Machine Protection Status and Plans

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13th HL-LHC Collaboration Meeting, Vancouver (Canada), 25.-28. September 2023

Outline

- Status and plans for the machine protection hardware for HL-LHC
  - Energy Extraction systems
  - Coupling Loss Induced Quench systems (CLIQ)
  - Quench Heater Power Supplies & DQLIMs
  - Powering Interlock Controller
  - Instrumentation Feedthrough Systems
  - Cold & Warm diode stacks
  - ElQA patch panel racks
  - Current Lead Heater Regulator Systems
  - Quench Detection System
  - Ethernet enabled Data Acquisition (EDAQ)
- Critical failure cases for HL-LHC & Damage studies
  - Spurious firing of CLIQ
  - Crab cavity failures
  - Damage studies with sc. sample coils
- Conclusions

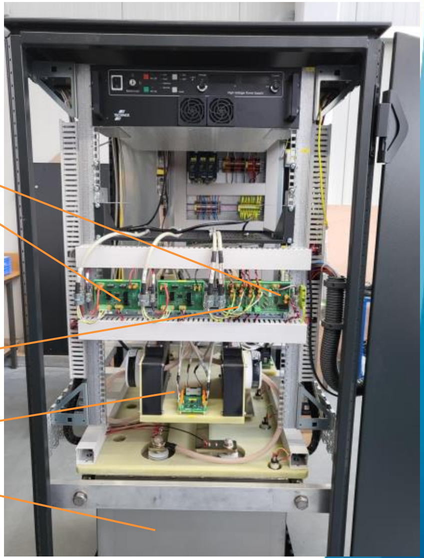
Energy Extraction Systems

- All Energy Extraction systems for the IT String (6+1 x 2 kA & 1+1 x 600 A) have been **installed in the IT String** following their delivery and successful testing.
- **Call for tender** for 24 x 2 kA and 20 x 600 A finished.
- **Approval** for contract negotiation requested to CERN's October 2023 Finance committee.
- Delivery of **series units** expected between end 2025 and mid 2026.

See also M. Pojer's talk in the joint session of WP3/WP6a/WP7/WP16 Tue PM

Coupling Loss Induced Quench (CLIQ)

- **Capacitors** for IT String units & tunnel series have been **produced** and **delivered** to CERN.
- The first of the series CLIQ unit has been delivered to CERN in March 2023 and **was successfully validated**.
- **Safety assessment, vibration and EMC studies** have been successfully performed (Safety report).
- The production of the 6 + 2 CLIQ units for the IT String is ongoing and they are expected to be ready for the **installation in the IT String in December 2023**.
- The production of the 24 units for the tunnel will start in 2024 and should be finished early 2025.



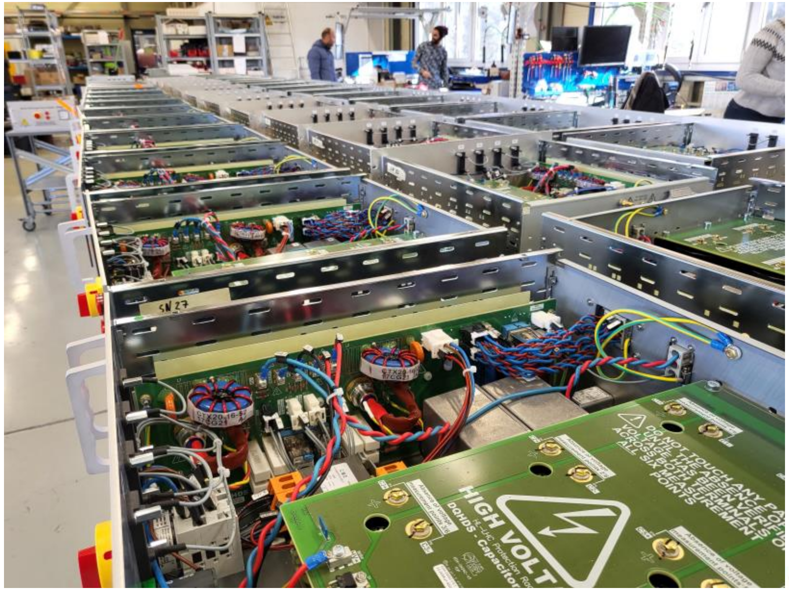
See also M. Pojer's talk in the joint session of WP3/WP6a/WP7/WP16 Tue PM

Quench Heater Power Supplies (DQHDS) for the IT String

- All 60 units (52 + 8) for the IT String have been **manufactured**.
- **Testing** of the units is ongoing.
- They will be delivered to the **IT String in October 2023**.
- Seven DQLIM units have been produced at CERN and will be installed into the IT String in October 2023

Series production:

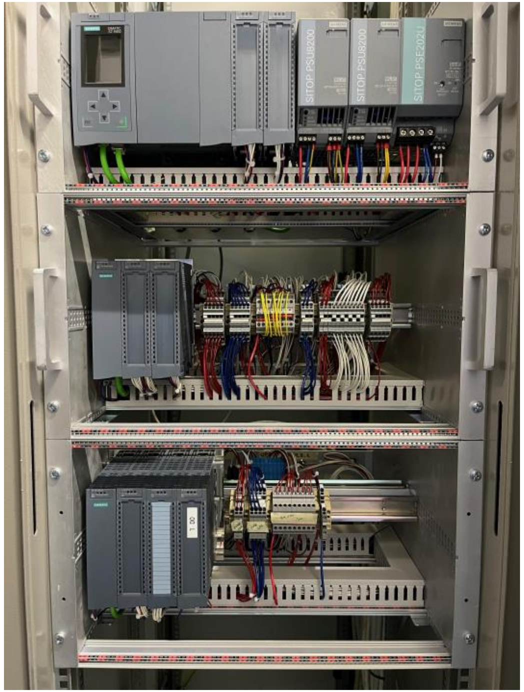
- The units for the tunnel will be provided as **in-kind contribution** from Japan under the lead of KEK.
- Nichicon has introduced (small) **modifications in the capacitor** model (new base-plate, reduced variation of capacitance [4.7 mF +20% -5 %])
- 20 prototype capacitors have been delivered to CERN from KEK and **have been successfully validated.**

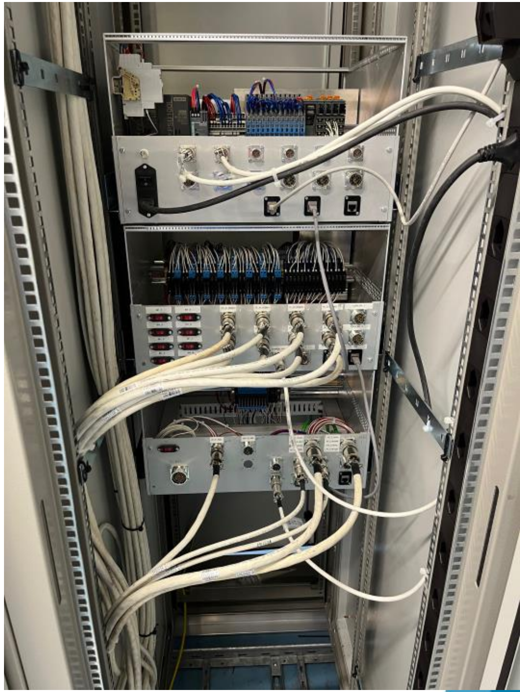


See also M. Pojer's talk in the joint session of WP3/WP6a/WP7/WP16 Tue PM

Powering Interlock Controller

- The **first prototype** of the new Powering Interlock Controller (PICv2) has been **installed in the IT String** following successful testing in the lab
- The final layout of the PICv2 for the LHC tunnel is currently still under study and should be available in December 2023.





Instrumentation Feedthrough System (IFS)

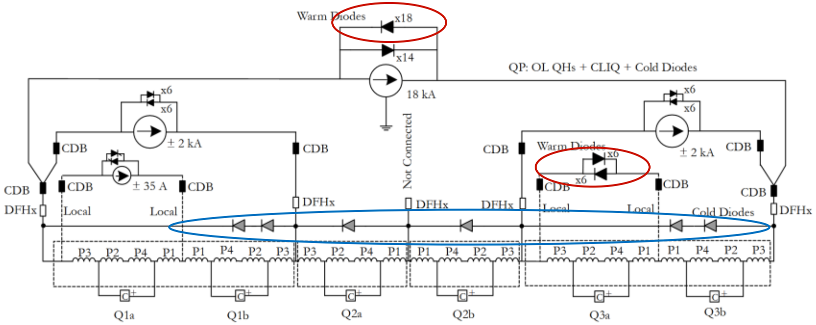
- **Three different types/sizes** of IFS boxes have been designed to cover the needs of the HL-LHC cryo-assemblies (L, M, S).
- **44** out of a total of a total of 144 have been **assembled and tested**.
- IFSs are provided to WP3 as needed for the equipment of the cryo-assemblies

IFS boxes after assembly and electrical tests

IFS boxes installed on first Q2A magnet being prepared in SM18 test bench (F1).

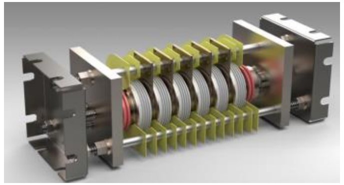
IFS boxes installed on first Corrector Package cryostat being prepared in SMI2

Diodes



Cold diode stack for DCM

- First prototype **assembled and fully qualified** (RT, 77 K and 4 K) → **ready for the installation** in the DCM.
- Endorsed for use in IT String by MCF #123
- Test report EDMS 2956417



Warm diode rack

- Warm diode stacks with six diodes **manufactured and validated in industry.**
- Diode rack with ten redundant diode stacks **assembled, tested and installed in the IT String**:
  - three redundant stacks for the main IT power converter
  - two antiparallel redundant stacks for the Q3a branch
- Test report EDMS 2895231

