Use of Instrumentation in a Radiological Environment

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Headlines:

Instrumentation Identification
Radiological Environment
LHC measurements and Process

Instrumentation

- Think about instrumentation as a complete system – sensor, wiring feed through, DAQ rather than just the sensor itself.
  - Total system cost per measuring point can be ~ $500 - $1000 – trade offs to make between cost, size, accuracy, easy of use, environment

Courtesy of John Weisend

- Define requirements:
  - Resolution : what is the smallest detected change
  - Precision (reproducibility or stability): how close to the measurement value?
  - Accuracy: Closest between the results of a measurement and the true value.
  - Operating Range, excitation, Output signal, Size, Offset, Stability, interchangeability, Ease of Use, Cost
  - Effect on its environment
  - Environmental compatibility:
    - •Robustness
    - •Response time
    - •Magnetic field effects
    - •Radiation resistance
    - •Electromagnetic noise effect

Instrumentation Rules of Thumb - Courtesy of John Weisend

- Don't use more accuracy & precision than required
- Use commercially produced sensors whenever possible – there is a lot available
- When possible, mount sensors outside cryostat (e.g. pressure transducers, flow meters)
- For critical devices inside of cryostats, install redundant sensors whenever feasible
- Be sure to consider how to recalibrate sensors
- Once R&D is done, minimize number of sensors in series production of cryostats

Measurement of uncertainty, u

- The probable resolution, precision, or accuracy of a measurement can be evaluated using uncertainty analysis.
- Same unit than the quantity measured.

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2 + \ldots + u_n^2}$$

- Source of measurement uncertainty

1) Sensor excitation
2) Sensor self-heating (in cryogenic environment)
3) Thermo-electric voltage and zero drift
4) Thermal noise
5) Electromagnetic noise
6) Sensor calibration
7) Interpolation and fitting of the calibration data

Heat Sinking of Wires and Measurements Techniques

- Critical to the proper use of temperature sensors in vacuum spaces
  - You want to measure the temperature of the sensor not that due to heat leak down the wire
- Use 4-wire measurement
- Use low conductivity wires with small cross sections

Table 4-3 Wire heat-sinking lengths required to thermally anchor to a heat sink at temperature *T* to bring the temperature of the wire to within 1 mK of *T*

Material	T_1 [K]	T_s [K]	Heat-sinking length, L_2 (mm) for wire sizes 0.21 mm^2 (24 AWG)	0.032 mm^2 (32 AWG)	0.013 mm^2 (36 AWG)	0.005 mm^2 (40 AWG)
Copper	300	80	160	57	33	19
	300	4	688	233	138	80
Phosphor-Bronze	300	80	32	11	6	4
	300	4	38	13	7	4
Manganin	300	80	21	4	4	2
	300	4	20	7	4	2
304 ss	300	80	17	6	3	2
	300	4	14	5	3	2

Note: Values are calculated assuming wires are in a vacuum environment, and the thermal conductivity of the adhesive is given by the fit to the thermal conductivity of GE 7031 varnish.

Courtesy of John Weisend

Ref: "Cryogenic Instrumentation" – D.S. Holmes and S. Courts *Handbook of Cryogenic Engineering*

Commercial Sources of Cryogenic Instrumentation

- Don’t reinvent the wheel – there is a lot already available. Catalogs can help you choose the correct sensor for your application

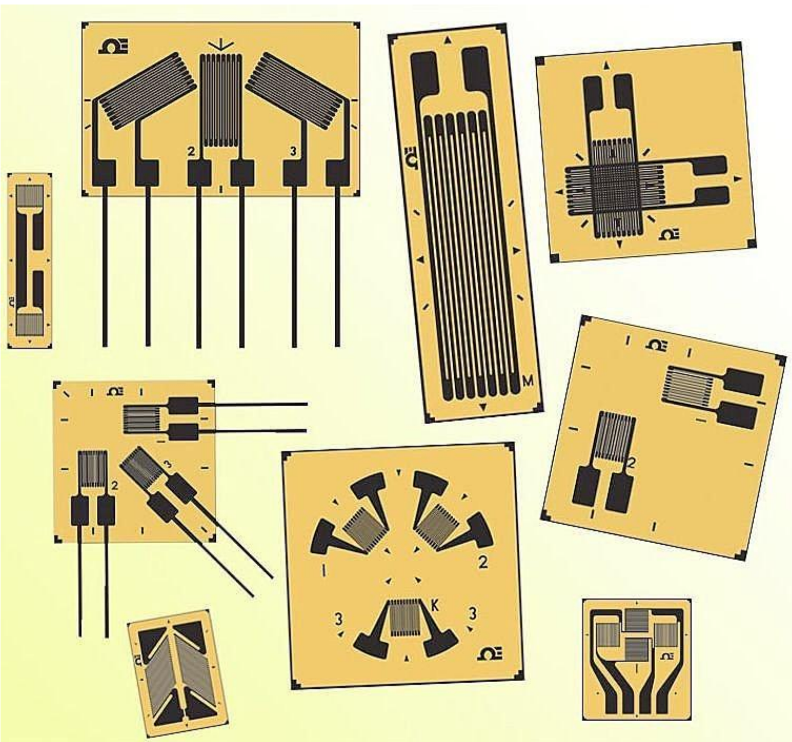
- Two US Sources:
  - Lakeshore Cryogenics http://www.lakeshore.com/
  - Scientific Instruments http://www.scientificinstruments.com/

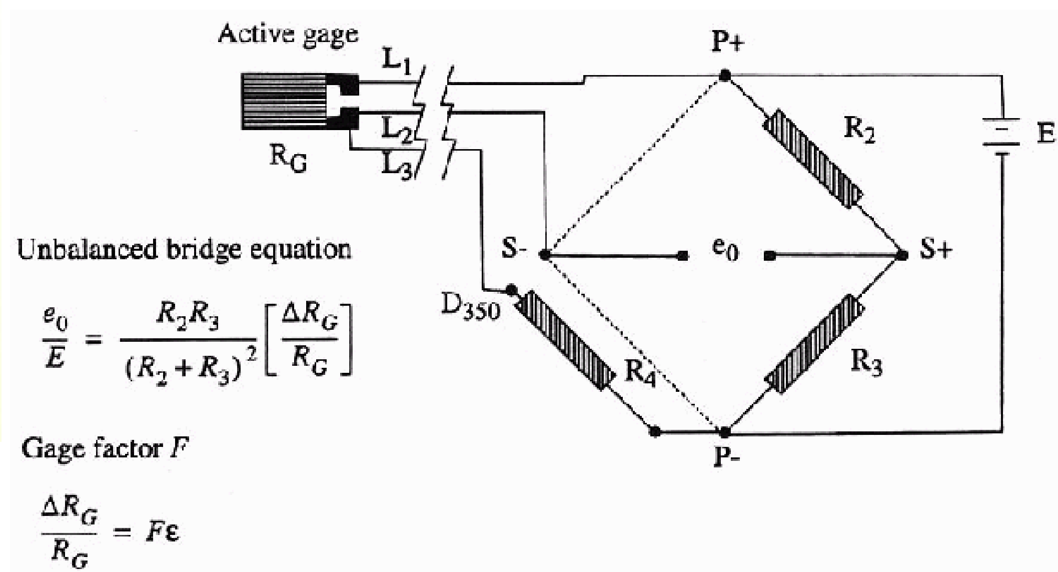
Courtesy of John Weisend

Strain Measurement

- Bond resistance strain gages, with relative resistance change according to the formula:

$$\frac{\Delta R}{R} = F_s\left(\frac{\Delta L}{L}\right)$$





Level Measurement

- Superconducting level gauges for LHe service
- Differential pressure techniques
- Capacitive technique
- Self heating of sensors
- Floats (e.g. LN_2)

Courtesy of John Weisend

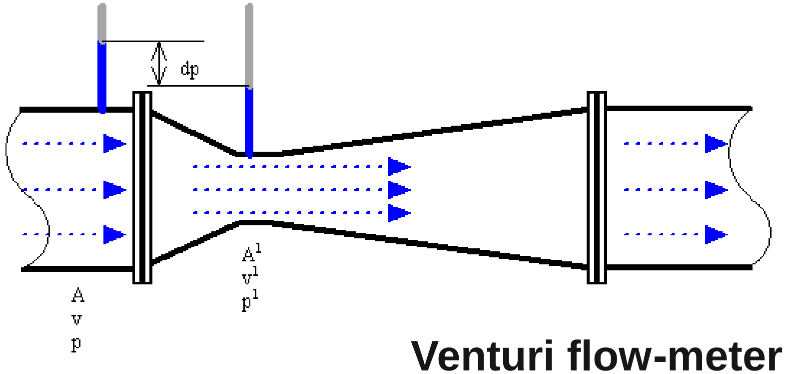
Flow Measurement

- Measure a mass flow or a volumetric flow

- Differential pressure

(simple construction, no moving parts, external instrumentation and low maintenance) *e.g. Orifice, Venturi, V-Cone, Pitot tube*

$$\rho\frac{v^2}{2} + p + \rho g z = \text{constant}$$



Venturi flow-meter

- Variable Area flow-meters

(simplest and cheapest types of meter)

- Thermal Mass

$$q = \Delta T\left[k + 2\left(k C_v \rho \pi d \tilde{v}\right)^{1/2}\right]$$

- Others: Turbine, Vortex, Target

Flow Measurement

	Ultimatea ccuracy	range-ability	pressure loss and piping requirements	recommended applications	cost
orifice	1 - 2 %	medium	high / 10-30 D	clean gas	low
venturi	1 %	medium	low / 5-10 D	dirty gas	high
V-cone	0.5-1 %	medium	medium / 3-5 D	short pipes	medium
pitot tube	3%	medium	low / 20-30 D	velocity meas.	low
variable area	1-10 %	medium	medium / none	flow indicator	low
positive displacement	1 %	good	high / none	consumption measurement	high
thermal mass	1 %	good	low / none	mass flow measurement	high
turbine	0.3 %	good	high / 10-20 D	accuracy	high
vortex	0.75 %	good	low / 15-25 D	no maintenance	medium
target	0.5-2 %	low	high / 10-20 D	no maintenance	low

Handbook of Applied Superconductivity, Volume 2

Print ISBN: 978-0-7503-0377-4

Temperature Sensors

- Metallic resistors
  - Platinum RTD
  - Rodium-iron RTD
- Semiconductor resistors
  - Carbon-glass RTDs
  - Carbon-Glass resistors
  - CernoxTM
  - Silicon Diodes
  - Germanium RTD
  - Ruthenium Oxide

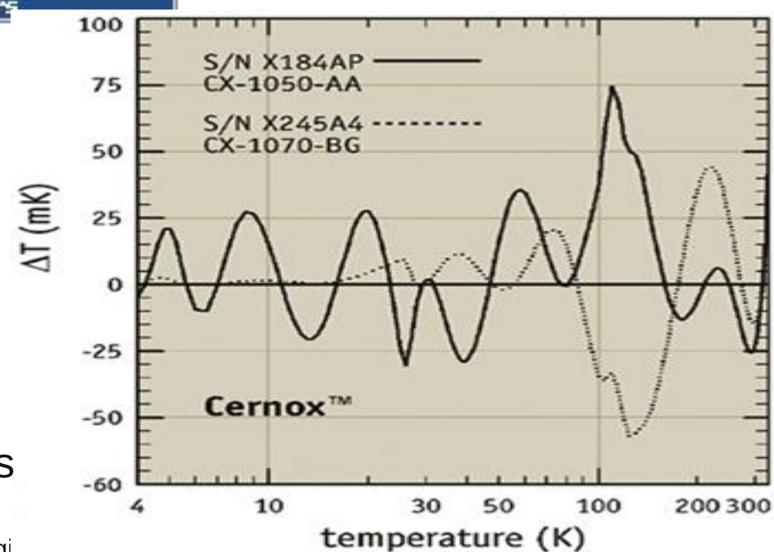
- Semiconductor Diodes (fast response time, wide range)
- Capacitor
- Thermocouples

Temperature Measurement

Temperature Range of Typical Lake Shore Sensors *		
Diodes	**Model**	**Useful Range**
Silicon Diodes	DT-670	1.4 - 500 K
GaAlAs Diode	TG-120	1.4 - 475 K
Positive Temperature Coefficient (PTC) RTDs		
100 ? Platinum RTD	PT-100, 250 Ω full scale	30 - 675 K
100 ? Platinum RTD	PT-100, 500 Ω full scale	30 - 800 K
Rhodium-Iron RTD	RF-800-4	1.4 - 400 K
Negative Temperature Coefficient (NTC) † RTDs		
Germanium RTD	GR-200A-1000	2 - 100 K
Germanium RTD	GR-200A-250	1.2 - 40 K
Carbon-Glass™ RTD	CGR-1-500	3 - 325 K
Cernox™ RTD	CX-1050 AA or SD	3.5 - 325 K
Cernox™ RTD	CX-1030 AA or SD	2 - 325 K
High-Temperature Cernox™ RTD	CX-1030-SD-HT	2 - 420 K
Rox™ Ruthenium Oxide RTD	RX-102A	2 - 40 K
Rox™ Ruthenium Oxide RTD	RX-202A	3 - 40 K

* Sensors sold separately.
† Single excitation current may limit the low temperature range of NTC resistors

Lakeshore Cryogenics
http://www.lakeshore.com/



Induced off-set (mK) for neutron and gamma rays

Temperature Sensors + Radiation environment

→ By principle, use redundant system

CERN Test benches:

- Thermo cycle
- Irradiation test : fluence values close to 10^{15} neutrons/cm^2, corresponding to 2.10^4 Gy

