



Fast failures from CLIQ and quench heater firing, effect of beam screen shielding and consequences for protection electronics

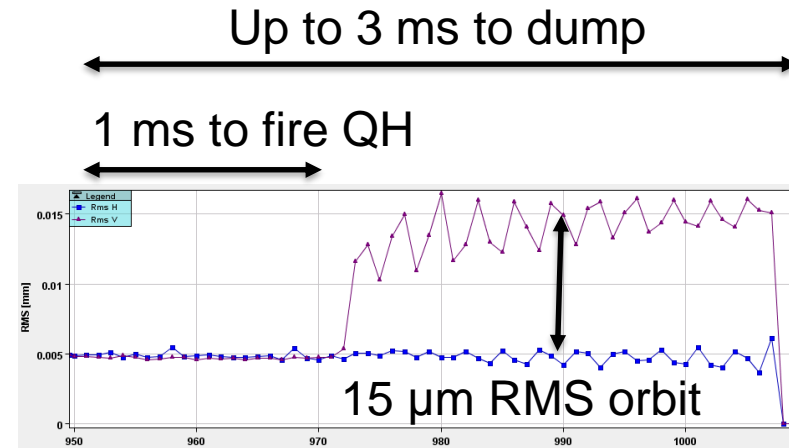
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CERN TE-MPE-PE



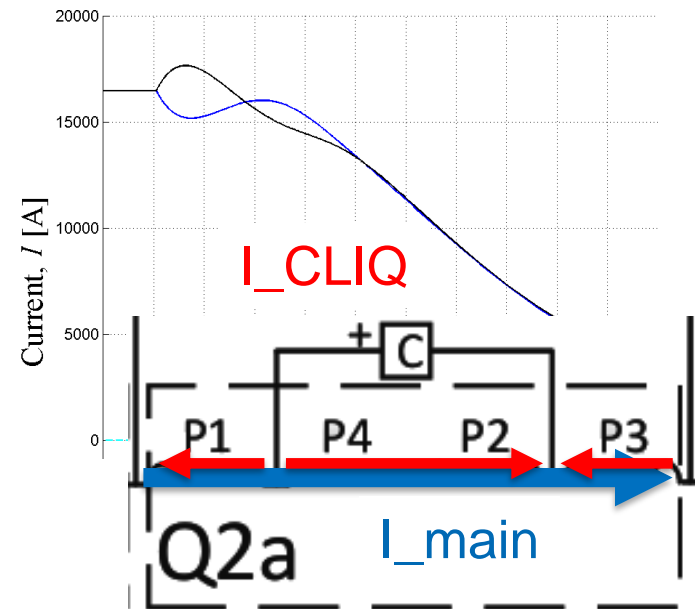
8th HiLumi meeting, CERN, 16th October 2018

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.



Quench of MB.C28L5 on July 12th 2016



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)	7.15	200	643	1.7
LF (old)			700	1.8
HF (new)			472	1.28
LF (new)			412	1.08

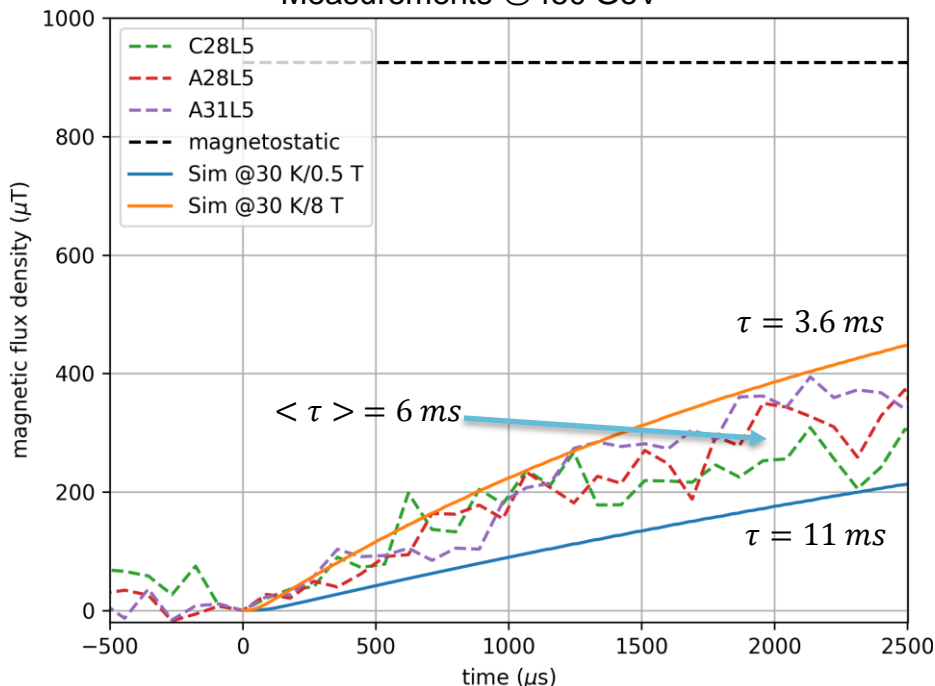
HL-LHC optics v1.3 with ATLAS crossing bump

