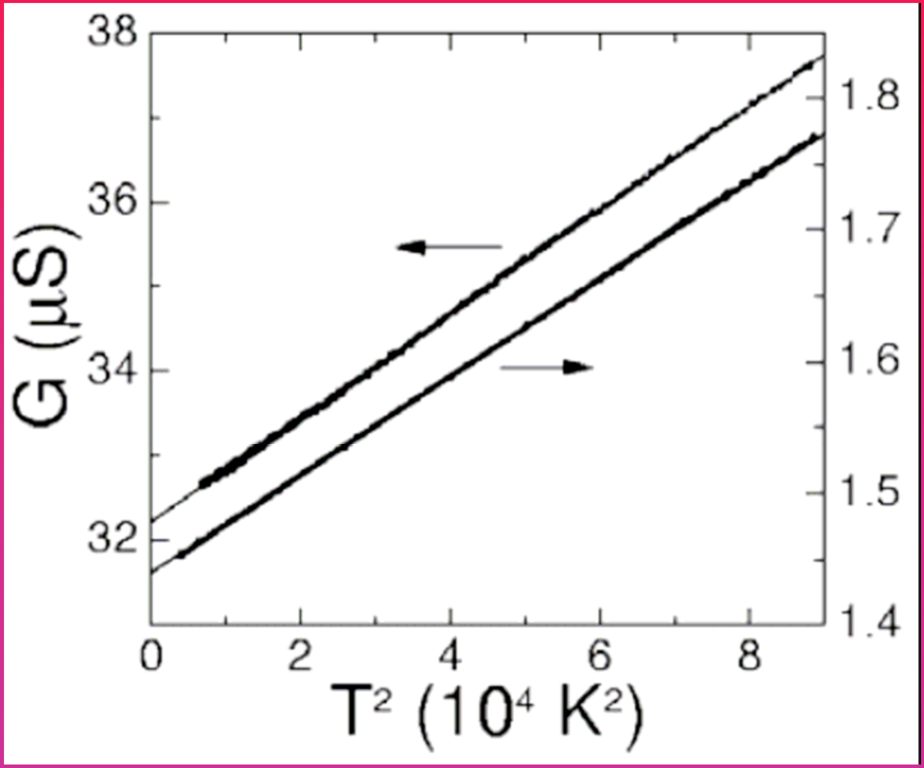
$$\Omega = 40\mu m \times 10\mu m \times 500nm = 200\mu m^{3}$$

