Effect of beam screen shielding and transient effects in superconducting magnets during QH and CLIQ discharge (+ recent triplet quench)

Matthieu Valette, L. Bortot, B. Lindström, M. Mentink, A. Navarro, E. Ravaioli, E. Stubberud, A. Verweij, D. Wollmann
CERN TE-MPE-PE

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Introduction

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

  - Only observed with MB magnets so far, the beam was dumped before in other circuits

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

Up to 3 ms to dump

1 ms to fire QH

15 µm RMS orbit
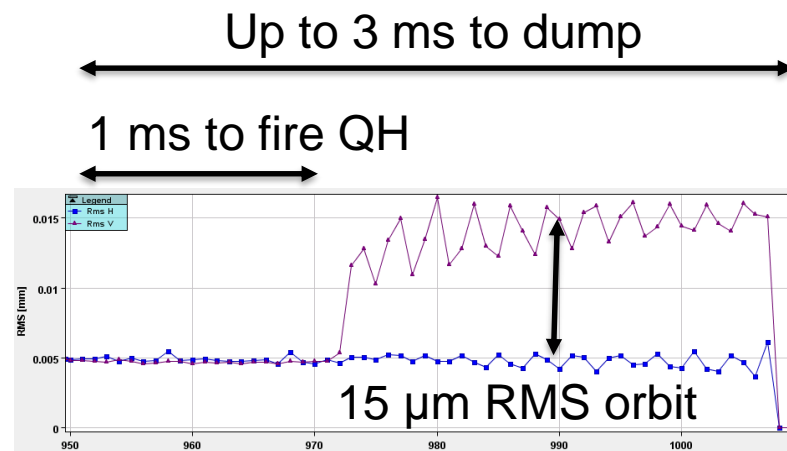
Quench of MB.C28L5 on July 12th 2016

I_CLIQ

I_main
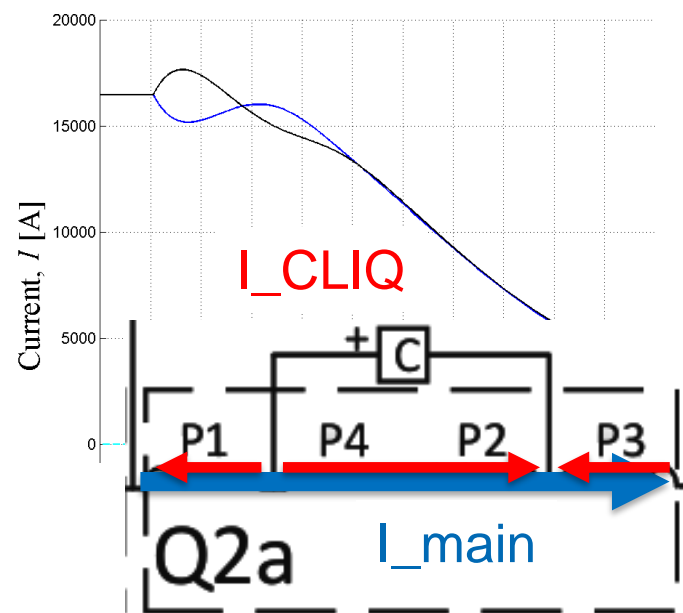
CLIQ discharge in Q2a

LH-LHC magnets with QH

- With HL-LHC intensities and optics, one must dump before triggering Quench protection systems.
- **Spurious firing of 1 QH circuit** as main failure case.
- Kicks **above 1 σ** should be avoided.
- Review of expected kicks lead to an update of connection schemes for MQXF and IPD.
- Kicks from Q2b, Q2a, Q3a (with large β-function) are still critical and need to be reviewed.