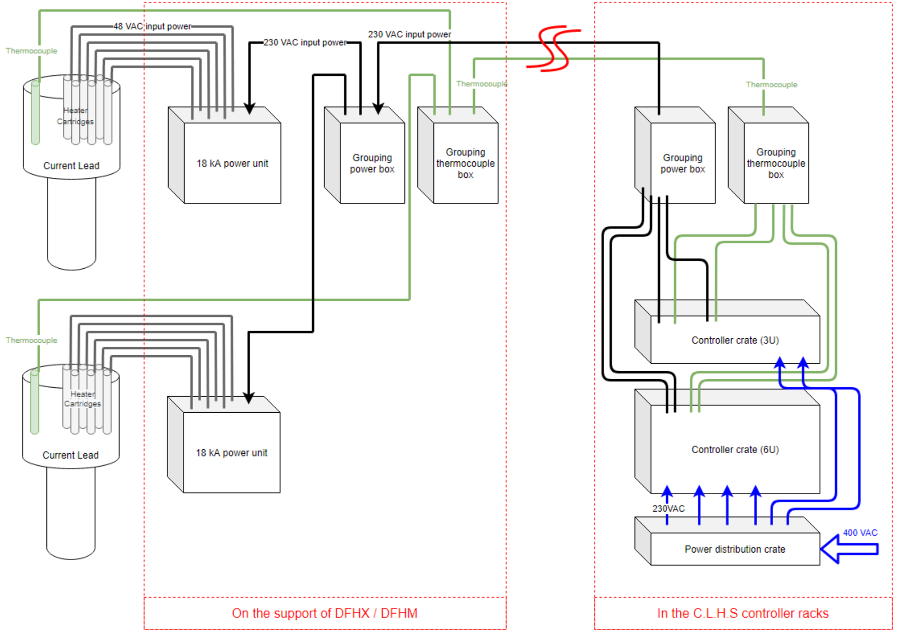
ElQA patch panel racks

- ElQA patch panel racks have been introduced for the 120 A and 200 A HL-LHC circuits to
  - Allow for **safe disconnection and reconnection** of the DC warm cables,
  - **Group the V-tap wires** of these circuits in a common place to dispatch only the V-taps needed for the protection of the 120A circuits to power converters,
  - Perform ElQA and diagnostics in **low radiation area**.
- The ElQA rack has been **installed in the IT String.**
- Specification in EDMS 2598227

ElQA patch panel rack in the IT String

Current Lead Heater Regulator System

- WP7 is providing the **powering and the regulation** of the **current lead heaters** for the DFHX and the DFHM:
  - Power units (AC transformers, breakers, cabling)
  - Power and Thermocouple grouping box on DFHX/M
  - Power and Thermocouple (JX) cables from DFHX/M to control rack
  - Dispatching box for Power and Thermocouple in the control rack
  - Control crates for DFHX/M
  - Power distribution crate
- The **assembly** of the equipment for the IT String has started.
- Specification in [EDMS 2786821]



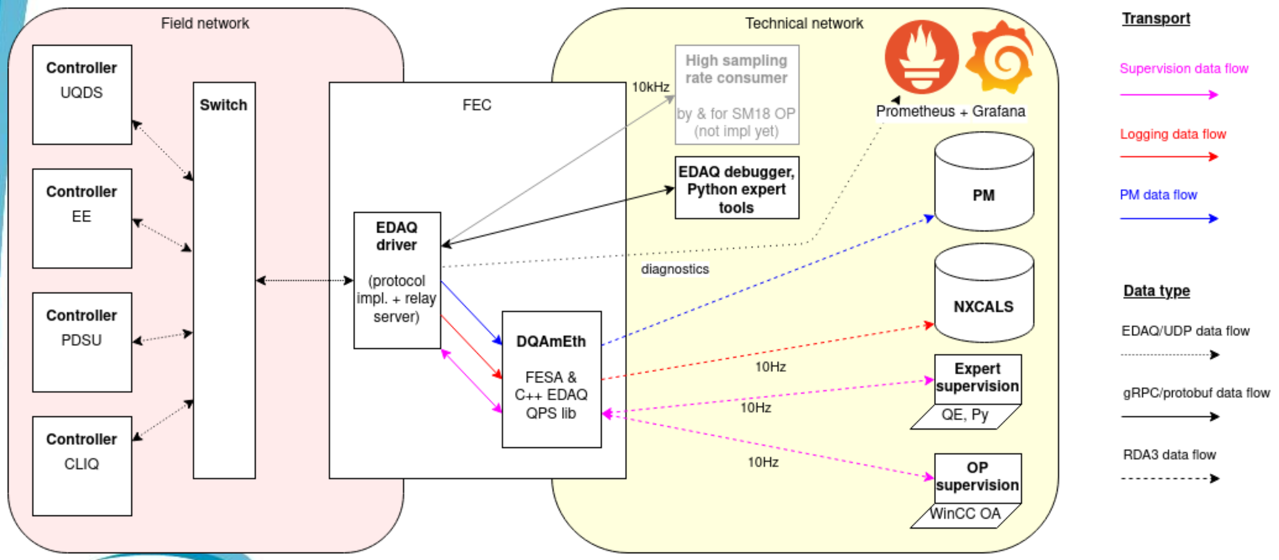
Quench Detection System

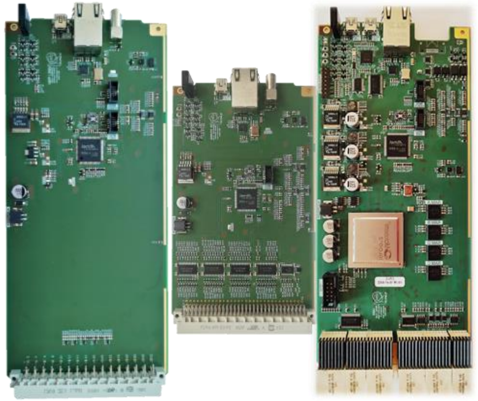
- The Quench Detection System with the new ethernet based data acquisition system (EDAQ) for the HL-LHC circuits has been successfully **deployed and commissioned** in the **SM18 test bench F1** @ CERN.
- **Assembly** of the Quench Detection System and the Protection device supervision units (PDSU) for quench heater power supplies & CLIQ for the IT String is **ongoing**.
- The IT String units will be supplied by June 2024.