Beyond CBT: temperature up to 300K

$$G = G_0\left[1+\left(\frac{T}{T_0}\right)^2\right]$$

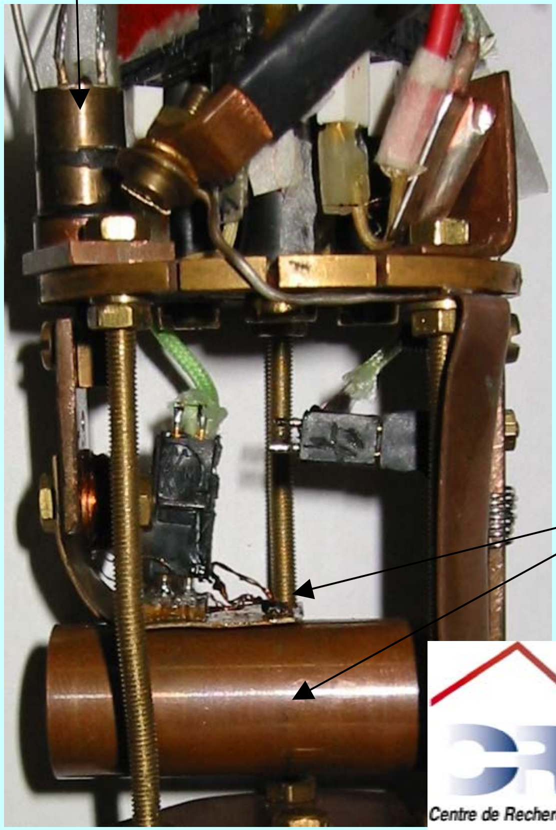
$$T_0 = 720K \text{ (AlOx)}$$



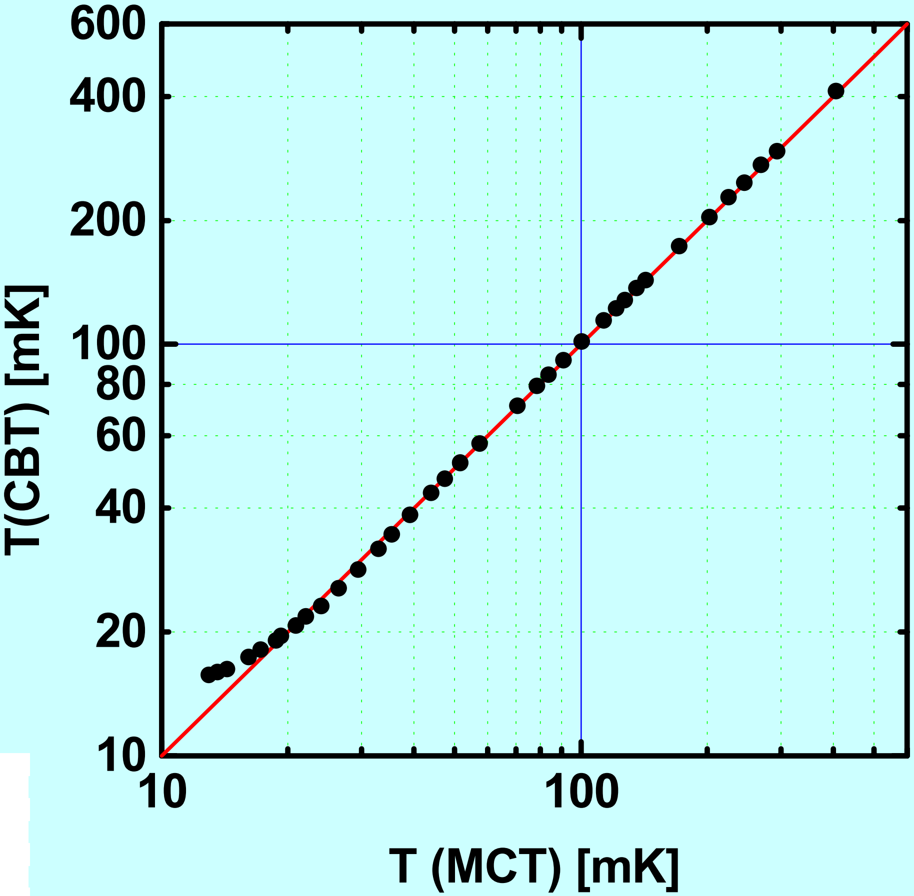


Comparison between MCT and CBT

FP5
„Dissemination of the european ultra low temperature scale (ULT DISSEMINATION)“

