Quench of Triplet quadrupole
(RQX.R1, 03.06.2018)

- Observations
  - Beam
  - Triplet circuit
  - Cryogenic system
- Simulations
- Summary

B. Lindstroem, E. Ravaioli, A. Verweij, D. Wollmann

More details:
- Analysis of the sequence of events in RQX.R1 circuit on 3 June 2018, Internal note, TE-MPE, EDMS 2025613
- 168th and 169th MPP
- A. Verweij: Analysis of IT quench, 351st LMC, 20.06.2018
Beam observations during triplet event

- Significant orbit movement in B1
- No orbit change observed in B2
- Beams dumped by losses in collimators
- Max kick before beam dump: 0.2 urad

Plotting two consecutive turns identifies the source of the orbit distortion in the triplet R1

- Offset = 0.58 mm
- <10 um
- ~250 um
- 18 ms
Re-cap nested triplet circuit

- Nested circuit with two main power converters (RQX and RTQX2) and one trim converter (RTQX1). The event originates in Q1.
Re-cap geometry of triplet

Average = \((3.67 + 5.42)/2 = 4.55 \text{ mm}\)

Average = \((-3.67 - 4.00)/2 = -3.84 \text{ mm}\)
Circuit observations versus beam observations

- Current change in RQTX1 at beam dump: -1.7 A
- Quench detected only 18ms after beam dump
- Total current change in RQTX1 at moment of PC off: -7 A
- Usually quench: quench detected with $U_{res} > 100$ mV (current change tens of mA) → very fast developing quench, detected very late, due to missing symmetric quench detection in triplet quads

15 January 2019
Daniel Wollmann
Observations in cryogenic system

- Temperature oscillations in helium bath before event
- Triplet R1 warms up from ~1.97 K to ~2.16 K
- Helium temperature above lambda point means less cooling for magnet at energy deposition due to debris from IP
Observations in circuit versus simulations

- Observed behaviour in circuit well reproduced by simulations
- Very fast current decay was achieved in simulations by defining high normal zone propagation velocity

\[ I_{Q1} = I_{RQX} + I_{RTQX1} \]
\[ I_{Q2} = I_{RQX} + I_{RTQX2} \]
\[ I_{Q3} = I_{RQX} \]
Expected kick strength & beam offsets from circuit measurements

- Expected kick from measured current change at 6.2 kA (TF = 30.312 T/m/kA, and max ∆I 1.7 A)
  - B1 kick: $6.7 \times 10^{-8}$ rad
  - B2 kick: $6.0 \times 10^{-8}$ rad

- Expected offset from calculated kick:
  - 82 µm offset at BPMS.2R1.B1
  - 39 µm offset at BPMS.2R1.B2

- But, observed B1 offset: 250 µm, B2 offset: <10 µm

→ Factor 3 discrepancy

- Correct orbit in triplet confirmed by Q1 k-modulation measurements on 16.06.2018

→ Detailed study of field distortions during quench due to:
  - Inter-filament Coupling Currents (IFCC)
  - Inter-strand Coupling Currents (ISCC)
  - Current re-distribution in sc. Cables (CRC)
Inter-Filament Coupling Currents (IFCC)

Currents (only 1/4 magnet cross-section shown)

Magnetic field induced in the magnet aperture

<table>
<thead>
<tr>
<th>in [mT]</th>
<th>From BPM</th>
<th>From ΔI</th>
<th>IFCC</th>
<th>ISCC</th>
<th>CRC</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1, ΔB_X</td>
<td>+0.7</td>
<td>+0.233</td>
<td>+0.014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1, ΔB_Y</td>
<td>&lt;0.1</td>
<td>+0.000</td>
<td>+0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2, ΔB_X</td>
<td>&lt;0.1</td>
<td>−0.197</td>
<td>+0.022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2, ΔB_Y</td>
<td>&lt;0.1</td>
<td>+0.000</td>
<td>+0.003</td>
<td></td>
<td></td>
<td></td>
</tr>
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Inter-Strand Coupling Currents (ISCC)

Currents (only 1/4 magnet cross-section shown)

Magnetic field induced in the magnet aperture

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<td>+0.022</td>
<td>+0.048</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2, ΔB_y</td>
<td>&lt;0.1</td>
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Current Redistribution in the Cable (CRC)

Currents (only 1/4 magnet cross-section shown)

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<tbody>
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<td>B1, ΔBₓ</td>
<td>+0.7</td>
<td>+0.233</td>
<td>+0.014</td>
<td>−0.026</td>
<td>+0 / +0.967</td>
</tr>
<tr>
<td>B1, ΔBᵧ</td>
<td>&lt;0.1</td>
<td>+0.000</td>
<td>+0.002</td>
<td>+0.000</td>
<td>+0.000</td>
</tr>
<tr>
<td>B2, ΔBₓ</td>
<td>&lt;0.1</td>
<td>−0.197</td>
<td>+0.022</td>
<td>+0.048</td>
<td>+0 / +0.636</td>
</tr>
<tr>
<td>B2, ΔBᵧ</td>
<td>&lt;0.1</td>
<td>+0.000</td>
<td>+0.003</td>
<td>+0.000</td>
<td>+0.000</td>
</tr>
</tbody>
</table>

The real cable redistribution currents are between two extreme cases

- Infinite contact resistance between strands: Effect is zero
- Zero contact resistance between strands: Effect is maximum (full redistribution)
Kicks from IFCC, ISCC and CRC

- Dipole kicks observed in beam can be explained by current redistribution in the sc. cables during the quench
- The other effects studied are one order of magnitude too small
- Note, that the exact values of many parameters used in the simulations are unknown: number of quenched turns, initial length normal zone, normal-zone propagation velocity, turn-to-turn quench propagation time, conductor properties, ...

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<td>+0.014</td>
<td>−0.026</td>
<td>+0 / +0.967</td>
<td>+0.221 / +1.188</td>
</tr>
<tr>
<td>B1, ΔBᵧ</td>
<td>&lt;0.1</td>
<td>+0.000</td>
<td>+0.002</td>
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<td>+0 / +0.636</td>
<td>−0.127 / +0.509</td>
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Summary

- Beam dump observed on 03.06.2018 due to losses in the collimation system has it’s origin in the triplet R1 (Q1)
- Very fast (symmetric) quench leading to beam dump after 240 turns → QPS detection only ~40 ms after onset of quench
- Origin of event most likely due to warm up of helium in combination with debris from the IP
- Asymmetric response of B1 and B2 can be explained by current redistribution in sc. cables during the quench
QPS signal names