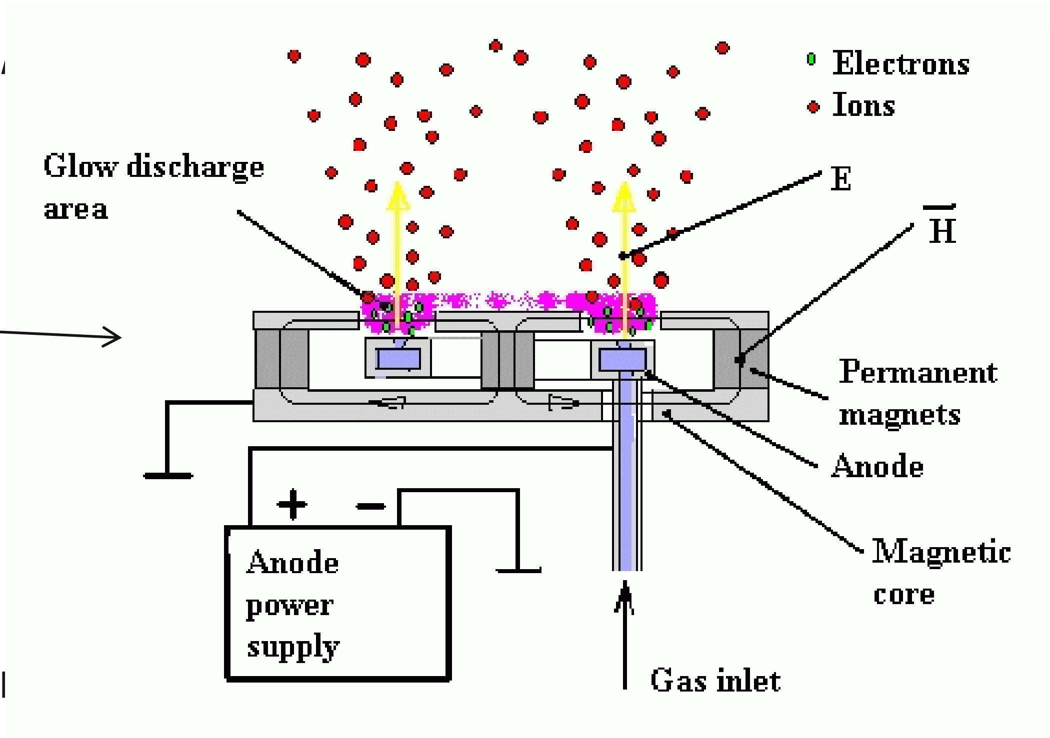
Thermometer (+number tested)	R @ 1.8K	dR/dT @ 1.8K	σ_T @ 1.8K	beam heating mK/(n.cm^{-2}.s^{-1})	ΔT Irradiation for 4 10^{14}n.cm^{-2}	Expected ΔT in LHC
AB (44)	6600 Ω	-10600 Ω.K^{-1}	8.10^{-5}	9 10^{-10}	+2 mK	< 2 mK
TVO (44)	5700 Ω	-3300 Ω.K^{-1}	3.3 10^{-5}	3 10^{-10}	+0.3 mK	< 0.5 mK
CX (66)	12600 Ω	-12000 Ω.K^{-1}	2.5 10^{-5}	10^{-10}	+1 mK	< 2 mK
Ge (5)	9000 Ω	-8000 Ω.K^{-1}	1.2 10^{-4}	0	+300 mK	+300 mK
RhFe thin-film (46)	15 Ω	+0.7 Ω.K^{-1}	3.10^{-5}	0	+12 mK	+3 mK/year
RhFe wire (36)	5.4 Ω	+0.6 Ω.K^{-1}	2.6 10^{-5}	0	+5 mK	+1.5 mK/year
Pt (22)	1.7 Ω	+3.5 10^{-4} Ω.K^{-1}	-	-	+1.5 K	-

Table 1 Results of irradiation at 1.8 K (average values)

Ref: "Neutron irradiation tests in superfluid helium of LHC cryogenic thermometers" by Amand,, et. al., International Cryogenic Engineering Conference - 17, Bournemouth, (1998), 727-730

Pressure Measurement

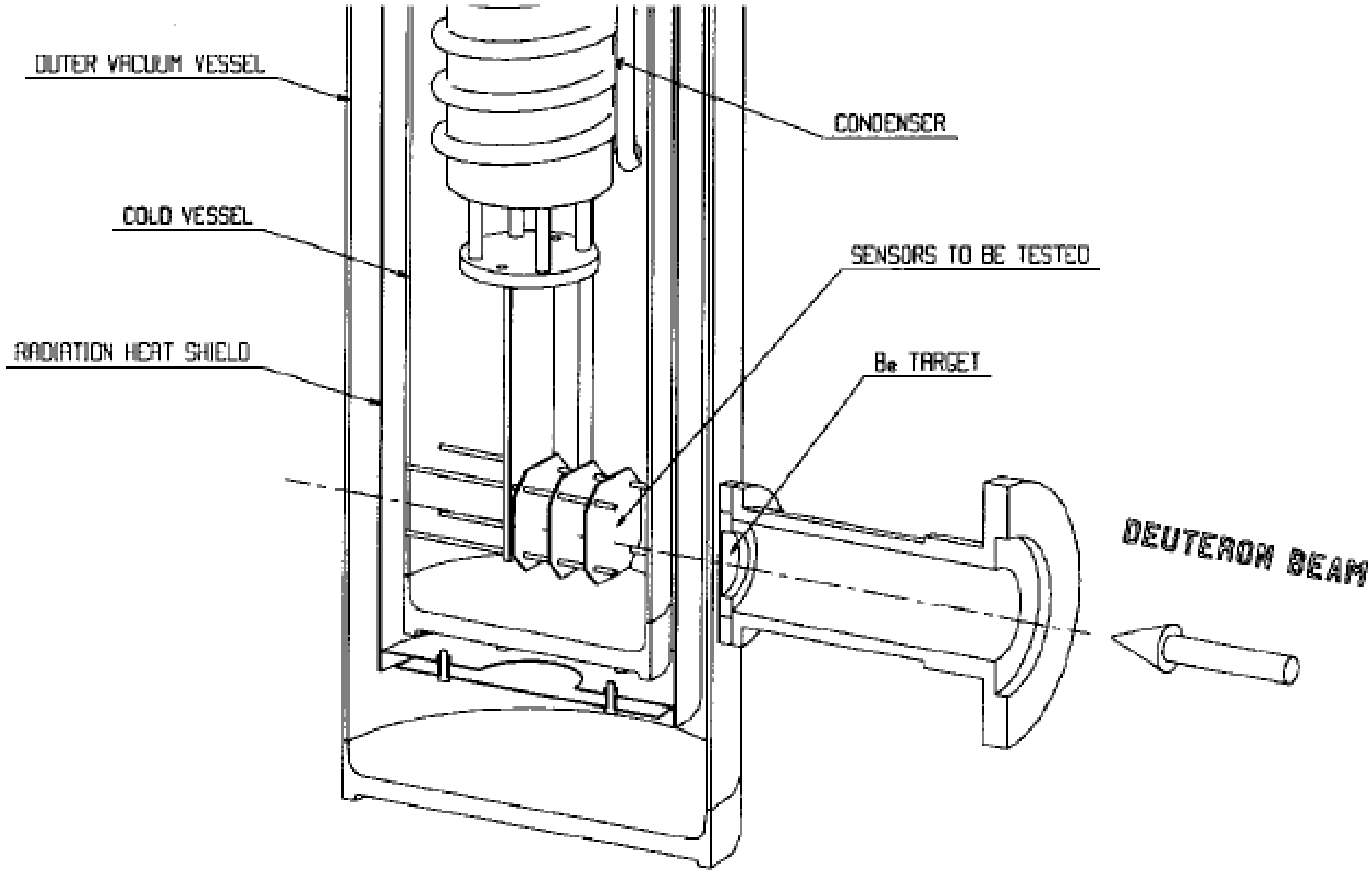
- Type: Absolute, differential, gauge
- Vacuum gage, e.g. cold cathode
- Problems with room temperature pressure measurement
  - Thermal acoustic Oscillation
  - Time response
- Some cold pressure transducers exist
- Capacitance pressure sensors



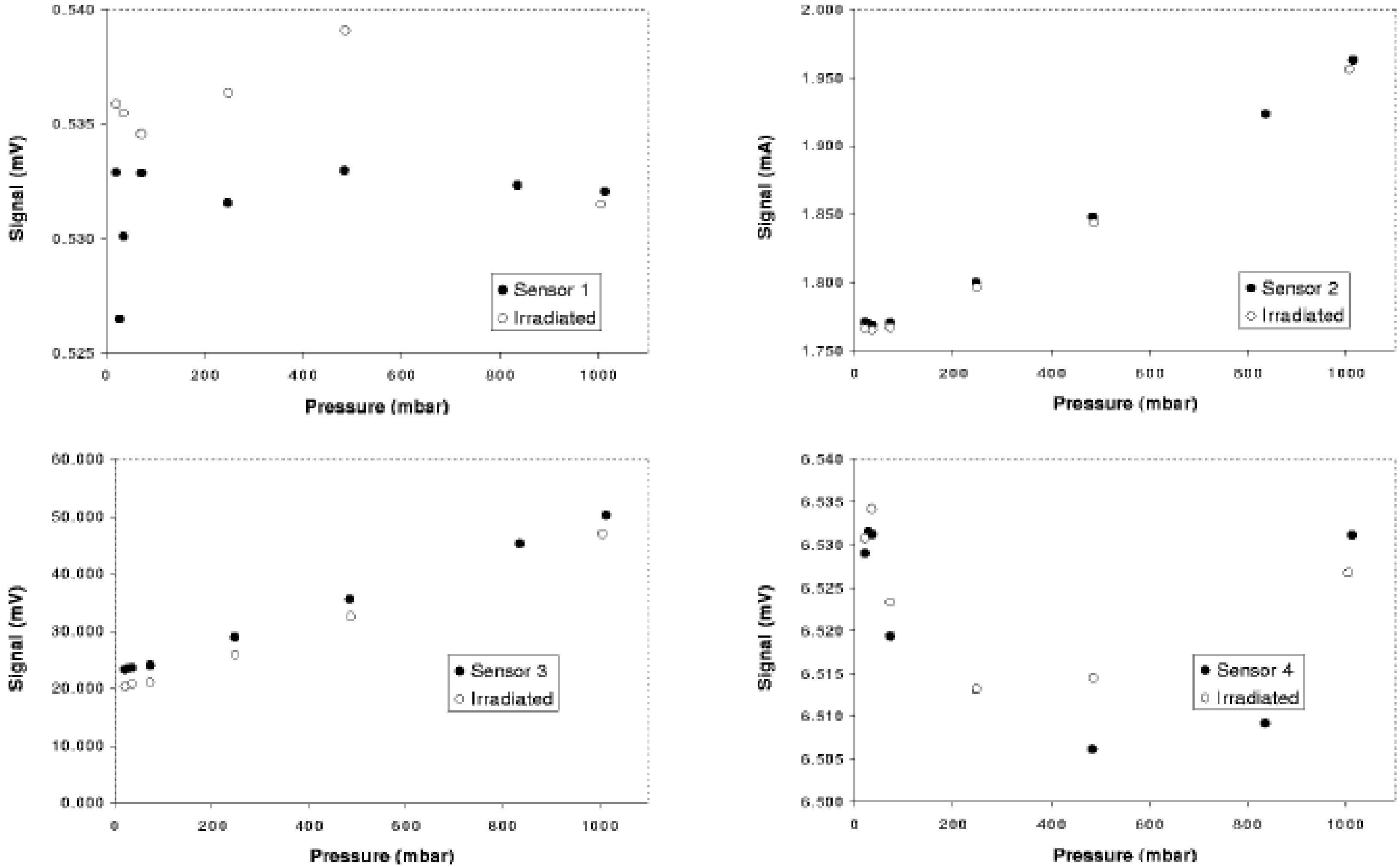
Pressure Measurement – Irradiation Test

Irradiated by neutrons (1-20 MeV, 10^15 n/cm^2)

➔ 10 years of LHC operation at full intensity



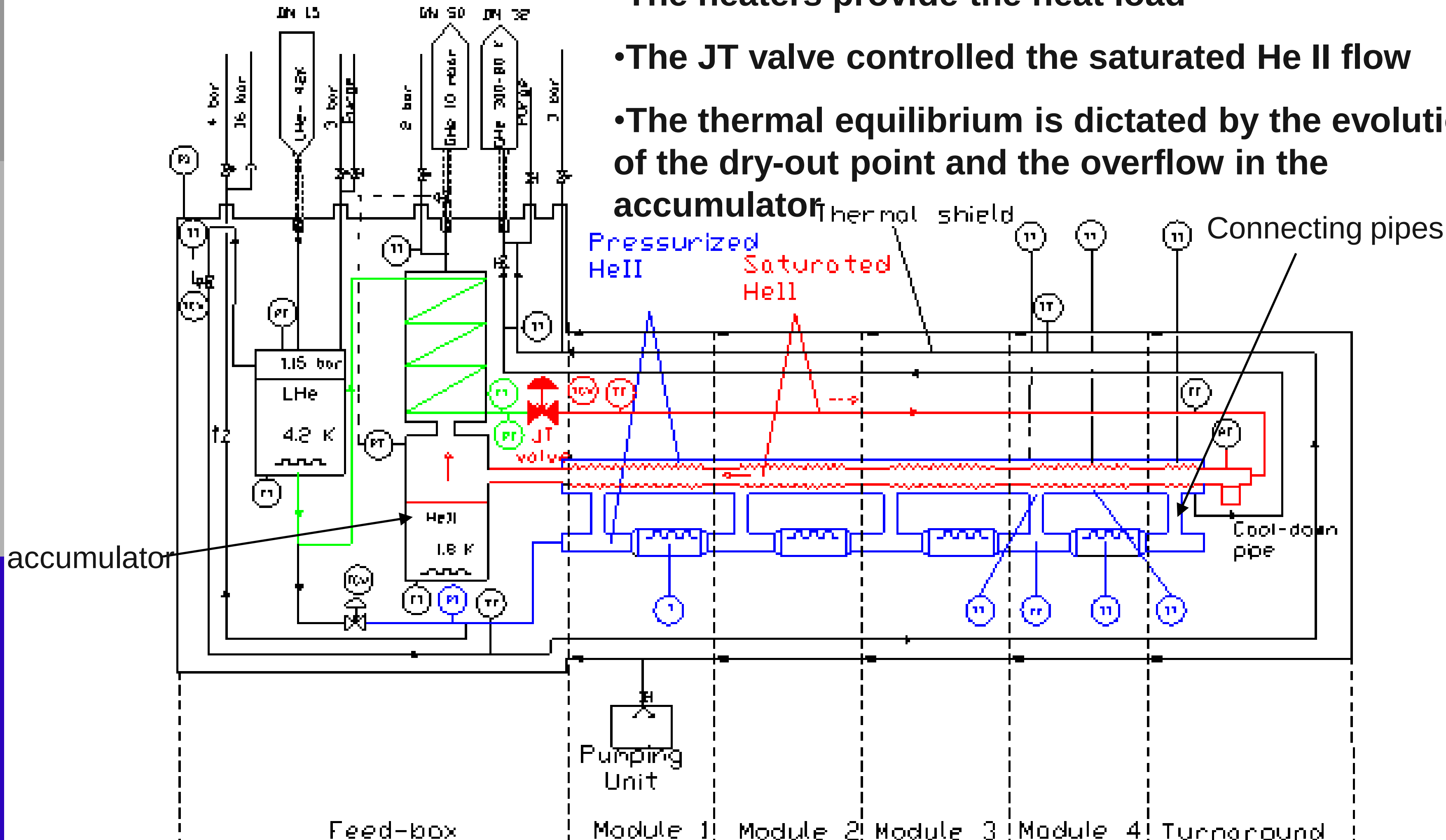
Pressure Measurement – Irradiation Test



Ref: Amand,, et. al., Neutron Irradiation Tests of Pressure Transducers in Liquid Helium, Advances In Cryogenic Engineering (2000) , 45B, 1865-1872

