Effects of magnet-circuit protection equipment on the circulating beam

- Effects of quench heater and CLIQ discharges on beam
- Mitigations and interlocking
- Selected progresses in WP7

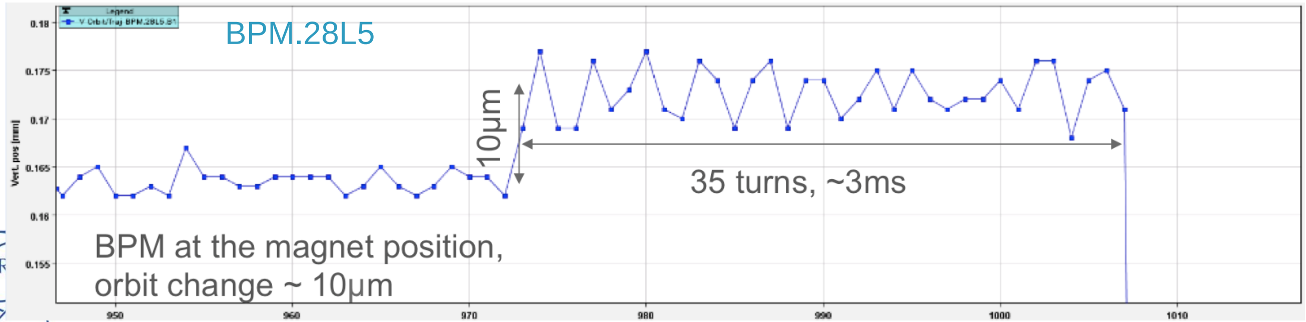
D. Wollmann for WP7

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

9th HL-LHC Collaboration Meeting, Fermilab, USA, 14 - 16 October 2019

Motivation

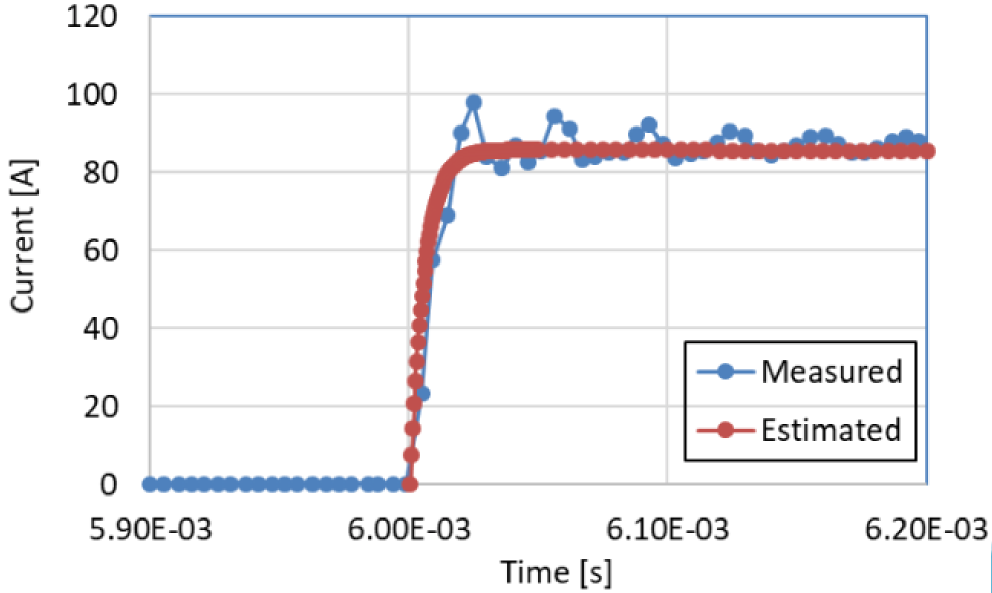
- Quench heaters (QH) impact the **circulating beam**, if not dumped before triggering → observed and verified for LHC main dipoles
- Change of the current (quench, CLIQ discharge, …) in triplet magnets causes **dipole kick** on circulating beam, due to offset in one plane (crossing angle) → observed during quench of RQX.R1, 03.06.2018.
- Stronger effect in HL-LHC than in LHC due to:
  - **more QH** (11 T, triplet, D1, D2), QH + CLIQ (triplet)
  - larger **beta functions** → $d\alpha \propto \sqrt{\beta}$ → Triplet (~8 km → ~21 km), D1 (~5 km → ~19 km) D2 (~1.7 → ~6.4 km)



