Experience with quench protection equipment effects on the beam in LHC - additional slides

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

With inputs from: M. Blumenschein, D. Carrillo, R. Denz, B. Lindstrom, E. Ravaioli, F. Rodriguez Mateos, M. Mentink, A. Siemko, D. Sollich, J. Uythoven, M. Valette, A. Verweij, C. Wiesner, M. Zerlauth

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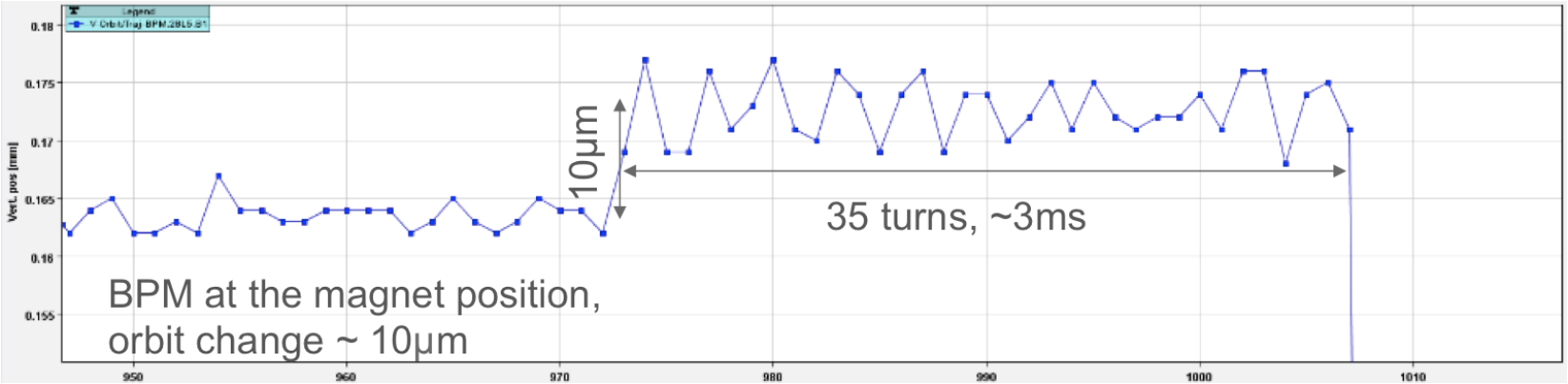
Orbit oscillation during LHC dipole quenches



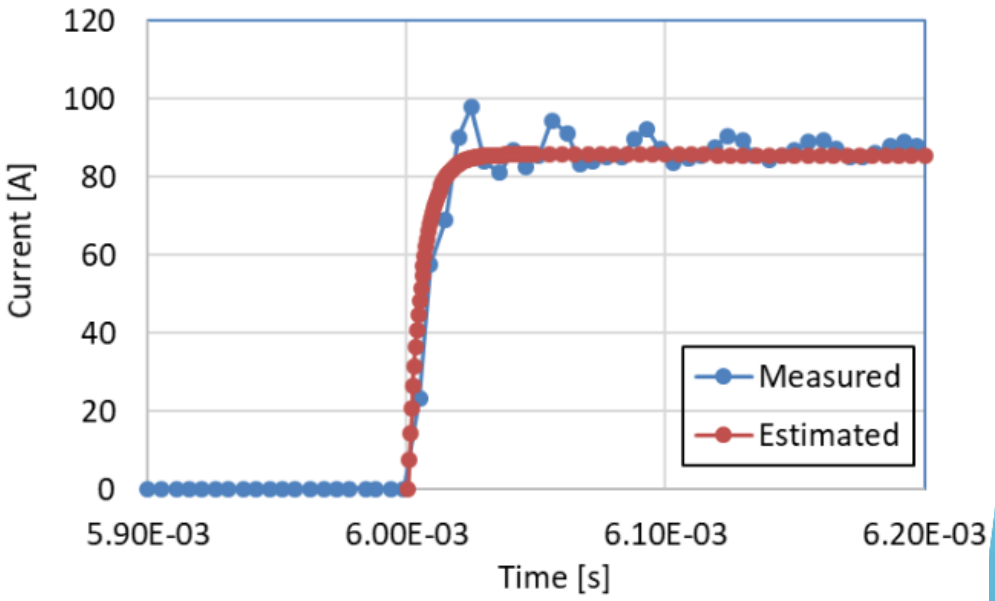
- Losses observed during beam dump following a magnet quench (2017) → traced back to small orbit oscillation ~ 35 turns (3 ms) before the beam dump)
- Analysis of previous beam dumps due to dipole quenches (all around the ring) revealed that this behavior can be observed systematically for beam dumps triggered via QPS → PIC →BIS
- Check with QPS experts revealed that up to 5 ms delay between quench heater power supply and PIC trigger could be explained by variation in opening times of mechanical relays
- Effect has never been observed for LHC triplet (probably due to different QPS architecture)