Example 1: HXTU - Process and Instrumentation Diagram

- The heaters provide the heat load
- The JT valve controlled the saturated He II flow
- The thermal equilibrium is dictated by the evolution of the dry-out point and the overflow in the accumulator



Instrumentation

Instrumentation	Total	Range	Accuracy
Temperature (Cernox®, Pt100)	54	1.6 – 40 K, 50 K – 300 K	± 5 mK, ± 5 K
Pressure (Absolute, Differential)	5	0-1.3 bar, 0-0.13 bar, 0-7.5 mbar	0.2%, 0.03 mbar
Level (AMI)	5	0-6", 0-12", 0-28"	± 2% FS
Flowmeter (Turbine+RT)	2	0-20 g/s	± 2% FS
Heaters (Electrical resistances)	12	55, 90, 240 Watts	
Control Valves	6	0-100 %	

Temperature sensors implemented in the pressurized He II bath

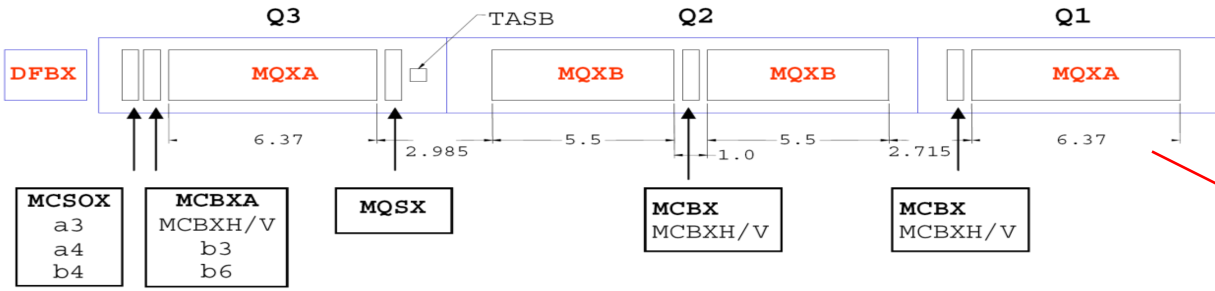
- Error of +/-5 mK on the temperature measurements.
- Stainless steel tubes to route the wires.

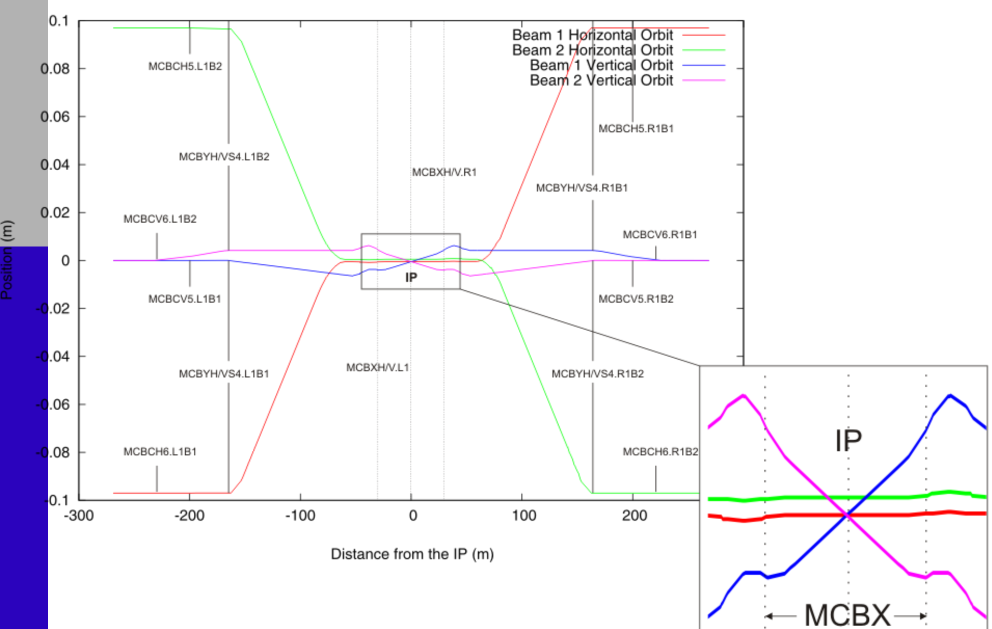
Example 2: The Low-β Magnet Systems at the LHC

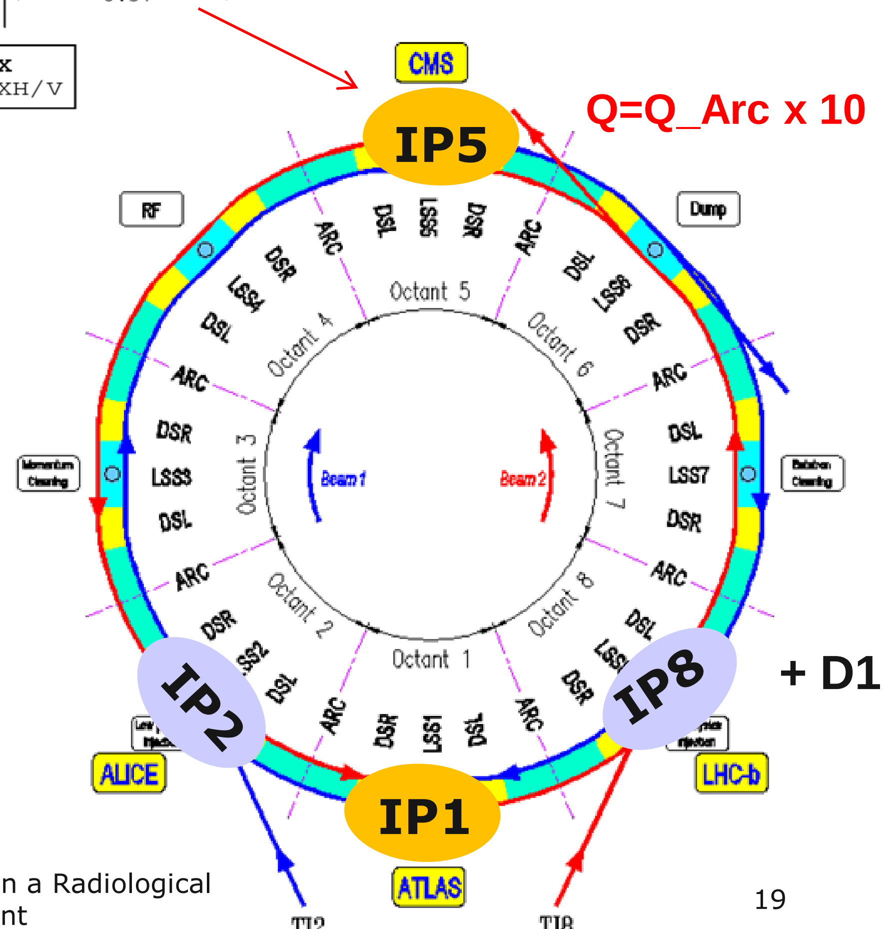
➔ **Critical system for LHC performance**

Inner Triplet for final beam focusing/defocusing

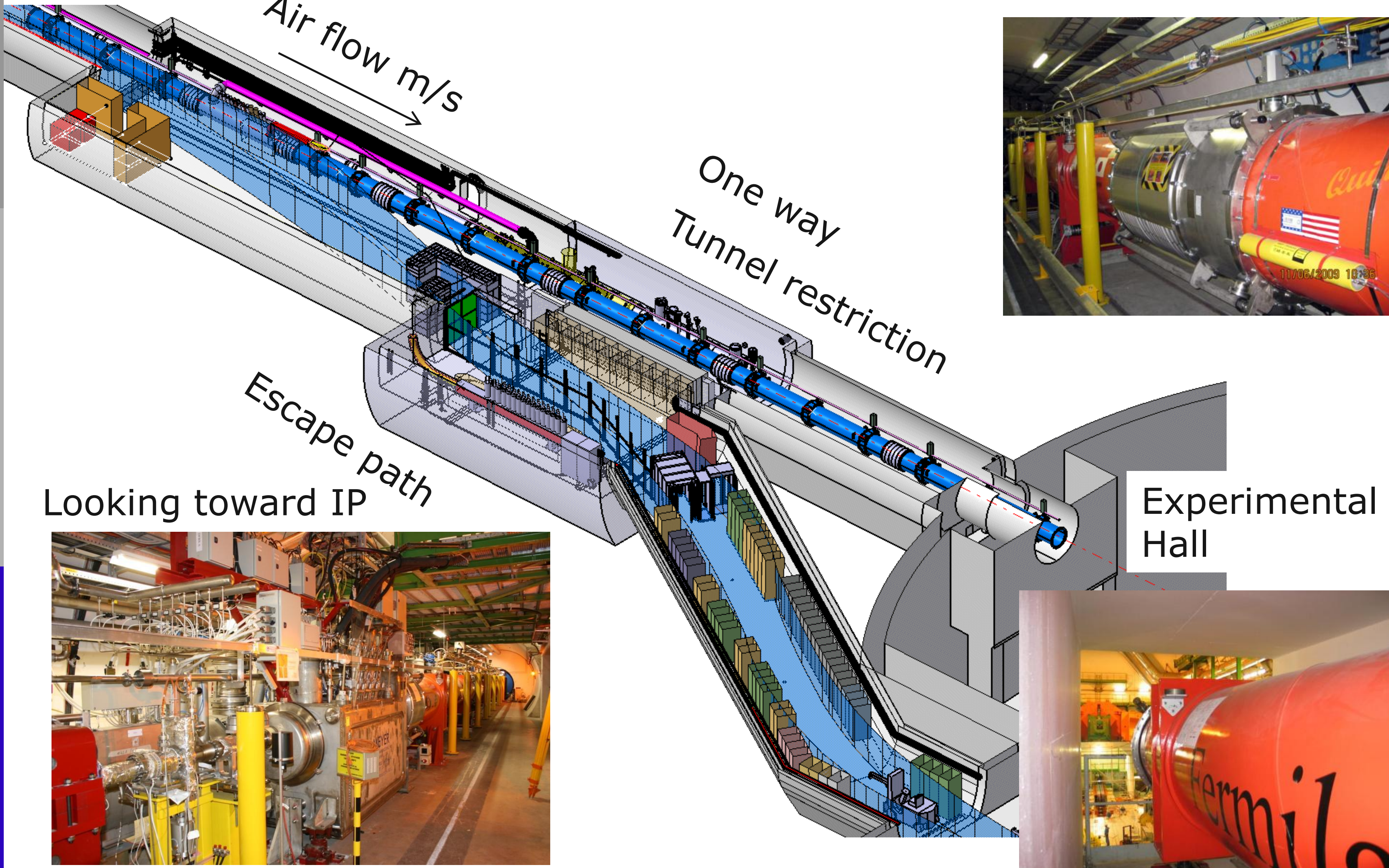
American contribution to the LHC machine







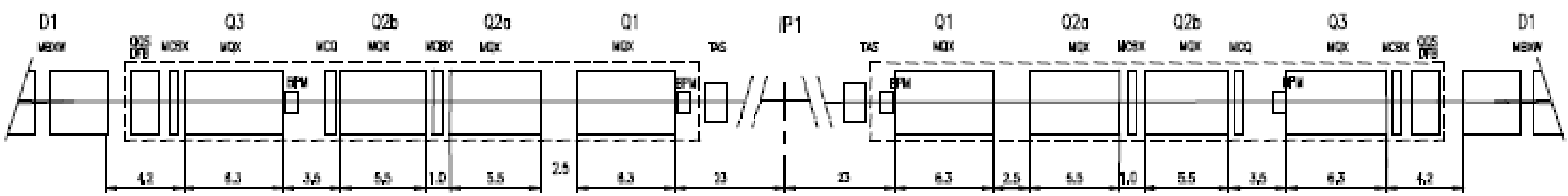
Underground views : 80-120 m below ground level



