CERN

Instrumentation for cryogenics at CERN

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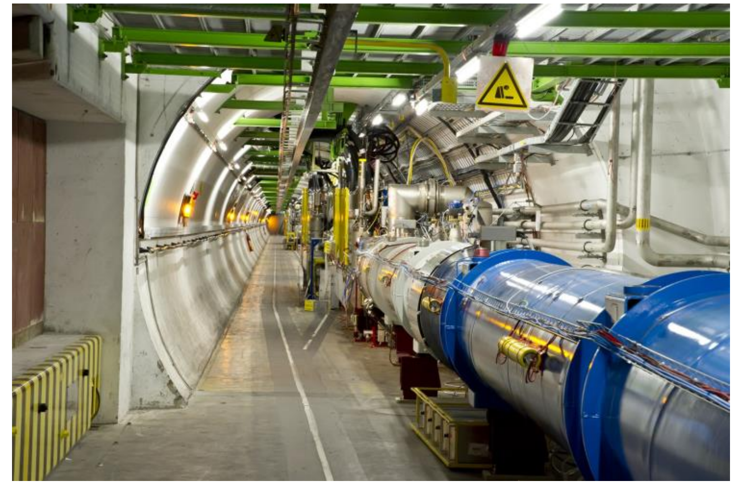
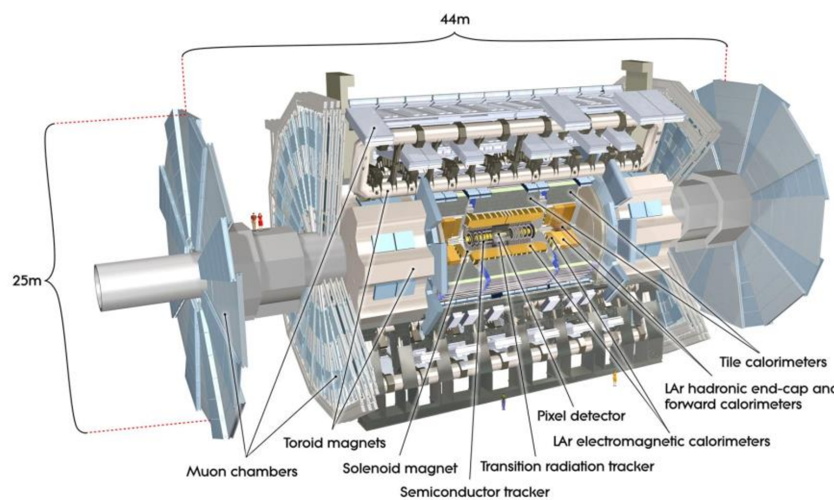
Overview

- Introduction
- Turn-key facilities
- Radiation areas: LHC tunnel
- Measurement channel acquisition design under radiation constraints
- Radiation qualification
- Operational results
- Conclusions

CERN: Cryogenics

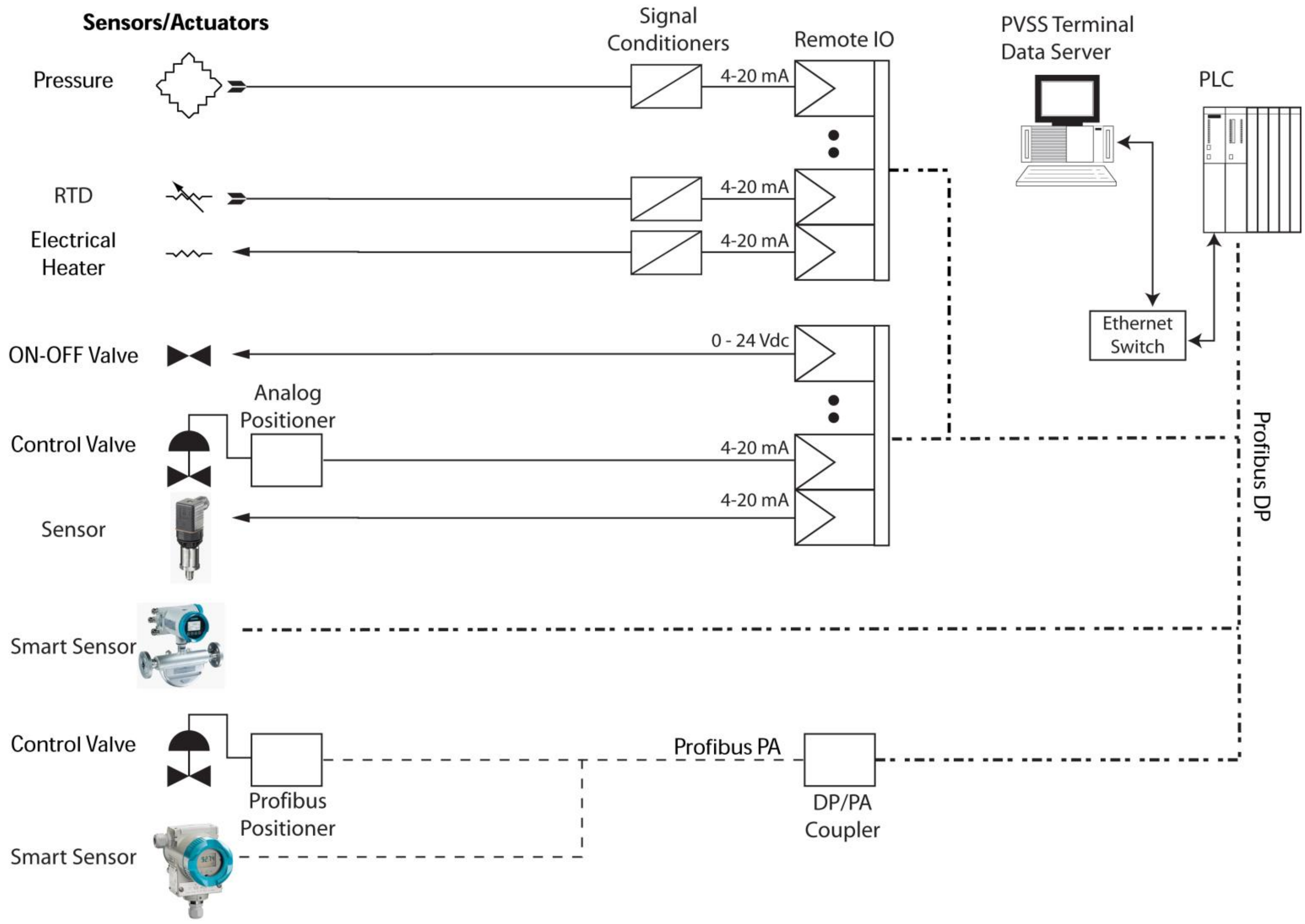
Refrigerators & most distribution equipment: turn-key procurement
Cryogenics in accelerator areas: particular constraints => non-commercial parts





Instrumentation: Turn-key procurement

Sensors, actuators, electronics, etc. ⇔ available from industry



Instrumentation: Turn-key procurement

CERN limit of supply: PLC and Remote IO (RIO)

Present Trend: Move toward smart sensors

- Typically connected to industrial fieldbuses (profibus: CERN supported fieldbus)
- Most are available for 4-20 mA HART but its features seldom used @ CERN
- Provide new features and a wider array of diagnostics data
- Accuracy/resolution figures set by sensor and not by RIO
- Additional cost partially offset by simplified cabling + removal of RIO

However industrial/commercial solutions not fully satisfactory for:

- Reading cryogenic temperature sensors (<20 K)
  problems with electrical cabinet integration or RIO signal resolution
- Superconducting LHe level gauges:
  Supplied by different vendors and wide array of active measurement lengths
  Signal conditioner usually lack terminals for remote disabling to avoid burnout.