Quench heater discharge: Ultrafast current rise

- **Ultra fast** effect, quench heaters reaching full current/field within less than 1/2 LHC turn

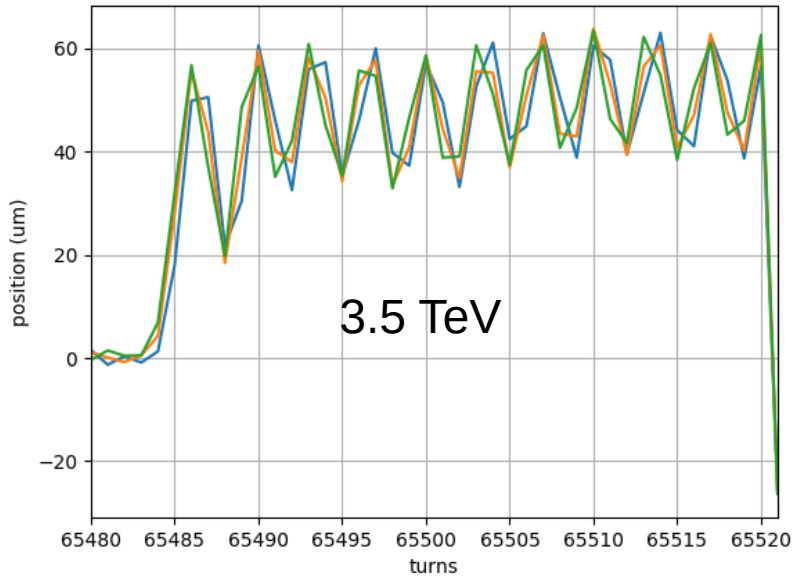
  MB: ~ 29 us; MQXF: ~ 35 us

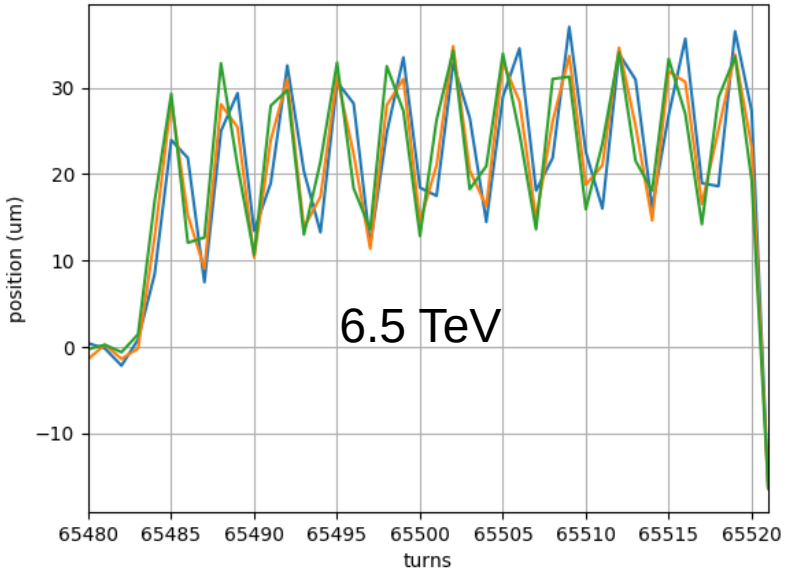
- **Spurious triggering** of one QH unit cannot be excluded



