Measurements of temperature on LHC thermal models

Christine Darve[1], Juan Casas[2], Moyses Kuchnir[1]

[1]: **Fermi National Accelerator Laboratory, Batavia, IL, USA**

[2]: **CERN, European Laboratory for Particle Physics, Geneva, CH**

Measurements of temperature on LHC thermal models

- Thermal measurements on models
  - Presentation of both projects
  - Sensors implementation
  - Results
- Use of cryogenic thermometers at Fermilab and at CERN
- Uncertainty evaluations

Introduction to LHC thermal models

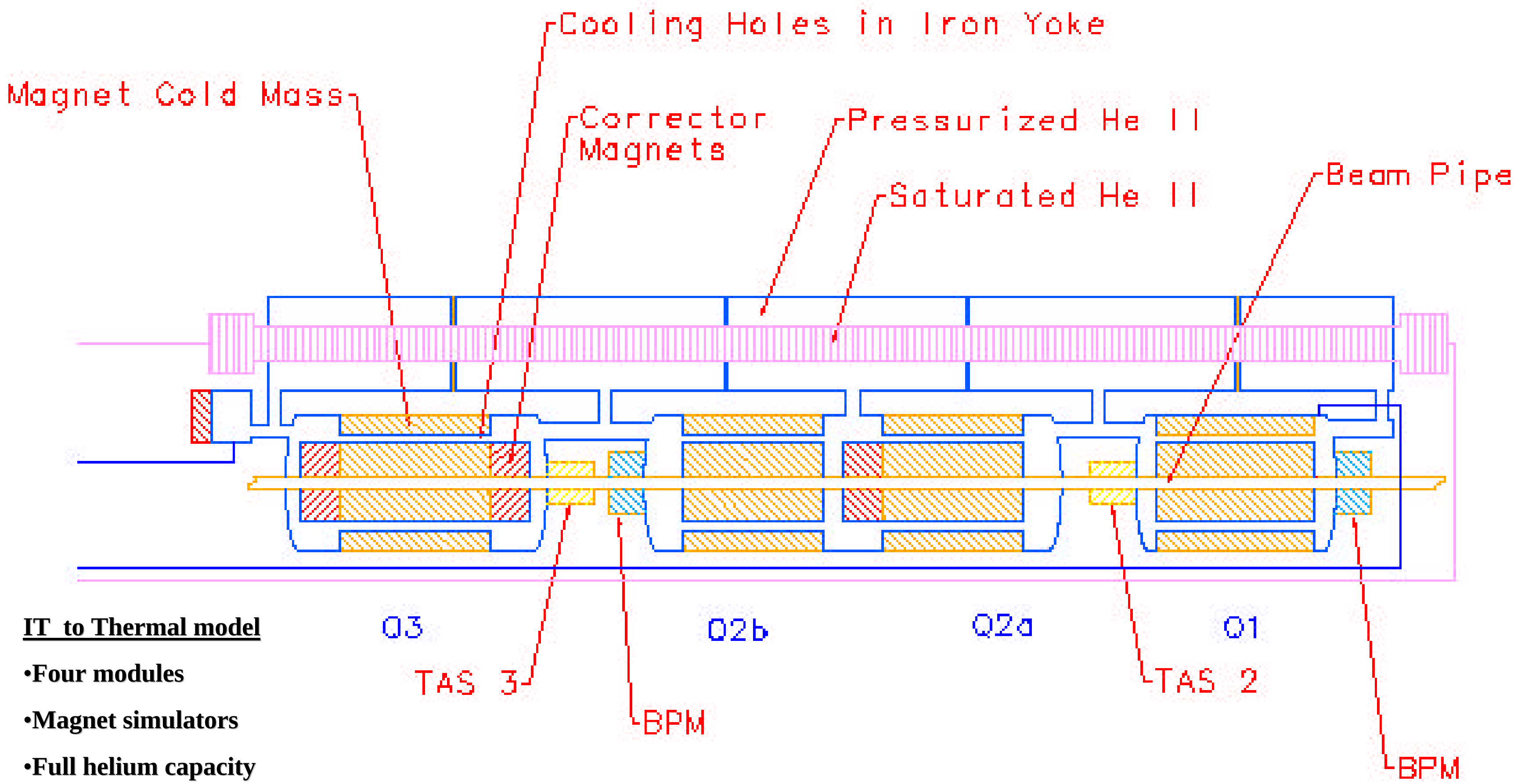
Inner Triplet heat exchanger test unit (US-IT-HXTU)

- Validation of the Inner Triplet cooling scheme
  - Heat transfer based on the exchange between the two-phase saturated He II used to extract heat loads generated in the stagnant pressurized He II bath.
  - Extreme heat loads due to the detector proximity : nominal Q'=7 W/m.

- Investigation in a linear model-based predictive control
  - Reduce requirements on temperature sensor, cryogenic sys. performance
  - Self-regulating process

- Related project: Small scale heat exchanger test
  - Material property measurements: Kapitza resistance.
  - Results used to estimate the wetted area of the full-scale model.