Quench heater discharge: Ultrafast current rise

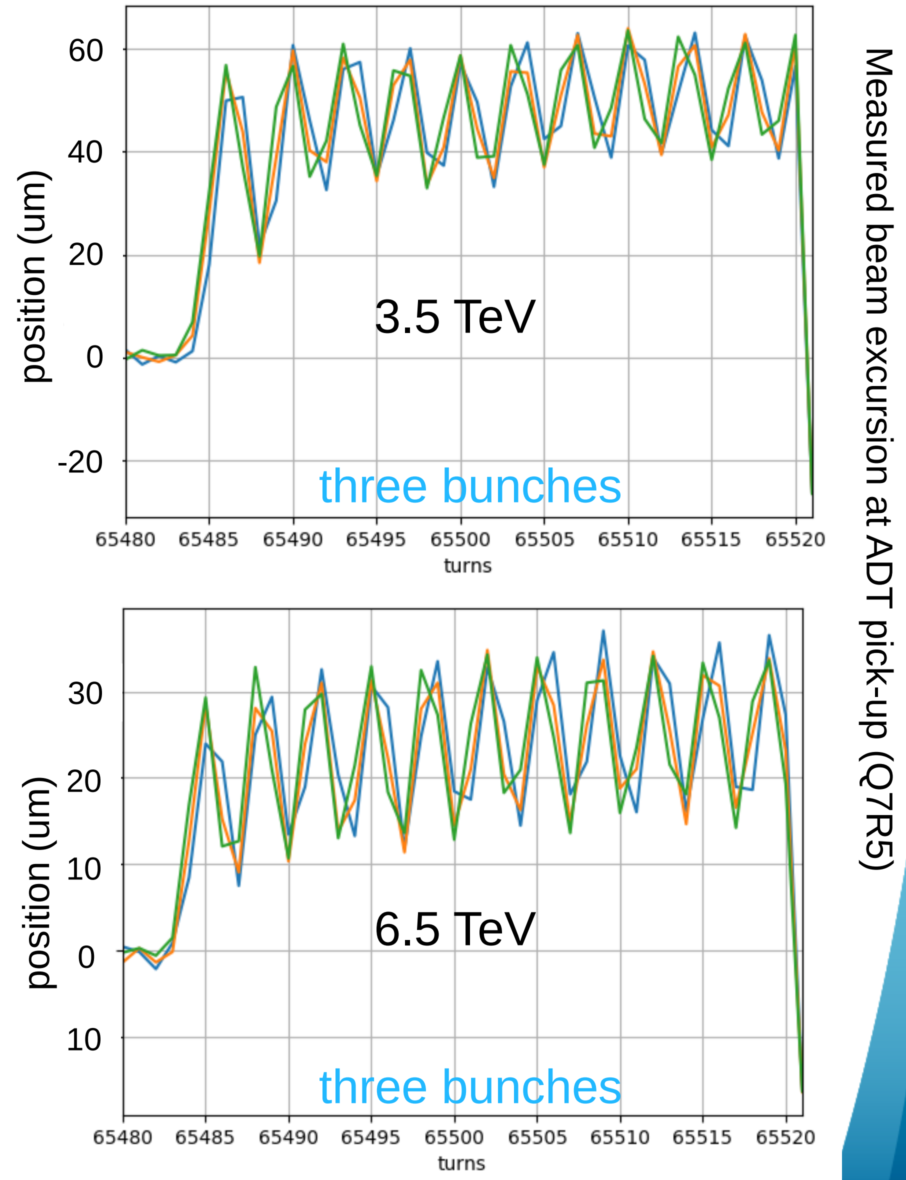
- **Ultra fast** effect, quench heaters reaching full current/field within less than 1/2 LHC turn

  MB: ~ 29 us; MQXF: ~ 35 us
- **Spurious triggering** of one QH unit cannot be fully excluded.

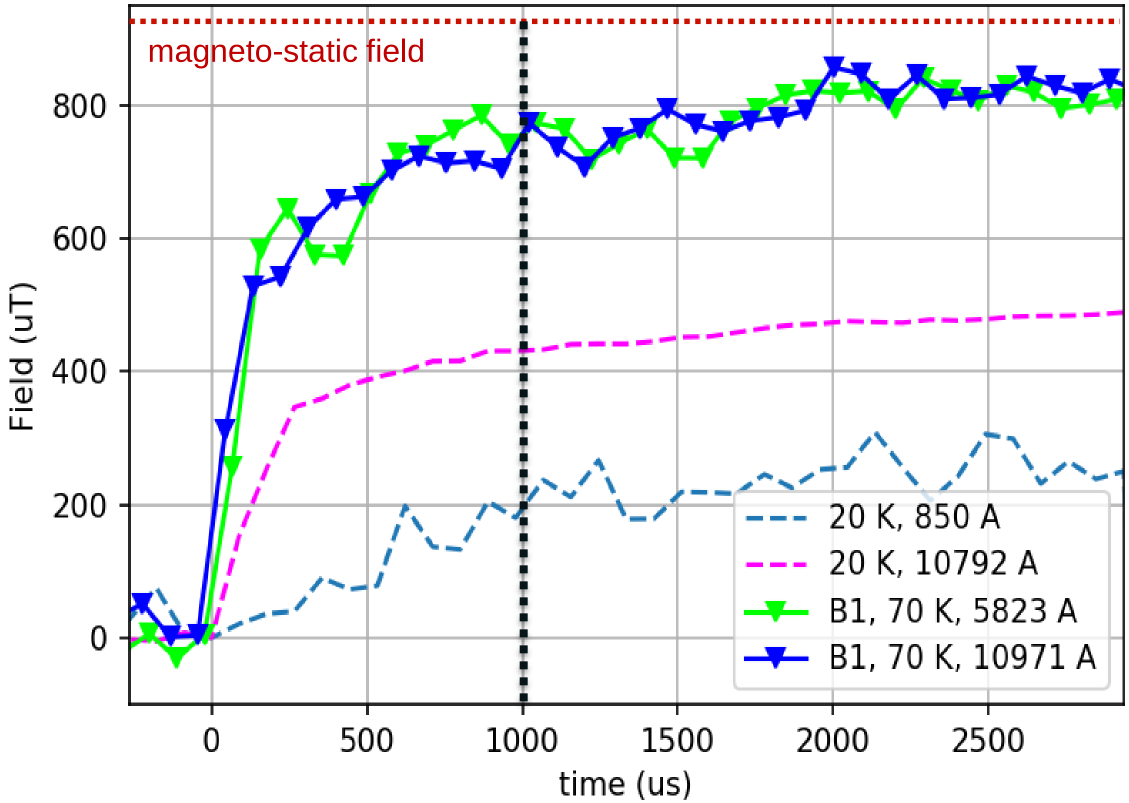


Dedicated experiments with MB.C28L5

- 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 on beam & magnetic field from quench heaters **derived** from **beam position** measurements