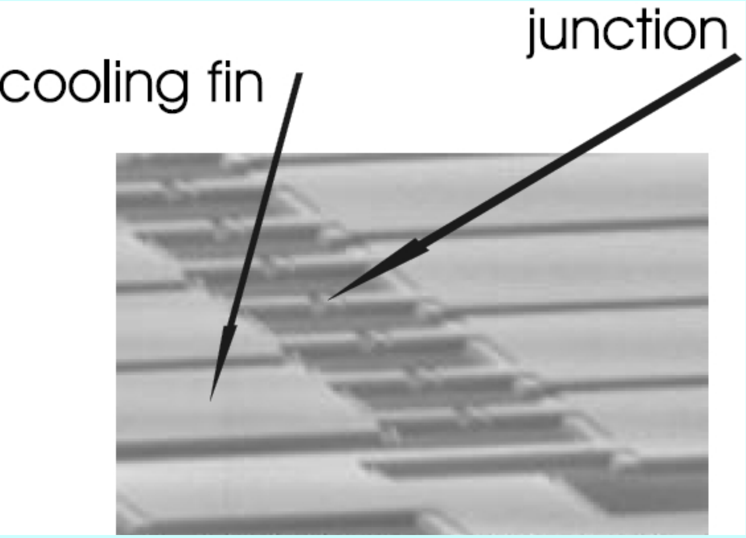


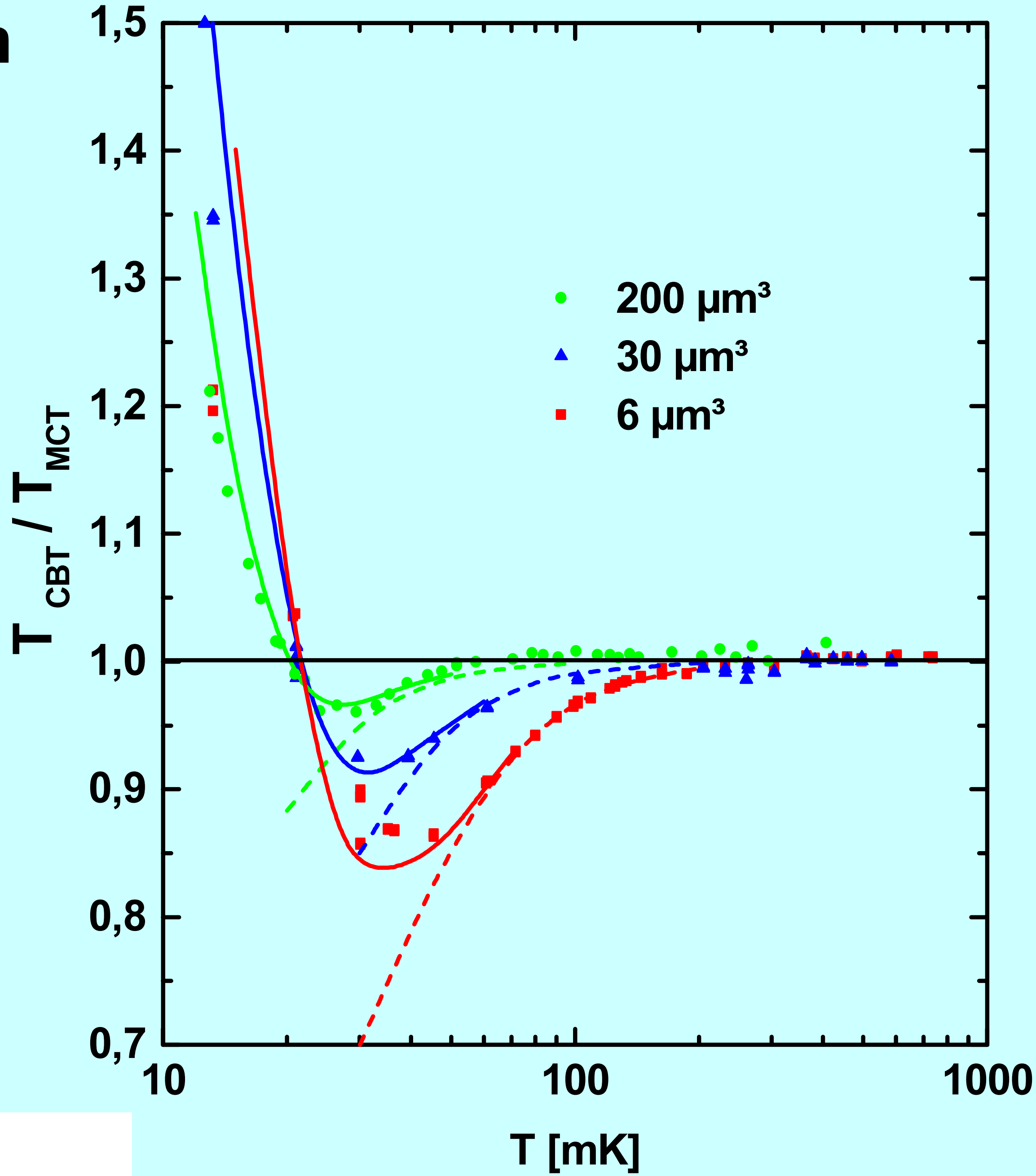
2 CBTs



Centre de Recherches sur les