From the LHC Inner Triplet to the Inner Triplet heat exchanger test unit

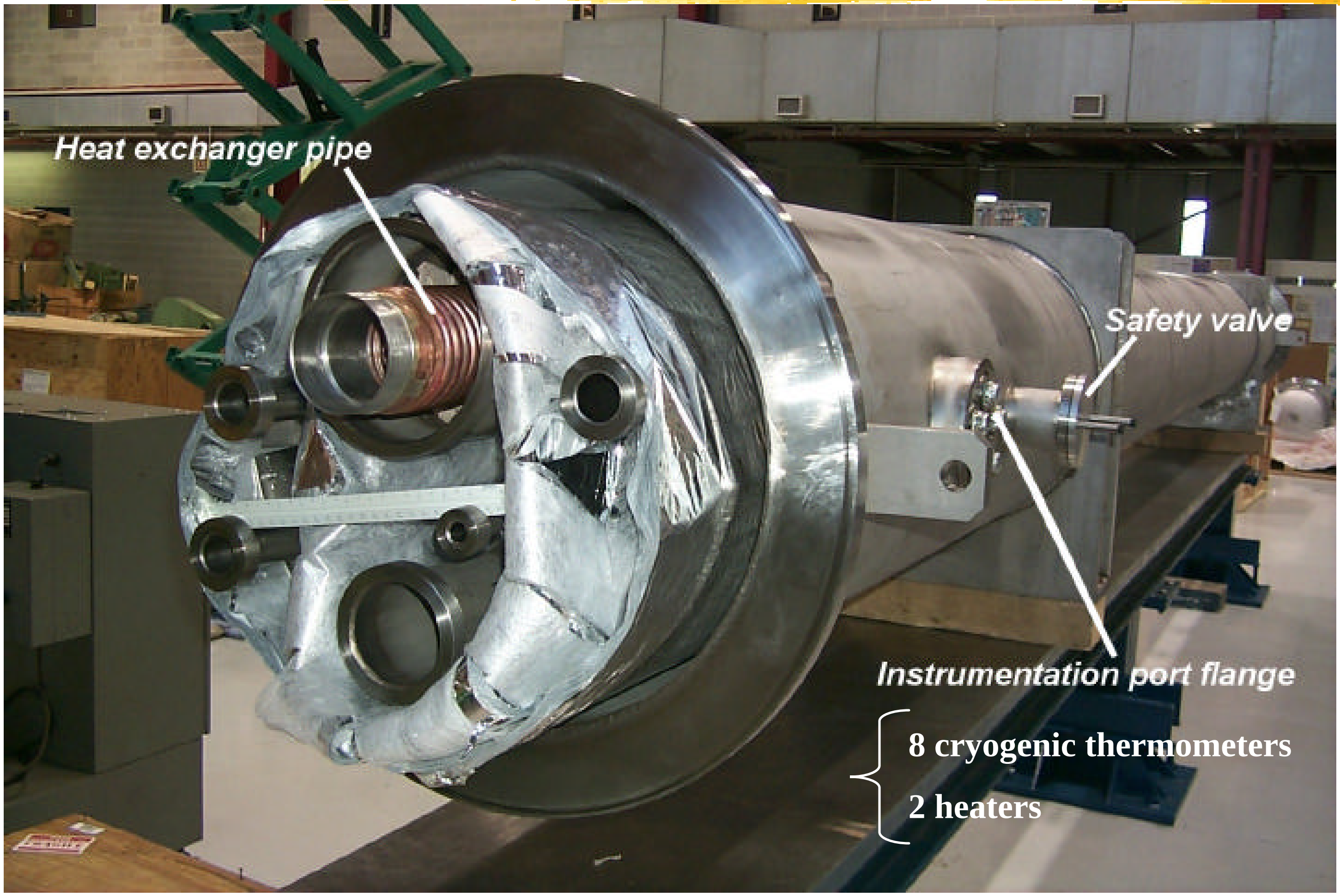


IT to Thermal model

- **Four modules**
- **Magnet simulators**
- **Full helium capacity**

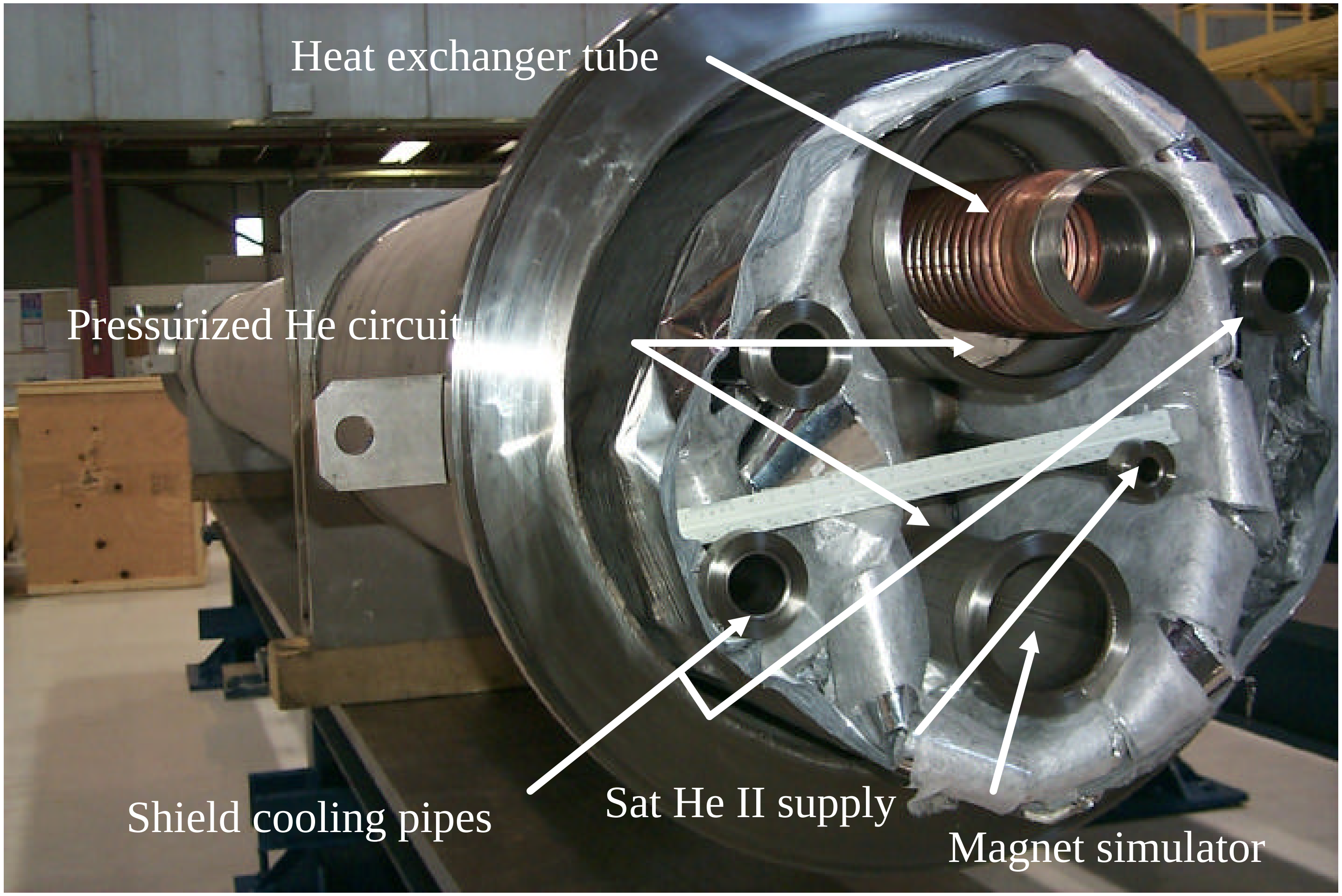
Inner triplet heat exchanger test unit

Modules



Inner triplet heat exchanger test unit

Piping system



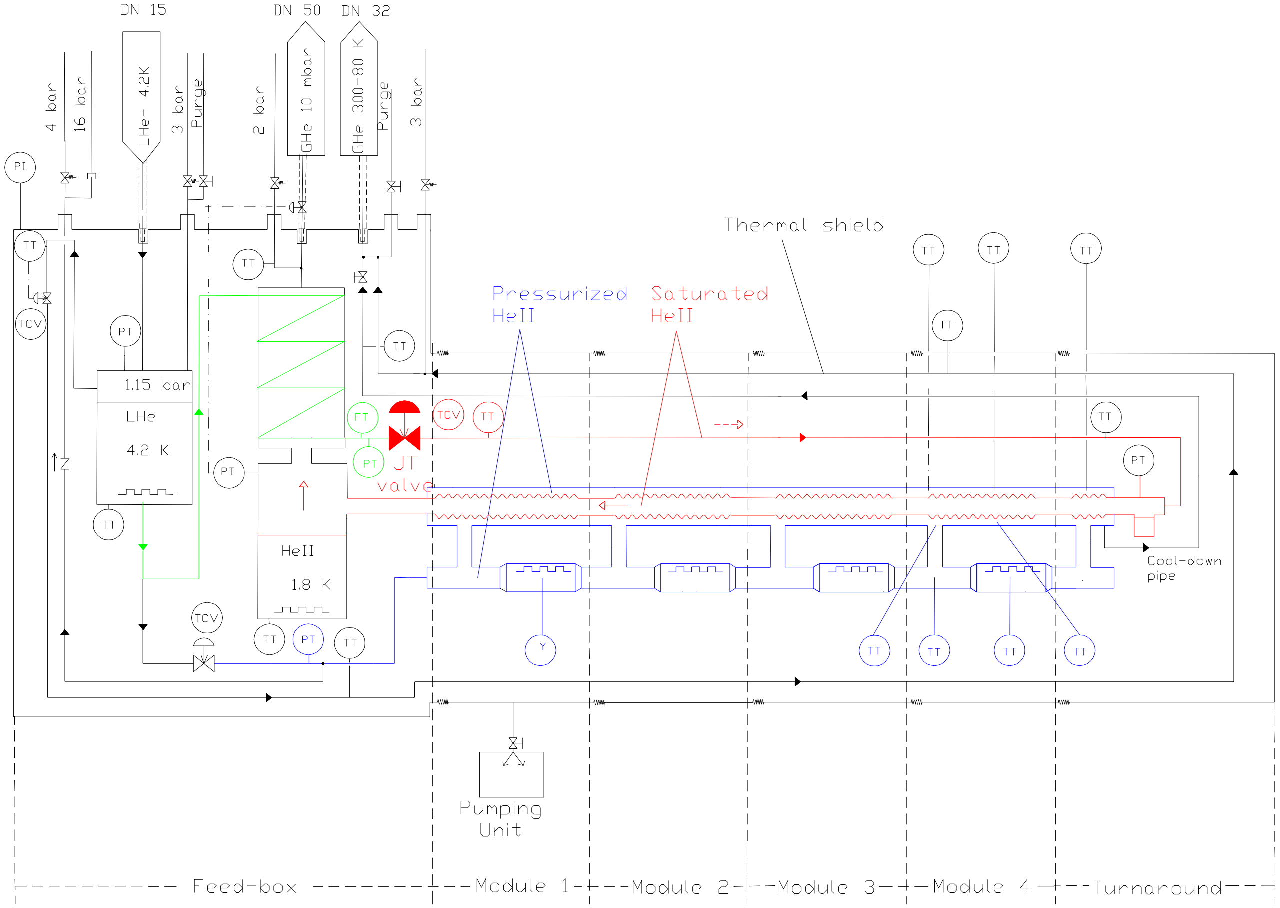
Inner triplet heat exchanger test unit

Instrumentation port flange

---Turnaround

Feed-box---

Inner triplet heat exchanger test unit



Thermal measurements on the US-IT-HXTU

- Why do we perform thermal measurements?
  - To measure the temperature rise along the He II heat load path, for different LHC heat load scenarios-> maximum: heat load, Tsat.
  - To understand the behavior of He II (co-current two-phase flow, wetted area).
  - To calibrate and measure the performance of the HX tube.
  - To validate the theoretical model->ultimate LHC condition (472W).

- Function of temperature measurements
  - Display the transport of the heat load from pressurized to saturated He II.
  - Indicator to check the evolution towards steady-state conditions.
  - Variable parameter, Tsat, for various measurements of the HX tube performance.

Thermal measurements on the US-IT-HXTU

⇨ How are they implemented ?

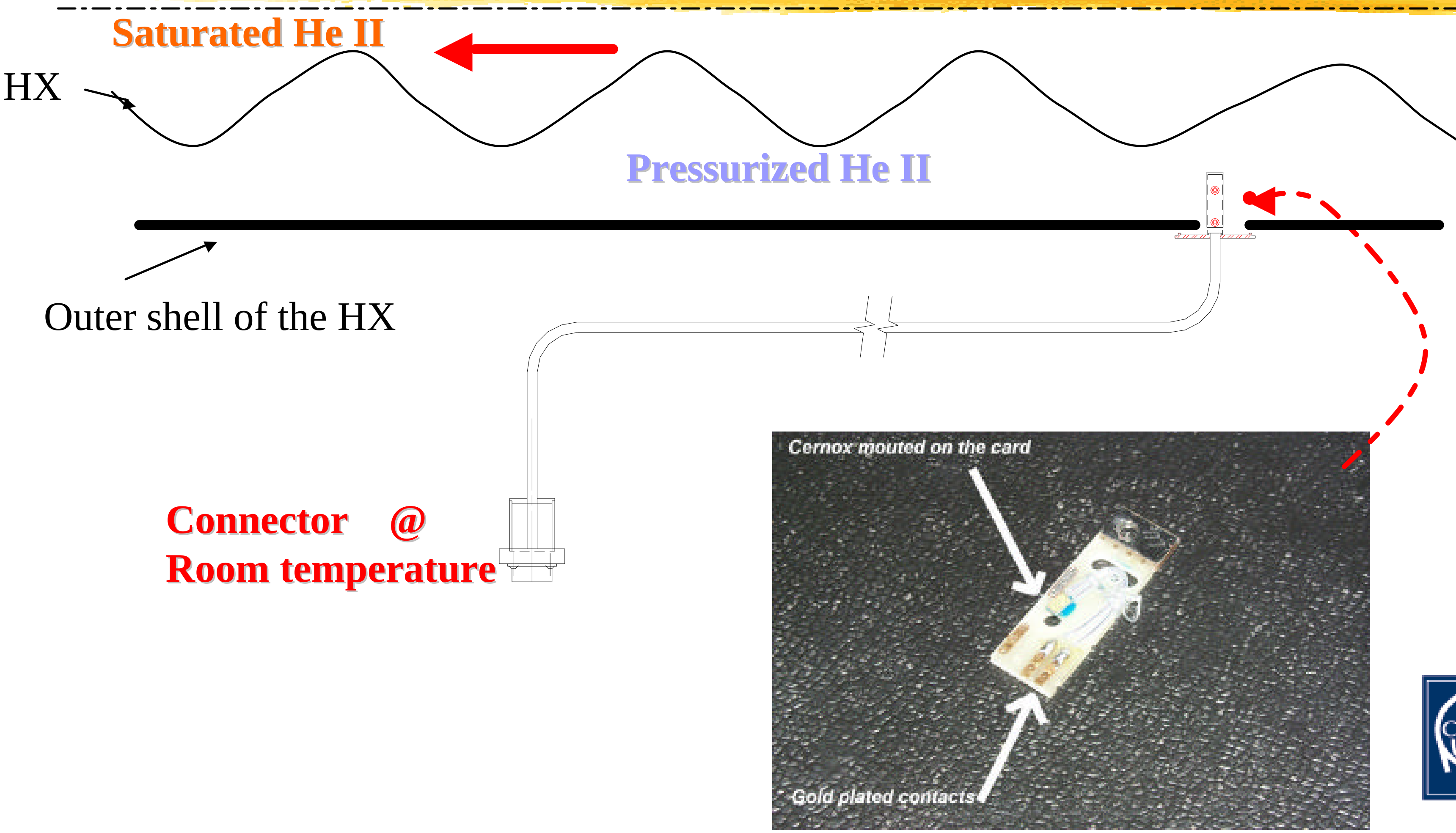
Pressurized He II temperature

- Glued to printed circuit board (PCB) card.
- Thermometers immersed in pressurized He II bath along the HX tube (pressurized side) and magnet simulator pipes.
- Thermometer wires routed through a 3 m long feedthrough from the pressurized He II bath to the room temperature.

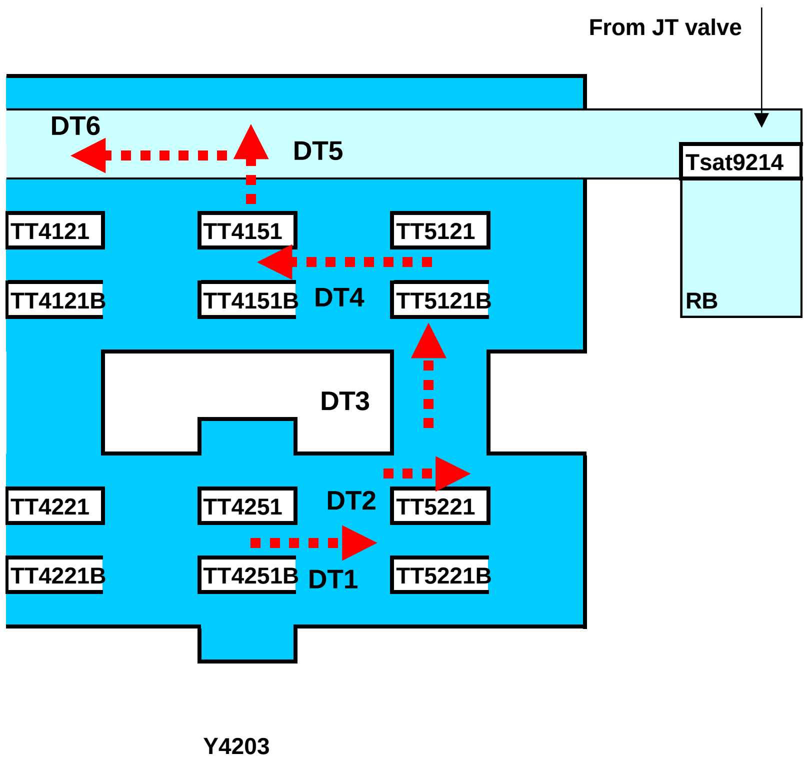
Saturated He II temperature

- Measurement of the saturated temperature provided from the pressure measurement.
- To reduce air leaks through the instrumentation feedthrough (subatmospheric circuit).

Thermal measurements on the US-IT-HXTU



Thermal measurements on the US-IT-HXTU



DT1: from the Module thermal center,
to the module end within the pressurized He II

DT2: within the connecting pipe

DT3: between connecting pipe and He II HX

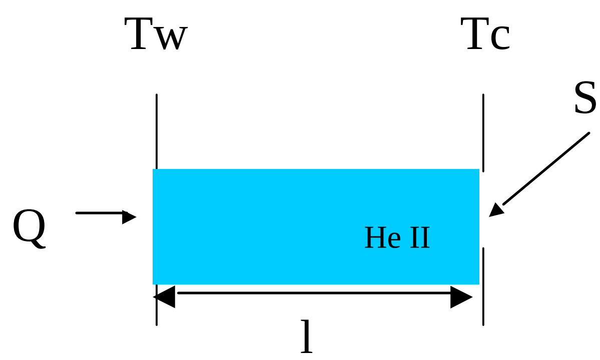
DT4: within the pressurized He II side of He II HX

DT5: across the He II heat exchanger wall

DT6: due to the vapor pressure drop.
Vapor V= 448 cm/sec

Thermal measurements on the US-IT-HXTU

- Heat transfer into and through pressurized He II (DT 1 - 4)

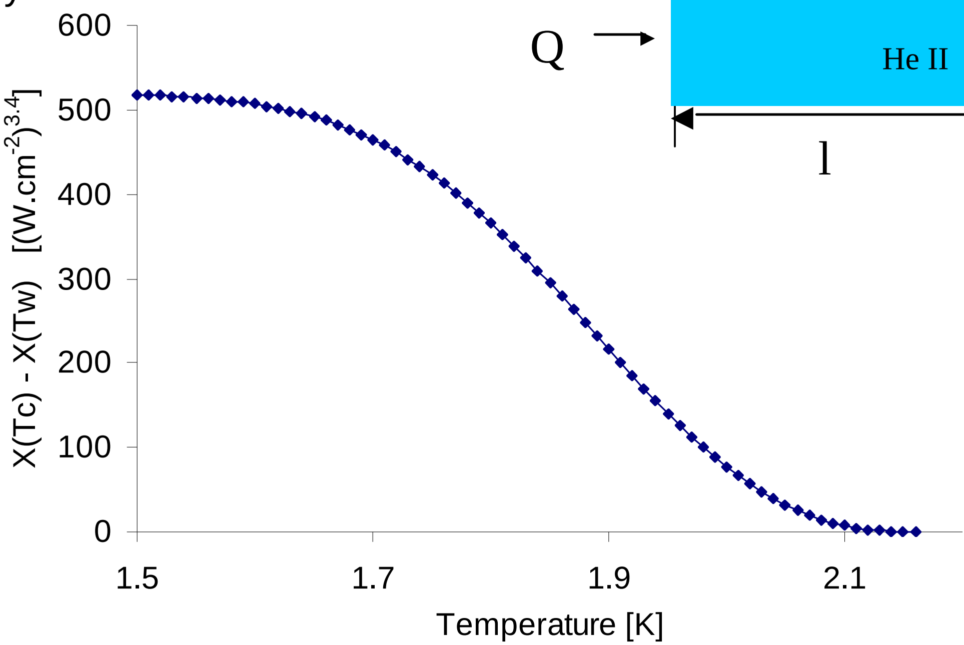


One-dimension model

In steady-state, heat flux Q' is given by:

$$Q' = S \cdot \left(\frac{X(Tc) - X(Tw)}{l} \right)^{0.29}$$

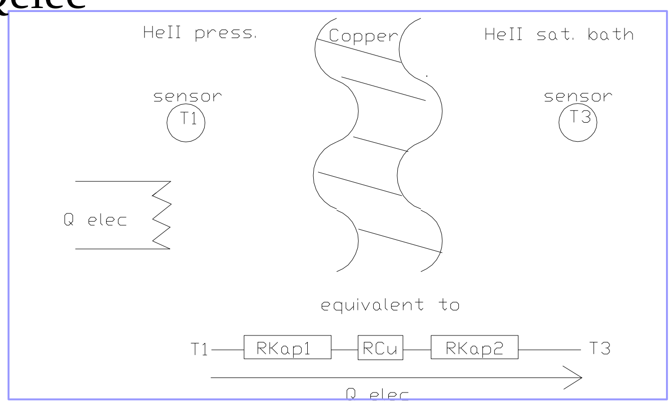
$$X(T) = 520 \cdot \left(1 - e^{-\left(3 \cdot (2.16 - T)^{2.5}\right)}\right)$$