Dedicated experiments with MB.C28L5

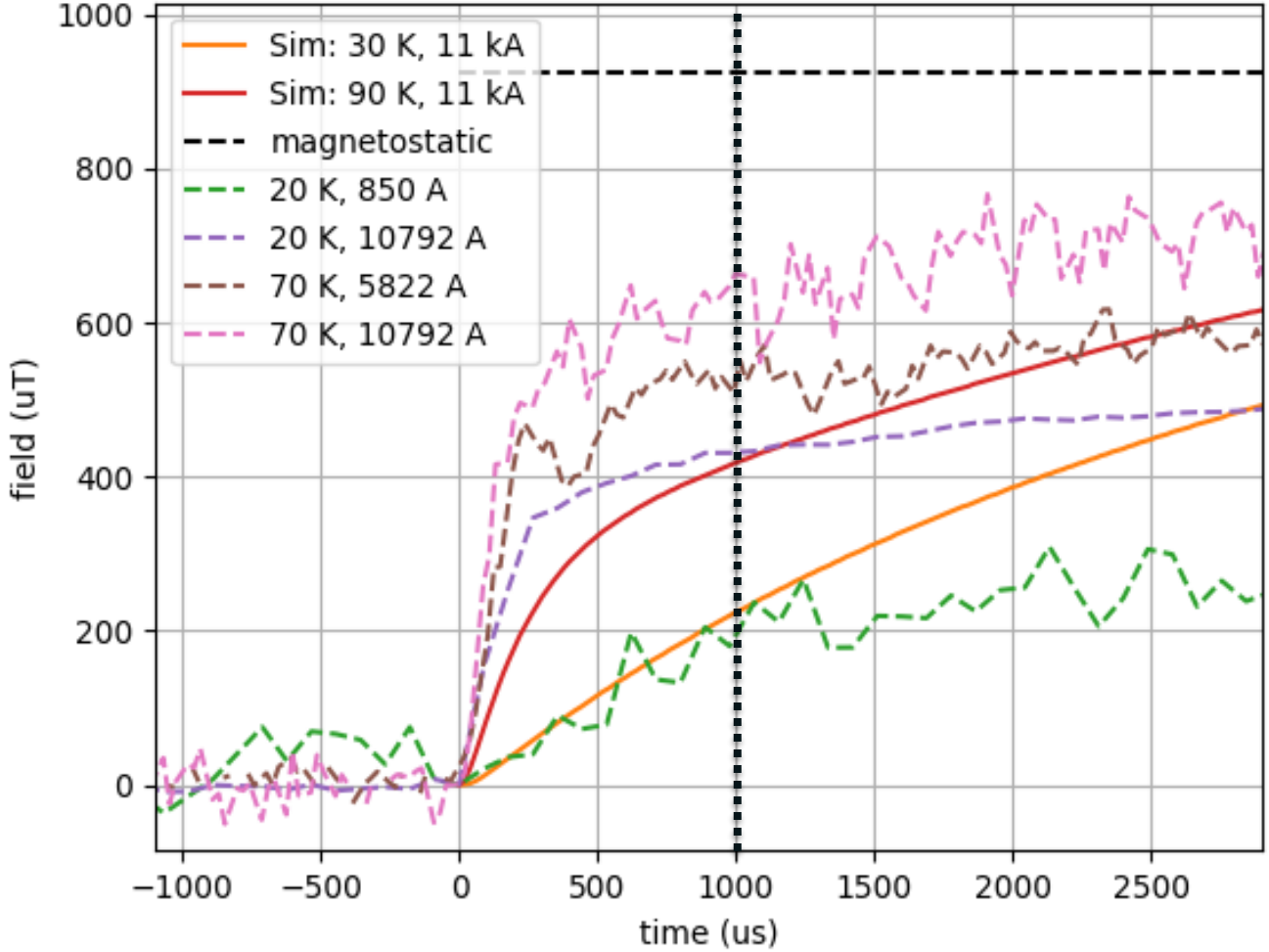
- MB.C28L5
- Beam screen temperatures ~20 K (nominal) and ~70 K
- Quench heaters fired at injection energy (450 GeV), 5822 A (3.5 TeV) and 10792 A (6.5 TeV)
- Kick & magnetic field from quench heaters reconstructed beam position changes





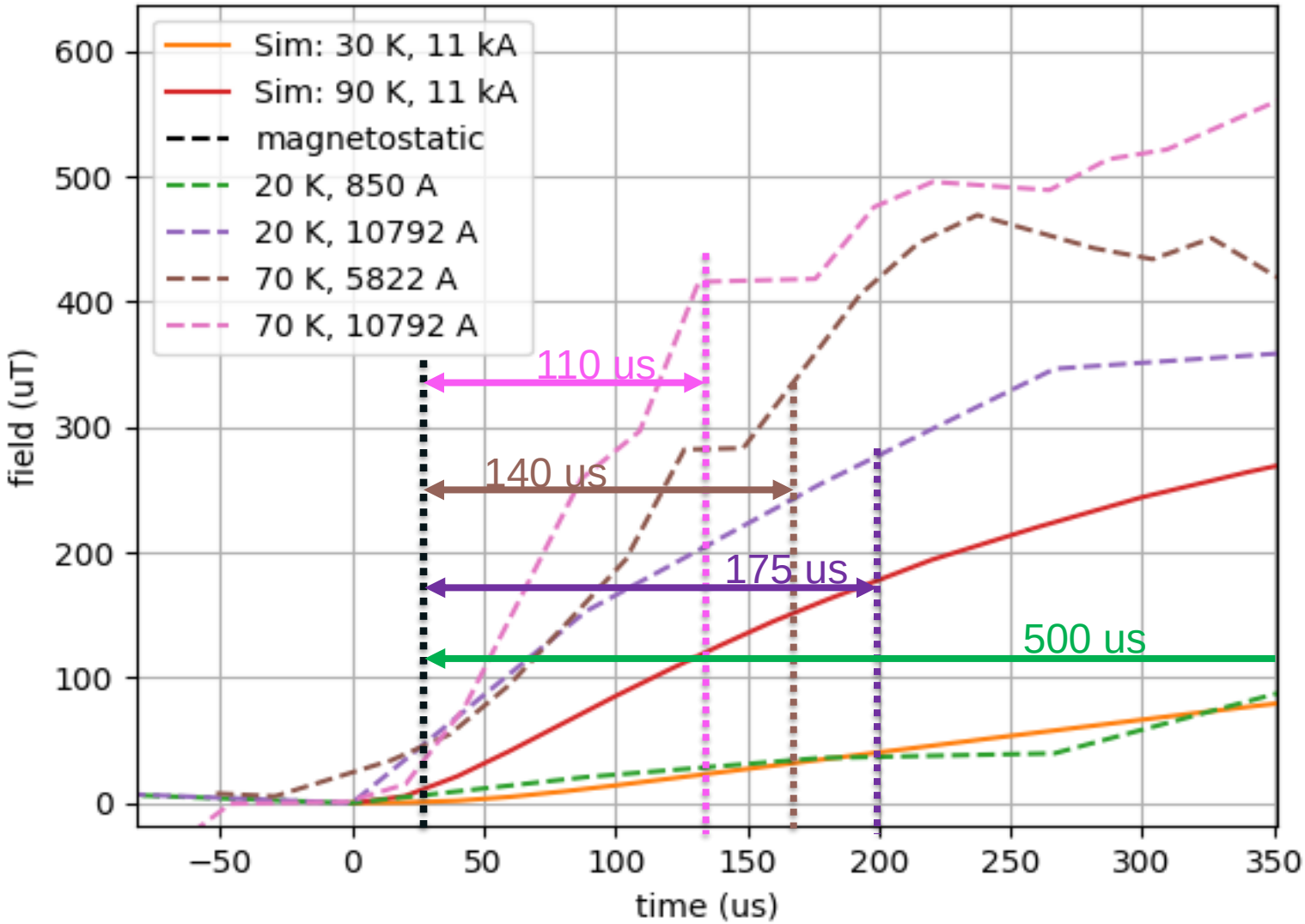
Measured beam excursion at ADT pick-up (Q7R5)