Experience from LHC dipoles (dedicated measurements)

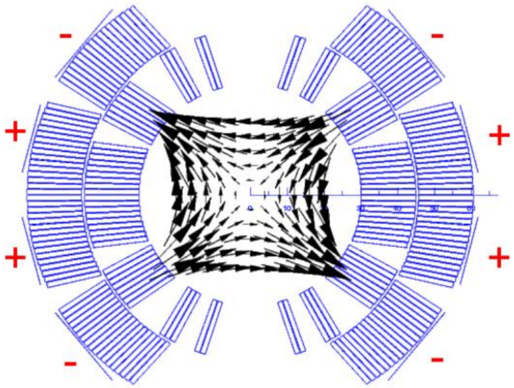


- Fast rise of field from quench heaters reaching up **to 80 % of magneto static** value after 1 ms
- Measurements show **two time constants**
- Rise time depends on beam screen **temperature** and main circuit **current**
- **Qualitative** good agreement with expectation
- Quantitative **discrepancy** between simulations and measurements
- **Detailed studies** of shielding effects required (experiments & simulations)

Expected kicks from QH firing in HiLumi magnets

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 (48 QH)	2.5	→	33.7
Triplet (single QH)	0.6	→	1.3

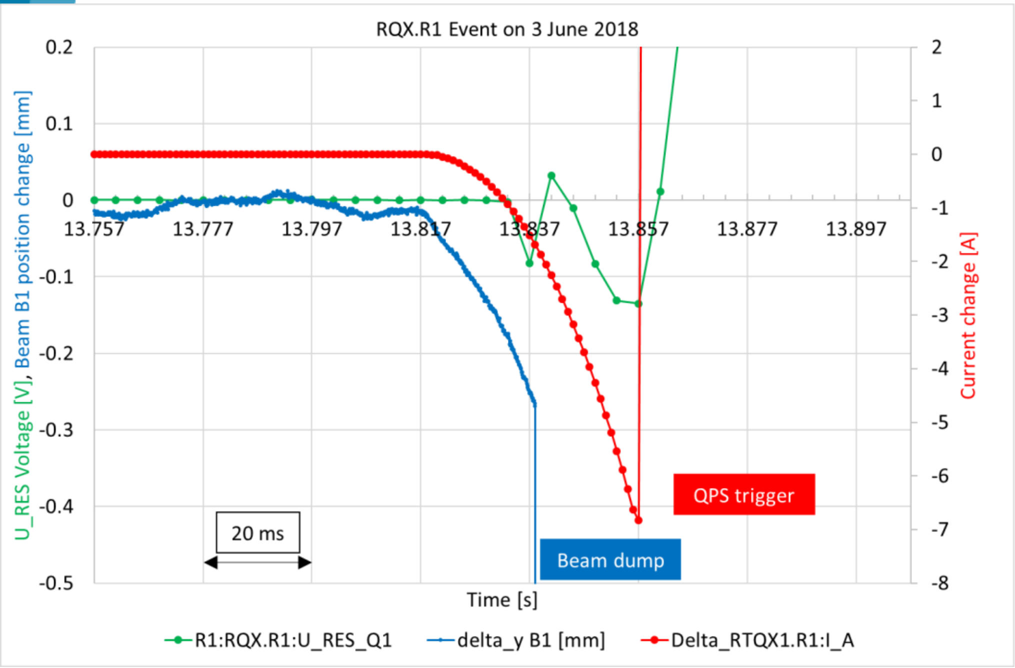
Comparison of kicks from quench heater discharges (magnetostatic values)



Polarity of 11 T QH strips

- Impacts of quench heaters on beam has been **reduced**/mitigated for HL-LHC magnets by change of **connection schemes** (dipole → quadrupole fields or other higher orders)
  - 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 power supply. The effect of all 48 quench heaters on the beam remains critical
- Quench detection systems will ensure that a **beam dump is initiated before the discharge** of quench heaters and CLIQ is triggered

