EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 333

SIGNAL CONDITIONING FOR CRYOGENIC THERMOMETRY IN THE LHC

J. Casas, P. Gomes, K.N. Henrichsen, U. Jordung and M.A. Rodriguez Ruiz

Abstract

Temperature measurement is a key issue in the Large Hadron Collider (LHC), as it will be used to regulate the cooling of the superconducting magnets. The compromise between available cooling power and the coil superconducting characteristics leads to a restricted temperature control band, around 1.9 K. An absolute accuracy of 10 mK below 2.2 K, and 5 K above 25 K, is necessary. For resistive thermometers covering the full temperature range, and having a negative dR/dT sensitivity, this is typically equivalent to a relative accuracy DR/R of 3 10-3 over 3 resistance decades. Also, to limit the thermometer's self-heating, the sensing current must be limited to few mA. Furthermore, the radiation levels next to the accelerator are expected to significantly degrade the performance of conventional analog electronics.

As these stringent requirements are not met by commercial conditioners, three different architectures have been developed at CERN. The first compresses the input dynamic range using a logarithmic transfer function; the second partitions the input range into three linear regions; the third converts resistance linearly into the frequency of a square wave. They fulfill the above specifications and provide industrial robustness in terms of thermal drift, galvanic protection, and compact packaging, while optimizing cost-to-performance ratio. This paper describes the principles of their design, compares their characteristics and shows results of field tests. Future developments include Application Specific Integrated Circuit versions, Fieldbus interfacing, and radiation tolerant re-design.

LHC Division

Presented at the 1999 Cryogenic Engineering and International Cryogenic Materials Conference
(CEC-ICMC'99), 12-16 July 1999, Montreal, Canada

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 1 December 1999

SIGNAL CONDITIONING FOR CRYOGENIC THERMOMETRY IN THE LHC

J. Casas, P. Gomes, K.N. Henrichsen, U. Jordung, M.A. Rodriguez Ruiz

CERN, European Organization for Nuclear Research
1211 Geneva 23, Switzerland

ABSTRACT

Temperature measurement is a key issue in the Large Hadron Collider (LHC), as it will be used to regulate the cooling of the superconducting magnets. The compromise between available cooling power and the coil superconducting characteristics leads to a restricted temperature control band, around 1.9 K. An absolute accuracy of 10 mK below 2.2 K, and 5 K above 25 K, is necessary. For resistive thermometers covering the full temperature range, and having a negative dR/dT sensitivity, this is typically equivalent to a relative accuracy $\Delta R/R$ of $3\ 10^{-3}$ over 3 resistance decades. Also, to limit the thermometer's self-heating, the sensing current must be limited to few μA. Furthermore, the radiation levels next to the accelerator are expected to significantly degrade the performance of conventional analog electronics.

As these stringent requirements are not met by commercial conditioners, three different architectures have been developed at CERN. The first compresses the input dynamic range using a logarithmic transfer function; the second partitions the input range into three linear regions; the third converts resistance linearly into the frequency of a square wave. They fulfill the above specifications and provide industrial robustness in terms of thermal drift, galvanic protection, and compact packaging, while optimizing cost-to-performance ratio. This paper describes the principles of their design, compares their characteristics and shows results of field tests. Future developments include Application Specific Integrated Circuit versions, Fieldbus interfacing, and radiation tolerant re-design.

INTRODUCTION

The various components of the LHC cryogenic system work at temperatures from ambient down to 1.6 K. Depending on the actual temperature value, different accuracies are required on its measurement. Between 300 K and 25 K, an uncertainty of 5 K can be tolerated to monitor the warmer components and the general cool-down. However, at the nominal operation of superconducting magnets (below 2.2 K) only 10 mK inaccuracy is allowed, to give enough room for the regulation band of the cryogenic controller, while avoiding magnet quench and minimizing the cooling effort of the cryogenic system.

Table 1 shows the allowed uncertainty on temperature measurement on the LHC machine, for the different temperature ranges. The accuracy budget is to be evenly shared between the sensor and the signal conditioning (Figure 1). The aimed resolution has to be ten times better than the overall accuracy ($dT < 1mK$, below 2.2 K).