Experience from LHC dipoles (dedicated experiment)



- Triggering of QPS in test mode via current source
- 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)

Rise time of magnetic field (10 % → 65 % at 1 ms)



Summary from LHC dipole experiment results

- Effect of **beam screen** temperature increase from **20 K → 70 K**:
  - Faster rise time and higher magnetic field reached **as expected**
  - Quantitative **changes not reproduced** by models
- Effect of **increased main field** with beam screen at **70 K**:
  - Faster rise time and higher magnetic field reached **as expected**
  - **Quantitative order** of change **correct**, details to be understood
- Effect of **increased main field** with beam screen at **20 K**:
  - Much faster rise time and significantly higher magnetic field reached
  - **Relative change in good agreement** with models

Energy (TeV)	I (A)	T (K)	ρ (10^{-10}Ω.m)	QH field rise time (10% → 65% at 1ms) (us)	fraction of magnetostatic field after 1 ms
0.45	850	20	2.5	500	0.22
6.5	10792	20	5.22	175	0.47
3.5	5822	70	17.4	140	0.57
6.5	10792	70	18.52	110	0.69

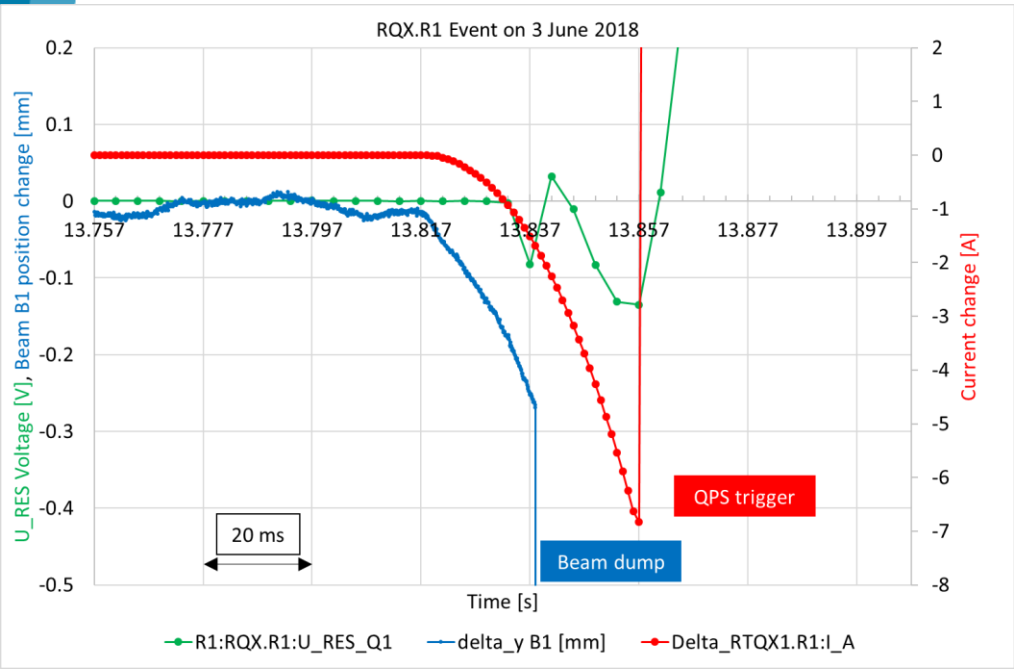
Expected kicks from HiLumi magnets with all QH fired

