EUROPEAN
SPALLATION
SOURCE

Use of Instrumentation in a Radiological Environment

Christine Darve

For the ASP2012

Headlines:

Instrumentation
Identification
Requirements
Installation techniques

Radiological Environment

LHC measurements and Process

Instrumentation

- "An instrument is a device that measures and/or regulates physical quantity/process variables such as flow, temperature, level, or pressure.

- Requirements:
  - Operating Range, excitation, Output signal, Size, Offset,
  - Stability, interchangeability, Ease of Use, Cost

  - 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.

  - Effect on its environment

  - Environmental compatibility:
    - Robustness
    - Response time
    - Magnetic field effects
    - Radiation resistance
    - Electromagnetic noise effect

Instrumentation basic recommendations

- Don't use more accuracy & precision than required
- Use commercially produced sensors whenever possible
- Mount sensors to provide an easy access for maintenance
- Install redundant sensors for critical devices in remote location
- Be sure to consider how to recalibrate sensors
- Once R&D is done, minimize number of sensors in series production

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

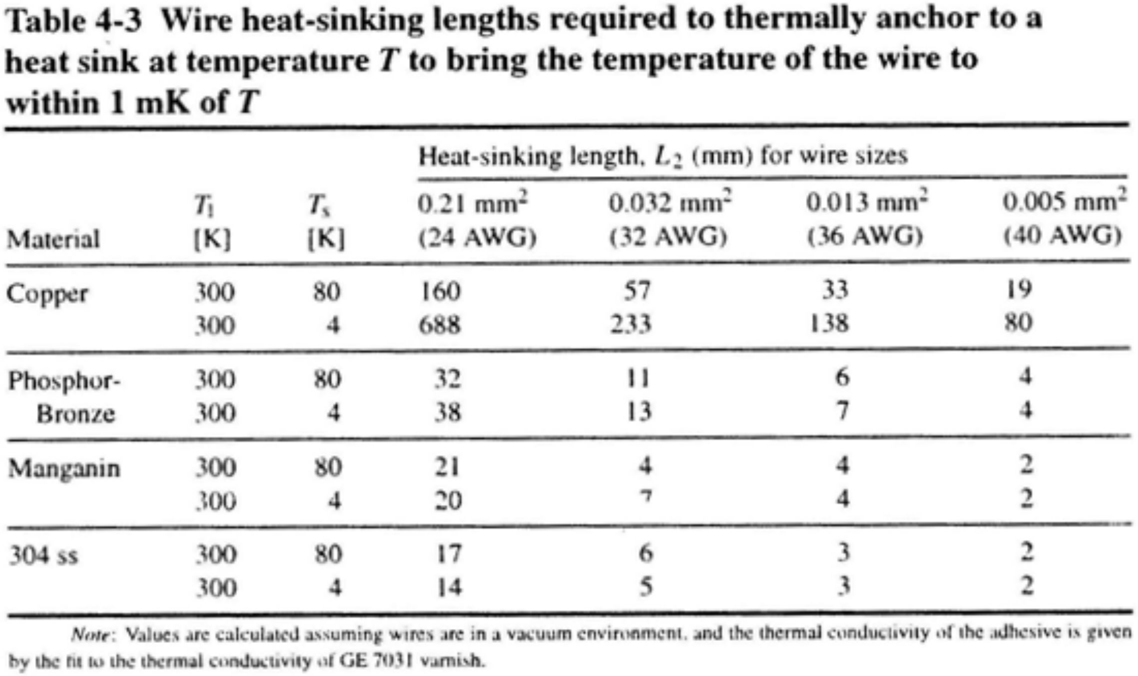


Table 4-3 Wire heat-sinking lengths required to thermally anchor to a heat sink at temperature T to bring the temperature of the wire to within 1 mK of T

			Heat-sinking length, L_2 (mm) for wire sizes			
Material	T_1 [K]	T_s [K]	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

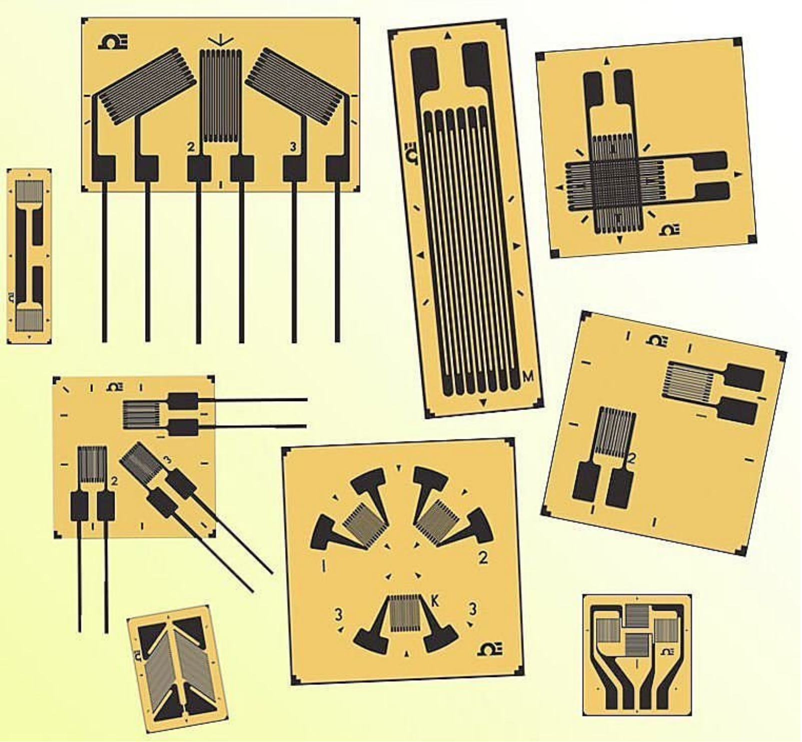
Note: Values are calculated assuming wires are in a vacuum environment, and the thermal conductivity of the adhesive is given by the fit to the thermal conductivity of GE 7031 varnish.

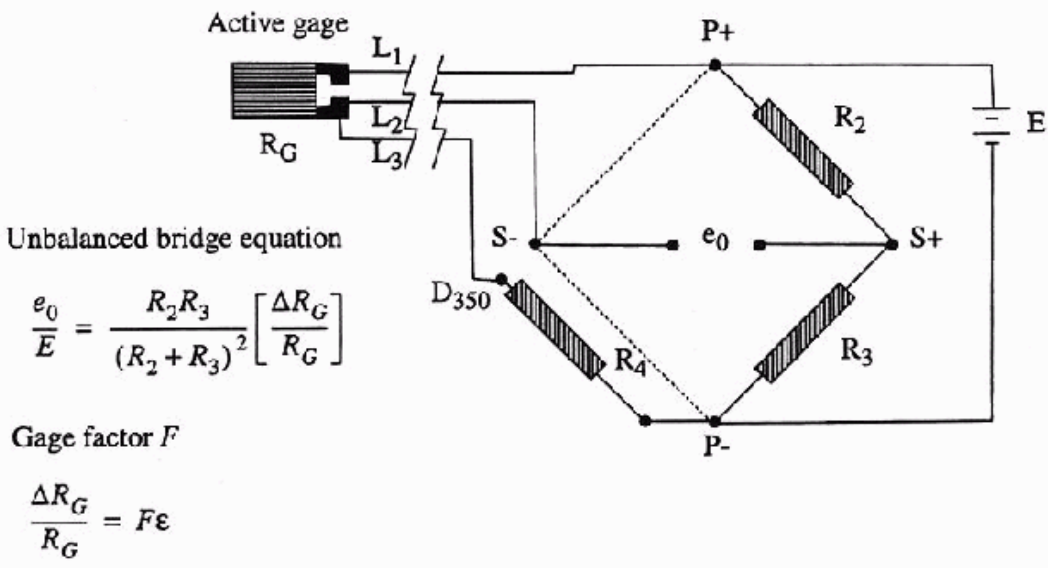
Ref: "Cryogenic Instrumentation" – D.S. Holmes and S. Courts
Handbook of Cryogenic Engineering

Strain Measurement

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

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





Unbalanced bridge equation

$$\frac{e_0}{E} = \frac{R_2 R_3}{(R_2 + R_3)^2}\left[\frac{\Delta R_G}{R_G}\right]$$

Gage factor F

$$\frac{\Delta R_G}{R_G} = F\varepsilon$$

Level Measurement

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

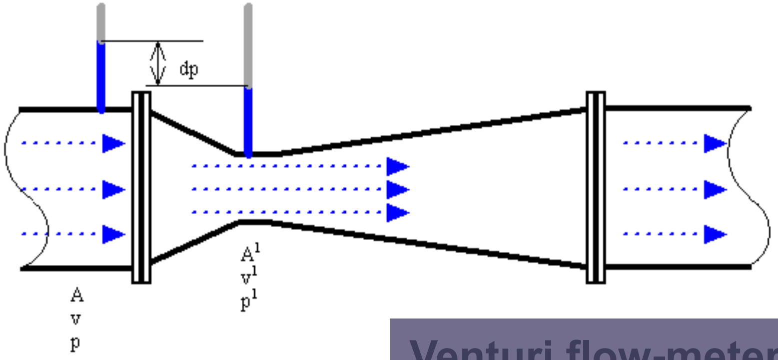
Flow Measurement

- 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

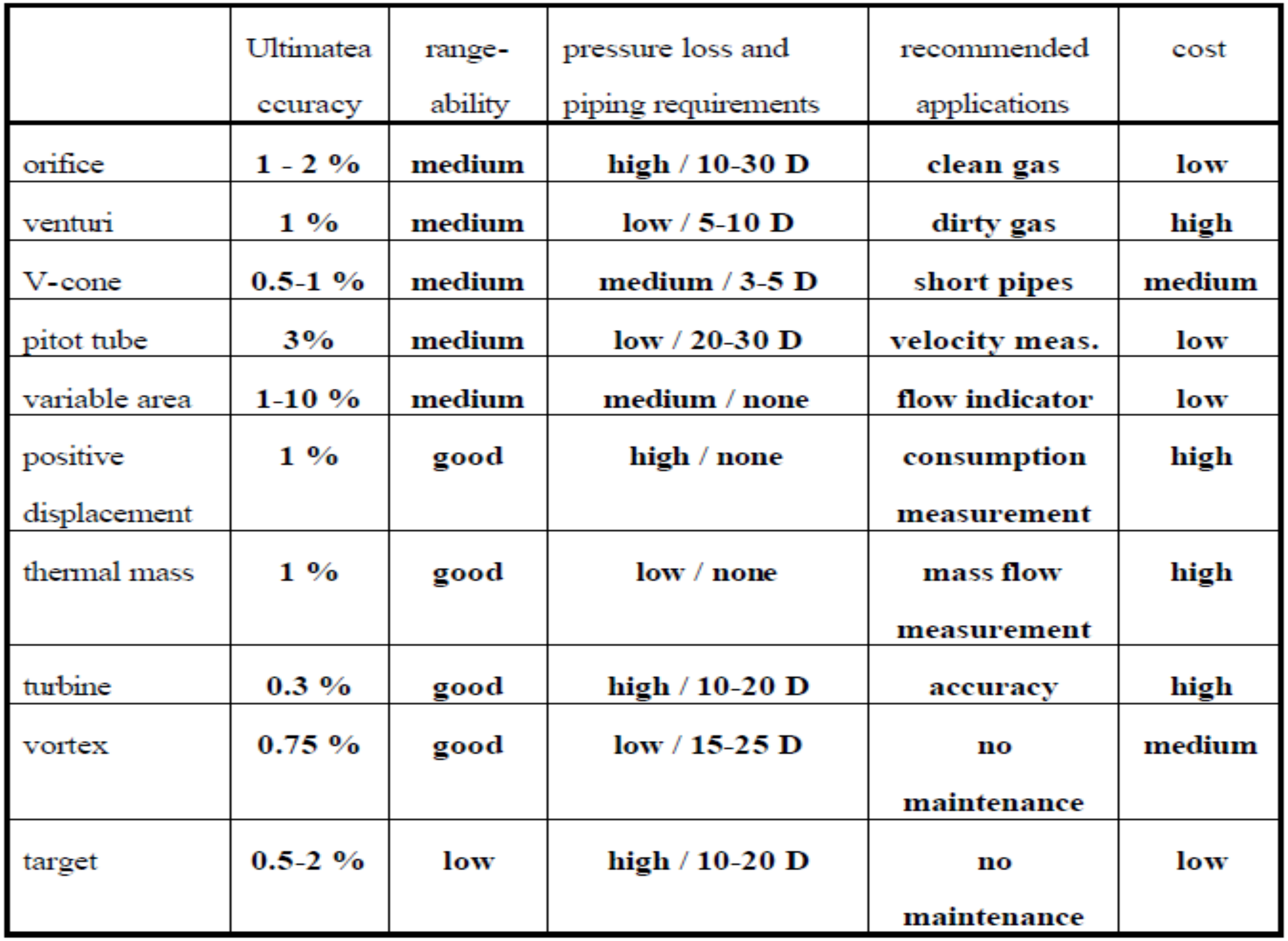
(simplest and cheapest types of meter)

- Thermal Mass

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

- Others: Turbine, Vortex, Target

Flow Measurement

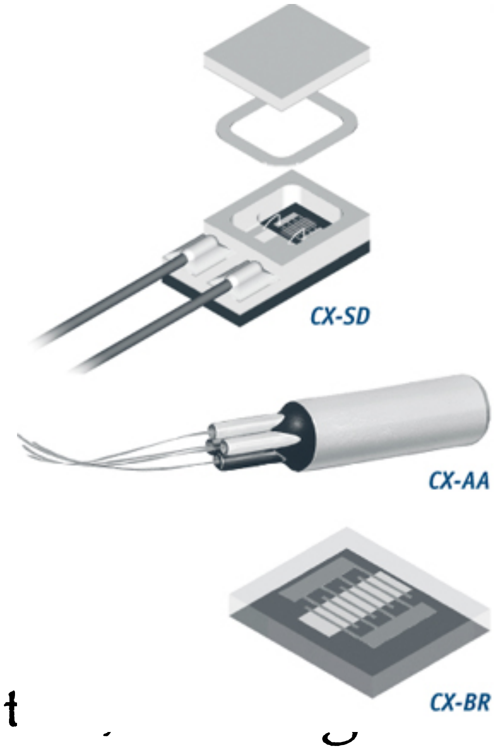


	Ultimatea ccuracy	rangeability	pressure loss and piping requirements	recommended applications	cost
orifice	1 - 2 %	medium	high / 10-30 D	clean gas	low
venturi	1 %	medium	low / 5-10 D	dirty gas	high
V-cone	0.5-1 %	medium	medium / 3-5 D	short pipes	medium
pitot tube	3%	medium	low / 20-30 D	velocity meas.	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

