Machine Protection Systems

- Run 2 re-cap & Observed failure cases
- Machine protection key events
- MPP & rMPP
- Intensity ramp-ups
- Have we been running safely?

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Re-cap Run 2

No damage to machine equipment or experiments due to beam
No damage to circuits due to powering failures or quenches

- 2015 commissioning year, 6.5 TeV, conservative beta* (80 cm) and slow ramp-up of stored energy → iron out LS1 left overs, re-discover LHC after LS1, condition machine
- 2016 – 2018: reducing beta* (and with it safety margins) from 40 cm to finally 25 cm
- 2017 – 2018: increasing use of high level tools to reduce crossing angle and beta* during the fill → dynamic change of parameters within quasi static critical hardware limits
- 2017/2018: implementation of new (software) interlocks (DOROS BPM & Phase advance) to guard the reduced aperture margins

Observed failure cases / events (non-exhaustive)

Known/expected

- UFOs
- Beam induced quenches
- Shorts in circuits
- MKI erratics
- MKD and MKB erratics
- Injection of high intensity beam in empty machine
- Injection in wrong beam
- ….

New

- 16L2 UFOs with fast instability
- Spurious firing of multiple quench heaters (following inj. losses)
- Symmetric triplet quench with orbit offset
- Beam dump N_2 leaks
- Ultra fast kicks in beam due to quench heater firing in main dipoles
- …

Requires reliable machine protection systems, diverse redundancy and vigilant hardware experts, MP experts & OP teams!

Machine Protection – in key events
2015

- 1st asynchronous beam dump with circulating beam:
  - MKD erratic B2, generator C
  - low intensity, no beam kicked onto TCDQ
  - Generator replaced & improved generator cleaning procedure
- TDI jaw material issues:
  - hBN, heating, outgassing
  - Limited batch length to 144b (25 ns)
  - Replaced in YETS 2015/16
- ULO & UFOs causing dumps and quenches
  - ULO bump
  - Adjusting BLM thresholds to allowing quenches
  - Adjusting QPS thresholds (IPQs)

Machine Protection – in key events

2016

- Intermittent inter-turn short in MB.A31L2
  - Paused machine operation for powering tests on RB circuit in sector 12
  - Reduce risk of quenches and fast power aborts in sector 12
    - Deactivation of Global Protection Mechanism
    - Reduction of BLM thresholds
    - Increase QPS threshold on MB.A31L2
  - Magnet replaced EYETS 2016/17
- Beam dump block N_2 leak
  - Implementation of additional SIS interlock + BigSister warning and iterative adaptation of operational pressure
  - Defined allowed intensities in case of severe N_2 pressure drop
- MKI erratic with quench of triplet in IP2
  - 4 batches on TDI
  - Onset of quench in Q2

Machine Protection – in key events

2017

- Beam dump block (UD62) at ambient pressure
  - Paused high intensity operation
  - Ensuring continuous flow of N_2 (stack of N_2 bottles/ nitrogen line)
  - Study behaviour of core material at high temperatures in air
- 16L2 UFOs
  - Fastest beam instability (< 10ms) observed so far in the LHC
  - Installation of additional diagnostics & solenoid
  - Lowering of BLM thresholds around 16L2
  - Use of 8b4e beams
- Injections into abort gap (Abort Gap Keeper parameters)
  - Improvement of procedure for change of abort gap keeper length
  - Flat top of MKI adjusted
  - Injection inhibited, if train too long (SIS)
- Implementation of phase advance interlocking (TCDQ – TCT)

Machine Protection – in key events 2018

- MKBV flash-over
  - Lowered voltage in MKBV.C/D.B2 (20%)
  - Study of new worst case failure scenarios also for H-plane
  - Investigations to improve insulation of magnet HV busbars and adding two MKBH
- Symmetric triplet quench with orbit drift
  - Fast developing orbit offset in B1 (no change in B2), beams dumped BLMs
  - Quench detected only 40 ms after event start
  - Correct behaviour of circuit protection verified
  - Non-symmetric behaviour of B1/B2 most likely due to current re-distribution
- Multiple injections of high intensity beam on crystal collimators
  - Verification that no damage has occurred
  - Strengthening of operational procedure (use in MDs and EoF only)

(r)MPP

SPS & LHC Machine Protection Panel (MPP)

- 73 MPP meetings since 2015
- Machine protection topics for the LHC and the injectors (SPS, Linac4)
- Changes to MP systems, commissioning of MP systems
- Validation of new system designs relevant for machine protection
- Studying (new) failure cases in LHC and HL-LHC

restricted MPP (rMPP)

- 33 rMPP meetings since 2015
- Ad hoc issues concerning machine protection during LHC operation
- Follow-up of check lists (intensity ramp-up & periodic)
- Review of machine protection critical MDs