Table 1. Required overall T accuracy and resolution

T span [K]	accuracy [mK]	resolution [mK]
1.6 ↔ 2.2	10	1
2.2 ↔ 4.0	20	2
4.0 ↔ 6.0	30	3
6.0 ↔ 25	1 000	100
25 ↔ 300	5 000	500

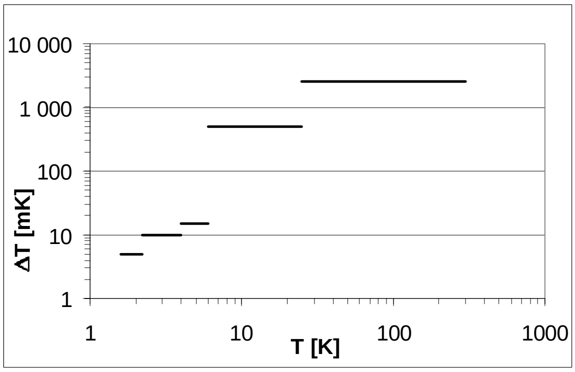

Figure 1. Required conditioning temperature accuracy

Sensors

Cryogenic temperature sensors currently used at CERN can be classified according to four main attributes, as shown in Table 2. CERNOX™ (CX), TVO® and RhFe cover the full temperature range with a single sensor. AllenBradley® (AB) and Pt100 can be combined to cover respectively low and high temperature scales, or used alone in applications not requiring full range measurements.

In terms of resistive values, CX's span is the largest among all sensors (3 decades), requiring wide dynamic range signal conditioning. Also covering the whole temperature range, RhFe spans over only 2 decades of resistance, with the advantage of less demanding dynamic range, but with the consequence of limited sensitivity.

Sensors with negative dR/dT (Figure 2), like CX, TVO® and AB, show high resistance and high sensitivity (dR/R / dT/T) (Figure 3) at low temperatures, where measurement accuracy has to be at its best. This semiconductor behavior relaxes the constraints on conditioner accuracy for low temperature measurement. On the other hand, at low temperature metallic sensors like RhFe exhibit a sensitivity one order of magnitude worse, demanding much more accurate signal conditioning.

Signal conditioning

The basic principle used to read resistive sensors consists in sending a known sensing current, over a pair of wires, and reading the voltage developed at the resistor leads, via another pair of wires. After amplification and correction, the read signal can be sent to the process controller under different formats, either analog or digital.

Table 2. Typical characteristics of cryogenic temperature sensors currently used at CERN

	T span [K]	R span [Ω]	dR/dT [Ω/K]	(dR/R) / (dT/T)
CX	1.6 ↔ 300	30 000 ↔ 30	-40 000 ↔ - 0.1	-2.7 ↔ - 1.0
TVO®	1.6 ↔ 300	9 000 ↔ 900	-7 000 ↔ - 0.7	-1.3 ↔ - 0.2
RhFe	1.6 ↔ 300	6 ↔ 110	+0.7 ↔ +0.4	+0.2 ↔ +1.0
AB	1.6 ↔ 100	10 000 ↔ 100	-12 000 ↔ - 0.3	-3.0 ↔ - 0.2
Pt100	73 ↔ 300	18 ↔ 110	+0.4 ↔ +0.4	+2.0 ↔ +1.0

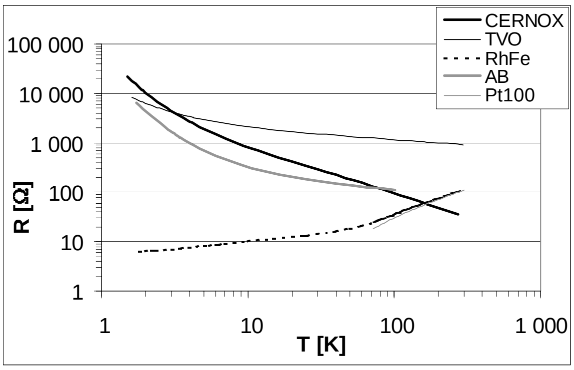

Figure 2. Typical thermometers transfer function R(T)

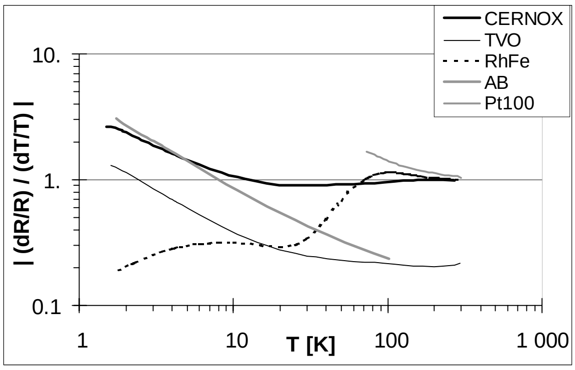

Figure 3. Dimensionless sensititvity vs temperature

Table 3. Conditioner's accuracy and resolution required by each type of sensor, below and above T = 6 K