The low-β magnet system safety specification

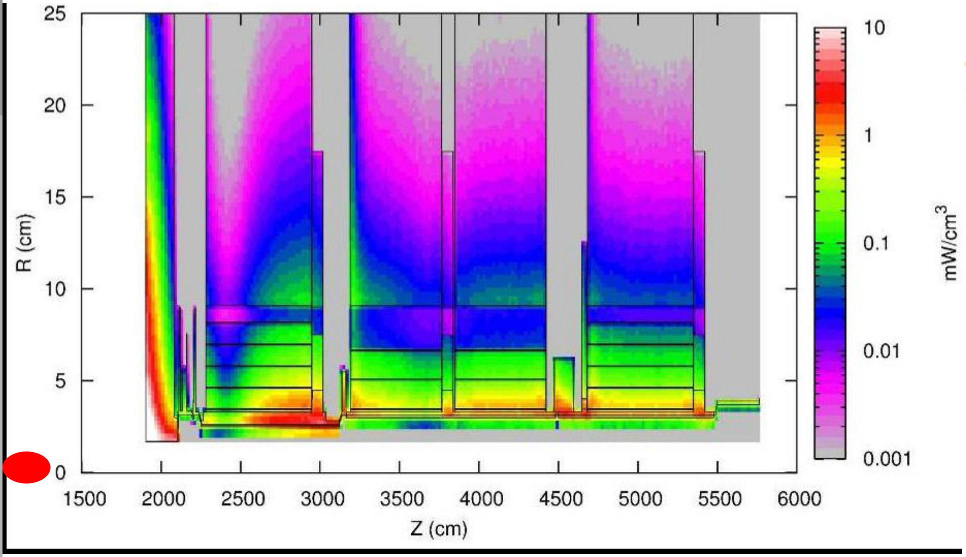
Design and operation requirements:

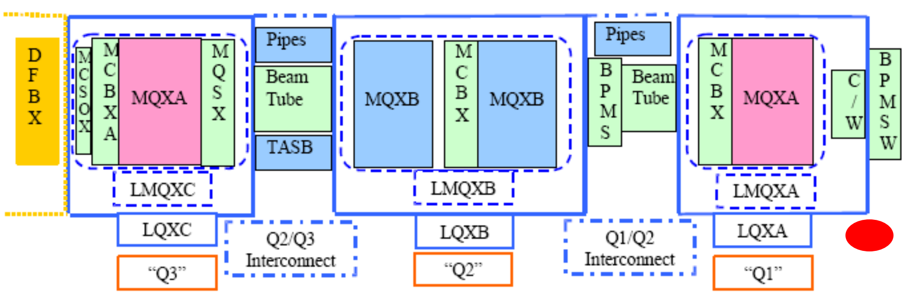
- Critical system for LHC performance, but the system operation and maintenance should remain safe for personnel and for equipment,
  e.g. escape path, absorbed radiation dose, embrittlement, polymer prop. decay.
- Equipment, instrumentation and design shall comply with the CERN requirements,
  e.g. ES&H, LHC functional systems, Integration
- Risks identified: Mechanical, electrical, cryogenics, radiological
- Cryogenic risk → FMEA, Use the Maximum Credible Incident (MCI)
- Radiological → Use materials resistant to the radiation rate permitting an estimated machine lifetime, even in the hottest spots, exceeding 7 years of operation at the baseline luminosity of $10^{34} cm^{-2} s^{-1}$.
- Personnel safety: Keep residual dose rates on the component outer surfaces of the cryostats below 0.1 mSv/hr.
- Apply the ALARA principle (As Low As Reasonably Achievable).



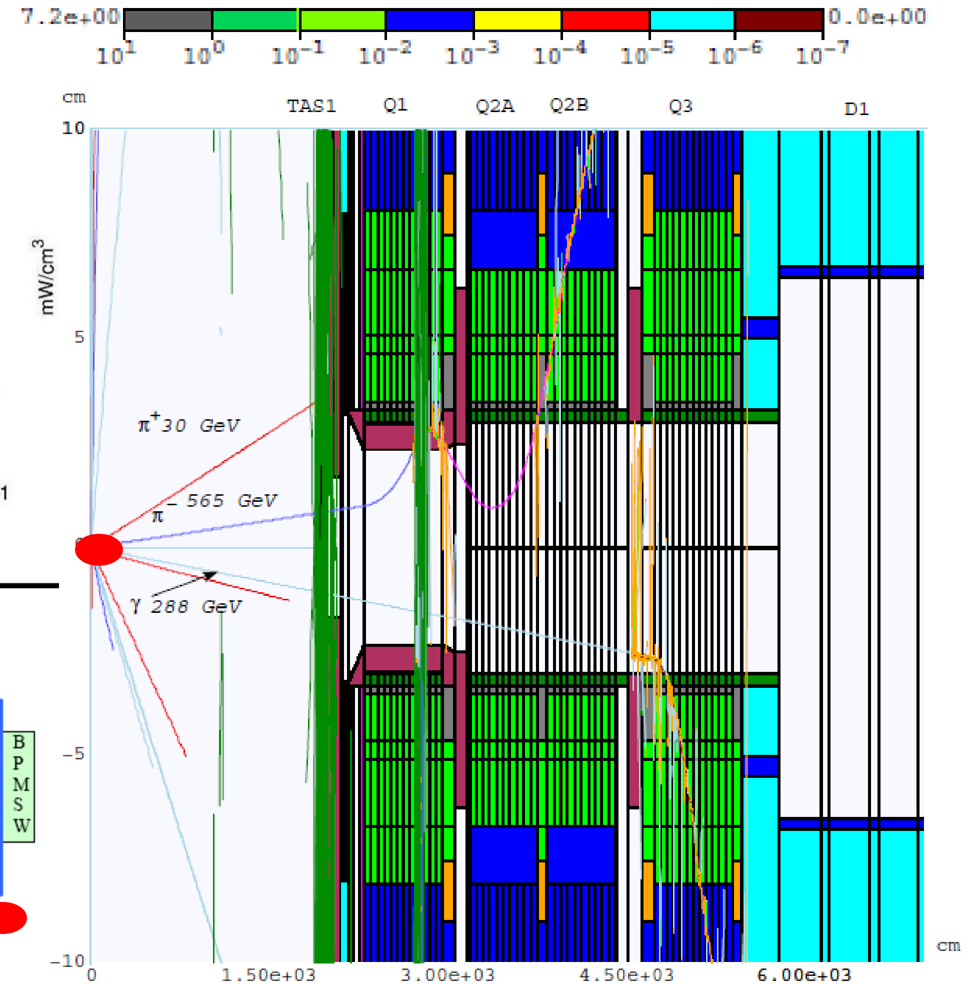
Radiological risk - Power density (mW/cm^3)

IR5 azimuthally averaged power distribution.

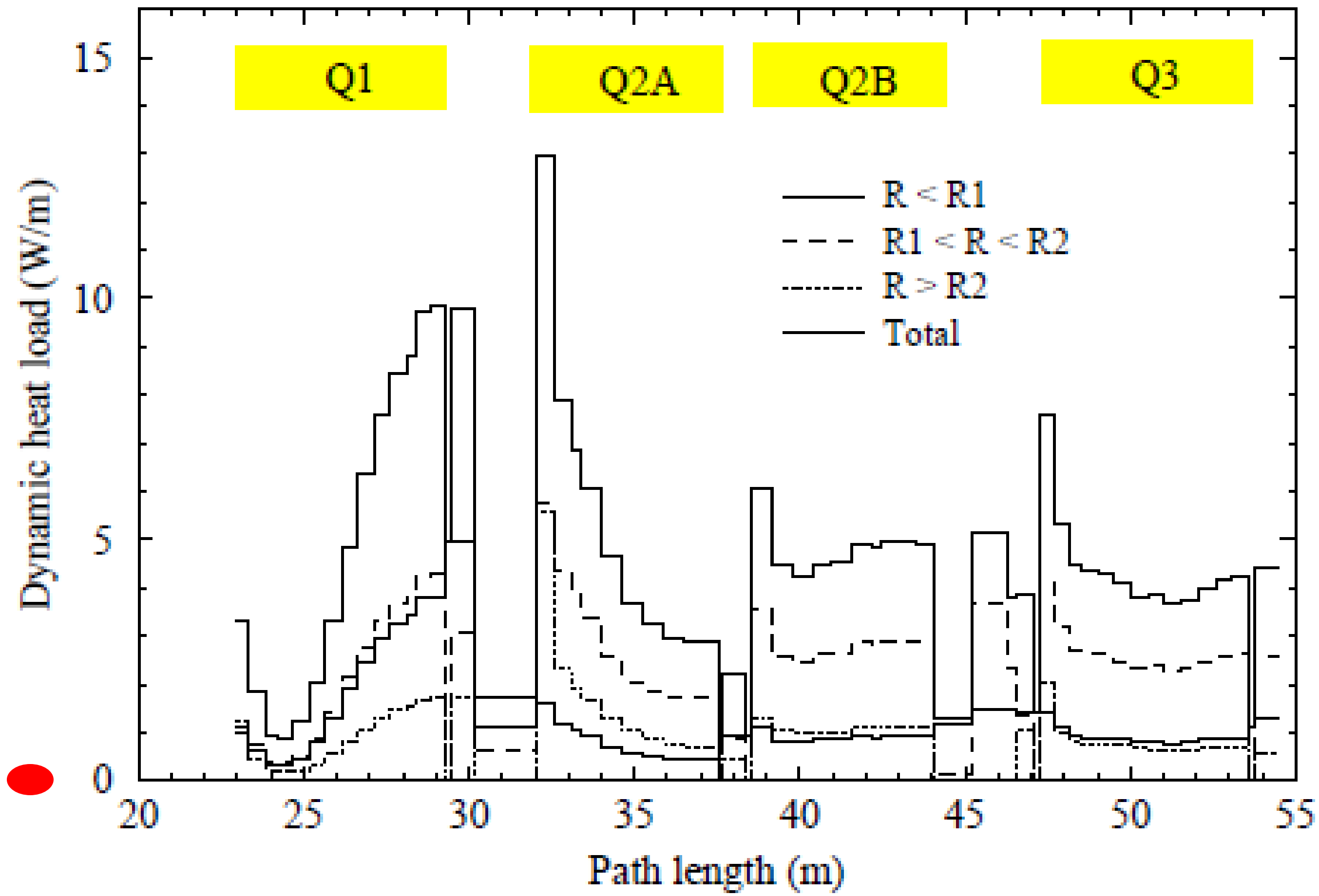




Particle tracks reaching the inner triplet and those generated there for a *pp-collision in* the IP1

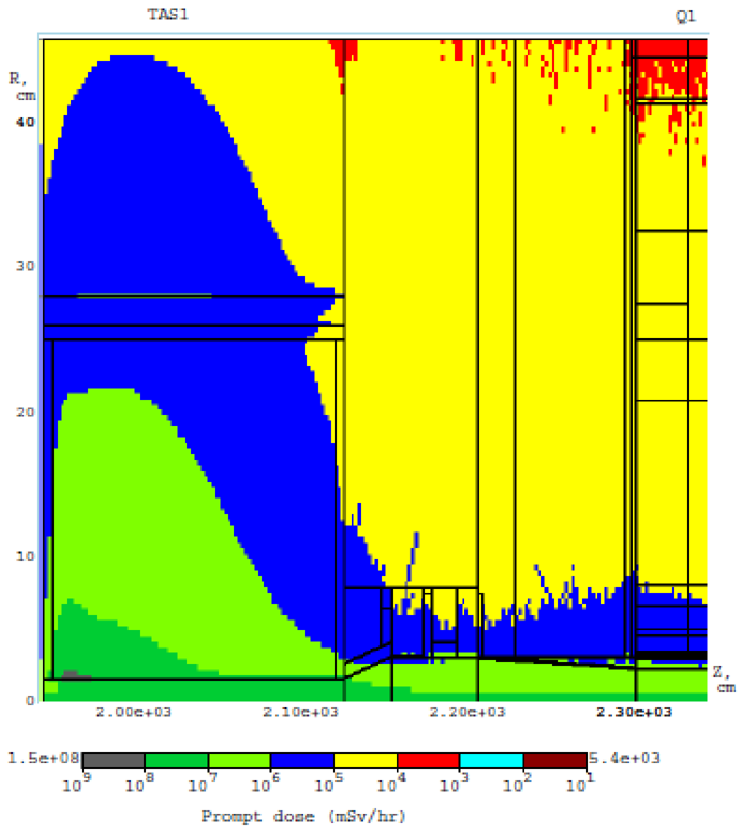


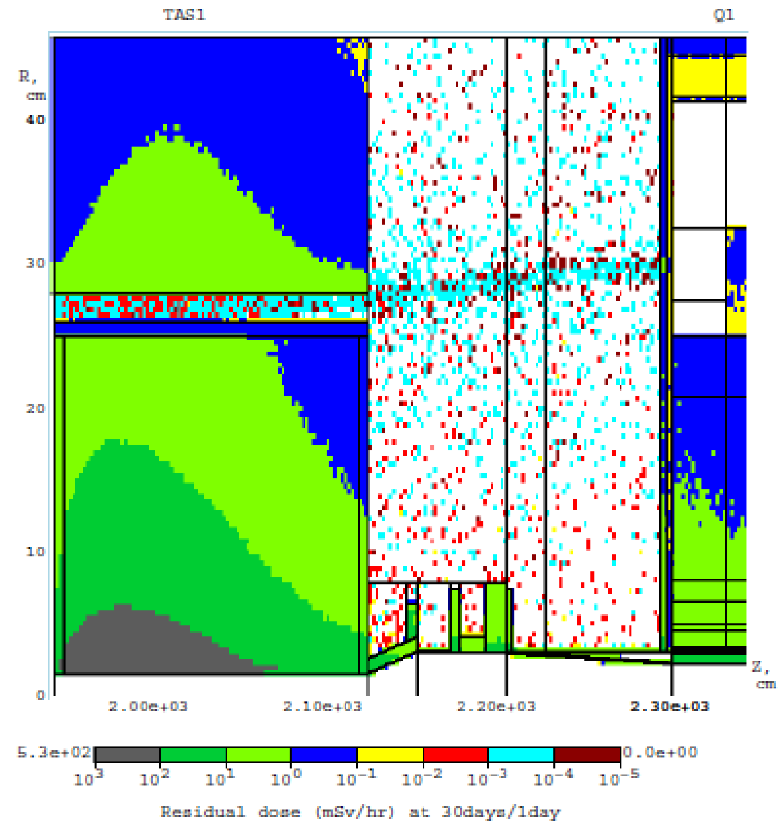
Radiological risk - Power density (mW/cm^3)



