



Machine protection considerations on magnet protection and new equipment

Daniel Wollmann for WP7

Acknowledgments

A. Apollonio, M. Bonura, L. Bortot, F. Menendez Camara, G. D'Angelo, R. Denz, K. Kulesz, M. Mentink, B. Lindstroem, F. Rodriguez Mateos, V. Raginel, C. Senatore, A. Siemko, J. Steckert, J. Uythoven, M. Valette, A. Verweij, A. Will, S. Yammine, M. Zerlauth



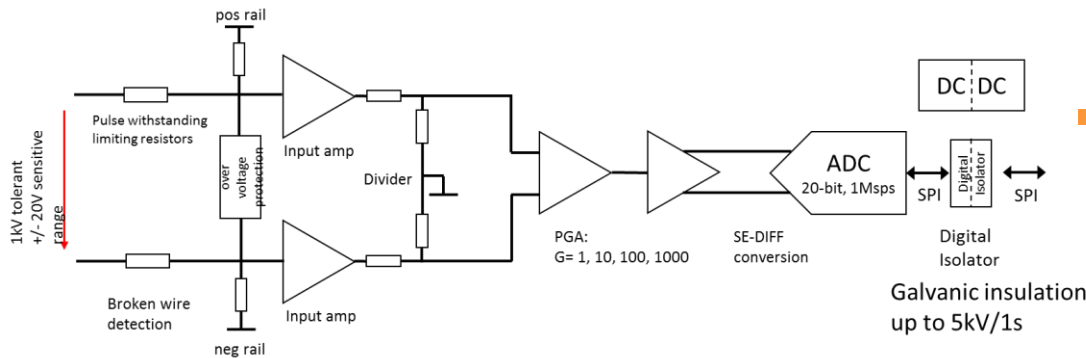
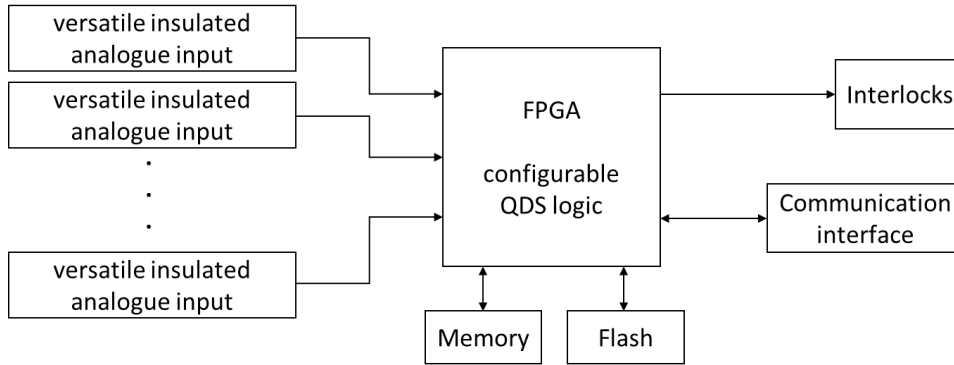
7th HL-LHC Collaboration Meeting, 13.-16.11. 2017, CIEMAT Madrid

Outline

- Magnet and circuit protection:
 - Status of hardware development
 - Effects on circulating beam
 - Qualification of cold diodes for triplet circuit option
- Magnet component damage studies with beam
- SPS crab cavity tests – machine protection considerations
- Update on availability

Quench Detection and Data Acquisition System

For details see:
J. Steckert, Thu AM,
WP3/6a/7



- Prototype development of **universal 8 channel detection with improved diagnostics** for 11 T QDS advancing well → first **prototype** expected by **end 2017**
- Closely following magnet tests in SM18 to gain experience with Nb_3Sn quench detection



Status of Protection hardware

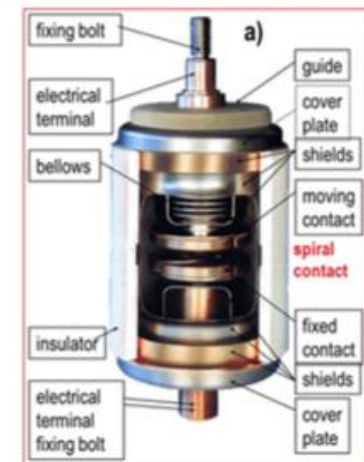
Coupling Loss Induced Quench (CLIQ) units

- 6 units (3 x V1, 3 x V2) manufactured and in use (US collaboration, SM18) or under test.
- 5 units (V2) to be manufactured by industry for SM18 tests → choice of manufacturer ongoing
- V3 for string test and tunnel operation under design



