A Machine Protection Systems perspective on the commissioning

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Acknowledgement: MPP members

November 25th, 2021, 10th LHC Operations "Evian" Workshop

Outline

- **Commissioning 2022**
  - Commissioning procedures, checklist tool and experience from 2021 beam test
- **Intensity ramp-up**
  - Strategy and proposal for 2022
  - Ramp-up scenarios after stops of nominal operation
- **Intensity limitations**
- **Major Event Reports**
- **Machine-protection view on Run 3**
- **Conclusions and outlook**

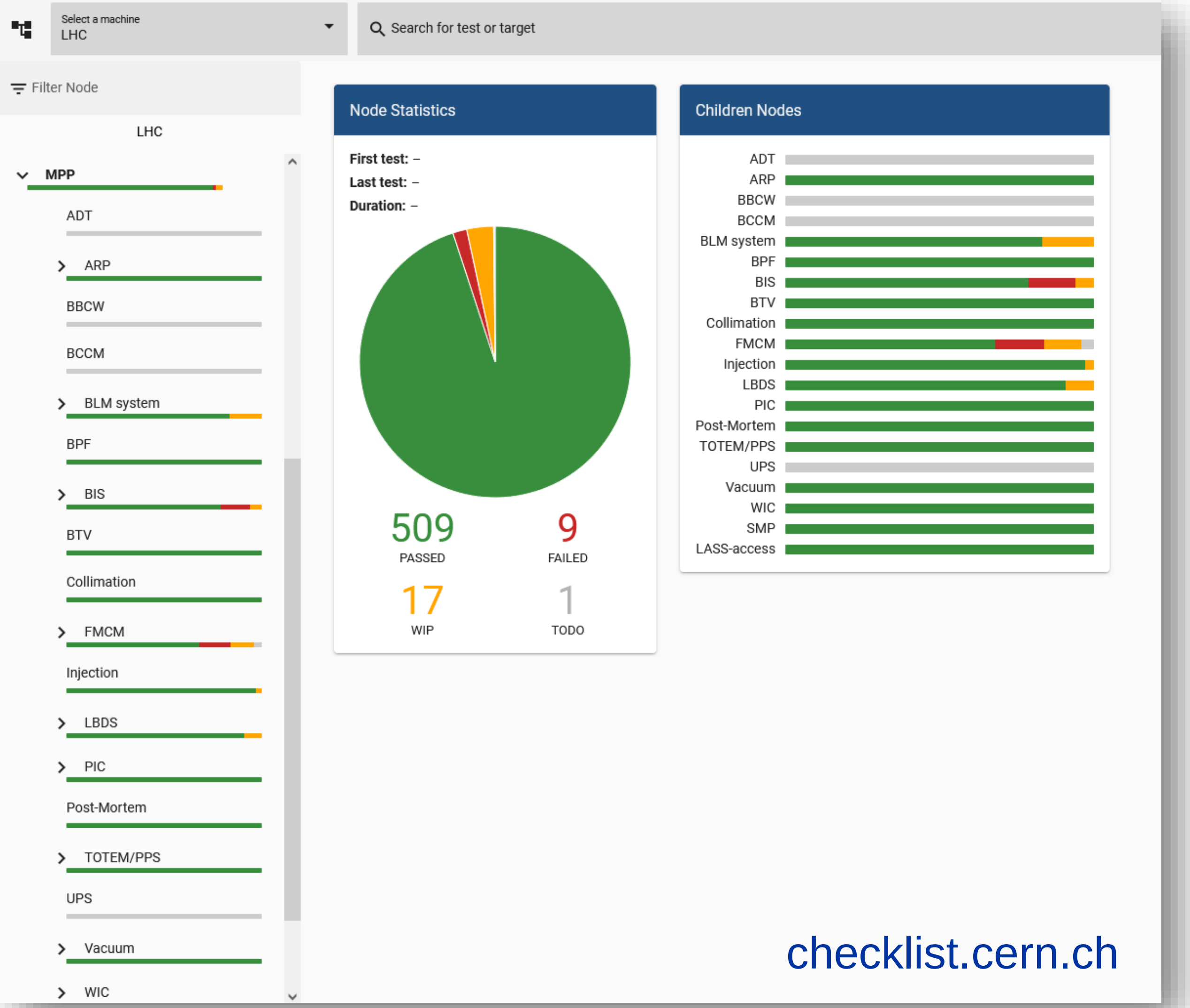
Commissioning procedures

- As preparation for the beam test in 2021 and the commissioning in 2022 → commissioning procedures for the machine-protection systems reviewed in the MPP and necessary updates identified
- Note that beam test required reduced commissioning, while full commissioning and validation is needed for 2022

MPS System	MPP presentation	Procedure	Release date / Comments
Collimation System	21.05. ✓	889345 v.2.3	V2.3 under approval
Injection Protection System	23.04. ✓	889343 v.4.0	08.06.2016
Beam Interlock System	19.02. ✓	889281 v.3.0	21.04.2016
Powering Interlock System	19.02. ✓	896390 v.4.0	12.02.2016
Vacuum System	26.03. ✓	896391 v.1.0	03.06.2016
Beam Dump System	23.04. ✓	896392 v.3.0	02.06.2016
