



The Radiation Tolerant Electronics for the LHC Cryogenic Controls: Basic Design and First Operational Experience

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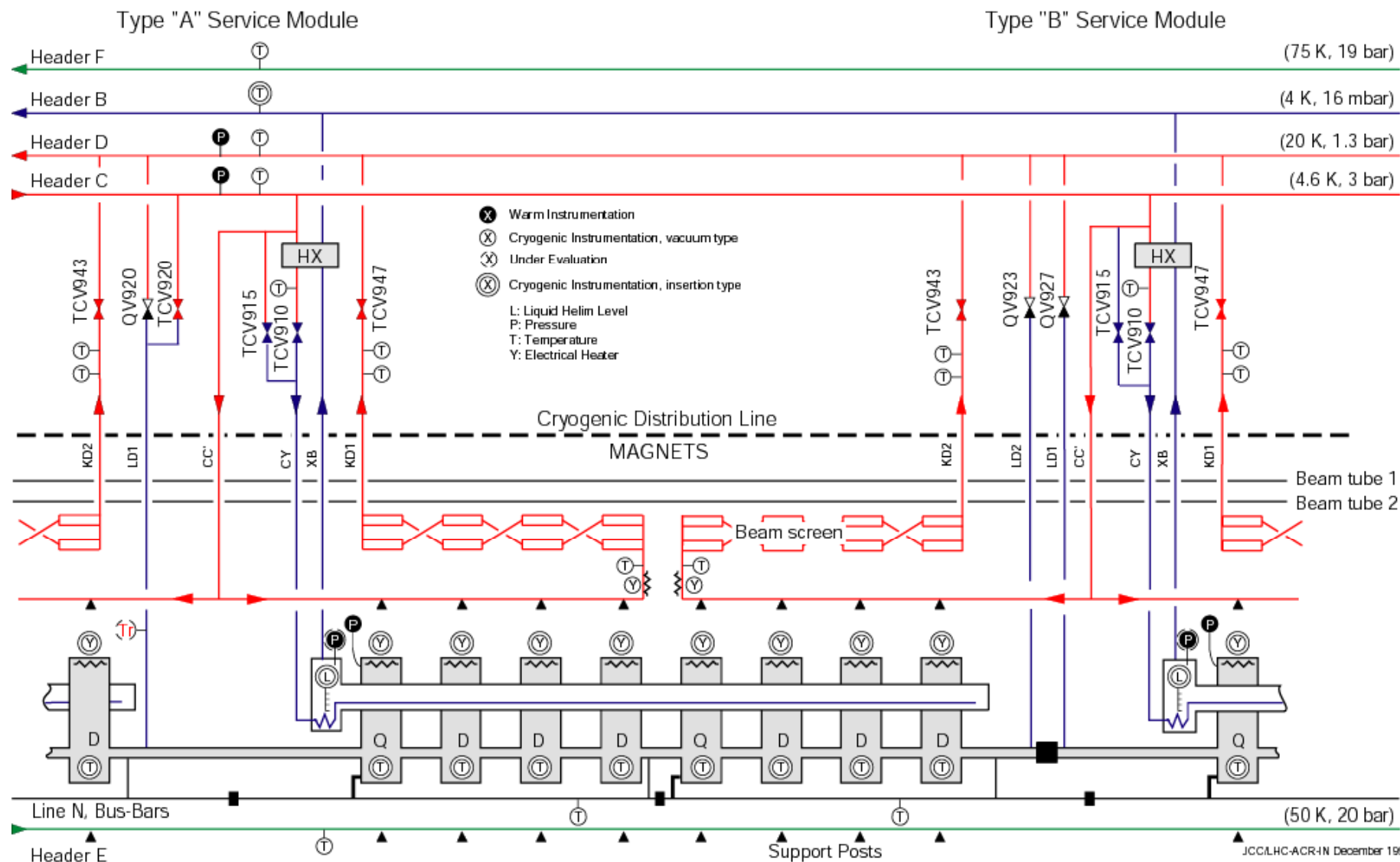


Summary

- » The LHC instrumentation and control for the tunnel cryogenics is distributed over the 27 km long tunnel and about 30 protected areas; requiring extensive use of scattered radiation tolerant remote IO
- » The radiation qualification of the main components is described.
- » The sheer size of the LHC cryogenics is simply enormous requiring the handling of large series procurement of electronic cards and the associated components.
- » Requires a robust Quality Assurance policy.
- » Tunnel electronics is of Radiation Tolerant grade as it is aimed to survive about 1 kGy and 10^{13} neutron/cm².