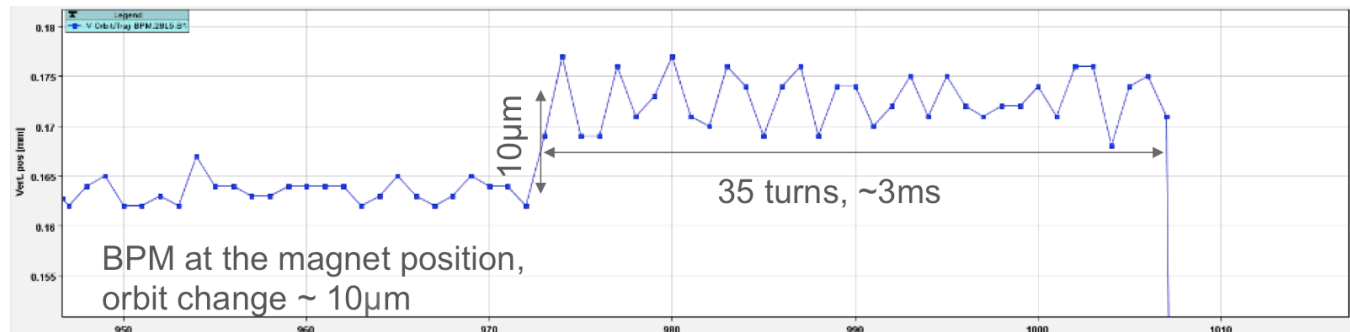
Energy Extraction Systems

- To be used in super-ferric quadrupole, D2 orbit correctors, ... (see E. Todesco, Thu PM, WP3/6a/7)
- Components for two, 1 kA monopolar modules received, **assembly has started**
- 1st work package in Addendum with Lodz University (design of the 2 kA breaker) has been completed. **Design of controls part has started**



Effect of magnet protection on beam

- Quench heaters (QH) and Coupling Loss Induced Quench (CLIQ) systems impact the circulating beam, if not dumped before triggering → observed and verified for LHC main dipoles
- Stronger effect in HL-LHC than in LHC due to:
 - **more QH** (11 T, triplet, D1, D2), **inner layer QH** (triplet), QH + CLIQ (triplet)
 - larger **beta functions** → Triplet (~8 km → ~21 km), D1 (~5 km → ~19 km) D2 (~1.7 → ~6.4 km)
- **Ultra fast** effect, QH reaching full current/field after **~35 us** (1/2 turn), CLIQ reaching peak field after ~12 ms.
- **Spurious triggering** of one QH or CLIQ unit cannot be excluded.



Expected kicks from HiLumi magnets

For details see:
M. Valette, Wed PM,
WP5/7/10/14

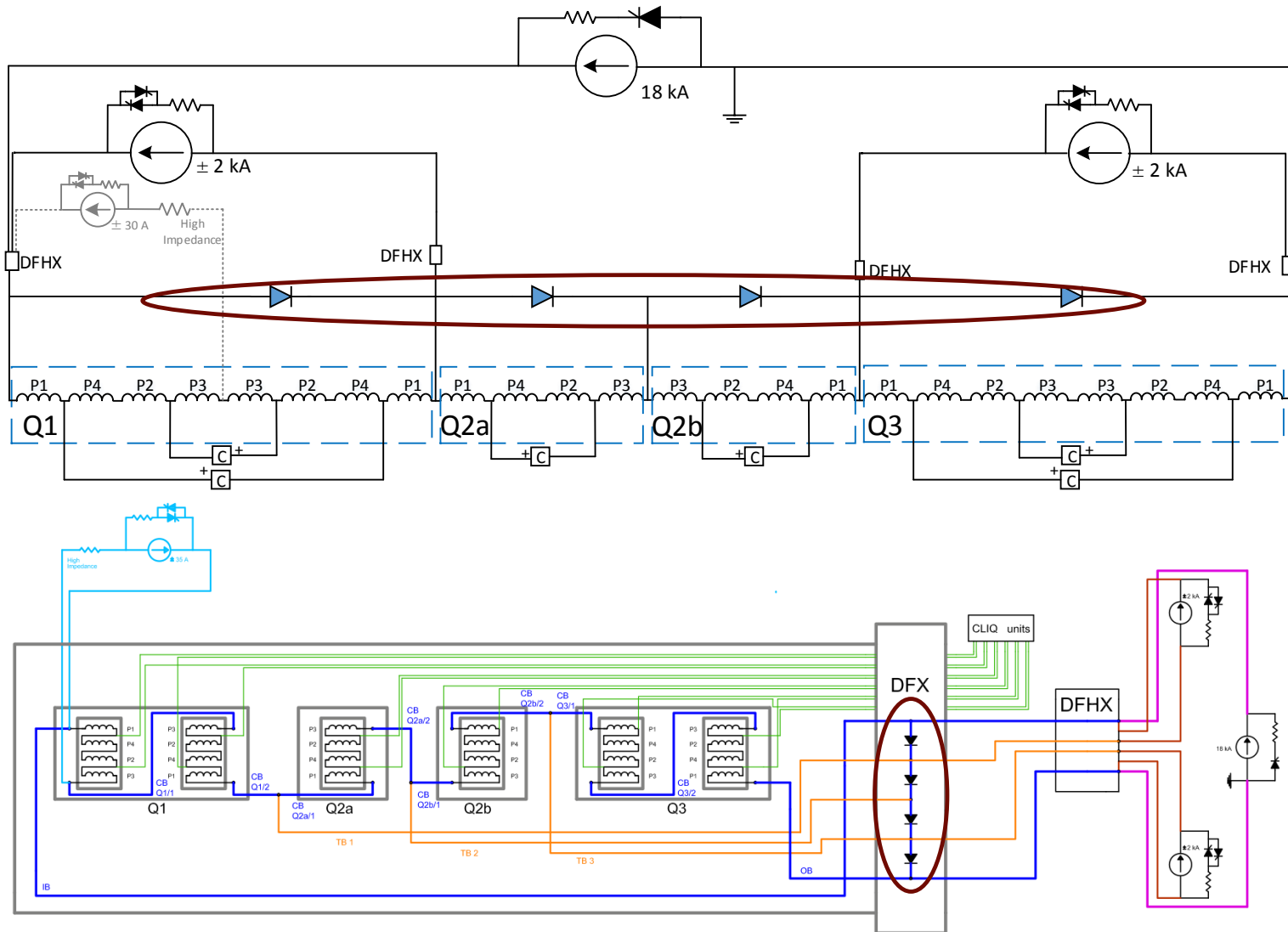
Magnet (all QH)	LHC kick (sigma)	→	HL-LHC kick (sigma)
MB	0.3	→	0.5
D1	1.4	→	2.0
D2	1.2	→	2.4
11 T - dipole	0.4	→	0.4
Triplet	2.5	→	29 (OL) 52 (IL+OL)

