# Machine Protection and Failures - Overview

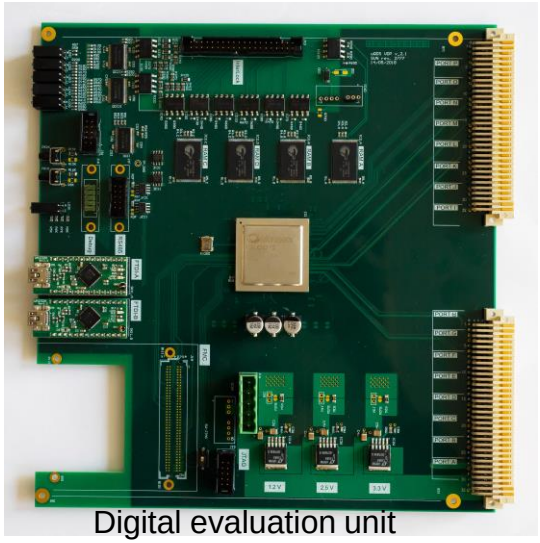
- Status of magnet / circuit protection HW
- Radiation hardness & damage experiments
- Effects of magnet protection equipment on beam
- Crab cavity tests in SPS
- Circuit Protection & Availability Studies

Daniel Wollmann for WP7

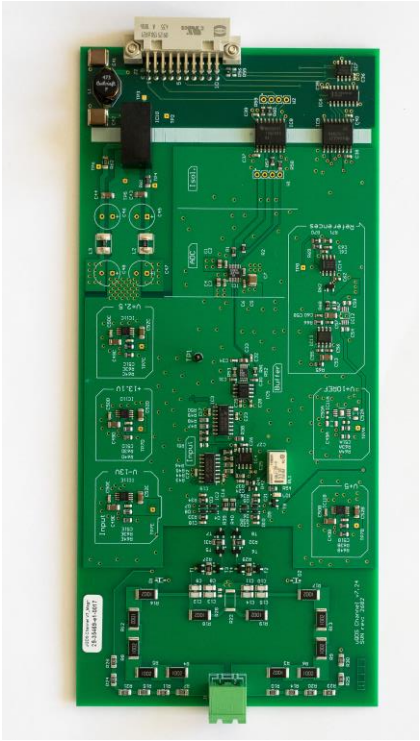
8th Annual HL-LHC Collaboration Meeting, 15.-18.10.2018, CERN

# Quench Detection and Data Acquisition system

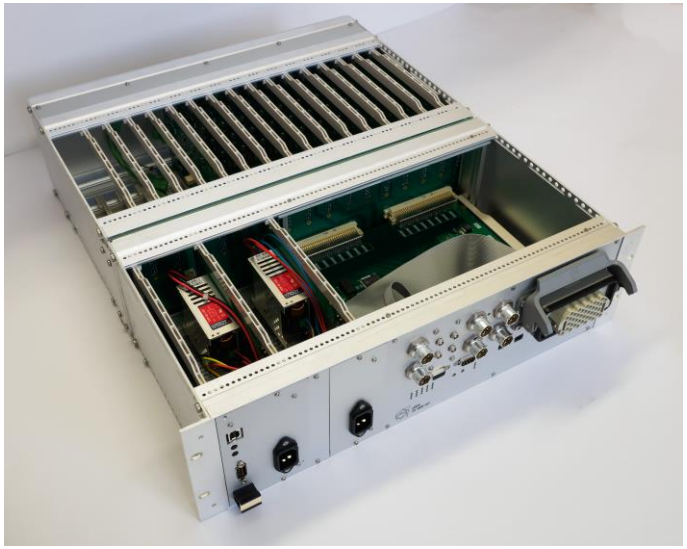
- Several **uQDS** units are currently under extensive **type testing**
- One uQDS unit is under test in CHARM
- Supervision layer for 11 T protection systems is currently **under definition**



Digital evaluation unit



Frontend input channel v6.6



Redundant power supplies & digital part

See talks by
- J. Steckert WP5/WP7/WP9/WP11 Wed PM
- E. De Matteis WP5/WP7/WP9/WP11 Wed PM
- T. Podzorny WP5/WP7/WP9/WP11 Wed PM

