Cryogenic Safety Aspect of the Low-β Magnet Systems at the LHC

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Headlines:

The low-β magnet system description and specification

Identification of risk (Cryogenics and Radiological)

Safety risk assessment

Mitigating the risk

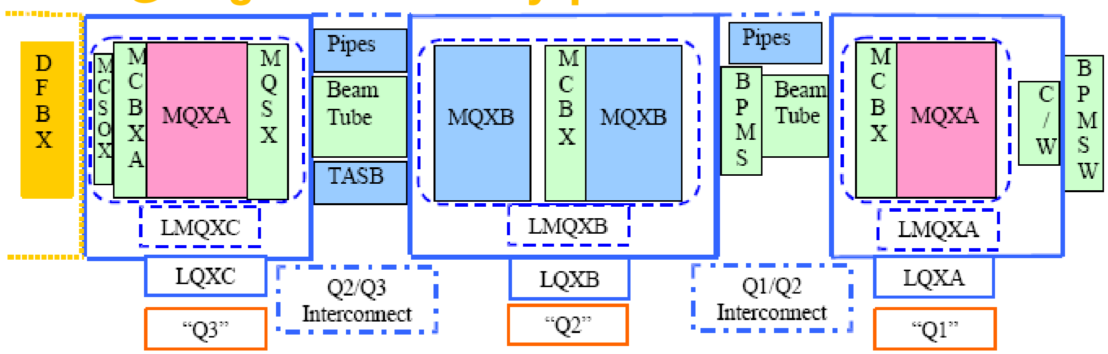
Engineering process approaches

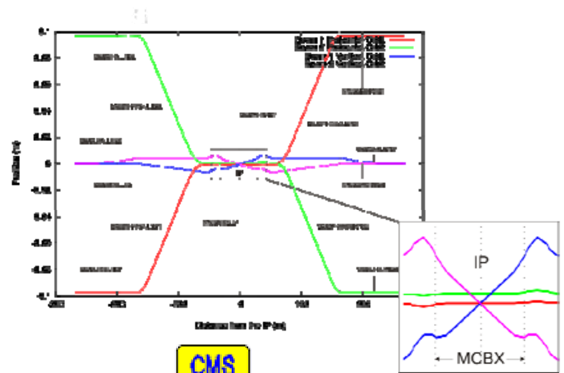
The low-β magnet systems at the LHC

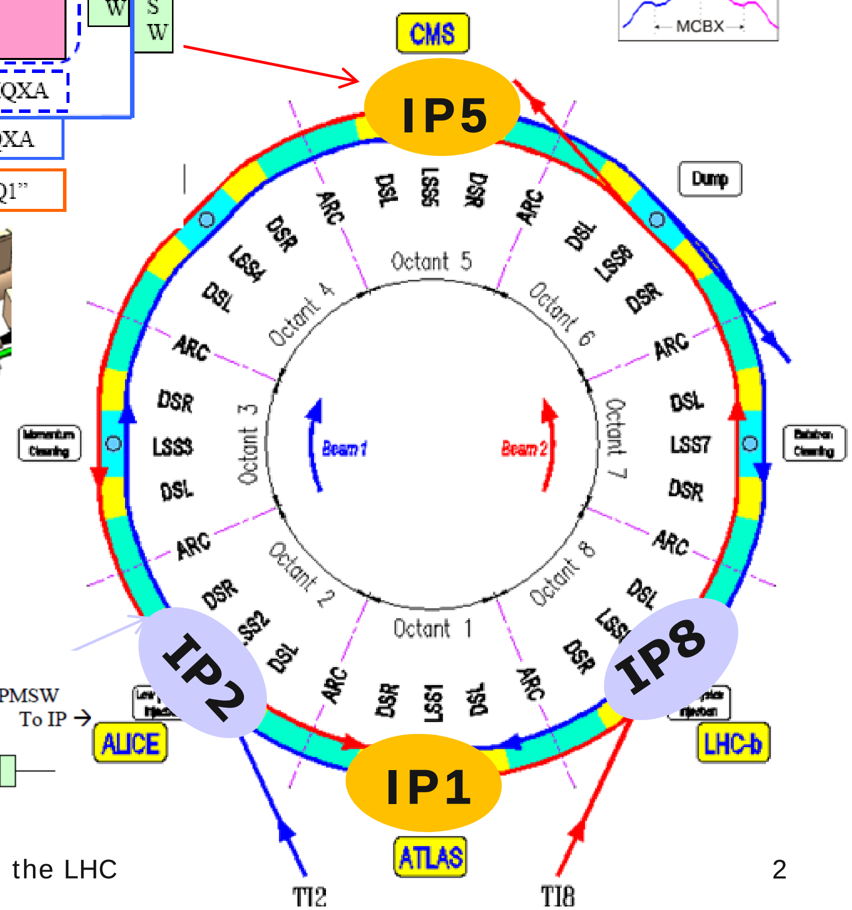
Inner Triplet for final beam focusing/defocusing