CLIQ

- All six units: compensation of dipole and quadrupole components
- Single unit:
 - Q2a/b: quadrupolar field → 20% beta beating after ~2 ms
 - Q1/Q3: skew dipolar field → 1 sigma kick after 4 ms

- **Optimize** QH connection scheme → **reduced kick** and/or **quadrupole field**
- Issue **beam dump before triggering** QH discharge
- Issue **beam dump on CLIQ discharge**
- **Ultra fast** kicks need to be kept **< 1.2 sigma** to avoid dangerous losses (> 1 MJ) in the collimation system

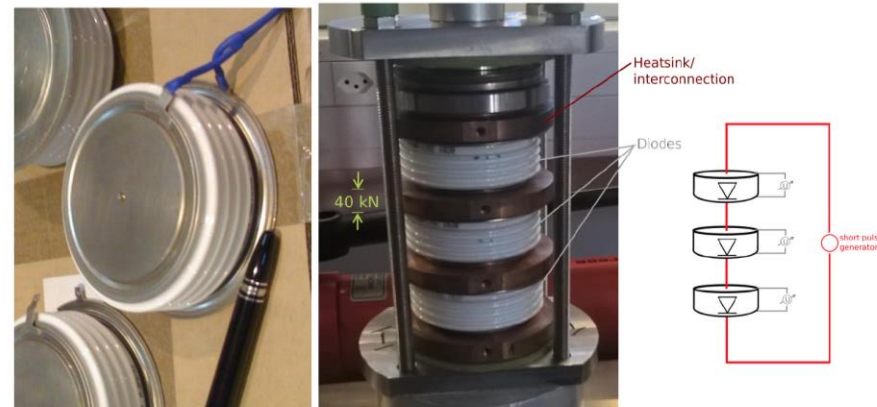
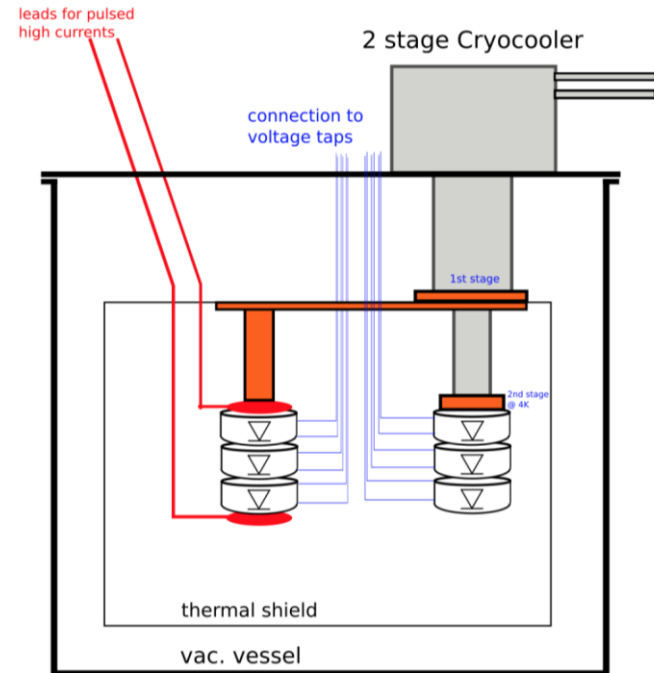
Triplet with cold diodes - option