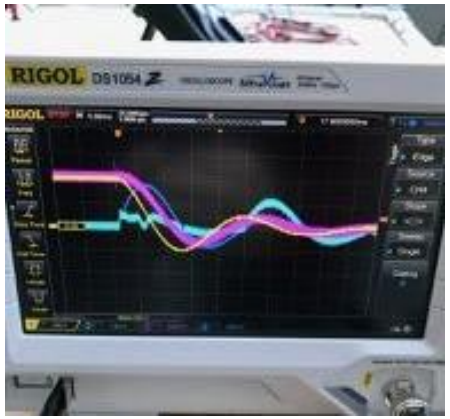
# Energy Extraction Systems

- Prototype **2 kA vacuum breaker system** has been successfully tested @ CERN
- A **pre-series of four 2 kA** Energy Extraction systems for the test stations being ordered in industry

Controls & Switches

See talks by
- B. Panev WP3/WP7 Tue AM
- D. Carrillo WP5/WP7/WP9/WP11 Wed PM

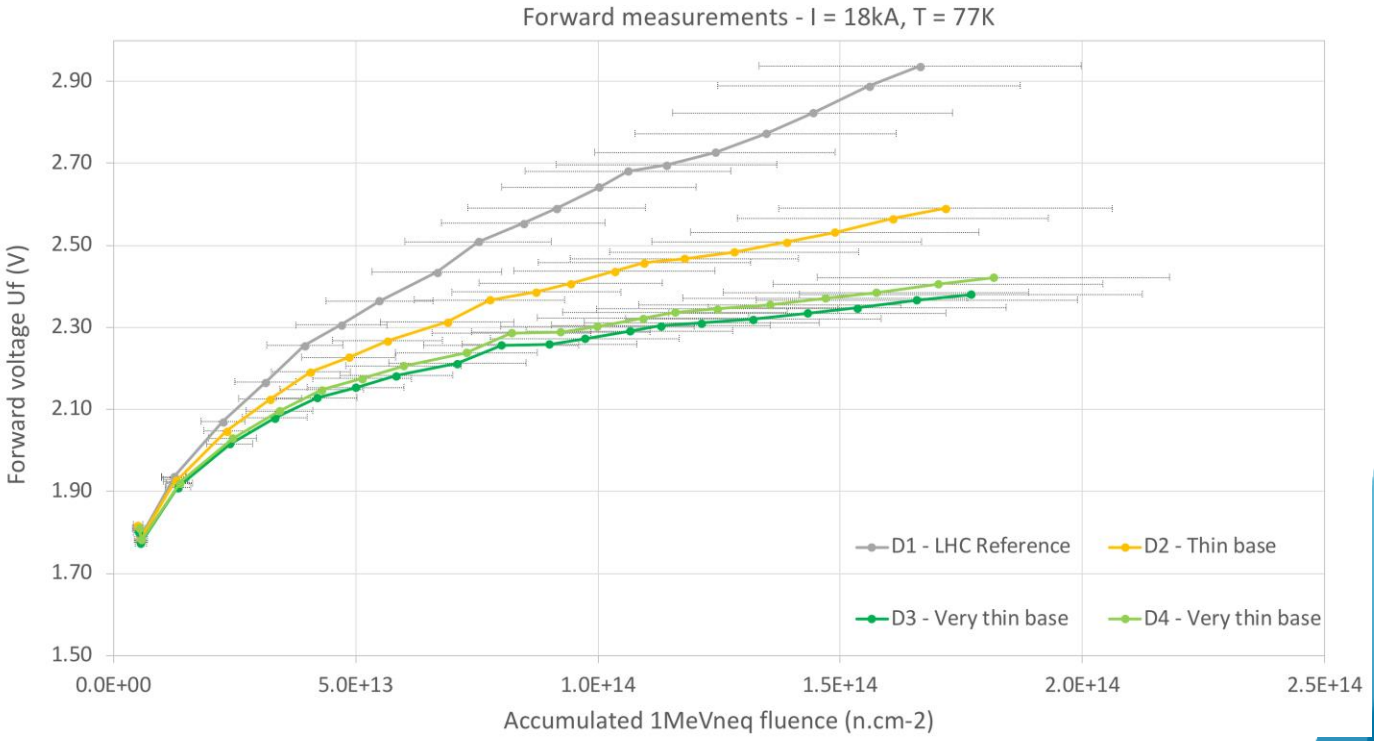
# CLIQ




- 5 CLIQ units ordered in industry, first of them was manufactured and successfully underwent the **factory acceptance test**