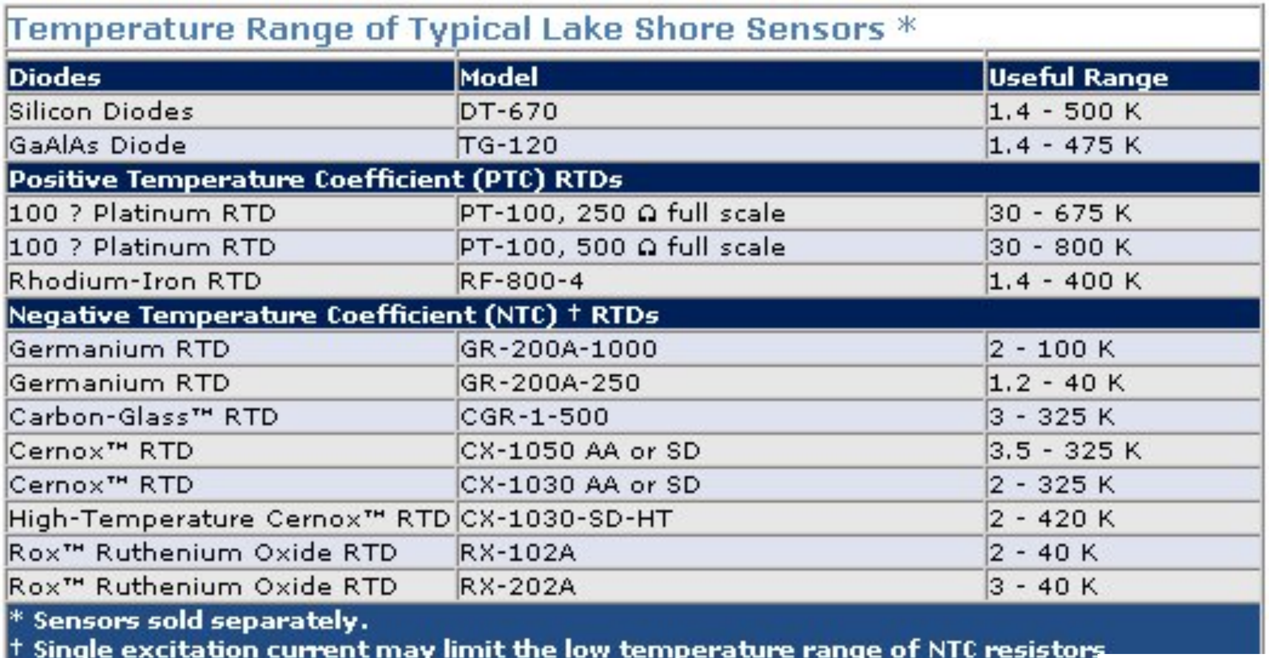
Print ISBN: 978-0-7503-0377-4

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 t
- Capacitor
- Thermocouples

Temperature Measurement

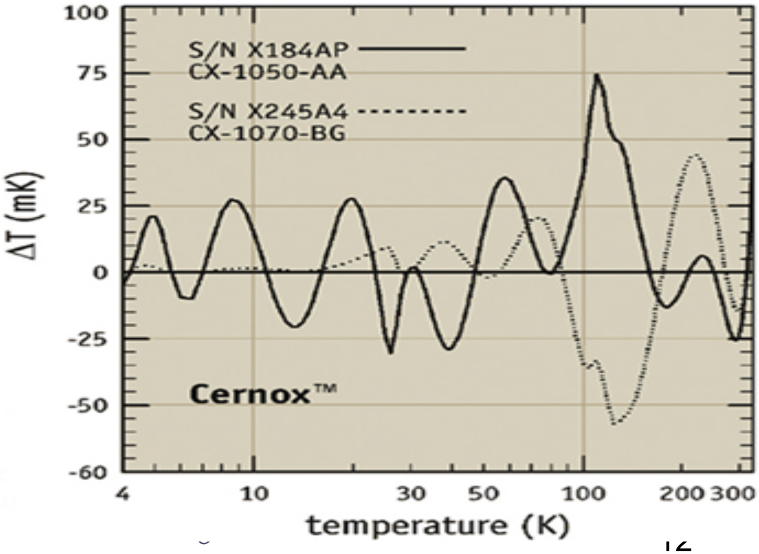


Temperature Range of Typical Lake Shore Sensors *

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/



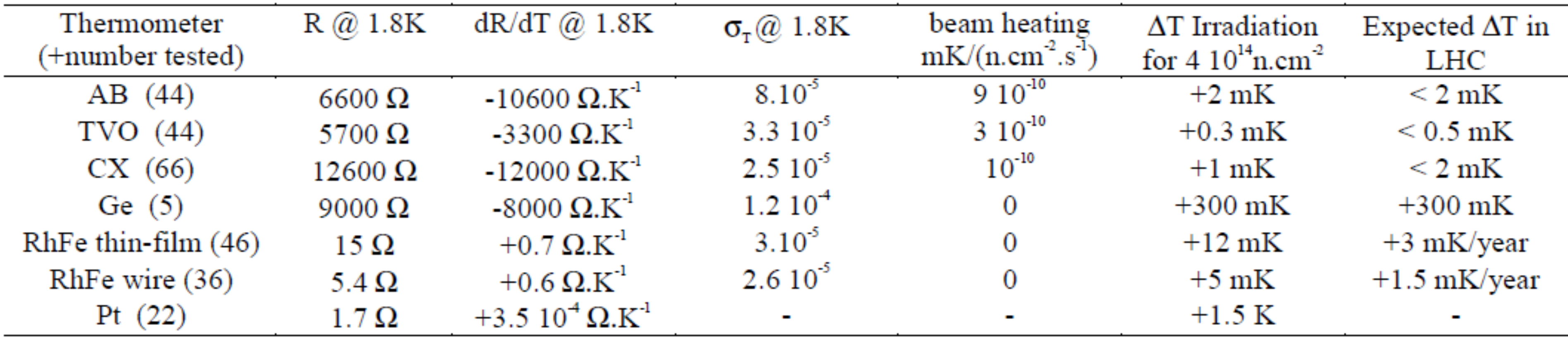
Induced off-set (mK) for neutron and gamma rays

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



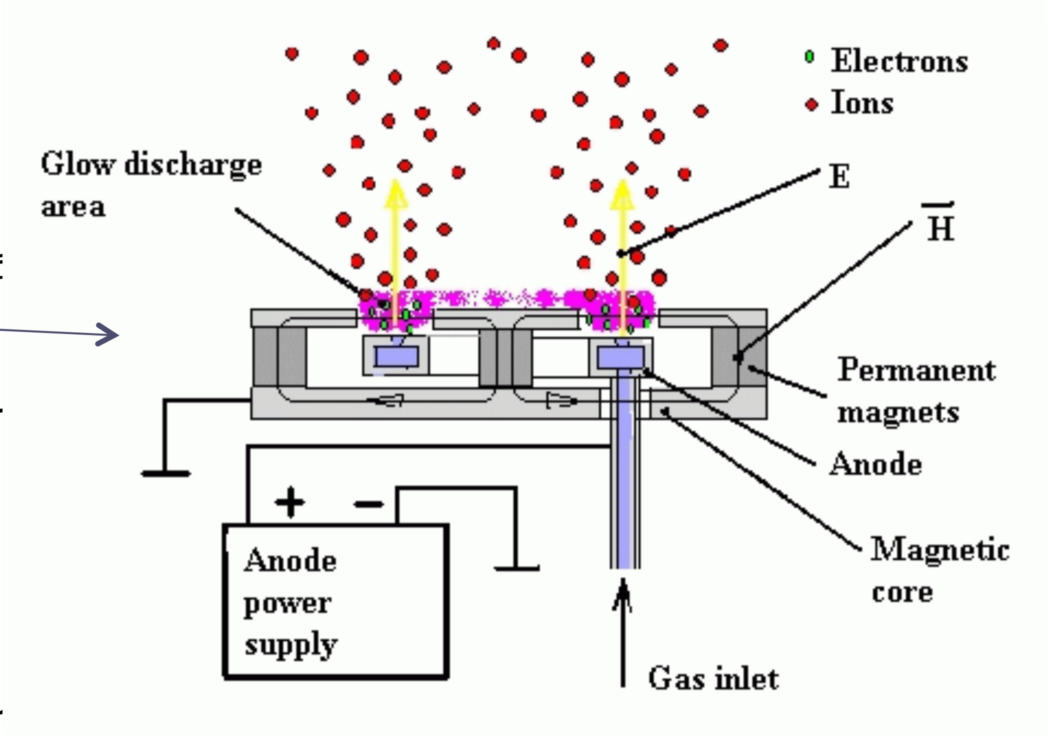
Thermometer (+number tested)	R @ 1.8K	dR/dT @ 1.8K	σ_T @ 1.8K	beam heating mK/(n.cm^{-2}.s^{-1})	ΔT Irradiation for 4 10^{14}n.cm^{-2}	Expected ΔT in LHC
AB (44)	6600 Ω	-10600 Ω.K^{-1}	8.10^{-5}	$9\ 10^{-10}$	+2 mK	< 2 mK
TVO (44)	5700 Ω	-3300 Ω.K^{-1}	$3.3\ 10^{-5}$	$3\ 10^{-10}$	+0.3 mK	< 0.5 mK
CX (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

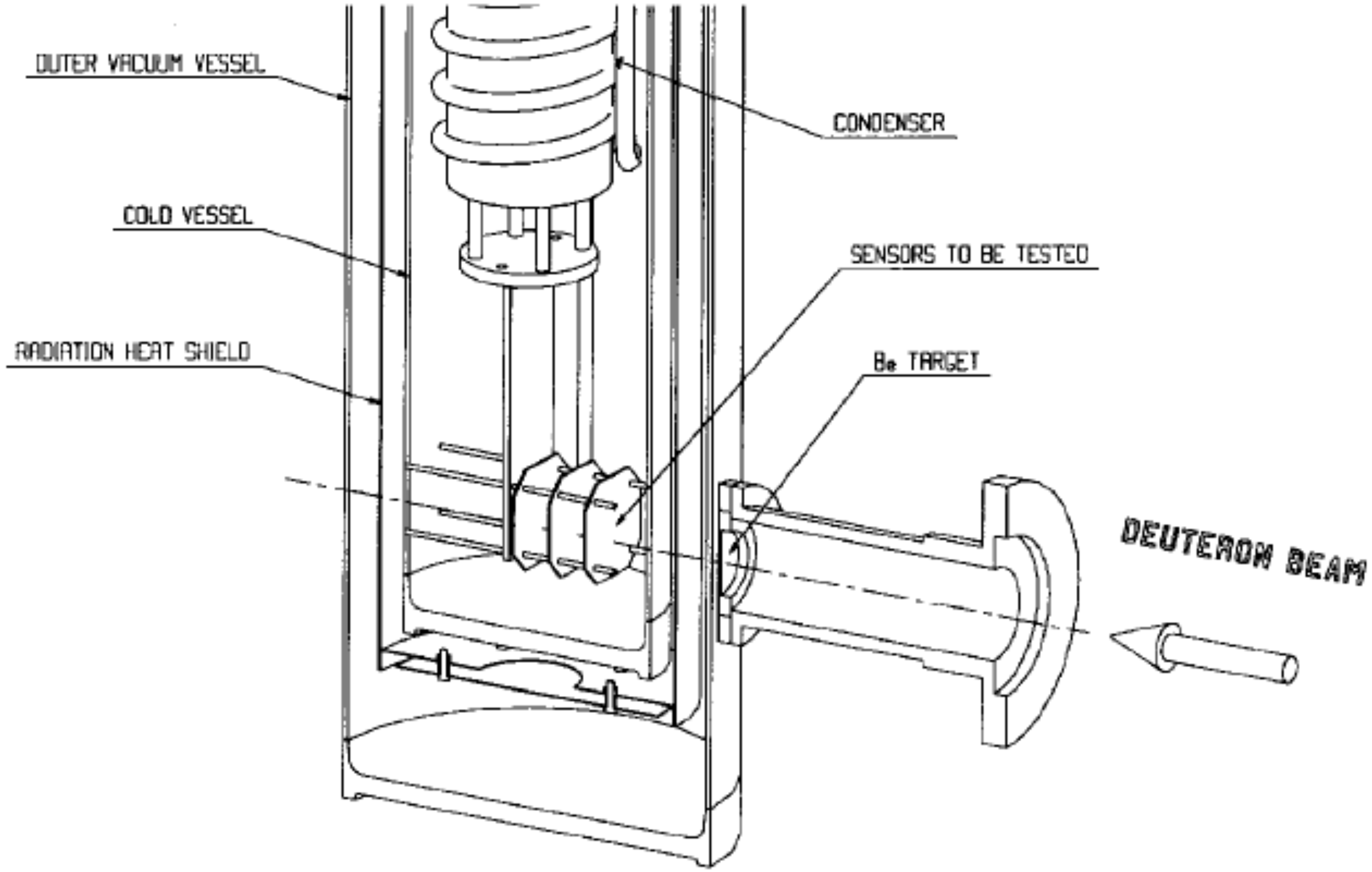
Pressure Measurement

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

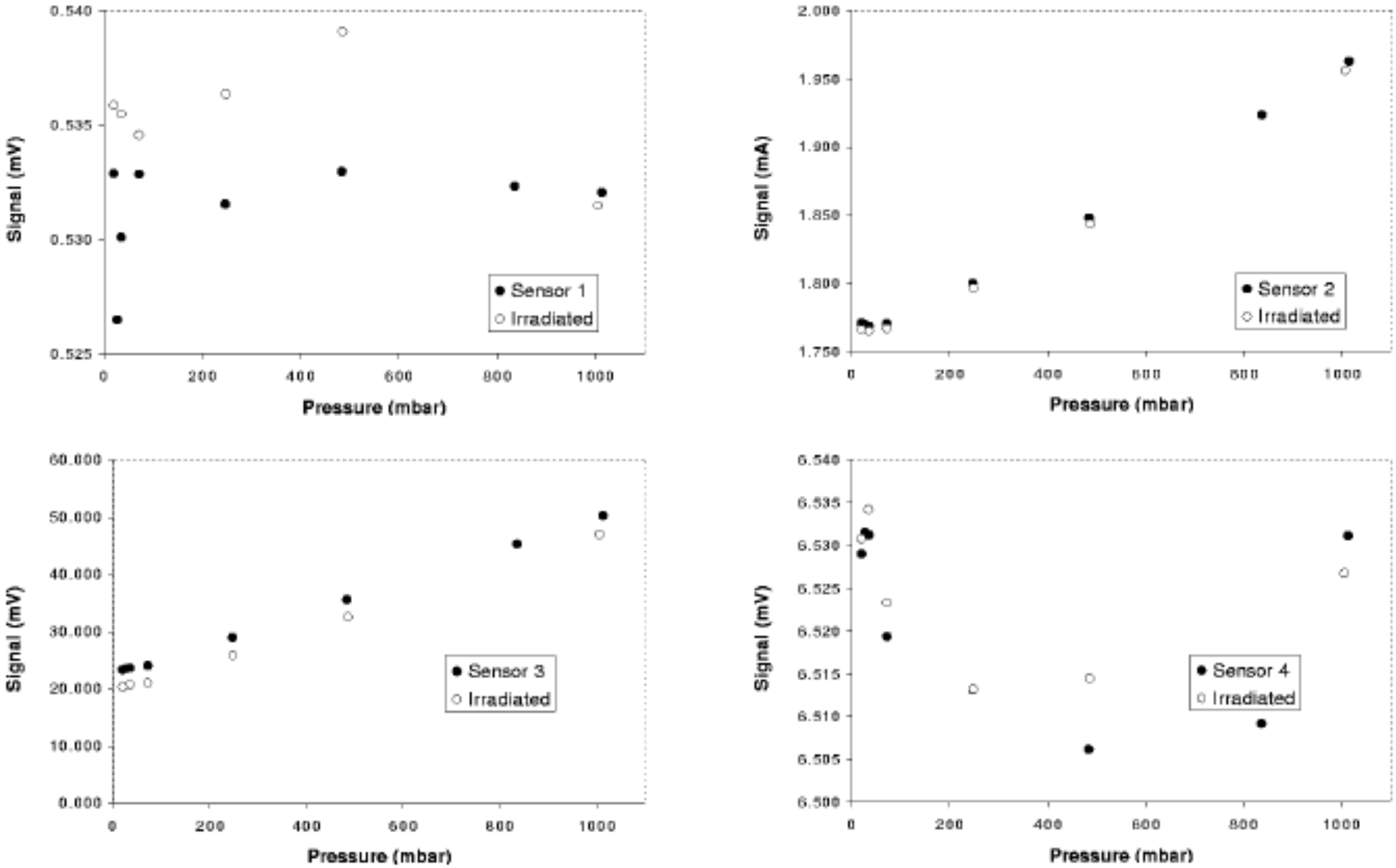


Pressure Measurement – Irradiation Test

Irradiated by neutrons (1-20 MeV, 10^15 n/cm^2) ➔ 10 years of LHC operation at full intensity