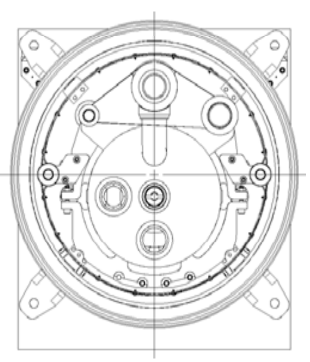
American contribution to the LHC

@ high luminosity points

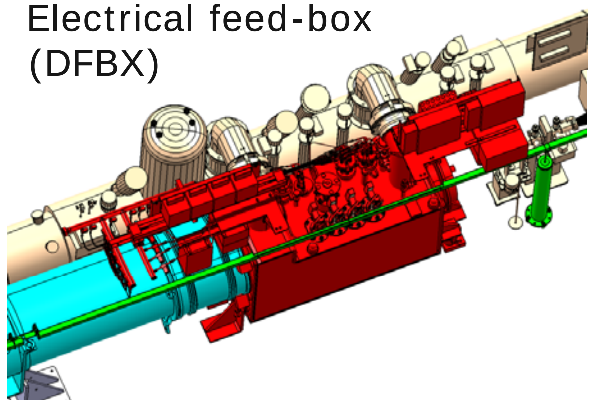






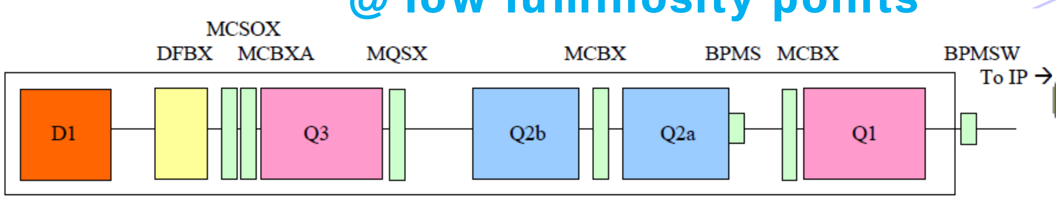


Electrical feed-box (DFBX)