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
MBXF, MBRD	7.78	168	Quad-rupole field	0.3
11 T-dipole	5.5	150		0.03
MQXF (Q2b)				
HF (old)			643	1.7
LF (old)	7.15	200	700	1.8
HF (new)			472	1.28
LF (new)			412	1.08

HL-LHC optics v1.3 with ATLAS crossing bump

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

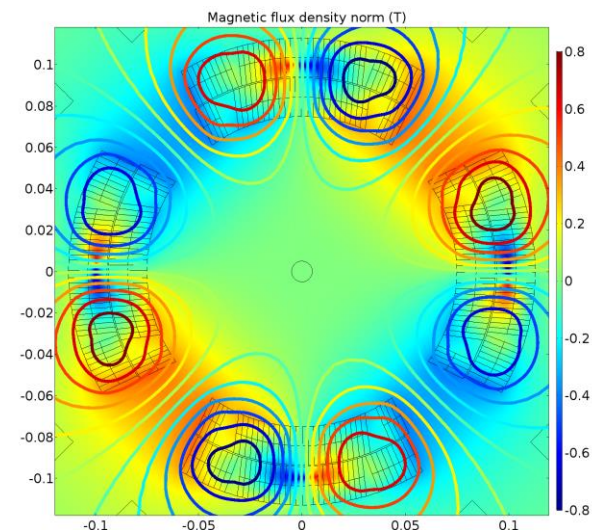Measurements @450 GeV
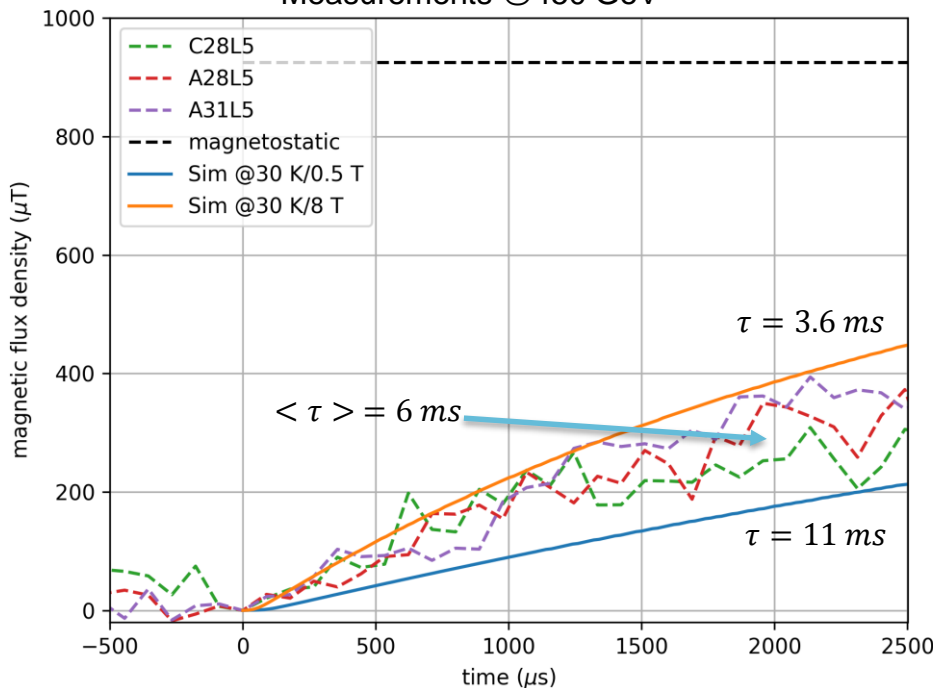
Measurements @6.5 TeV
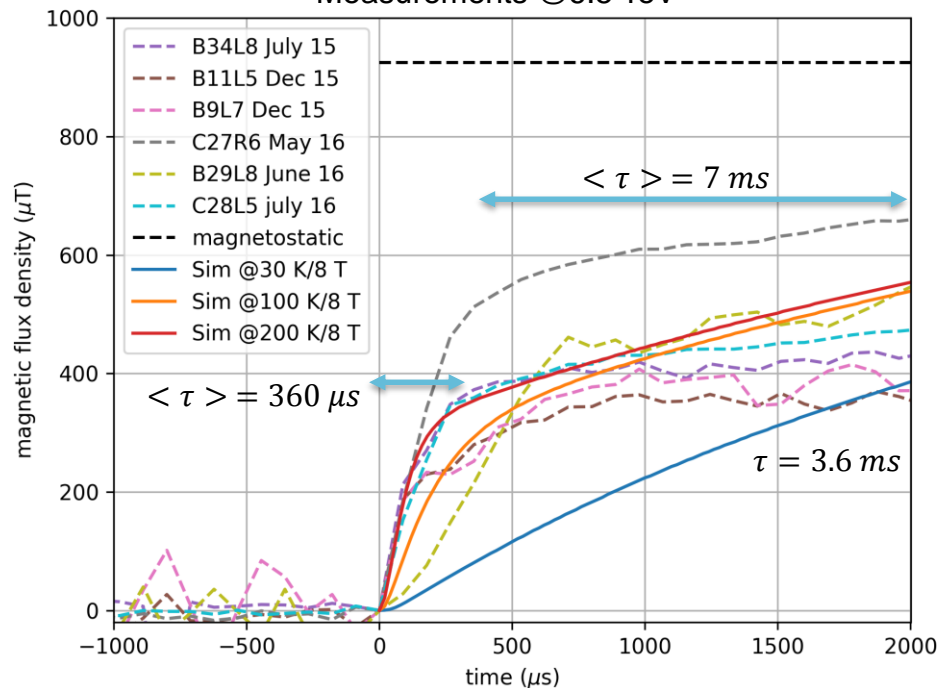
- Resistivity is off by a factor 2 ($\tau \propto \frac{1}{\rho_{Cu}}$)