Très Basses Températures

Comparison between MCT and CBT

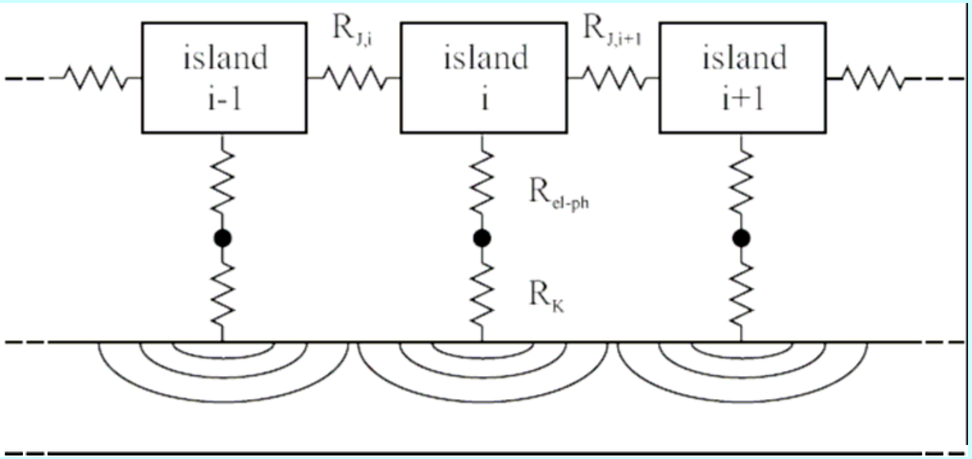


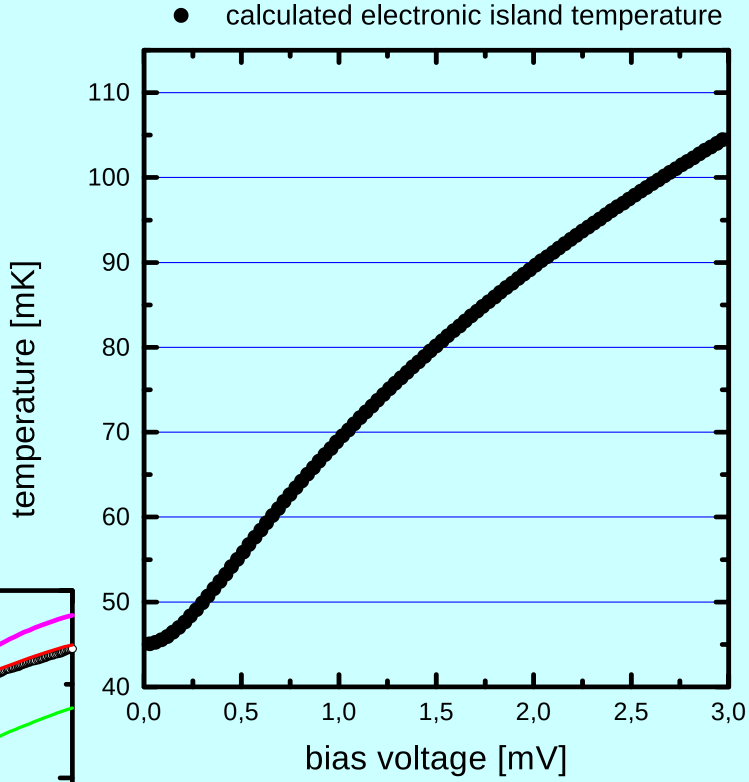