FMCM	19.02. ✓	896393 v.3.2	02.03.2018
BLM System	30.04. ✓	896394 v.3.4	Approval closed 13.03.2018
Warm Magnet Interlock System	19.02. ✓	896395 v.3.0	24.02.2016
Safe Machine Parameter System	19.02. ✓	1112187 v.1.0	01.08.2016
Software Interlock System	30.04. ✓	1062498 v.1.3	15.01.2020
TOTEM / CTPPS	21.05. ✓	No procedure	-
ARP	21.05. ✓	No procedure	-
UPS test	-	1773693 v.0.1	Version 31.03.2017, Approval closed 07.2019
Transvers damper (ADT)	Tbd	In work	Commissioning needs to be defined
Beam-Beam Compensator Wire	Tbd	2384198 v.0.1	Under approval 11.06.2020. To be finalized.
Beam Charge Change Monitor	19.11. ✓	Draft	(Note: not part of 2022 commissioning)

Checklist tool and beam test

- Commissioning tasks were implemented in the new LHC-MPP tree inside the OP checklist tool* before the beam test
- The progress of tests was tracked by the operation and equipment teams
- Checklist tool will be used to follow the commissioning of the machine-protection systems in 2022
- Beam test allowed to apply the defined commissioning tasks in practice:
  → Obsolete and missing tests (e.g., INJ BIS) identified
- Commissioning procedures to be updated for 2022 based on the discussion in the MPP and the experience gained from the beam test → **To be circulated for approval before end of January 2022**