- Initial shielding only due to the coil.
- Second phase with eddy currents in the BS.
- Reproducible with 200 K BS temperature (!)
- The BS appears not to shield for the first 200 µs

Effect of a CLIQ discharge

- Same as for QH, spurious discharge of one unit assumed as main failure case.
- From connection scheme:
  - Q2: change of quadrupole field
  - Q3: dipole field of 48 mT
- From simple model (sine function to max distortion):
  - Q2: 100% β-beating and small dipole kick in 12 ms => need to dump in 2 ms.
  - Q3: kick of 1 σ/ turn: **critical,** needs to be reviewed and simulated in time domain

Q2, peak field (12 ms)

Magnetic flux density norm (T)

Q3, peak field (20 ms)


Magnetic flux density norm (T)
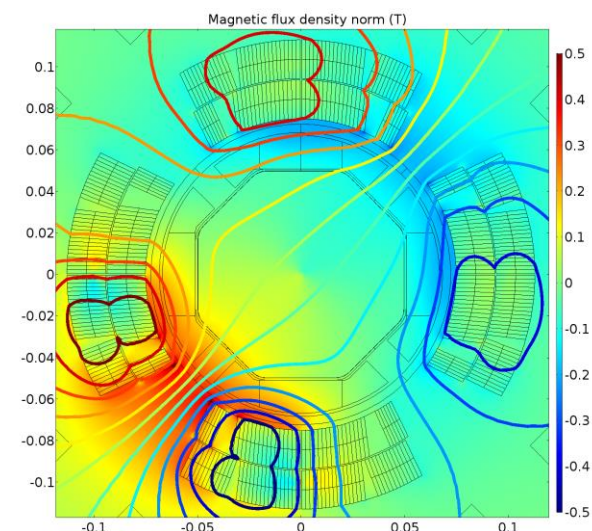
Shielding during a CLIQ discharge

- Following triplet quench event, inconsistency of shielding effects for QH and newfound criticality of CLIQ discharge in Q3:

=> Time-domain simulations for CLIQ discharges <u>including fast transient effects</u>.

