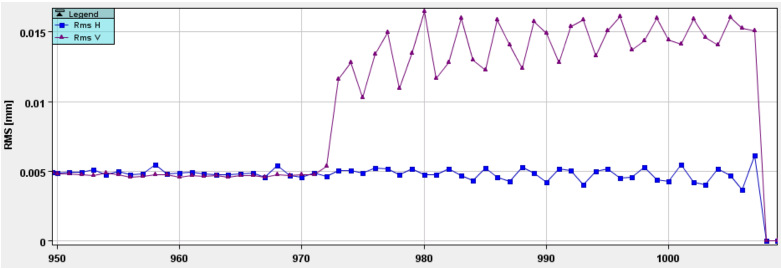
Quench Heaters, CLIQ and triplet quench: Effect of beam screen shielding and other transient effects in magnets; consequences for protection electronics

Matthieu Valette, B. Lindström, E. Ravaioli, D. Wollmann
CERN

PE section rehearsal for the 8th HiLumi meeting, CERN, 11th October 2018

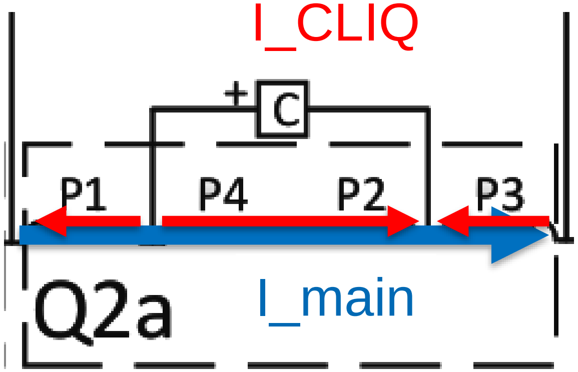
Introduction

- During LHC operation and dedicated LHC MDs: Quench Heaters (QH) kick the beam when discharging



Quench of MB.C28L5 on July 12th 2016

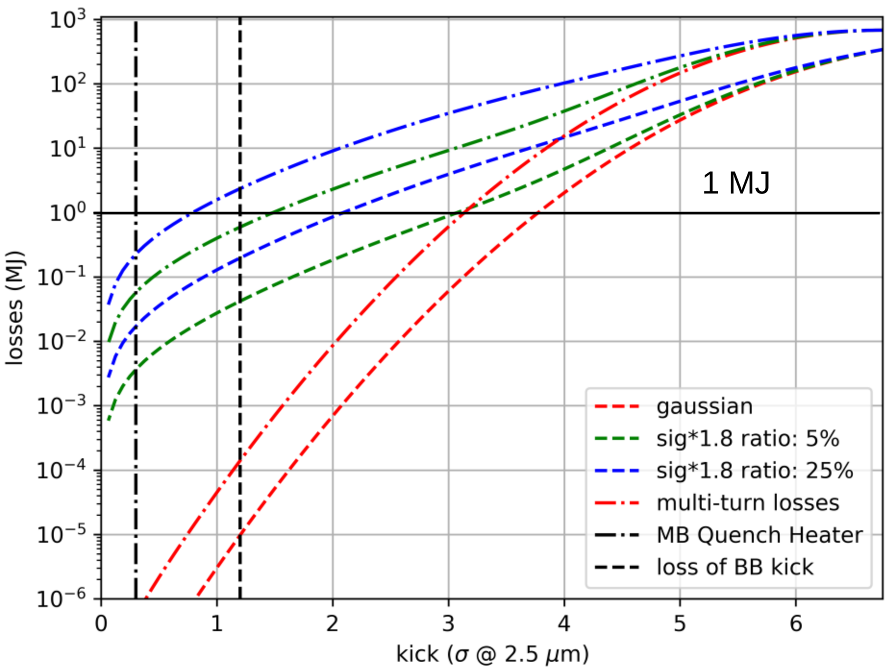
- CLIQ (used to protect MQXF) will discharge 2 kA in the triple circuit.