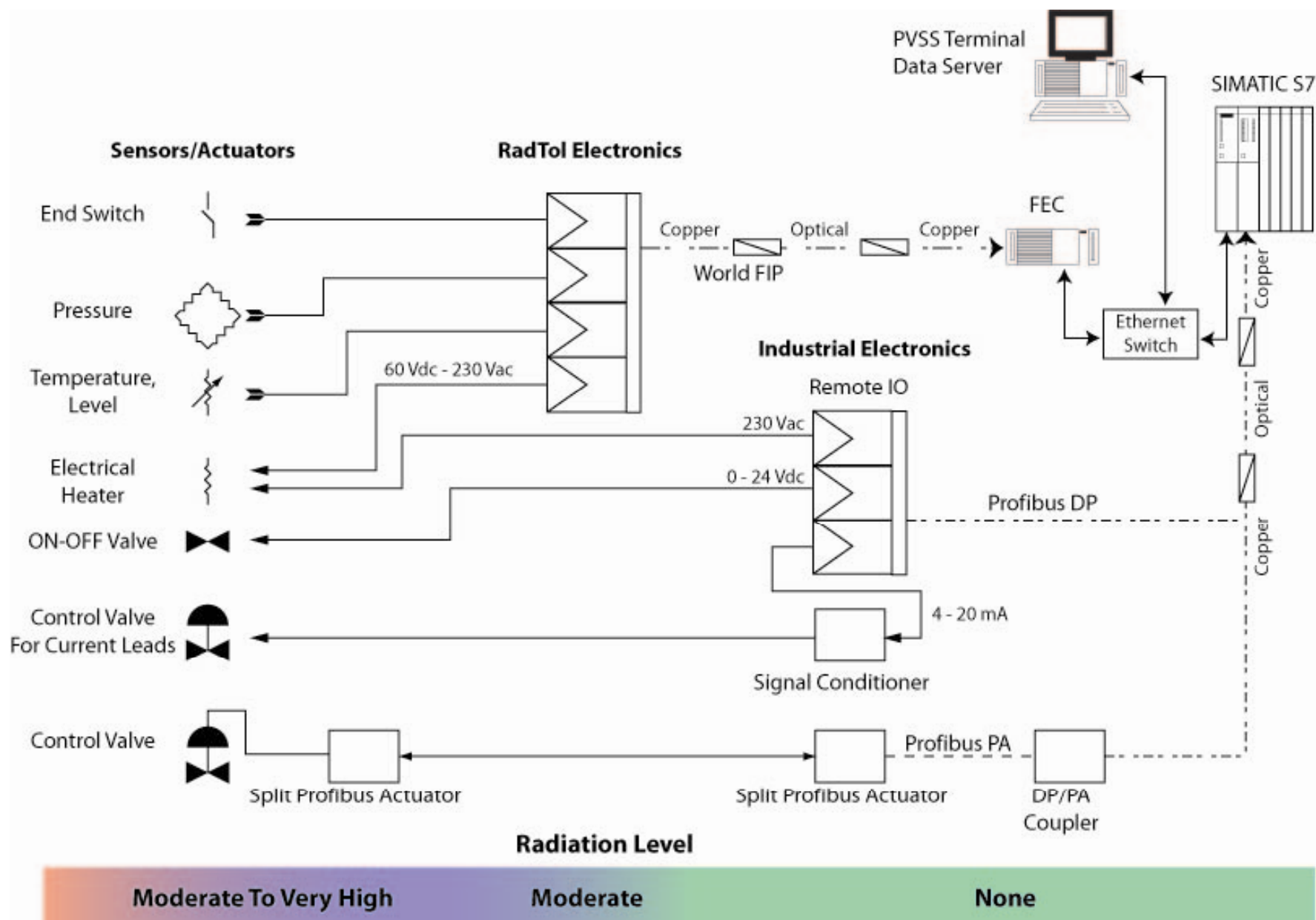


LHC Standard Cell





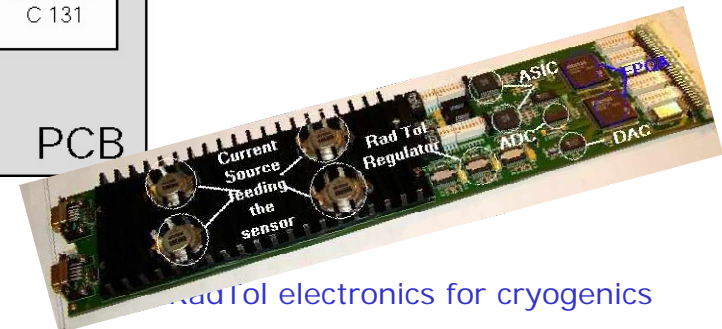
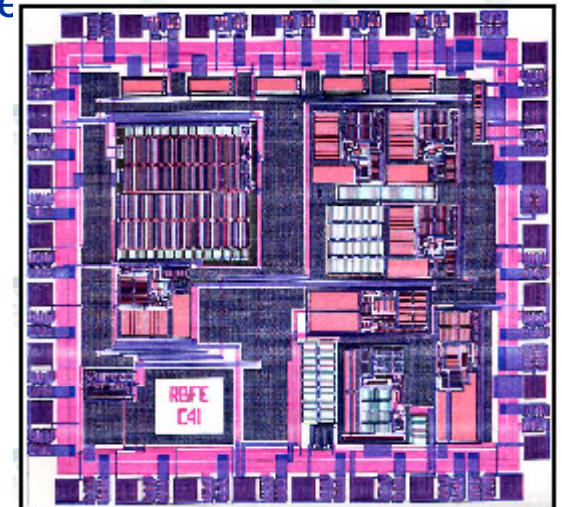
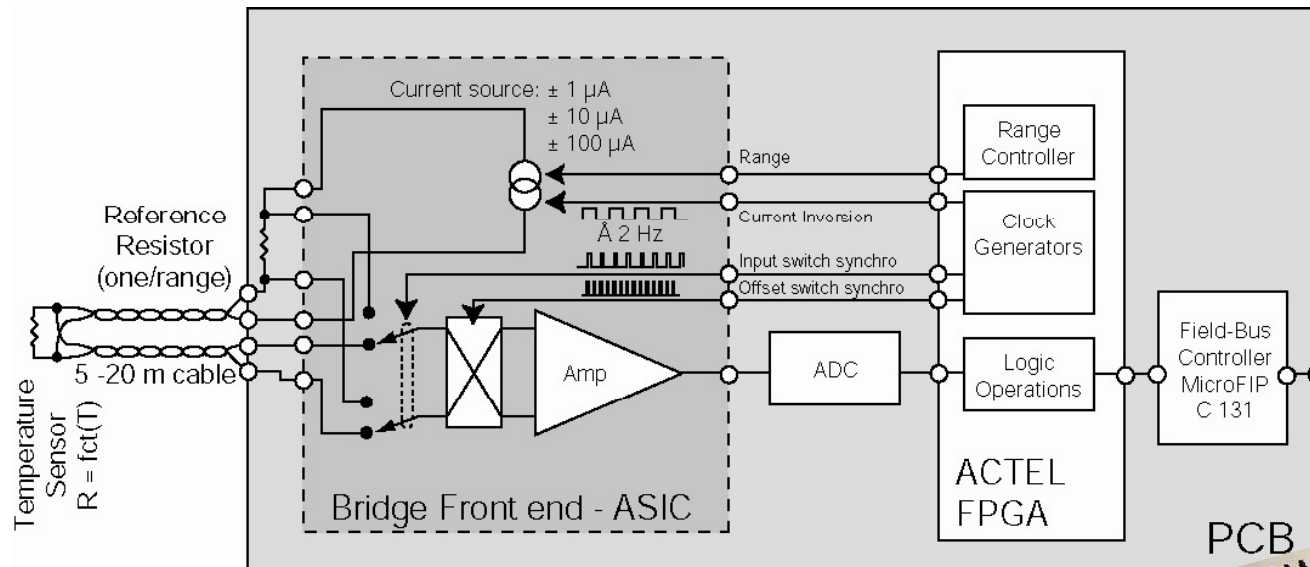
Environmental Constraints





Design: Basics

- A comparison bridge providing excellent performance against TID and temperature effects
- A quarter micron ASIC using IBM technology
- COTS for OP-Amps, ADCs, DACs and passive components
- Anti-fuse FPGAs with triplicated logic
- Micro FIP C131 WorldFIP bus controller
- The sensors used are mostly the equivalent of variable resistors and the front end is optimized for this task.