	T < 6 K			T > 6 K		
sensor	**R span [Ω]**	**ΔR/R [10^{-3}]**	**dR [mΩ]**	**R span [Ω]**	**ΔR/R [10^{-3}]**	**dR [mΩ]**
CX	1 500 ↔ 30 000	3.3	900	30 ↔ 1 500	8.9	60
TVO®	2 600 ↔ 9 000	1.3	700	900 ↔ 2 600	1.8	300
RhFe	6 ↔ 8.5	0.5	0.6	8.5 ↔ 110	6.0	15
AB	500 ↔ 10 000	3.1	300	100 ↔ 500	5.8	100
Pt100				18 ↔ 110	9.8	200

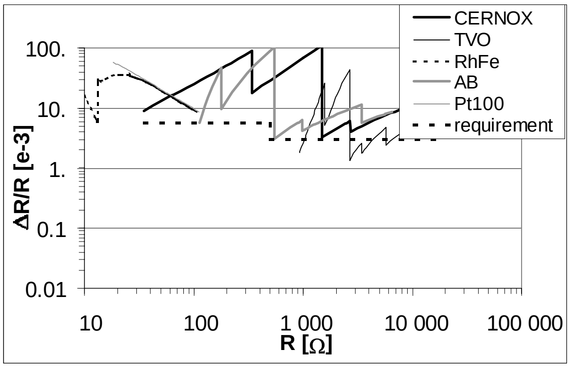

Figure 4. Required accuracy

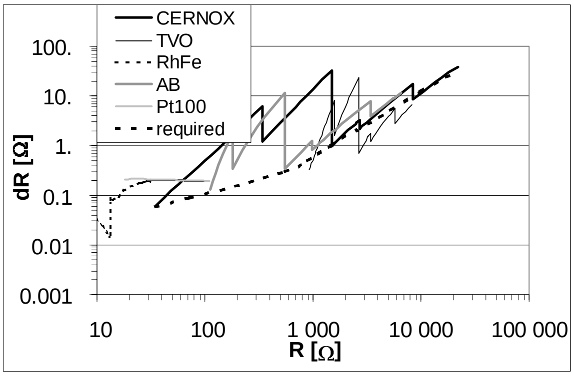

Figure 5. Required resolution

For each type of thermometer, the signal conditioning accuracy and resolution requirements are summarized in Table 3 and plotted in Figure 4 and Figure 5. The RhFe sensor imposes quite severe constraints on the conditioning electronics, with $\Delta R/R < 0.5\ 10^{-3}$ for $R < 8.5\Omega$, thus requiring techniques beyond the scope of the conditioners described in this paper.

A conditioner satisfying $\Delta R/R < 3\ 10^{-3}$ for $R > 500\Omega$ and $\Delta R/R < 6\ 10^{-3}$ for $R < 500\Omega$ is adequate for CX, AB and Pt100 thermometers. A TVO® sensor would impose a three times better accuracy on the resistance measurement.

As the sensor's resistance will be calculated linearly from the read voltage (Eq. 1), the relative accuracy is the addition of the voltage and the sensing current uncertainties.

$$R_{sensor} = U_{read} / I_{sense} \qquad \Delta R/R = \Delta U/U + \Delta I/I \qquad (1)$$

The read signal has to be digitized in order to be usable by computerized control or diagnostics. Industrial control equipment typically employs 12-bit Analog to Digital Converters (ADC) and the targeted temperature accuracy cannot be satisfied unless some type of signal compression is implemented. This paper presents two compression architectures that are mixed logarithmic+linear (LOG+LIN) and linear piecewise (LIN pw).

The resistance measurement accuracy must be split between the accuracy of the analog circuitry and that of the ADC, which can be expressed in terms of the ADC Least Significant Bit (LSB). Figure 6 and Figure 7 show respectively the accuracy and resolution imposed by the resistance measurement, and also the accuracy and resolution attained by the combination of different compression algorithms and a minimum size ADC.