Effect of quench in LHC triplet on beam

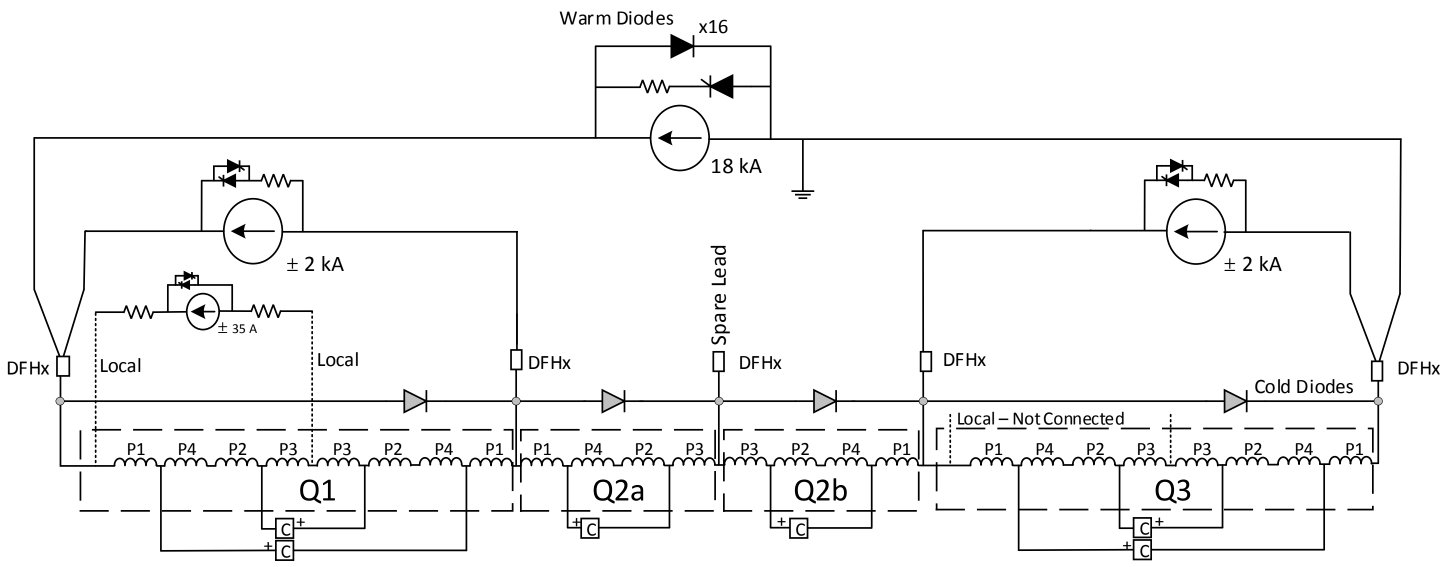


Event overview:

- 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 large 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 → based on beam loss monitors
- HL triplets will have **symmetric quench protection** initiating beam dump (backed up by beam loss monitors)

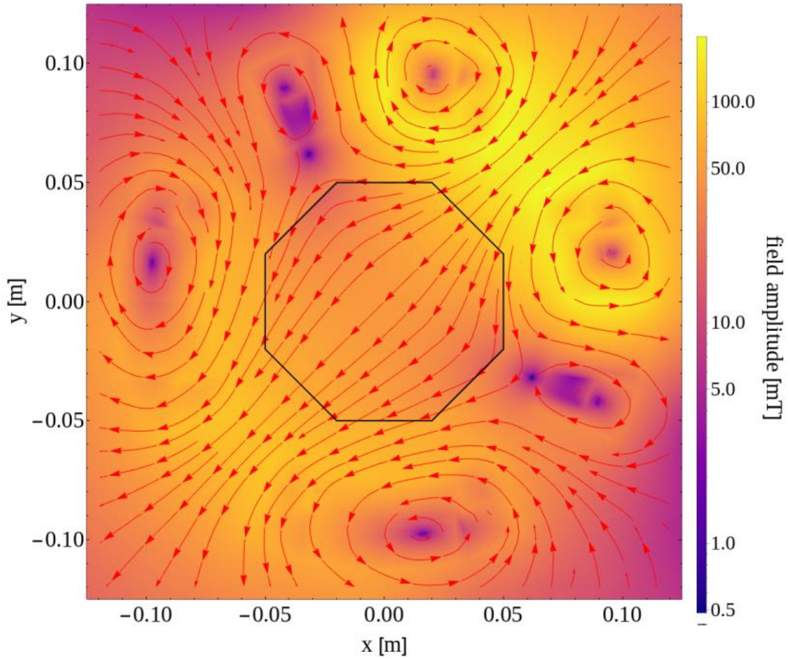
Effect of one spurious CLIQ discharge in IT