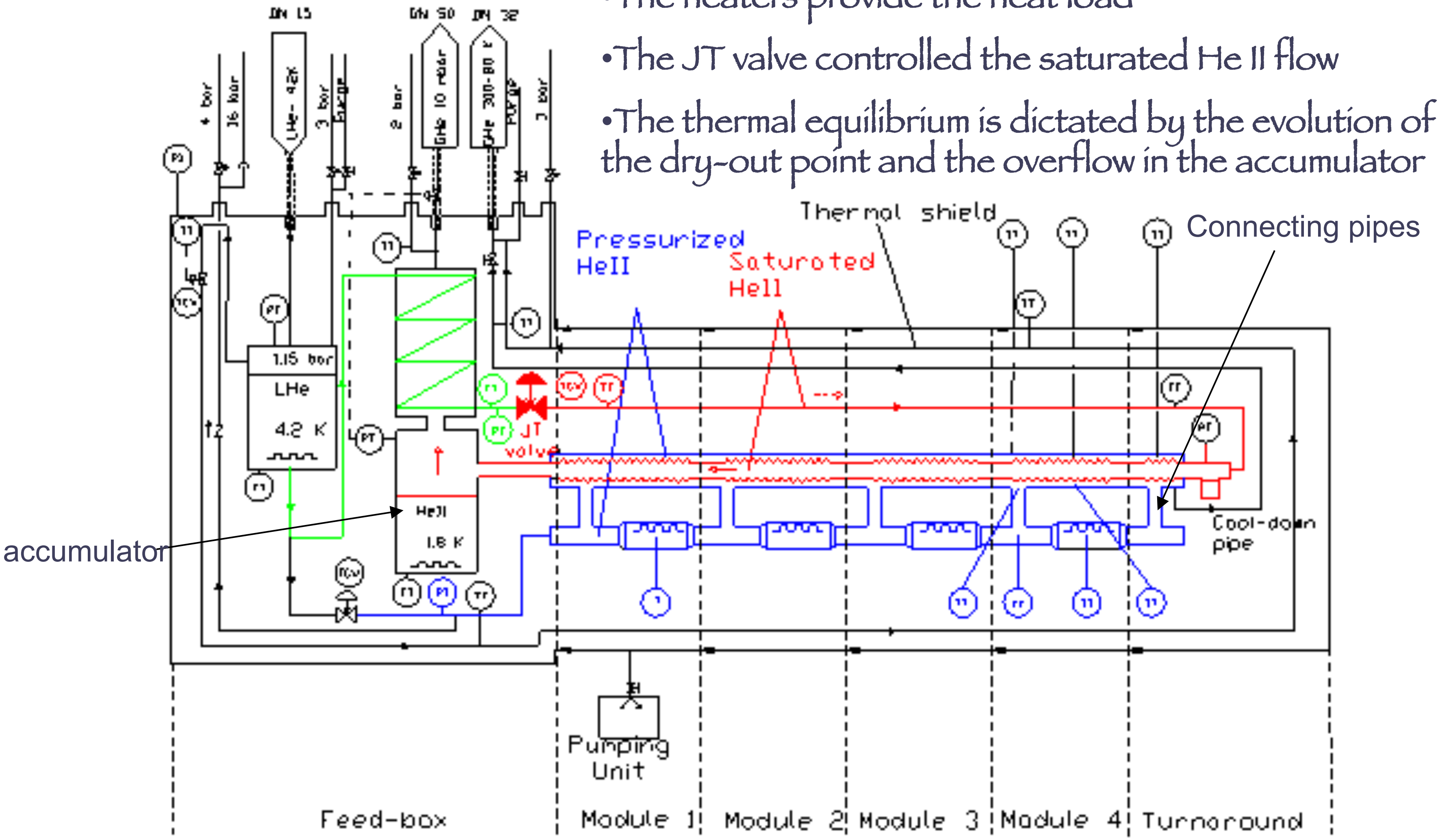
Pressure Measurement – Irradiation Test



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

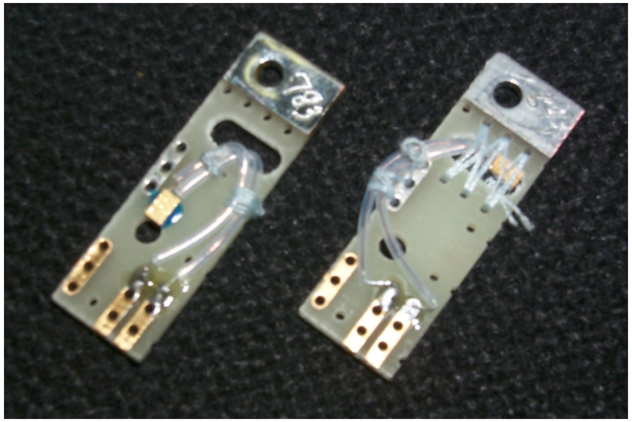
- The heaters provide the heat load
- The JT valve controlled the saturated He II flow
- The thermal equilibrium is dictated by the evolution of the dry-out point and the overflow in the accumulator



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



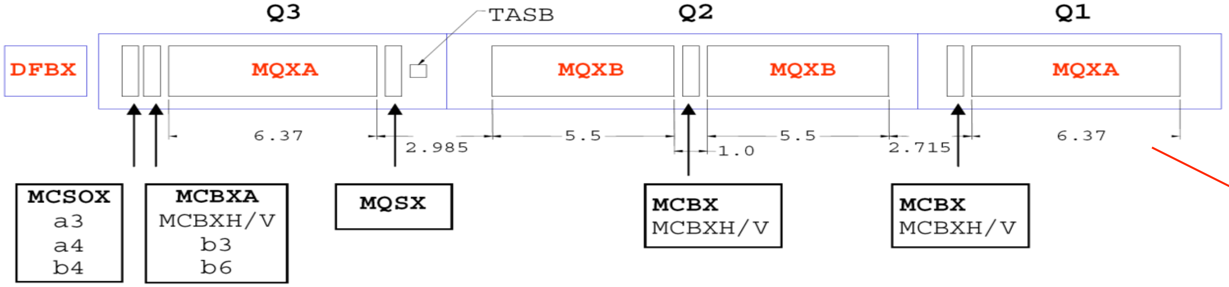
- Error of +/-5 mK on the temperature measurements.
- Stainless steel tubes to route the wires.

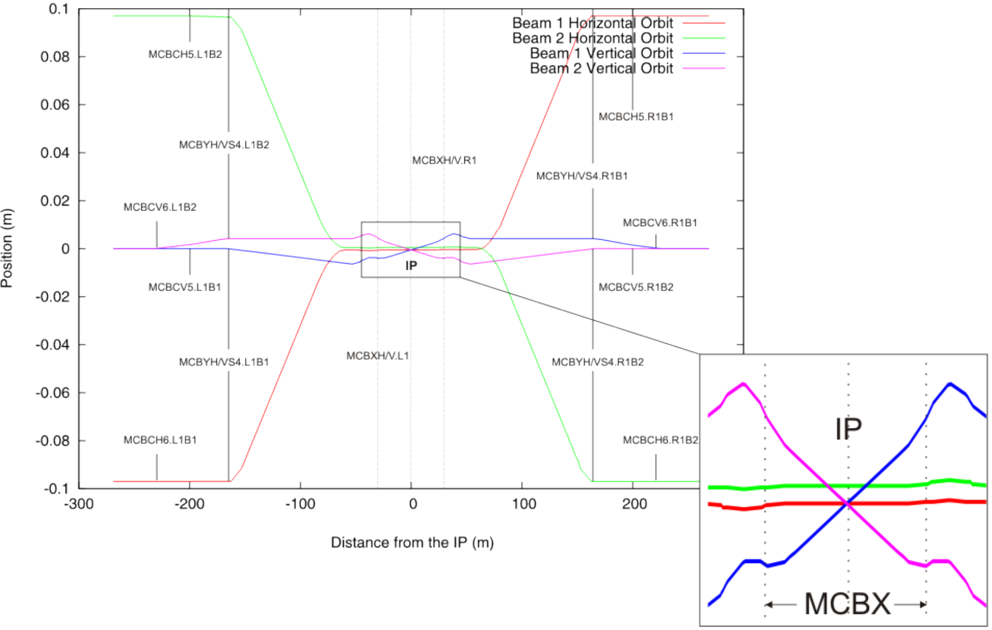
Example 2: The Low-β Magnet Systems at the LHC

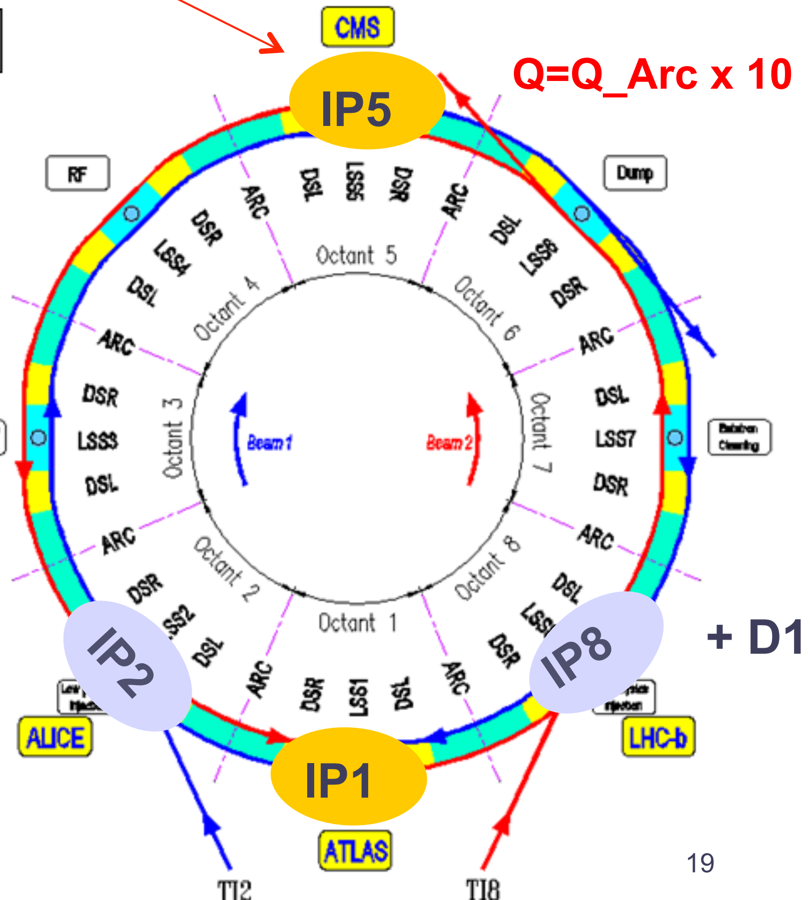
➔ Critical system for LHC performance

Inner Triplet for final beam focusing/defocusing

American contribution to the LHC machine





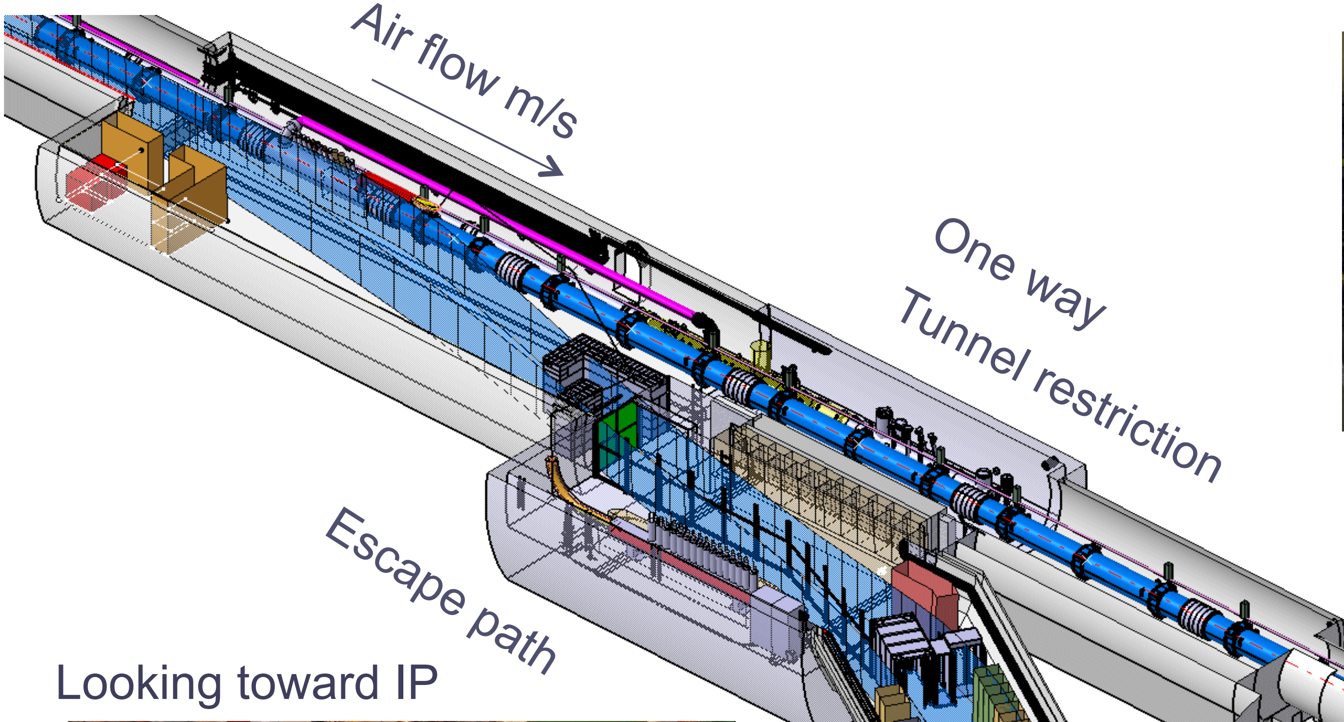


Q=Q_Arc x 10

+ D1

CD – Use of Instrumentation in a Radiological Environmen

Underground views : 80-120 m below ground level

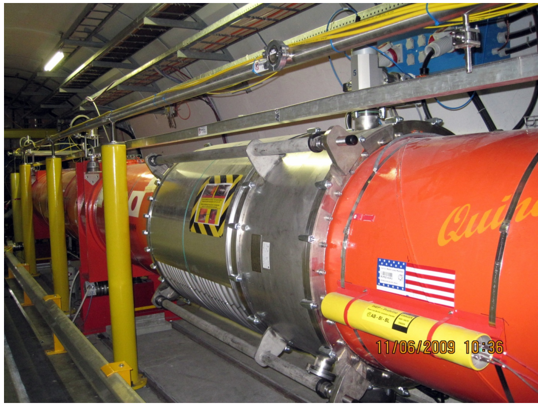


Air flow m/s

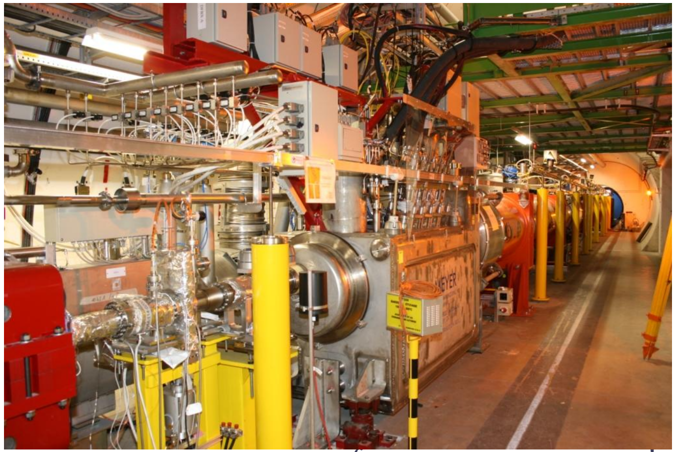
One way
Tunnel restriction

Escape path

Experimental
Hall



Looking toward IP



The low-β magnet system safety specification

Design and operation requirements:

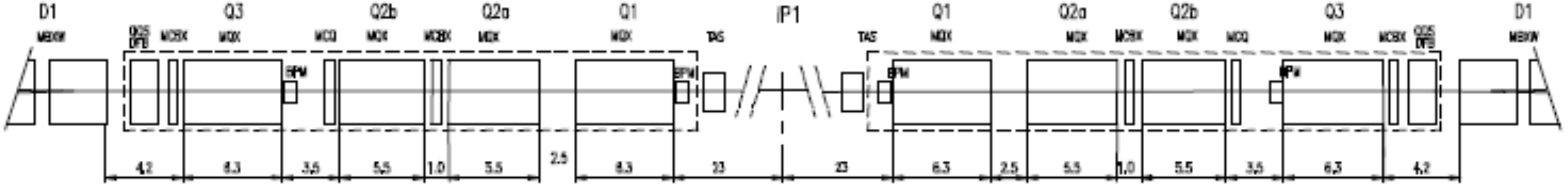
- Critical system for LHC performance, but the system operation and maintenance should remai
safe for personnel and for equipment,
  e.g. escape path, absorbed radiation dose, embrittlement, polymer prop. decay.
- Equipment, instrumentation and design shall comply with the CERN requirements,
  e.g. ES&H, 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 $10^{34}cm^{-2}s^{-1}$.