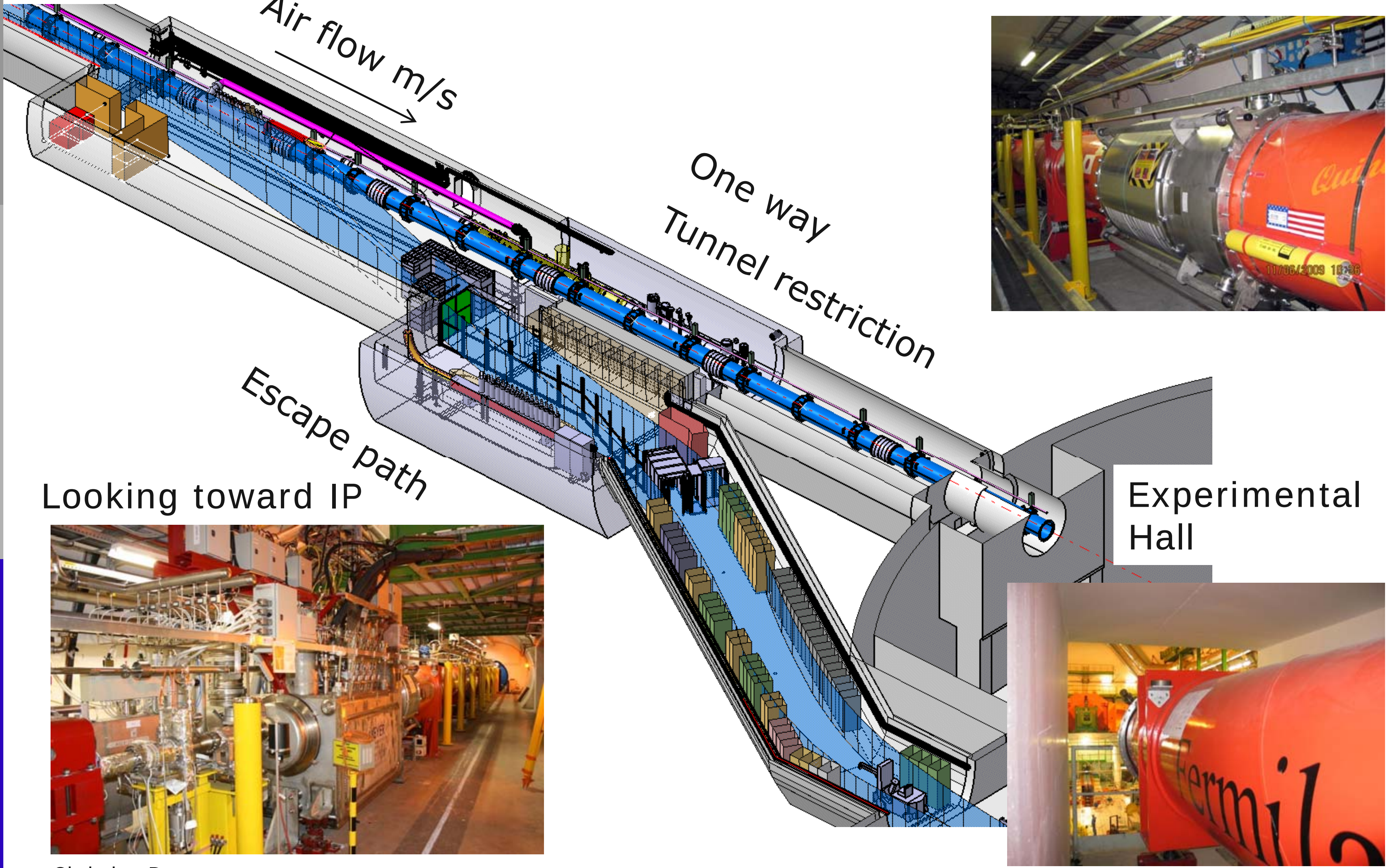


Q3

@ low luminosity points



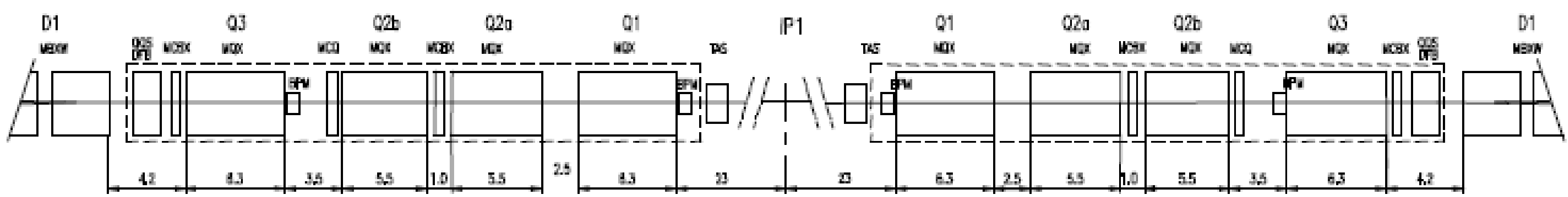
Underground views : 80-120 m below ground level



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).



Cryogenic risk through the Maximum Credible Incident (MCI)

Case 1: Electrical arc (inner triplet conductors) at nominal current
→ No personnel is allowed in the tunnel.