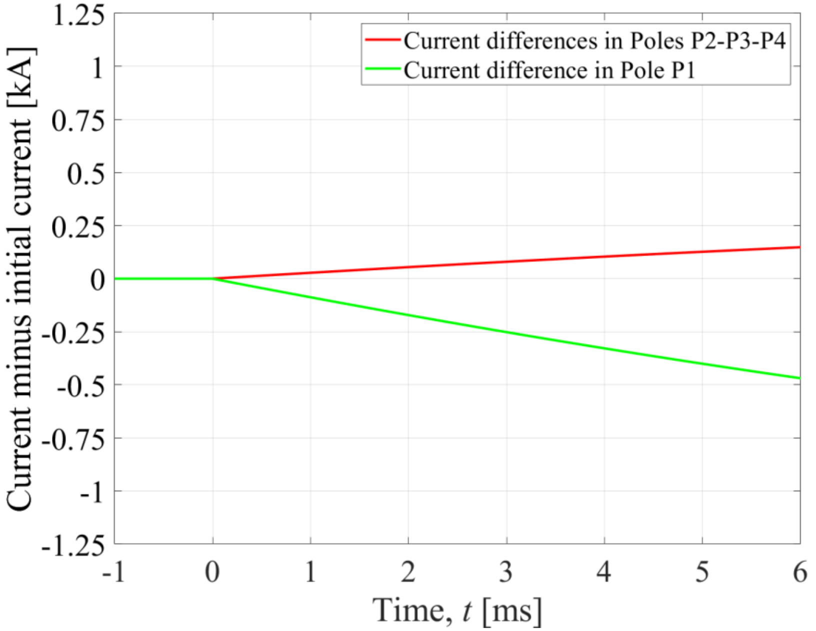


Old baseline

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

Spurious CLIQ discharge in Q1/Q3

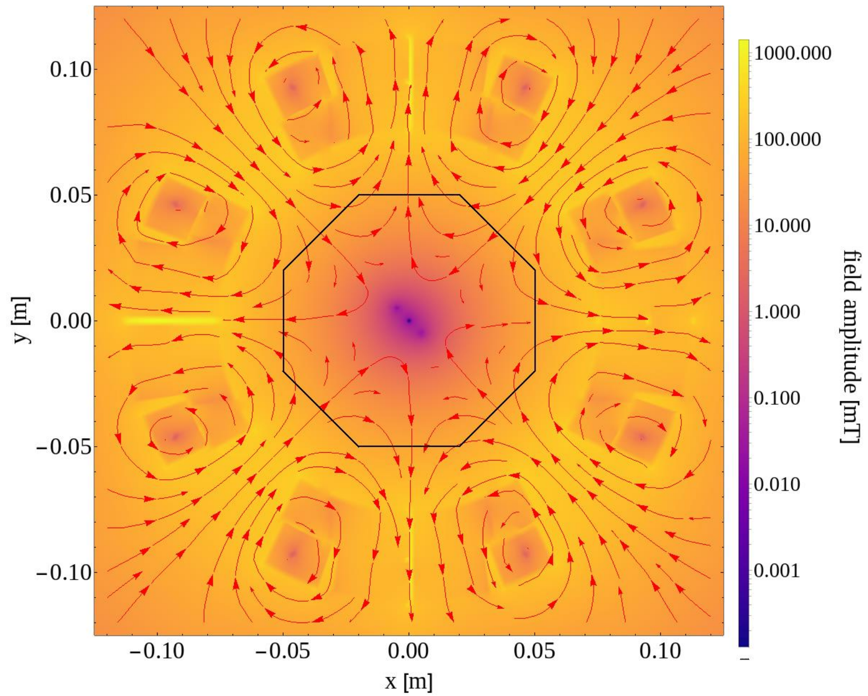


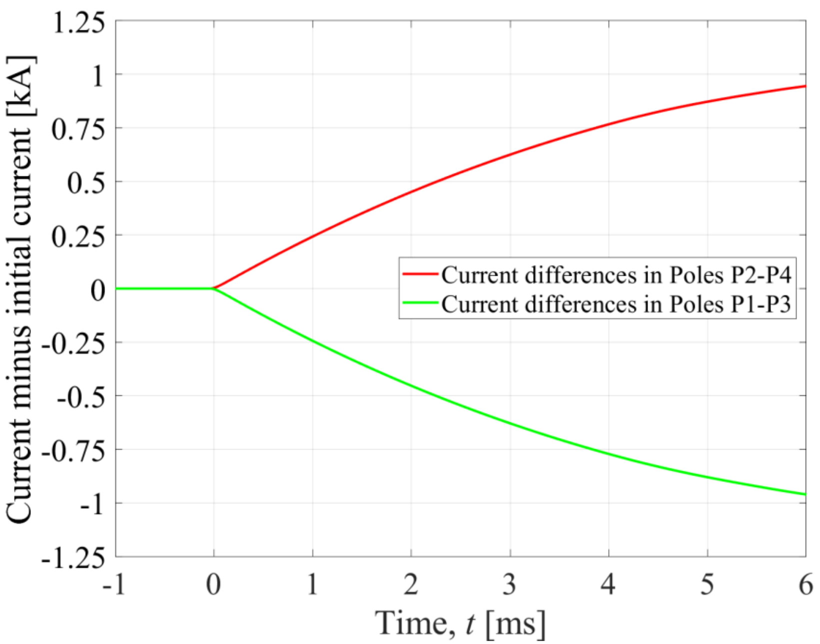


- **Asymmetric** discharge into the poles of the Q1a/b (respectively Q3a/b)
- **Skew dipole** field in magnet causing **kick of beam**
- Additional (much weaker) dipolar kick during discharge of magnet current due to beam offset (Q1: up to 9.8 mm, Q3: up to -17.1 mm)