Magnet (all QH)	LHC kick (sigma)	→	HL-LHC kick (sigma)
MB	0.3	→	0.5
D1	1.4	→	2.0 → < 0.5
D2	1.2	→	2.4 → < 0.5
11 T - dipole	0.04	→	0.4 → 0.03
Triplet	2.5	→	33.7
Triplet (single QH)	0.6	→	1.3

Comparison of kicks from quench heaters 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.
- **Measurements** during MQXF short model test and new HL triplet beam screen were not conclusive due to limited bandwidth of measuring devices → dedicated studies required

Effect of quench in LHC triplet on beam



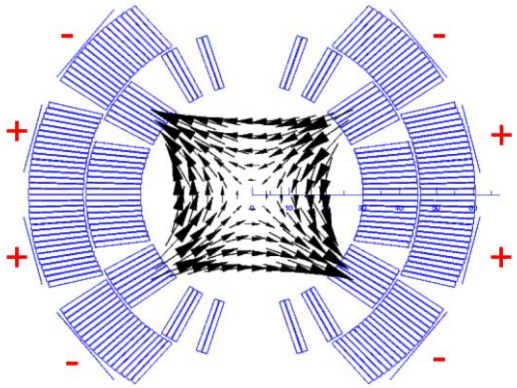
Event overview:

- Symmetric quench of RQX.R1 due to cryo-control problem
- Orbit offset of ~250 um with dI = 1.7 A (I_circuit = 6.2 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"

- Small changes in triplet current can cause important beam kicks due to big 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

Mitigations for effects of magnet protection equipment on beam

- QHs in quadrupole connection schemes (or other higher orders) instead of skew dipole scheme, if possible when taking into account other critical parameters (e.g. voltages heater to coil)
- Interlock sequence needs to ensure that beams are dumped before the quench heater and CLIQ discharge is triggered
- Symmetric quench detection for inner triplet
- CLIQ connection scheme to avoid asymmetric discharges in poles
- Interlocking spurious discharge of CLIQ and quench heater power supplies
- Study shielding of beam screen & coils → simulations & experiments