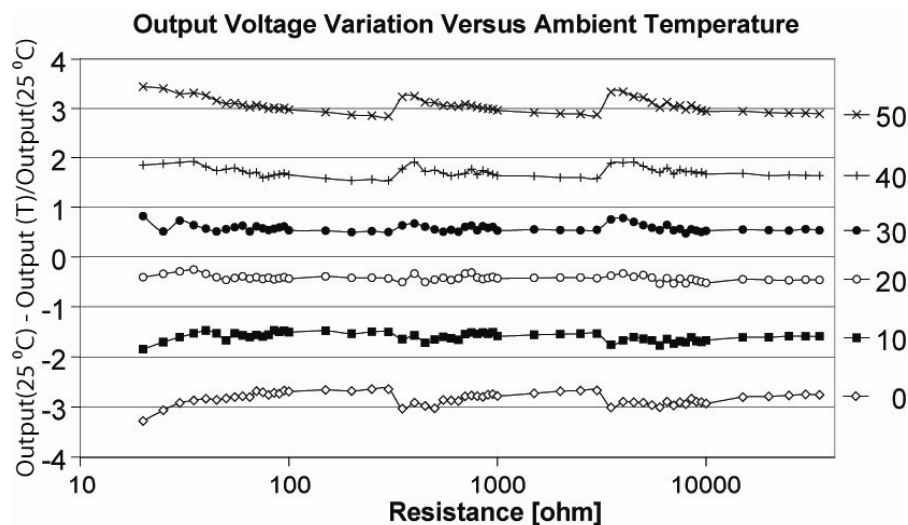
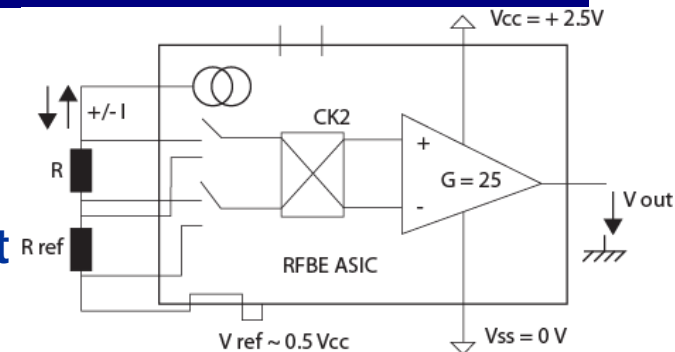




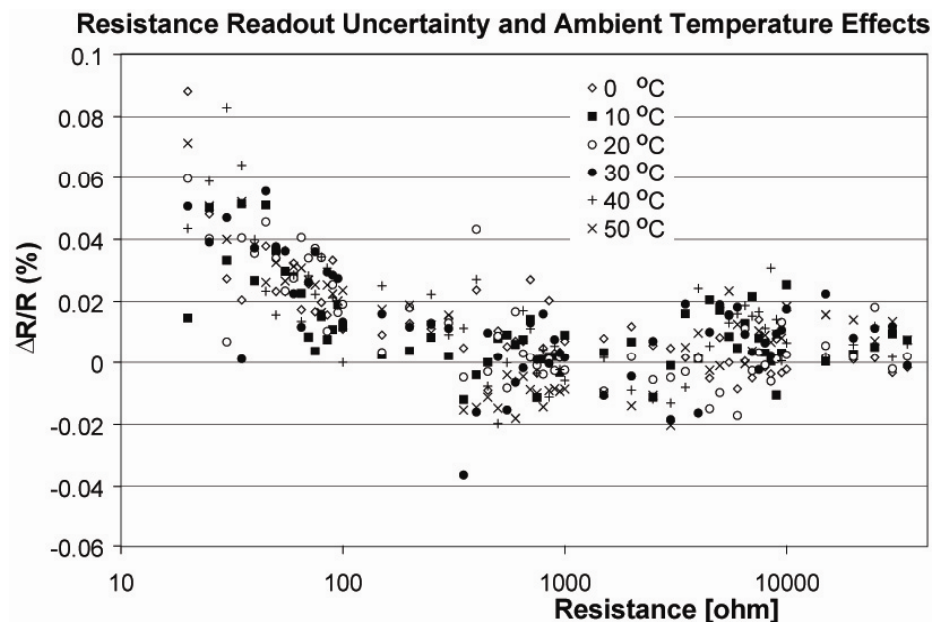
Design: Compensation for Variations

TEMPERATURE & RADIATION COMPENSATION => NO ADJUSTMENTS

- Comparison bridge for resistance measurement
- Temperature range 0 to 50 °C
 - » Amplifier exhibits voltage offsets of up to 6%
 - » NO adjustments and thermal effects within typ 0.04% for R thanks to
 - Inversion of excitation current and amplifier inputs
 - custom low TCR (10 ppm/K) and high accuracy (0.01%) resistor
- Uncertainty depend mainly in non-linearities of ADC or amplifier stage



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Design: Integrated Circuits

ANALOG: Analog components are used for buffer amplifiers, voltage regulators, analog power amplifiers and linear power supplies.