CLIQ discharge in Q2a

Acceptable orbit shifts in the HL-LHC

- Damage limit of LHC collimators for fast (<1 ms) losses: 1 MJ
- Conservative assumptions on the beam distribution:
  - Any sustained orbit shift larger than 0.8 σ must be avoided



LH-LHC magnets with QH

- From triggering: spurious firing of 1 QH circuit as main failure case
- Review of expected kicks lead to an update of connection schemes
- Some kicks are still critical (Q2b, Q2a, Q3a)

Expected kicks from QH protecting HL-LHC magnets

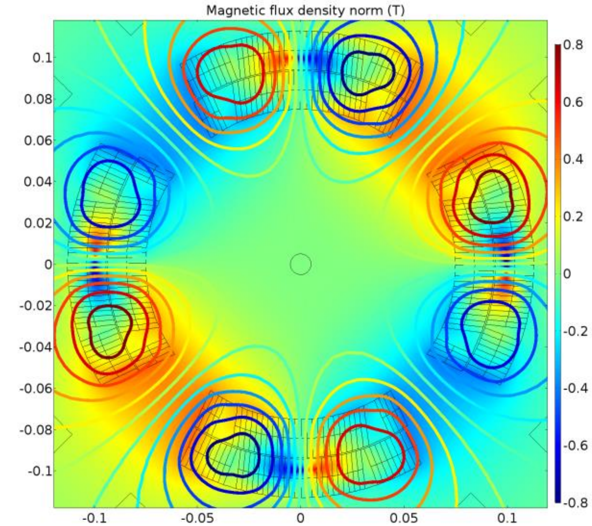
Magnet	L (m)	I_{QH} (A)	B (μT)	Kick (σ)
MB	14.3	80	450	0.4
MQ	3.1	80	430	0.1
IPD (D1, D2, D34)	9.45	200	1.25	0.4
New IPD (MBXF, MBRD, 11T)	7.78	168	Quad-rupole field	0.
MQXF (Q2b)				
HF (old)	7.15	200	643	1.7
LF (old)			700	1.8
HF (new)			472	1.28
LF (new)			412	1.08

HL-LHC optics v1.3 with ATLAS crossing bump

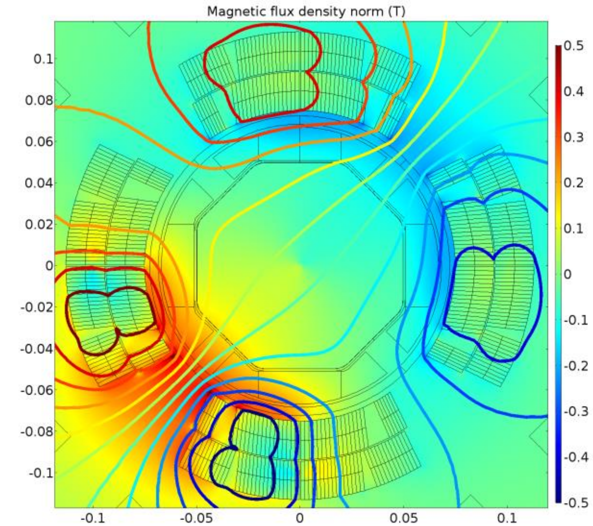
Effect of a CLIQ discharge

- Same as QH, a spurious discharge is assumed as the main failure case.
- From connection scheme:
  - Q2: quadrupole field
  - Q3: dipole field of 48 mT
- Assuming a sine function to the max field distortion:
  - Q2: β-beating => OK
  - Q3: kick of 1 σ/ turn **critical**

Q2, peak field (12 ms)



Q3, peak field (20 ms)



Beam screen shielding

- For copper (8 T, 30 K, RRR=10)

  $$\rho = 6.6 \times 10^{-10}\ \Omega.\mathrm{m}$$

- Skin depth for $\tau_{QH} = 20\ \mu$s (50 kHz) :

  $$\delta = 20\ \mu m\ < 80\ \mu m \text{ (BS copper layer)}$$

- Field change driving the eddy currents:

  $$\frac{dB_{QH}}{dt} = 67\ T.s^{-1}, \qquad j{\sim}1\ A.mm^{-1}$$

- Eddy current decay time:

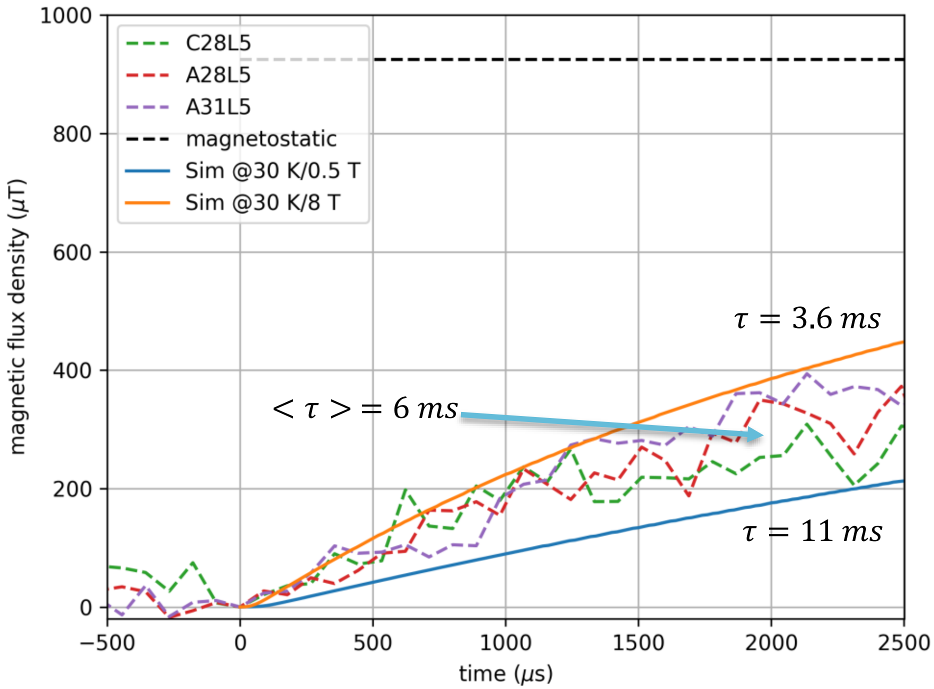
  $$\tau = \frac{L_{eddy}\ S_{BS}}{\rho_{Cu}\ l_{magnet}} \propto \frac{1}{\rho_{Cu}} {\sim} 10\ ms$$