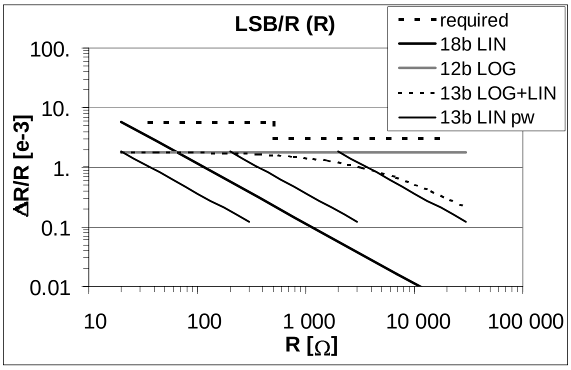

Figure 6. Required ADC accuracy

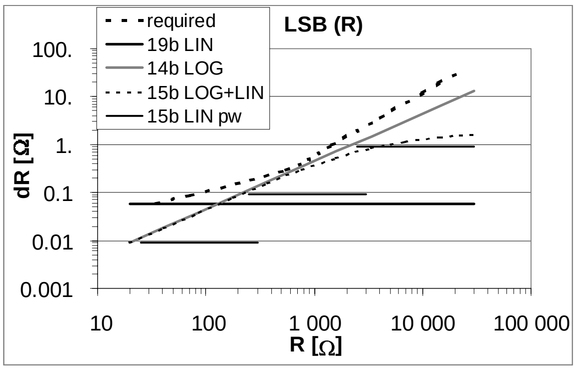

Figure 7. Required ADC resolution

Table 4. ADC accuracy and resolution required for each type of conditioner transfer function

	for CX, AB, Pt100 and TVO®		for CX, AB, and Pt100 only	
conditioner	**accuracy [bit]**	**resolution [bit]**	**accuracy [bit]**	**resolution [bit]**
LIN	18	19	18	19
LOG	13	15	12	14
LOG+LIN	14	16	13	15
LIN pw	14	16	13	15

Table 4 summarizes these requirements. Due to its lower sensitivity, the TVO® typically needs 1 more bit than other sensors. For all sensors, the resolution normally requires 2 more bits than the accuracy.

It is clear that a 12-bit resolution ADC is not sufficiently accurate (above 4.5 K) for all the mentioned conditioning architectures. We are thus considering the use of larger ADC, with a suitable network interface.

LOGARITHMIC CONDITIONER

The first conditioner (Figure 8) incorporates a logarithmic compression of the input dynamic range. A DC sensing current of 10 μA develops a voltage (0.2 mV ↔ 200 mV) across the thermometer, which is raised by an instrumentation amplifier. The offset and gain, before and after the logarithmic amplifier, have to be manually adjusted. Power supply, input and output are galvanically isolated to 750 V.

The overall performance against ambient temperature variation is limited by the Logarithmic IC. This explains the improvement in temperature drift at higher resistances, for LOG+LIN in comparison with LOG (Figure 9 and Figure 10). The relationship between input and output is given by the following equations for LOG and LOG+LIN respectively:

$$I_{loop} = 4 + 16/3 \cdot \mathrm{Log}_{10}(R/20) \quad \text{[mA]} \qquad (2)$$

$$I_{loop} = 4 + 8/3 \cdot \mathrm{Log}_{10}(R/20) + 8/(20k-20) \cdot (R-20) \quad \text{[mA]} \qquad (3)$$

The rejection of power supply drift is good for R > 500 Ω ($|\Delta R/R \ / \Delta V| < 0.7\ 10^{-3}$ /V, Figure 11), but quite poor for small R.

Several tens of these conditioners have been installed in cryogenic experiments at CERN, yielding good results (Figure 12), provided the ambient temperature does not change more than a few degrees.