See also J. Steckert's talk in the joint session of WP3/WP6a/WP7/WP16 Tue PM

Ethernet enabled data acquisition (EDAQ)

- The Quench protection systems (QDS, PDSU, CLIQ, EE) for the HL-LHC will use a novel **ethernet based data acquisition** system
- Deployed for the **first time** in the SM18 testbenches @ CERN
- EDAQ specifications in [EDMS 2616562]()

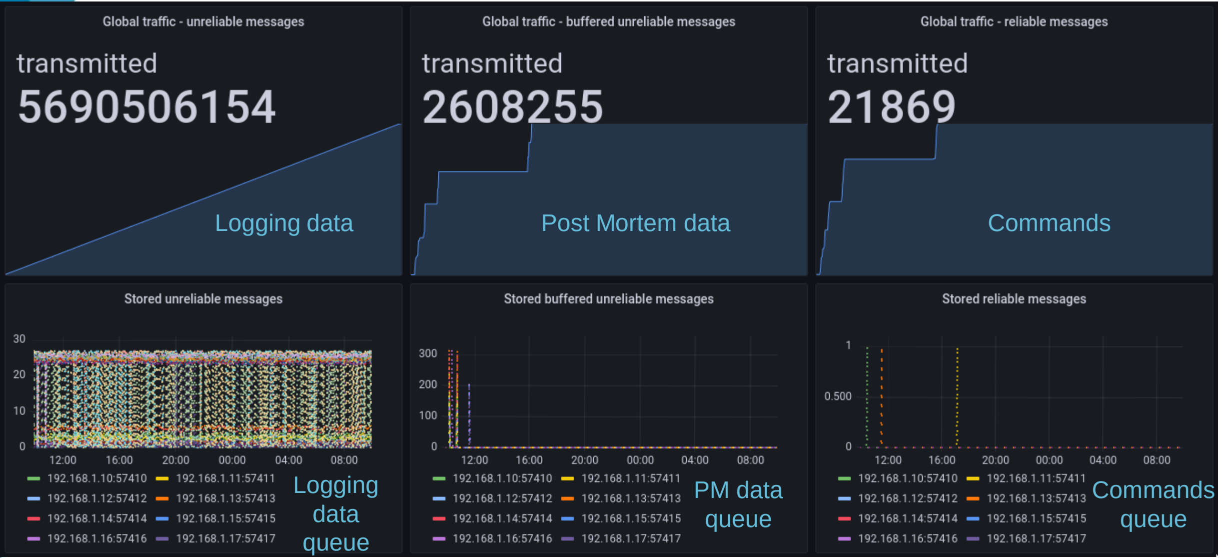




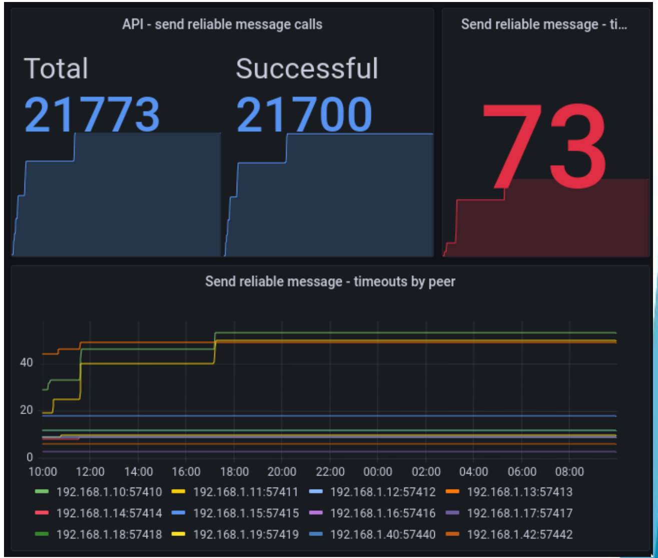
EDAQ controller

- Microcontroller based (Cortex M4F architecture & 100 Mbps Ethernet)
- Synchronization **accuracy < 1us**
- Data throughput **> 20 Mbps**
- Continuous logging rate **up to 10 kHz**

EDAQ monitoring



Overview of EDAQ traffic in the SM18 facility (24h)



Fine monitoring of commands: 73 packets lost of 21773 transmission attempts (< 0.5%)

- Extensive **monitoring of the EDAQ performance** has been implemented in **preparation** for the EDAQ deployment in the **IT String**.
- https://mpe-grafana.cern.ch/d/Skz58ImSk/edaq-sm18?orgId=1&refresh=5s