Magnetic field transients in MB magnets: Beam measurements vs FEM Simulation

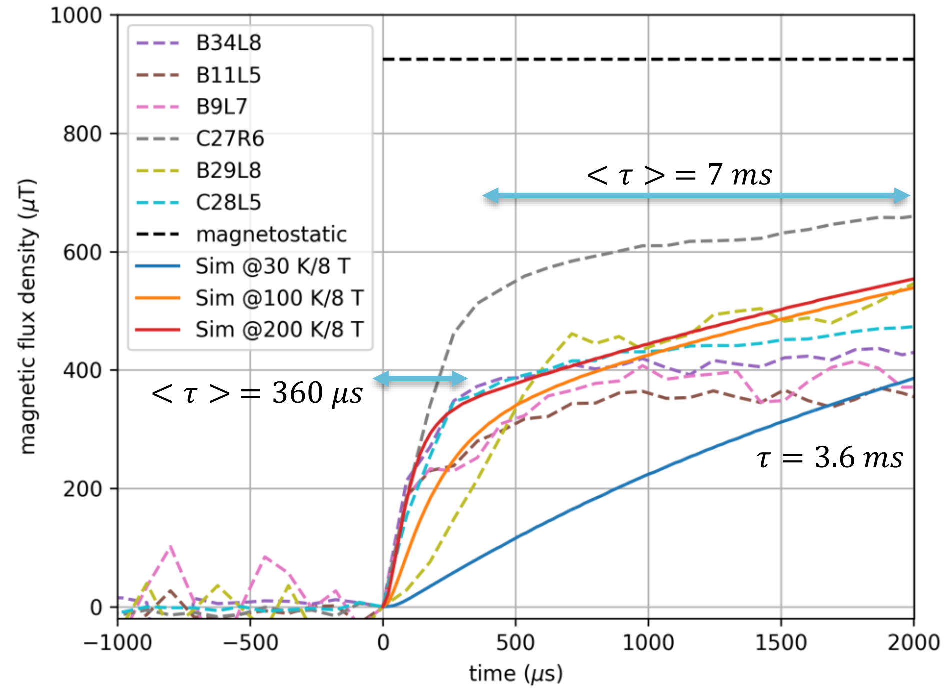
- Beam measurements during quenches and MD:
  - Using 570 BPMs per beam, reconstruction of the kick from the orbit:
  - Assuming +/-50 µm resolution: +/-40 µT @6.5 TeV
    +/-150 µT @450 GeV
- FEM Simulations done with COMSOL:
  - Eddy currents in Beam screen (RRR=100)
  - Inter filament & inter strand coupling currents (IFC & ISC) in the superconductor.
  - Magneto-resitivity

Comparison: measurements vs simulations

Measurements @450 GeV



Measurements @6.5 TeV



- Resistivity if off by a factor 2

- Two phases transient:
  - coil shielding ?
- Initial resistivity off by 1 order of magnitude
- Reproducible with 200 K BS temperature

Conclusion on protection from spurious QH discharges

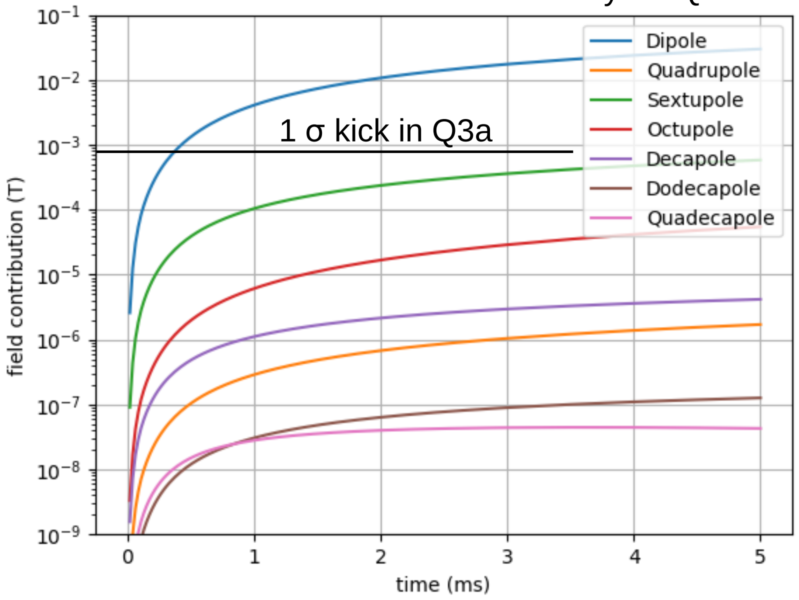
- Despite mitigation via improved connection schemes, some QH kicks from the MQXF magnets with large β-function remain critical.
- Simulation models need to be improved to reproduce the measured behavior.
- Measurements with the MQXF beam screen (different geometry) need to be performed.
- Assuming similar behavior as MB BS: reduction of the field/kick $<60\%$ max for 1 ms (~11 turns)
- We need a fast (<8 turn) interlock on spurious QH firing.

Shielding during a CLIQ discharge

- A triplet quench event, and inconsistency of shielding effects for QH lead to a full revalidation of the simulations for CLIQ discharges.

- Assuming the shielding behavior is correct: 1 σ kick reached after 350 µs (~3.5 turns).