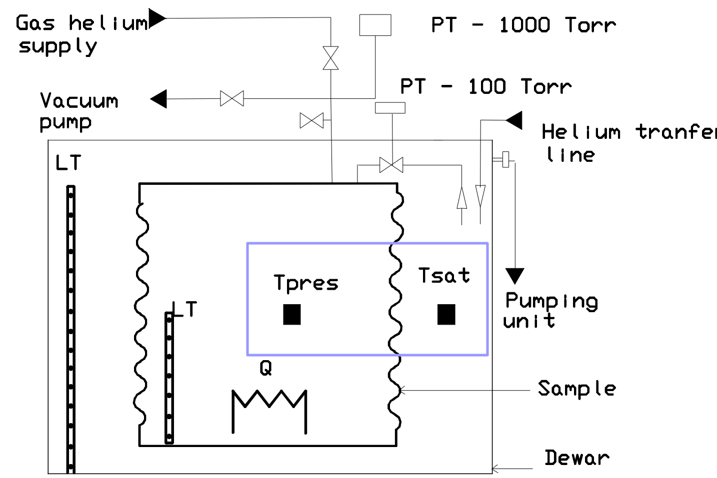


US-IT-HXTU- Small scale HX

Kapitza Resistance and DT 5

$$Rth=(Tpres-Tsat)/Qelec$$



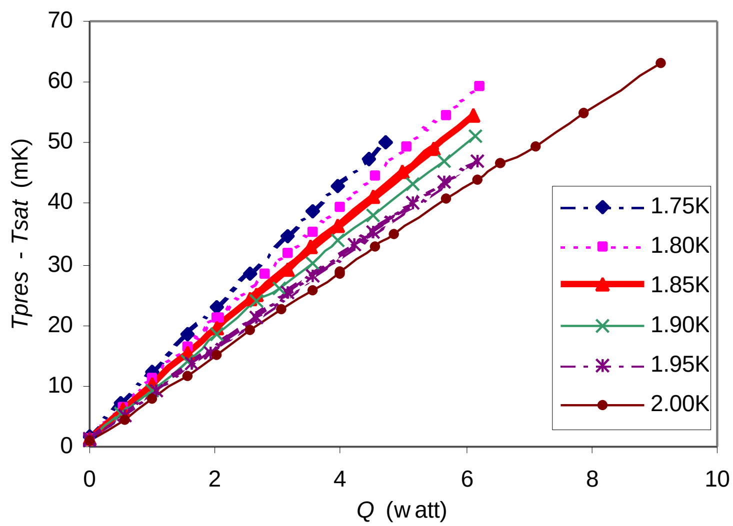


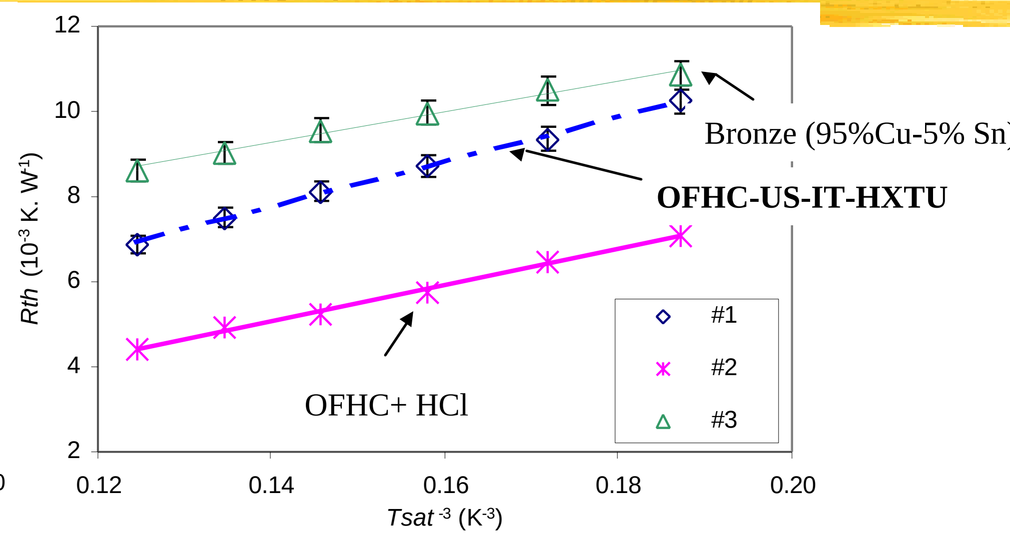
$$Rth=2.Rkapitza+Rcu=\alpha(1/Tpres^3)+b$$

$$\begin{cases} \alpha = \dfrac{2}{Ckapitza \cdot S} \\ \beta = \dfrac{e}{S \cdot Ccu} \end{cases}$$

Rkapitza

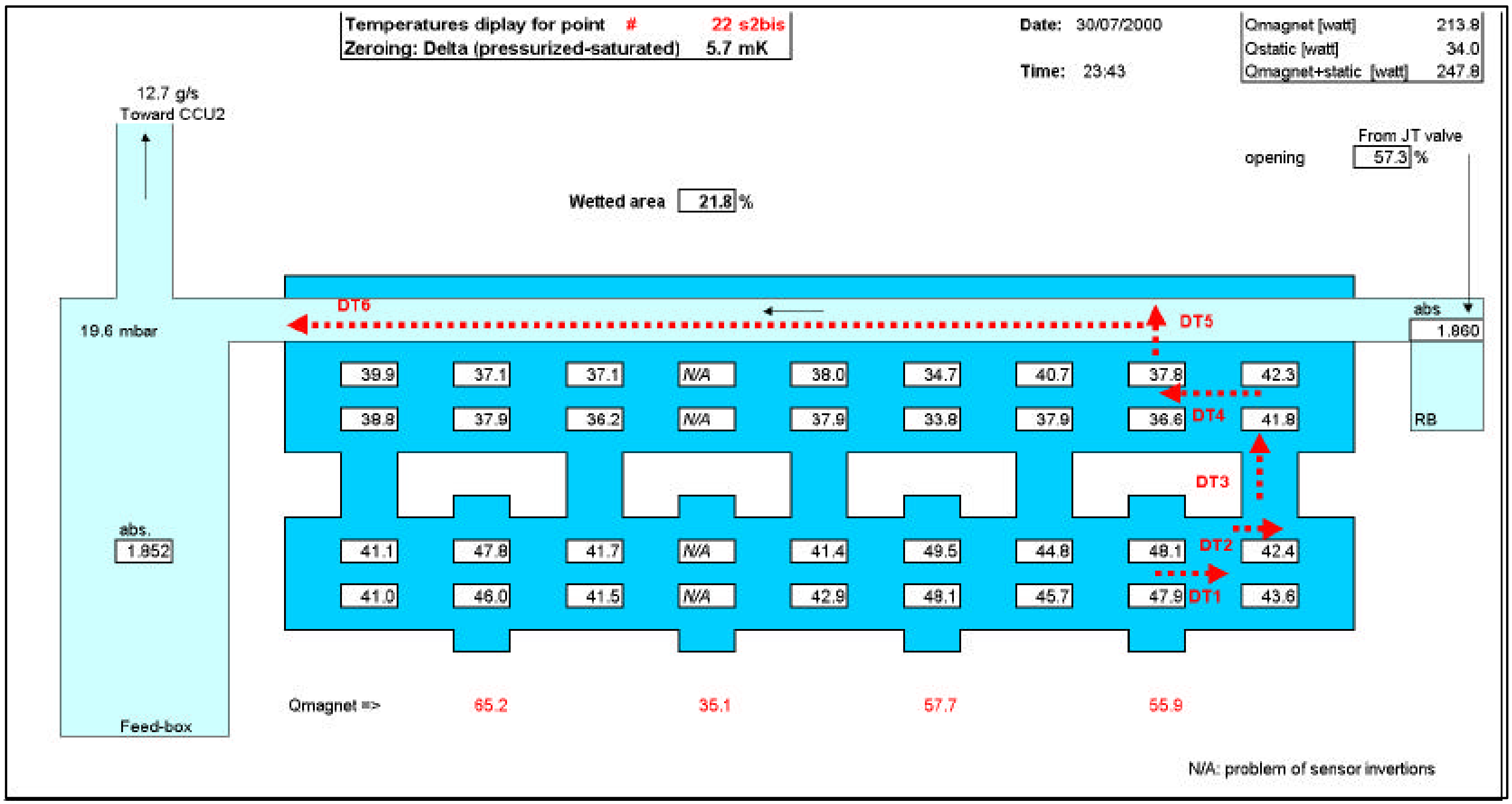
Thermal measurements on the small-scale heat exchanger test unit - results



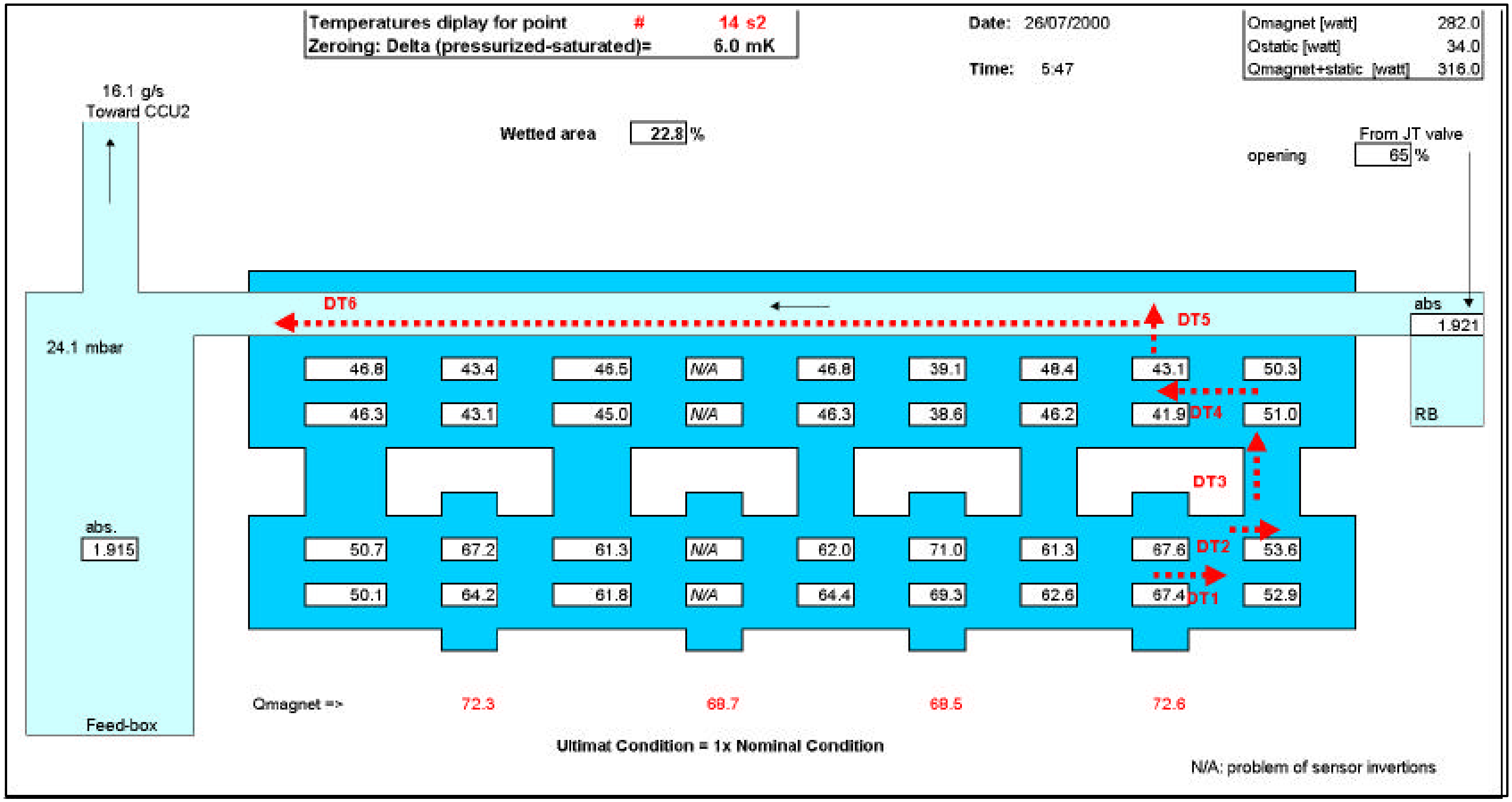


	#1 - OFHC	#2 – OFHC + HCl	#3 - Bronze
Characteristics			
OD/ ID (mm)	97/86	97/86	123/101
Wall thickness (mm)	0.7	0.7	0.5
Corrugation depth (mm)	5	5	11
Corrugation pitch (mm)	12.4	12.4	11.7
Surface (cm^2) for one side	416	416	978
Shape of the corrugated pipe	Helical	Helical	Bellows
Surface treatment	None	Hydrochloric acid	None
Results			
CKapitza ($W \cdot K^{-4} \cdot m^{-2}$)	893	1138	565
Kapitza conductance @ 1.85 K ($W \cdot K^{-1} \cdot cm^{-2}$)	0.565	0.72	0.357
Thermal conductivity @ 1.85 K ($W \cdot K^{-1} \cdot m^{-1}$)	88	88	2.4
Relative performance	Ref.	27%	-37%