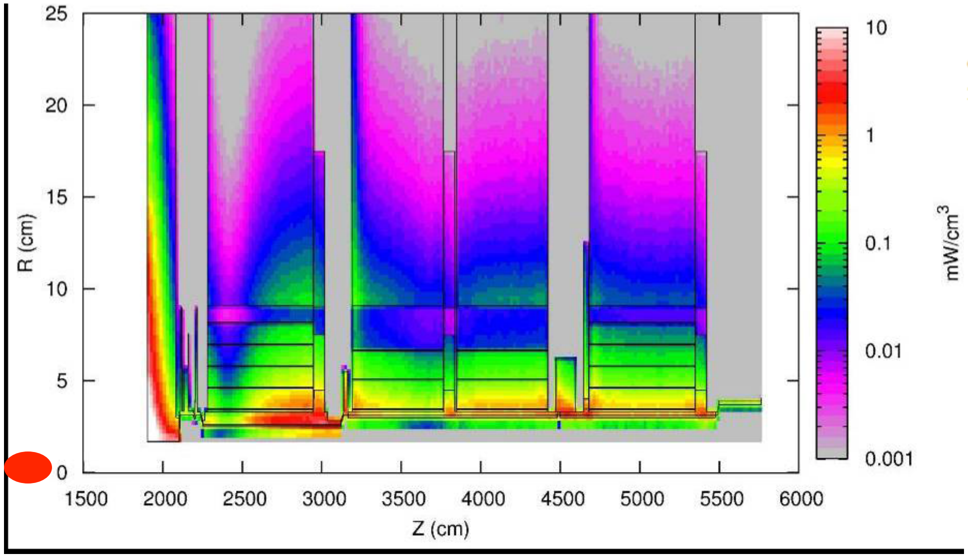
Personnel safety: Keep residual dose rates on the component outer surfaces of the cryostats below 0.1 mSv/hr.

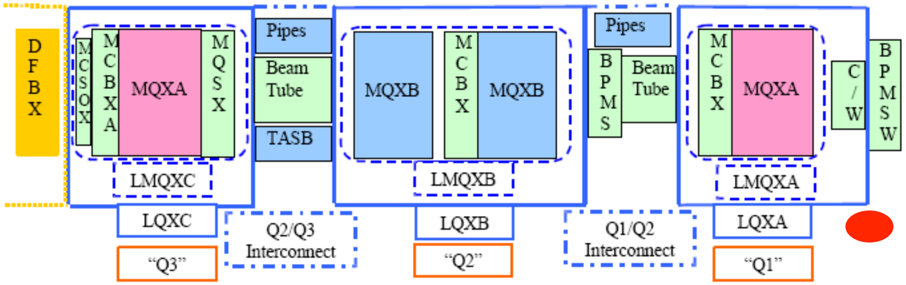
Apply the ALARA principle (As Low As Reasonably Achievable).



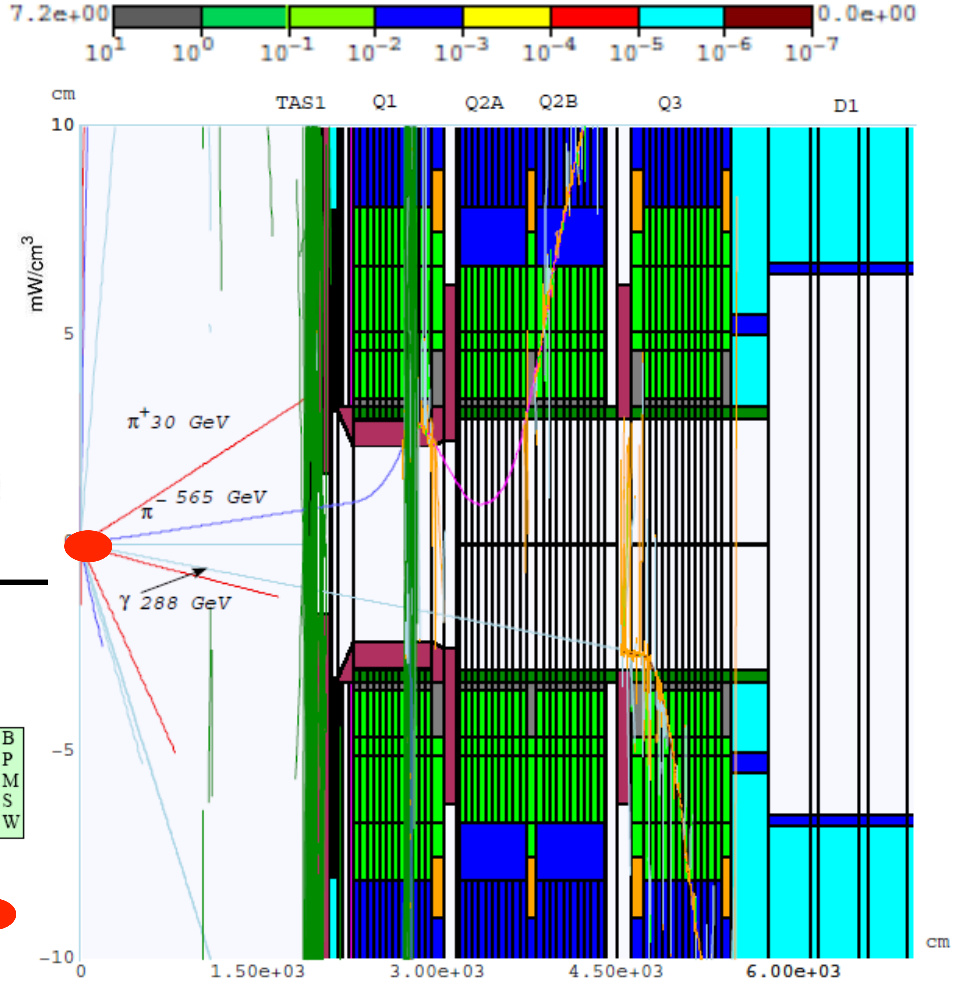
Radiological risk - Power density (mW/cm^3)

IR5 azimuthally averaged power distribution.

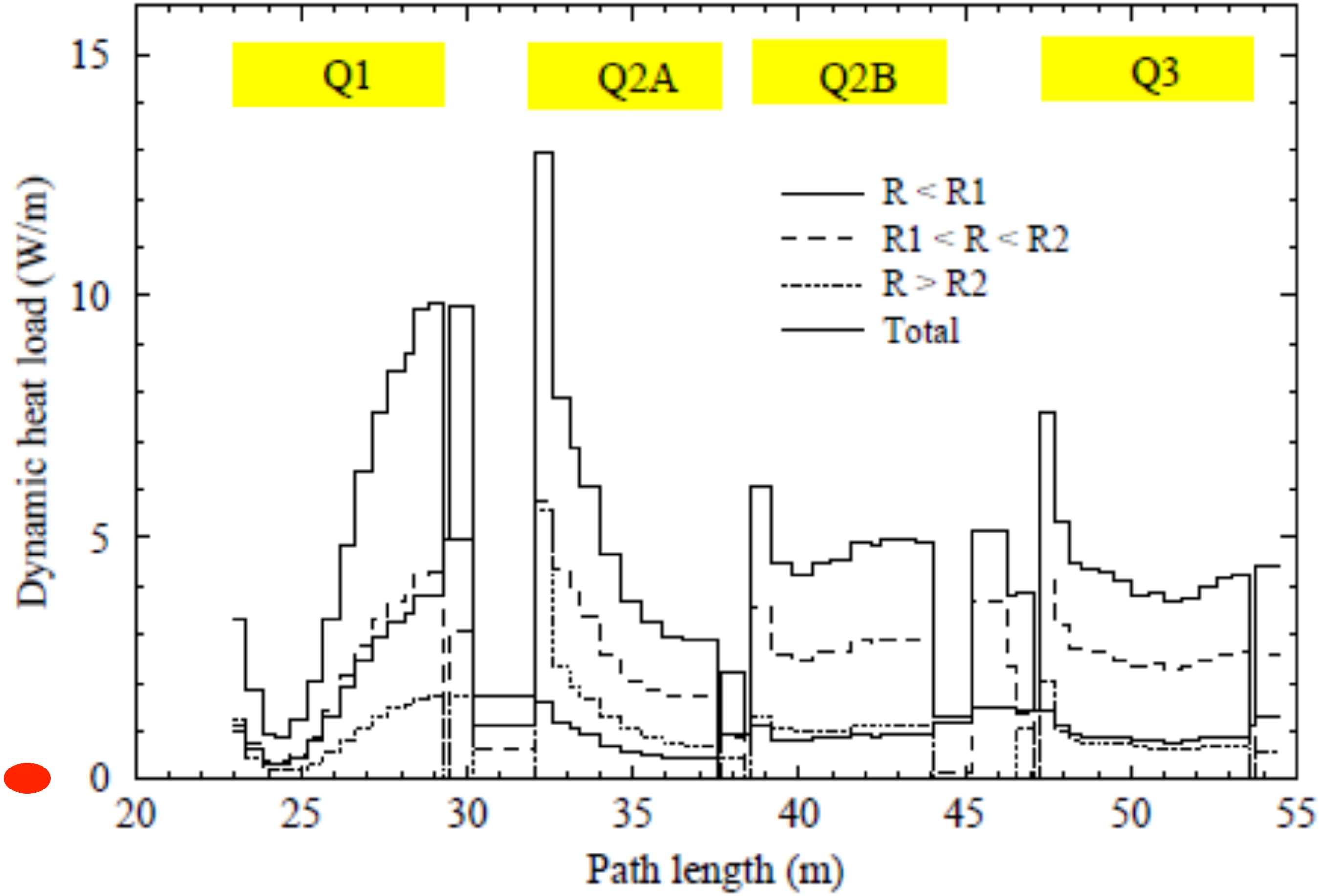




Particle tracks reaching the inner triplet and those generated there for a *pp-collision in* the IP1

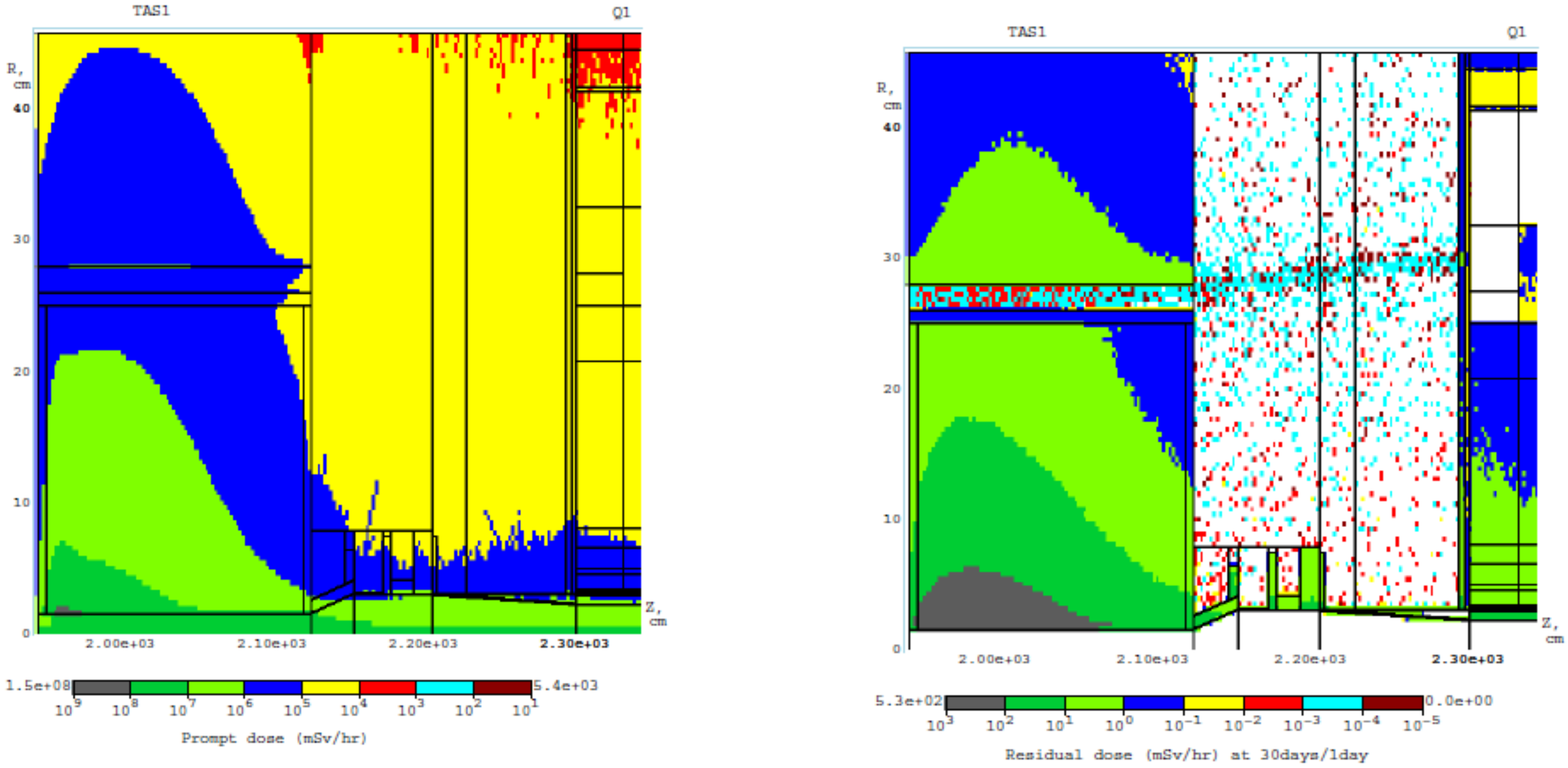


Radiological risk - Power density (mW/cm^3)