=> CERN custom analog signal conditioners are provided for these applications

Instrumentation: Requirements

Most measurement requirements are satisfied by standard industrial apparatus;
to the extent that it looks as if the data-sheets sets the process requirements….
However some applications require a closer look-up:

- Modified instrument for cryo-operation (example: Coriolis mass flow meters)
- Temperature measurement concerns:
  - Platinum thermometers do not have an "official" conversion below 72 K
    Class A ± 0.3 K @ 73 K
    Used at CERN down to 30 K: does satisfies table below?
  - Sensors with little literature concerning accuracy (example: CLTS)
  - Long term drift
- Actual measurement performance difficult to assess

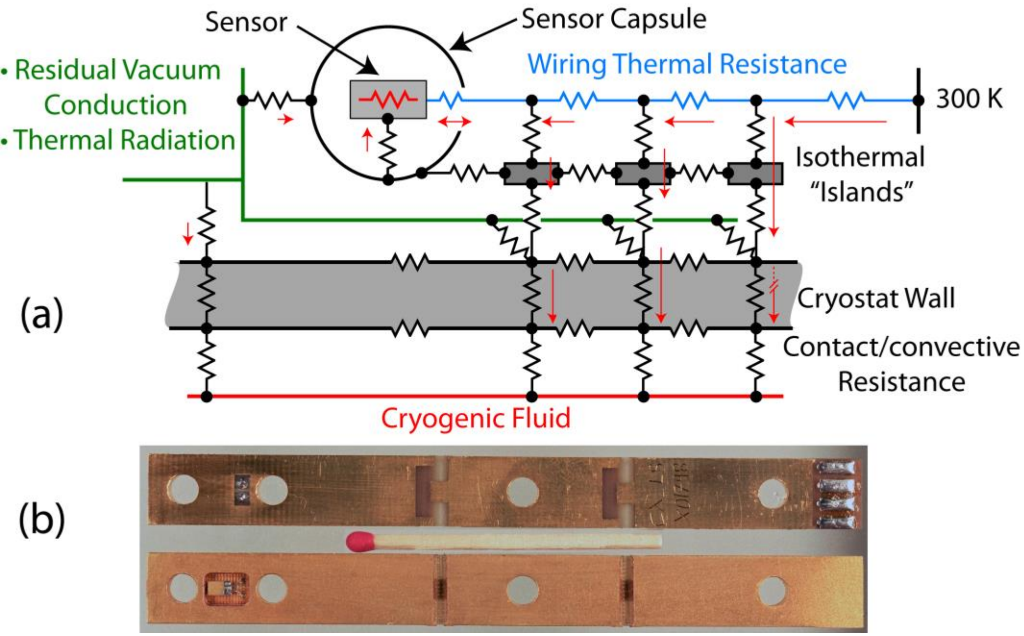
	Refrigerator Plants	Cold Compressor	Plant & Compressor	LHC tunnel
Mounting	Insertion		External	Both
Temperature Range	Specified accuracy [K]			
1.6 – 2.2	n.a.	n. a.	n.a.	± 0.01
2.2 – 4	n.a.	± 0.025	n.a.	± 0.02
4 – 6	± 0.1	± 0.05	± 0.5	± 0.03
6 – 10	± 0.1	± 0.05	± 0.5	± 1
10 – 25	± 0.3	± 0.1	± 1	± 1
25 – 50	± 0.3	± 0.3	± 1	± 2
50 – 80	± 0.3	± 0.3	± 1	± 5
50 - 300	± 0.5	± 0.5	± 3	± 5

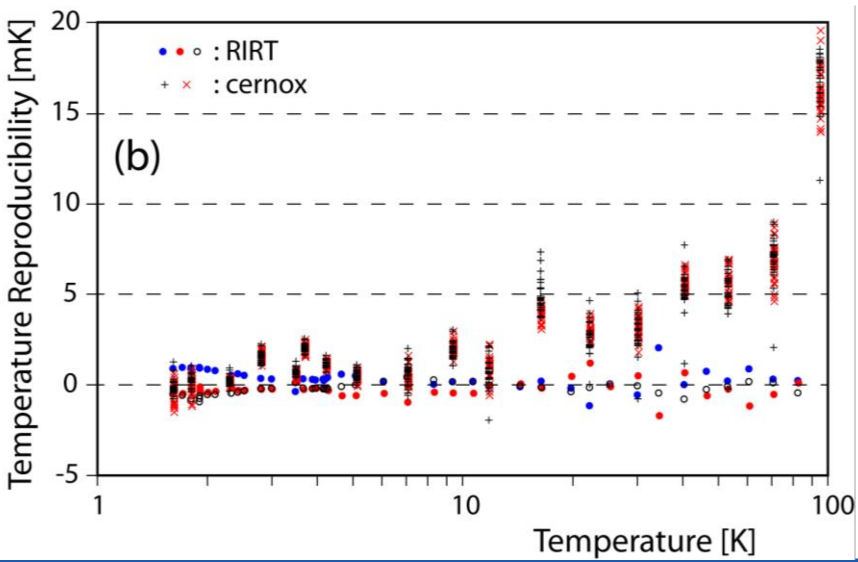
Instrumentation: CERN thermal anchoring

Most challenging LHC measurement channel is temperature:

- Superconducting magnet temperature is a control parameter
- Accuracy has a direct impact in regulation band
  - Accuracy budget is 0.01 K split in the sensor & electronics

Temperature sensors followed a very strict selection and QA procedure
Thermal anchoring compatible with large series production was designed:
calibration in “final” conditions & provide reliable measurement under vacuum.