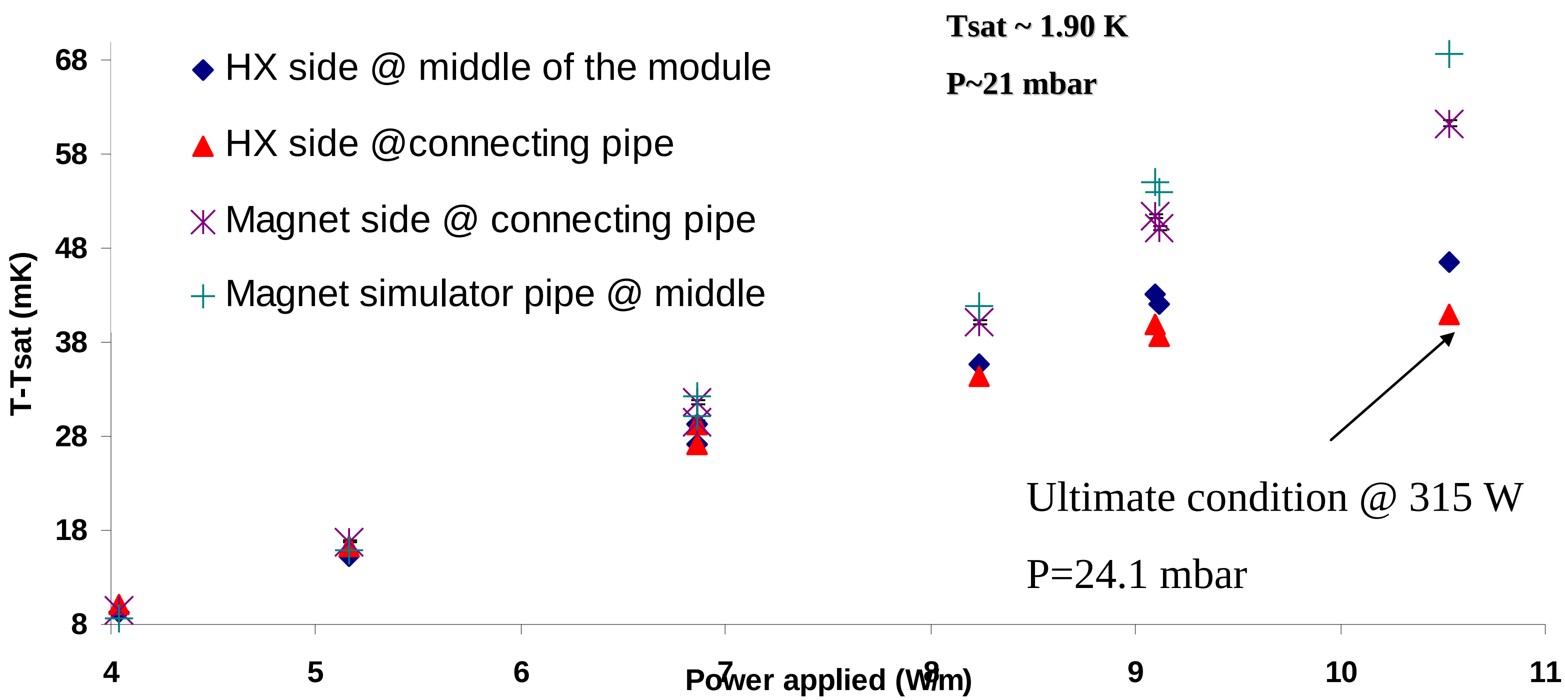
US-IT-HXTU - Nominal Condition: 248 W



US-IT-HXTU - Ultimate Condition: 315 W



US-IT-HXTU - Some results

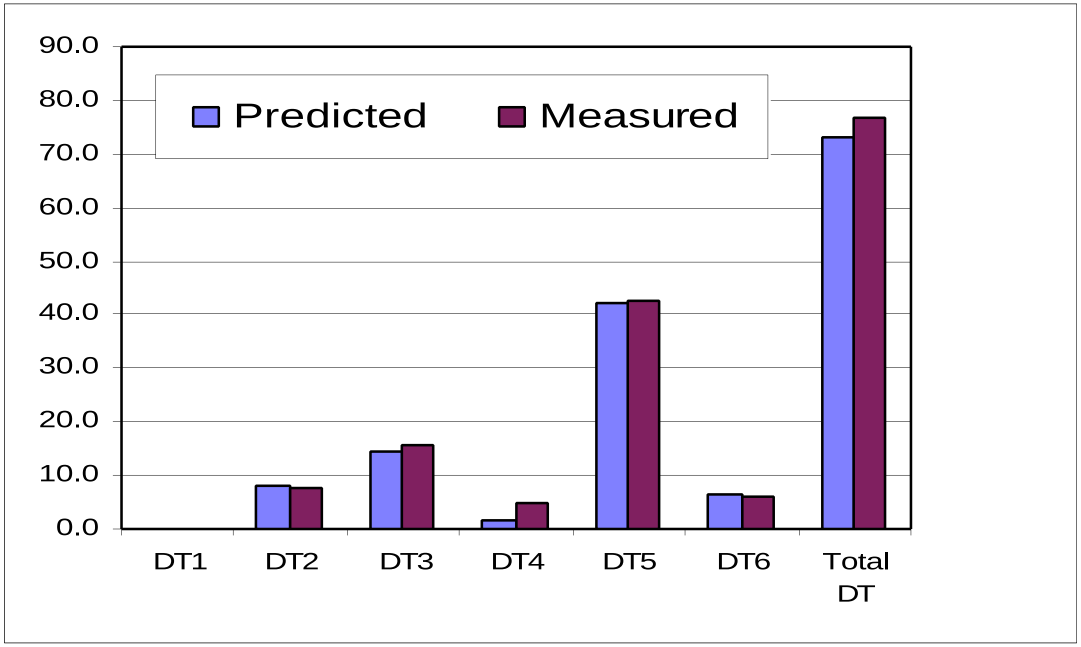


C/C: The difference of temperature on the heat exchanger interface < 50 mK.
The thermal gradient within the heat exchanger pipe is still to be measured in december at CERN.

Thermal measurements on the US-IT-HXTU

Heat loads on the US-IT-HXTU extrapolated from the heat load in the Inner Triplet at IP5 or IP1, by Tom Peterson.

Example for Tsat= 1.915 K , Q'tot= 315 W



Equations:

$dT/dx=-f(T)\ q^m$

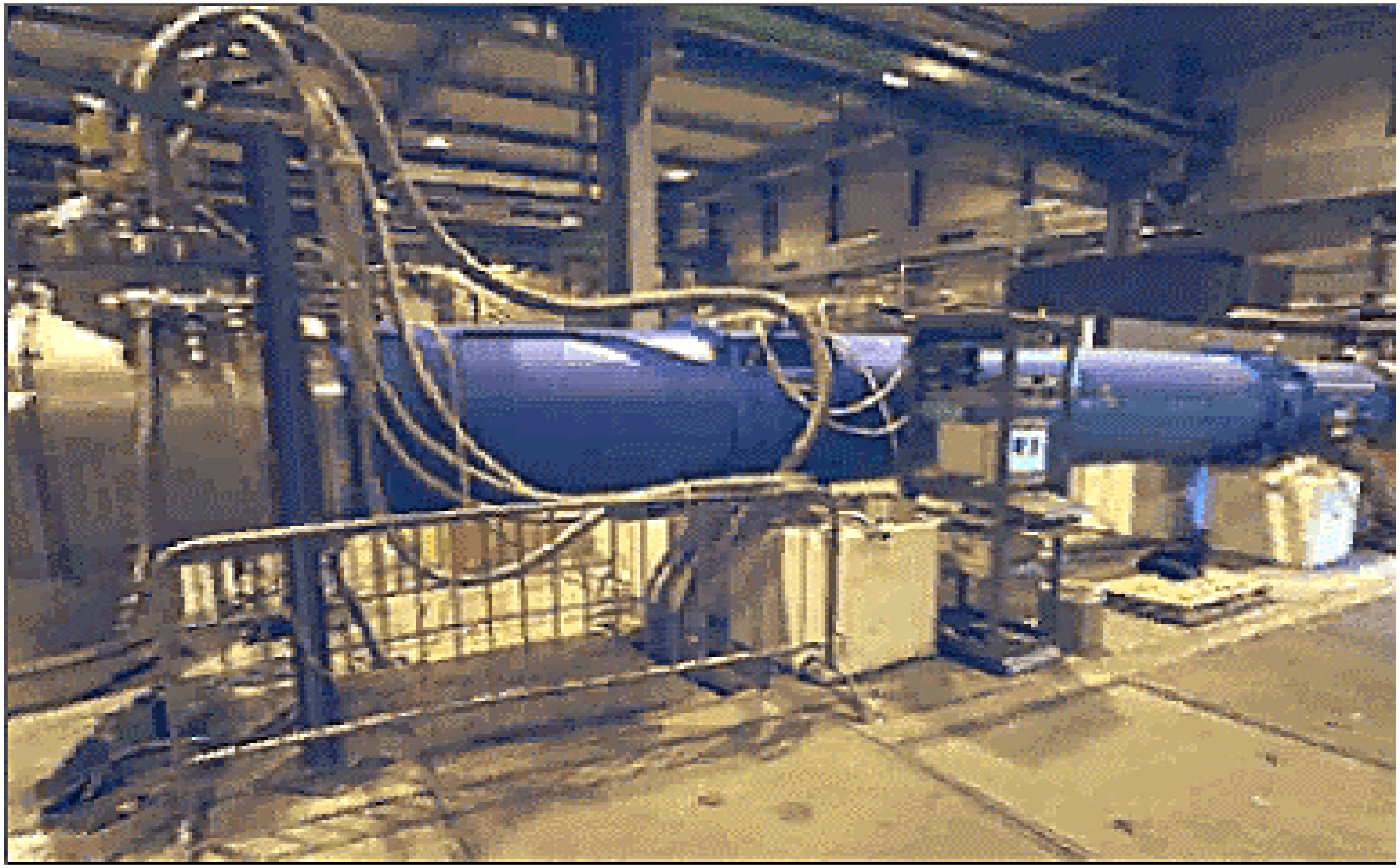
$\Rightarrow \Delta T=q^3 L/1200$

Introduction to LHC thermal models

Cryostat thermal model (CTM)

- Measurements of the LHC cryostat dipole performance
  - + Heat loads to the actively cooled shield and to the dummy cold mass.
  - + Components performance:
    - Multi-Layer Insulation,
    - support posts,
    - beam screen,
    - cryogenic thermometers.
- Conditions under investigation
  - Steady-state and transient modes for the LHC conditions
  - Insulation vacuum degradation
- Adoption of an actively cooled screen @ 5-10 K (CTM3)?