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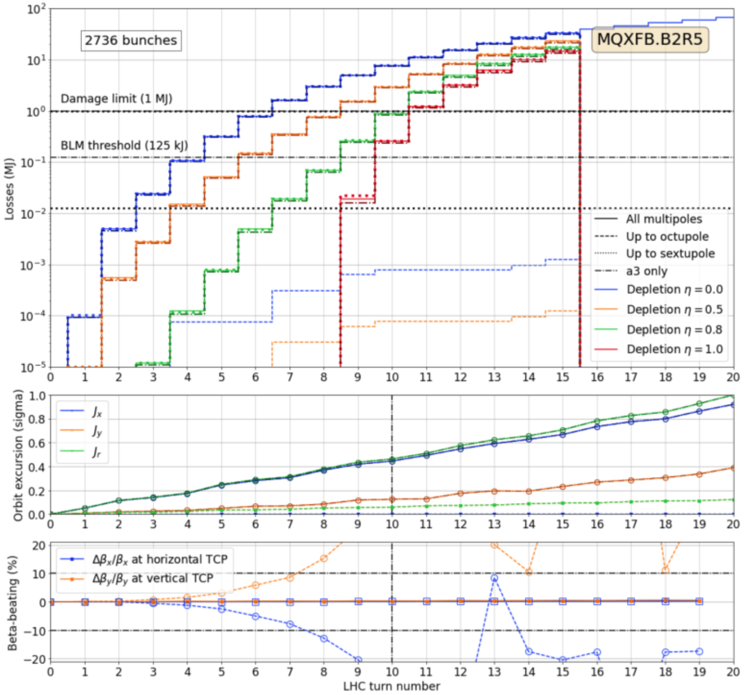
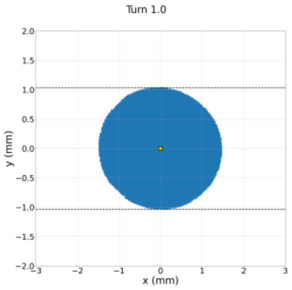
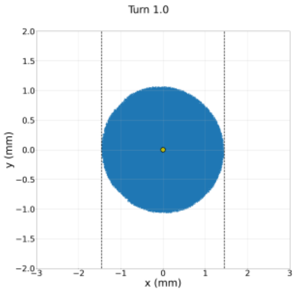
Impact of spurious CLIQ discharge on beam

- The use of Coupling Loss induced Quench systems (CLIQ) for the protection of the HL-LHC triplets will introduce a **new fast failure** for the **beam** in the LHC in case of a spurious discharge of one unit
- CLIQ discharge creates **strong skew octupole component** (same level as sum of lattice octupoles) causing a **distortion of the particle distribution** leading to fast losses in the collimation systems → **critical loss levels reached after 5 turns**.
- **Fast interlock** will be implemented via the protection device supervision units (PDSU) directly linking to the BIS.

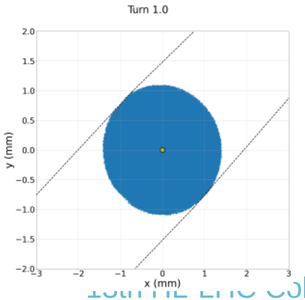




TCP.D6L7 (vertical)



TCP.C6L7 (horizontal)

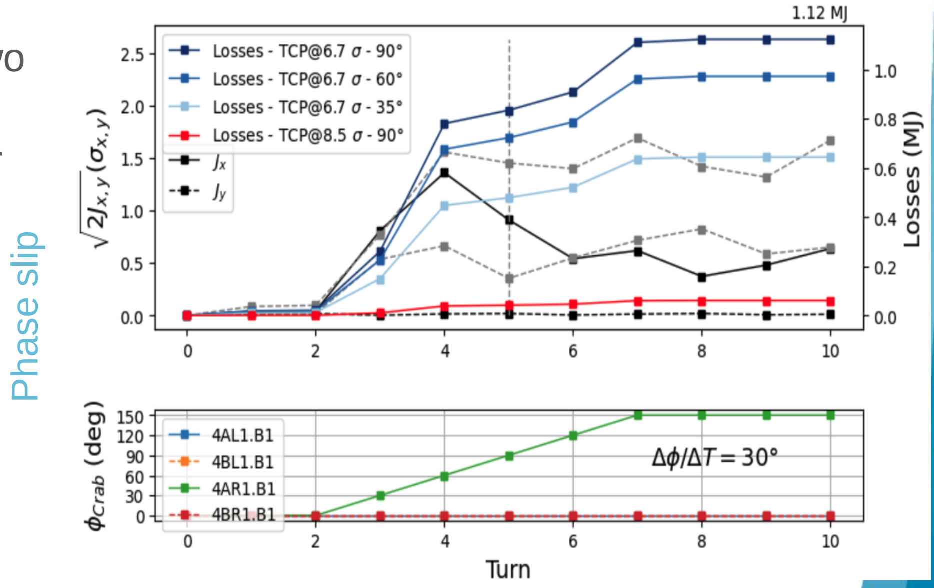


TCP.B6L7 (skew)

Onset to damage margin	**450 μs**
Propagation via BIS from P1 to P6	- 100 μs
LBDS synchro.	- 89 μs
Extraction	- 89 μs
Allowed interlock reaction time	**= 170 μs**