- If the shielding behavior is simulated consistently:
1 σ kick reached after 350 µs (~4 turns)

(but due to inconsistency of shielding effects simulation in the QH case it should be measured)

Field contribution from the various components of the field distortion induced by CLIQ
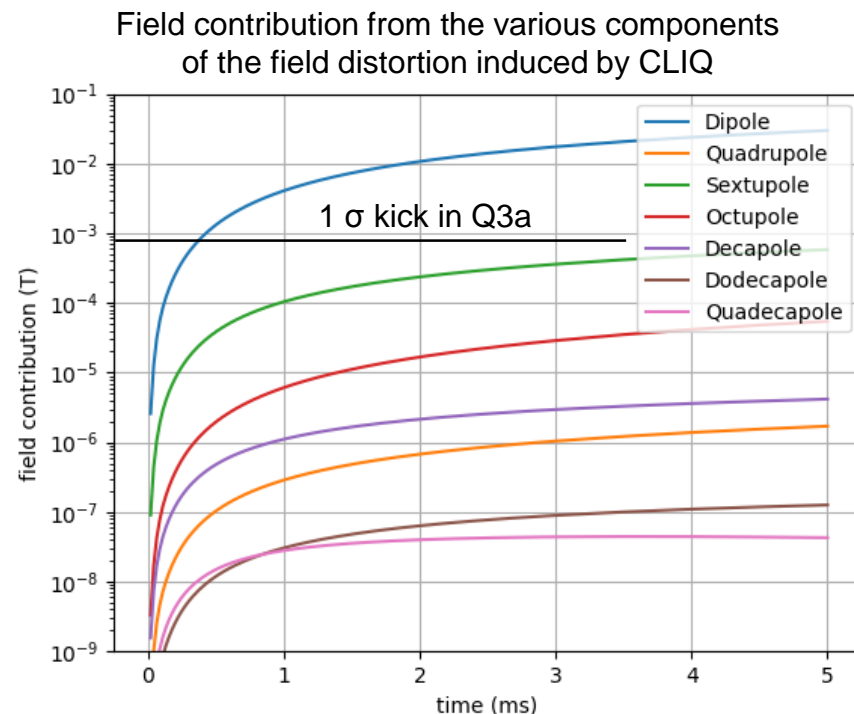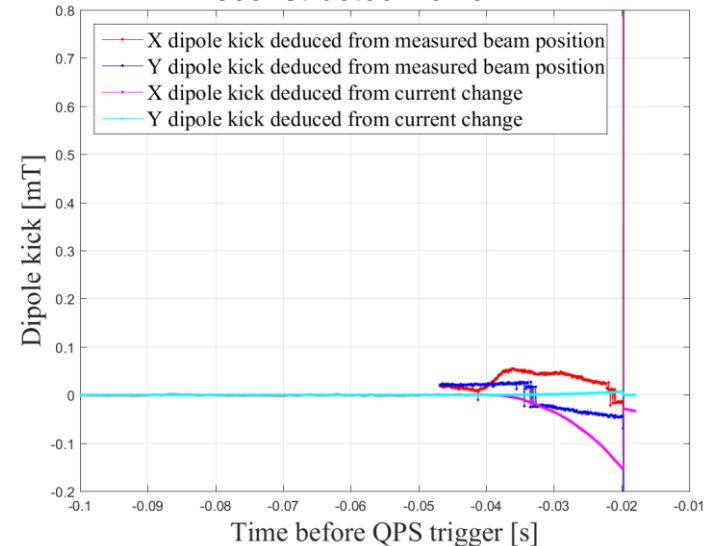
Triplet quench event (June)

- A recent quench of Q1R1 lead to a large orbit drift and eventually a dump due to losses.

- This event was not picked up by the QPS (symmetric quench).

- The current change (7 A) in the magnet is only responsible for a third of the observed kick.

