Cryogenic Safety Aspect of the Low-\(\beta\) Magnet Systems at the LHC

Christine Darve

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Headlines:

The low-\(\beta\) magnet system description and specification

Identification of risk (Cryogenics and Radiological)

Safety risk assessment

Mitigating the risk

Engineering process approaches
The low-\(\beta\) magnet systems at the LHC

Inner Triplet for final beam focusing/defocusing

American contribution to the LHC

@ high luminosity points

Electrical feed-box (DFBX)

@ low luminosity points

ICEC23 - Cryogenic Safety Aspect of the Low-\(\beta\) Magnet Systems at the LHC
Underground views: 80-120 m below ground level

Air flow m/s

One way
Tunnel restriction

Escape path

Looking toward IP

Experimental Hall
The low-$$\beta$$ 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 $$10^{34} \text{cm}^{-2}\text{s}^{-1}$$.

- **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 cm²
- 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 cm²
- 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)

- Add three additional DN200 safety relief devices to the existing three DN65.
- Removal of the thermal screen in front of the safety valve.
- Deflector to allow personnel interventions and to protect carbon steel equipment.
- Installation of ODH monitoring systems, signs, evacuation siren and flashing light.
- Staged relief: one dedicated relief device to open at lower pressure level than others.

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Temperature distribution

Oxygen concentration

12 m in 6 sec

Temperature (K)

ODH sign

DN200 Safety Device

Preliminary numerical simulation

Courtesy of CERN/TGS

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

For comparison: Arc magnet ~ 1 Gy/yr

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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 $2 \times 10^4$ 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.

By courtesy of N. Mokhov

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.

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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)

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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-$\beta$ magnet system area.

“Compact” DFBX area
Engineering process approach

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

<table>
<thead>
<tr>
<th>What-If</th>
<th>What-If</th>
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</thead>
<tbody>
<tr>
<td>Quench on the low beta magnet system</td>
<td>Power Supply Power Outage</td>
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<tr>
<td>Cold compressor stops</td>
<td>Thermometry crate dies</td>
</tr>
<tr>
<td>Compressed air fails</td>
<td>Fieldbus: e.g. Profibus or WorldFIP fails</td>
</tr>
<tr>
<td>Cryostat Insulating vacuum break</td>
<td>Industrial PC: e.g. FEC fails</td>
</tr>
<tr>
<td>QRL line rupture</td>
<td>PLC fails</td>
</tr>
<tr>
<td>Helium return line leaks/ruptures</td>
<td>Ethernet Network fails</td>
</tr>
<tr>
<td>He supply line leaks/ruptures</td>
<td>UNICOS/SCADA communication loss</td>
</tr>
<tr>
<td>Water cable leaks/ruptures</td>
<td>CIENT communication loss</td>
</tr>
<tr>
<td>Current leads overloaded</td>
<td>DB, Logging communication loss</td>
</tr>
<tr>
<td>Beam Interlock System Fails</td>
<td>QPS and power supply fail</td>
</tr>
<tr>
<td>Large radiation dose achieved</td>
<td>Power Interlock Controller fails</td>
</tr>
</tbody>
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⇒ 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

• 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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