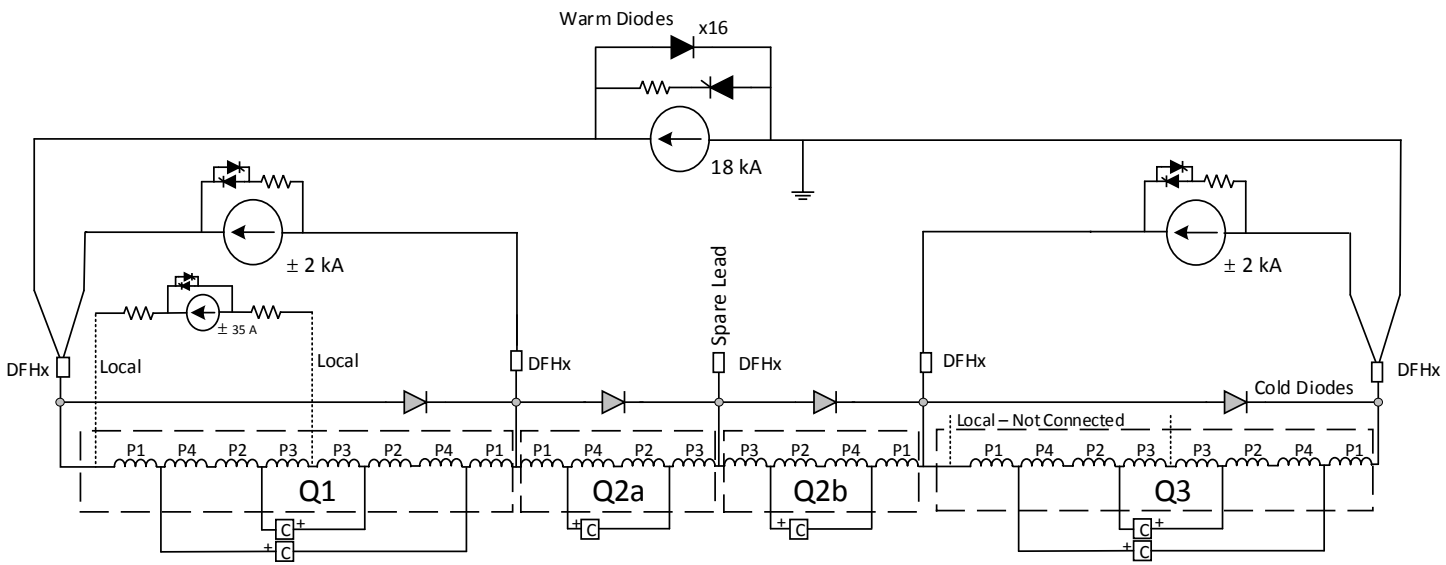


Polarity of 11 T QH strips

Step	Duration
Detection QH discharge (di/dt ≈ 4 MA/s)	100 µs
Detection CLIQ discharge (di/dt ≈ 200 kA/s)	< 500 µs
Communication DQHSU → PIC → BIS	12 µs
Beam abort sequence	270 µs
Total	< 1 ms

CLIQ slides for reference

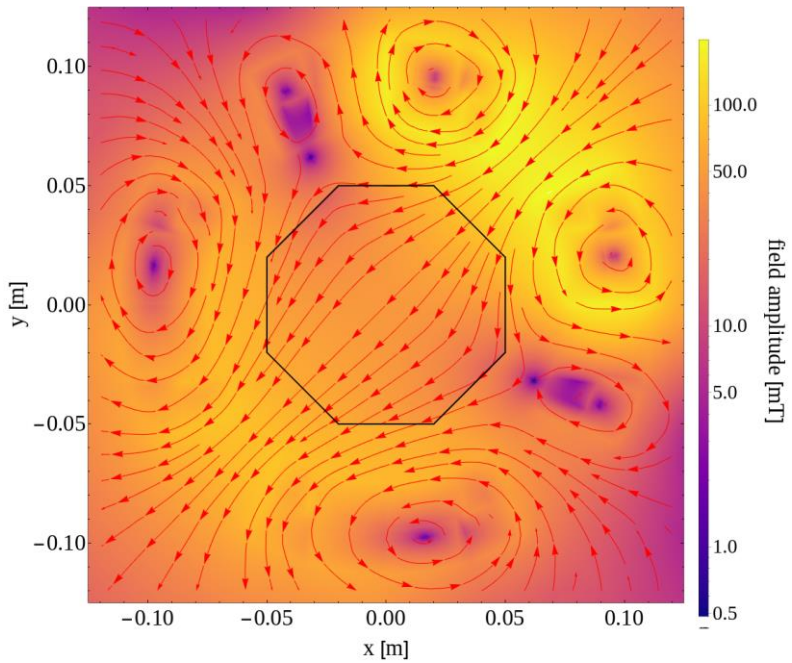
Effect of one spurious CLIQ dis-charge in IT