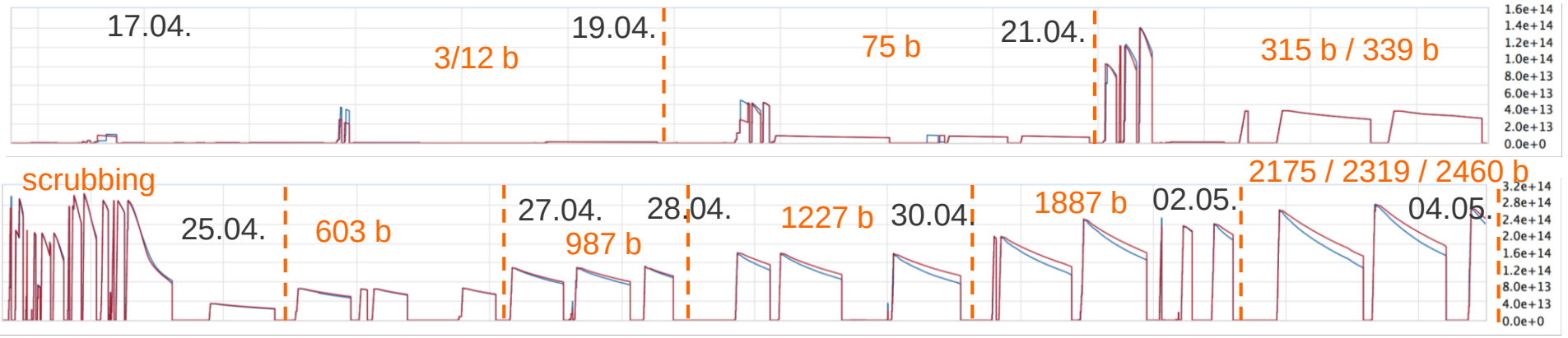
Machine protection system experts & OP experts

Intensity Ramp-up - Motivation

- **Step-wise** increase of **injected and stored beam energy** after YETS and long shutdowns to
  - **Identify and mitigate issues** in machine protection relevant **systems** remaining after individual system tests and hardware commissioning
  - Identify issues related to **stored beam intensity** and other beam related parameters and establish mitigation measures
  - **Establish** operational **cycle** and train OP teams
- Per step: **3 fills, 20h stable beams**, checklist
- **Ions** (stored beam energy < 14 MJ): 2 fills, 6h stable beams

- Other stops: three standard ramp-up scenarios established in 2017 and successfully used

Re-cap Intensity ramp-up 2018 & checklists



- 3 - 12 - 72 - 300 - 600 - 900 - 1200 - 1800 - 2400 – 2550

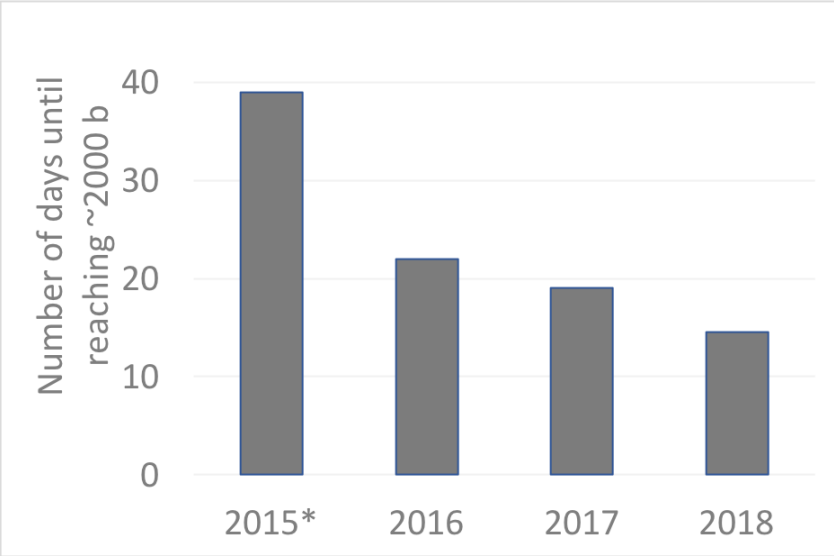
Establish cycle
MP dominated
Intensity dominated