Old baseline connection scheme

Spurious CLIQ discharge in Q2

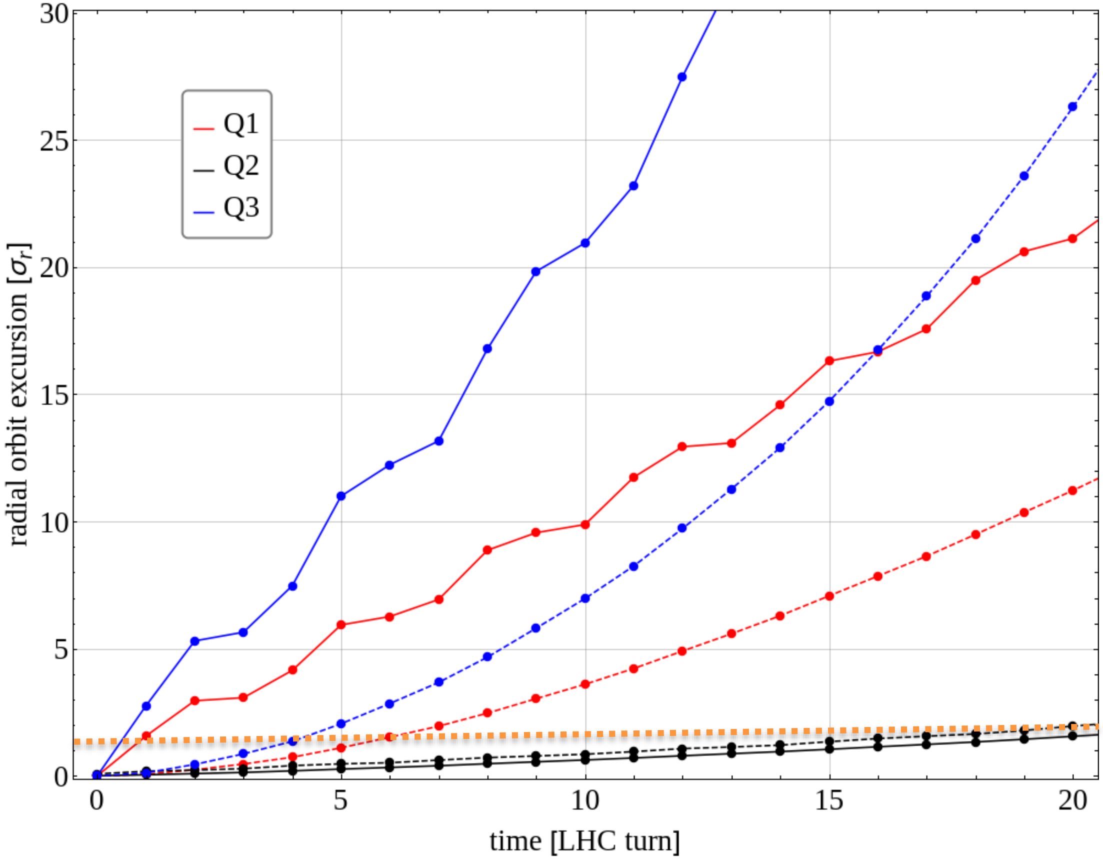




- **Symmetric discharge** into P1-P3 and P2-P4 of Q2a/b
- **Octupolar** field
- Dipolar kick developing during discharge of magnet current due to beam offset (up to 16.6 mm) in Q2

Old baseline connection scheme

Effect on the circulating beam



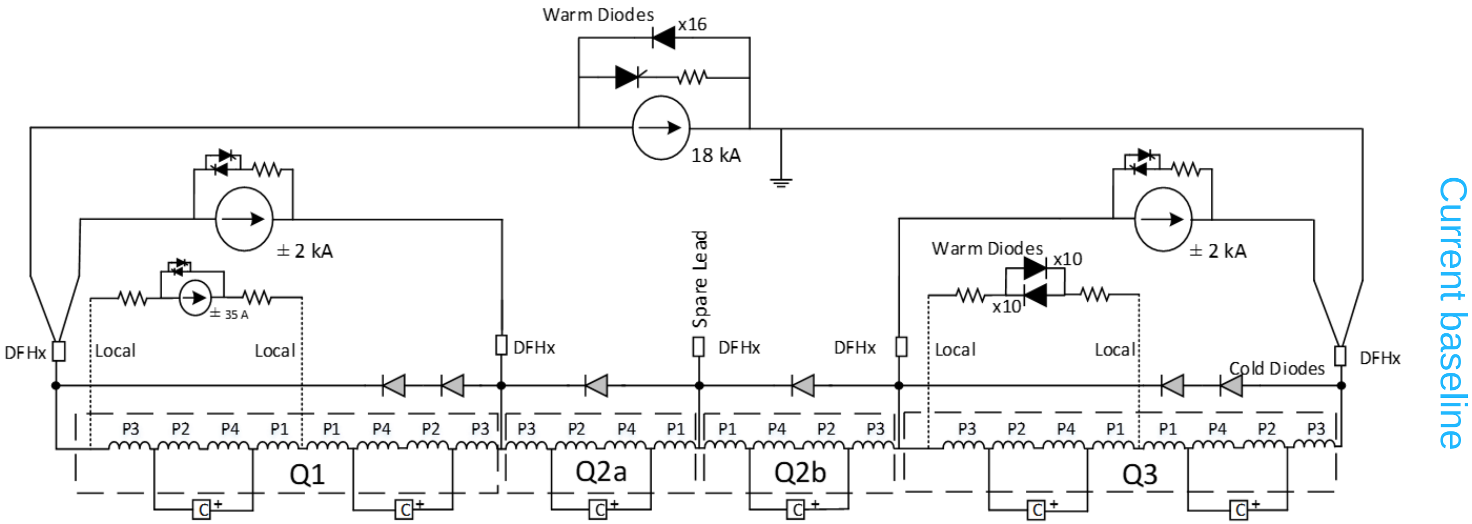
Q1, Q3:
- Solid lines: without beam screen
- Dashed lines: with beam screen (model not validated)

Q2:
- Solid line: with beam screen
- Dashed line: without beam screen (model not validated)