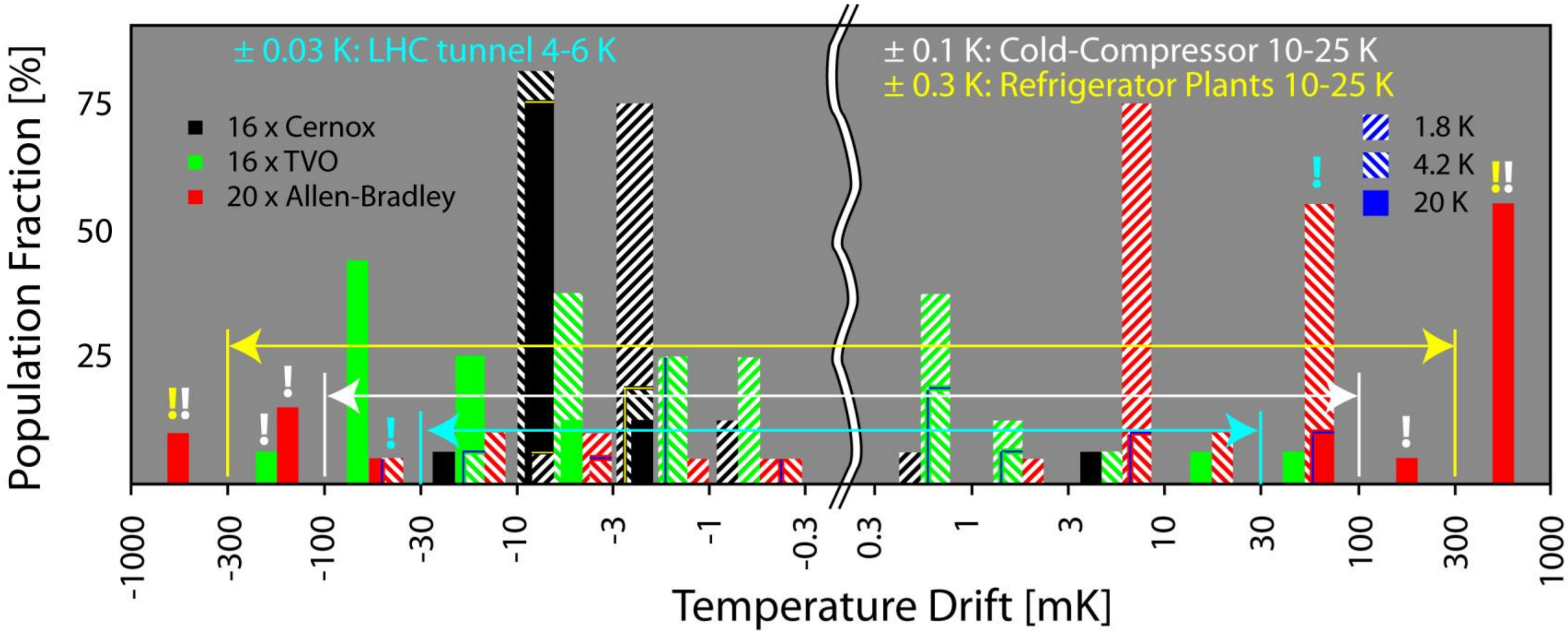




Instrumentation: Thermometer Stability

Long term stability is difficult to assess;
thermal cycles are used to accelerate ageing

Test: 100 Temperature cycles between 4.5 – 300 K in GHe (no humidity)
$\Rightarrow$ Only CERNOX satisfies the accuracy requirements above 4 K
This imposes complete control of all parameters affecting the measurement like individual calibration, signal conditioning, thermal anchor, etc.

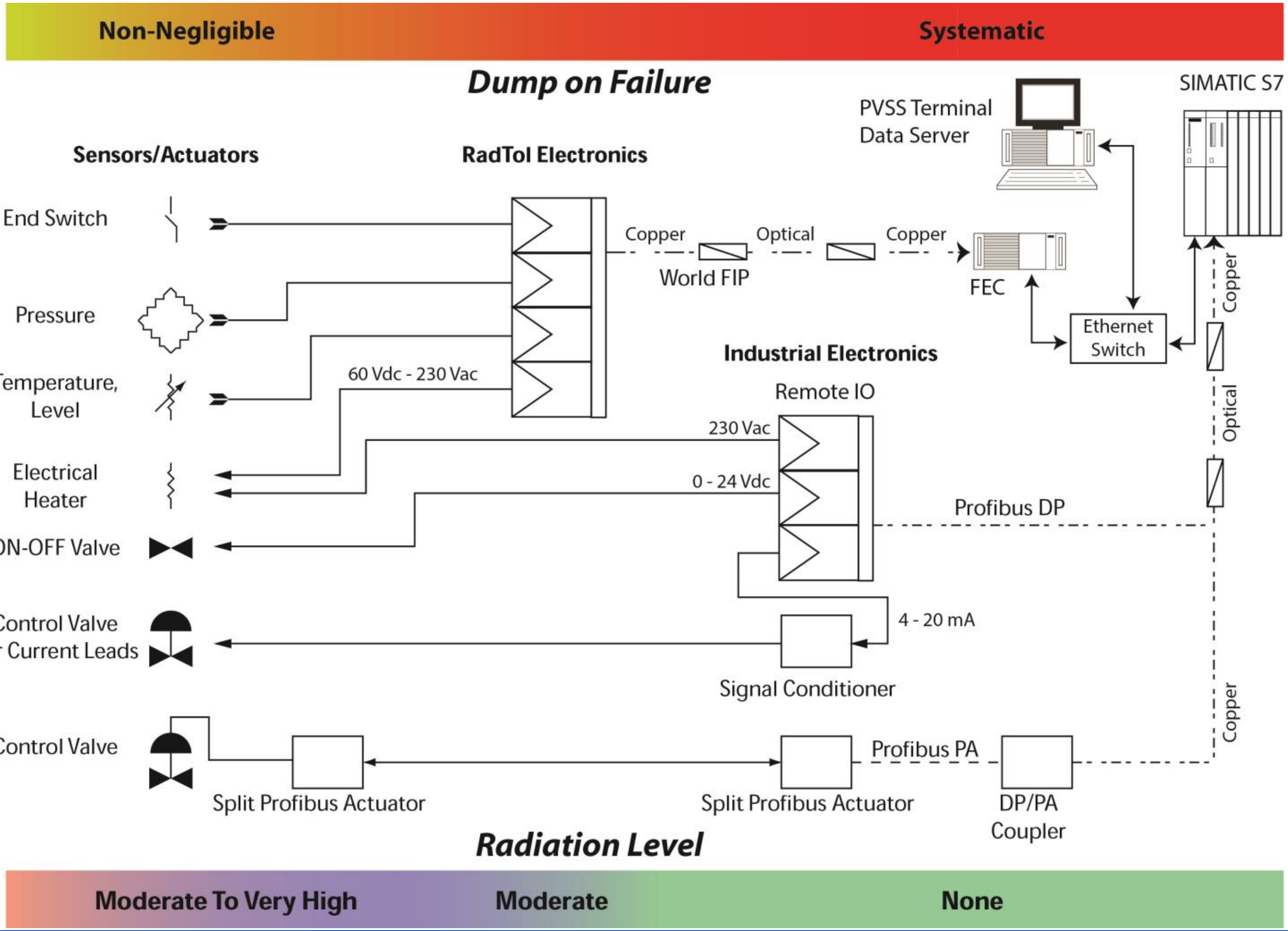


Instrumentation: Radiation Design

Turn-key equipment trend towards smart fieldbus instruments

Radiation => fieldbus instruments: the dumber the better…..

Example LHC case:



Instrumentation: Radiation Design

Radiation is a very challenging environment that require:

- Radiation dose maps from calculation-intensive simulation (FLUKA modelling)
- Optimize location of sensor, conditioning electronics (& PLC)
- Design, select or customize sensor and/or signal conditioning electronics
- Suitable irradiation test-area (particle type, dose rate, etc.)
- Reference comparison apparatus, usually not rad-hard
- Strict QA policy for procurement and management of spare parts
- Dealing with obsolescent parts for machines with a lifespan > 20 years

=> Whenever possible avoid radiation tolerant equipment!

In an accelerator environment fast particles may appear in radiation free areas:

- May cause malfunction and unforeseen stops
- Requires consolidation without appropriate test-time

LHC cold-compressors, valve-boxes & HTS leads thermometers were victim of radiation events and relocating the sensitive equipment was the solution:

- Magnetic bearings controls within maximum tolerable cable length
- Use of LHC split SIPART valve positioners
- Relocate RIO and profibus interfaces
- Consolidate HTS leads temperature measurement cards
- …..