Courtesy F. Rodriguez Mateos, S. Yammine, F. M. Camara

Qualification of cold diodes for radiation levels

- **Adaptation** of LHC type diffusion diodes for triplet currents and time constants (7 kA, ~ 100 ms).
- → Qualification for HL-LHC radiation levels required. Staged approach:
 - **Irradiation and in-situ testing** in CHARM in 2018 to reproduce earlier results.
 - Depending on results further testing in CHARM or other facility OR modification of diodes and re-testing.
- **Turn-key cryo-cooler based cryostat ordered - \$\$**

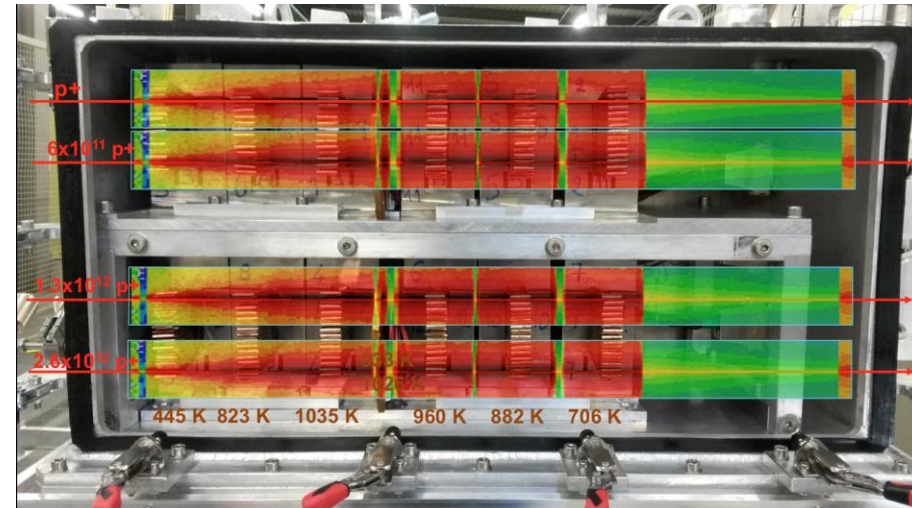
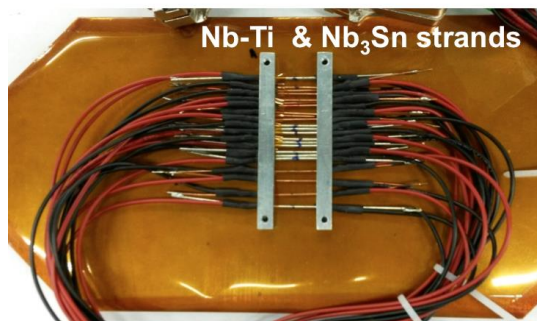
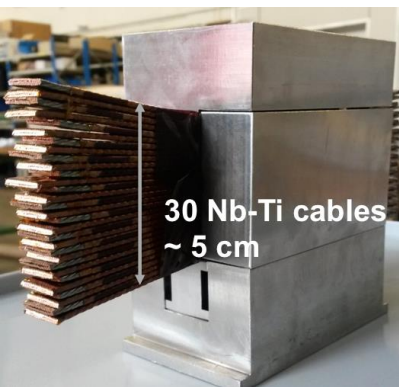


Magnet component damage due to instantaneous beam impact

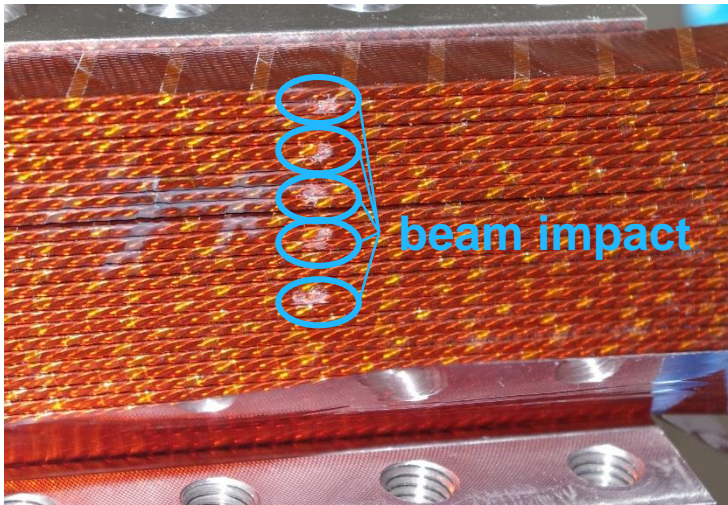
For details see:
D. Wollmann, Tue PM,
WP7/10/14

- Increased bunch intensities for HL-LHC beams increase criticality of ultra-fast failures (injection / dump) → Do we need to improve the efficiency of passive absorbers (TCDQ, TDIS, TCDD, ...) to protect sc. magnets from particle showers and beam?
- Experimental road-map:

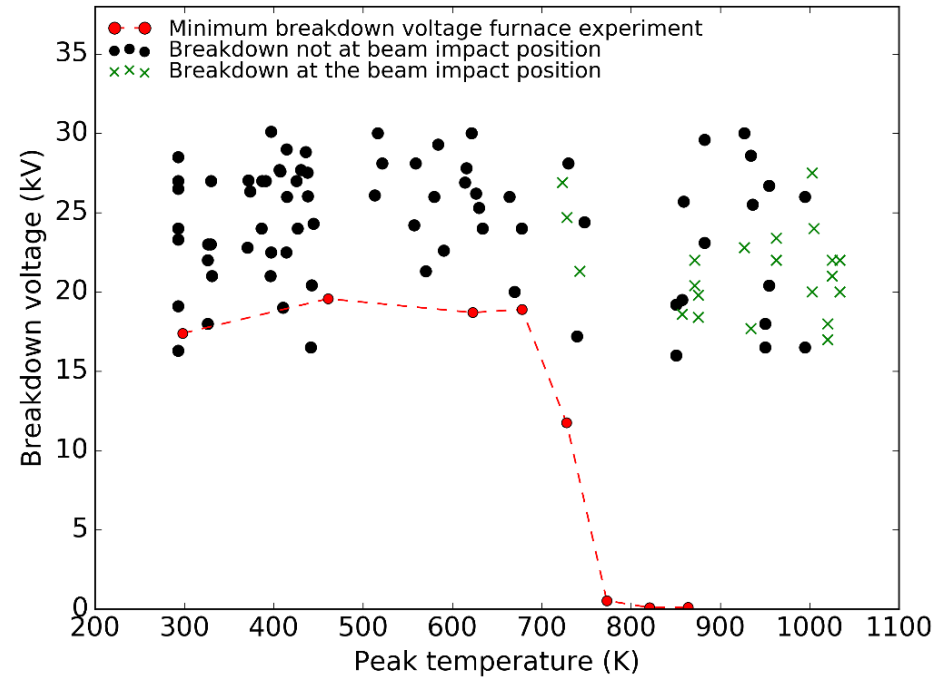
- 2015
 - Polyimide **insulation degradation** due to heating over **hours** (furnace) – peak temperatures ~460 K – ~860 K
- 2015/16
 - J_c **degradation** of Nb-Ti and Nb₃Sn due to heating over **seconds** (capacitive discharge) – peak temperatures ~640 K - ~1250 K
- 09.2016
 - Degradation of **polyimide insulation** and J_c of Nb-Ti and Nb₃Sn due to **direct impact of 440 GeV protons** → **see below**



Degradation of Polyimide Insulation

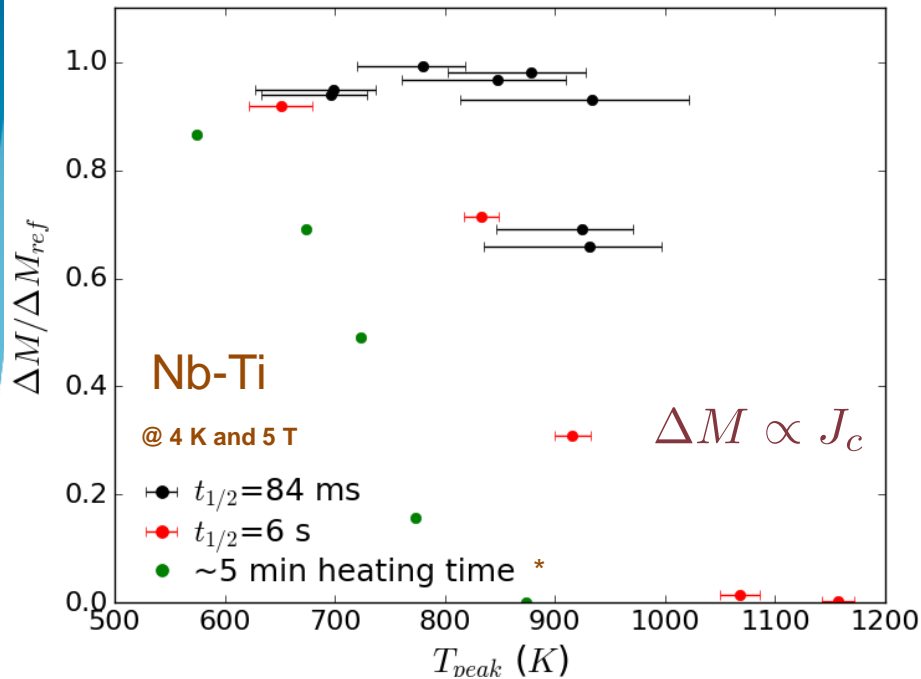


Side view of a Nb-Ti cable stack after beam impact



- Degradation due to **chemical decomposition** as function of temperature and exposure time.
- Degradation for **T > 700 K** due to heating over **hours**.
- **No degradation** measured after beam impact with peak temperatures **up to ~1050 K** for **few ms**
 - **Weakening** of the insulation at the **point of the beam impact** was observed for **T > 850 K**