Critical orbit excursion ~1.5 sigma

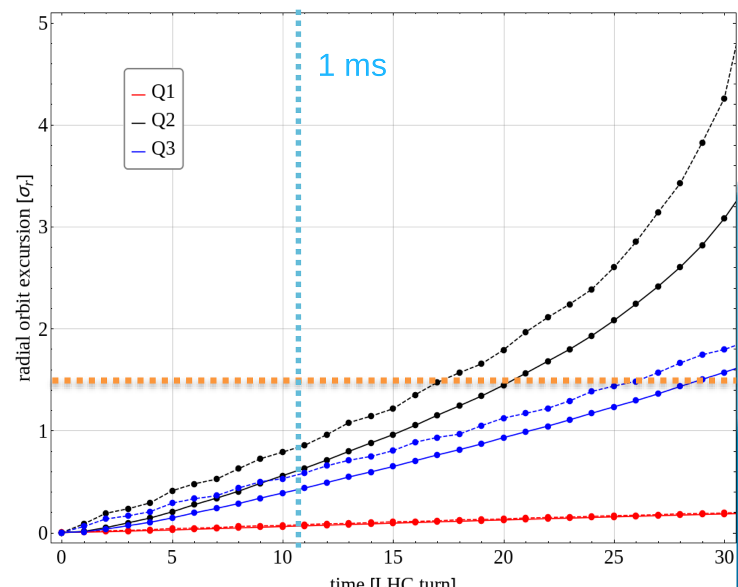
- Spurious discharge of one CLIQ unit into **Q1 or Q3** causes **critical orbit excursion** within one LHC turn (89 us) → **no possibility to actively interlock**
- CLIQ discharge into **Q2** reaches critical levels after only ~ 20 turns → **sufficient time** to actively interlock and dump the beams before critical loss levels will be reached

Mitigation of effect of spurious CLIQ firing on circulating beam



- 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
Communication DQHSU → PIC → BIS	12 μs
Beam abort sequence	270 μs
Total	< 1 ms



Q1, Q2, Q3:
- Solid lines: with beam screen
- Dashed lines: without beam screen (model not validated)

Progress on WP7 protection equipment

R&D **successfully finished** for protection hardware:

- Quench Detection
  - UQDS R&D (incl. radiation tests) successfully finished
  - UQDS successfully used for **protection** during various HL-LHC test campaigns in **SM18: 11 T, CCT, MgB_2 links**
- Energy extraction
  - Prototyping successfully finished for 600 A and 2 kA EE systems (IGBT [for test stations] & **in-vacuum switches** [for tunnel])
  - **Pre-series** of four 2 kA and four 600 A EE systems has been **delivered** to CERN and **acceptance tests** were **successfull**y performed
- Cold diodes
  - Cold diode prototypes **successfully radiation tested** up to levels expected in the tunnel
  - Most radiation resistant diode type chosen for tunnel
  - Design of **diode press-pack** for triplet **started**
- MBH (11 T) protection
  - **Prototype rack** for 11 T protection produced at CERN and **successfully tested**

R&D on controls for protection equipment and integration into controls environment **ongoing**

UQDS v2.1 crate serving as the base line prototype for the HL-LHC QDS.

2kA Energy Extraction Systems pre-series

11 T protection rack prototype

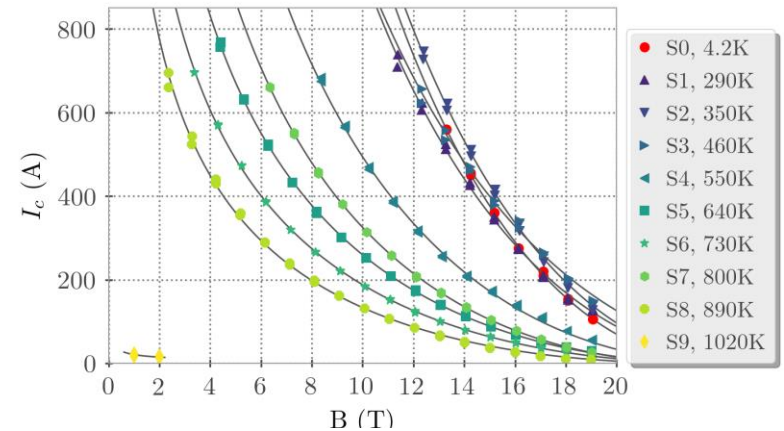
More details on cold diodes see joint session of WP7/10 Tue afternoon

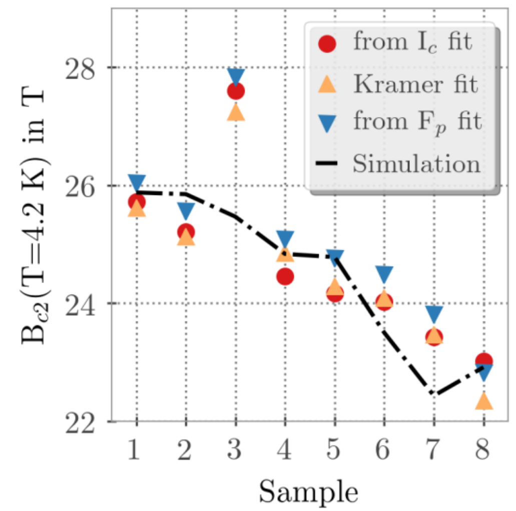
Damage of sc. strands due to beam impact

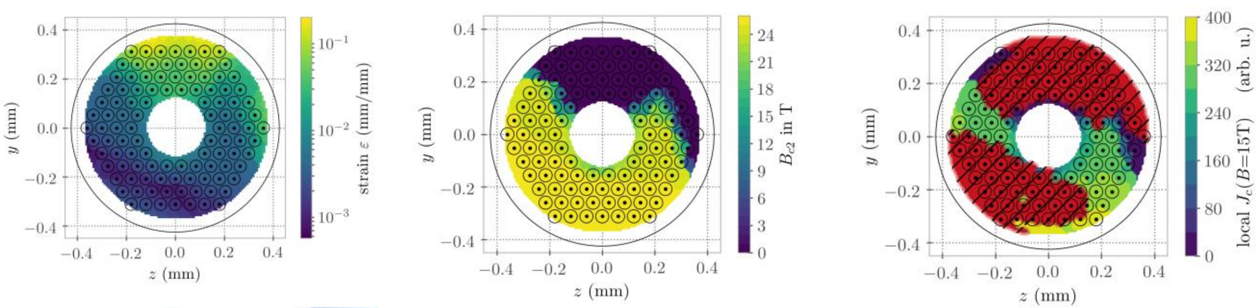
Damage limits of sc. magnets due to **beam impact** not well understood → impacted sc. strands samples with **440 GeV protons (SPS) at 4 K**