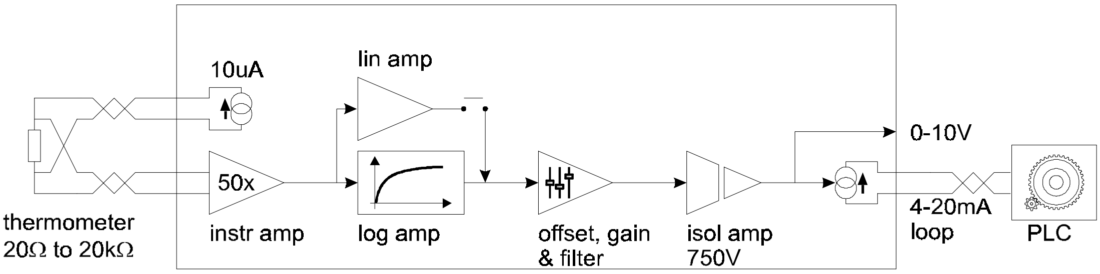

Figure 8. Logarithmic conditioner block diagram

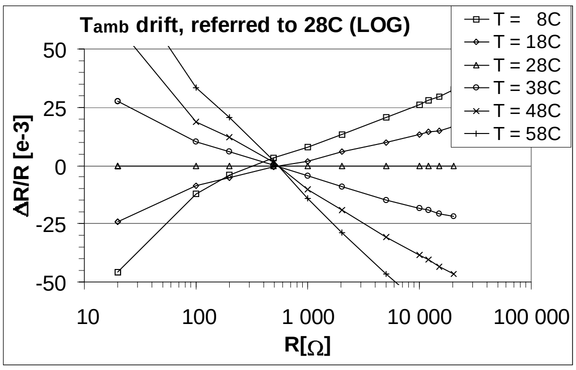

Figure 9. Thermal drift (LOG function alone)

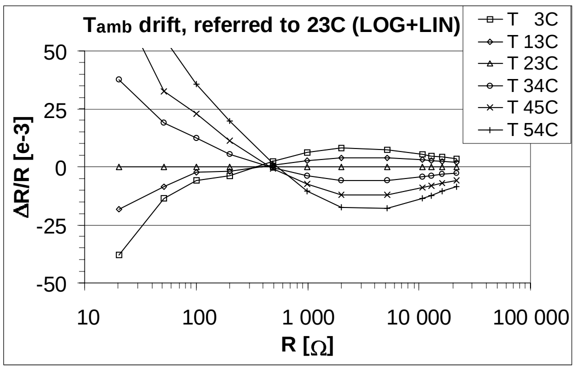

Figure 10. Thermal drift (combined LOG+LIN)

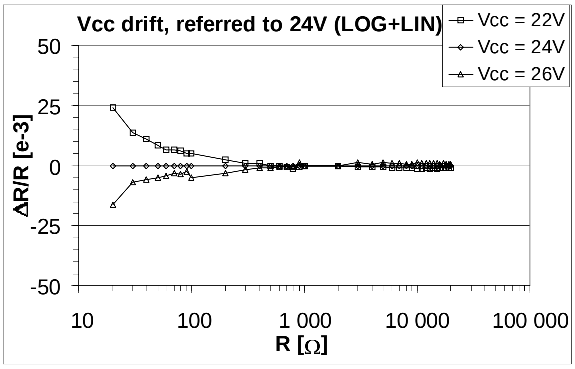

Figure 11. Power supply drift

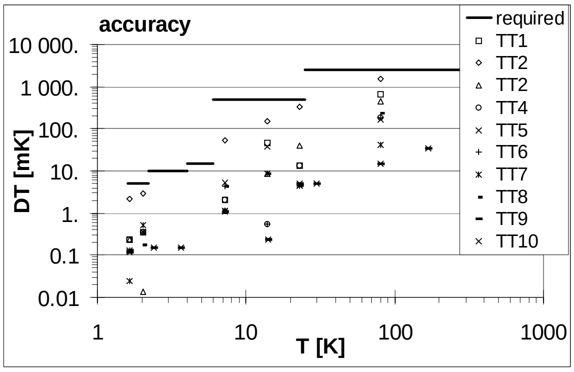

Figure 12. Field measurements

LINEAR MULTI-RANGE CONDITIONER

In order to reduce the ADC size, a linear multi-range conditioner has been developed. The input span is partitioned into three regions (Table 5), one decade wide each, with the gain proportional to the sensing current. The thermal drift due to the logarithmic IC is thus avoided, at the expense of more complex circuitry for controlling the gain (Figure 13).

Furthermore, the sensing current can be lower for high R values (low T), reducing the self-heating of the sensor, and higher for small R values, increasing the voltage developed at the sensor and its signal to noise ratio. The thermocouple voltages are cancelled by the use of a bipolar sensing current, oscillating at 4 Hz.

The sensing current creates a voltage (±3.5 mV ↔ ±40 mV) across the thermometer, which is increased, by an instrumentation amplifier, (to ±0.875 V ↔ ±10 V), and then rectified and smoothed. When this voltage raises above 10 V, the gain controller selects a sensing current 10 times lower, leading to the same reduction in voltage. If the voltage drops below 0.875 V, a 10 times higher current is selected. The gap between 0.875 V and 1 V corresponds to a hysteresis in the transfer function (Figure 14), that prevents oscillation between consecutive ranges when close to the switching point.