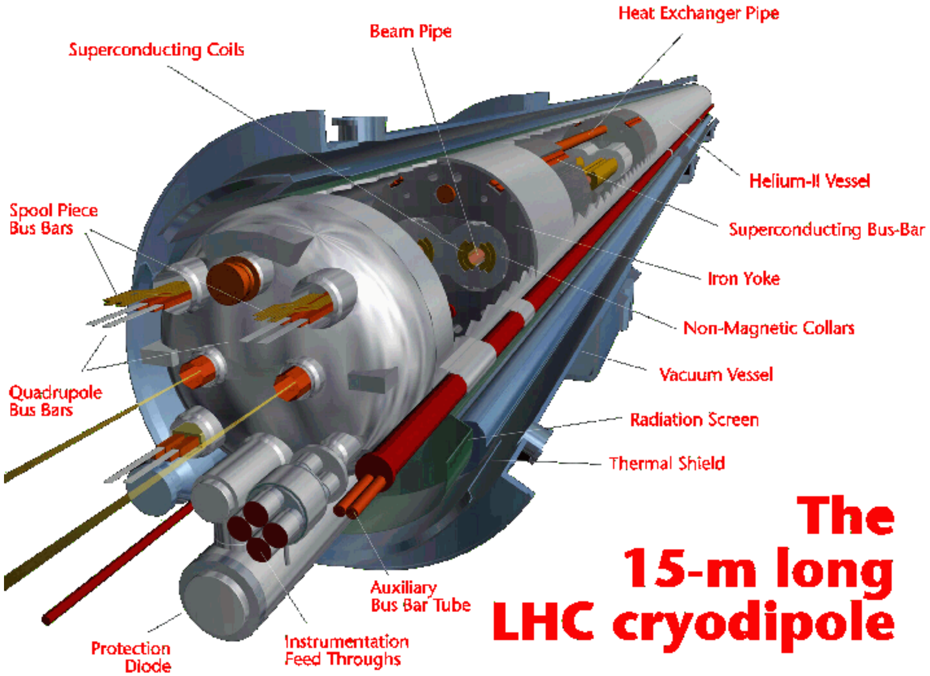
Instrumentation: Radiation Design

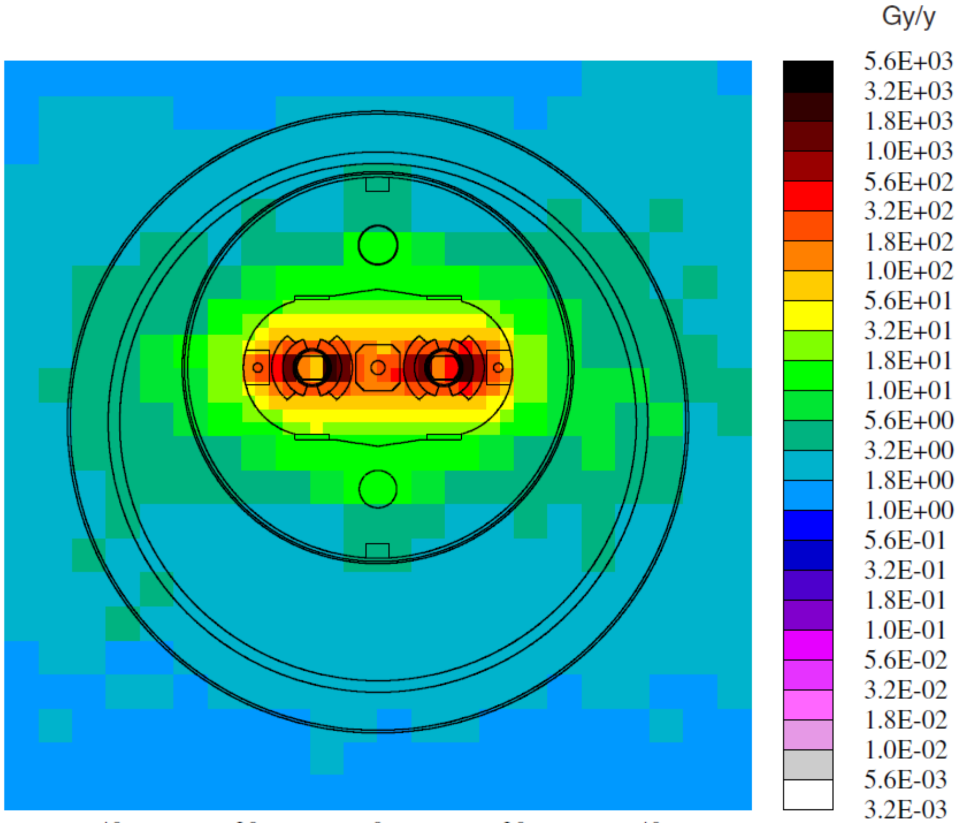
Radiation maps required to set experimental qualification doses

LHC case:

- Cold devices need to be rad-hard
- Electronics can be “radtol” (< 1 kGy) if placed at centre & below the dipoles.
- Long straight areas: radiation far too high => electronics in protected areas

=> Use as much radtol electronics to save cable cost





Cold Instrumentation: Radiation Design

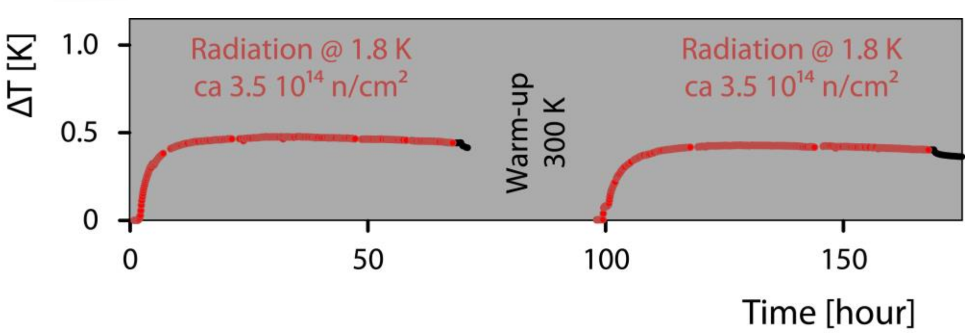
Cold Instruments need to be rad-hard
Assumed rad-hard by design: superconducting LHe level meters
    Same material as magnets

BEWARE: Radiation qualification shall be performed in final operational conditions
Thin film Ge sensors reported in 1997 to be rad-hard!
Excellent LHC candidate

Temperature shift after $2 \cdot 10^{14}$ n/cm^2 and 3000 Gy dose

Type	Shifts, mK, at selected temperatures			
	287.5 K	77.4 K	4.24 K	1.87 K
TVO	-130	-85	-12	–
TTR 1B #147	-530	-20	-10	-10

Irradiation @ room temperature
Drift is deduced from calibration before & after irradiation.
OK for LHC use



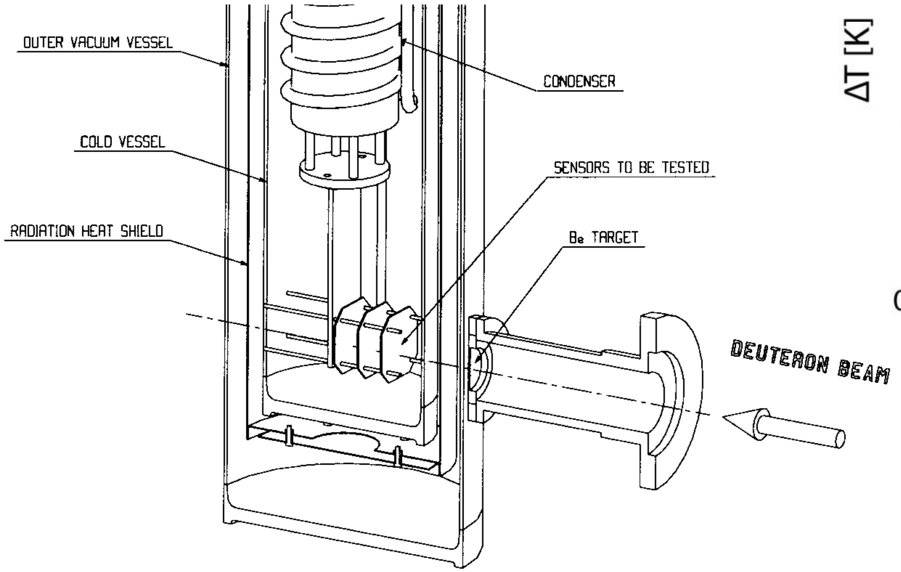
CERN irradiation test:
Complete repair after annealing at room temperature!
Drift not visible in previous report
2 orders of magnitude OFF
Not usable in LHC conditions