Field contribution from the various components of the field distortion induced by CLIQ



Conclusion on protection from spurious QH discharges

- The shielding from CLIQ discharges in the MQXF must be measured to confirm what fields level can be reached within 1 ms (critical time for interlocking on currents).

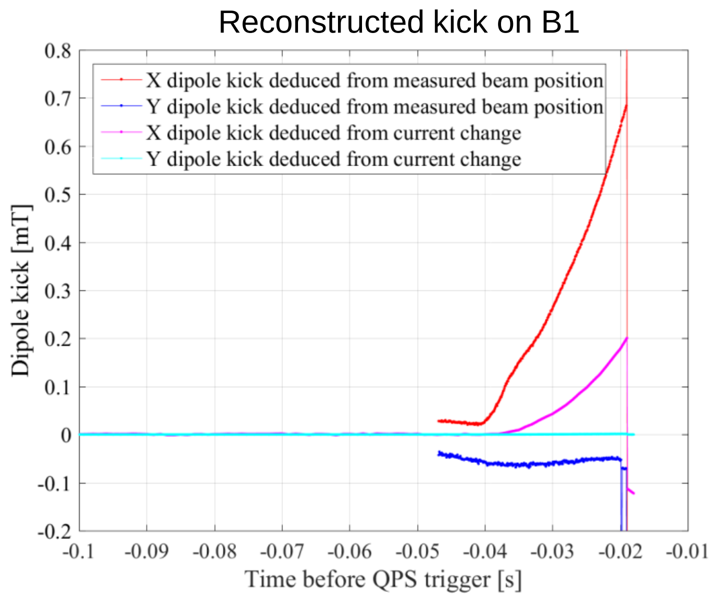
- As of the previous simulations: a fast interlock (<150 μs) would be needed to protect against a spurious CLIQ discharge.

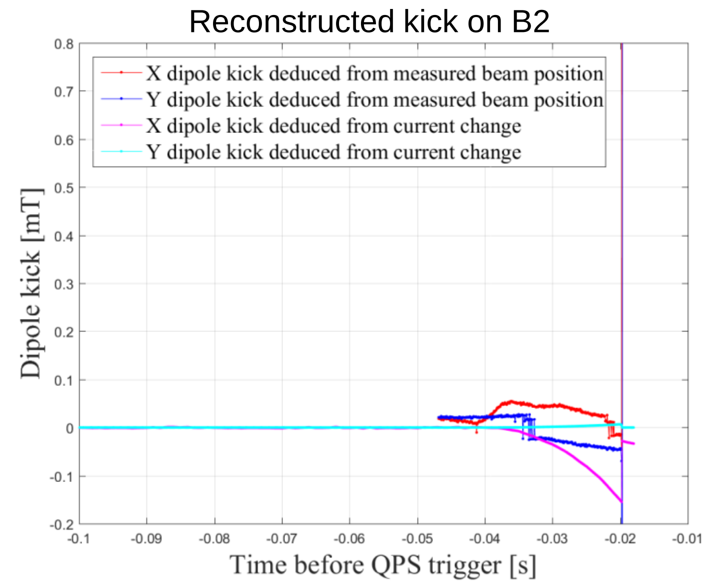
- Current change in the magnet after 100 μs: ΔI = 15 A (~0.1%)