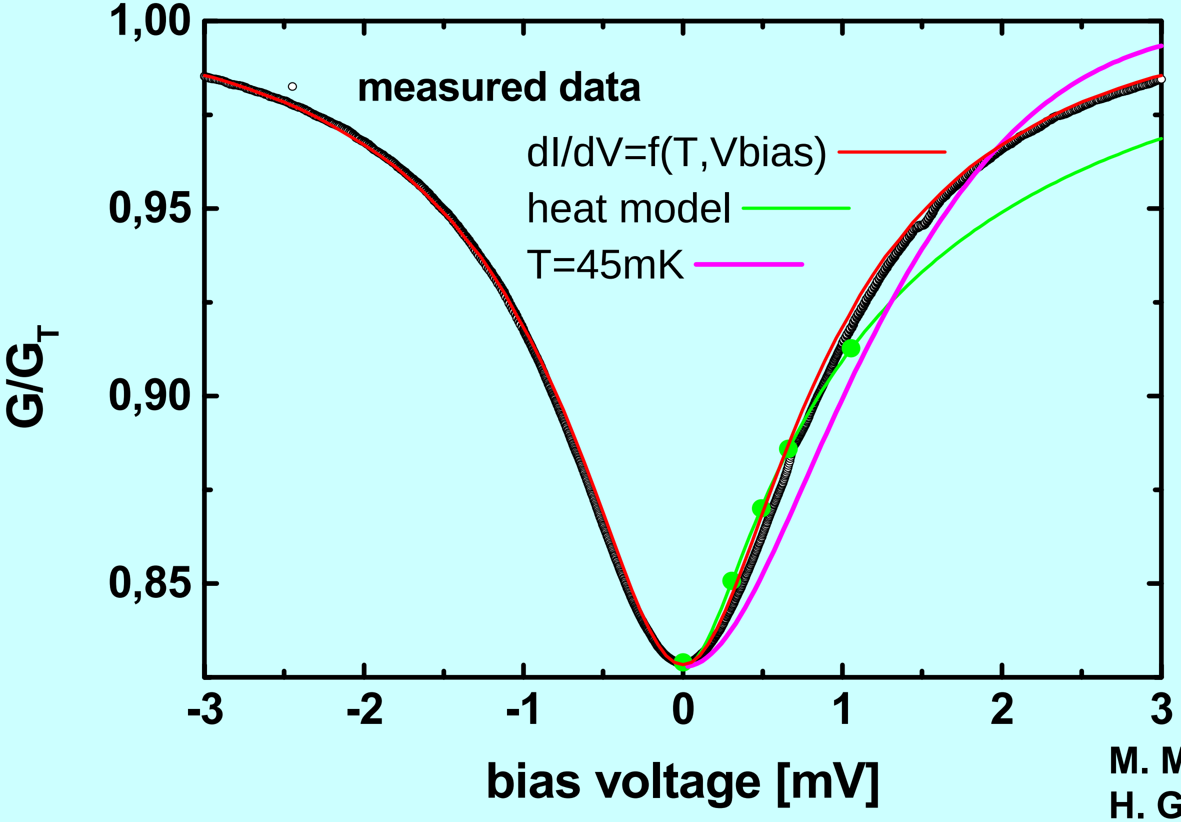
CRTBT
Centre de Recherches sur les Très Basses Températures