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

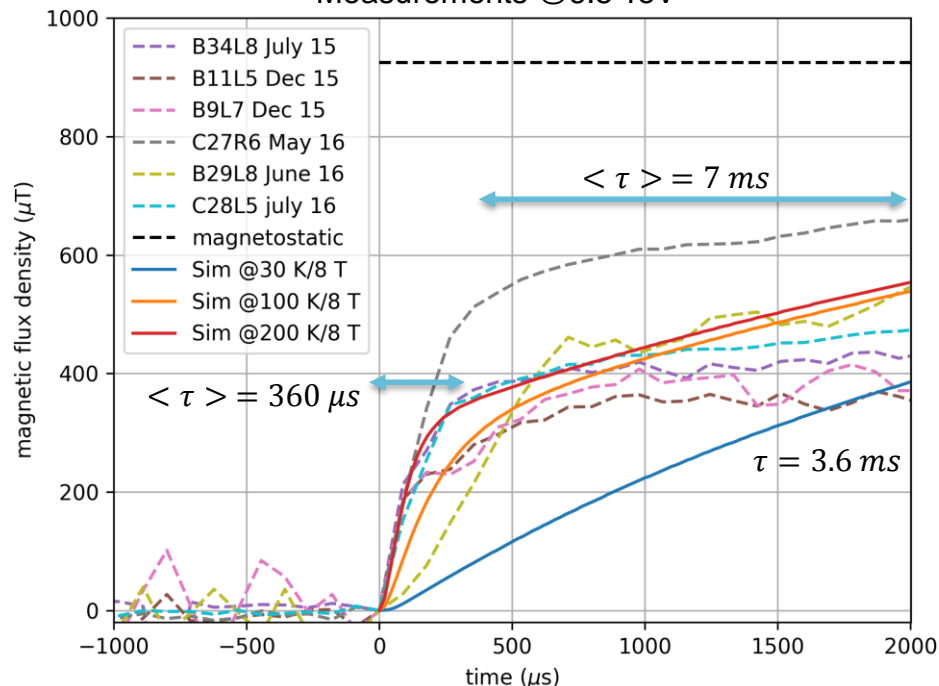
- Beam measurements during quenches and MD:
 - Using 570 BPMs per beam, reconstruction of the kick from the orbit:
 - Assuming +/-50 μm resolution: +/-40 μT @6.5 TeV
+/-150 μT @450 GeV
- FEM Simulations done with COMSOL:
 - Eddy currents in Beam screen (RRR=100)
 - Inter filament & inter strand coupling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

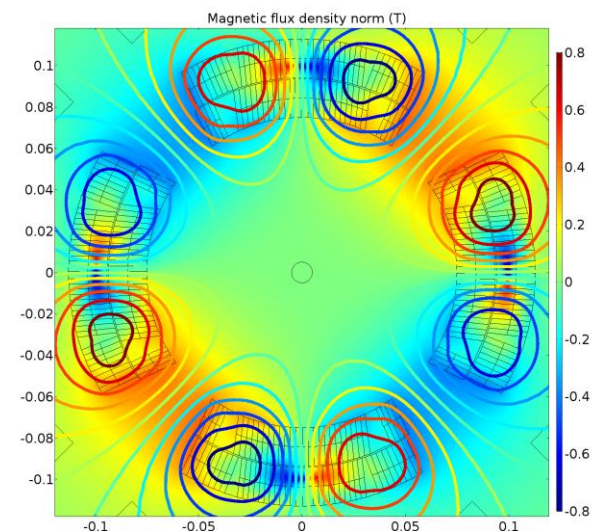
Conclusion on protection from spurious QH discharges

- Despite partial mitigation via improved connection schemes, some QH kicks from the MQXF magnets 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).
- => need a fast (~ 1 ms) interlock on spurious QH firing.
- Efforts to mitigate by slowing down the current discharge in the QH circuit by 1 ms are ongoing.

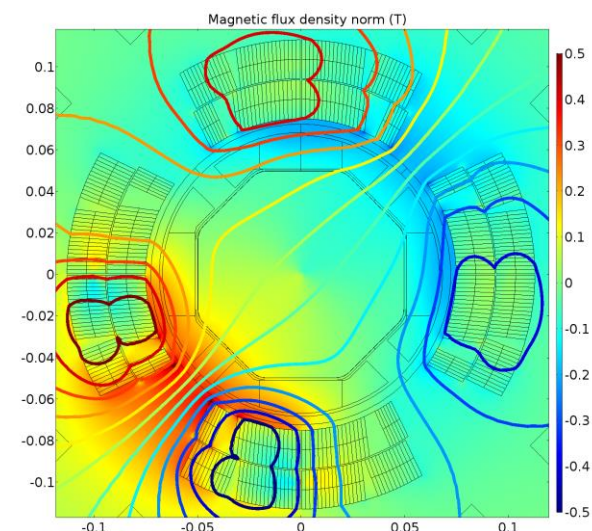
Effect of a CLIQ discharge

- 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)