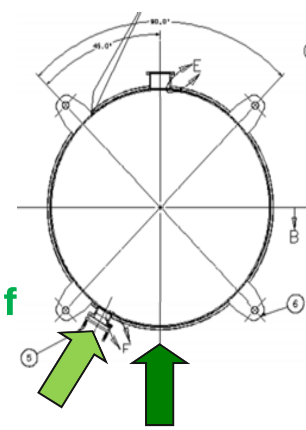
- Opening to the vacuum/helium space = 60 cm^2
- Maximum pressure in the insulating vacuum shall not exceed 1.17 bara
- Maximum flow venting at the safety relief device = 15 kg/s
- Helium discharge temperature though the safety relief valve = 20 K

➔ Number of recommended safety relief device=3 DN200 + 3 DN65

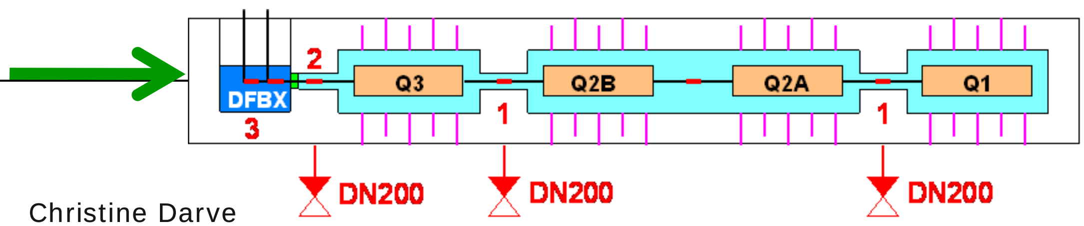
Case 2: Minor electrical arc (inner triplet conductors) at reduced current or leak from the helium space to the insulating vacuum
→ Personnel is allowed in the tunnel.

- Opening to the vacuum/helium space = 4 cm^2
- Maximum pressure in the insulating vacuum shall not exceed 1.03 bara
- Maximum flow venting at the safety relief device = 1 kg/s
- He. discharge temperature though the safety device=80 K

➔ Number of recommended safety relief device=1 DN200



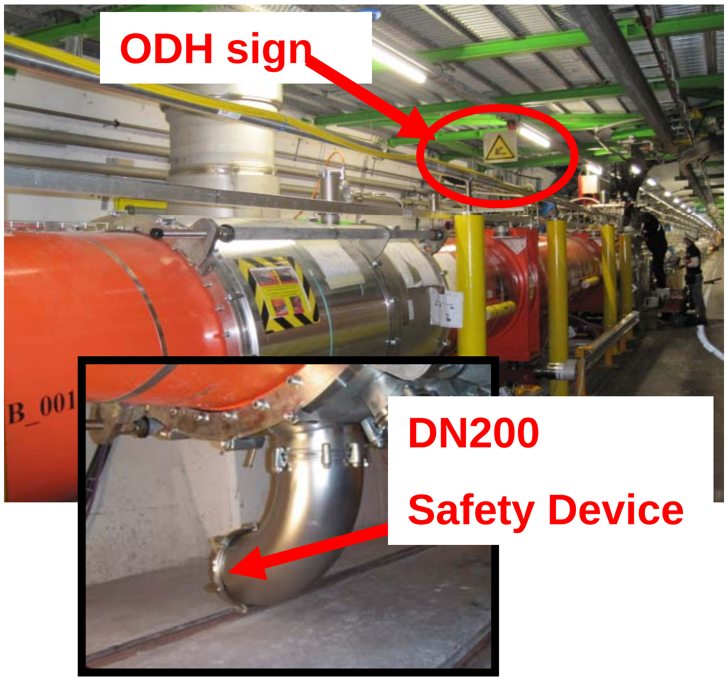
New DN200 @ high luminosity points:

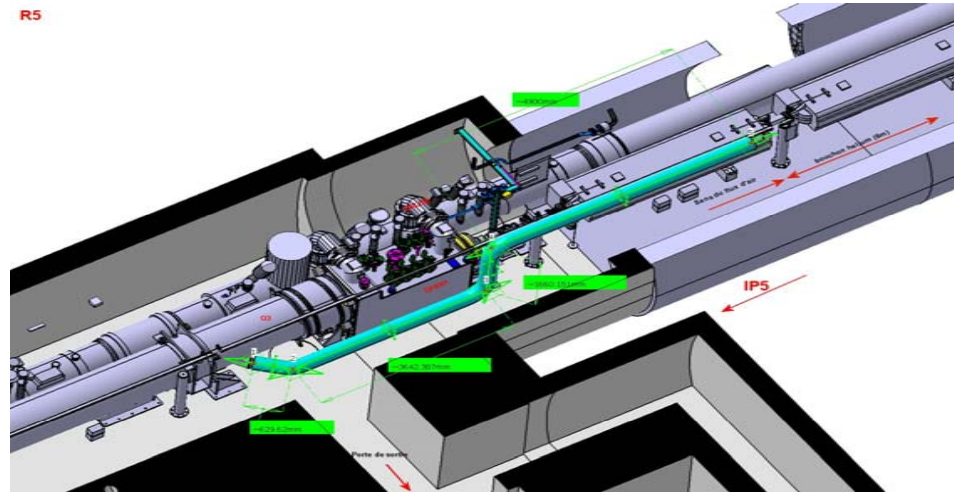


* Existing relief device

* New DN200 relief device

Consequences of the Maximum Credible Incident (MCI)