Power dissipation in the baseline IP5 inner triplet components. R1=35 mm, R2=81 mm in Q1 and Q3 and R2=67 mm in Q2a and Q2b

Radiological risk - Absorber





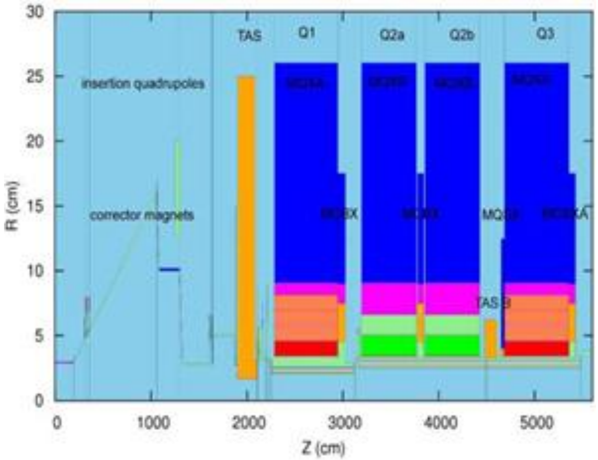
Azimuthally averaged prompt dose equivalent (left) and residual dose rate on contact after 30-day irradiation and 1-day cooling (right) in mSv/hr in the TAS-Q1 region at the baseline luminosity

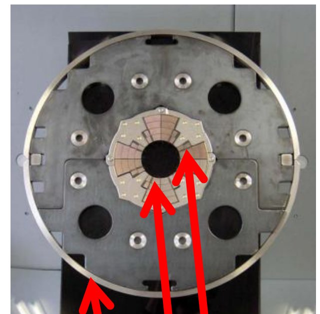
➔ The maximum of 12.5 mW/g (or 100 MGy/yr) at 15 cm (z=1960 cm) is determined by photons and electrons coming to the absorber

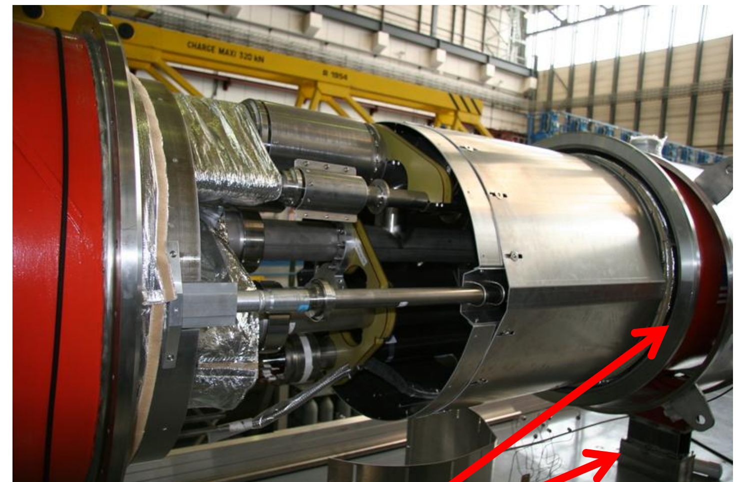
Radiological risk

"Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions", by N.V. Mokhov et. al

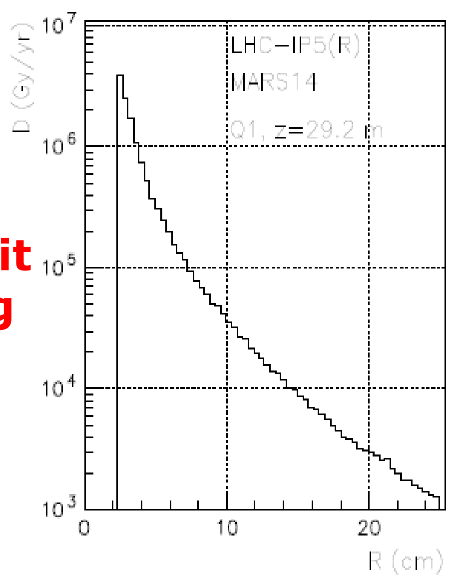
IR5 azimuthally averaged power distribution







Radial distribution of azimuthally averaged dose (Gy/yr)



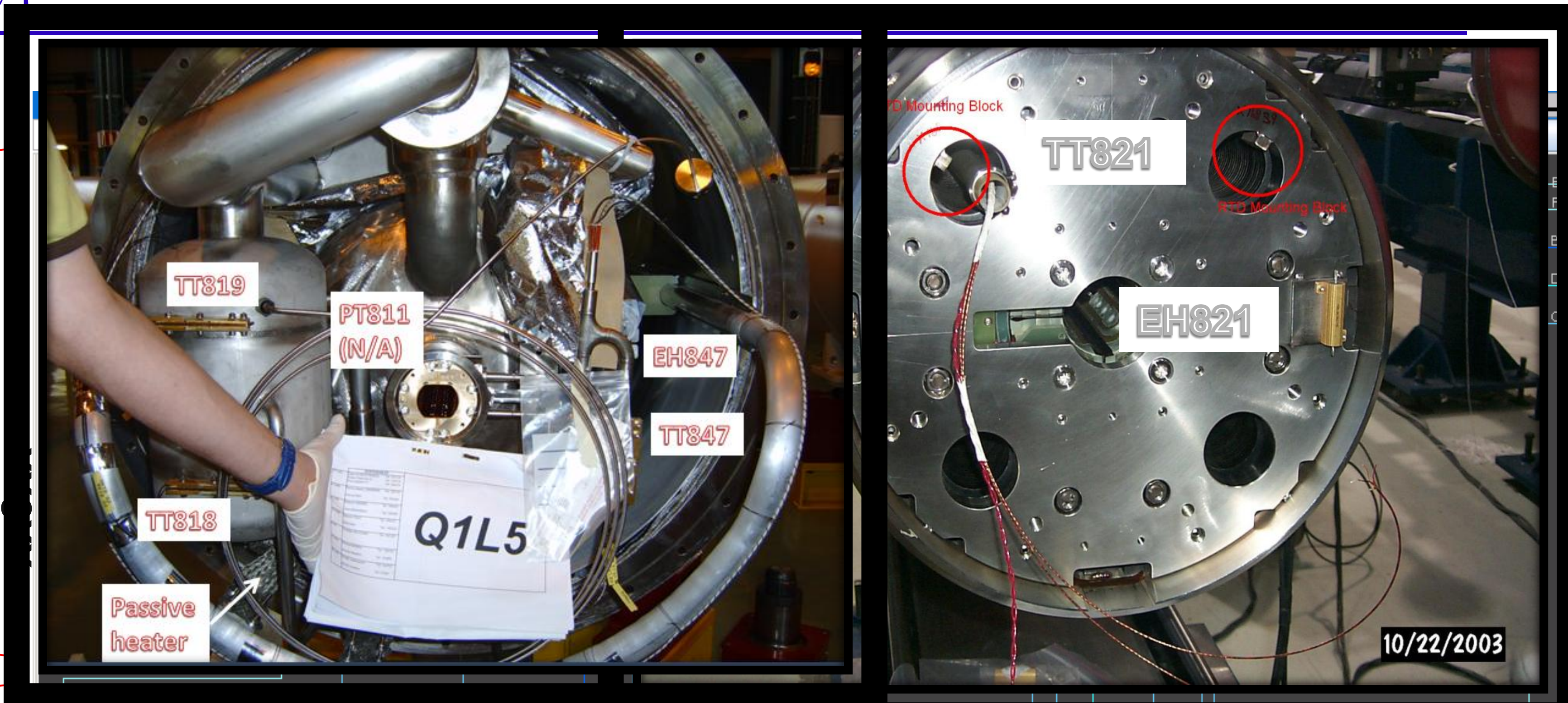
→ Magnet quench limit =1.6 mW/g

Element	z-region (m)	P (W)	D (kGy/yr)
Pipe		0.841	
Bore		1.994	
Helium	54.45-58.83	0.108	523.2
Jack		0.936	310.6
Ins+vessel		0.488	
r=9 cm		1.014	74.18
r=15 cm	54.485-58.795	0.470	20.85
r=30 cm		0.272	6.074