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



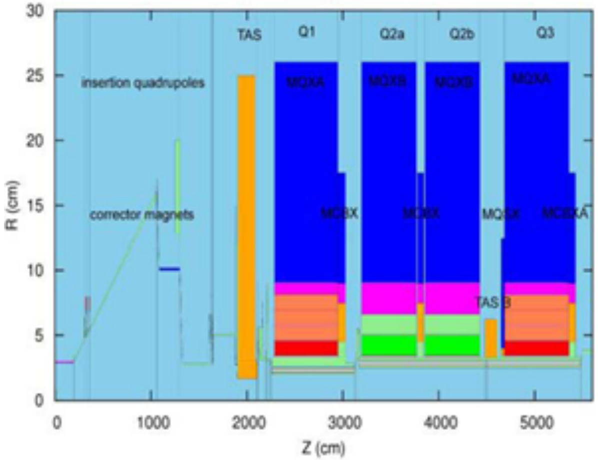
Azimuthally averaged prompt dose equivalent (left) and residual dose rate on contact after 30-day irradiation and 1-day cooling (right) in mSv/hr in the TAS-Q1 region at the baseline luminosity

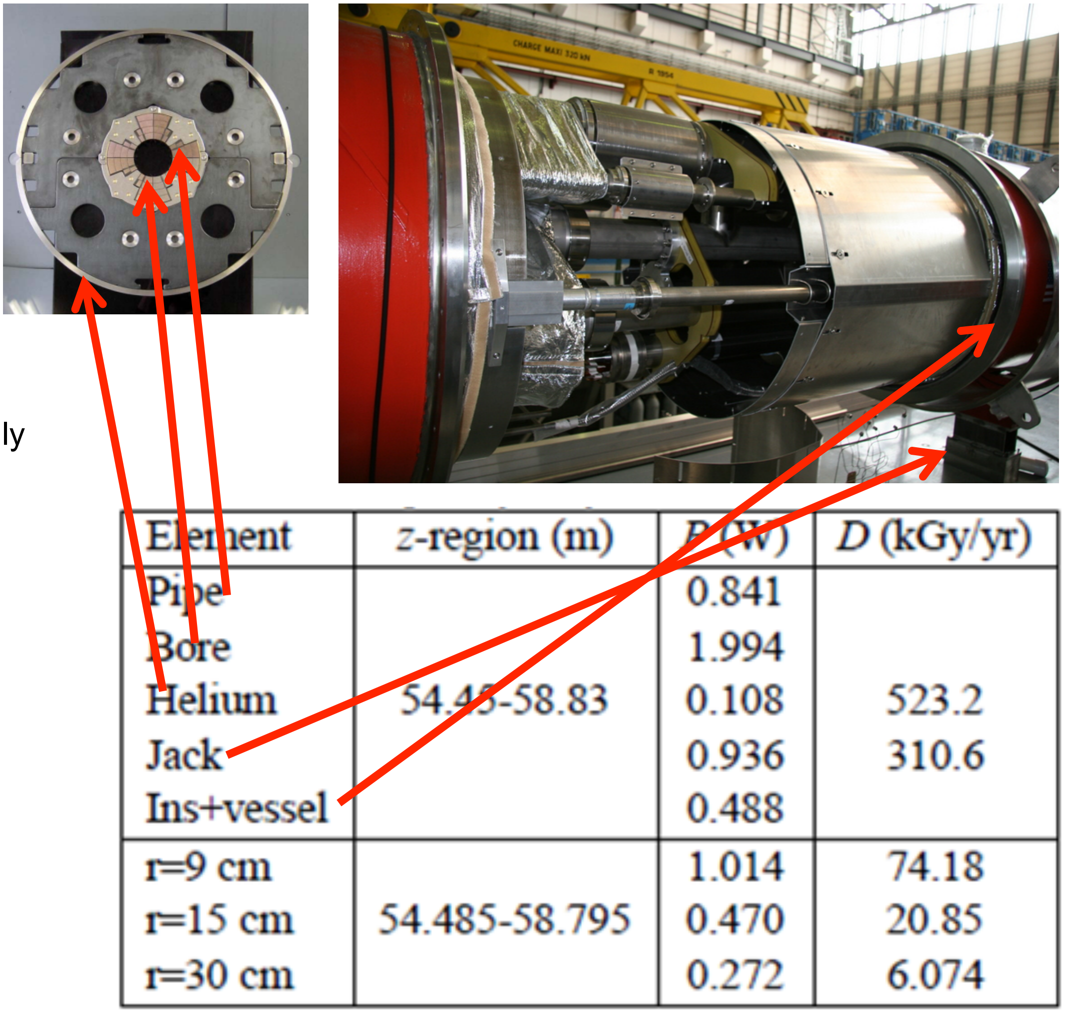
➔ The maximum of 12.5 mW/g (or 100 MGy/yr) at 15 cm (z=1960 cm) is determined by photons and electrons coming to the absorber

Radiological risk

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

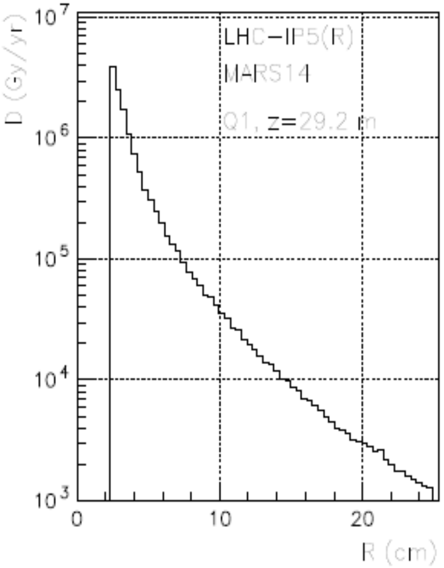
IR5 azimuthally averaged power distribution





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

Radial distribution of azimuthally averaged dose (Gy/yr)

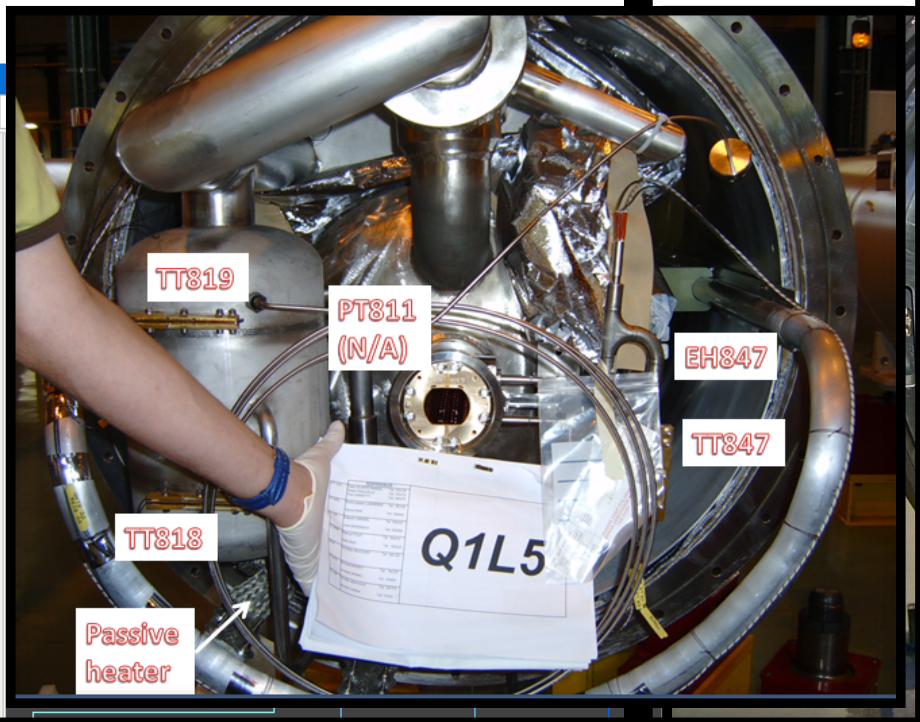


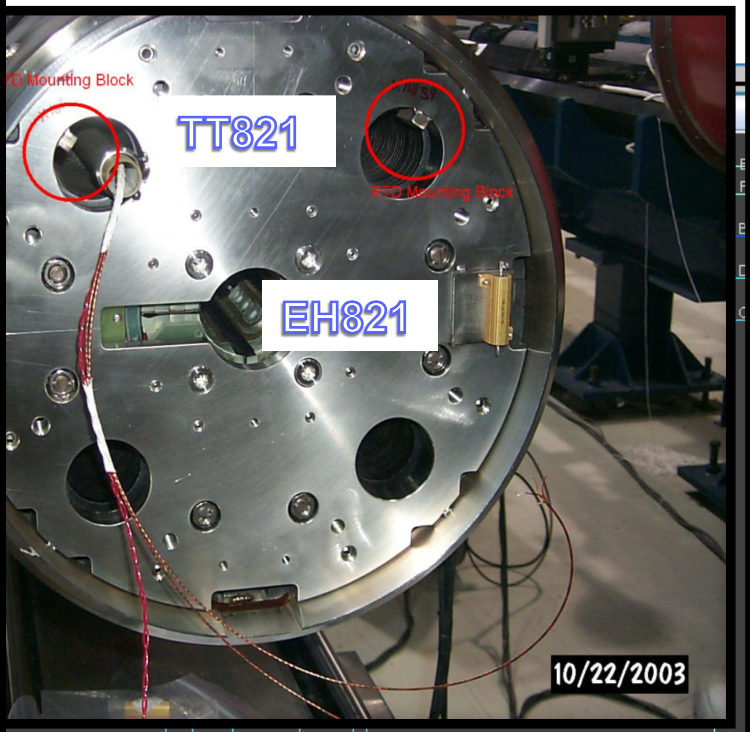
→ Magnet quench limit =1.6 mW/g

For comparison : Arc magnet ~ 1 Gy/yr

Type of instrumentation

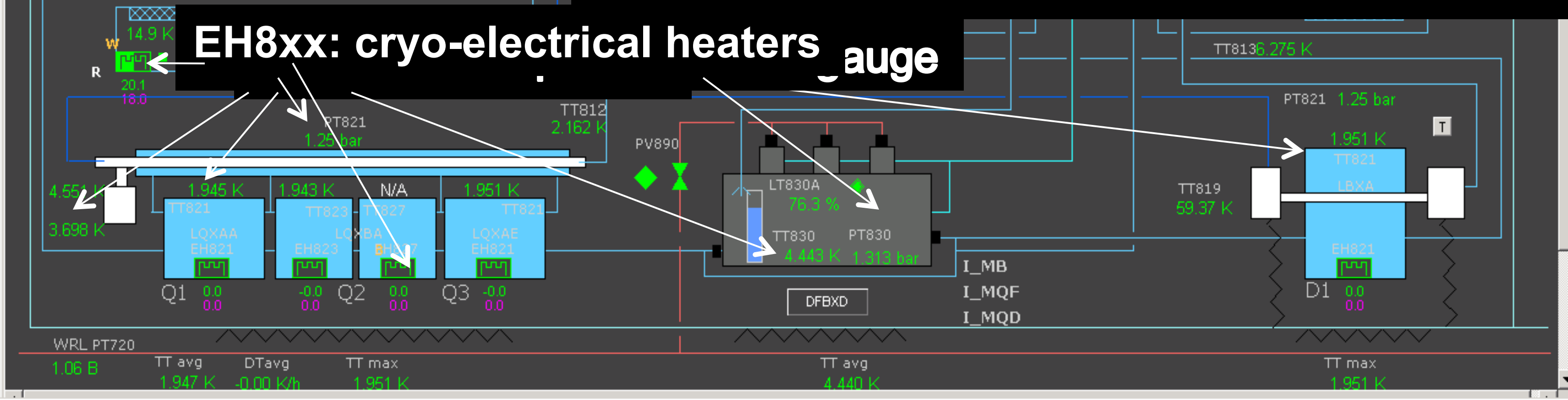
Interface with QRL





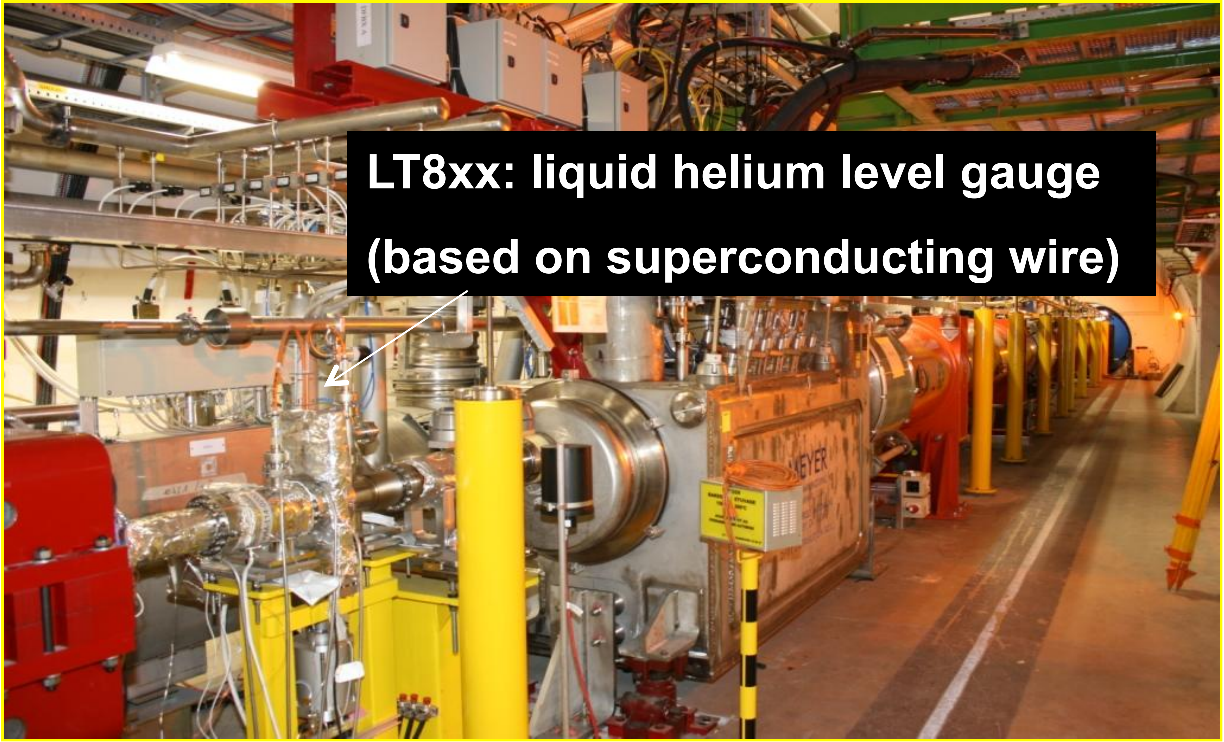
Low-β system

xx8xx



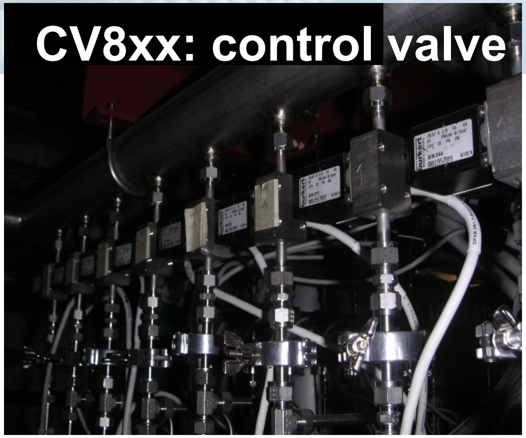
EH8xx: cryo-electrical heaters

Type of instrumentation

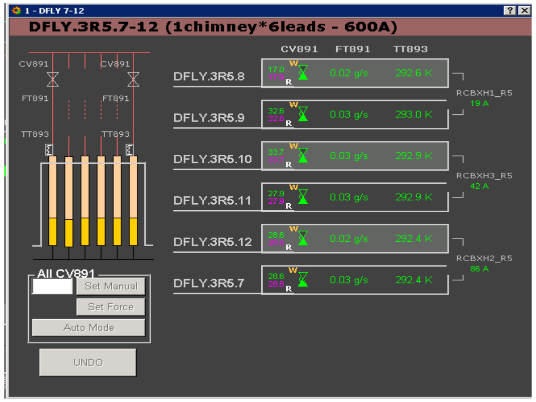


LT8xx: liquid helium level gauge

(based on superconducting wire)