HiLumi HL-LHC PROJECT CERN

Triplet quench event

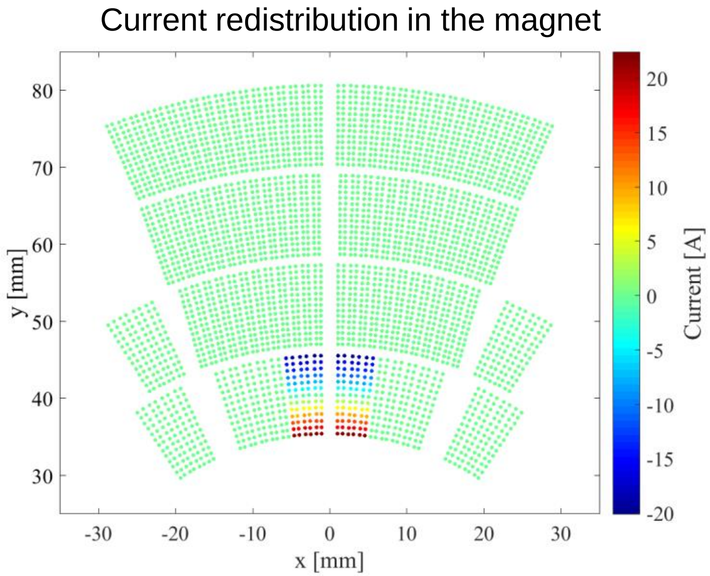
- A recent quench of Q1R1 lead to a large orbit drift leading to a dump due to losses.
- This event was not picked up by the QPS.
- The current change in the magnet is only responsible for a third of the observed kick.

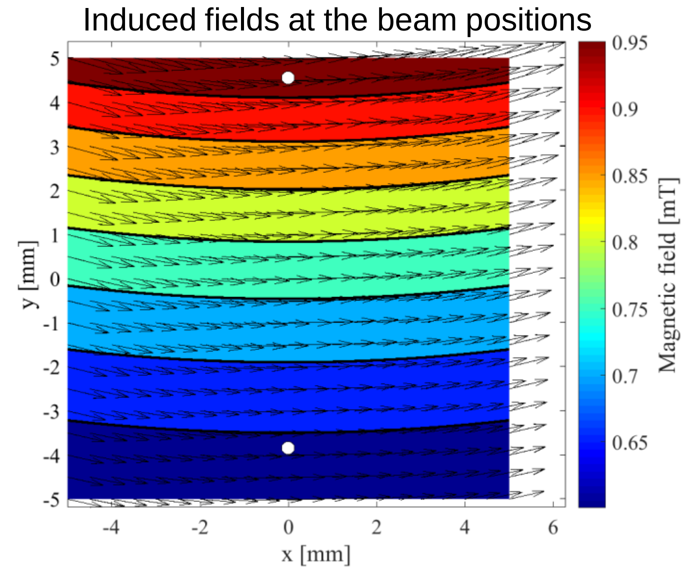




Reproduction of the field distortion

- IFC & ISC effects are also too weak/slow to explain the field change of 700 μT.
- Current redistribution in 6 half-turns along the whole length of the magnet allows the necessary field to be reconstructed.
- This event was too slow (10 ms) to be shielded by the beam screen.





Consequences for the MQXF

- A large symmetric quench, quenching half the cross section of six turns along the 6.37 m of the MQFA.1R1 allows reproducing the observed orbit drift.
- This quench was likely caused debris from the outgoing beam (B1, on top) and was facilitated by the loss of He super-fluidity (T_{He} > 2.15 K).
- If such an event were to happen with HiLumi intensities: collimator damage is expected (upgrade of QDS needed for Run 3 ?).
- The QDS of the MQXF will include comparison of voltages across all pole combinations and protect against a similar event (cf. Jens & Ernesto).
- The protection would still be vulnerable against a quench with double symmetry or other unforeseen failures (need for an FMCM-like interlock on the triplet circuit ?).

General conclusion

- Spurious Quench Heater/CLIQ discharges can give large kicks to the beam and need to be interlocked against.
- Interlocks protecting against such failures should be made fast (< 1 turn).
- Models used to reproduce the magnetic transient should be improved to reproduce LHC events.
- CLIQ /QH discharges in test models of the MQXF should be measured to benchmark models and identify critical timescales.

Outlook

- The MQXFS4b is being tested this week in SM18.
  - Measurements of single QH circuit discharge and CLIQ firing are planned.

- An LHC MD is planned for block 4 (Oct 30th), the parameters affecting beam screen resistivity (BS temperature, magnet current) will be scanned further to investigate the discrepancy between model and measurements.

HL-LHC PROJECT

Thank you for your attention