# Irradiation test of triplet cold by-pass diodes

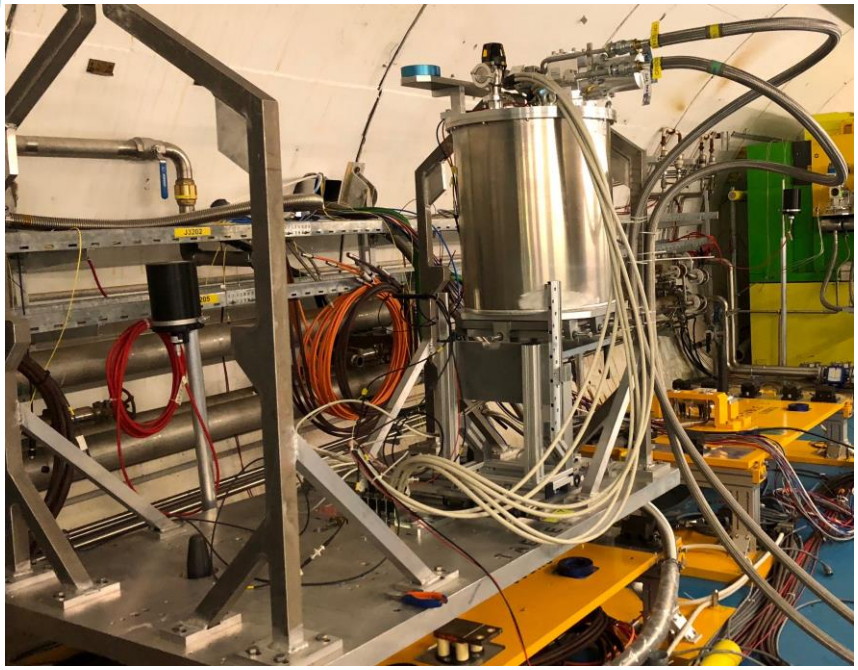
- Cold diode irradiation cryostat installed in CERN's **CHARM facility**
- Two stacks of four **diodes (77K, 4K)**, weekly measurement of forward characteristic up to 18 kA, turn on voltage, reverse blocking voltage and capacitance.
- Measurements to be continued until November (end of protons in injectors), expected to reach total **~10 kGy and ~2e14 1MeVneq/cm$^2$**
- **Annealing** tests will be performed after the end of the irradiation period

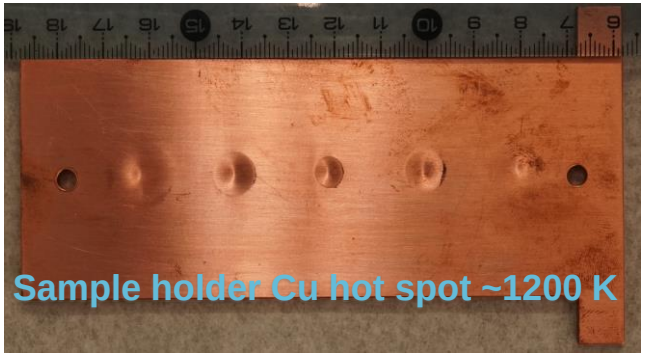



See talks by
- G. D'Angelo Plemary Wednesday AM
- A. Monteuuis WP7/WP10 Wednesday AM