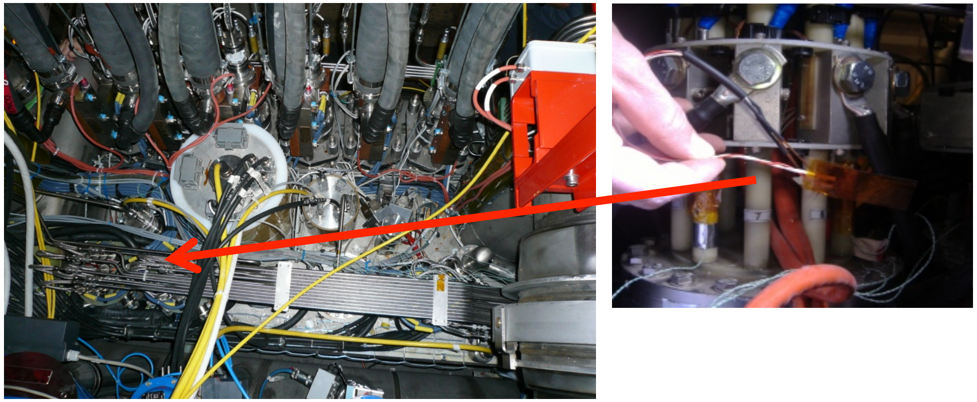
CV8xx: control valve



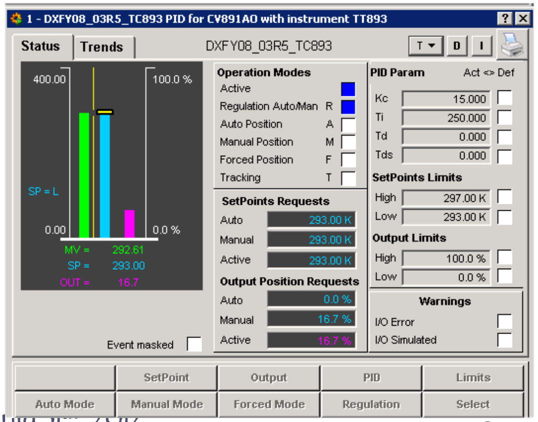
1 - DFLY 7-12

DFLY.3R5.7-12 (1chimney*6leads - 600A)

	CV891	FT891	TT893	
DFLY.3R5.8	17.0 17.0 W R	0.02 g/s	292.6 K	RCBXH1_R5 19 A
DFLY.3R5.9	32.6 32.6 W R	0.03 g/s	293.0 K	
DFLY.3R5.10	33.7 33.7 W R	0.03 g/s	292.9 K	RCBXH3_R5 42 A
DFLY.3R5.11	27.9 27.9 W R	0.03 g/s	292.9 K	
DFLY.3R5.12	28.6 28.6 W R	0.02 g/s	292.4 K	RCBXH2_R5 86 A
DFLY.3R5.7	28.6 28.6 W R	0.03 g/s	292.4 K	



- *HTS leads
- *VCL leads
- *Inner triplet feed through



1 - DXFY08_03R5_TC893 PID for CV891AO with instrument TT893

DXFY08_03R5_TC893

MV = 292.61
SP = 293.00
OUT = 16.7

Event masked ☐

Operation Modes
Active ■
Regulation Auto/Man R ■
Auto Position A ☐
Manual Position M ☐
Forced Position F ☐
Tracking T ☐

SetPoints Requests
Auto 293.00 K
Manual 293.00 K
Active 293.00 K

Output Position Requests
Auto 0.0 %
Manual 16.7 %
Active 16.7 %

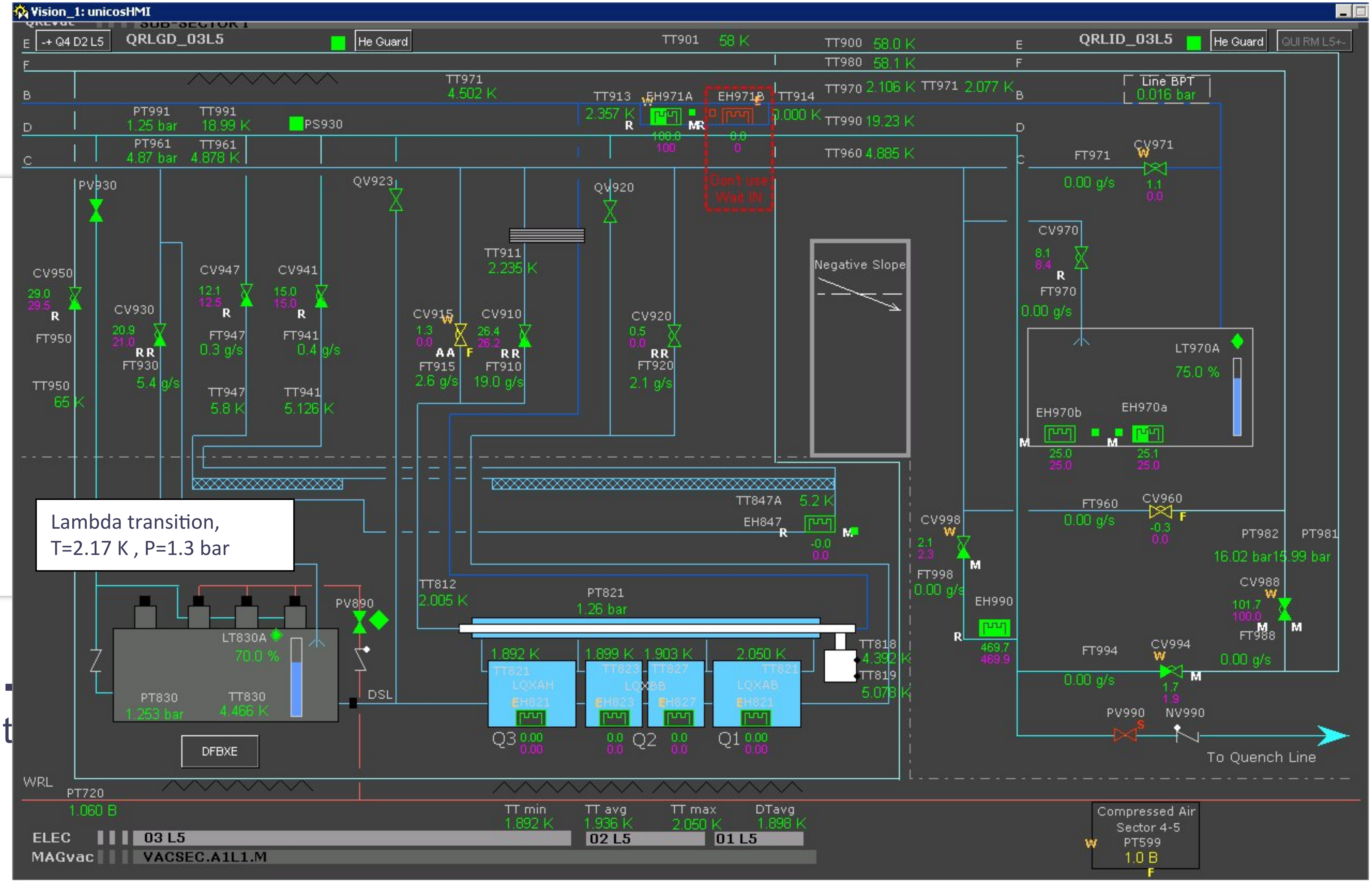
PID Param Act <> Def
Kc 15.000 ☐
Ti 250.000 ☐
Td 0.000 ☐
Tds 0.000 ☐

SetPoints Limits
High 297.00 K ☐
Low 293.00 K ☐

Output Limits
High 100.0 % ☐
Low 0.0 % ☐

Warnings
I/O Error ☐
I/O Simulated ☐

Reliability – Performance measurement



Lambda transition,
T=2.17 K , P=1.3 bar

Radiological risk

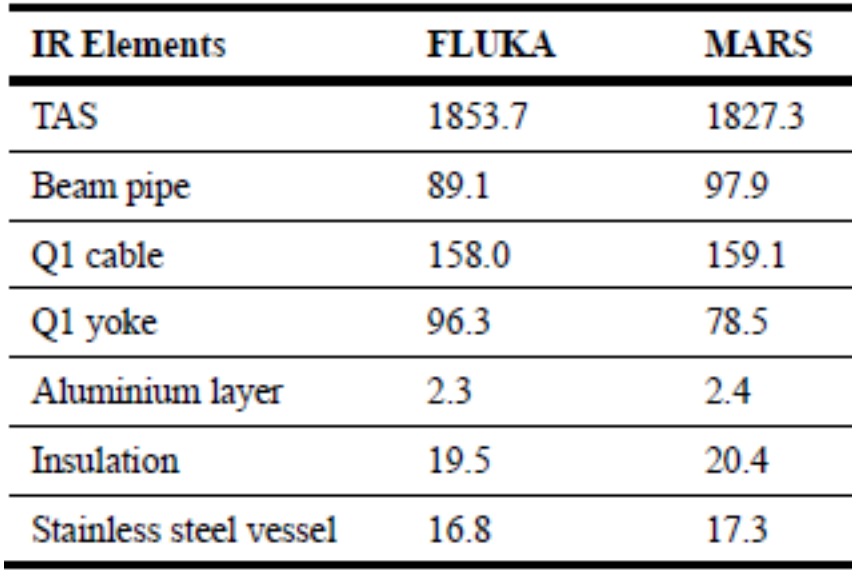
In order to compare energy deposition results with FLUKA 2006.3 and MARS 15

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).

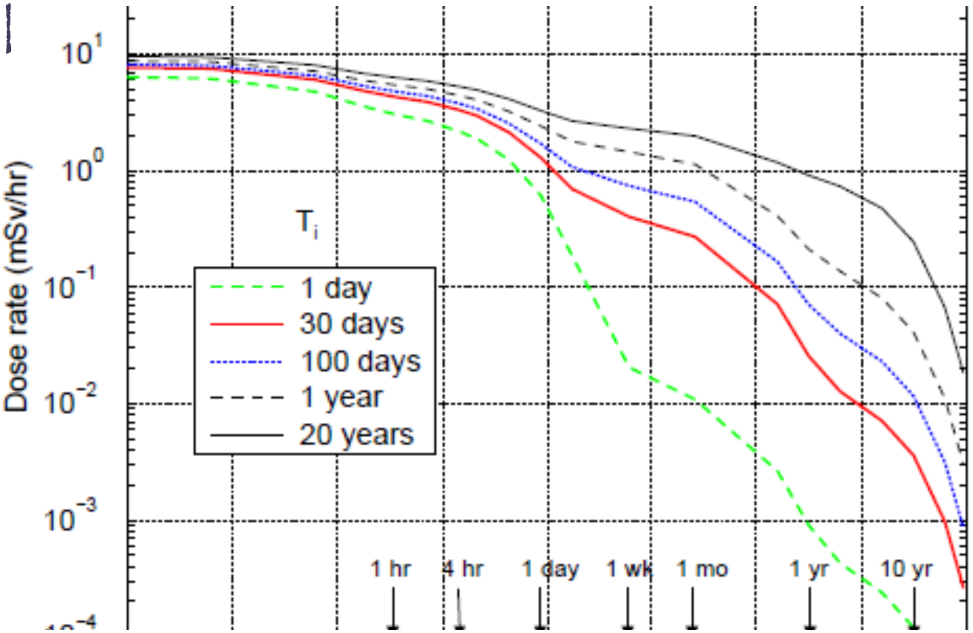
- PEEK versus Kel-F material used for the DFBX low temperature gas seal

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

Radiological risk mitigation

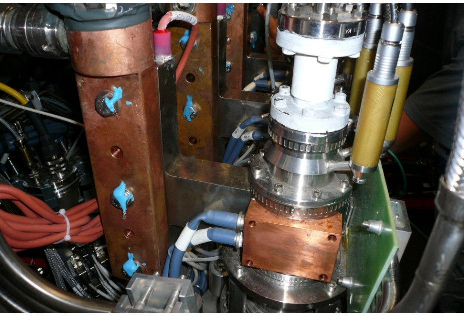
- Specific hazard analysis is requested to intervene on the low-b systems
- Radiological survey systematical performed (< 1mSv/hr)
- Procedures written based on lessons learned
- Limit the personnel exposition time
- Process control w/ interlocks and alarm level for each operating mode

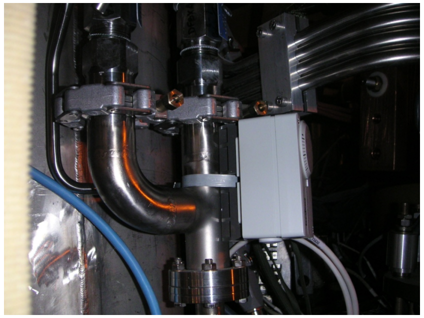
Averaged over surface residual dose rate (mSv/hr) on the Q1 side (z=2125 cm, bottom) of the TAS vs irradiation and cooling times. *By courtesy of N. Mokhov*

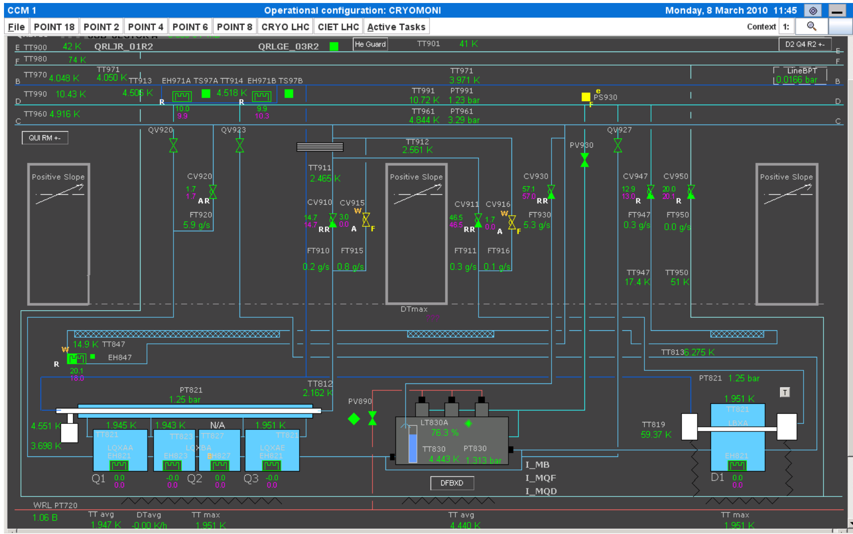


Risk mitigation: control operation upsets

- 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)