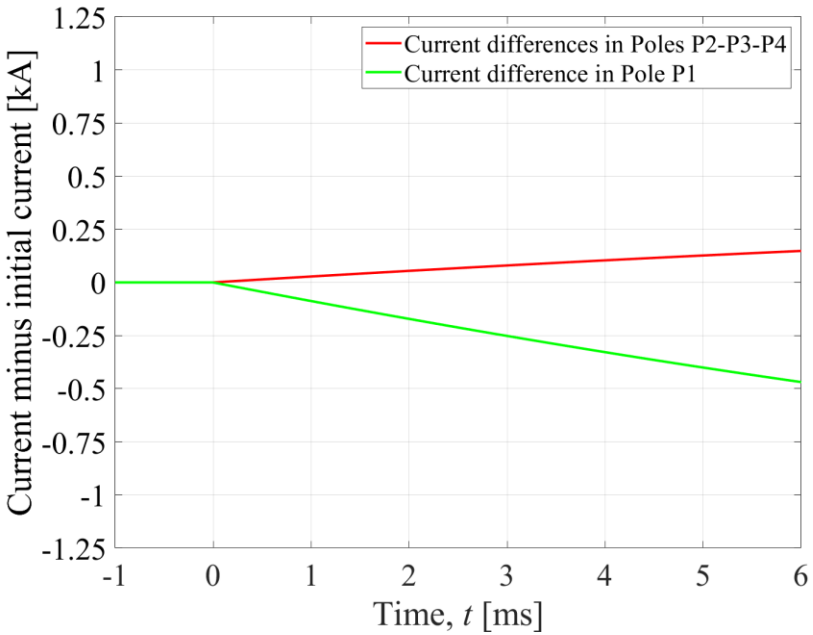


Old baseline

- A spurious discharge of a single CLIQ unit cannot be excluded

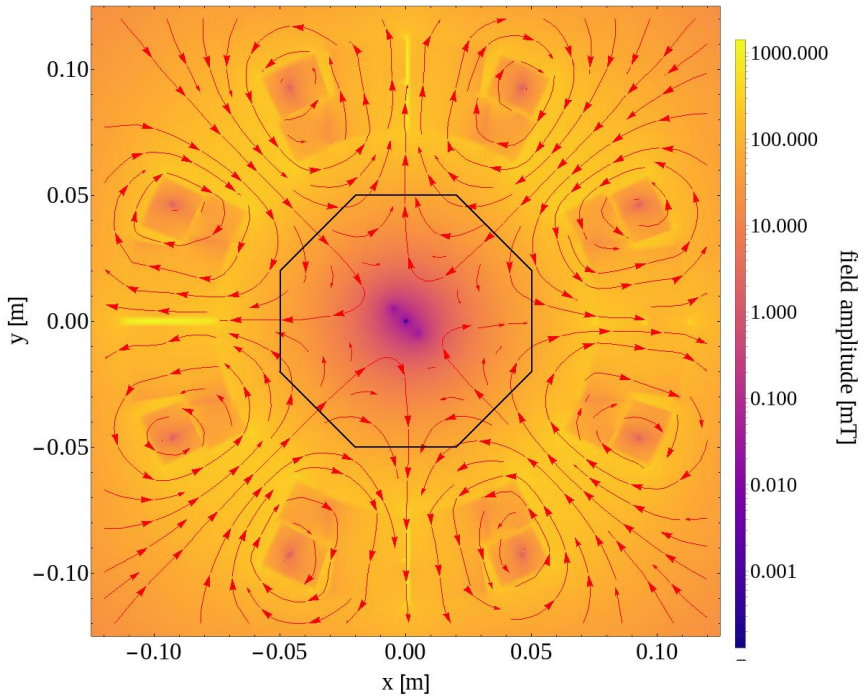
Spurious CLIQ discharge in Q1/Q3

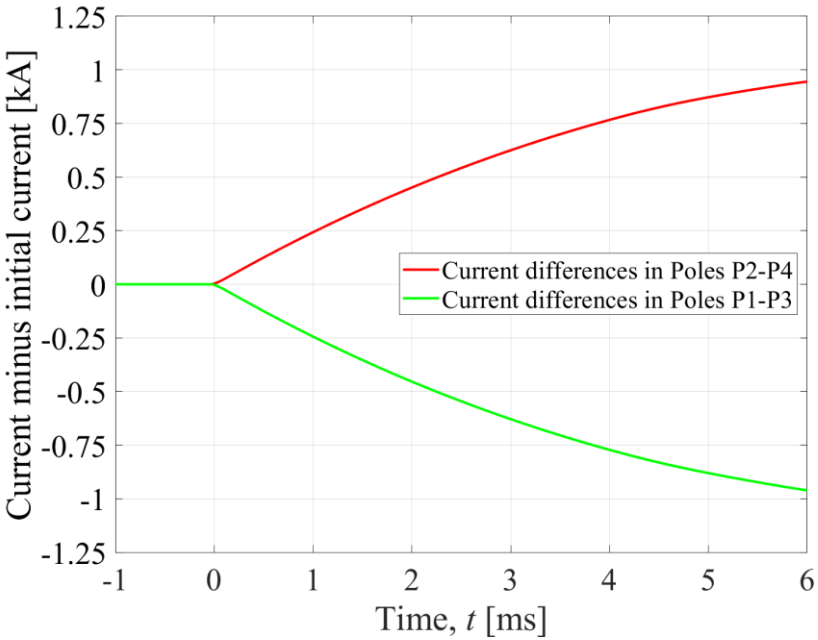




- Asymmetric discharge into the poles of the Q1a/b (respectively Q3a/b)
- Skew dipole field in magnet causing kick of beam
- Additional (much weaker) dipole component during discharge of magnet current due to beam offset (Q1: up to 9.8 mm, Q3: up to -17.1 mm)