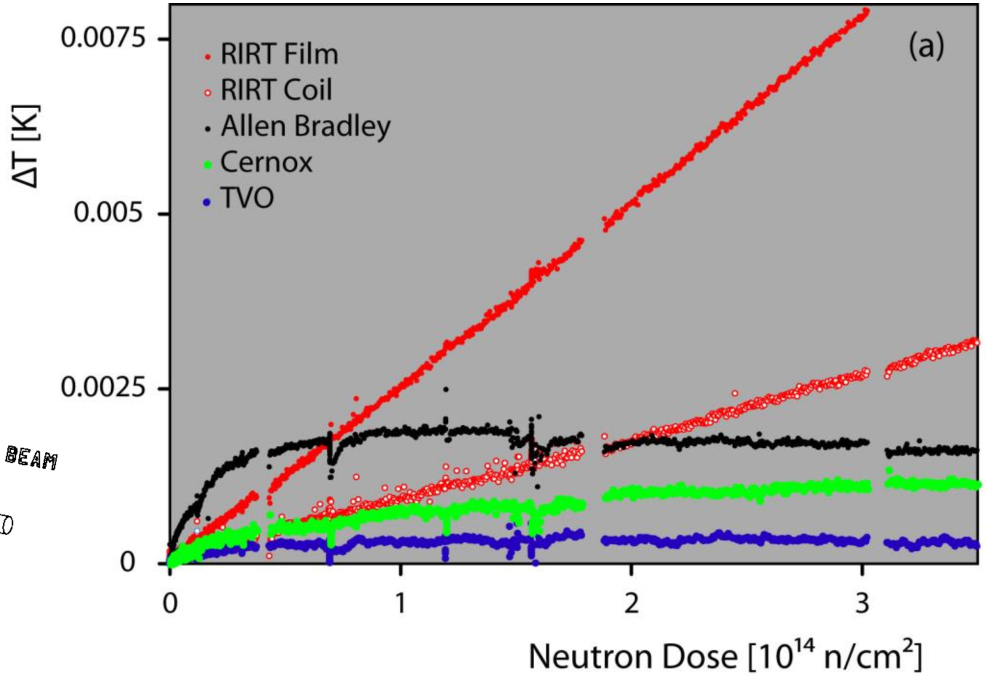
Cold Instrumentation: Radiation Design

Radiation tests in cold conditions are extremely difficult to perform:

- Select/design cold-sensors, CERN case: selection from commercial catalogues
- Require a reference comparison instrument
  Temperature sensors <-> LHe bath saturation pressure & bulb, remote sensor
- Continuous filling LHe filling
- Remote analog electrical signals acquisition.

Accumulated dose still too low comparing to worst LHC zones after 20 years operation.

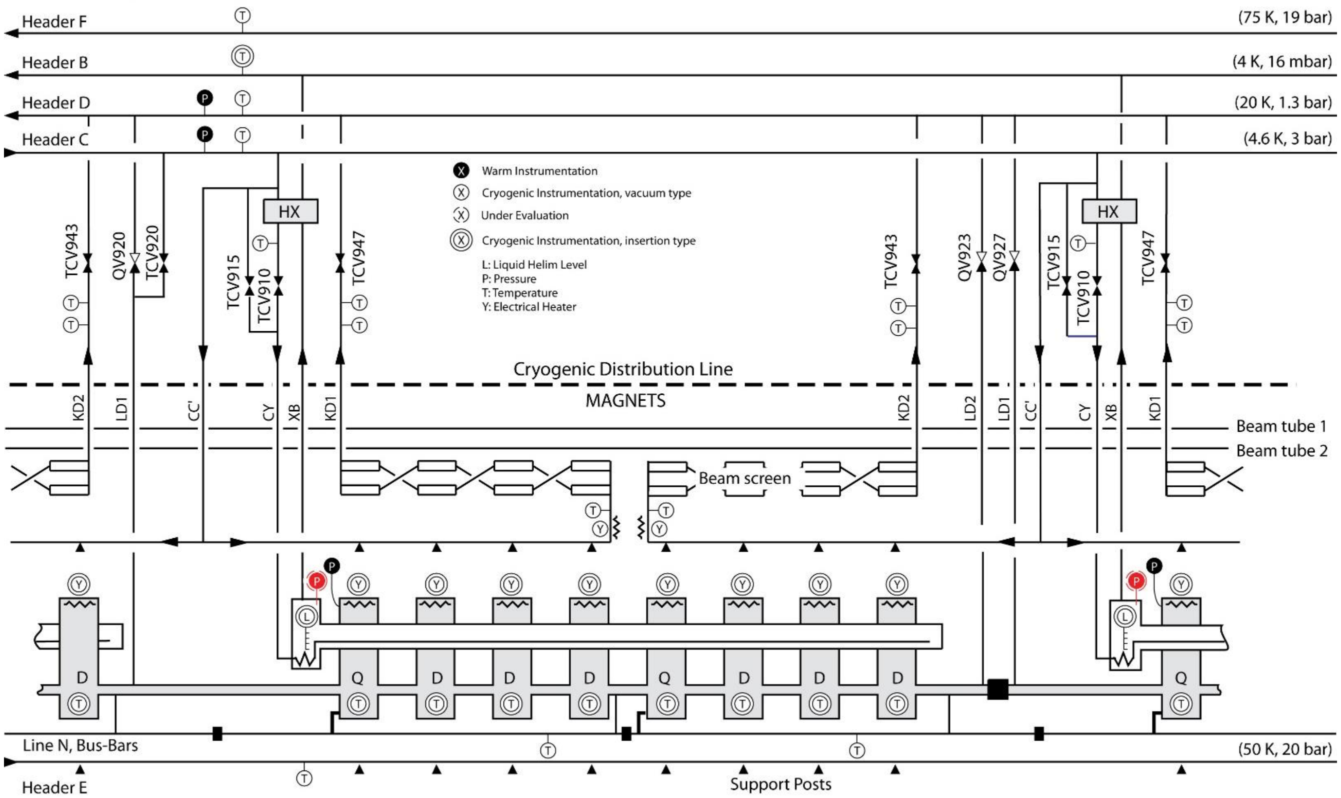




Warm Instrumentation: Radiation Design

LHC instrumentation exposed to radiation is made of mostly:

- Thermometers that cannot be changed => qualification is mandatory
- Pressure sensors => qualified for ranges 0-2 and 0-20 bara
- Valves that are (were) considered intrinsically radhard:
  - On/OFF pneumatic made of basic elements (coils, magnets,..)
  - Proportional valve: split design, assumes rad-hard piezo electric element
- Electrical heaters
- …



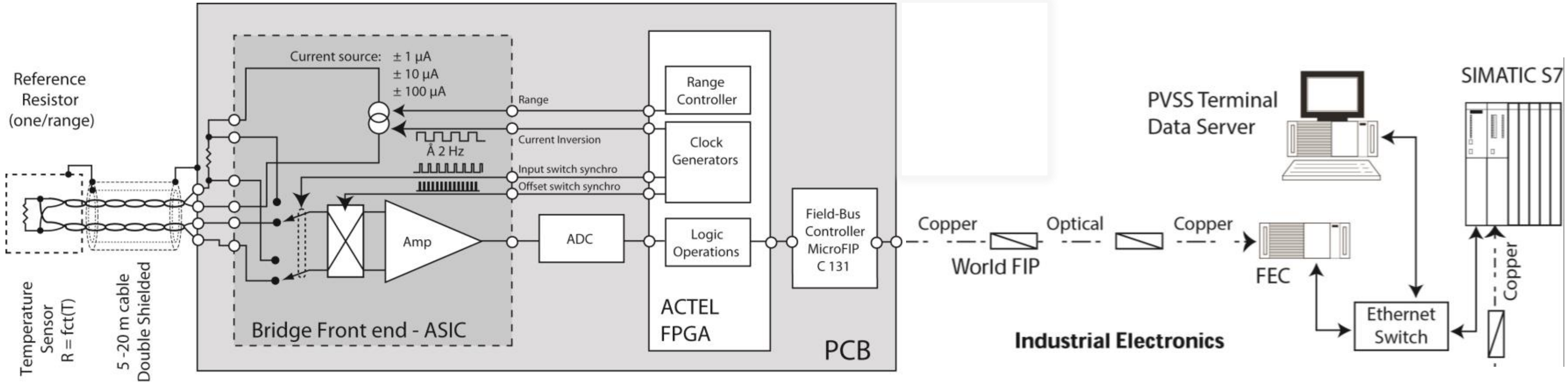
Instrumentation: Signal Conditioning Radiation Design

Signal conditioning radiation hardness is limited by the weakest component.