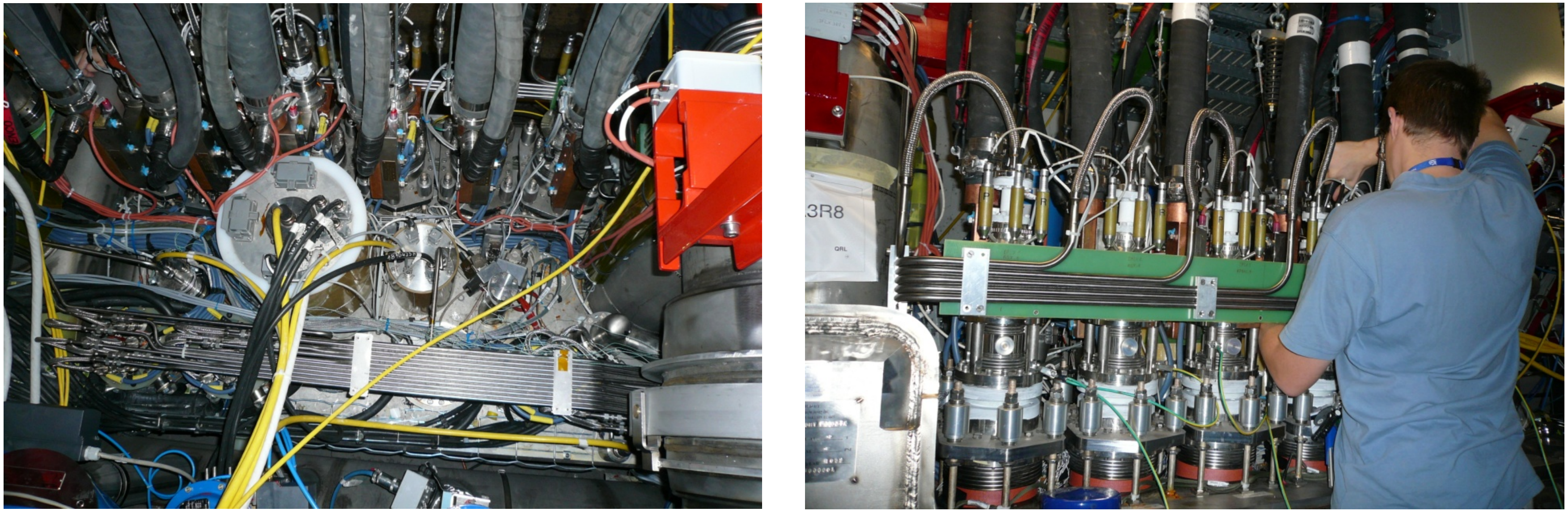




CD - Use of Instrumentation in a Radiological Environment

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-b magnet system area.



"Compact" DFBX area

Engineering process approach

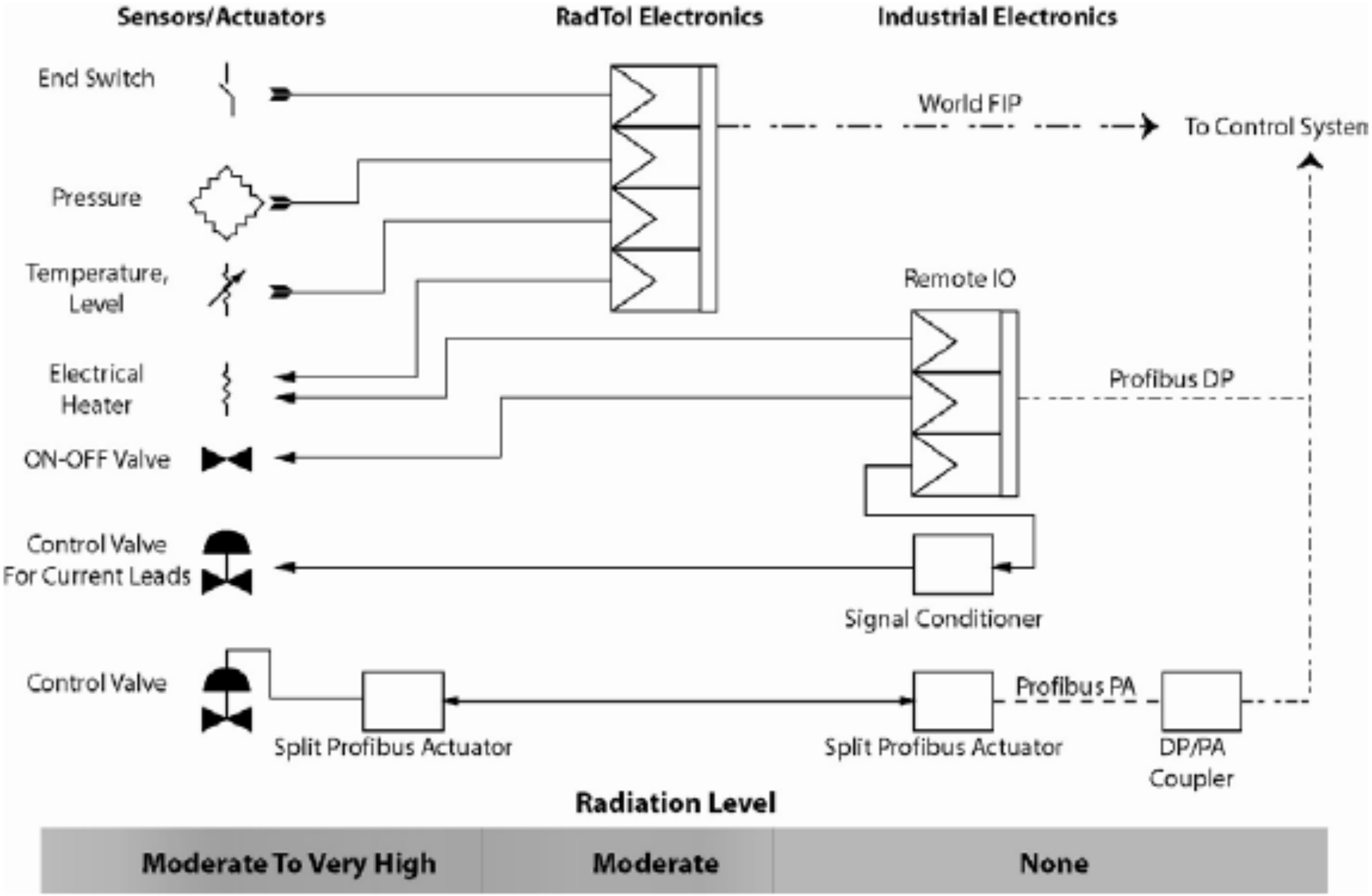
Opening to a new Engineering process approach:
A new engineering manual was issued at Fermilab:

- 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

Engineering Process sequences

Requirements and Specifications
↓
Engineering Risk Assessment
↓
Requirements and Specifications Review
↓
System Design
↓
Engineering Design Review
↓
Procurement and Implementation
↓
Testing and Validation
↓
Release to Operations
↓
Final Documentation

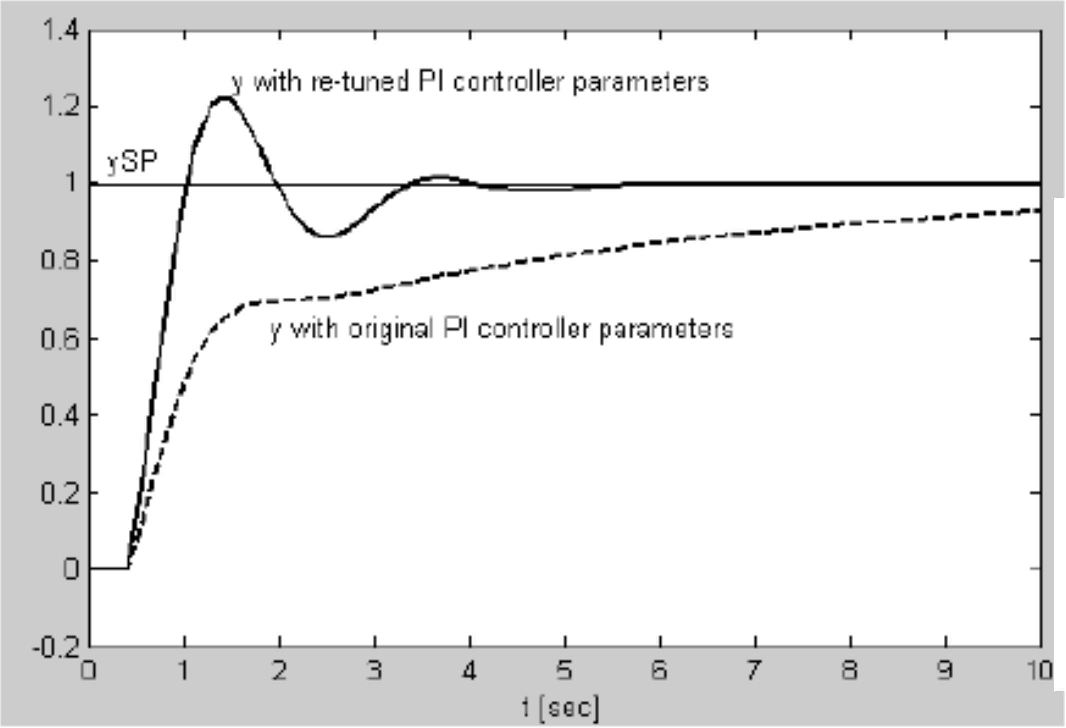
Cryogenic Instrumentation Identification

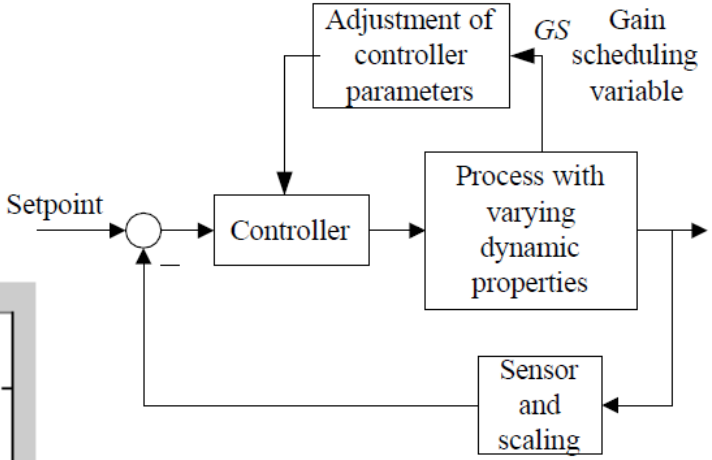


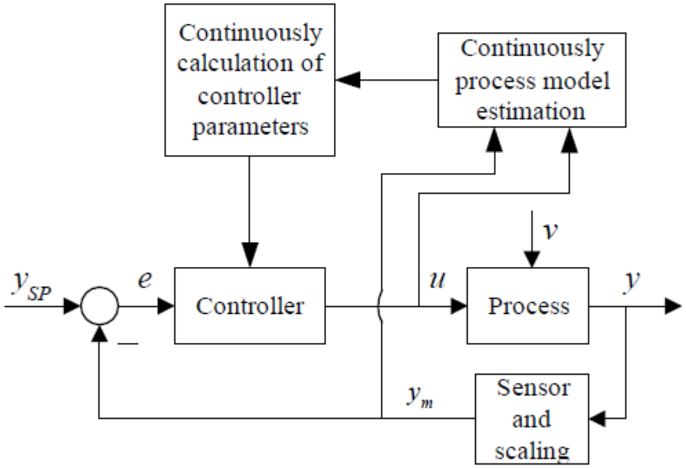
Ref: "First Experience with the LHC Cryogenic Instrumentation", by N. Vauthier et al, LHC Project Report 1078, 2007