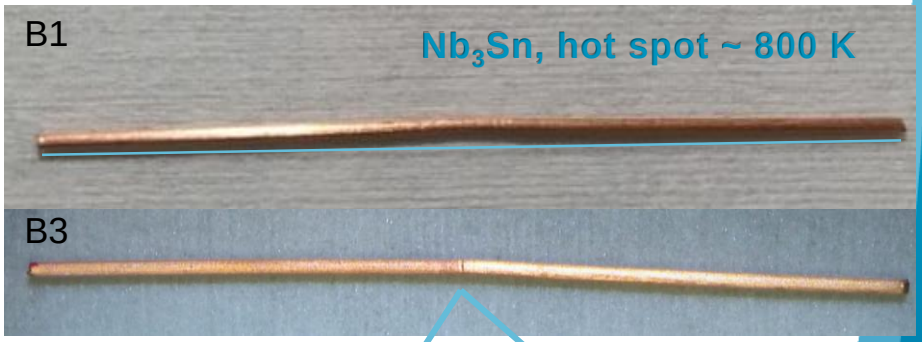
# Damage of sc. strands due to direct beam impact

- Experiment performed with **Nb-Ti, $Nb_3Sn$ and HTS** strands **5 K** in HiRadMat with 24 b **(~3e12 p**, $sigma_{x,y}$=1.1mm) @ **440 GeV**
- Hotspots **up to 1250 K** reach in strands
- **Critical current** measurements will be performed in collaboration with Uni-GE starting Oct/Nov. 2018
- **Microscopic analysis** of strands and witness material ongoing










See talk by
- A. Will WP7/WP14 Thu AM

# Effect of magnet protection equipment on beam

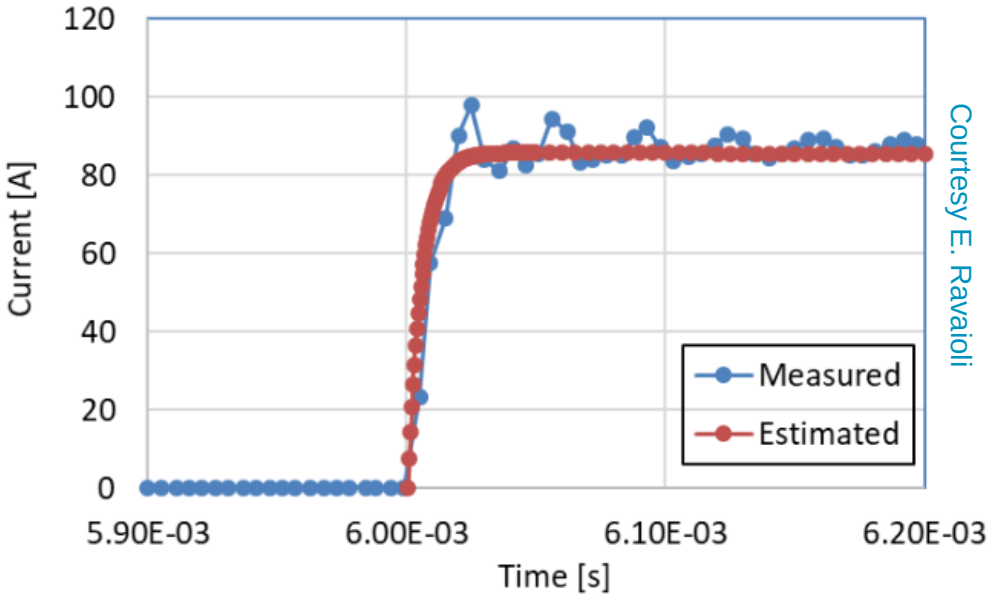
- Quench heaters (QH) impact the **circulating beam**, if not dumped before triggering → observed and verified for LHC main dipoles
- Change of the current (quench, CLIQ discharge, …) in triplet magnets causes **dipole kick** on circulating beam, due to offset in one plane (crossing angle) → observed 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** → Triplet (~8 km → ~21 km), D1 (~5 km → ~19 km) D2 (~1.7 → ~6.4 km)