Results:

- **Nb-Ti** strands
  - **No degradation** of critical current observed (max. hot spot temperature ~1200 K)
  - **Thermal stability** of strands **degraded** with increasing hot spc temperature.
- **Nb_3Sn** strands
  - Significant **I_c degradation** for hot spots **> 460 K**
  - Significant **B_{c2} degradation** observed for hot spots above > 460 K, due to residual strain
  - Good agreement between measurements and **thermo-mechanical simulations**
    - I_c degradation dominated by **filament breakage**
    - B_{c2} degradation due to **residual strain** from copper matrix







More details see joint session of WP7/14 Tue afternoon

Status of circuit protection studies

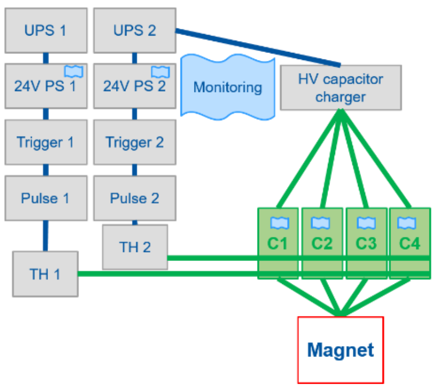
- MgB2 link and leads: protection studies done: large margin
- Triplet mains: protection studies finished, including failure cases and k-mod trim
- Triplet RCBXFA/B correctors: protection studies done by CIEMAT. Protection on B (EE or self-protected) to be finalised, awaiting experimental data
- Triplet High-order superferric correctors: Protection studies done by INFN. Self-protected (except skew quad). Cross-check by CERN still to be done
- RBXF (D1): protection studies incl. failure cases done by KEK. Good margin
- RBRD (D2): protection studies incl. failure cases done by INFN and cross checked by CERN:
- RCBRD (D2 orbit correctors): protection studies done. Final choice of the EE ;to be decided, also awaiting experimental data.
- RB.A67 and RB.A78 including the MBH (11 T dipole): protection studies done incl. failure cases.
- Hollow e-lens: preliminary studies for protectability done
- Busbars: protection studies done: good margin

Very good advancement on circuit protection studies at CERN & collaborating institutes

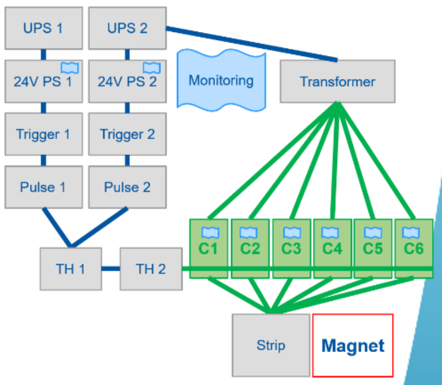
Status of reliability studies

- Monte-Carlo tool for **availability and performance simulations**, developed at CERN in 2017/18/19, ready for use
  - Allows for advanced modelling of **reliability and availability** of HL-LHC and HL-LHC systems
  - Refined input data thanks to great progress on **fault tracking in LHC run 2**, for both LHC and injectors
- Ongoing modelling work:
  - Continuous updates of HL-LHC **availability and integrated luminosity** production estimates
  - **Sensitivity analyses** to key performance indicators, useful to address uncertainty on new system designs (e.g. failure rates and recovery times of new systems)
- **Reliability studies** for HL **equipment**:
  - Reliability studies performed for 11 T **protection architecture and hardware** → reliability targets confirmed
  - Reliability and availability studies ongoing for **triplet protection**, with definition of reliability targets for CLIQ, quench heater power supplies and UQDS
  - **Essential input** for (protection) **HW design**

CLIQ model



QH model



Summary

- Fast orbit offsets have been **observed in the LHC** due to firing of quench heaters
- Quench heater connection schemes have been changed to **quadrupole schemes** where possible → reduction of kick strength
- Spurious CLIQ discharges in Q1 or Q3 would have caused **fastest failure** in the LHC → mitigated by change of CLIQ connection scheme
- In case of a **quench** in the HL triplets, the interlock sequence will ensure that a **beam dump request is sent before a discharge** of quench heater power supplies and CLIQ units is initiated
- **Spurious CLIQ discharges** will be interlocked and **initiate immediately a beam dump** and re-trigger the remaining CLIQ units
- R&D for **protection equipment** (QDS, EE, cold diodes, CLIQ) **well advanced** and prototypes / pre-series systems successfully qualified at CERN → R&D ongoing for controls
- Significant **reduction of I_c** observed in Nb_3Sn strands for **hotspots > 460 K** due to **beam impact**
- Circuit protection studies are **well advanced**
- Reliability studies provide **essential input** for the **design** of protection **HW** (reliability targets)

Thank you for your attention!