Adaptive Controller : Proportional Integral Derivative

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



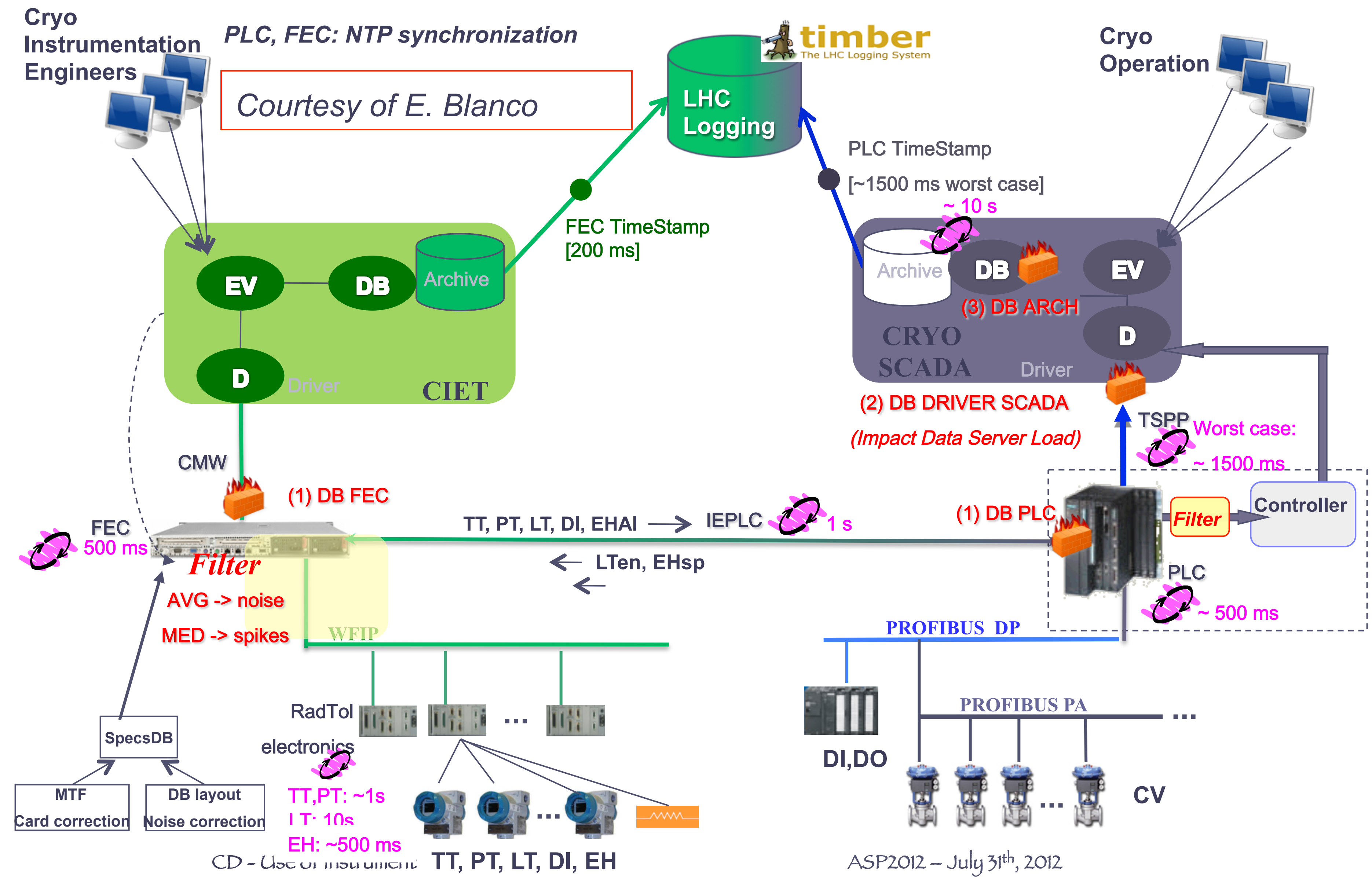




Availability : Data flow & LHC Logging Cryogenics Data

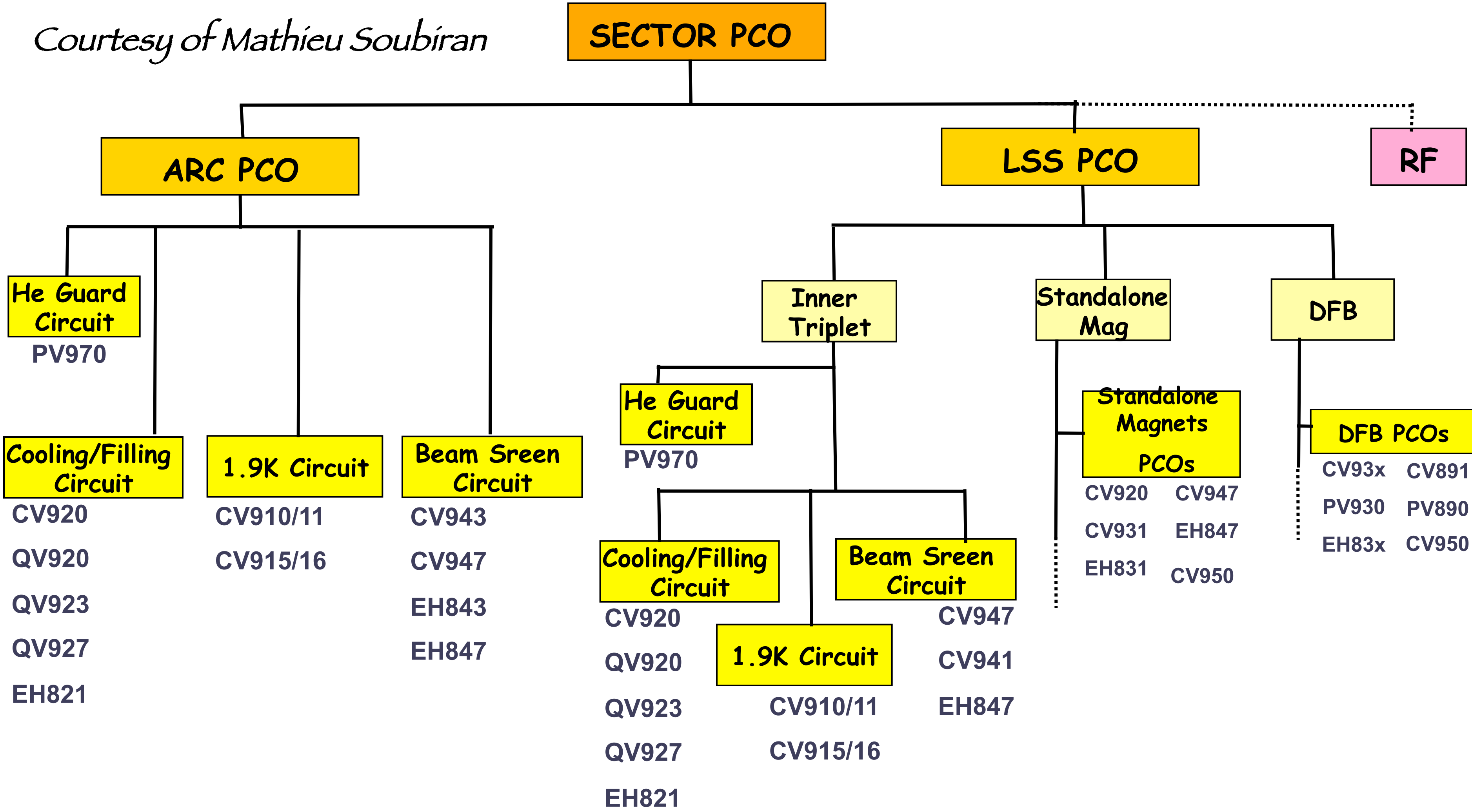
PLC, FEC: NTP synchronization

Courtesy of E. Blanco



Availability : Process Control Object

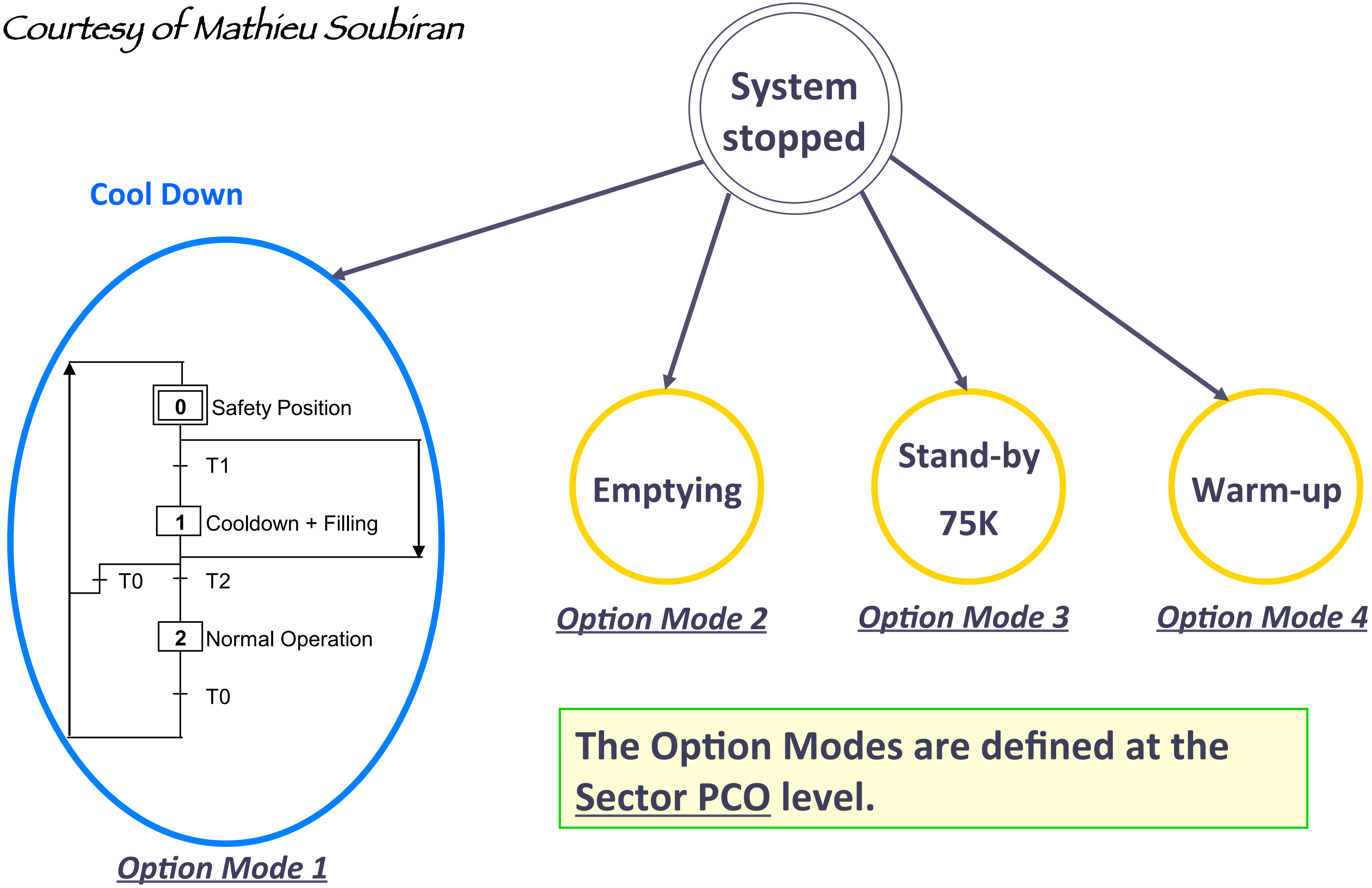
Courtesy of Mathieu Soubiran



- **SECTOR PCO**
  - **ARC PCO**
    - **He Guard Circuit**
      - PV970
    - **Cooling/Filling Circuit**
      - CV920
      - QV920
      - QV923
      - QV927
      - EH821
    - **1.9K Circuit**
      - CV910/11
      - CV915/16
    - **Beam Sreen Circuit**
      - CV943
      - CV947
      - EH843
      - EH847
  - **LSS PCO**
    - **Inner Triplet**
      - **He Guard Circuit**
        - PV970
      - **Cooling/Filling Circuit**
        - CV920
        - QV920
        - QV923
        - QV927
        - EH821
      - **1.9K Circuit**
        - CV910/11
        - CV915/16
      - **Beam Sreen Circuit**
        - CV947
        - CV941
        - EH847
    - **Standalone Mag**
      - **Standalone Magnets PCOs**
        - CV920 CV947
        - CV931 EH847
        - EH831 CV950
    - **DFB**
      - **DFB PCOs**
        - CV93x CV891
        - PV930 PV890
        - EH83x CV950
  - **RF**

Availability : Option modes / steppers

Courtesy of Mathieu Soubiran



System stopped

Cool Down

0 Safety Position

T1

1 Cooldown + Filling

T0

T2

2 Normal Operation

T0

Emptying

Stand-by 75K

Warm-up

Option Mode 1

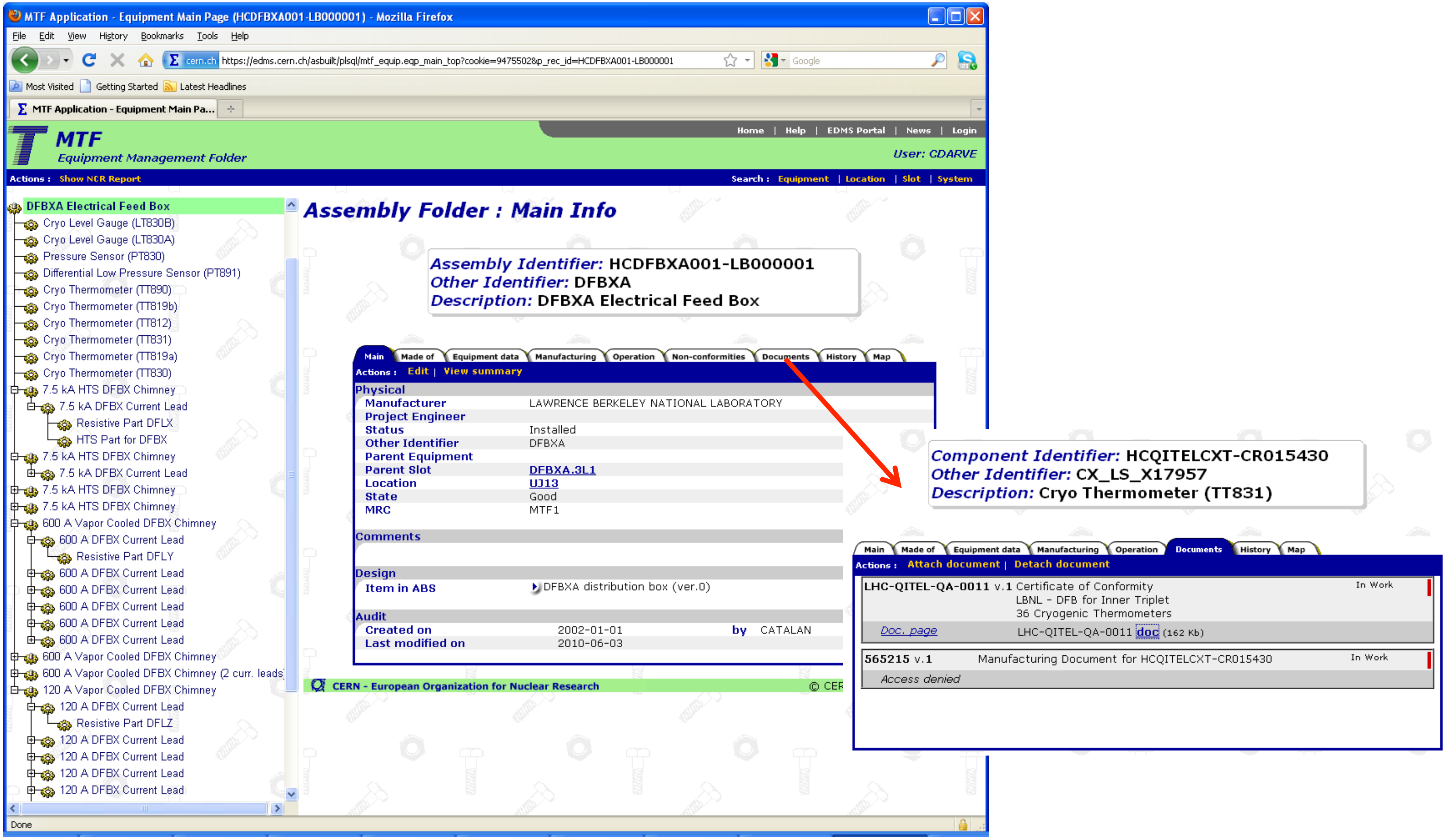
Option Mode 2

Option Mode 3

Option Mode 4

The Option Modes are defined at the Sector PCO level.

Traceability - MTF



- DFBXA Electrical Feed Box
  - Cryo Level Gauge (LT830B)
  - Cryo Level Gauge (LT830A)
  - Pressure Sensor (PT830)
  - Differential Low Pressure Sensor (PT891)
  - Cryo Thermometer (TT890)
  - Cryo Thermometer (TT819b)
  - Cryo Thermometer (TT812)
  - Cryo Thermometer (TT831)
  - Cryo Thermometer (TT819a)
  - Cryo Thermometer (TT830)
  - 7.5 kA HTS DFBX Chimney
    - 7.5 kA DFBX Current Lead
      - Resistive Part DFLX
      - HTS Part for DFBX
  - 7.5 kA HTS DFBX Chimney
    - 7.5 kA DFBX Current Lead
  - 7.5 kA HTS DFBX Chimney
  - 7.5 kA HTS DFBX Chimney
  - 600 A Vapor Cooled DFBX Chimney
    - 600 A DFBX Current Lead
      - Resistive Part DFLY
    - 600 A DFBX Current Lead
    - 600 A DFBX Current Lead
    - 600 A DFBX Current Lead
    - 600 A DFBX Current Lead
    - 600 A DFBX Current Lead
  - 600 A Vapor Cooled DFBX Chimney
  - 600 A Vapor Cooled DFBX Chimney (2 curr. leads)
  - 120 A Vapor Cooled DFBX Chimney
    - 120 A DFBX Current Lead
      - Resistive Part DFLZ
    - 120 A DFBX Current Lead
    - 120 A DFBX Current Lead
    - 120 A DFBX Current Lead
    - 120 A DFBX Current Lead

Assembly Folder : Main Info

Assembly Identifier: HCDFBXA001-LB000001
Other Identifier: DFBXA
Description: DFBXA Electrical Feed Box

Physical

Manufacturer	LAWRENCE BERKELEY NATIONAL LABORATORY
Project Engineer	
Status	Installed
Other Identifier	DFBXA
Parent Equipment	
Parent Slot	DFBXA.3L1
Location	UJ13
State	Good
MRC	MTF1

Comments

Design

Item in ABS: DFBXA distribution box (ver.0)

Audit

Created on	2002-01-01	by	CATALAN
Last modified on	2010-06-03		

CERN - European Organization for Nuclear Research © CER

Component Identifier: HCQITELCXT-CR015430
Other Identifier: CX_LS_X17957
Description: Cryo Thermometer (TT831)

LHC-QITEL-QA-0011 v.1 Certificate of Conformity
LBNL - DFB for Inner Triplet
36 Cryogenic Thermometers
In Work
Doc. page LHC-QITEL-QA-0011 doc (162 Kb)

565215 v.1 Manufacturing Document for HCQITELCXT-CR015430
In Work
Access denied