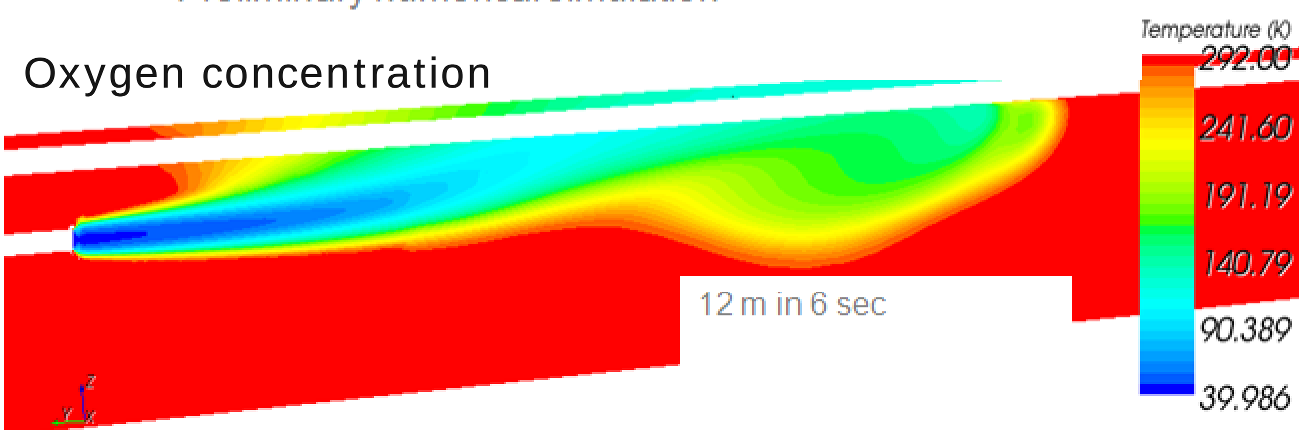




Courtesy of CERN/TGS

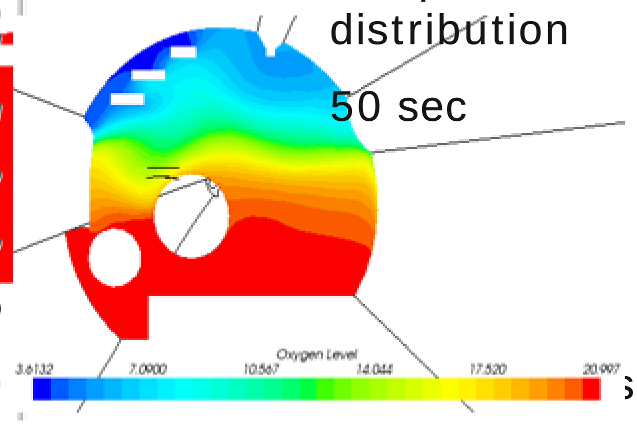
Preliminary numerical simulation

Oxygen concentration



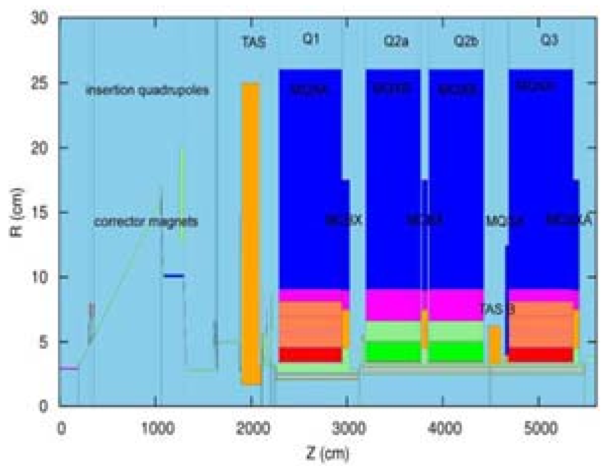
Temperature distribution

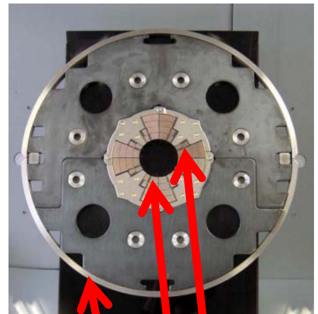
50 sec

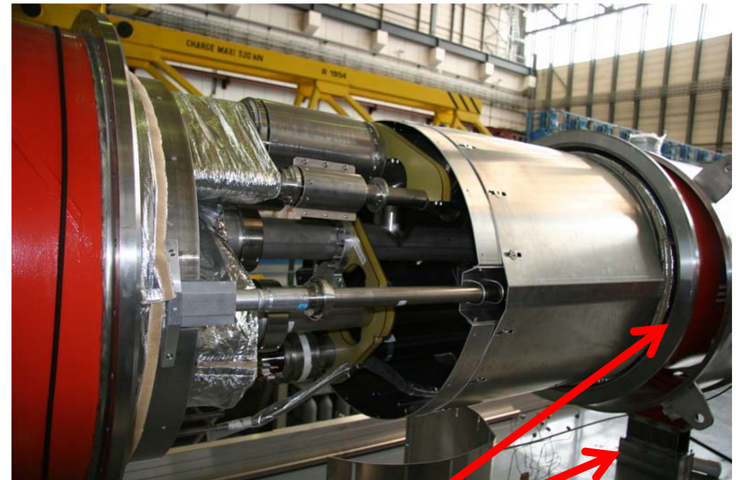


Radiological risk (*By courtesy of N. Mokhov*)

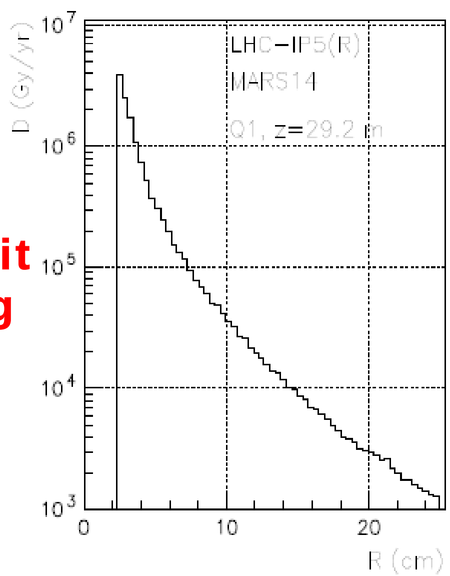
IR5 azimuthally averaged power distribution







Radial distribution of azimuthally averaged dose (Gy/yr)



