Effects of Protection Equipment on the Beam & Reliability Studies for the circuit protection Systems

A. Apollonio, T. Cartier-Michaud and D. Wollmann for WP7


Outline

- Effects of Protection Equipment on the Beam and Mitigations
  - Introduction
  - Effects of quench heater discharges on beam
  - Impact of fast current changes in the triplet
  - Summary

- Reliability Analysis for Circuit protection Systems
  - Reliability requirements and reliability analysis steps
  - Failure scenarios & Effects of periodic inspections/maintenance
  - Monte Carlo models for 11 T and IT protection
  - Component level reliability analysis for protection systems (QDS, CLIQ, HDS, ...)
  - Summary
Effects of Protection Equipment on the Beam and Mitigations
Effect of magnet protection equipment on beam

- Quench heaters (QH) impact the circulating beam, if not dumped before triggering → observed and verified for LHC main dipoles.

- Change of the current (quench, CLIQ discharge, …) in triplet magnets causes dipole kick on circulating beam, due to offset in one plane (crossing angle) → observed during quench of RQX.R1, 03.06.2018.

- Stronger effect in HL-LHC than in LHC due to:
  - more QH (11 T, triplet, D1, D2), QH + CLIQ (triplet)
  - larger beta functions → Triplet (~8 km → ~21 km), D1 (~5 km → ~19 km) D2 (~1.7 → ~6.4 km)
Quench heater discharge: Ultrafast current rise

- **Ultra fast** effect, quench heaters reaching full current/field within less than 1/2 LHC turn
  - MB: ~ 29 us; MQXF: ~ 35 us
- **Spurious triggering** of one QH unit cannot be fully excluded.
Experience from LHC dipoles (dedicated experiment)

- Fast rise of field from quench heaters reaching up to 70% of magneto static value after 1 ms
- Measurements show two time constants
- Rise time depends on beam screen temperature and main circuit current
- Qualitative good agreement with expectation
- Quantitative discrepancy between simulations and measurements
- Detailed studies of shielding effects required (experiments & simulations)
## Expected kicks from HiLumi magnets with all QH fired

<table>
<thead>
<tr>
<th>Magnet (all QH)</th>
<th>LHC kick (sigma)</th>
<th>→</th>
<th>HL-LHC kick (sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>0.3</td>
<td>→</td>
<td>0.5</td>
</tr>
<tr>
<td>D1</td>
<td>1.4</td>
<td>→</td>
<td>2.0 → &lt; 0.5</td>
</tr>
<tr>
<td>D2</td>
<td>1.2</td>
<td>→</td>
<td>2.4 → &lt; 0.5</td>
</tr>
<tr>
<td>11 T - dipole</td>
<td>0.04</td>
<td>→</td>
<td>0.4 → 0.03</td>
</tr>
<tr>
<td>Triplet (48 QH)</td>
<td>2.5</td>
<td>→</td>
<td>33.7</td>
</tr>
<tr>
<td>Triplet (single QH)</td>
<td>0.6</td>
<td>→</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Comparison of kicks from quench heater discharges (magnetostatic values)

- Impacts of quench heaters on beam has been reduced/mitigated for HL-LHC magnets by change of connection schemes (dipole → quadrupole fields)
  - Applied for 11 T, D1 and D2
- HL triplet quench heater connection scheme has been optimised to reduce the effect of a spurious discharge of a single quench heater power supply. The effect of all 48 quench heaters on the beam remains critical
- Quench detection systems will ensure that a beam dump is initiated before the discharge of quench heaters and CLIQ is triggered
Effect of quench in LHC triplet on beam

Small changes in triplet current can cause important beam kicks due to large beta functions and crossing angle (beam offset from magnetic centre)

Quenches are sufficiently slow to allow dumping the beams before critical loss levels are reached

HL triplets will have symmetric quench protection

Event overview:

- Symmetric quench of RQX.R1 due to cryo-control problem
- Orbit offset of ~250 um with \( \delta l = 1.7 \text{ A} \) \((I_{\text{circuit}} = 6.2 \text{ kA})\) causing beam loss induced beam dump
- QPS triggering ~20 ms after beam dump
- Detailed analysis of event documented in internal note: B. Lindstrom, E. Ravaioli, "Analysis of the sequence of events in the RQX.R1 circuit on 3 June 2018"
Effect of one spurious CLIQ discharge in IT

- A spurious discharge of a single CLIQ unit cannot fully be excluded
Spurious CLIQ discharge in Q1/Q3

- **Asymmetric** discharge into the poles of the Q1a/b (respectively Q3a/b)
- **Skew dipole** field in magnet causing **kick of beam**
- Additional (much weaker) dipole component during discharge of magnet current due to beam offset (Q1: up to 9.8 mm, Q3: up to -17.1 mm)
Spurious CLIQ discharge in Q2

- **Symmetric discharge** into P1-P3 and P2-P4 of Q2a/b
- **Octupolar** field
- Dipole component developing during discharge of magnet current due to beam offset (up to 16.6 mm) in Q2
Effect on the circulating beam

- Spurious discharge of one CLIQ unit into Q1 or Q3 causes critical orbit excursion within one LHC turn (89 us) → no possibility to actively interlock
- CLIQ discharge into Q2 reaches critical levels after only ~ 20 turns → sufficient time to actively interlock and dump the beams before critical loss levels will be reached
Mitigation of effect of spurious CLIQ firing on circulating beam