For comparison : Arc magnet ~ 1 Gy/yr

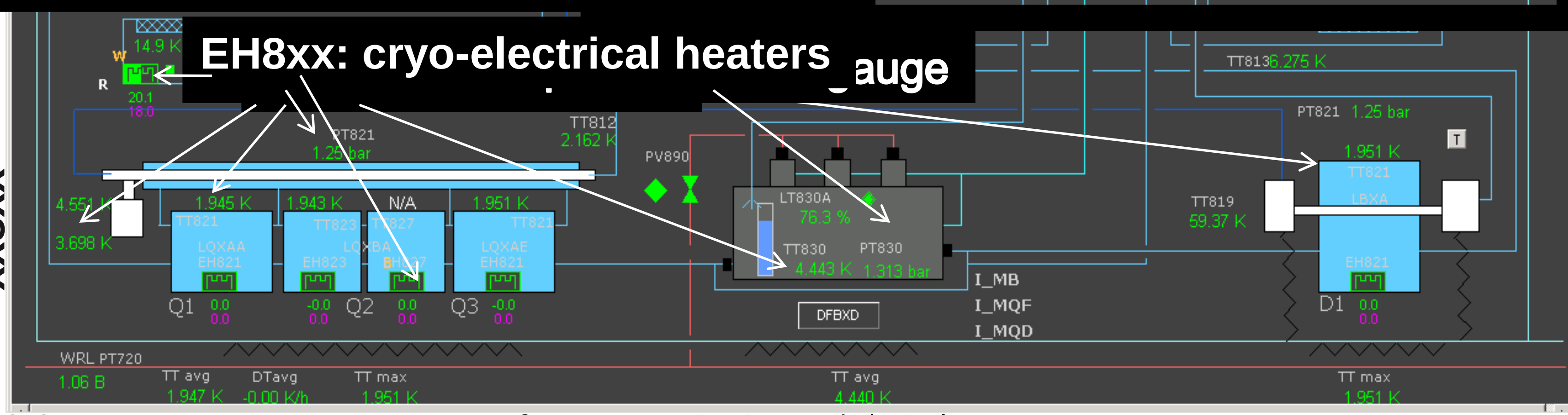
Type of instrumentation

Interface with QRL

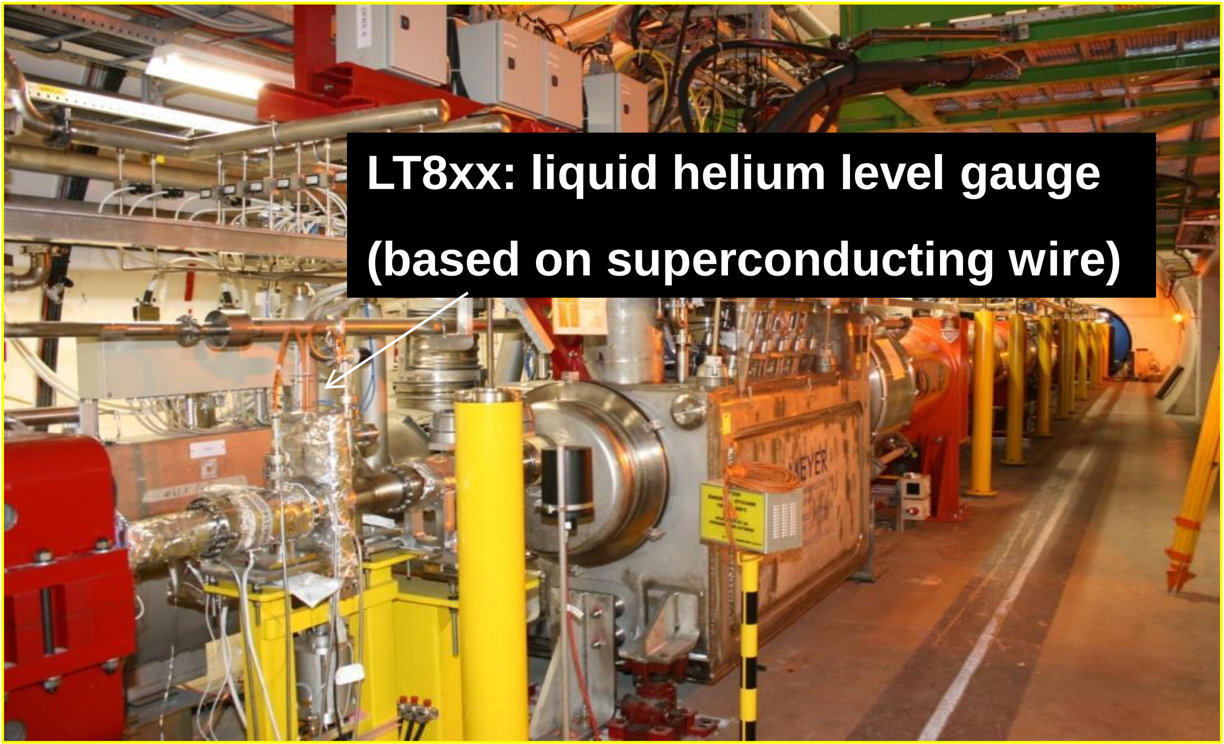


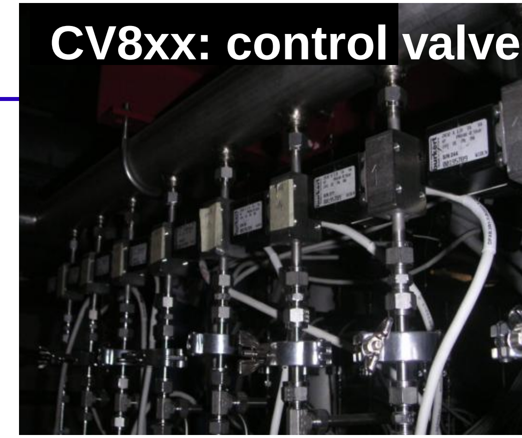
Low-β system

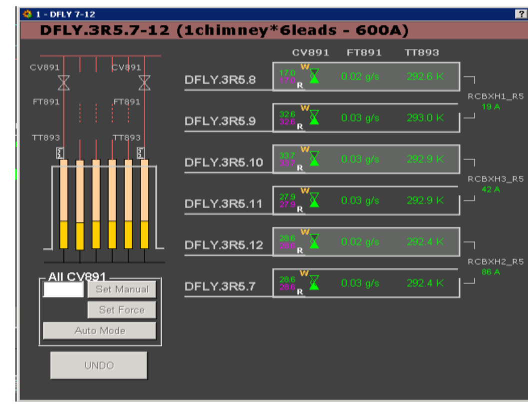
xx8xx

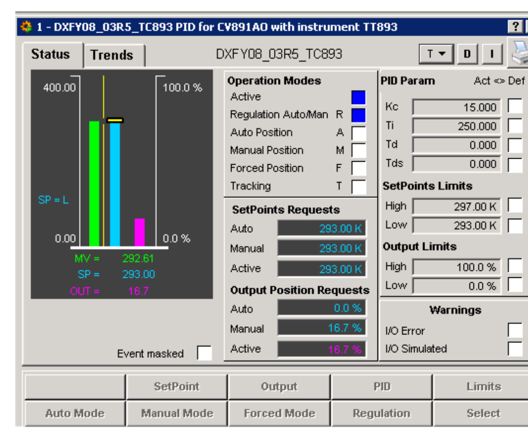


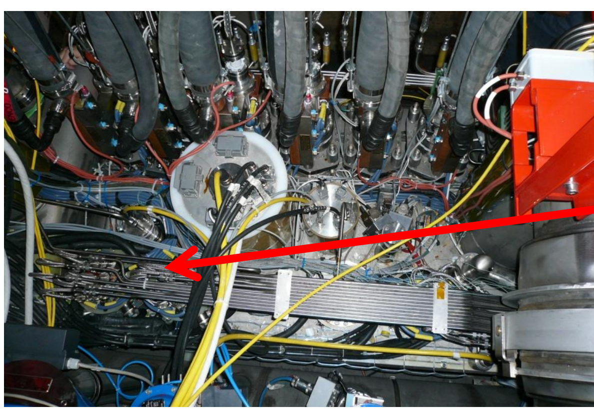
Type of instrumentation

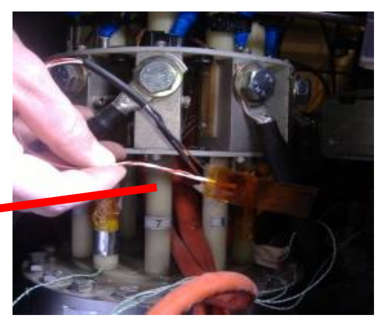










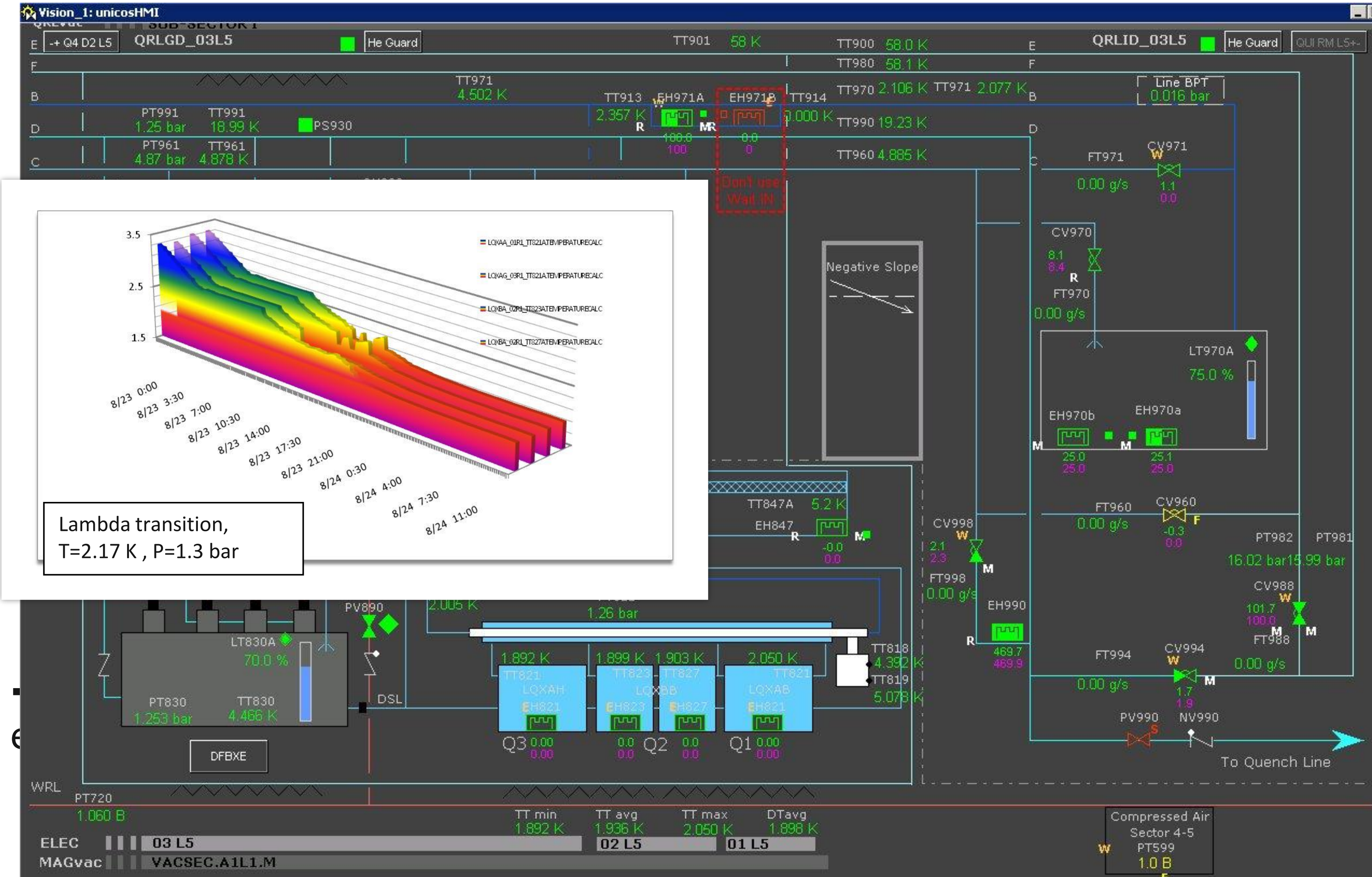


***HTS leads**

***VCL leads**

***Inner triplet feed through**

Reliability – Performance measurement



Radiological risk

In order to compare energy deposition results with FLUKA 2006.3 and MARS 15

Energy deposition in GeV/primary, for proton-proton collision.

Power = Energy*10^9 *1.602*10^−19 *L*A*10^−24

L = luminosity in collisions· 10^35 cm-2s-1

A = reaction cross section (including inelastic scattering and single diffraction events) in barn (80 mbarn)

IR Elements	FLUKA	MARS
TAS	1853.7	1827.3
Beam pipe	89.1	97.9
Q1 cable	158.0	159.1
Q1 yoke	96.3	78.5
Aluminium layer	2.3	2.4
Insulation	19.5	20.4
Stainless steel vessel	16.8	17.3

➔ Power [W] =1.28*Energy [GeV/collision]

Power density[mW/cm^3] =1280*Energy [GeV/cm^3 /collision]

Comparison of total heat loads (W), upgrade luminosity L=1035cm^-2s^-1

IR Elements FLUKA MARS

Radiological risk mitigation

- The inner-triplet final design included additional radiation shielding and copper absorber (TAS)

- The chosen instrumentation and equipment are radHard and halogen free (neutron irradiation experiment performed on temperature sensors : fluence values close to 10^{15} neutrons/cm^2, corresponding to 2.10^4 Gy).

- PEEK versus Kel-F material used for the DFBX low temperature gas seal

- LHC tunnel accesses modes were defined, e.g. control and restricted modes

Radiological risk mitigation

- Specific hazard analysis is requested to intervene on the low-β systems

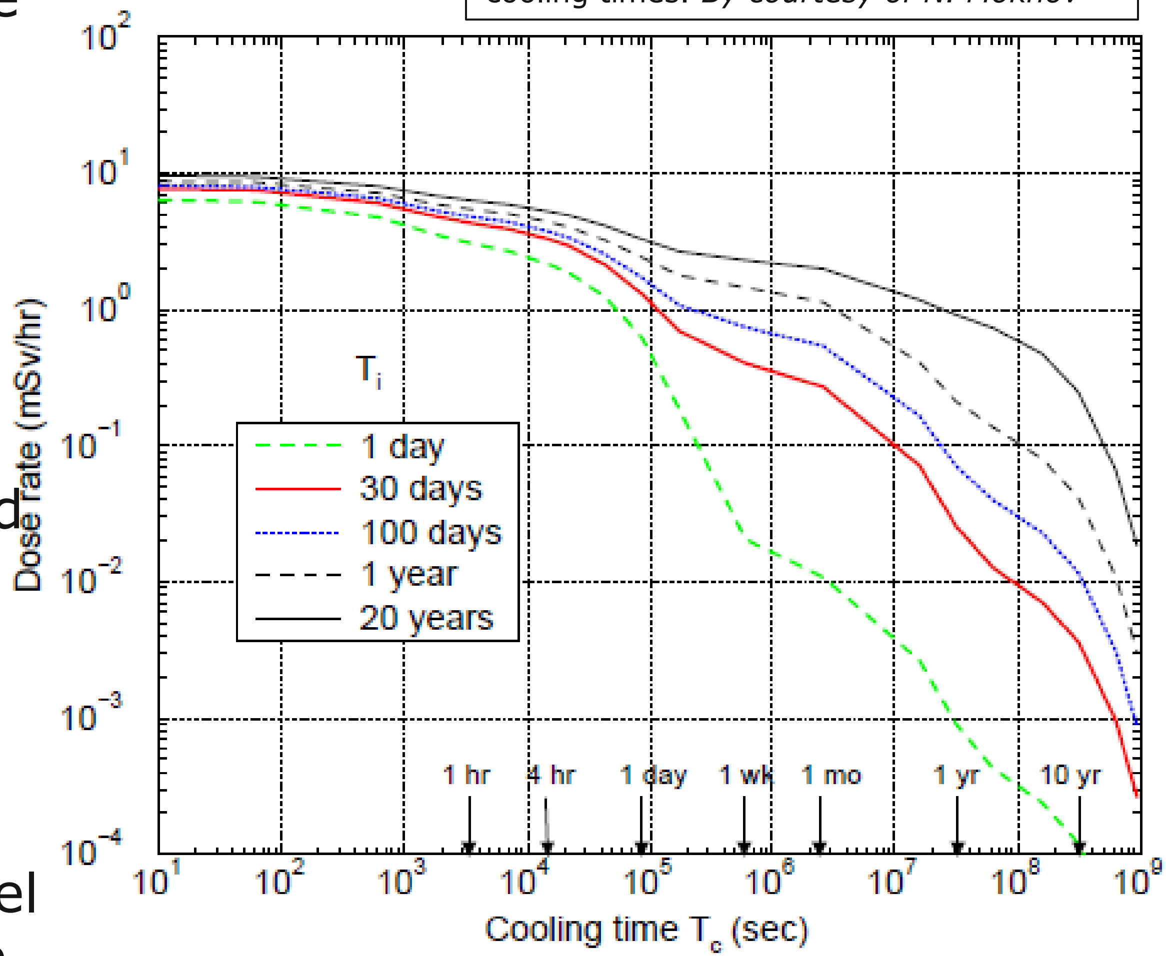
- Radiological survey systematical performed (< 1mSv/hr)

- Procedures written based on lessons learned

- Limit the personnel exposition time

- Process control w/ interlocks and alarm level for each operating mode

Averaged over surface residual dose rate (mSv/hr) on the Q1 side (z=2125 cm, bottom) of the TAS vs irradiation and cooling times. *By courtesy of N. Mokhov*



Risk mitigation: control operation upsets

- The so-called "Cryo-Start" and "Cryo-Maintain" threshold were tuned

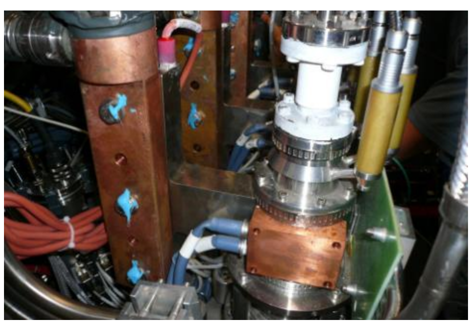
- Temperature switch ultimately protect the operation of the HTS leads by using the power converter

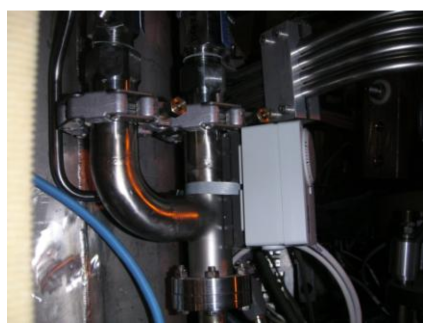
- Temperature switch on the safety relief valve to monitor possible helium leak