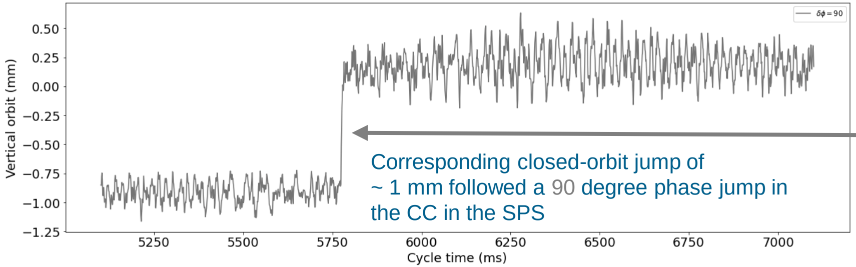
Crab Cavity failures - simulations

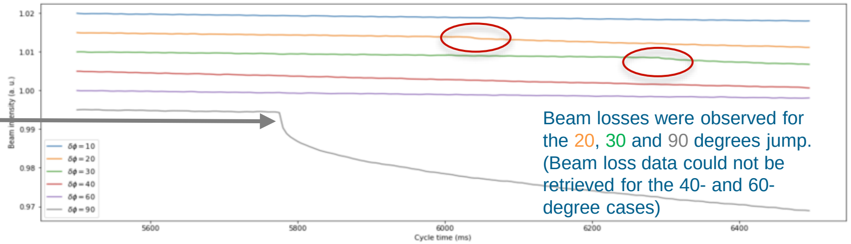
- **Phase slip**
  - Phase change in one crab cavity over 5 turns by **30 degree per** turn
  - Shift of centre of bunch by **1.4 sigma** within two turns after the start of the failure
  - **Up to 1.12 MJ lost** after 10 turns (0.8 MJ after 3 turns)
  - 60-degree phase advance between CC and TCP would limit losses below 1 MJ.
- **Fast interlocks for phase and voltage** are required for machine protection.
- **Phase advance** between crab cavities and primary collimators **smaller than 60 degree** will reduce their criticality.



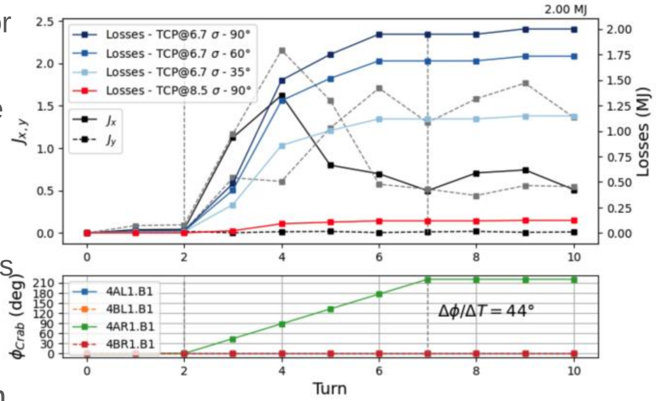
Worst case 4AR1.B1

Crab cavity failures – experiments

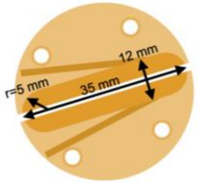




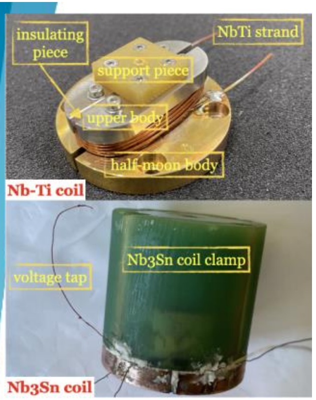
- Recently experiments to measure the impact of **CC phase jump** have been performed in the SPS (thanks to the RF team):
  - 10, 30, 40, 60, 90 degrees phase jump at constant CC voltage ➔ **orbit changes** have been observed for all cases and **beam losses** were observed (beam loss data missing for 40- and 60-degree cases).
  - Measurements **do not provide** additional input on the **dynamics of the failure case** due to the limited time resolution of the BPMs (1 ms) and BLMs (5 ms) in the SPS → **Simulations remain** the best way to **predict the criticality** of the failure cases.
  - The maximum **achievable phase change per turn must be reviewed**: theoretical limit 44-degree versus 30-degree limit observed experimentally in 2022. In case of 44 degrees the losses would increase to 2 MJ within 10 turns.
- Future experimental studies on crab cavity failure cases (phase slip, quench) in the SPS require **improved turn-by-turn diagnostics** of the orbit and beam losses.