Reconstructed kick on B1
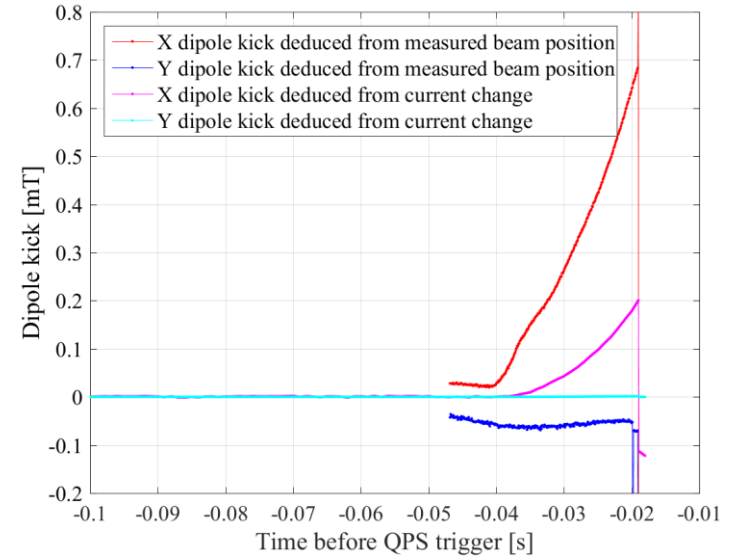
Reconstructed kick on B2

Reproduction of the field distortion

- Current redistribution in 6 half-turns along the whole length (6.37 m) of the magnet allows the necessary field (700 µT) to be reconstructed.

- This event was too slow (10 ms) to be shielded by the beam screen.

- Full report on the event: EDMS Nr: 2025613

Current redistribution in the magnet
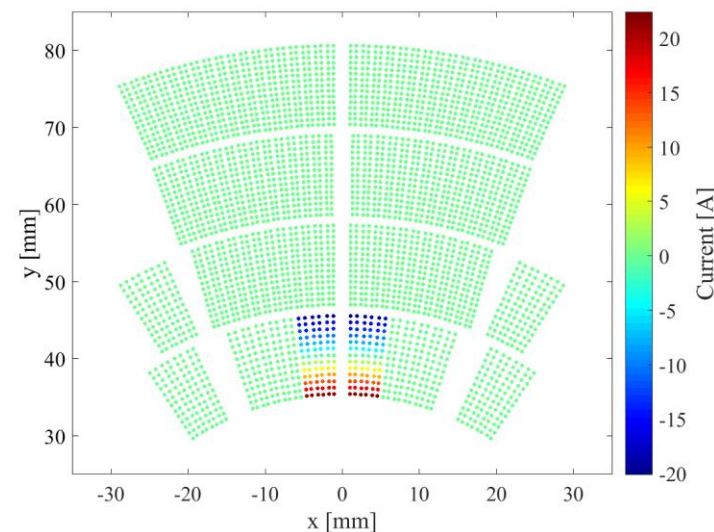
Induced fields at the beam positions
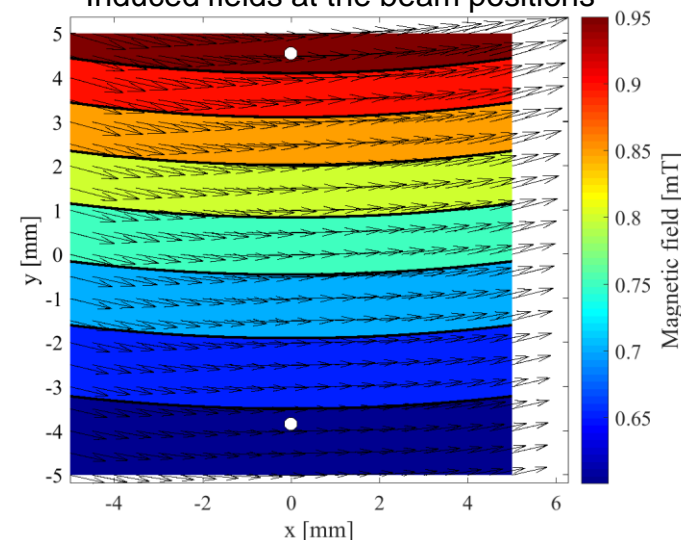
Consequences for the MQXF

- An extensive symmetric quench, quenching 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.