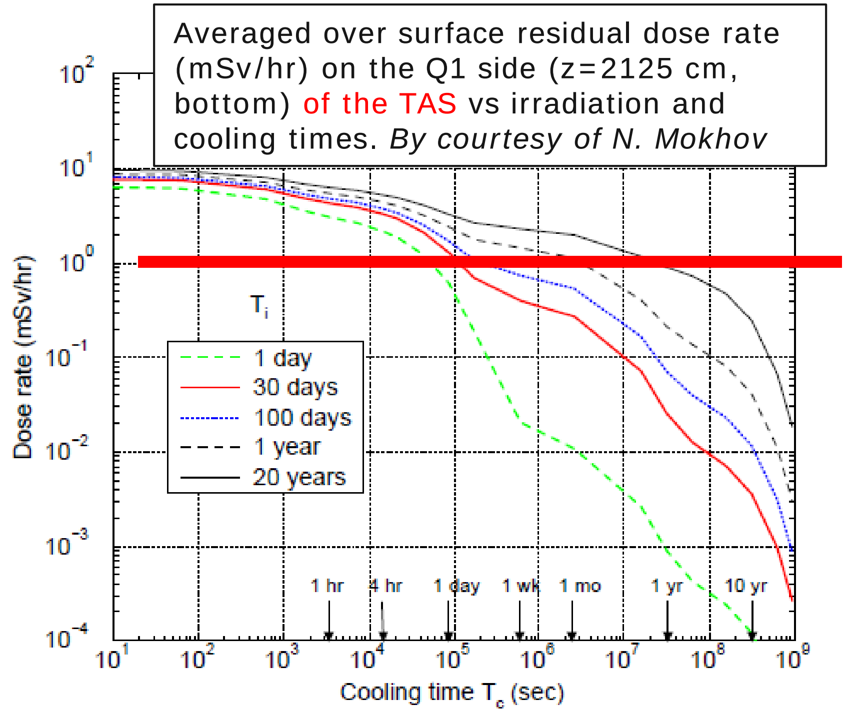
→ Magnet quench limit =1.6 mW/g

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

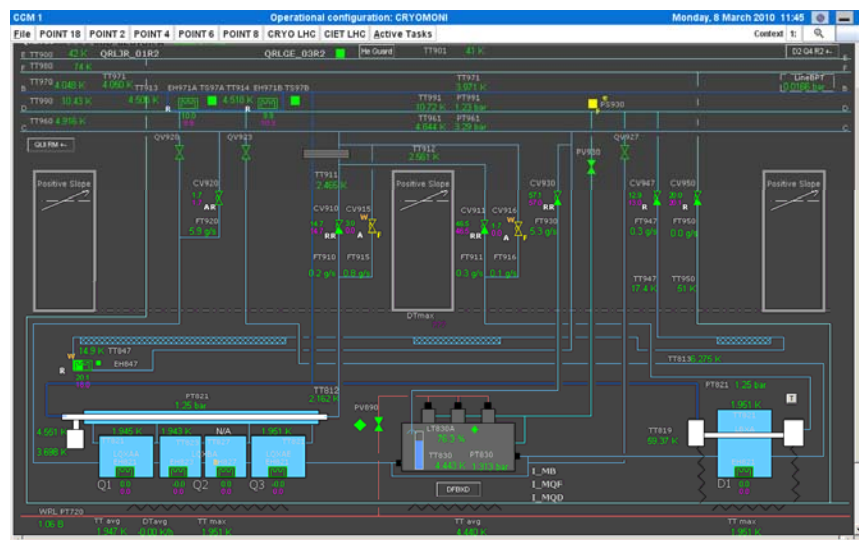
Radiological risk mitigation

- 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
- Specific hazard analysis is requested to intervene on the low-β magnet systems Radiological survey is systematical performed prior intervention (< 1mSv/hr)
- Procedures written based on lessons learned and to limit the personnel exposition time
- The process control makes use of different interlocks and alarm level for each operating mode



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)