# Quench heater discharge: Ultrafast current rise

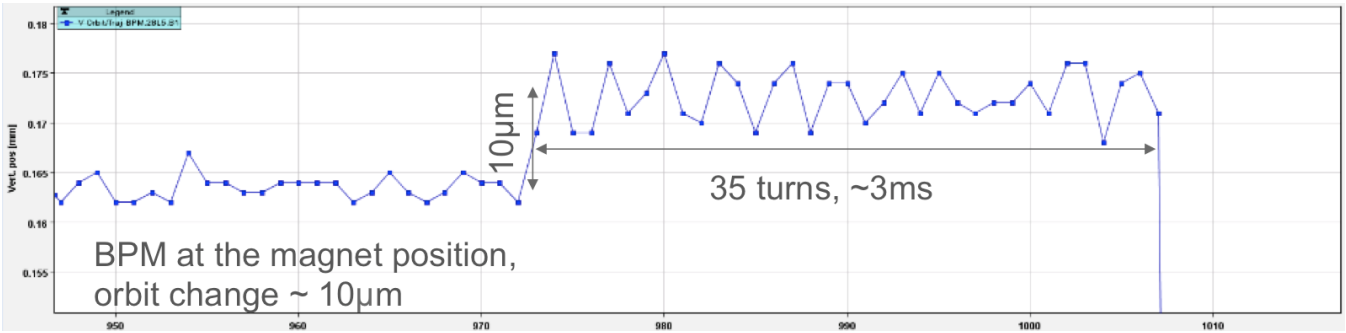
- **Ultra fast** effect, quench heaters reaching full current/field within less than 1/2 LHC turn

  MB: ~ 29 us; MQXF: ~ 35 us

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




Courtesy E. Ravaioli



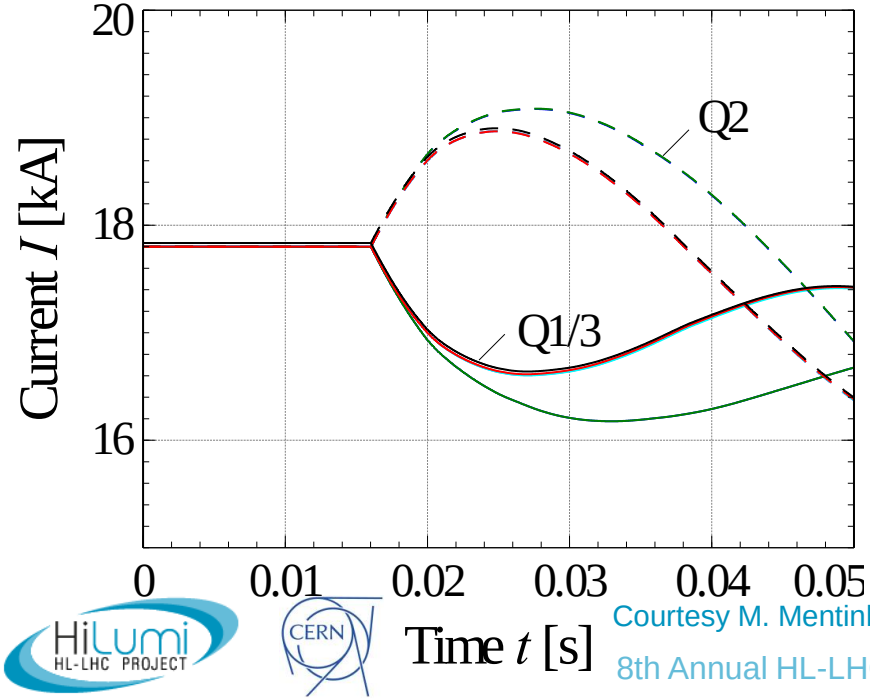
# Expected kicks from HiLumi magnets with all QH fired

| 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 | → | 29 |
| Triplet (single QH) | 0.6 | → | 1.3 |