Thermal measurements on the CTM

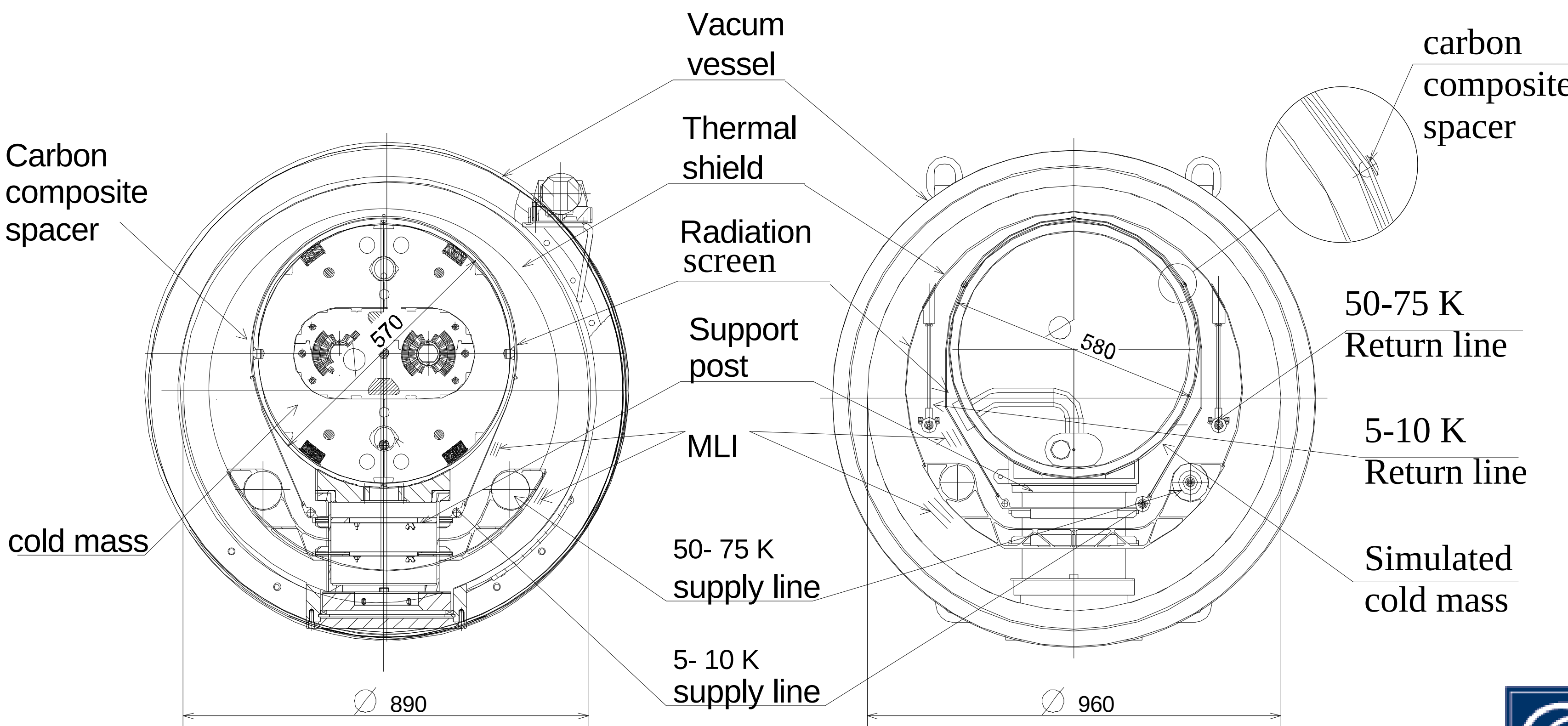


Thermal measurements on the CTM

View of the radiation screen

View of the dummy cold mass

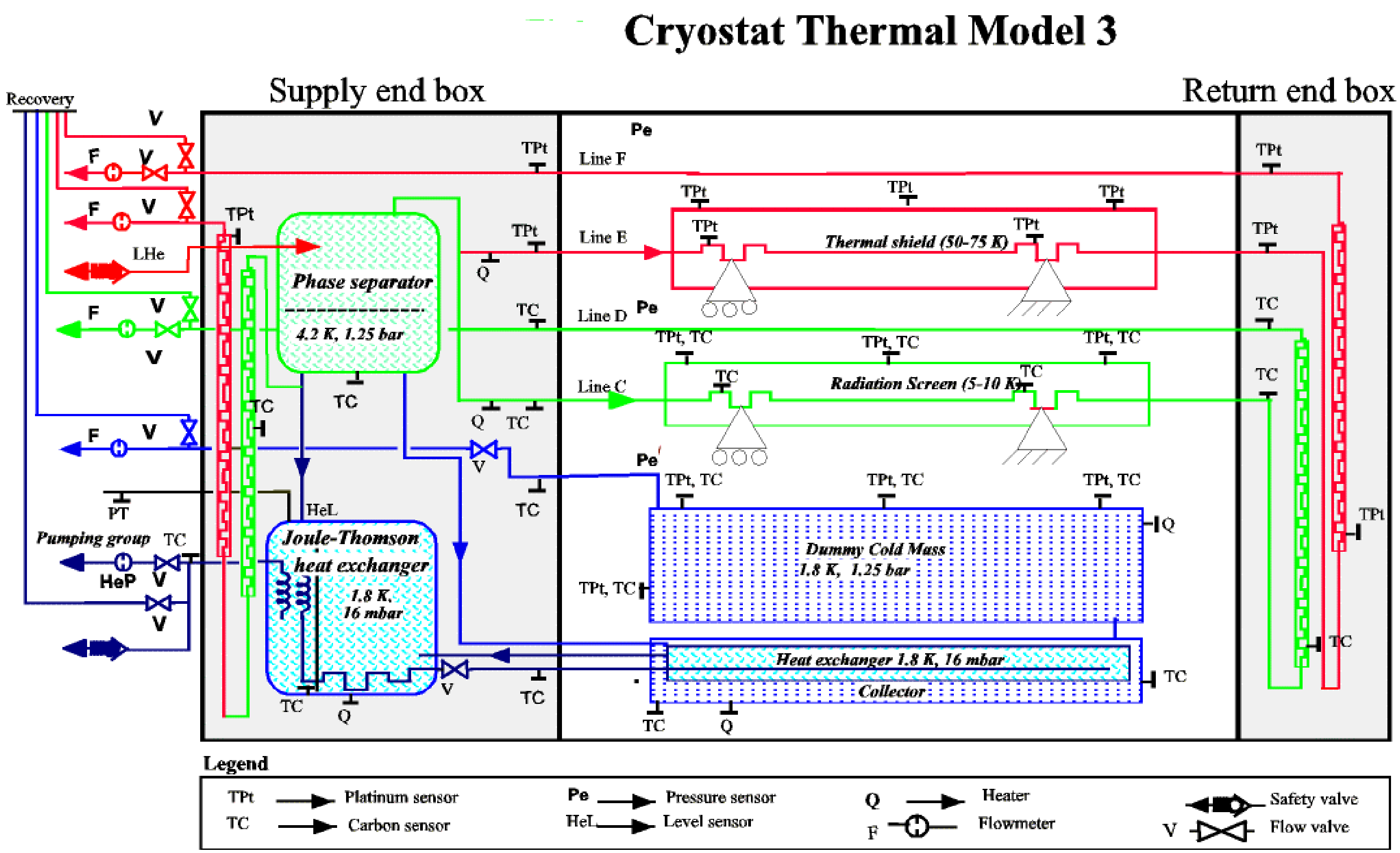
Thermal measurements on the CTM



LHC accelerator cross-section

CTM3 cross section

Thermal measurements on the CTM



Thermal measurements on the CTM

- Performance of the thermal shield (50-75K) and radiation screen(5-10K)

  The temperature is measured at each extremity of the helium pipes

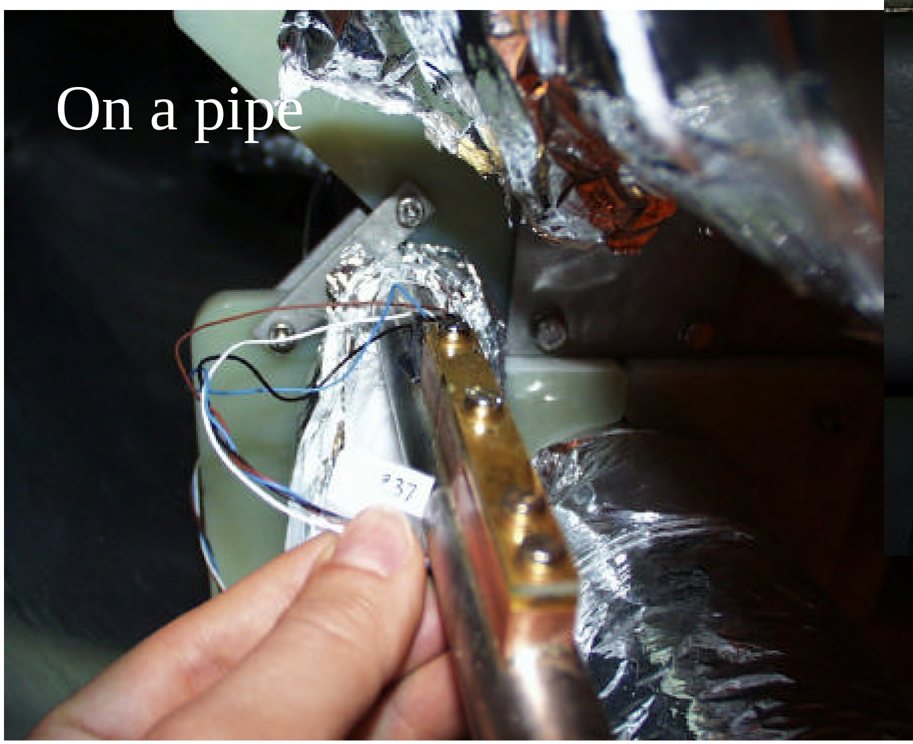
$$Q' = m' \cdot \Delta H \qquad \begin{cases} m' = \text{mass-flow}, \\ \Delta H = \text{enthalpy difference} \end{cases}$$

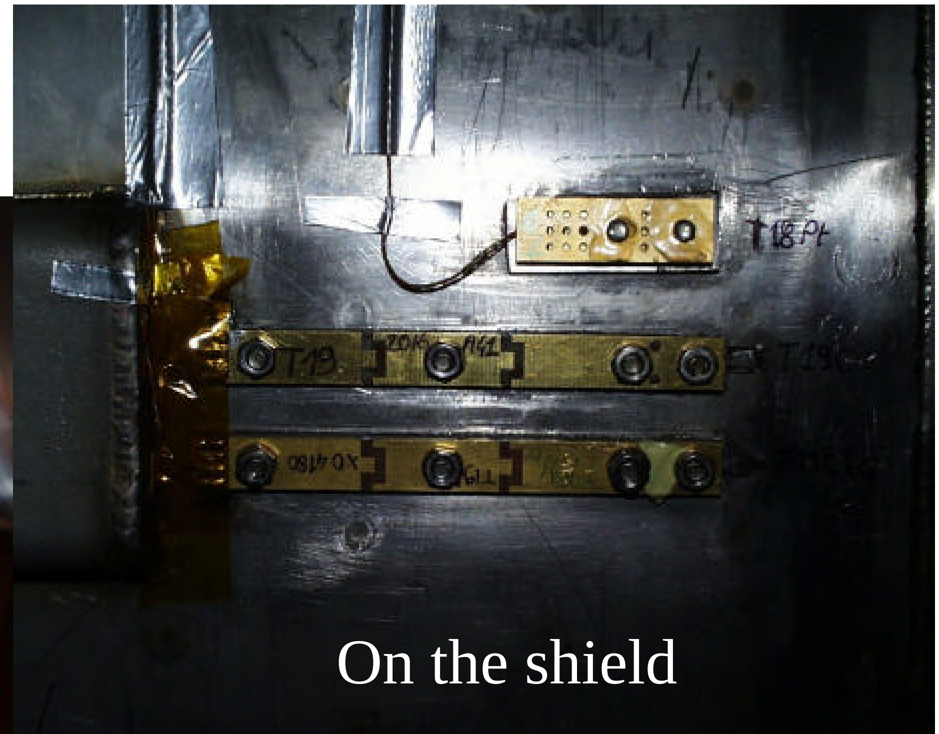
- Heat load to the dummy cold mass

  Heat load to the dummy cold mass is measured with the boil-off method

$$Q_{1.9\,K}' = m' \cdot L \qquad \begin{cases} m' = \text{mass-flow}, \\ L = \text{latent heat of vaporization} \end{cases}$$