- Implementation of a **Q2 like CLIQ connection scheme** for Q1 and Q3 in current IT baseline
- CLIQ discharge creates **octupole fields** in Q1, Q2 and Q3
- CLIQ discharge in Q1 and Q3 **less critical** than in Q2
- Spurious discharge of CLIQ units will be **interlocked** → beam dump ensured within **< 1ms** after start of discharge

<table>
<thead>
<tr>
<th>Step</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection QH discharge (di/dt ≈ 4 MA/s)</td>
<td>100 μs</td>
</tr>
<tr>
<td>Detection CLIQ discharge (di/dt ≈ 200 kA/s)</td>
<td>&lt; 500 μs</td>
</tr>
<tr>
<td>Communication DQHSU → PIC → BIS</td>
<td>12 μs</td>
</tr>
<tr>
<td>Beam abort sequence</td>
<td>270 μs</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&lt; 1 ms</strong></td>
</tr>
</tbody>
</table>
Summary – Effects of protection equipment on beam

- Fast orbit offsets have been observed in the LHC due to firing of quench heaters
- Quench heater connection schemes have been changed to quadrupole schemes where possible → reduction of kick strength
- Spurious CLIQ discharges in Q1 or Q3 would have caused fastest failure in the LHC → mitigated by change of CLIQ connection scheme
- In case of a quench in the HL triplets, the interlock sequence will ensure that a beam dump request is sent before a discharge of quench heater power supplies and CLIQ units is initiated
- Spurious CLIQ discharges will be interlocked and initiate immediately a beam dump and re-trigger the remaining CLIQ units
Reliability Analysis for Circuit protection Systems
Ongoing Availability/Reliability Activities in WP7

1. Top-down → Definition of reliability/availability targets for protection systems
   - Use LHC risk matrix to define acceptable frequency of failure scenarios

2. Intermediate → Breakdown of failure frequency into sub-system reliability/availability targets
   - Define acceptable reliability parameter space for protection sub-systems (failure rates, periodic inspection/test intervals, etc.)

3. Bottom-up → Demonstration that system designs are compliant to reliability targets
   - Component-level calculations
   - (Possible) refinement of architecture or component selection + iteration
**Definition of Reliability Requirements**

<table>
<thead>
<tr>
<th>LHC risk matrix</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>∞ year</td>
</tr>
<tr>
<td>S7</td>
<td>S6</td>
</tr>
</tbody>
</table>

- **Frequency**
  - 1 / hour
  - 1 / day
  - 1 / week
  - 1 / month
  - 1 / year
  - 1 / 10 years
  - 1 / 100 years
  - 1 / 1000 years

Example: 10 % probability of damaging the triplet in 100 years

Failure Mode and Effects Analysis: identification of **failure consequences** → establish acceptable **frequency** for failure mode occurrence
Failure Scenarios – Description

Protection studies carried out in collaboration with MPS experts and system designers

Failure Logic can be expressed in the form of fault trees

Each node has **assigned probabilities** of failure

Calculation of probability of top event **based on node probabilities**

**Static fault trees** do not account for relevant aspects of protection systems → **active monitoring** of component status, **periodic inspection/tests**, event sequencing

Developed **Monte Carlo model** to calculate probability of **failure to protect** the triplet

Effect of Periodic Inspection/Maintenance

Periodic inspection/tests of protection equipment can significantly improve reliability. Also quench events ‘count’ as tests, as missing redundancy will be detected during a discharge.

What is the minimum acceptable interval between periodic tests to respect protection requirements?
Example 1: 11T Magnet Protection

Single DQHDS Control

Double DQHDS Control
Example 1: 11T Magnet Protection

Top event: unprotected magnet + quench

unprotected magnet
\[ \geq 3 \text{ oo 16 DQHDS} \]
do not discharge

1\textsuperscript{st} DQHDS
does not discharge

2\textsuperscript{nd} DQHDS
does not discharge

3\textsuperscript{rd} - 16\textsuperscript{th} DQHDS
does not discharge

(A)symmetric quench

Reliability study demonstrated the limited gain in terms of protection of having a redundant DQHDS control unit and showed the importance of regular testing.
Example 2: IT Magnet Protection

**Protection target:** 10% probability of damaging a triplet magnet in 100 years (2% in 20 years)

Preliminary studies demonstrate that the **required protection level can be achieved with the baseline configuration (CLIQ + QH).** Results assume QH reliability close to LHC values, to be demonstrated for Nb3Sn magnets.
Conclusions - Reliability Analysis for Circuit protection Systems

- Definition of reliability targets for circuit protection systems based on detailed **failure mode analysis**, involving many magnet & equipment experts
- **Methodology and tools developed** and used in ongoing and future studies (LHC risk matrix, Reliability allocation based on complexity, AvailSim)
- Important results for designs of protection systems
  - **Confirmation** of final configuration of 11T protection architecture
  - Study of IT magnet protection → preliminary results show that baseline configuration (CLIQ + QH) will **meet the protection targets**
  - Future studies to define **sub-system reliability** requirements for IT
  - **Component level analysis** for CLIQ and quench heater power supplies ongoing
Questions?
Spare slides
Mitigation of effect of spurious CLIQ firing on circulating beam

- Implementation of a Q2 like CLIQ connection scheme for Q1 and Q3
- CLIQ discharge creates octupole field