# Fast current change due to CLIQ dis-charge

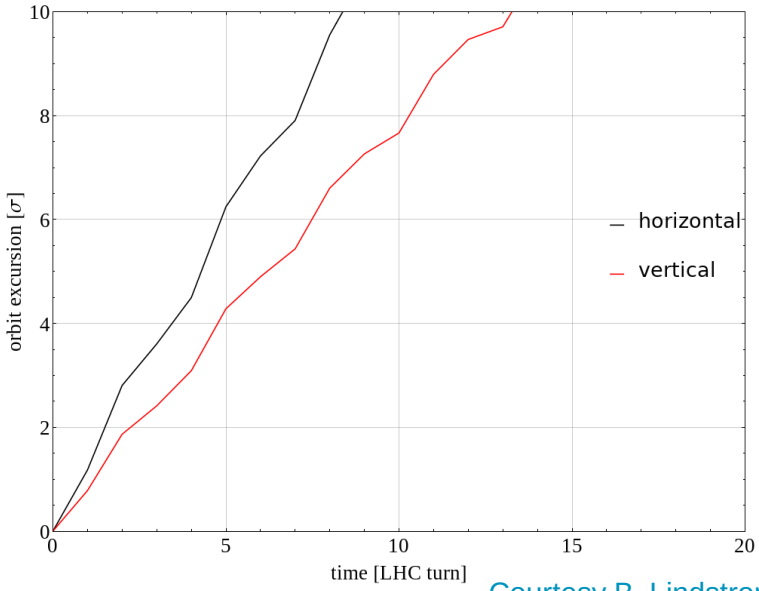
- Very efficient protection of triplet magnet by Coupling Loss Induced Quench (CLIQ) system, discharging up to 2 kA directly into the magnets
- Beams have offset in triplet – vertical (ATLAS), horizontal (CMS) - due to crossing angle → **change of current** in triplet magnets causes skew dipole kick
- Review of spurious discharge of CLIQ shows **very fast effect on beam** (~ 1 sigma per turn).
- After CLIQ discharge, peak current in triplet magnets reached within **10-15 ms**.

Currents in triplet circuits after discharge of all CLIQ units




Courtesy M. Mentink

Expected worst case orbit change during spurious discharge of CLIQ in triplet (Q3)




Courtesy B. Lindstrom

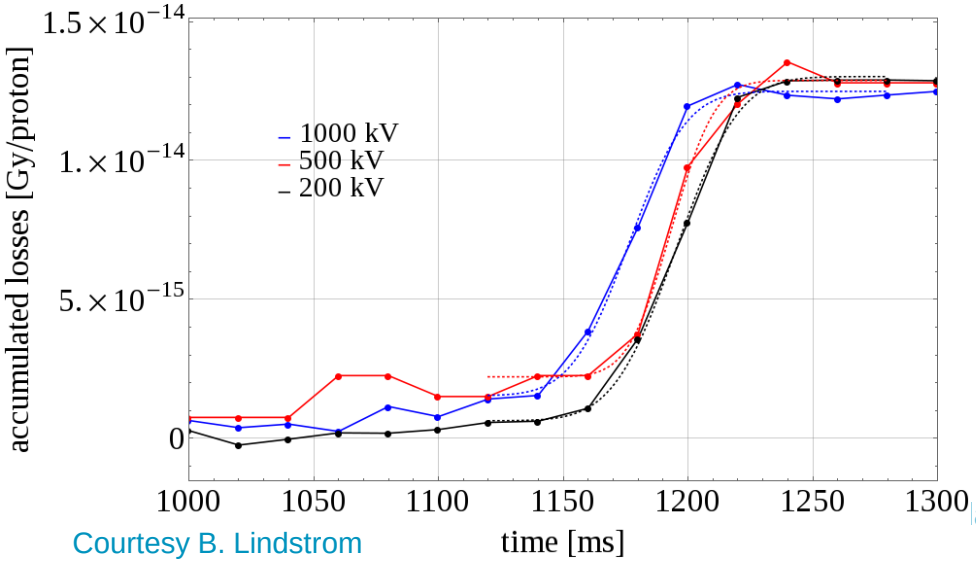
# Machine Protection requirements concerning QH and CLIQ discharges

- **Ultra fast** kicks need to be kept **< 1.2 sigma** to avoid dangerous losses (> 1 MJ) in the collimation system
- **Optimize** QH connection scheme → **reduced** kick (triplet) and/or **quadrupole** field (D1, D2)
- Issue beam dump **before triggering QH & CLIQ** discharges by quench protection electronics
- **Increase rise time** of current in QH circuit and CLIQ to gain time for detection and interlocking
- Reduce **probability** and interlock **spurious firing** of QHs & CLIQ
- Understand effect of **beam screen shielding** (experiments with beam, in SM18 & simulations)