M. Meschke, J. P. Pekola, F. Gay, R. E. Rapp, H. Godfrin, JLTP 134 (2004) 1119

Overheating of island







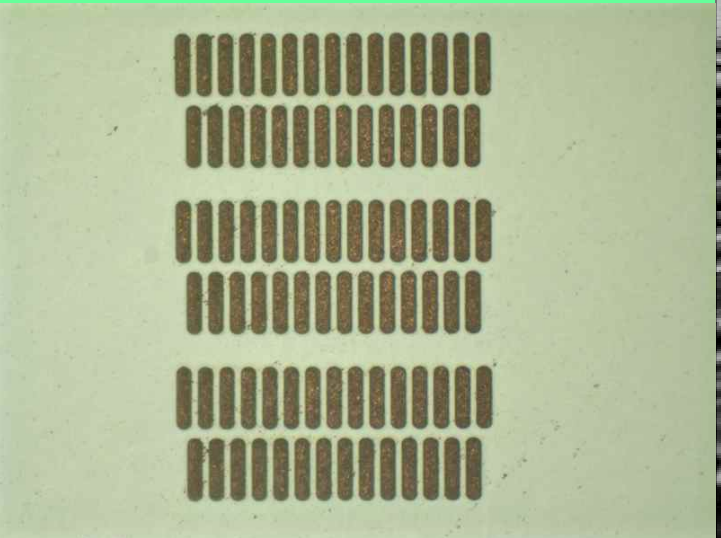
M. Meschke, J. P. Pekola, F. Gay, R. E. Rapp, H. Godfrin, JLTP 134 (2004) 1119

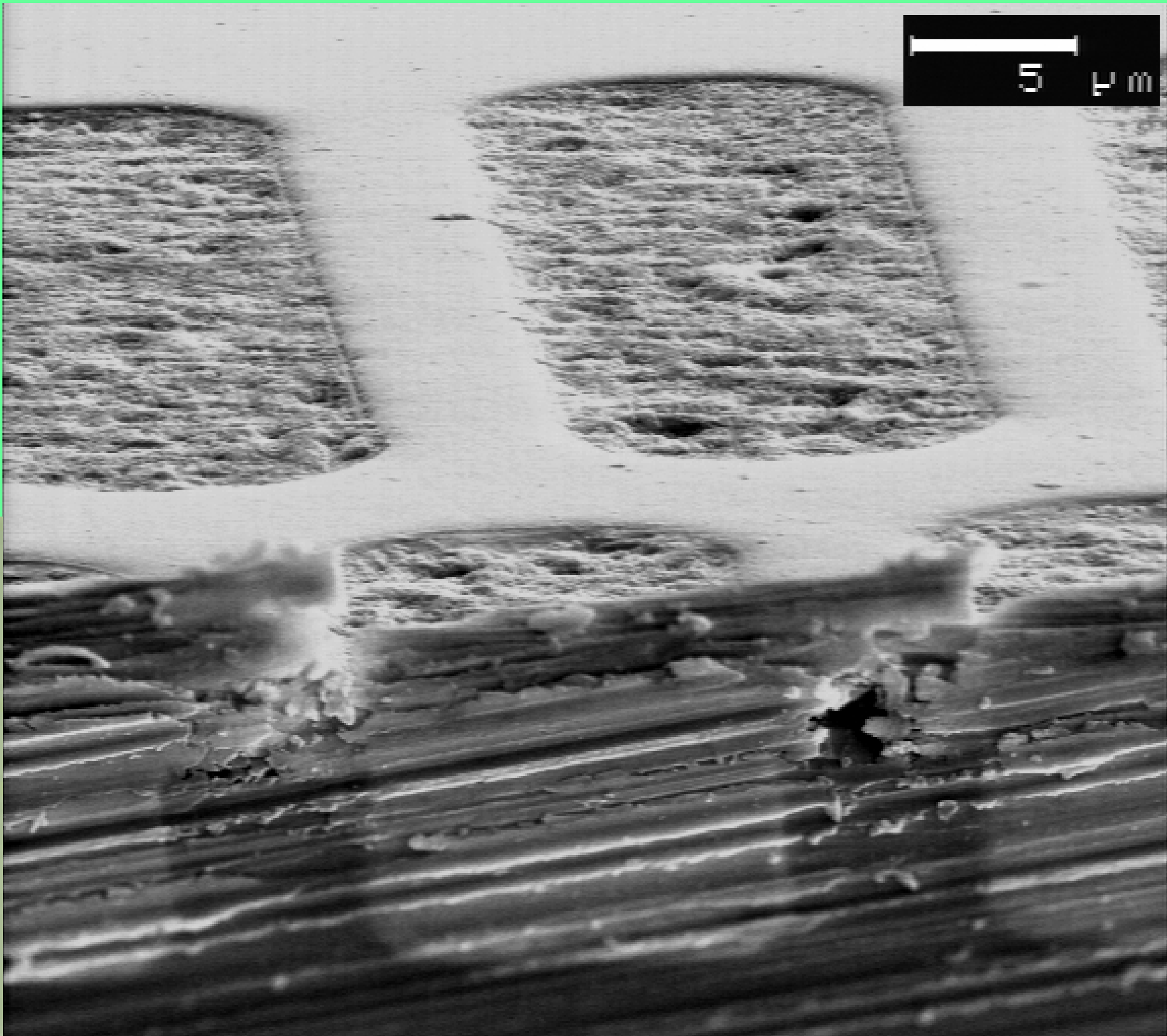
Increasing the volume (Antti J. Niskanen, TKK)