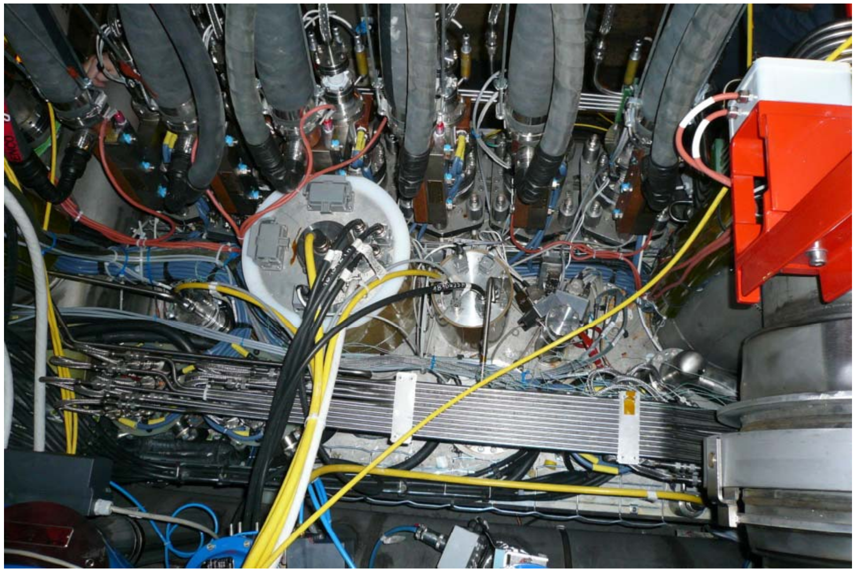


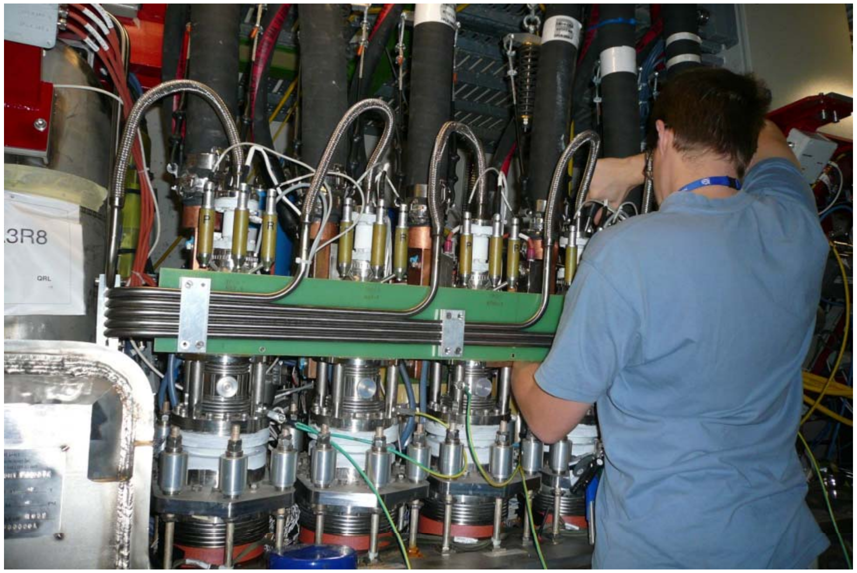
Risk mitigation : personnel training

•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

- Failure Mode and Effect Analysis
- “What-Ifs” Analysis

Table 3 Example of simplified “What-Ifs” Analysis

Quench on the low beta magnet system Cold compressor stops Compressed air fails Cryostat Insulating vacuum break QRL line rupture Helium return line leaks/ruptures He supply line leaks/ruptures Water cable leaks/ruptures Current leads overloaded	Power Supply Power Outage Thermometry crate dies
	Fieldbus: e.g. Profibus or WorldFip fails Inducstrial PC: e.g. FEC fails PLC fails Ethernet Network fails UNICOS/SCADA communication loss CIET communication loss DB, Logging communication loss
Beam Interlock System Fails Large radiation dose achived	QPS and power supply fail Power Interlock Controller fails

➔ Safe for personnel and equipment : safety valves are properly sized

Engineering process approach

Opening to a new Engineering process approach:

A new engineering manual was issued at Fermilab:

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

- 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

Conclusion

- The low-β system is among the most critical for the operation and performance of the LHC. For the planned upgrades, maintenance and removal will yield an inherent radiological risk

- This is a main motivation for a well established assessment of the cryogenic and radiological risks

- Based on the analysis, the hardware commissioning and the lessons learned (including other locations in the LHC) → mitigating risk

- Continuous improvement of availability, reliability, traceability is on-going

- In the sake of providing a coherent and methodological approach across HEP laboratories, a systematic safety analysis is recommended for future evolutions and projects

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