Damage of superconducting strands



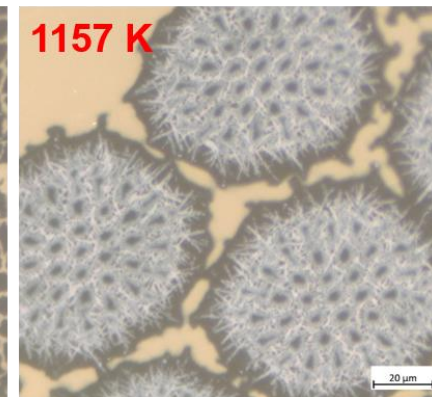
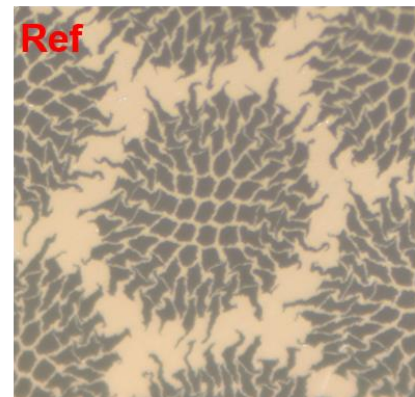
* C. Scheuerlein et al., Journal of Physics: Conference Series, vol. 234, no. 2. IOP Publishing, 2010

Nb-Ti strands:

- Degradation (J_c) starts at $T=924$ K
- J_c decreases with increasing exposure time
- Diffusion process + change of pinning behaviour
- Degradation of J_c caused by variations of α -Ti precipitates size and spacing
- If higher temperature or longer exposure time, **Ti diffuses outside filaments** to form Cu-Ti compound
=> $B_{c2}(T)$ reduction, filament merging

Nb₃Sn strands:

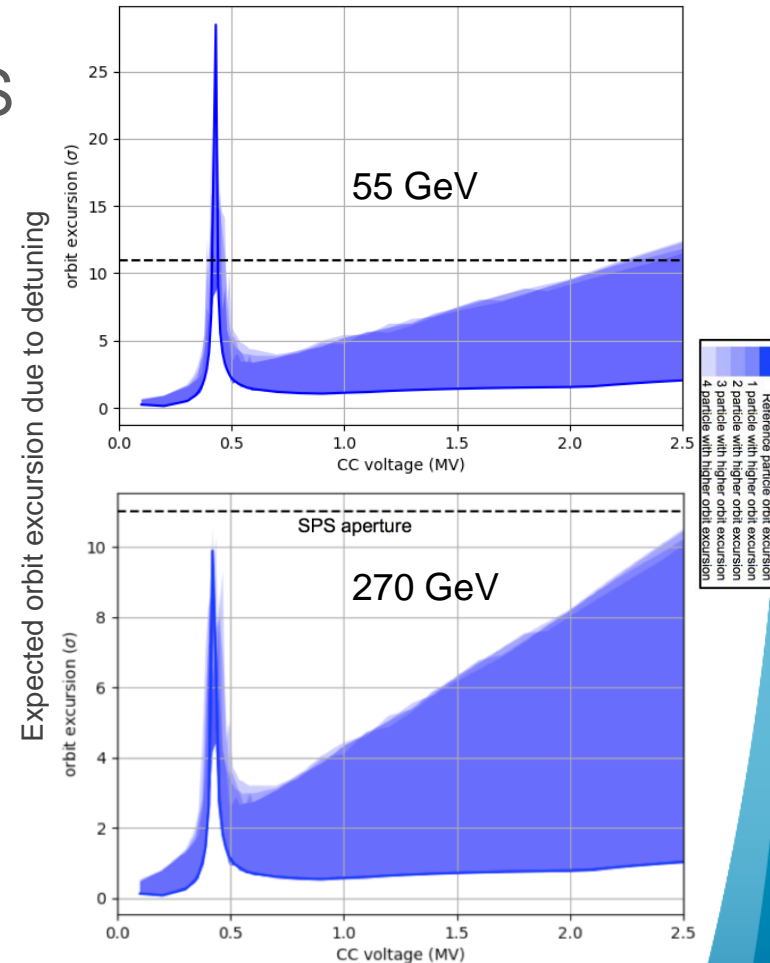
- Degradation (J_c) observed from 699 K (lowest peak temperature)
- J_c decreases with decreasing exposure time
- Degradation might be dominated by **stresses** and potentially **cracks** caused by fast heating and high **thermal gradients** → further studies on-going.