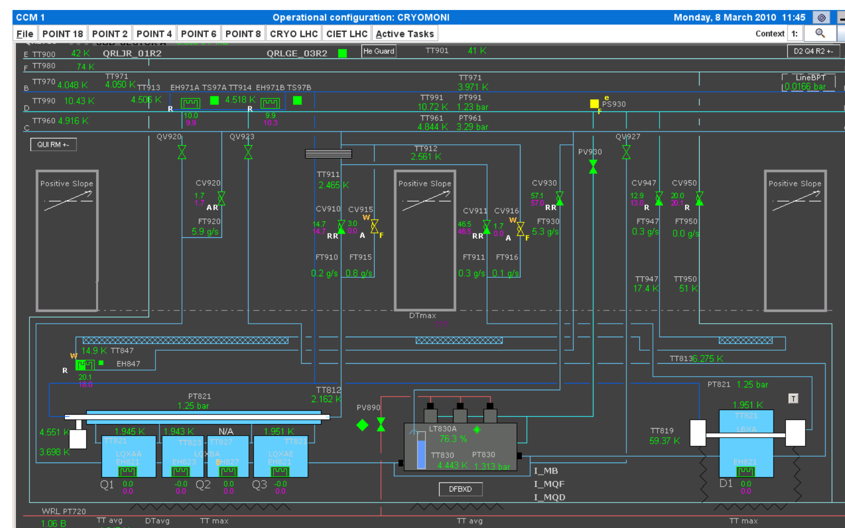
- Interlocks on insulating vacuum pressure measurement

- DFBX Vapor Cooled Lead (VCL) voltage drop is 160 mV

- If pressure in the helium distribution line rise, then isolate DFBX (w/ low MAWP)





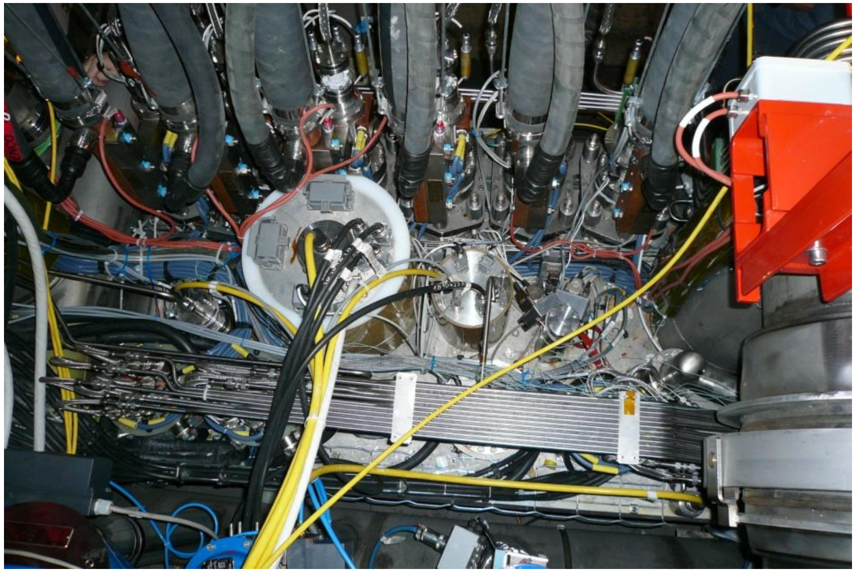


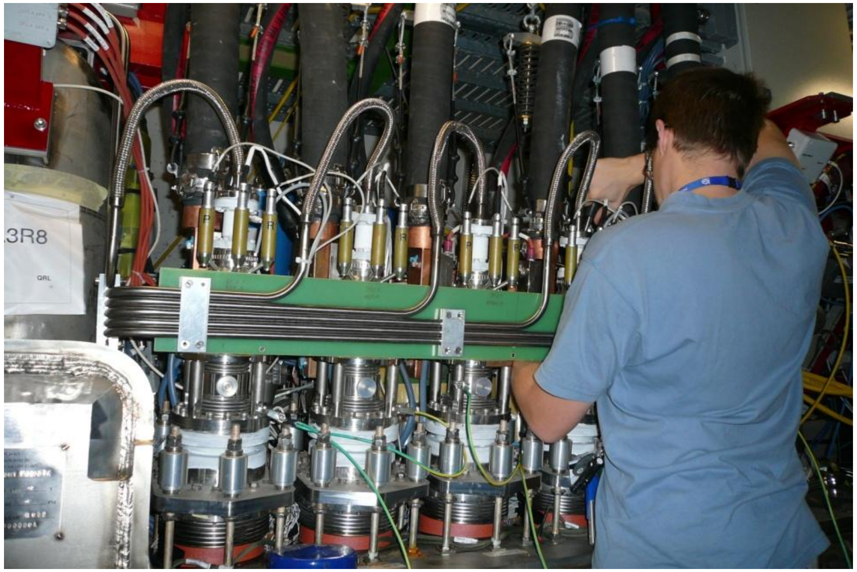
Risk mitigation : personnel training

•In addition to the use of software and hardware interlocks to limit risks, personnel's training is of prime importance.

•New classes comply with the CERN safety policy. They train the personnel to behave safely in a cryogenic and radiation environment.

•Awareness and preventive actions are mandatory to complete each technical task. Dedicated hazard analyses are enforced to work in the low-β magnet system area.





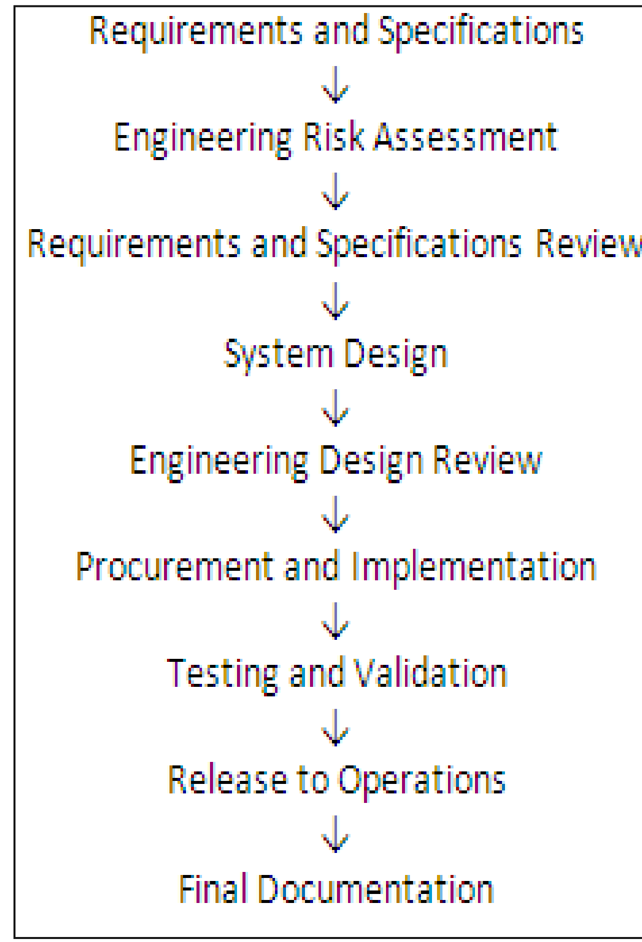
"Compact" DFBX area

Engineering process approach

Opening to a new Engineering process approach:

A new engineering manual was issued at Fermilab:

Engineering Process sequences

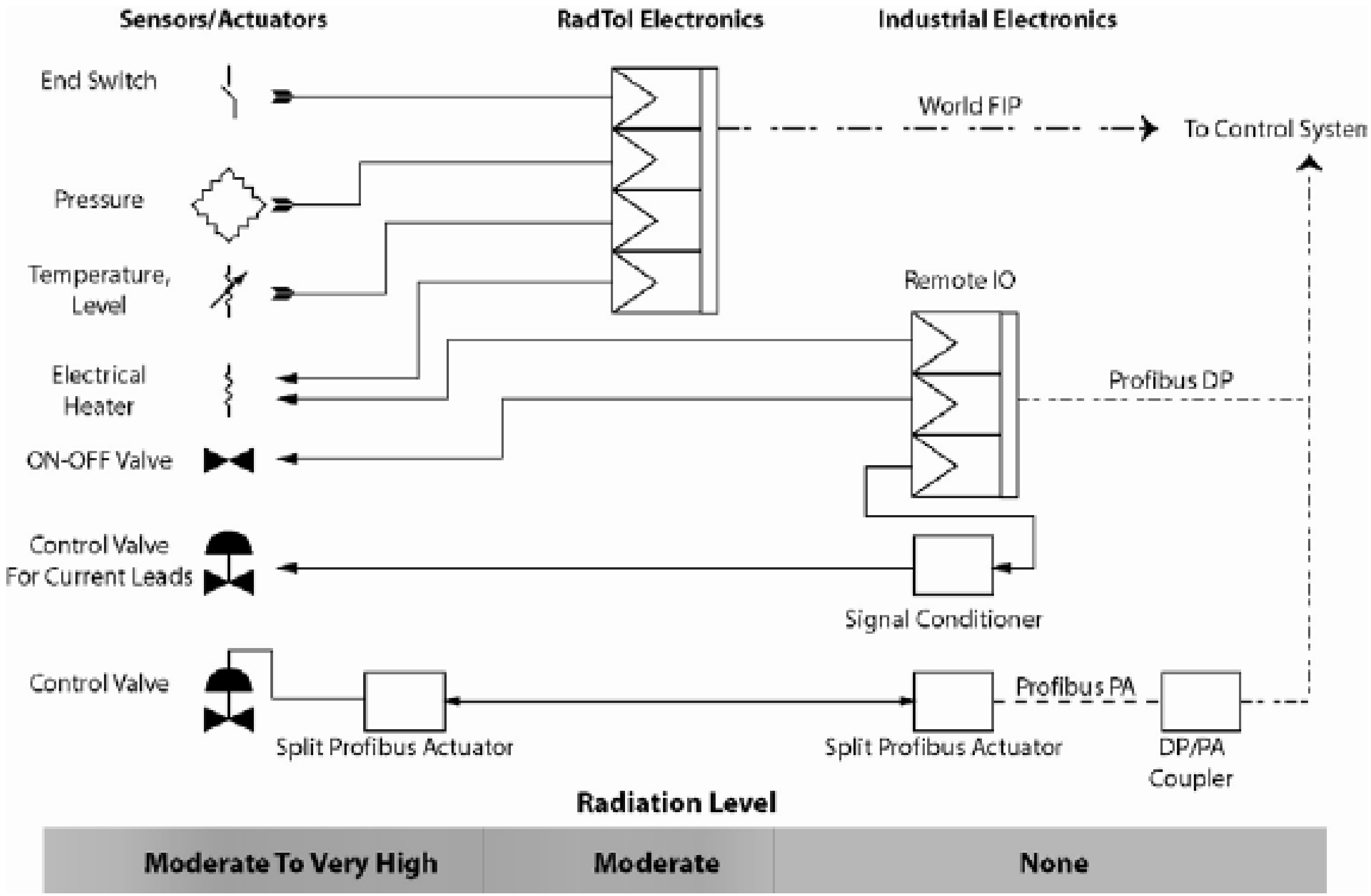


- This risk-based graded approach provides safe, cost-effective and reliable designs.

- The implementation flexible to loop within the given sequences.

- The implementation of this process will be adjusted to the Fermilab future projects

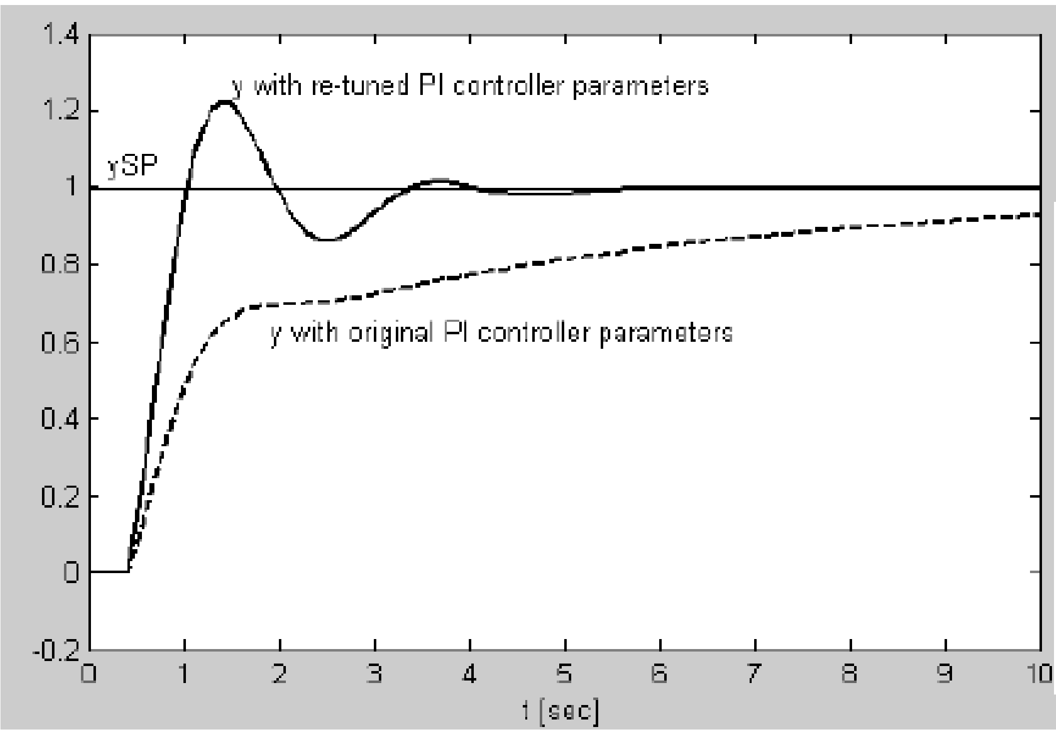
Cryogenic Instrumentation Identification