The selected range is indicated by two bit or a three level analog signal. Manual adjustments are necessary to correct general gain and offset and differential offset of the rectifier. Power supply, input and output are galvanically isolated to 750 V.

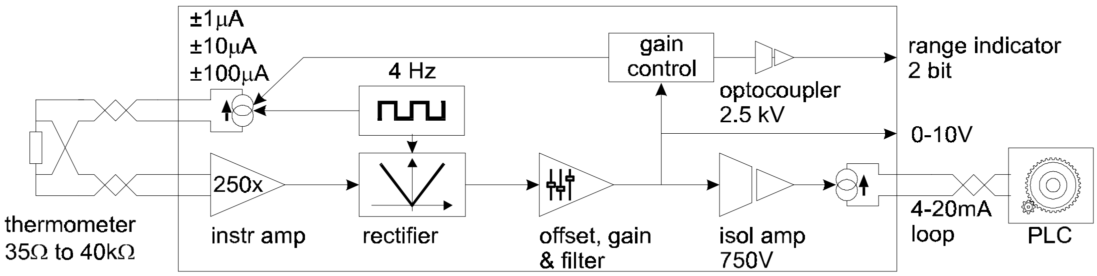

Figure 13. Linear multi-range conditioner block diagram

Table 5. Sensing current and conditioner transfer function, for each input range

R span [Ω]	I_{sense} [μA]	I_{loop} [mA]
35 ↔ 400	100	4 + 16 · R / 400
350 ↔ 4 000	10	4 + 16 · R / 4 000
3 500 ↔ 40 000	1	4 + 16 · R / 40 000

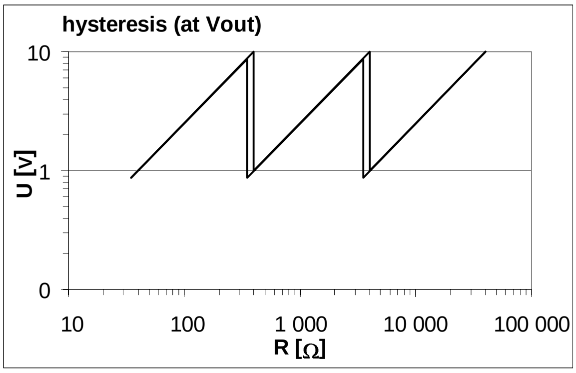

Figure 14. Hysteresis in the transfer function

The sensitivity to thermal drift ($|\Delta R/R\ /\Delta T_{amb}| < 0.11\ 10^{-3}$ /°C, Figure 15) is very low compared to LOG conditioner. The thermal performance is further improved (Figure 16) at the voltage output, without galvanic isolation.

The insensitivity to power supply drift is good for the whole input span, both at the current output ($|\Delta R/R\ /\Delta V| < 1.0\ 10^{-3}$ /V, Figure 17) and the voltage output ($|\Delta R/R\ /\Delta V| < 0.4\ 10^{-3}$ /V, Figure 18).

Figure 19 shows the excellent reproducibility of the conditioners' characteristics between three samples.

Several tens of these conditioners have been installed in cryogenic experiments at CERN, behaving in accordance with the requirements (Figure 20).