SPS crab cavity tests – MP considerations

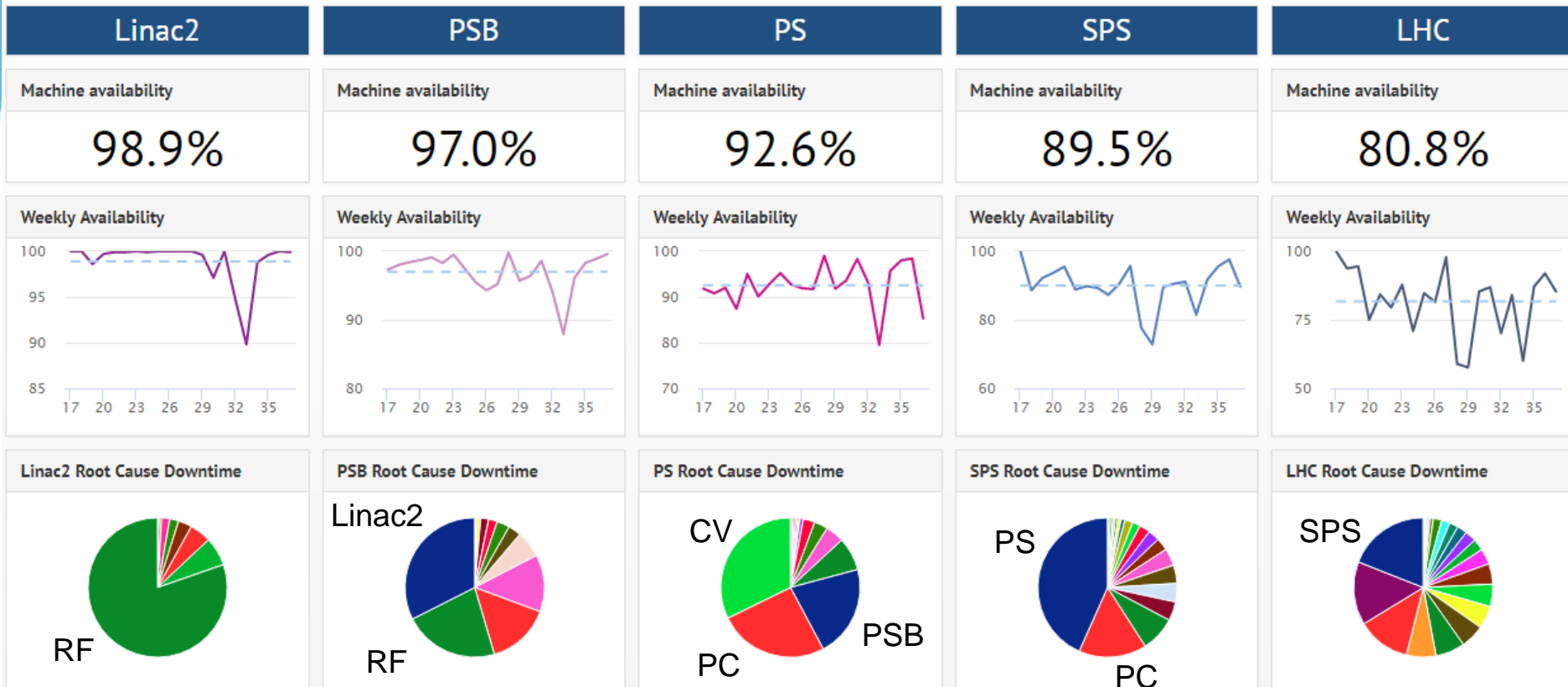
For details see:
M. Valette, Wed PM,
WP2/4/5/7

- Crab cavity faults can cause dangerous orbit excursion in the SPS
 - Voltage drop → not critical for SPS
 - Detuning → critical when driving resonant excitation
- Lower beam energies more critical (beam less stiff)
- Verification of failure cases and reliable protection with low intensity beams required
 - Before using high intensities in the SPS
 - Important** input for required **protection** measures in the **HL-LHC**