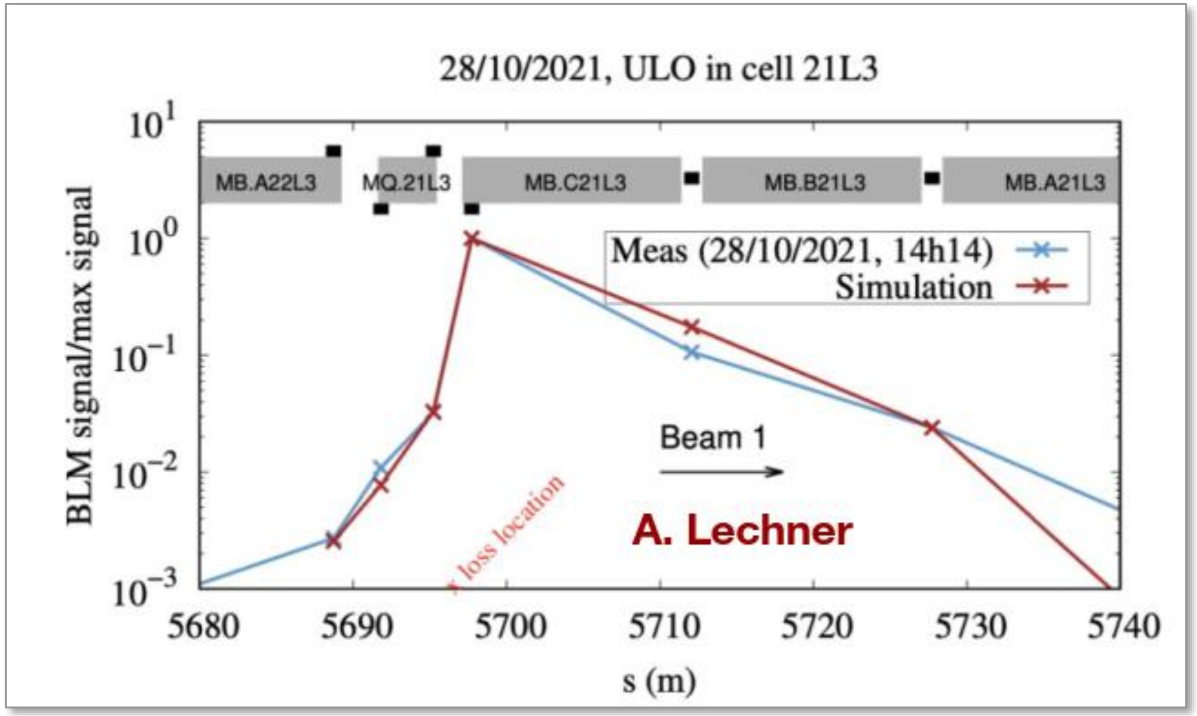
checklist.cern.ch

*many thanks to E. Matli and BE-CSS

Experience of the beam test

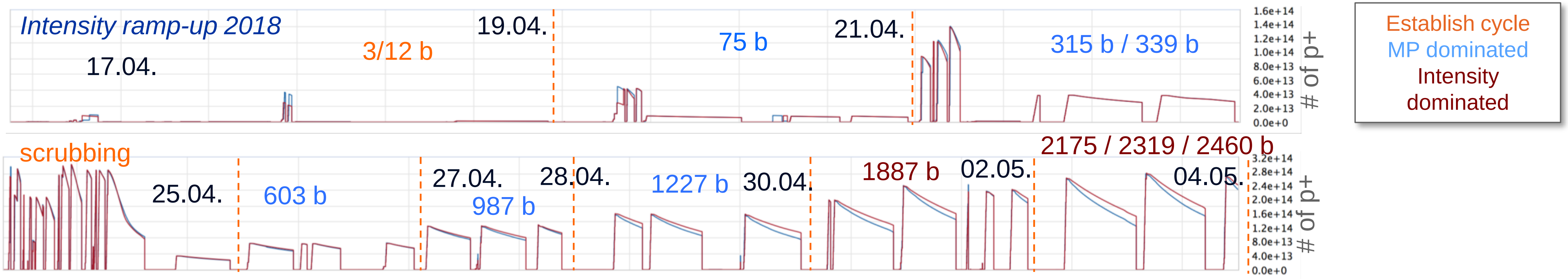
Machine protection related issues found:

- Regulation issues of RD converters causing FMCM triggering
- Issue with PM buffer rearming task for the BLMs
- Injection of nominal bunch into empty machine - incorrect SPS Probe Beam Flag (BCT4 calibration) not caught due to incomplete beam validation
- Aperture restriction in 21L3



Intensity ramp-up: motivation and strategy

- **Step-wise increase of injected and stored beam energy after YETS and LS to:**
  - establish operational cycle
  - identify and mitigate issues in machine-protection-relevant systems that are remaining after individual system tests and hardware commissioning
  - identify issues related to stored beam intensity and other beam related parameters and establish mitigation measures
- **Verify correct functioning of MP systems via checklists**
  - Filled by system experts and checked by rMPP before advancing to the next intensity step
  - Systems covered: magnet powering, interlocks, RF, beam instrumentation, operation, orbit, feedbacks, injection, beam dumping system, heating of equipment
  - Checklist tasks to be updated until FEB 2022
- **From 2016 to 2018, intensity ramp-up duration reduced from 22 days to 14.5 days**
  - Disclaimer: don't expect 2022 (coming out of the LS) to be as smooth as 2018…