Main components are radhard L4913 CERN voltage regulator, Poweramp OPA541 capable of driving 2A over 60V, etc

DIGITAL

ADC:

Temperature readout temperature require "linear" 14-15 bit ADC
=> Burr-Brown ADS7807UB 16-bit successive approximations using an external voltage reference

DAC: Electrical heaters and excitation current selection for superconducting level gauges impose 0.5% accuracy (8-bit)
=> Analog Devices AD565 12-bit

Microprocessor operations emulated by FPGAs coded in triplicate logic
=> Antifuse ACTEL A54SX72A & A54SX16A

WorldFIP industrial fieldbus selected after TCC2 irradiation tests
=> MicroFIP CC131 "mezzanine card" with fieldbus controller and driver



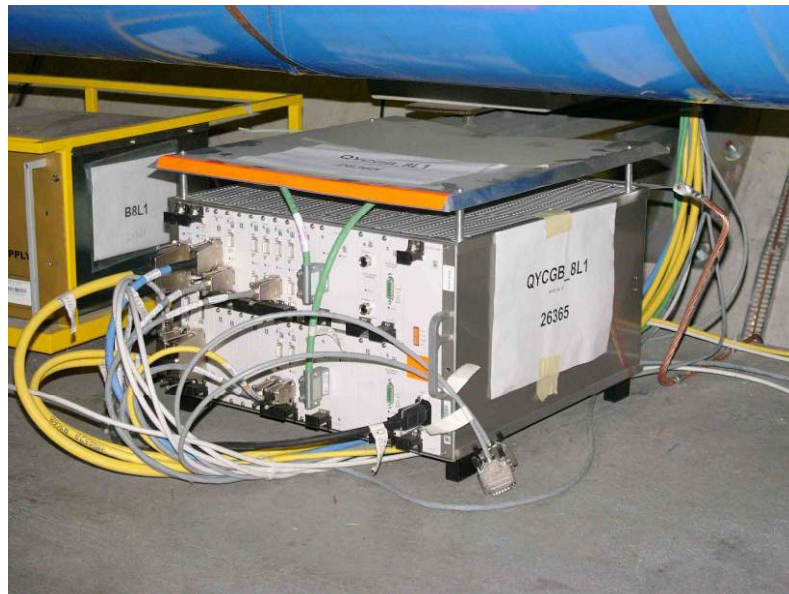
Design: Mechanics

The electronic cards are plugged onto a crate with a backplane that permit the exchange of analog and digital signals.

The LHC cold-masses (iron yoke) are used as radiation shield and the cryo crates are installed under the dipoles at a central location.

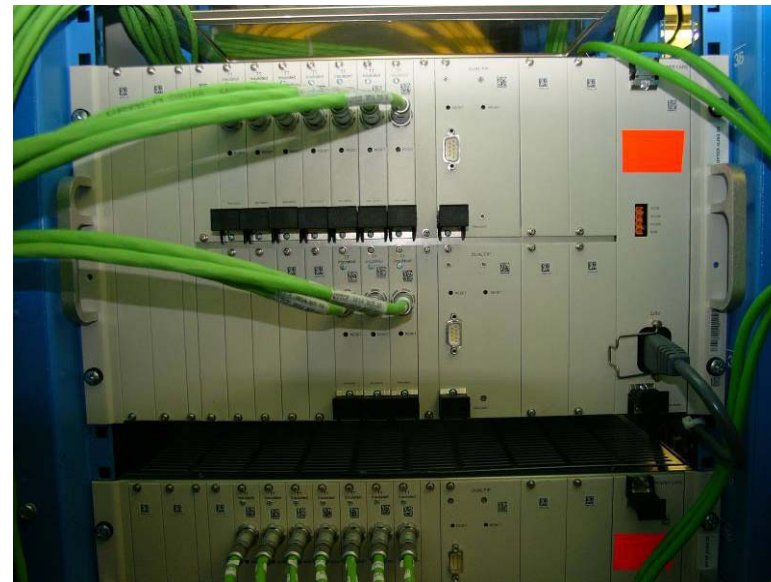
However in case of vacuum loss water condensation may drop onto the electronics and a “roof” has been provisioned. A gap between the roof and the crate permit proper passive convective ventilation

For the long straight section the crates are installed in standard racks in more or less protected areas.



Under Dipole

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19" Rack in protected area

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Design: Thermal

Passive cooling possible thanks to 3U/6U cards with twice the depth than usual (440mm)

=> large heat sinks

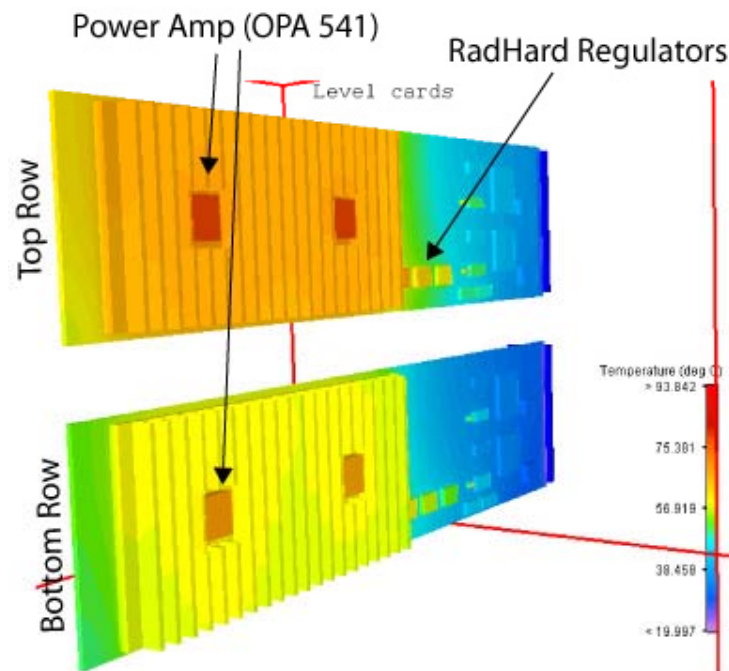
=> able to cope with the additional thermal power due to the overall higher dissipation provoked by the TID

=> No fan ventilation that would be a heavy maintenance constraint

Most of the thermal power is dissipated in the main power supply, dc programmable power supplies and readout of liquid helium level gauges that require currents with up to 0.15A and drive voltage 15 to 60 Vdc.