Radiation effects induce drift (similar to temperature effects) and change the state of digital circuits (can be a simple memory upset or a destructive event)

Analog signal conditioning relies on:

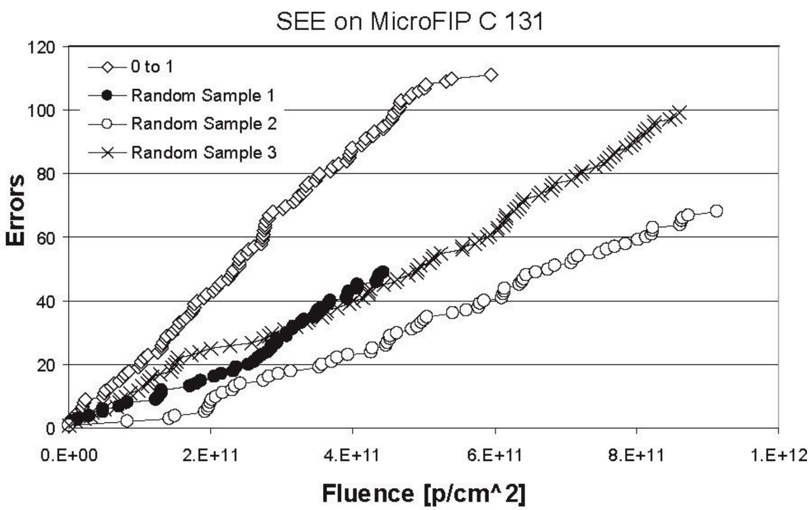
- Passive comparison bridge, comparison resistor (low TCR, qualified)
- Rad-hard by design ¼ micrometer IBM tek ASIC
- Accuracy set by amplifier and ADC non-linearities
- Local control performed by anti-fuse FPGA with triplicated logic
- Commercial microFIP communication interface: found to be rad-tol
  Note that new versions (same part number) are sensitive to radiation
- All mathematical calculations done remotely by FEC

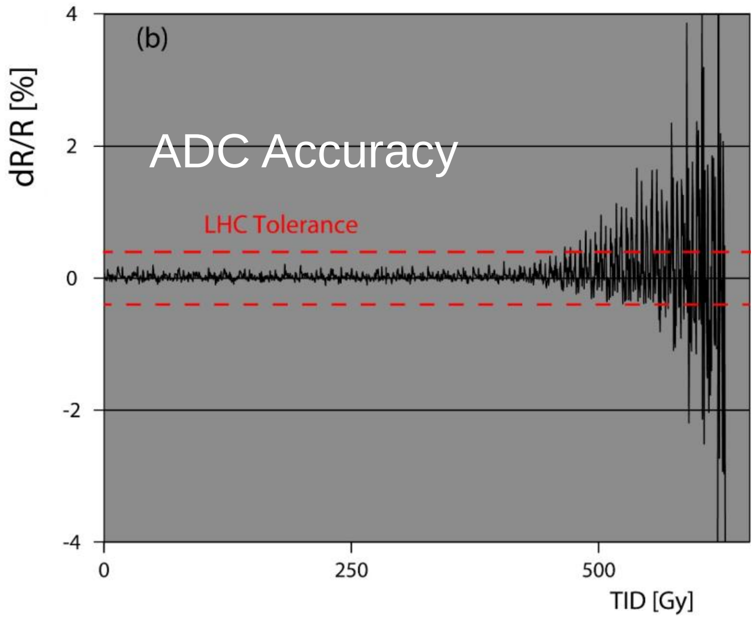


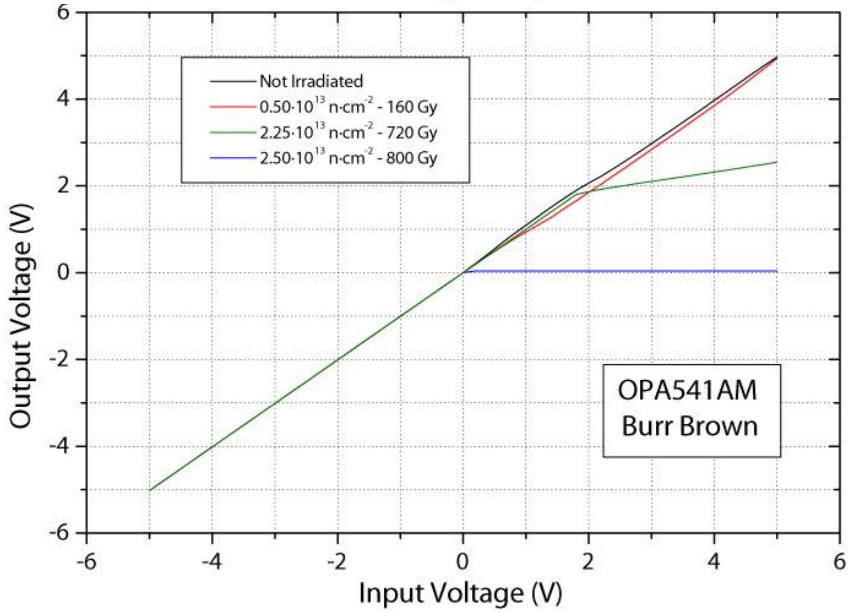
Instrumentation: Signal Conditioning Radiation Design

All individual components need to be qualified:

- Select, qualify, procure & maintain
- Both total dose and singular/transient effects need to be evaluated
- Radiation effects require compensation
- Adequate duplication of readings may be required







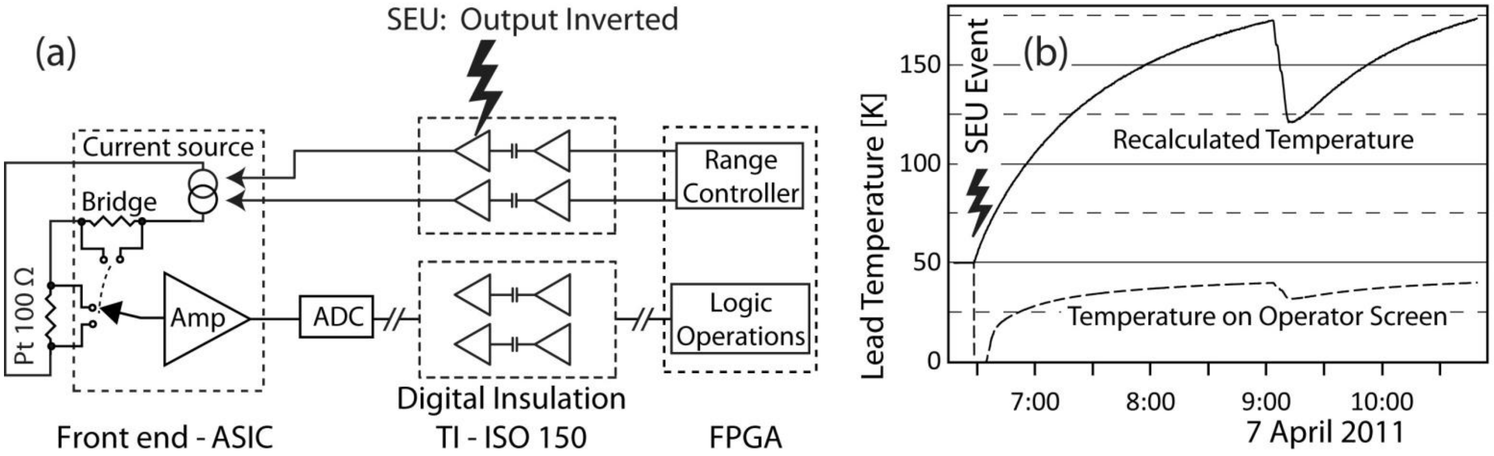
Instrumentation: Signal Conditioning Radiation Design