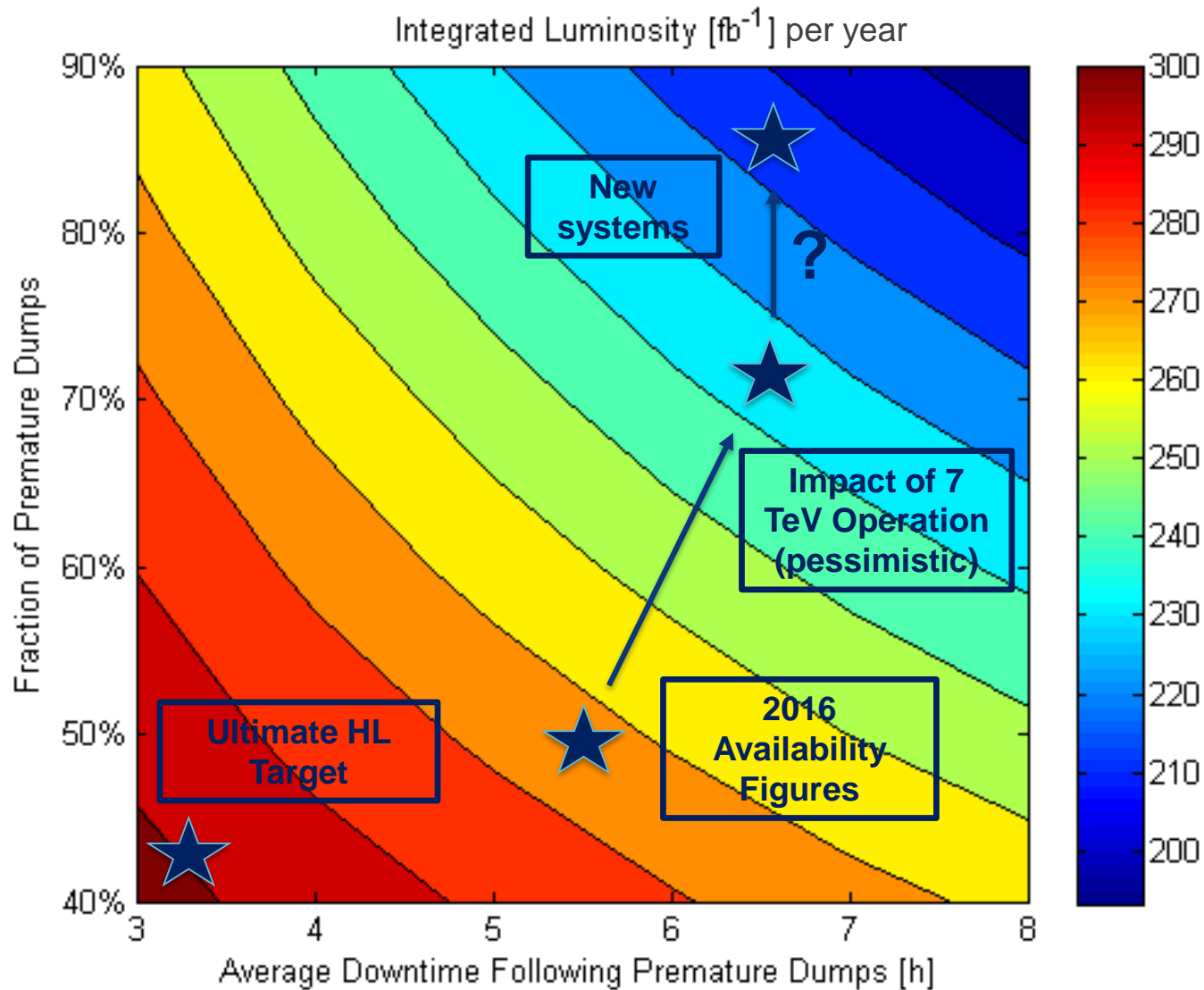
Accelerator Fault Tracker for the LHC Injectors

- In use from the beginning of 2017 in all injectors
- Important input for HL-LHC availability → Injector complex has biggest footprint on LHC availability → identification + consolidation of major sources of un-availability



Performance of Injector Complex May - Sep 2017

HL-LHC Sensitivity Analysis for Integrated Luminosity – updated numbers



Related talks during this workshop

- First results from superconducting magnet component damage experiments with beam. – **D.Wollmann, Tue PM, WP7/10/14**
- Crab Cavity failures: relevant parameters and combine failures – **M. Valette, Tue PM, WP8/12**
- Interlocking for HiLumi – what will be different? – **J. Uythoven, Tue PM, WP7/10/14**
- CLIQ and quench heater firing effects on the beam – **M. Valette, Wed AM, WP5/7/10/14**
- Updates on Availability – **J. Uythoven, Wed PM, WP7/10/13/15**
- Failure cases for the crab cavities in the SPS – **M. Valette, Wed PM, WP2/4/5/7**
- Status of HW development for EE, CLIQ and HDS – **B. Panev, Thu AM, WP3/6a/7**
- Status of HW for quench detection and circuit monitoring for HL-LHC – **J. Steckert, Thu AM, WP3/6a/7**
- Update on circuit protection simulations – **M. Mentink, Thu AM, WP3/6a/7**
- Detailed global view on protection and detection of the circuits – **R. Denz, Thu PM, WP3/6a/7**
- Need of energy extraction systems – **E. Todesco, Thu PM, WP3/6a/7**

Acknowledgments

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Conclusion

- Magnet and circuit protection:
 - Very **good progress** on hardware development
 - Ensure the initiation of the beam dump **BEFORE** firing of quench heaters / CLIQ
 - Optimize quench heater **connection scheme** to **reduce effect** on beam
- Magnet component damage studies with beam
 - Insulation & Nb-Ti damage limits well **within requirements** for HL-LHC fast failures → to be **verified with cryo-experiment** in 2018
 - Nb₃Sn further studies required
- SPS crab cavity test in 2018 requires checks on **failure modes** → important input for **HL-LHC protection**
- Tracking of faults in the LHC **injector complex** important for HL-LHC **availability optimization**