MPP proposal for intensity ramp-up 2022

- Continue successful strategy applied during Run 2
- Stepwise increase of stored energy and number of injected bunches:
  Use 3/12 - 75 - 300 - 600 - 900 - 1200 - 1800 - 2400 - 2700 bunches*

Establish cycle
MP dominated
Intensity dominated

- For each intensity step: monitor behavior during at least 3 fills and 20h stable beams, and validate via checklist
- Keep bunch intensity to ~1.15×10^{11} ppb during intensity ramp-up. Then, gently increase bunch intensity (e.g., in steps of 0.05×10^{11}) up to 1.4×10^{11} ppb, depending on machine behaviour and available bunch intensity
- Use of luminosity levelling already during the intensity ramp-up
- Insertion of TOTEM/CT-PPS, AFP, ALFA roman pots to agreed settings before the first luminosity levelling step for all fills at each intensity step
- Scrubbing: Verify heating of critical elements before going to next intensity step. Intermediate scrubbing checklist after ~300 bunches (RF power, heating, …), final checklist at the end of scrubbing
- During the Run: issue Cruise Checklist every ~8 weeks (e.g., between TS) to check behaviour of MP systems

*exact number of bunches will depend on agreed filling schemes and beams

Discussed at the 217th MPP

Ramp-up scenarios after stops of nominal operation

Stop >48 h with massive HW + SW interventions	Stop >48 h without massive HW + SW interventions	Triplet events with non-reversible position changes**
One fill with either pilot bunches or max. 2-3 nominal bunches into SB (cycle revalidation, etc.)	One fill with 2-3 nominal bunches into SB (cycle revalidation, etc.)	One fill with 2-3 nominal bunches into SB (re-adjust orbit in IP)
One fill with ~50 bunches and about 1-2 hours of stable beams		
One fill with 600 bunches and min. 2 hours of stable beams*	One fill with 600 bunches and min. 2 hours of stable beams*	
If > 2000 bunches have been reached, one fill with about half max. number of bunches and about 5 hours of stable beams		
Back to pre-stop intensities	Back to pre-stop intensities	Back to pre-stop intensity
In total, 3-4 fills for ramp-up	**In total, 2 fills for ramp-up**	**In total, 1 fill for ramp-up**

*known intensity step to disentangle wrong settings, de-conditioning, etc. from intensity dominated effects at full intensity

**E.g. triplet quench, warm up of triplet region, cryo stop in triplet region, …
Note: Fixed displays are available for WPS, pressure and thermal shield T covering ~1 week history, which should be used as indicators.

Endorsed at the 339th LMC, 28th March 2018
Note: For Run 3, the validation of the luminosity levelling steps has to be ensured for the ramp-ups.

Intensity limits: Equipment limits

Expected beam parameters for Run 3:
- Bunch intensity: 1.4×10^{11} ppb (2022), 1.8×10^{11} ppb (from 2023 on)
- Number of bunches: 2748 or 2496
- Emittance: 1.8 µm – 2.5 µm

- **IR3/7 collimators: No limitation identified up to HL-LHC beam parameters**
- **IR6 absorbers***
  - TCDQ: 1.8×10^{11} ppb ok if gap > 2.5 mm (plus tolerances, i.e. 3.6 mm settings)
  - TCDS: Ti plastification expected for ≥ 1.7×10^{11} ppb but considered acceptable (deformation far from circulating beam) → ok for 1.8×10^{11} ppb
  - Note: Following an asynchronous beam dump a series of test with and without beam is required to validate the integrity of TCDQ and TCDS
- **Vacuum window, dumpline****
  - Replacement with new HL-LHC compatible window is planned by TE-VSC during the YETS21-22. No limitation expected thereafter
- **TDE*****
  - Vessel and windows ready for Run 3 beam parameters
  - To be clarified if operational limits for the dump core will be required, based on ongoing material studies, TDE autopsy and HRMT56 experiment