Fast particles affect digital or power devices via Single Event Effects (SEE)
Digital status of digital circuits can be corrupted by Single Event Upsets (SEU)
Non destructive SEU can be tackled:

- By design at the electronics card level
- Repaired by performing a “reset” or a power cycle

Such events can provoke unexpected operational scenarios like shown here below:

- SEU affects a LHC HTS superconducting current lead temperature sensor => “negative” temperature => beam dump
- Once temperature increases readout looks “normal” but > 100 K instead of < 50 K => current lead quench when increasing magnets current
- Repaired by electronics reset.

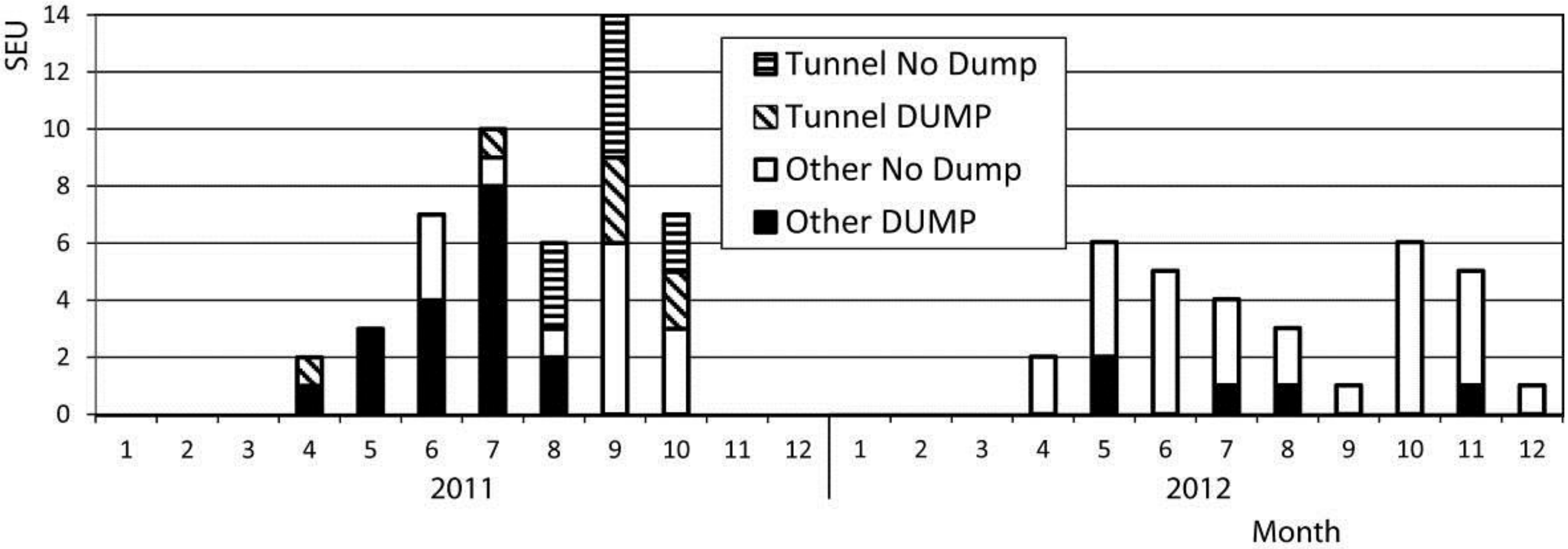


Instrumentation: Signal Treatment Radiation Design

SEU when foreseen during the design phase can be tackled effectively

However, if not expected to occur they can be very disruptive, for the LHC:

- Appeared in 2011 (due to increase in luminosity) and first events caused a systematic beam dump
- Operational experience permitted to implement appropriate procedures => no more systematic beam dump
- WFIP tunnel electronics consolidated by end 2011 => No more SEU
- SEU prone commercial equipment relocated by end 2012 => No more SEU

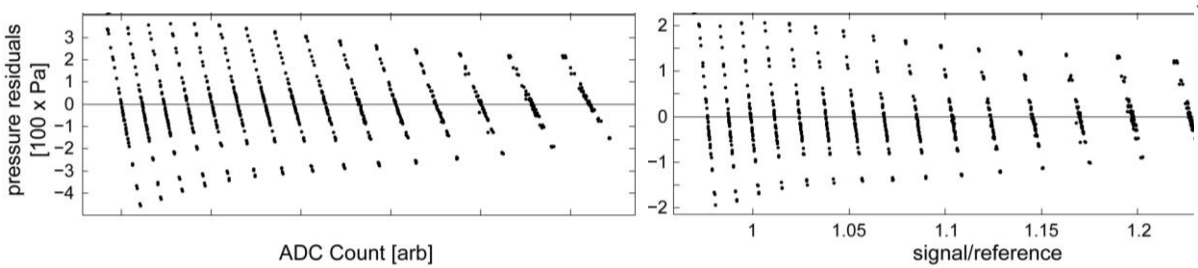


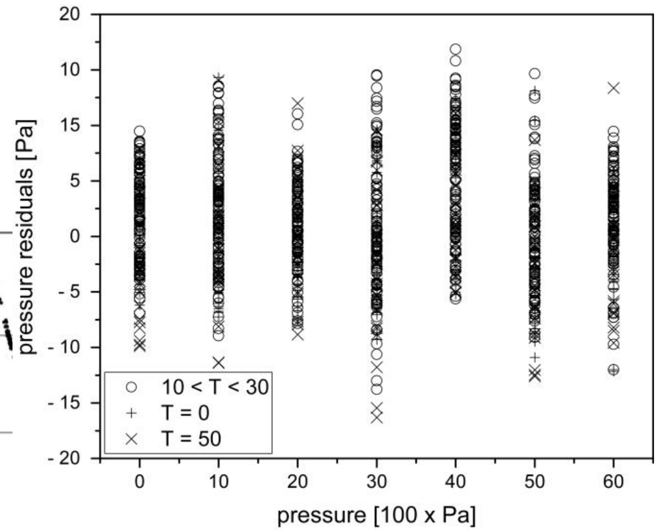
Instrumentation: Signal Treatment Radiation Design

LHC chain made of “dumb” sensor but full chain is equivalent to a “smart” device

Example - LHC pressure measurement chain:

- Sensor is made of sensitive membrane and temperature sensor (rad-hard)
- WFIP electronics (rad-tol) acquire signals for
  - measuring membrane
  - reference membrane
  - temperature sensor
- Temperature correction => 20 fold accuracy improvement
  Performed by remote commercial control computer
- Performance equivalent to a modern fieldbus based sensor