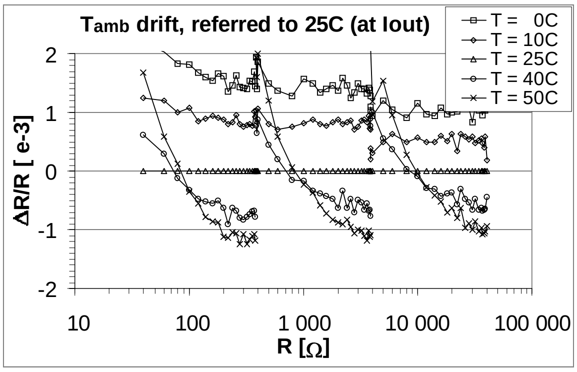

Figure 15. Thermal drift at the current output

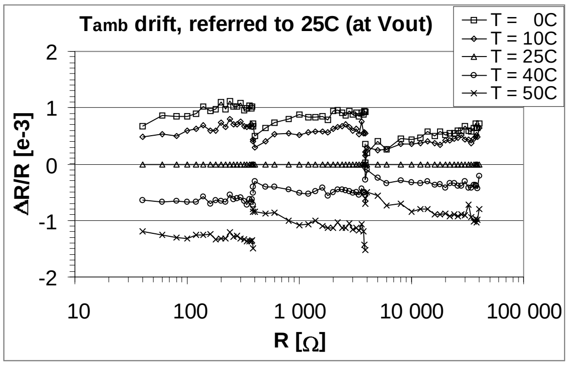

Figure 16. Thermal drift at the voltage output

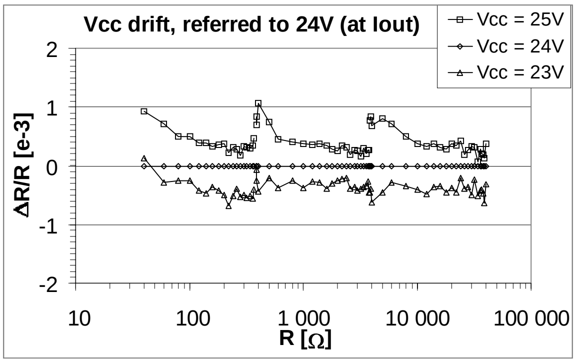

Figure 17. Power supply drift at current output

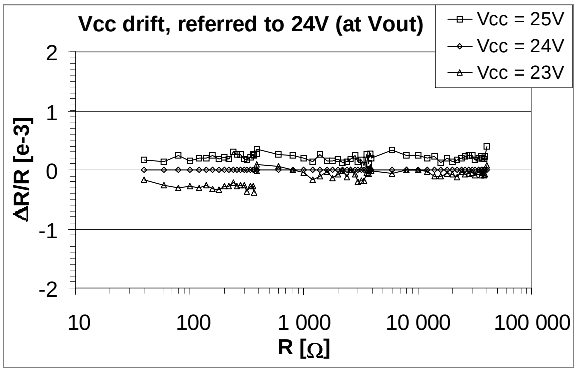

Figure 18. Power supply drift at voltage output

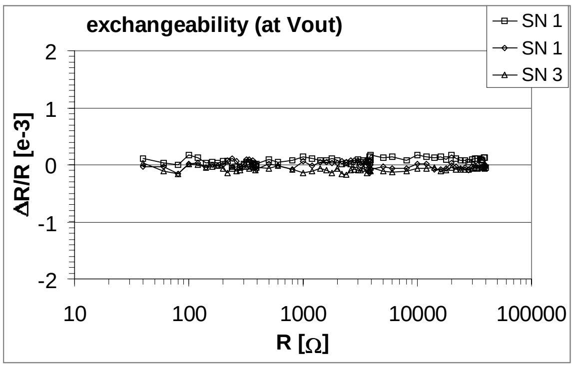

Figure 19. Exchangeability

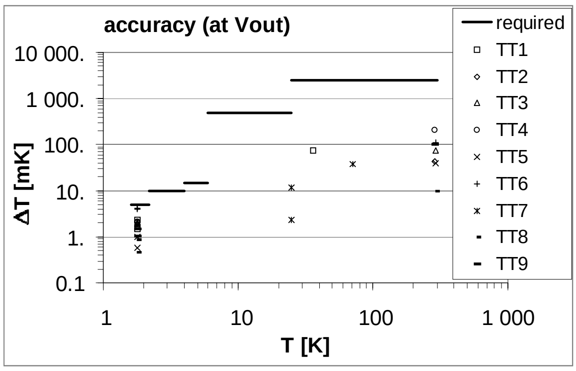

Figure 20. Field measurements

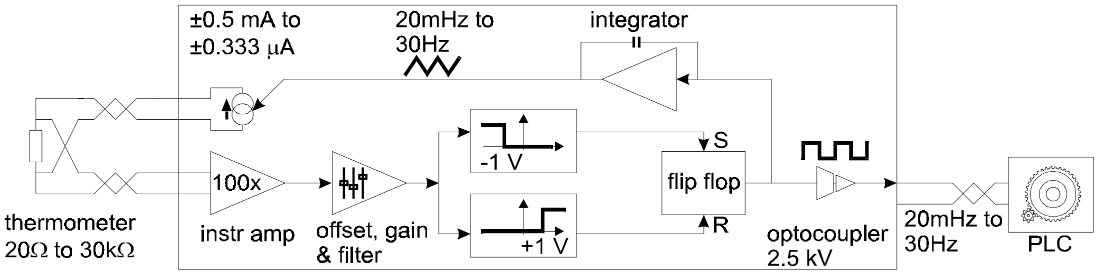

Figure 21. T2F conditioner block diagram

T2F CONDITIONER

This conditioner converts the voltage across the sensor resistance linearly into a frequency (Figure 21). The requirements on accuracy and resolution are no longer put on voltage amplitude measurement but rather on frequency measurement. The output frequency spans over three decades of dynamic range, like the measured resistance. The logarithmic compression nuisances or the complexity of a multi-range controller are traded by a simpler concept.