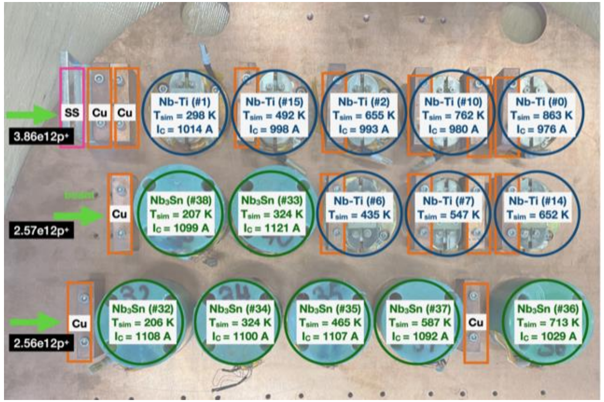


See also talk in the joint session of WP2/WP4/WP13 Thu AM

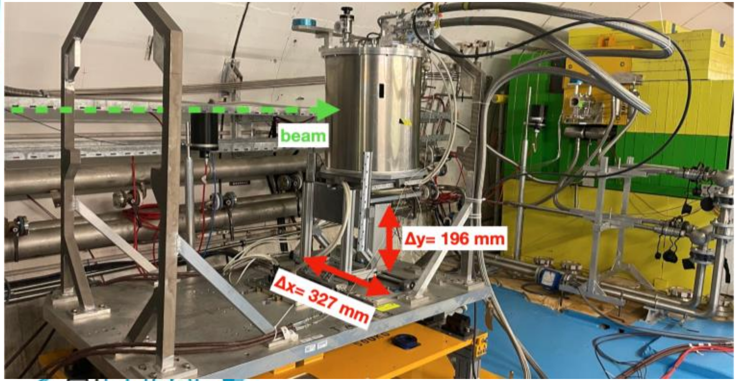


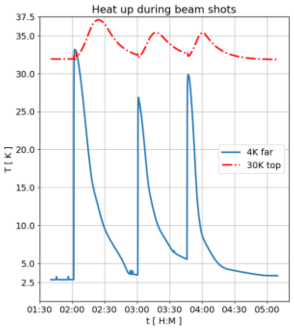
HiRadMat Damage experiment Oct 2022

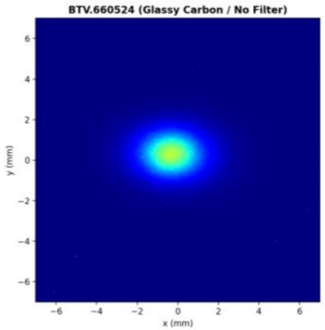


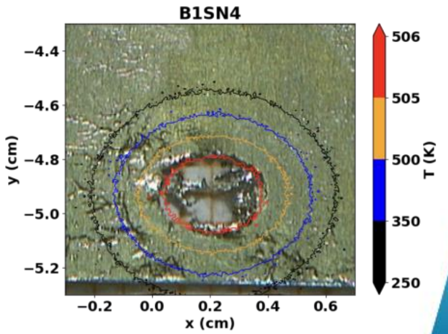


- Successful experiment performed in HiRadMat with **Nb-Ti and Nb_3Sn sample coils at 5 K**.
- Hotspots reached:
  - **Nb-Ti: 298 K – 863 K**
  - **Nb_3Sn: 206 K – 713 K**
- Coils will be qualified @ University of Geneva from October 2023









Conclusions

- WP7 has **delivered and installed** a significant part of its protection equipment for the **IT String** – the missing parts will be added in the coming months.
- The HL-LHC **quench detection** and new ethernet based **data acquisition** system have been **deployed and commissioned in the SM18 test benches** → important step before going into the IT String.
- **CLIQ and crab cavity failures** will be the most critical failure cases in HL-LHC.
- Future machine protection tests with crab cavities in the SPS require **turn-by-turn diagnostics**.
- WP7 has performed a damage experiment with beam **sc. sample coils at 5 K** in CERN's HiRadMat facility → impatiently waiting for the critical current measurements.

Thanks a lot for your attention!

Backup slides

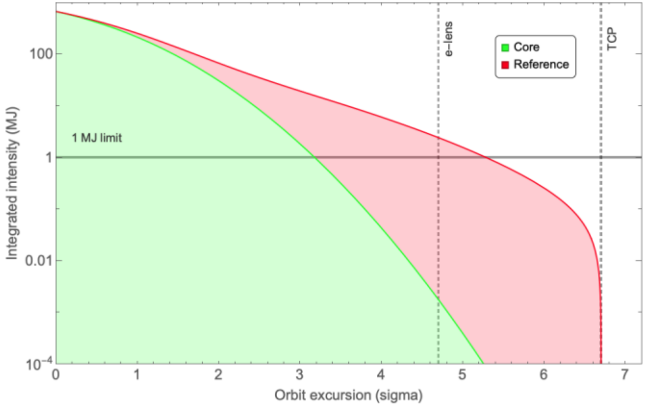
Machine conditions and parameters assumed in the following

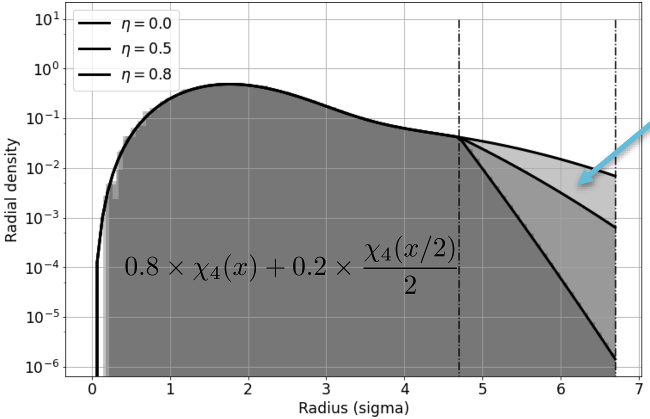
	Assumed parameters
Beam energy	7 TeV
Beam stored energy	674 MJ
Bunch intensity	2.2 x 10^{11} p^+/bunch (2736 bunches)
Beam emittance	2.5 μm
Primary cut (TCP) tight / relaxed	6.7 sigma / 8.5 sigma
Crossing angle at IP1-5	500 μrad
BLM threshold	125 kJ
BCCM threshold	340 kJ
Critical loss level (IP7)	1 MJ
Time required to safely extract beams after detection of a failure	270 μs (3 turns)

- HL-LHC layout v1.4/v1.5 with round optics (β* 15 cm)
- Collimator settings:
  - Preference from machine protection and collimation to use **tight collimator settings** for the restart after LS3: Primary cut (TCP) @ 6.7 sigma;
  - Settings of TCPs in **mm similar** to current Run3 settings & similar bunch intensities at the start of Run4;
  - Provide **maximum protection** of LHC aperture and margin in the collimation hierarchy for the **re-start after a long shutdown**;
  - Based on available aperture and **operational experience** (reproducibility, unexpected failure cases etc.) go to **relaxed collimator settings** (primary cut @ 8.5 sigma);
  - Hollow e-lens (not anymore baseline), target for studied failures:
    4.7 sigma – 6.7 sigma / 6.5 sigma – 8.5 sigma