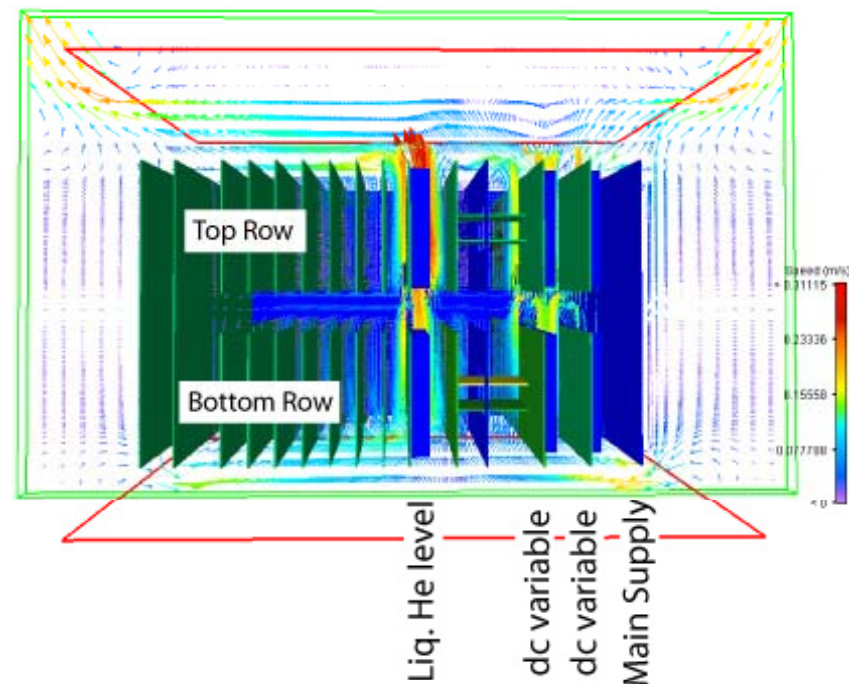
Figures below show examples of the thermal simulations in convective ventilation: Component temperature and air velocity field inside the crate.

Fan ventilation is required only for some crates installed in radiation protected areas



View of 2 Liq. He level measurement cards

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Front View of Crate: Field of Air Velocity

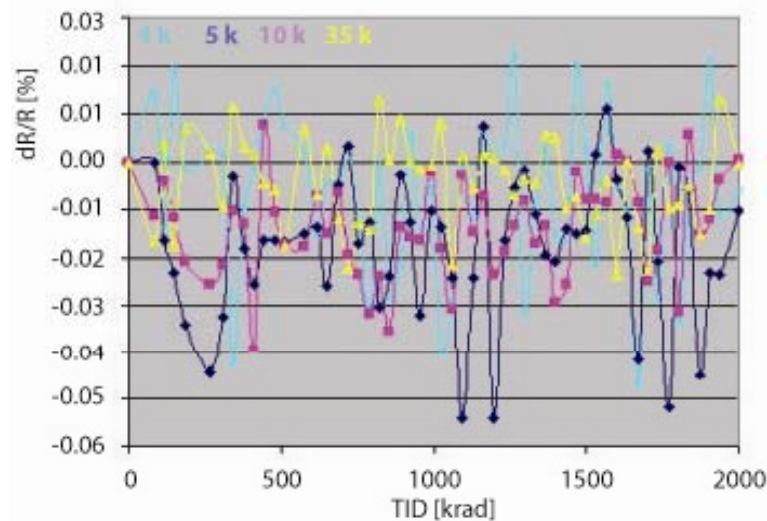


RadTol Qualification Analog

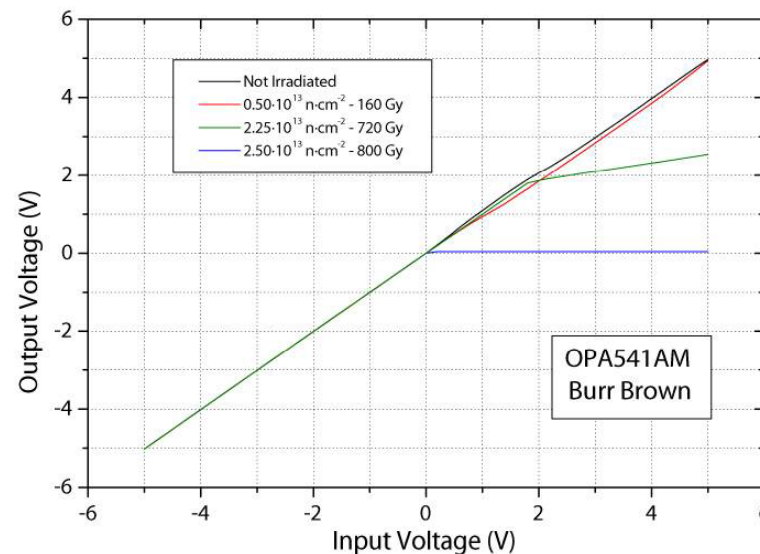
Front end ASIC PRBFE: it is radiation hardened by design and is fabricated in quarter micron IBM technology.

It provides signal amplification, a stable current source and inversion of the current + input amplifier polarities by a set of control terminals. Qualification in gamma rays verified that, as expected, it is a radhard device.

Other analog components like power amplifiers, operational amplifiers, voltage references, etc have been qualified either/both in a reactor (neutron radiation, see right figure) or in TCC2 that had a mixed radiation field.



PRBFE: TID (gamma) versus dR/R





RadTol Qualification Digital/Mixed

Digital circuits have been tested mainly for single events, but also to estimate the maximum survival TID.

ADC: ADS7807UB 16-bit successive approximations

Tested at PSI with a 60 MeV proton beam.

The overall accuracy decreases for TID above 400 Gy, and exceed the tolerable limits above 500 Gy => is it in principle the weakest component of the system.