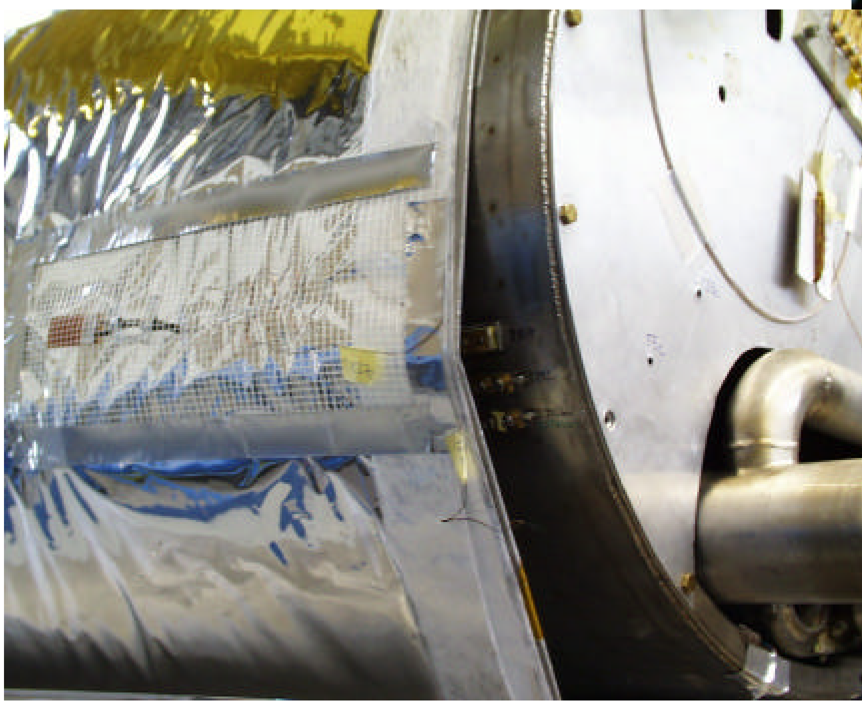
Implementation of sensors on the CTM

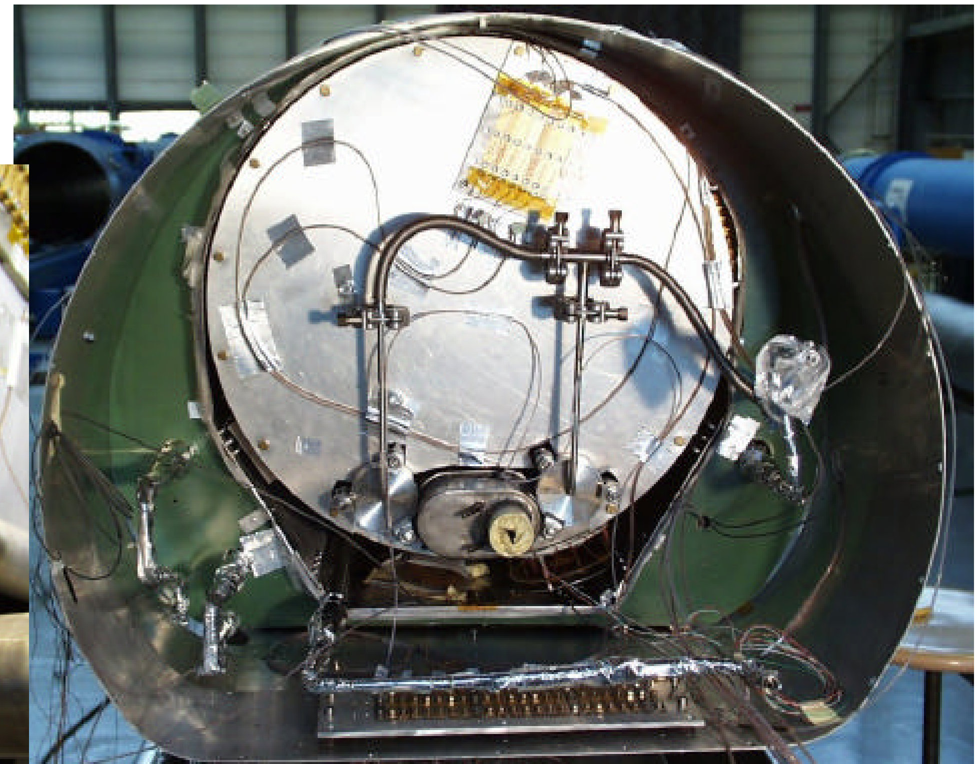




Implementation of sensors on the CTM

In the MLI





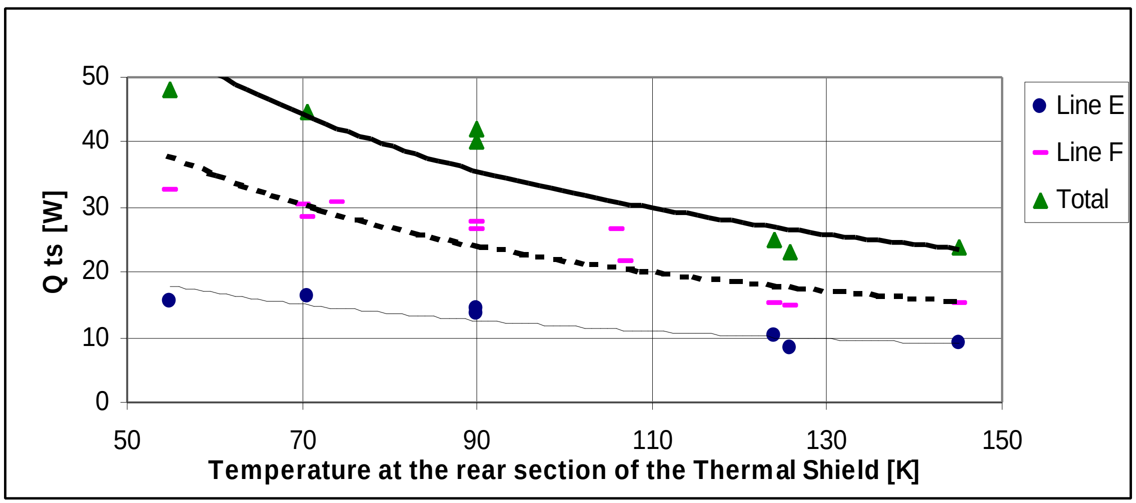
Thermalization of the instrumentation wires

Some results - CTM2

Total heat load measured:

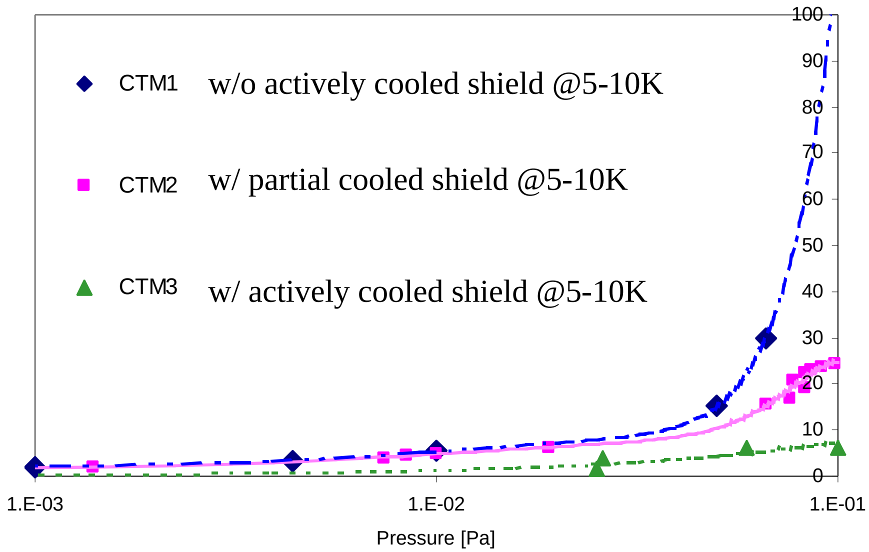
Heat inleak [W/m]	@ 50-75 K / Line E+F error: ± 5%		@5-10K / Line C+D error: ± 4.7%		@ 1.9 K error: ± 2.5%	
	measured	calculated	measured	calculated	measured	calculated
CTM1	4.78	4.58	0.23	0.24	0.18	0.19
CTM2	4.32	4.12	0.48	0.33	0.16 (1)	0.12

The contribution of the feed box on the measured He in-leak at 1.9 K is estimated to 390 mW.



CTM3 - Some results

Influence of the insulation vacuum degradation



Averaged heat loads (Watts): Insulation vacuum 7.5×10^{-5} Pa

Component	Average Temperatures K			50-75 K	5-10 K	1.9 K
Supply and return boxes						0.300
Thermal shield	68			43.2		
Radiation screen		8.7			3.1	
Cold-mass			1.8			0.441
Support System				14.9	1.1	0.129
Total CTM Cryostat				28.3	2.0	0.012

- CTM3, dummy cold mass experienced He leaks
  -> results difficult to interpret.
- MLI qualification on an horizontal cryostat was performed.
- Choice of the shield assembly: welded to the extruded pipe

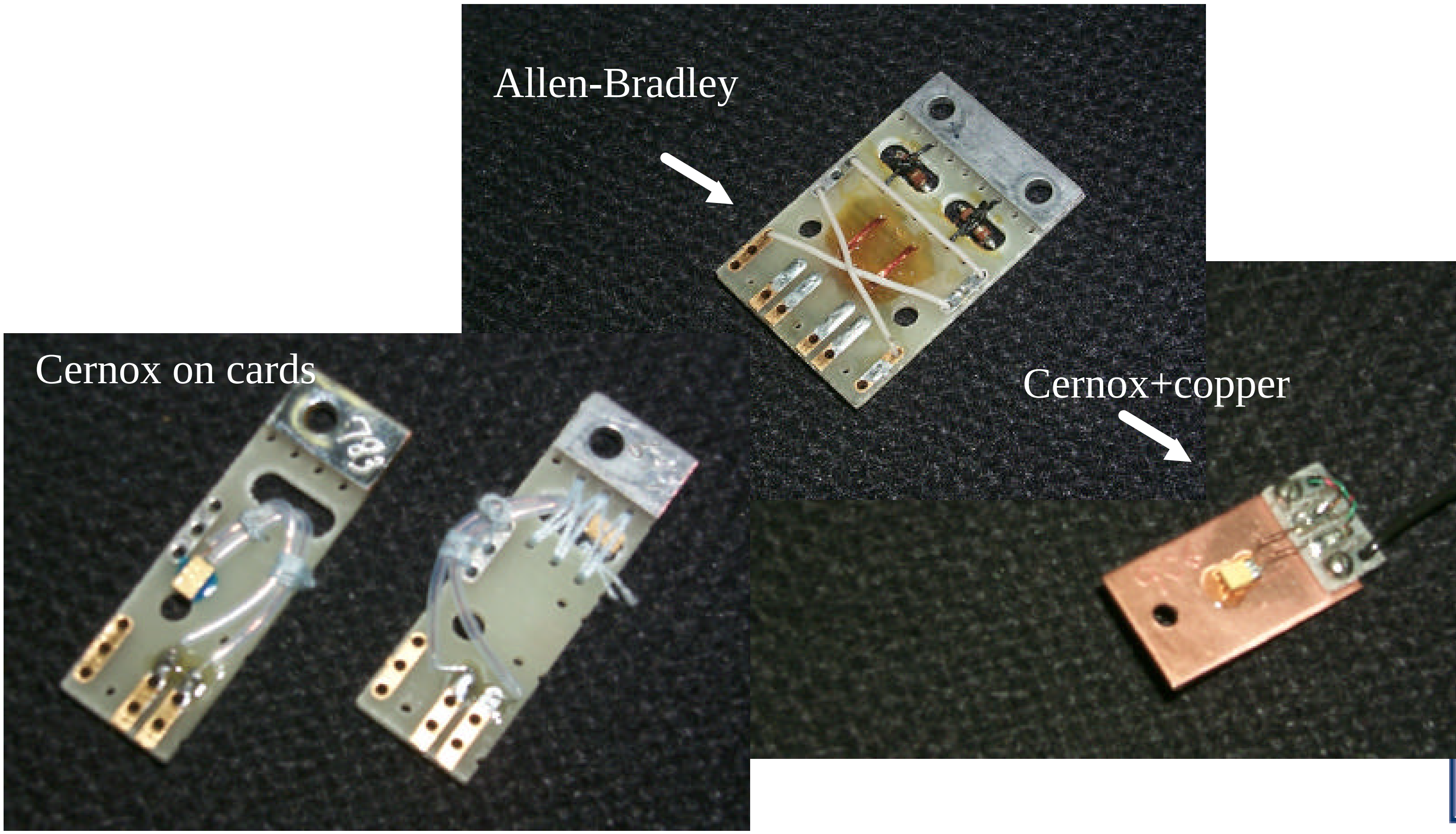
C/C: Since the cost of a radiation screen material is dominant and even if a better performance with a 5K cryostat was measured, the LHC cryostat will only consider to wrap 10 layers of MLI around the cold mass. No rigid radiation screen (5-10 K) will be used in the LHC accelerator.

Some cryogenic thermometers used at Fermilab - US-IT-HXTU

- Thermometer immersed into He II bath
  - Commercial sensors
  - Printed circuit board
  - Calibration facility
  - Chebychev polynom

- Pro and cons
  - + Cryogen true value
  - - Implementation
  - - Feedthrough&Connector

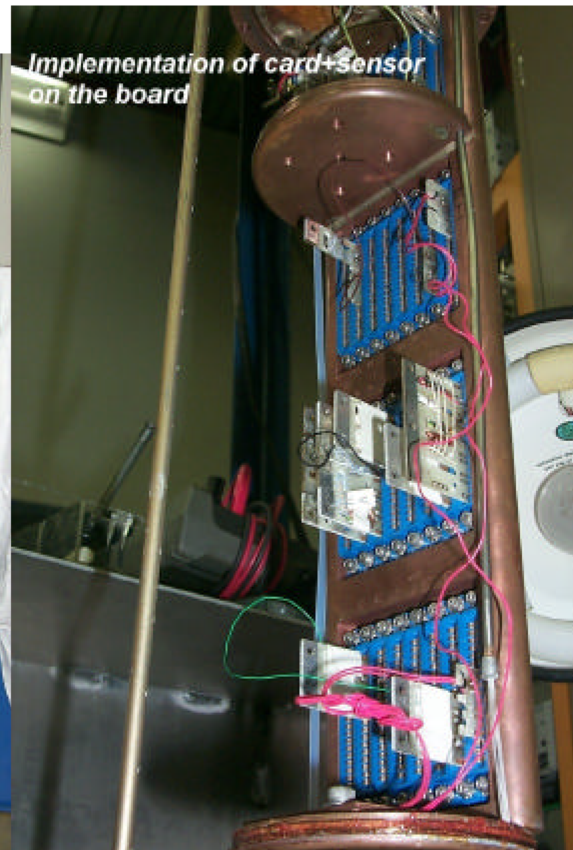
Some cryogenic thermometers used at Fermilab