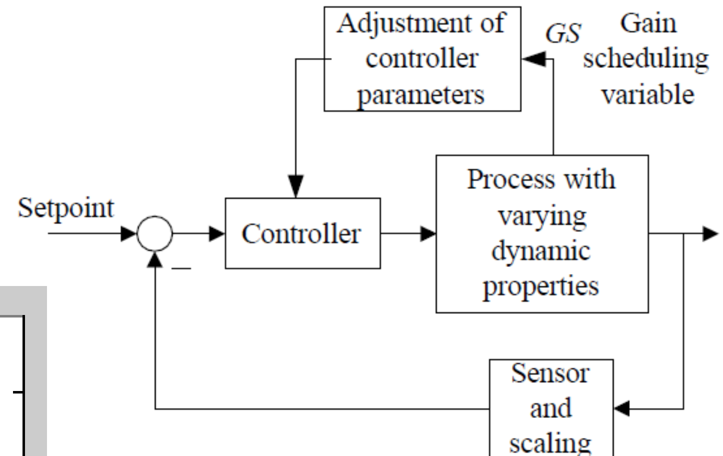


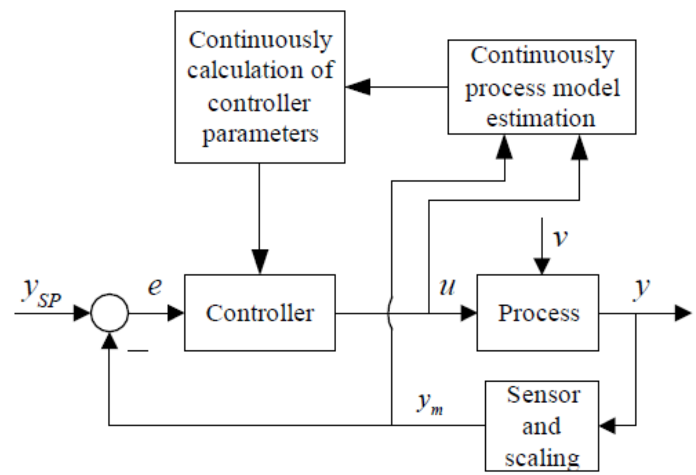
Ref: "First Experience with the LHC Cryogenic Instrumentation", by N. Vauthier et al, LHC Project Report 1078, 2007

Adaptive Controller : Proportional Integral Derivative

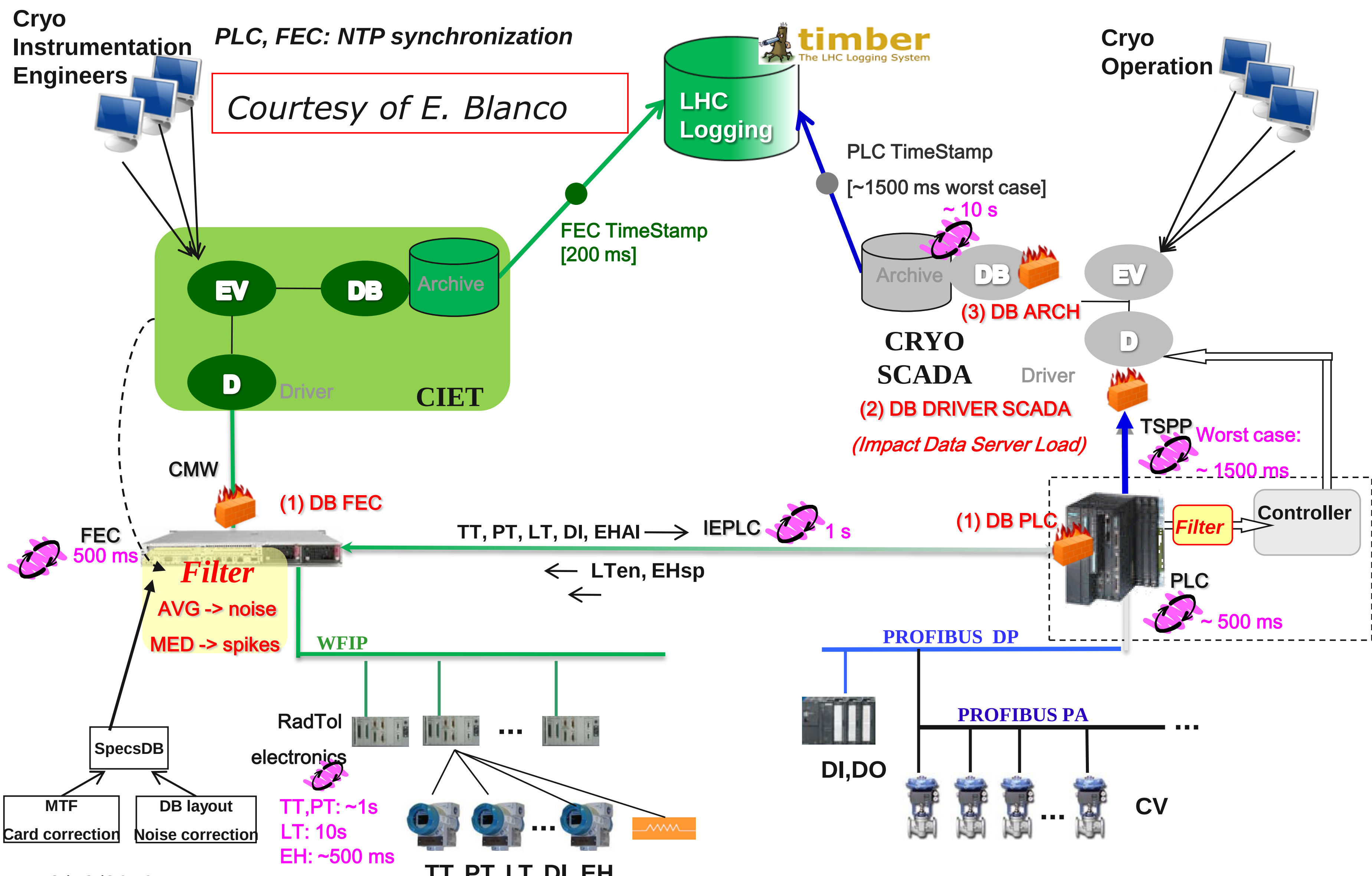
Example: Response in process output for control system with original and re-tuned PI controller parameters





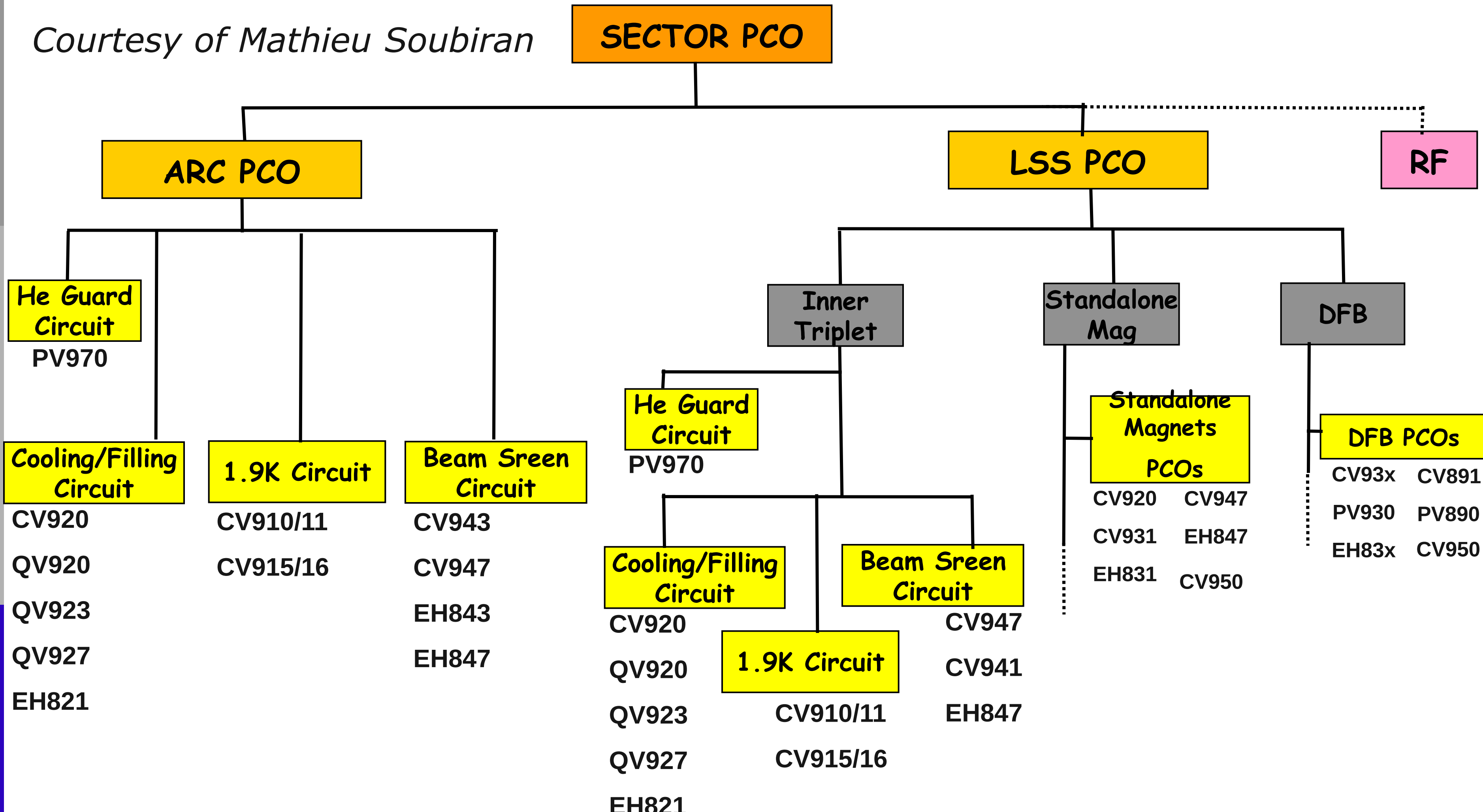


Availability : Data flow & LHC Logging Cryogenics Data



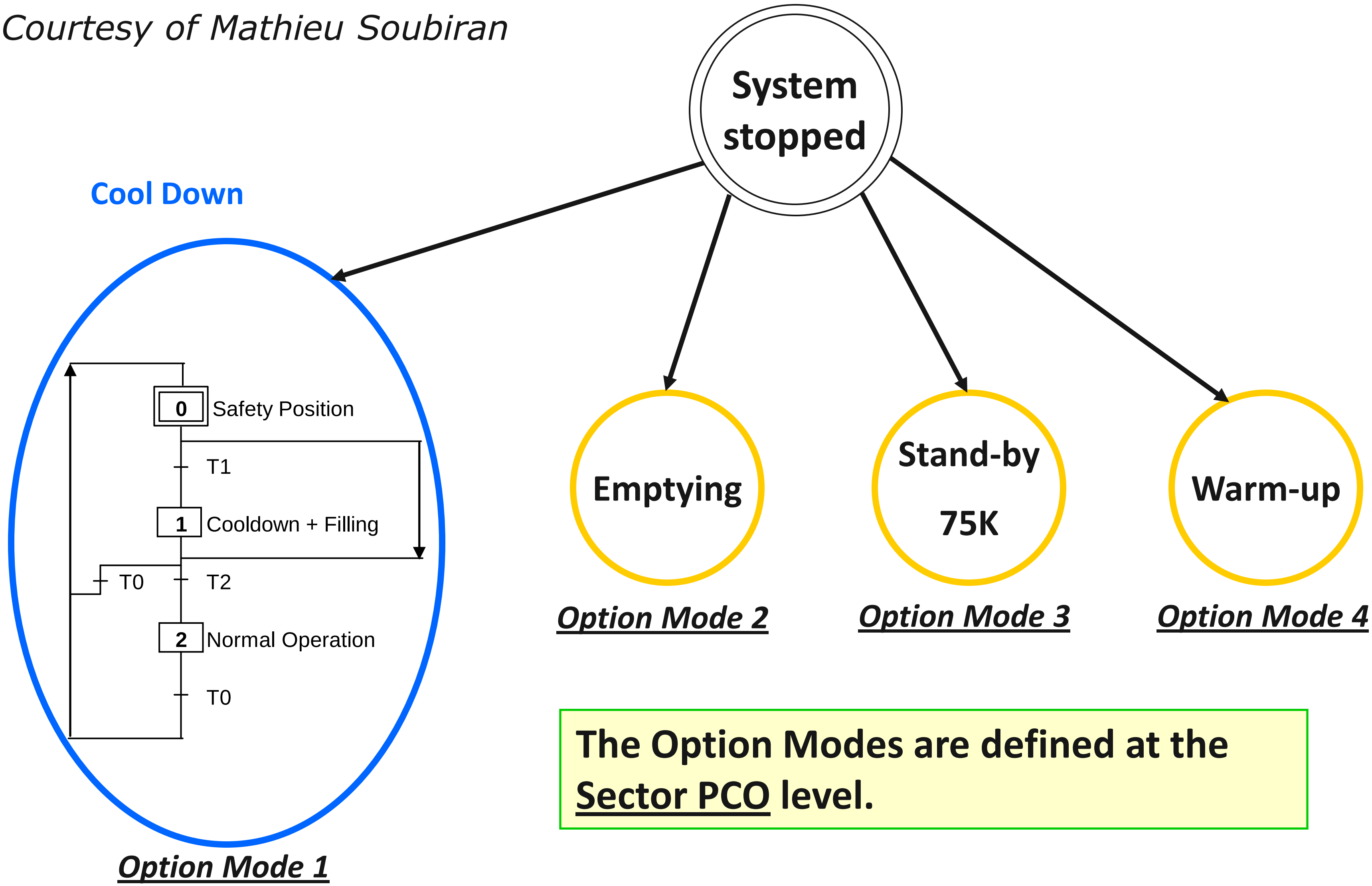
Availability : Process Control Object

Courtesy of Mathieu Soubiran



Availability : Option modes / steppers

Courtesy of Mathieu Soubiran



The Option Modes are defined at the Sector PCO level.

Traceability - MTF