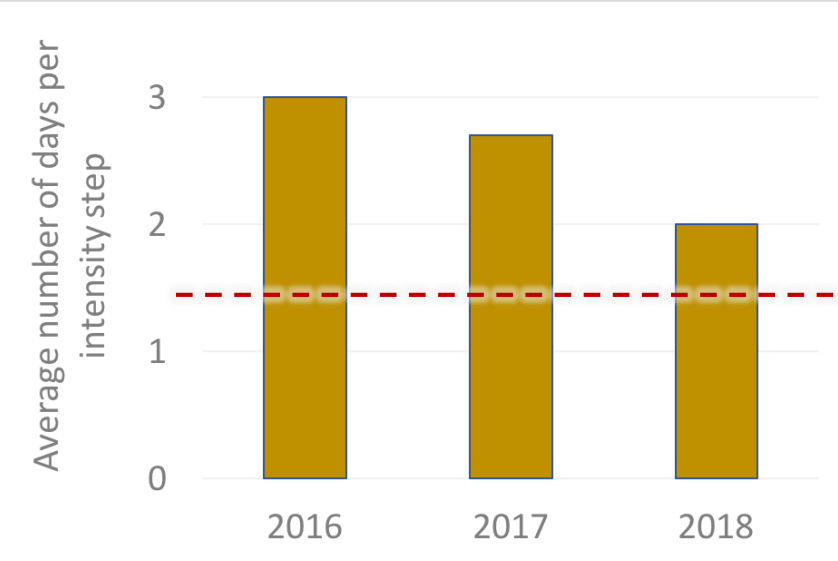
- Careful check of **high energy beam dumps** and documentation in 8 check lists covering (EDMS):
  - magnet powering, interlocks, RF,
  - beam instrumentation, operation, orbit, feedbacks,
  - injection, beam dumping system, heating of equipment, vacuum

Intensity ramp-ups Run 2

- 2015: commissioning year
  - 50 ns & 25 ns ramp-up
  - Increase of intensity until end of proton run
- 2016/17/18: 7 steps to reach 2000+ bunches
  - 3/12 - 75 - 300 - 600 - 900 - 1200 – 1800
  - 2016 → 2018: reduction ramp-up length by 35 %

Establish cycle
MP dominated
Intensity dominated





* 2015: 25 ns up to 1825 b

Issues discovered during intensity ramp-ups (1/2)

- Post Mortem / XPOC - missing data, data mis-aligned, missing files & synchronization, issues PM event builder stuck
- BIS timing mis-alignment
- Unbalanced rupture of the QPS internal quench loop
- Setup Beam Flag – glitches
- Beam Loss Monitors – communication issues BLM-SIS, un-physical readings in post mortem data
- Direct BLMs (IP6) – connected to LBDS of wrong beam
- Collimators & Roman Pots – LVDT position drifts, LVDT/resolver faults
- Orbit Feedback – orbit jumps at optics changes, zeroing of reference, offsets due to BPM calibrations

Establish cycle/beam commissioning
MP dominated
Intensity dominated
Random

Issues discovered during intensity ramp-ups (2/2)

- Dump Line – screen remaining in dump line, BTVDD images missing
- MKD and MKB erratics
- MKI – flashovers, MKI kicking last bunch of circulating beam
- Abort Gap Cleaning – in-sufficient cleaning, not functioning due to software issues / wrong parameters
- Radio Frequency – wrong low level settings
- QPS_OK flickering
- Beam current change monitor – false dumps
- BIS – too much attenuation of signal in fibre (3 dumps)
- Earth fault in circuits (RB, RCS)
- Training quenches

- QPS – single event upsets → dumps & communication issues
- UFO – 16L2 events causing beam dumps & quenches
- Collimators – un-physical temperature readings
- TDI – vacuum issues and heating (2016)
- Insufficient cooling of a collimator
- Decrease of bunch length < 1ns in cycle
- Instabilities
- Injection – high losses and satellites leading to beam dumps

Establish cycle /beam commissioning
MP dominated
Intensity dominated
Random

Have we been running safely?

LHC machine **protection systems worked well** avoiding damage in accelerator equipment and circuits, **but** we have experienced:

- Wrong parameters in protection systems
- Interlocks not acting as expected
- Operational mistakes
- Running with unvalidated machine configurations
- Software commissioning with hundreds of circulating bunches
- Unvalidated coupling knobs with strong impact in beta*
- Undetected quench heater firing
- Masking of critical interlocks during hardware commissioning
- Procedures not followed

Due to the **diverse redundancy** in the machine protection systems and **vigilant** hardware experts, MP experts & OP teams **no damage happened** in Run 2!

Fortune favours the brave?!

Conclusion continued …

- Intensity ramp-ups have been **essential to identify** and mitigate issues before physics production with stored energies of ~300 MJ
  - Length reduced from 2016 to 2018 by 35% indicating reduced number of issues
- **New failures** leading to very fast beam losses were experienced in Run 2 → **BLMs are last safety net** and should be **complemented** with a second system → beam current change monitor?!
- Successfully used luminosity server to **dynamically change** crossing angle and beta* → to be studied how this approach can be further developed/improved for Run 3 in a **safe context**

Outlook

Machine Protection workshop foreseen for May 2019

- Lessons learnt from Run 2
- Required changes in MP systems for LIU beams and other new operational parameters in Run 3
- Outlook to HL-LHC and presumable preparatory tests and studies required during Run 3 to prepare Run 4

MP3 workshop foreseen for first part of 2019

- Learning from circuit powering and operation in Run 2
- Outlook to HWC after LS2, mainly in view of possible dipole training to 7 TeV, and improved automatic analysis of tests

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