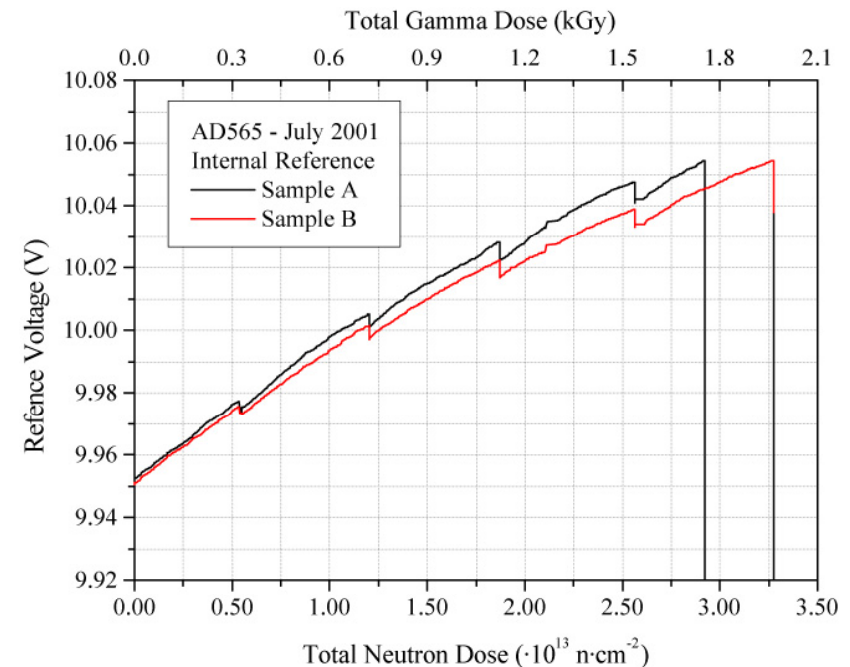
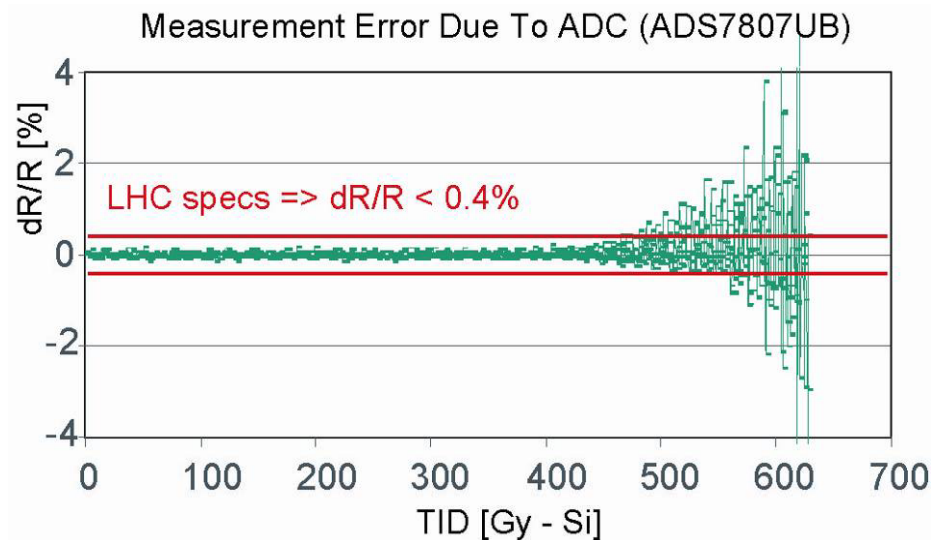
During the irradiation the current consumption increases significantly (e.g. over 10 fold)
Internal reference is unusable

DAC: AD565, internal voltage reference abruptly decreases above $2.5 \cdot 10^{13}$ n/cm².

FPGA: A54SX ACTEL family

Antifuse technology and programmed in triplicate logic

Tested within a system and failures observed before on other devices





RadTol Qualification Communications

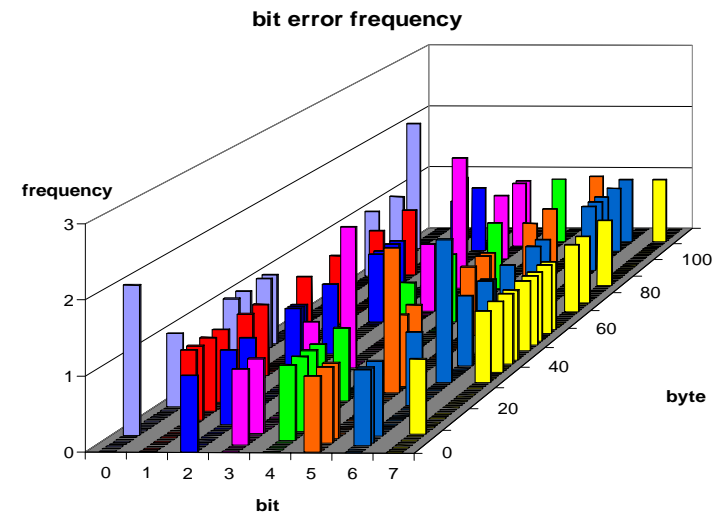
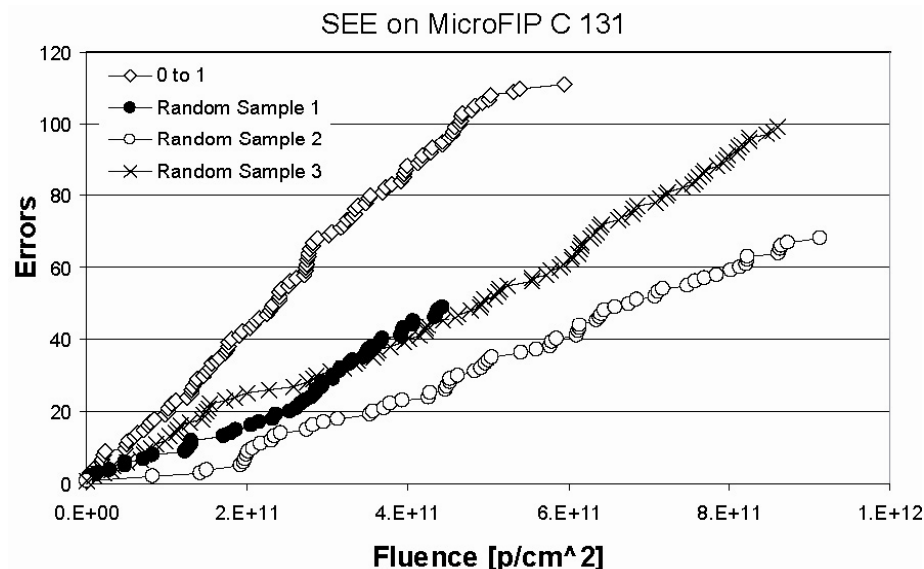
The communication relies on WorldFIP using MicroFIP CC131 cards operating in the micro-controlled mode.