Assumed beam distribution

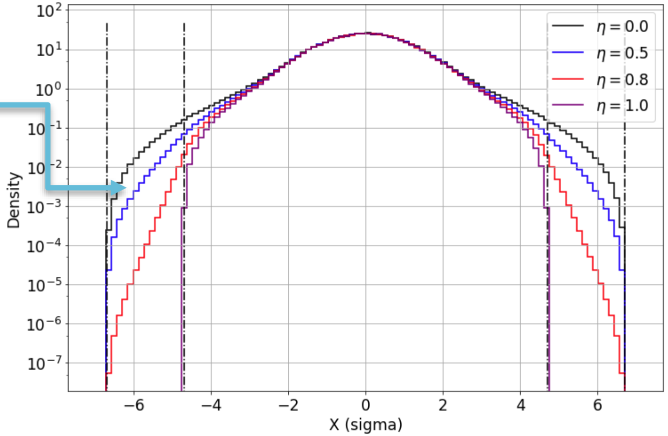
- **Double gaussian distribution** derived from **halo scrapings** with the collimators (2.4 MJ above 4.7 sigma).
- Translated into a 4 D beam distribution (sum of two modified radial χ - distributions).
- For relaxed settings, halo model is extrapolated to 8.5 sigma. **No re-population** of halo is taken into account.
- Halo depletion (e.g. by hollow e-lens) is modelled by multiplying the distribution with a modified probability density function deriving an **exponential decrease in the halo** between 4.7 sigma and the primary collimator cut → η := depletion factor (η= 1 for fully depleted halo).





Depleted halo

Projection



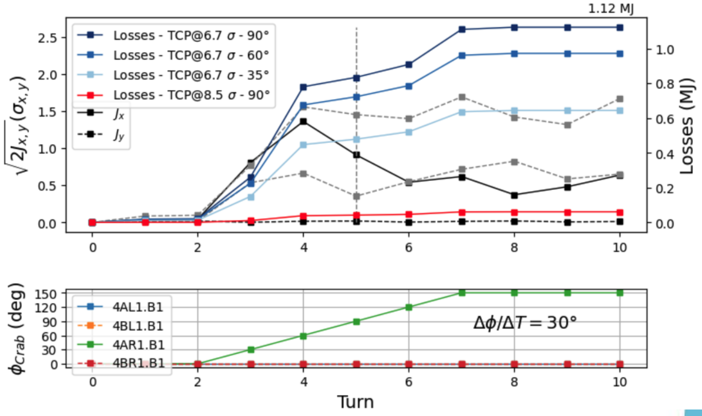
Crab cavity failures - Introduction

- Crab cavity failures have been studied for more than 10 years:
  - T. Baer, *Very Fast Losses of the Circulating LHC Beam, their Mitigation and Machine Protection*, CERN-THESIS-2013-233
  - B. Yee-Rendon et al., *Fast crab cavity failures in HL-LHC*, CERN-ACC-2014-0107
  - A. Santamaria Garcia, *Experiment and Machine Protection from Fast Losses caused by Crab Cavities in the High Luminosity LHC*, CERN-THESIS-2018-142
  - B. Lindstrom, Criticality of fast failures in the High Luminosity Large Hadron Collider, CERN-THESIS-2020-318
- **Failure cases:**
  - **Voltage drop**: Change of voltage in one crab cavity causing unclosed crabbing
  - **Phase jump**: Change of phase in one crab cavity within one turn
  - **Phase slip**: Change of phase in one crab cavity over multiple turns → **most critical case**
- As the crab cavity configuration and optics etc. have changed since the very detailed study by A. Santamaria Garcia, we have recently revisited the cases with the following **assumptions:**
  - Crab cavity voltage: 3.4 MV
  - Bunch length (4 sigma): 1 ns
  - Phase advance (90 degrees) between CC and TCP - results rescaled to other phase advances in post-processing
  - Complete collimation phase space coverage

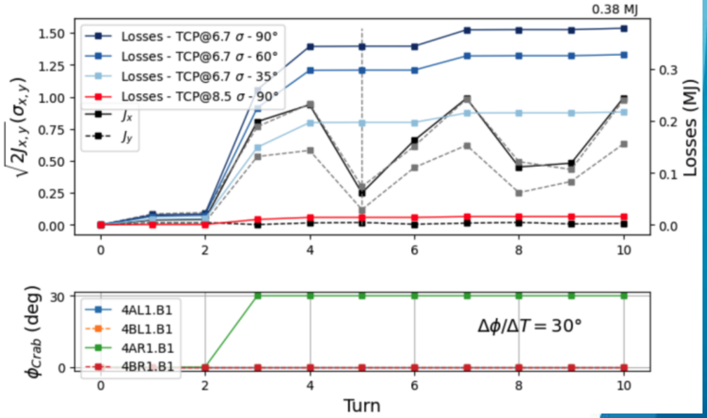
Crab Cavity failure: worst cases 4AR1.B1

- **Phase slip**
  - Phase change in one crab cavity over 5 turns by **30 degree per** turn
  - Shift of centre of bunch by **1.4 sigma** within two turns after the start of the failure
  - **Up to 1.12 MJ lost** after 10 turns (0.8 MJ after 3 turns)
- **Phase jump**
  - Phase change of **30 degree in one turn**
  - Shift of centre of bunch by **1.0 sigma** within two turns after the start of the failure
  - Up to 0.38 MJ lost within 10 turns (0.35 MJ after 3 turns)
- **Voltage drop**
  - Drop of voltage to **zero within one turn**
  - Up to 0.59 MJ lost within 10 turns (0.5 MJ after 3 turns)

Phase slip



Phase jump



Voltage drop