* Details in C. Bracco, 187th MPP; F. Carra, 193rd MPP; Minutes of 187th and 193rd MPP
** Details in G. Bregliozzi, "Evian" workshop 2021
*** Details in M. Calviani, "Evian" workshop 2021; J. Maestre/C. Torregrosa, 202nd MPP; Minutes of 202nd MPP; LHC-TDE-EN-0001

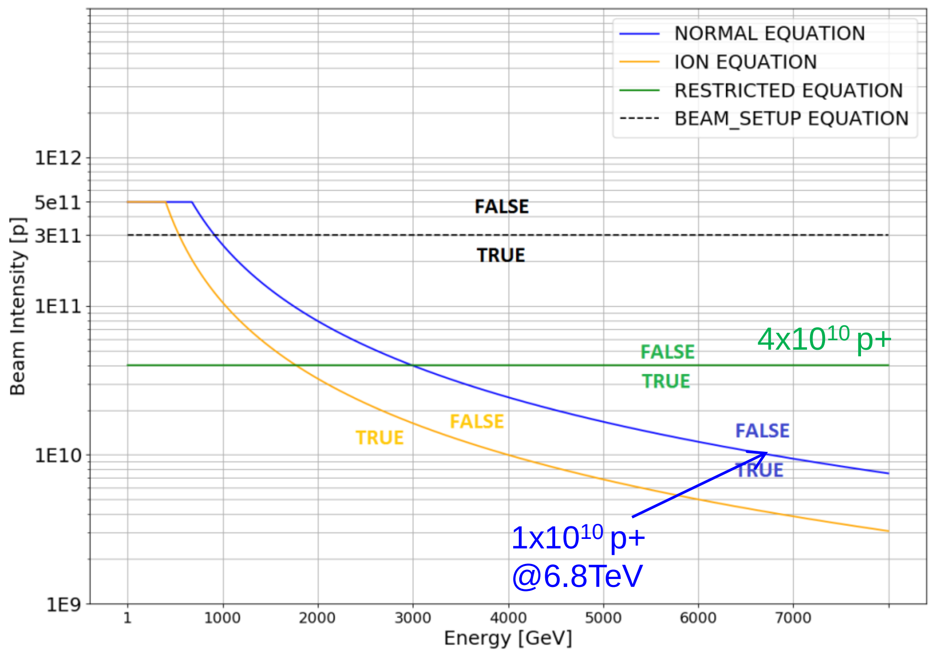
See D. Wollmann, LMC #425

Intensity limits: Operational limits

- **Setup Beam Flag (SBF)**
  - SBF allows for efficient commissioning by permitting to mask a part of the BIS inputs below a defined total intensity
  - Threshold equations for the SBF depend on beam energy and intensity and are stored in SMP
  - 'Normal' equation for Setup Beam Flag allows $1x10^{10}$ p+ at flat top (6.8 TeV).
  - **For Run 3, the 'restricted' equation was redefined to $4x10^{10}$ p+ (flat over all energies)**
    - This allows for 3 pilot bunches in the ramp and at top energy, facilitating optics measurements with AC dipole (191st MPP)
    - Procedure for use of 3 bunches for optics measurements to be finalized

- **ADT excitation**
  - Failure scenarios for operating the ADT in coherent excitation mode have been studied
  - Operational envelope for ADT excitation in Run 3 derived: Excitation window limited to 480 bunches; voltage limited to 5 kV at injection energy (211^{th} MPP)