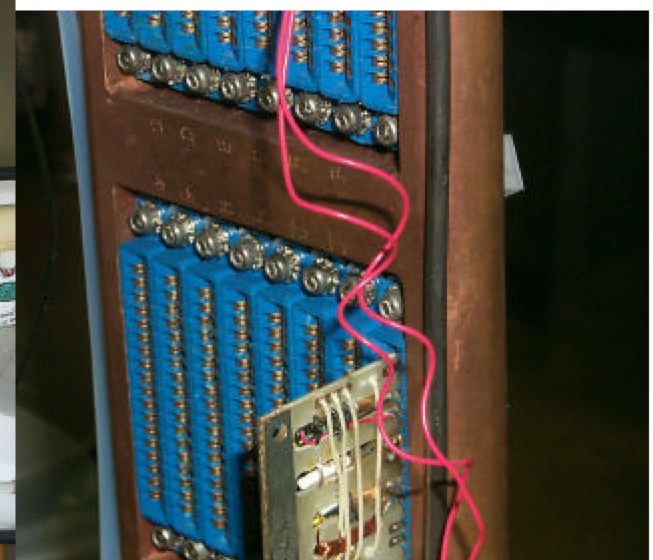


Fermilab
Discovering the Nature of Nature

Calibration of the thermometer

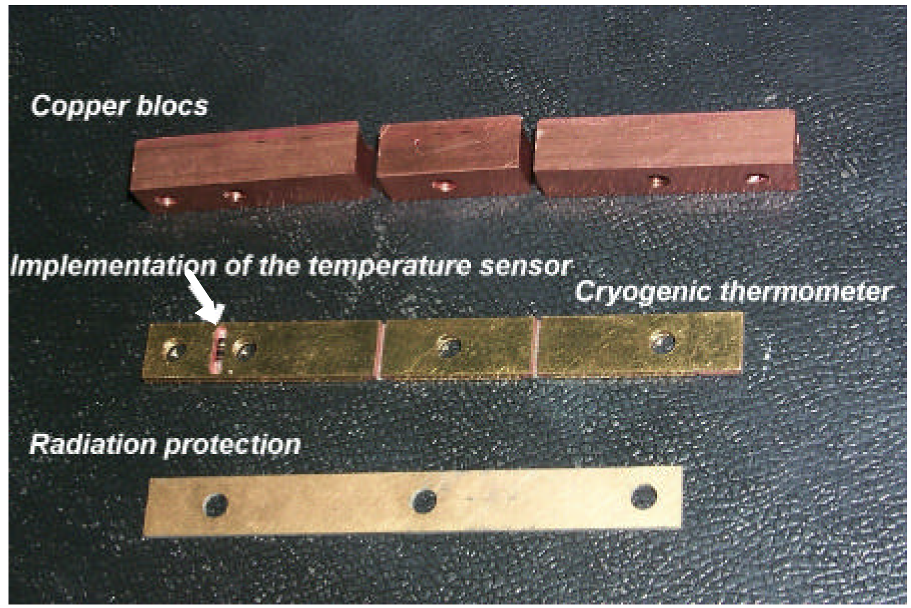
- Fermilab facility





Some cryogenic thermometers used at CERN - CTM

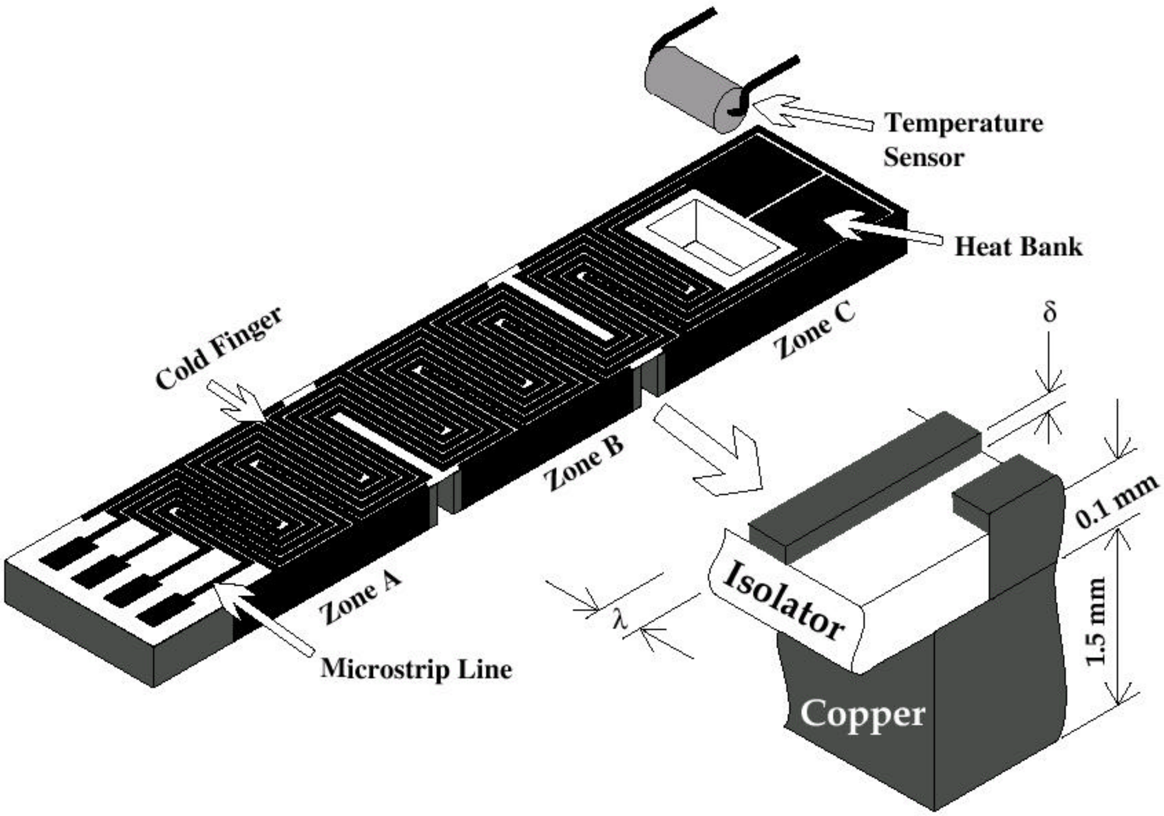
- Under vacuum: Industrial-type cryogenic thermometers with built-in heat intercept
  - Sensor implementation
  - Thermometric bloc
  - Accessories
    - Copper blocs
    - Radiation protection
    - Thermalization foil



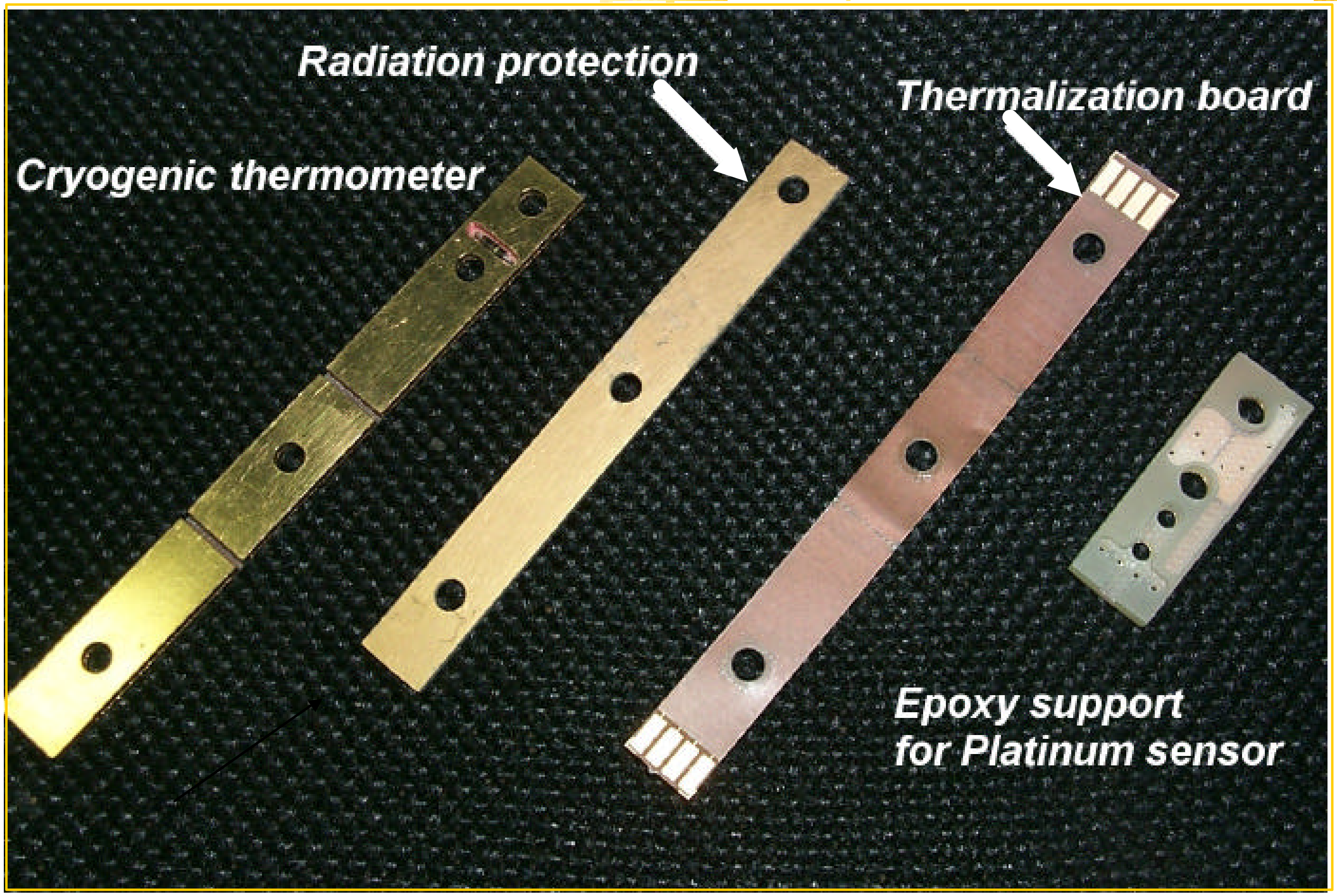
- Pro and cons
  - + Easy-to-use
  - - Thermal anchoring

Some cryogenic thermometers used at CERN

- Layout of the cryogenic thermometer



Some cryogenic thermometers used at CERN



// foil

Uncertainty evaluations

- **Measurement string**
  - Cryogenic thermometer
  - wire, conditioner
  - control system and acquisition
  - calibration fit
- **Environmental factor**
  - Thermo-cycling
  - Moisture
  - Magnetic field
  - Irradiation

Systematic error

- Calibration: fit
- Effect of the liquid level gauge

Statistical error

- Stability of the bath temperature
- Stability of (Tpres-Tsat)

Error± 5 mK at 1.8 K

Overheating

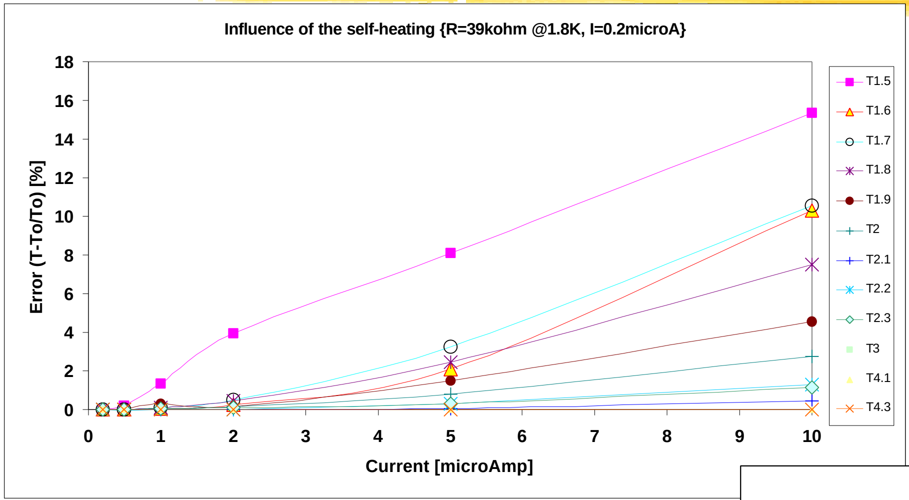
Check US-IT-HXTU thermal measurements:

- Thermometers calibrated with a 0.2 μA current but used with a 1 μA.
- Implementation on the PCB

- High resistance at low temperature (40 kΩ at 1.8 K)

- Large dispersion of resistance (40-12 kΩ at 1.8K)

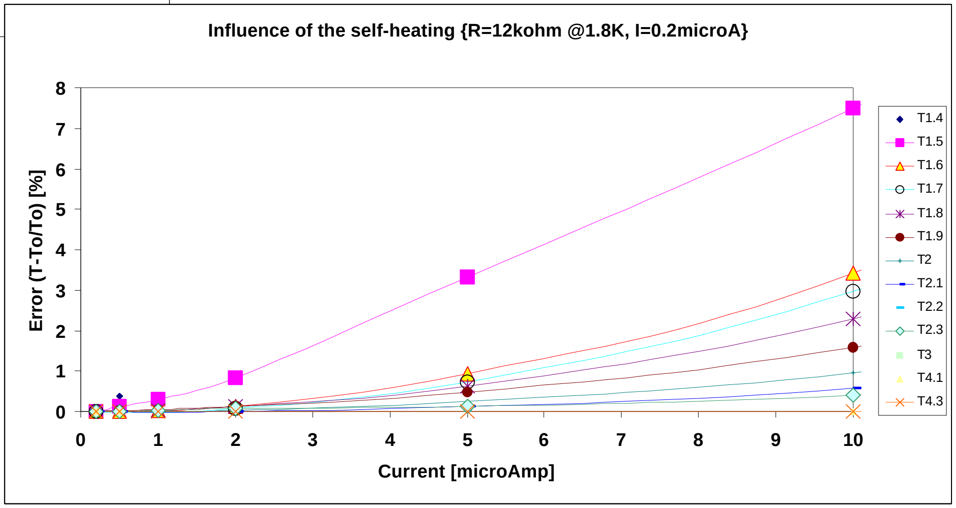
Overheating - Resistance influence



To = Temperature out of the calibration fit relative to a current of 0.2 µA used for the calibration data.