The sensing current follows a ramp of fixed slope (±10 μA/s). Once reached the upper (10 mV) or lower (-10 mV) threshold referred to the input, the ramp sign is inverted. This fixed voltage amplitude restricts the thermometer self-heating to a relatively low value.

Despite the fact that the working frequencies are below 50 Hz, the current control loop easily picks-up the mains noise. This effect is tackled by the use of a 50 Hz notch filter. In order to avoid spurious trigger of the flip-flop, a glitch detector is implemented, which introduces an extra delay on the oscillation period (Eq. 4).

$$f = 1 / (10^{-3} + 10^{3}/R) \qquad [\mathrm{Hz}] \qquad (4)$$

Manual adjustments are necessary for notch filter width and center frequency, for the glitch filter delay and for the current slope.

Figure 22 shows the deviation ($|\Delta R/R| < 2\ 10^{-3}$) between two conditioners, using the same transfer function. The accuracy obtained in field measurements (Figure 23) is well within the requirements. Further tests are under way to investigate temperature and power supply drifts.

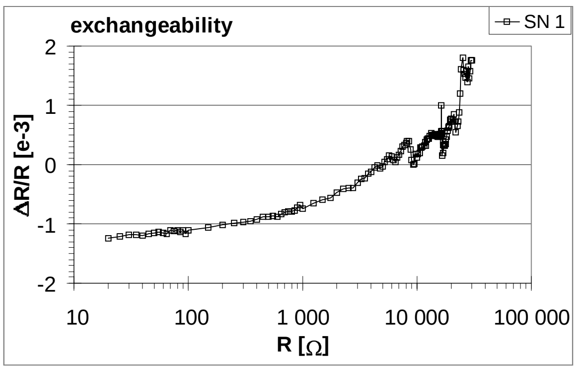

Figure 22. Exchangeability relative to SN2

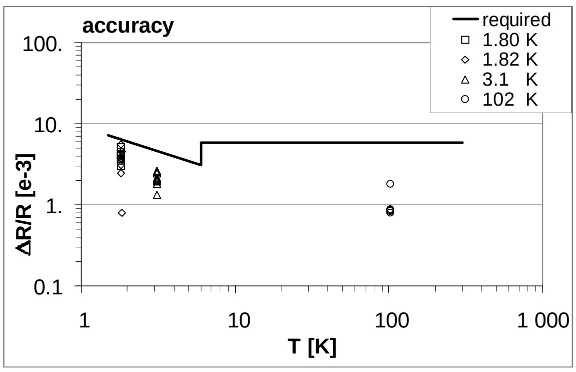

Figure 23. Field measurements

CONCLUSIONS

The cryogenic thermometer signal conditioners presented in this paper are used in a variety of applications. When fast response is required the LOG or LOG+LIN conditioner can be used. For higher accuracy at low temperature it would be necessary to reduce the sensing current. However, in this case the thermal drift of the input amplifier will be the dominant source of error for low values of the thermometric resistance.

The LINpw and T2F conditioners satisfy the LHC accuracy requirements. However their installation inside the LHC tunnel impose their redesign by using radiation tolerant integrated components, both passive and active. This problem is being solved by performing irradiation tests on commercial devices, and by porting the conditioners' design into a radiation hardened Application Specific Integrated Circuit (ASIC).

Once the design of a suitable signal conditioner for thermometers has been finalized, it will be necessary to adapt its characteristics in order to being able to use it as front end of other instruments like pressure sensors, liquid helium level gauges, etc.

The cryogenic control system requires temperature measurements distributed around the 27 km circumference LHC machine. The data exchange can be done with either point-to-point analog signal transmission or by using an industrial field network. Analog transmission implies a large investment in cabling and installation. In order to reduce this cost we are also investigating the performance of network components and ADCs, to integrate them together with the signal conditioners.