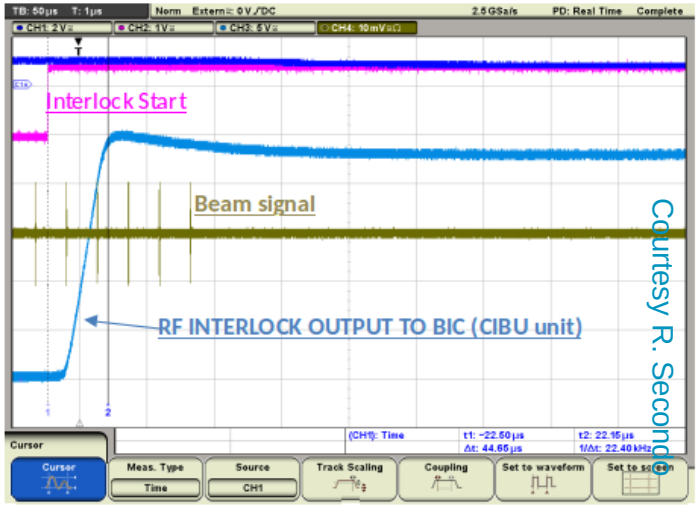
See talk by
- M. Valette WP3/WP7 Tue AM & WP2/WP3/WP6b/WP7/WP12 Wed AM

# Crab cavities

- Crab cavities failures can cause fast kicks on the LHC beam (1.4 sigma within few LHC turns)
- Successful test of crab cavities the SPS in 2018, which showed, that CC perform as expect.
- As predicted very fast failures (resonant excitations with loss rise times of ~50 ms) were observed
- Additional interlocks implemented for high intensity beam tests → CC-SPS MDs in run3 require further maturing of RF HW
- No indication of additional fast failures from crab cavities for HL-LHC but also no 'all-clear' for predicted failures




Courtesy B. Lindstrom




See talk by
- B. Lindstrom WP5/WP7/WP8/WP10 Thu PM

# Circuit Protection and Availability studies

Independent models for all major HL-LHC magnets (D1, D2, 11 T and QXF) allow detailed failure case studies for the HL-LHC circuits:

- Detailed studies of triplet **failure cases** (delayed or failed quench heater and CLIQ firing, symmetric quenches, etc) → expected over-currents in sc. link, required voltage withstand levels, acceptable material for tertiary collimators in case of asynchronous beam dump, …
- Study of triplet **circuit failure cases** in presence of the k-modulation trim
- Detailed study of 11 T behavior in **main dipole** circuit
- Detailed study of 11 T **trim** protection strategy and proposed hardware implementation

See talk by
- F. Rodriguez Mateos WP3/WP7 Tue AM
- M. Mentink WP5/WP7/WP9/WP11 Wed PM

Reliability and Availability studies on the new protection hardware are performed with Isograph-Plus:

- **Reliability requirements** for the 11 T dipole protection **implementation** → current **single QH trigger link** provides sufficient reliability
- Failure Mode Effect Analysis (FMEA) for the new inner triplet to identify **failure modes of the triplet** protection system and derive required hardware reliability

See talks by
- M. Blumenschein WP3/WP7 Tue AM
- D. Sollich WP5/WP7/WP9/WP11 Wed PM

# Conclusions

- Very good **progress** on R&D of HL-LHC **protection equipment** → **prototypes** successfully tested / under testing and **pre-series** production started
- Radiation tests for **cold diodes** on-going – intermediate results are very **promising** for the use of cold diodes in HL-LHC
- **Damage** tests on superconducting strands with 440 GeV protons at **5 K** have been successfully performed → analysis of samples started
- Circuit / magnet protection equipment can have **fast and important effects** on circulating beam → **reduce effects & interlock & reliability studies**
- Crab cavities performed in the SPS **as expected** → interlocking required for fast failures in HL-LHC

**Acknowlegments**
A. Apollonio, M. Blumenschein, M. Bonura, L. Bortot, G. D'Angelo, E. De Matteis, R. Denz, B. Lindstroem, F. Menendez Camara, M. Mentink, A. Monteuuis, B. Panev, T. Podzorny, F. Rodriguez Mateos, E. Ravaioli, C. Senatore, A. Siemko, J. Steckert, D. Sollich, J. Uythoven, M. Valette, A. Verweij, A. Will, S. Yammine, M. Zerlauth