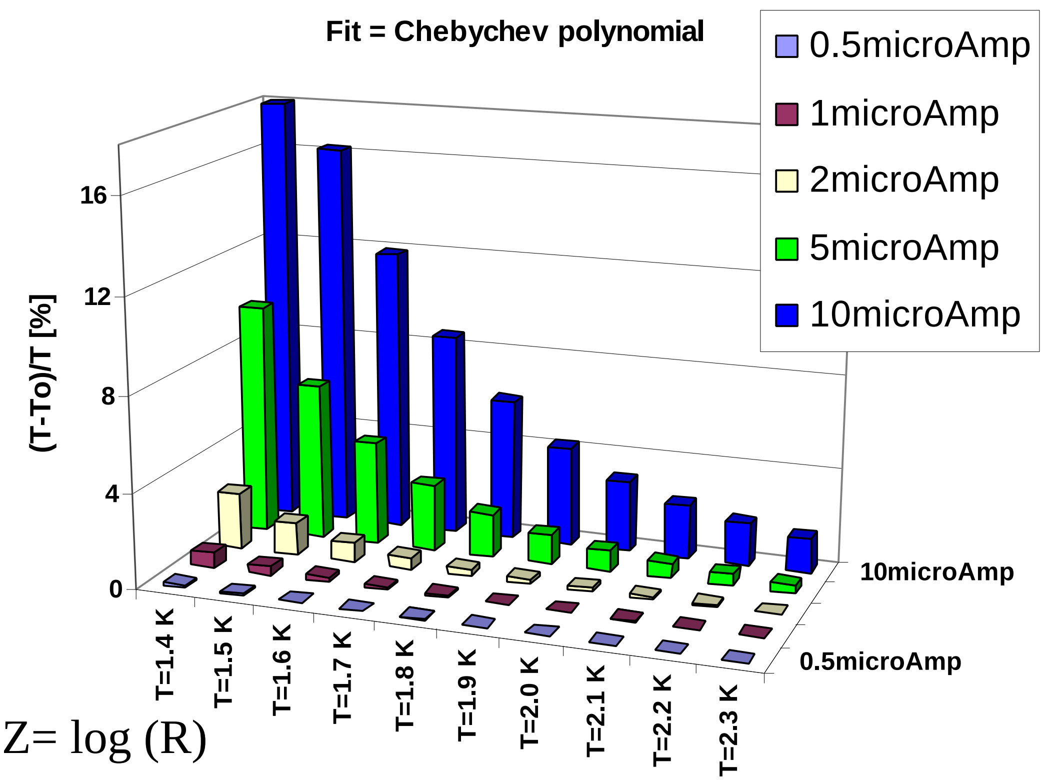
If : R=32 KΩ @ 1.8 K
I=1 µ A
then Error = 0.1%

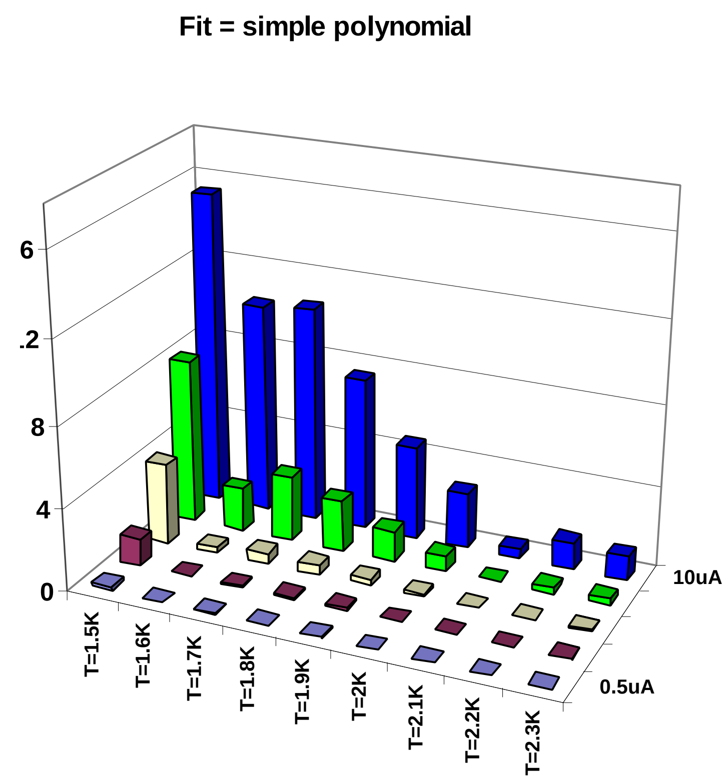
If : R=12 KΩ @ 1.8 K
I=1 µ A
then Error = 0.02%



Fermilab
Discovering the Nature of Nature

Overheating - fitting expression





$Z = \log(R)$

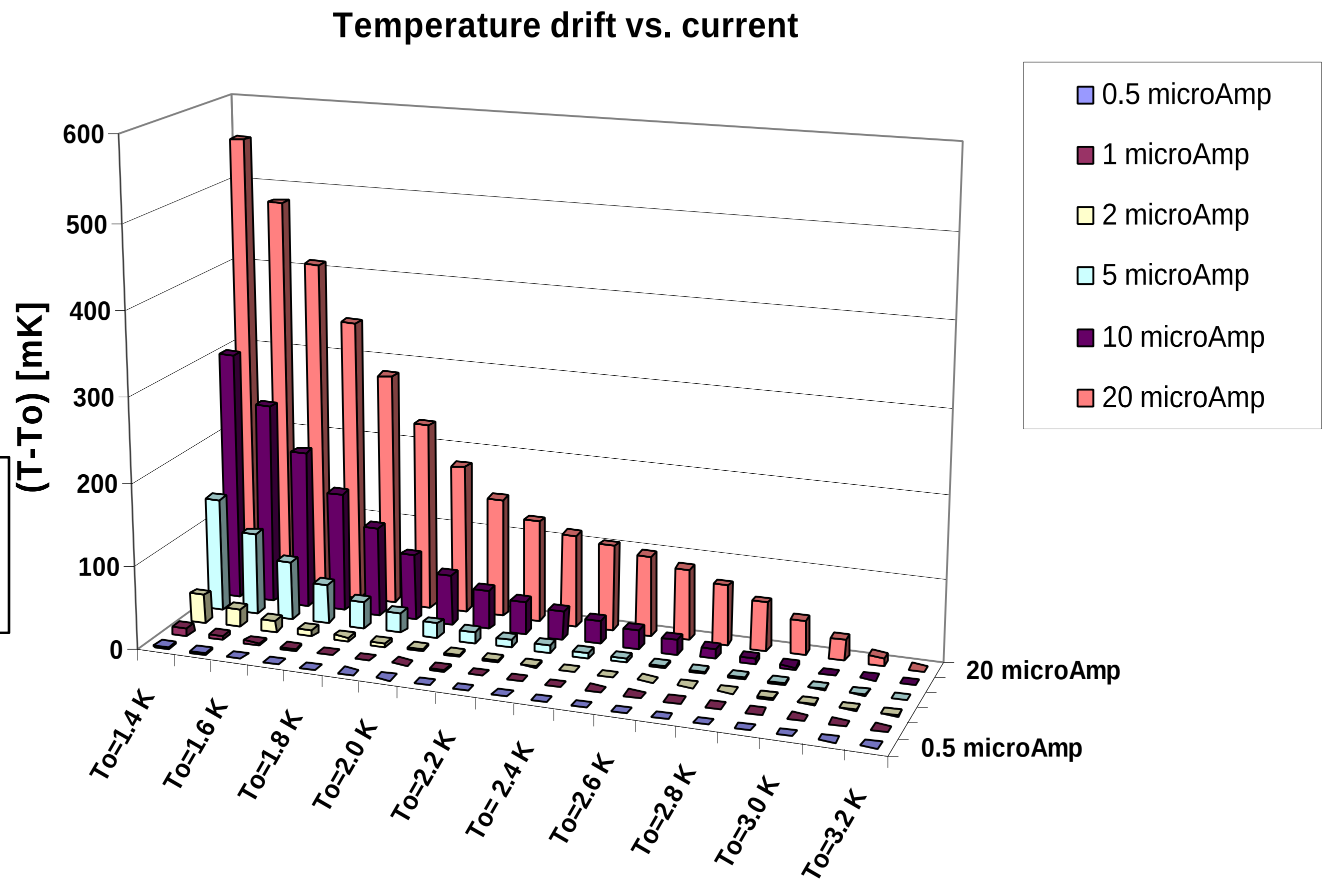
$X = ((Z-Zl)-(Zu-Z))/(Zu-Zl)$

$T = \Sigma\, Ai \cdot COS(i \cdot ARCCOS(X))$

$T = \Sigma\, Ai \cdot X^i$

CERN

Overheating - Current influence



Calibration fit:

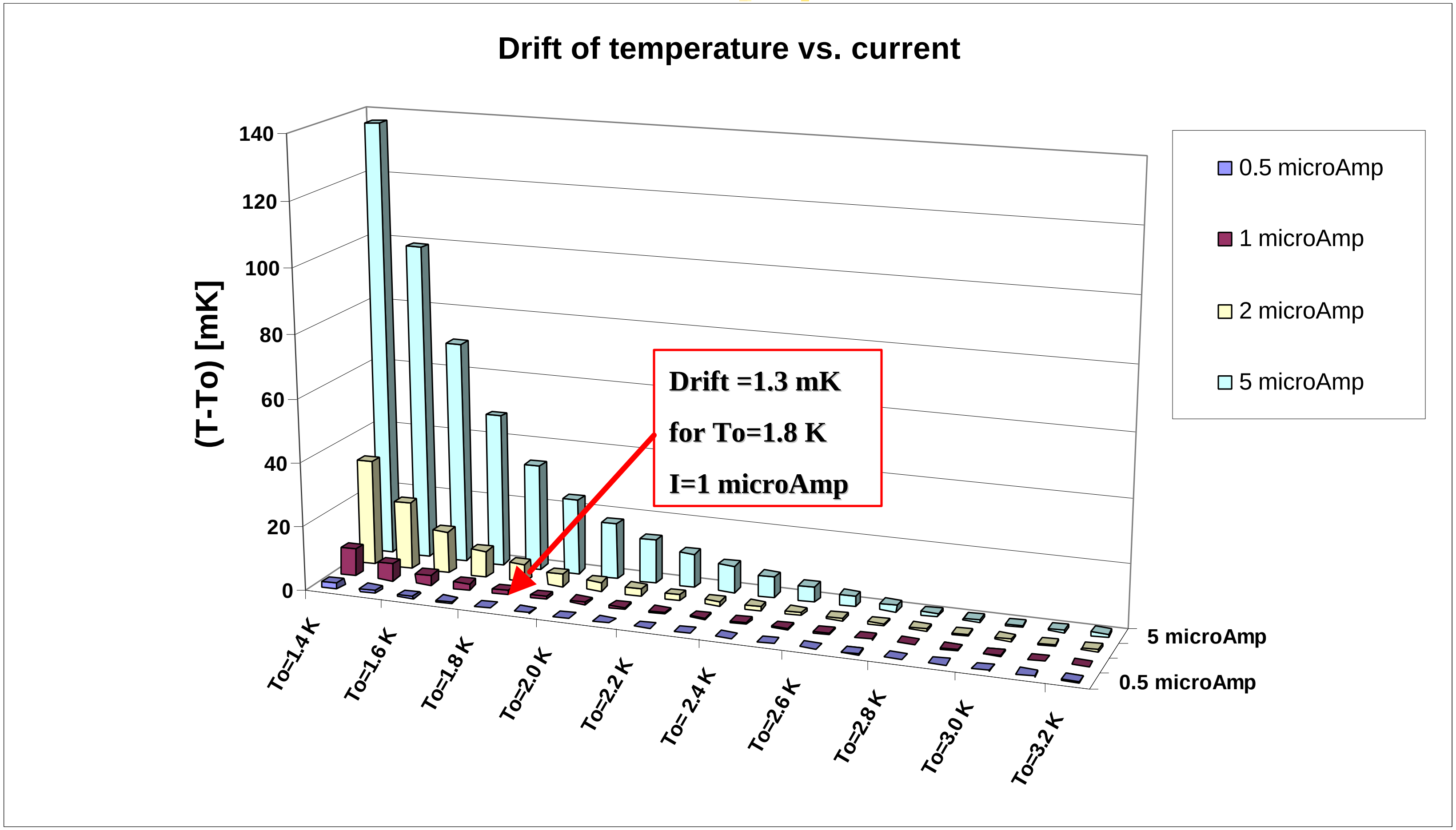
w/ R@ 0.2 microAmp

T=Cherb(R0.2)

To: R w/ 0.2 microAmp

T: R w/ 0.5- 20 microAmp

Overheating



Conclusion

- Measurement of thermal model performances
  - Temperatures rise in He II => US-IT-HXTU
  - Heat loads => CTM

- Improvement of techniques for measurements of temperature

- Better reliability