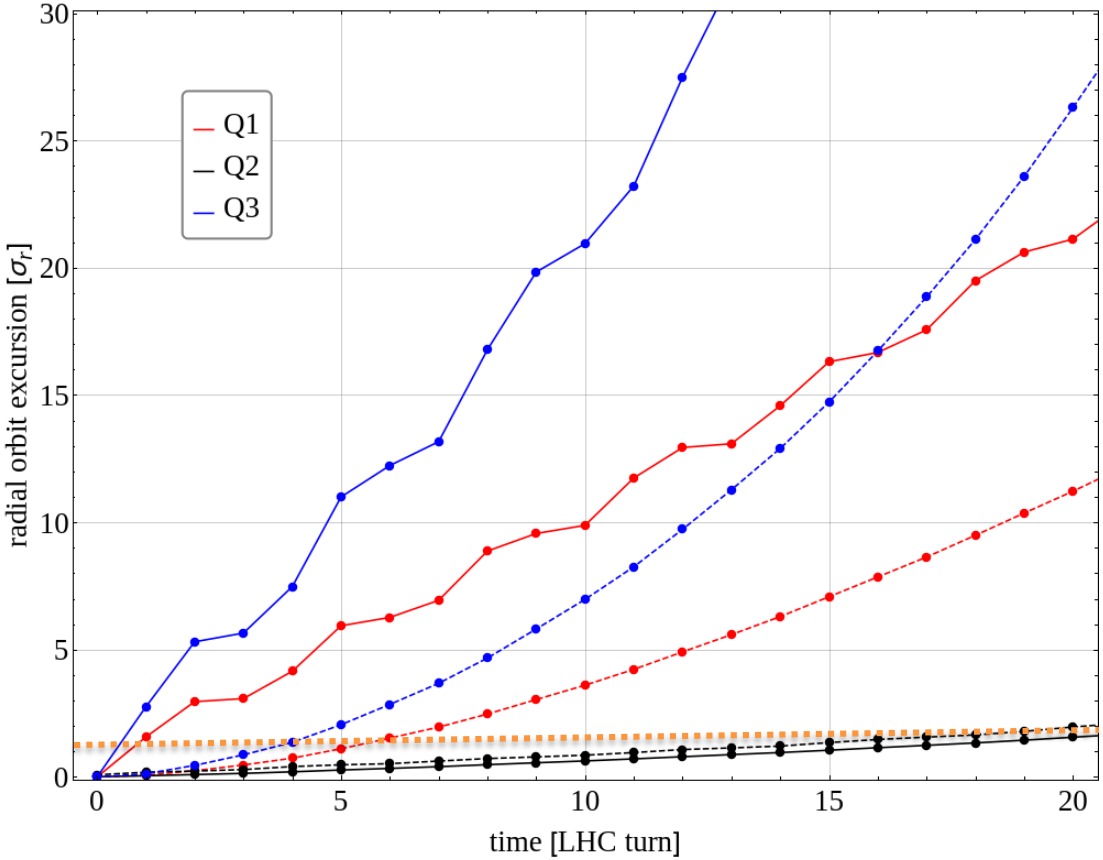
Spurious CLIQ discharge in Q2





- 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

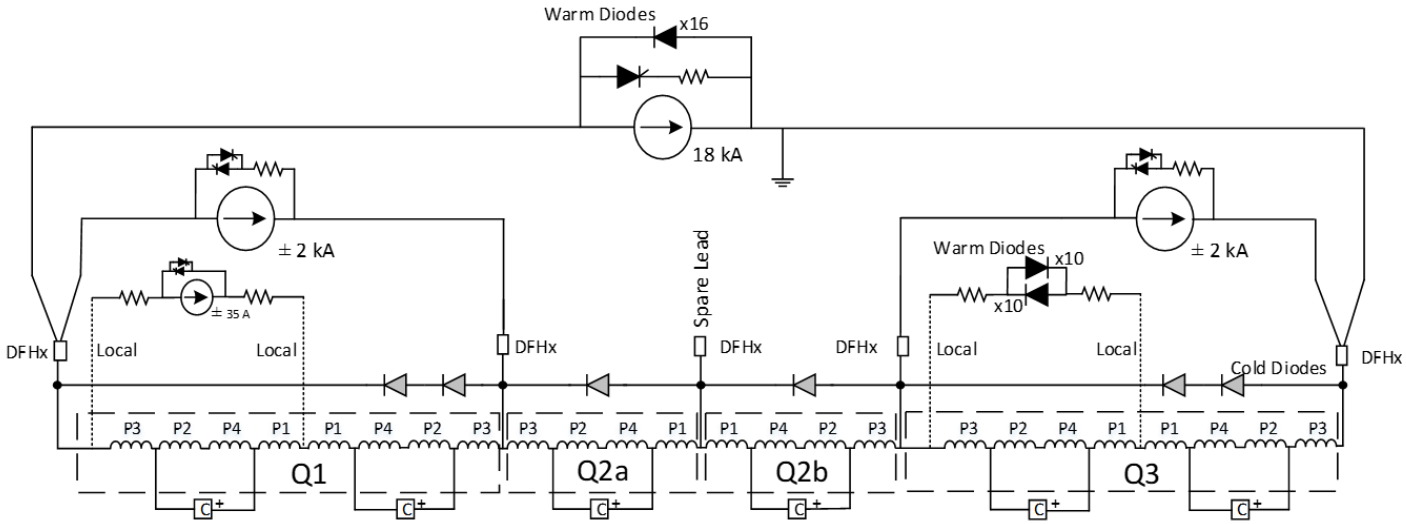


- Solid lines: without beam screen
- Dashed lines: with beam screen (model not validated)

Critical orbit excursion ~1.5 sigma

- 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 only after ~ 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



Current baseline

- 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

Step	Duration
Detection QH discharge (di/dt ≈ 4 MA/s)	100 µs
Detection CLIQ discharge (di/dt ≈ 200 kA/s)	< 500 µs
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