Q3, peak field (20 ms)



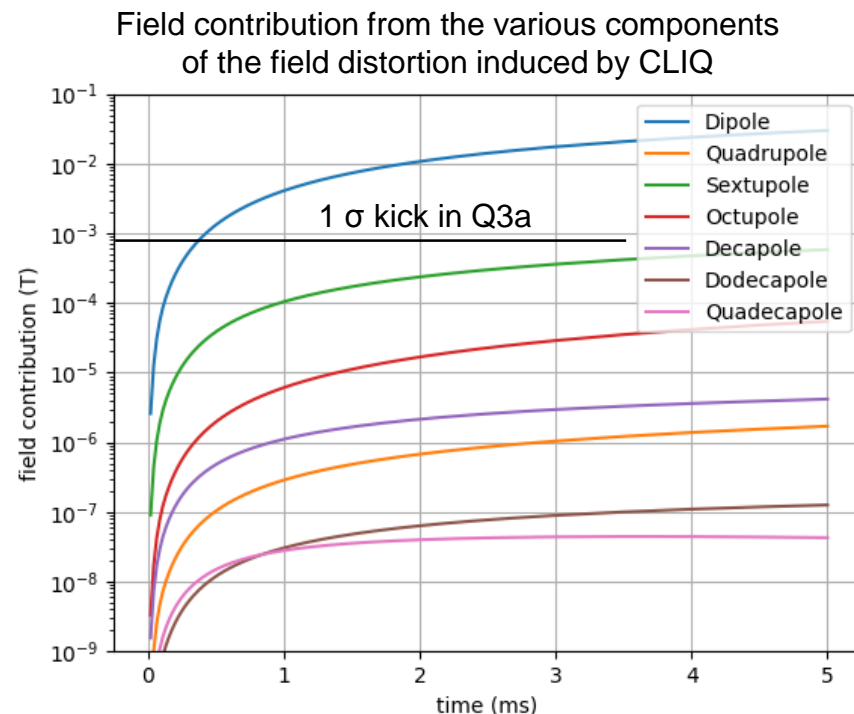
Shielding during a CLIQ discharge

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

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

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

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



Conclusion on protection from spurious CLIQ discharges

- As of the previous simulations: a fast interlock ($< 350 \mu\text{s}$) would be needed to protect against a spurious CLIQ discharge; e.g. interlock on current in CLIQ leads $< 15 \text{ A}$.
- 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).
- Solutions to have a lower initial current ramp rate should be investigated.

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.
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- 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:

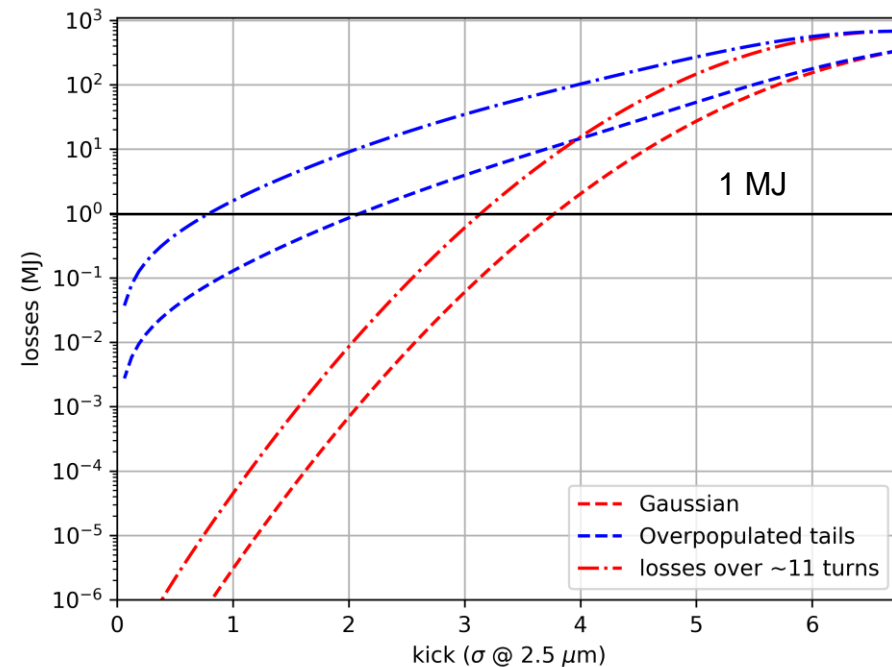
[Impact of superconducting magnet protection equipment on the circulating beam in HL-LHC,](#)
M. Valette et al. ,IPAC'18 Copenhagen

[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 (< 1 ms) is considered critical
- Assuming 5σ collimators ($\epsilon=3.5\text{ }\mu\text{m}$) and 720 MJ beam energy ($\epsilon=2.5\text{ }\mu\text{m}$) and for beam distributions with strongly overpopulated tails (as observed in the LHC) this limit is reached for an orbit shift of $\sim 1\sigma$



Alternative connection schemes

MQXF