WorldFIP was selected following the first irradiation results at the TCC2 area. It is a relatively robust card in what concern radiation tolerance.

The CC131 card is affected by single events. Apart a change in the configuration registers, SEU are dealt by refreshing the dynamic memory or by data treatment in the surface controls.

In the arc 2 errors / (year*CC131) are expected according to experimental data and calculated doses.

Malfunction observed for one sample at 800 Gy-Si and over four testes samples only one SEU affected the configuration parameters requiring a reset.



Number of bit errors on the CC131 dynamic memory



RadTol Cryo Electronics: Size

Card Type	Quantity
Back plane	853
Power Supply for Crate	908
Variable power supply 500-25W (Vac and Vdc)	320
Variable power supply 25W (Vdc)	824
Variable power supply 500W (Vac)	40
FIP Mother Board	1,266
FIP Daughter Board	1,266
Temperature_Pressure Transducer	3,138
Isolated_Temperature Transducer	1,364
Liquid Helium Level Transducer	413
12 Channel Digital Input	317
Card for analog signals fan-in	625
Crates with no top lid and no feet (19" Rack)	191
Crates with top lid and feet (under main LHC dipole)	662
TOTAL for PCB cards	11,334
TOTAL for cabinets	853



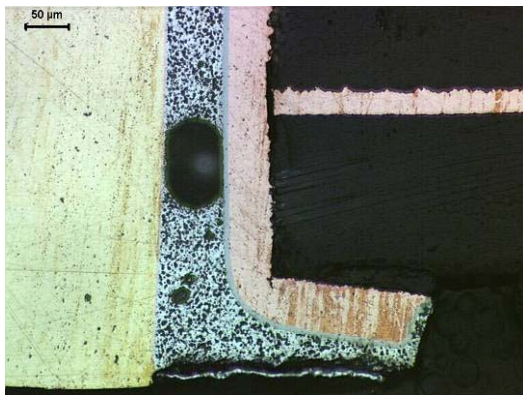
RadTol Cryo Electronics Procurement

More than 10'000 electronic cards were manufactured requiring handling of several thousands of COTS.
COTS LIFESPAN required change to non-qualified component: ADC from ADS 7807 UB to ADS 8507; new pin-to-pin compatible ADC used only in protected areas.

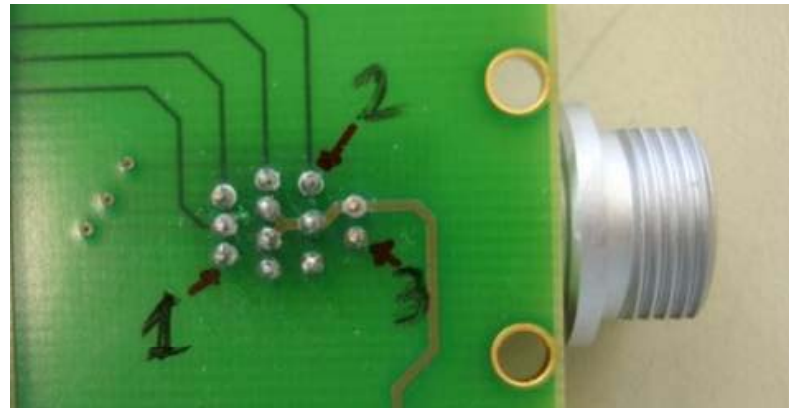
=> To be qualified at a later date

MANUFACTURING:

- PCB manufacturer modified the internal connections for evaluation card!
Very long and time consuming diagnostics
- Materials just OK with specs:
Crack in vias due to a too high soldering iron temperature during manual rework
To simulate long term degradation => 200 thermal cycles between -20 & 80 °C
=> 6% failures predicted on the delivered cards => over 150 kEuro potential loss
- Cleaning Issues: flux residues on evaluation cards
- Poor QA due to difficult economic situation of main subcontractor
=> Very long contract follow-up and CERN had to participate in repairs if schedule was to be kept



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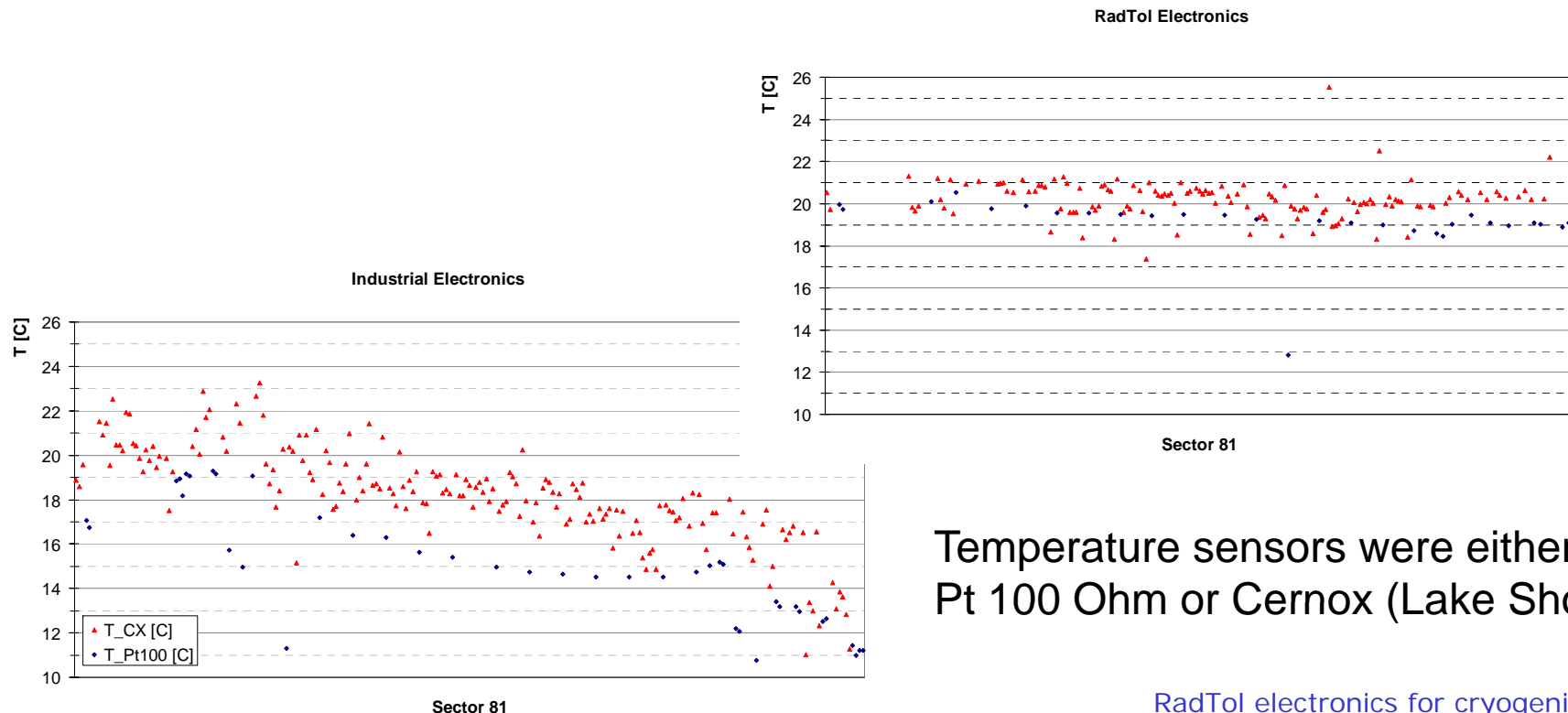
Comparative Performance Custom RadTol & Industrial