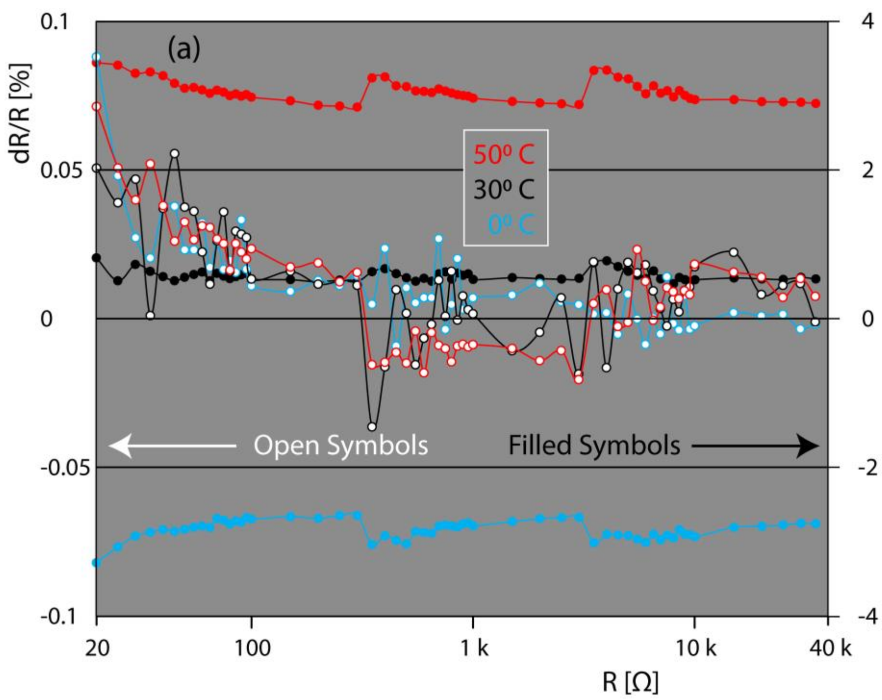
Instrumentation: Signal Treatment Radiation Design

LHC chain made of “dumb” sensor but full chain is equivalent to a “smart” device

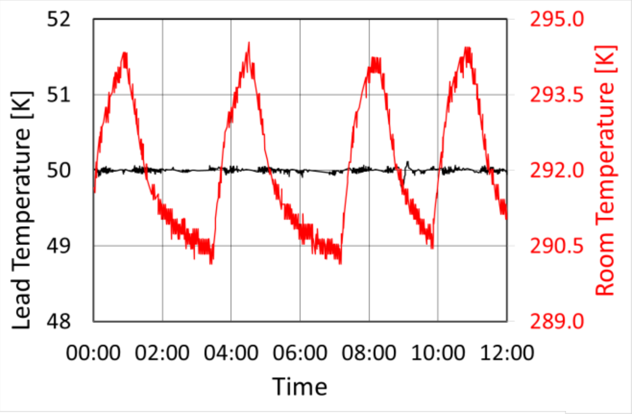
LHC temperature measurement chain:

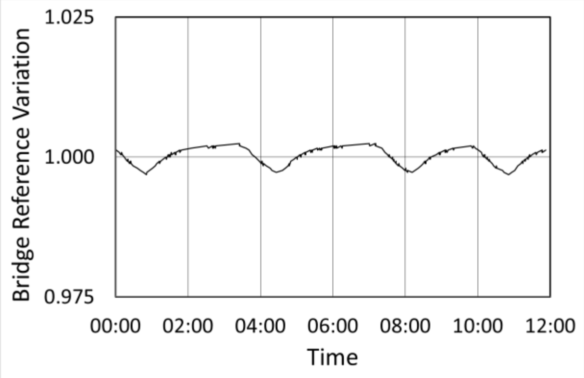
- Excellent immunity against radiation and ambient temperature effects
- Raw data permit to estimate temperature oscillation of cryo-crates

Test in climatic chamber:



Equipment in LHC underground area:



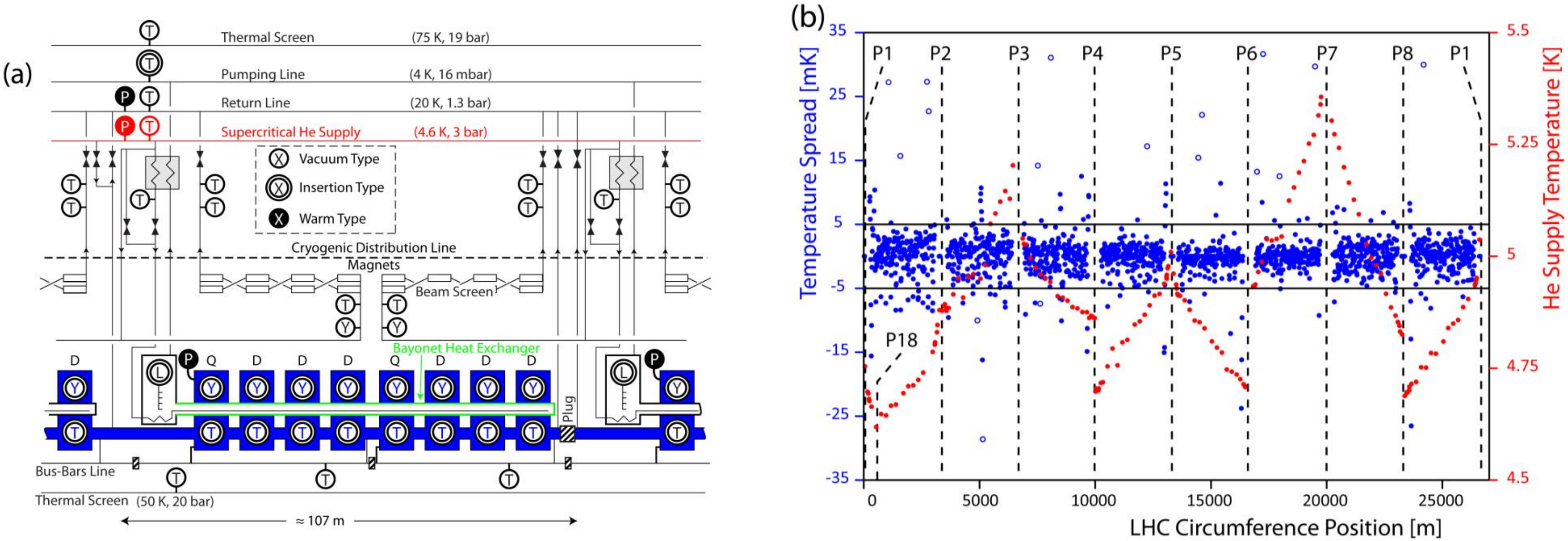


Instrumentation: LHC thermometry

LHC temperature readout is of "laboratory" quality in spite:

- Very hostile environment, worse than typical industrial installation
- Sheer quantity of measuring channels (9'000)
- Individual calibration => require QA during manufacturing
- Once installed difficult/impossible to exchange

Cross-check possible for superfluid pressurized bath => dispersion within ± 0.005 K



Conclusions

Radiation environments impose cumbersome qualification procedures and usually (always?) involve management of obsolescent parts
$\Rightarrow$ Whenever possible avoid radiation areas

Temperature readings are not trivial and in the range 6 to 50 K the requirements are hardly met by just a few sensors; and this only if appropriate thermal anchoring procedures and signal conditioning is applied.

The LHC accelerator imposed the investigation of radiation tolerant electronics in order to save cabling cost, remote electronics may be possible but would require up to 3 km long cables and ECM may become a problem
=> local electronics nevertheless mandatory

The LHC demonstrates that it is possible to perform laboratory-like measurement within a radiation environment, but this require the understanding of all the elements of the complete measurement chain.