- The QDS of the MQXF will include comparison of voltages across all pole combinations and protect against a similar event (cf. Jens & Ernesto).

- I-dot sensors will be added to the protection of the triplet and monitor rapid current changes in the circuit.

General conclusion

- Spurious Quench Heater/CLIQ discharges can kick the beam and need to be interlocked on in a fast way (~ 1 ms).

- Efforts to mitigate QH failures passively are ongoing.

- 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.

- The impact of magnet protection systems on circulating beam has to be taken into account during the specification and design of new equipment.

Outlook

- The MQXFS4b is being tested this week in SM18.
  - Measurements of single QH circuit discharge and CLIQ firing and the effect of BS shielding are planned using special magnetic field measurement system (L. Fiscarelli)

- An LHC MD is planned for MD 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.

- All previous critical timescales would be relaxed a lot with the inclusion of the e-lens in the baseline, but would imply a change of protection strategy currently base on the early detection of losses => based on orbit motion.

Thank you for your attention

For reference:

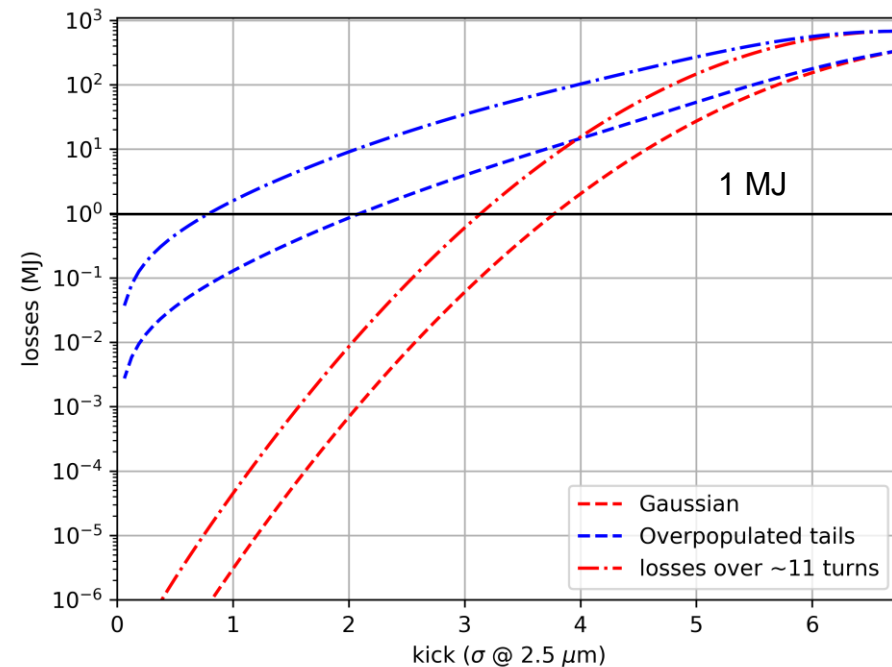Impact of superconducting magnet protection equipment on the circulating beam in HL-LHC,
   M. Valette et al. ,IPAC'18 Copenhagen

Simulation of transient effects in accelerator magnets

Stored energy in tails as function of beam distribution

- The deposition of energy > 1 MJ within very short time (< 1ms) is considered critical

- Assuming 5 σ collimators (ε=3.5 μm) and 720 MJ beam energy (ε=2.5 μm) and for beam distributions with strongly overpopulated tails (as observed in the LHC) this limit is reached for an orbit shift of ~1 σ

Alternative connection schemes

MQXF

New baseline

Old baseline

Old baseline

11 T dipole

New baseline

~0.11 T.m^{-1} Compared to 200 T.m^{-1} for the arc quads with similar β

Courtesy S. Izquierdo