2d -> 3d

V:200 μm³ -> 5000 μm³

T: 20mK -> 10mK



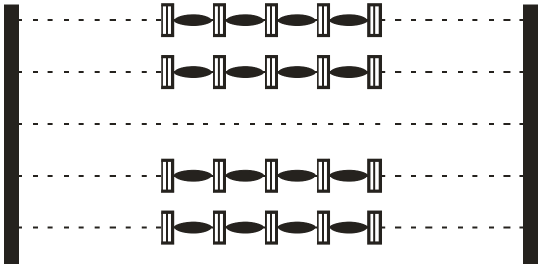


CBT for metrology? 0.1%!!

- **Inhomogenity of R_T in the array**

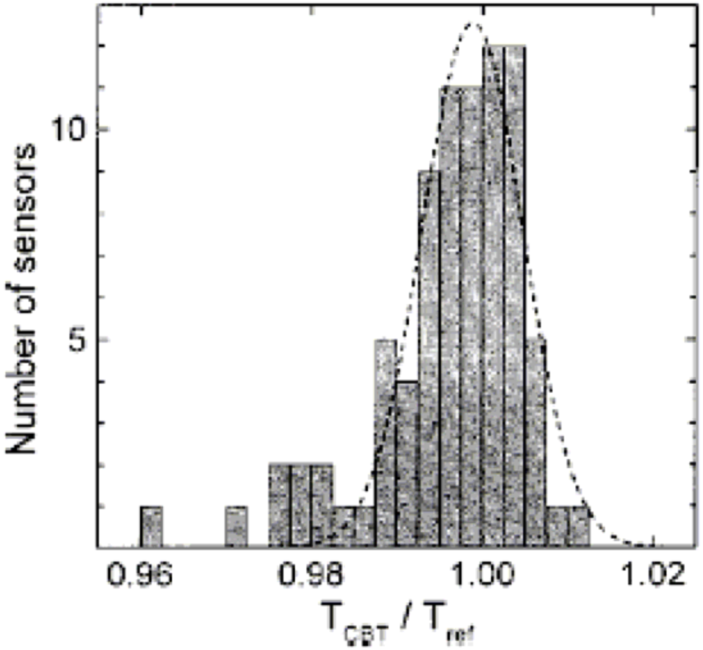
$$\frac{\delta R}{R} \approx 10\% \Rightarrow 1\% \text{ error in T}$$

- **Electromagnetic environment**



n junctions
m rows

n/m ~ 10
m=40...100



$$\frac{T_{CBT}}{T_{REF}(4.2K)} = 0.9988$$

$$\sigma = 0.59\%$$

J. P. Kauppinen, K. T. Loberg, A. J. Manninen, J. P. Pekola and R. A. Voutilainen REV SCI INSTR 69(1998)4166

Conclusion

- Primary
- Small and easy to use
- 10mK…30K
- Accuracy typically 1%
- Immune to magnetic fields (up to 30T tested)