The temperature readout around the tunnel is shown when using both industrial (Nov 2005, left) and radtol (Sept 2007, right) remote IO; the temperature correspond to the tunnel as it is before cool-down.

For the “industrial electronics” figure, it is possible to observe the temperature gradient along the tunnel that is decreasing from P8 to P1.

Qualitatively it can be seen that the dispersion is narrower for the radtol electronics, indicating a better accuracy than that found for industrial equipment.

At low temperature the radtol equipment is better adapted as it provides compensation for thermoelectric potentials and a lower sensor self-heating.



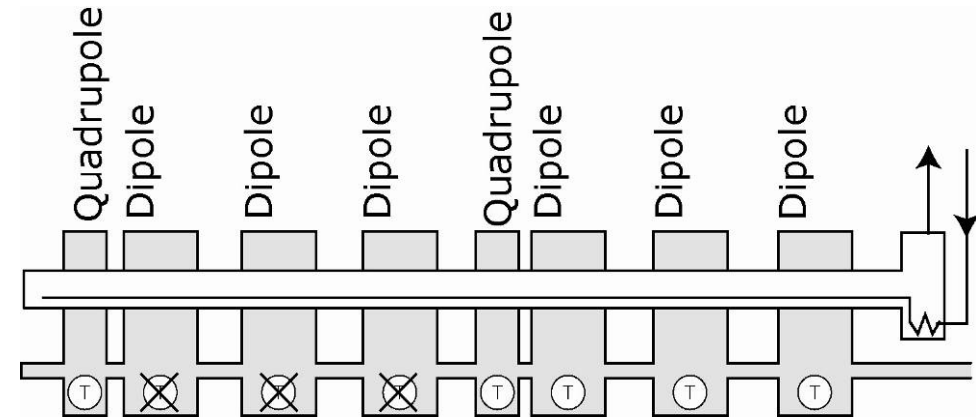


LHeII High Accuracy Thermometry

LHC cell: "Isothermal" over 107m

⇒ Temperature reproducibility typ. Better than 0.01 K

In-situ calibration is unfeasible within the control requirements (0.01 K)



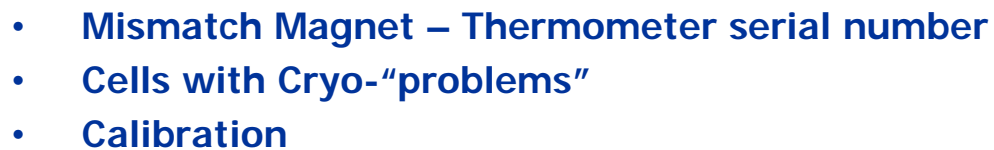
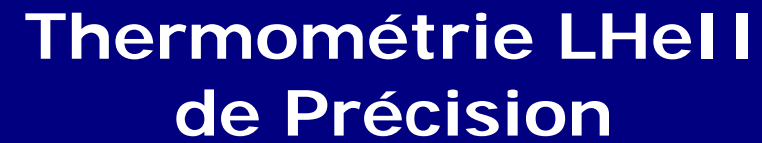
Budget savings required the reduction of acquisition channels

⇒ Reproducibility of many thermometers cannot be assessed

Nevertheless over 400 temperature measurements have been checked for 3 sectors

⇒ Less than 2% of channels are outside requirements

⇒ 1st time that +/- 0.01K reproducibility has been obtained without in-situ calibration!





Conclusions

The instrumentation and control system has been commissioned in cold conditions for the LHC and no major problem has been observed during the beam tests performed to date.

The most critical components have been qualified for radiation, although a higher usage than expected of ICs during fabrication and the necessity to fabricate additional cards has resulted in the use of equivalent pin-to-pin equivalents.

=> the deployment of new cards as well as the reclassification of protected zones would require new radiation qualification campaigns.

The readout channels performance is within the expectations in spite of a very ambitious goal in what concern targeted uncertainty and large scale deployment for the measurement of temperature in the 1.7 to 2.2 K range. The LHC has been, not only procured with electronic readouts as good as those previously found only in small laboratories, but also with remote IO that are more robust than the typical industrial type.

The quality assurance is based on the LHC standard that use MTF (Manufacturing and Test Folder) and on an automated test system that validates every single fabricated card identified by a unique serial number.

The next tasks will be related with the definition of a maintenance plan that will need to take into account the "local" TID and the tunnel access difficulties.