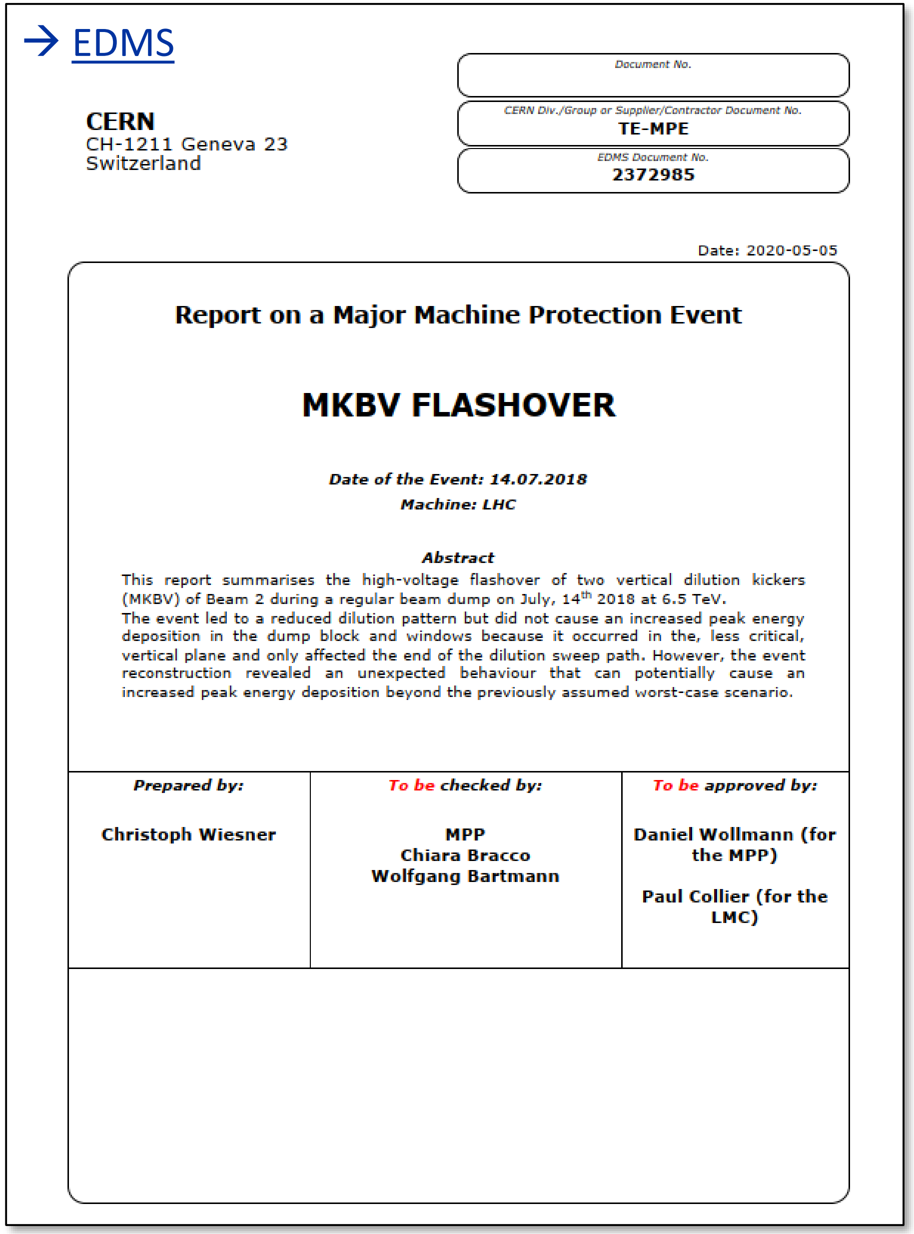
LHC_SBF intensity limits



R. Secondo, Safe Machine Parameters, EDMS No. 1096447

Major Event Reports

- Follow-up from Evian Workshop 2019: Document major machine-protection relevant events in a structured and concise way to learn for future events
- MPP proposal endorsed by the LMC and IEFC in May 2020
- Procedure: the MPP requests a *Report on a Major Machine Protection Event*, if considered necessary, in case of a machine-protection relevant event in the LHC or its injector chain that
  - caused damage to machine elements, OR
  - caused considerable downtime (>24h), OR
  - caused an unexpected beam loss pattern, OR
  - demonstrated that a machine-protection relevant system did not fulfil its function or showed an unexpected behaviour or non-conformity.
- Applying these criteria, ~8 events identified during Run 2 of the LHC (no claim for completeness)
- Report template available on EDMS


→ EDMS

CERN
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Document No.

CERN Div./Group or Supplier/Contractor Document No.
TE-MPE

EDMS Document No.
2372985

Date: 2020-05-05

Report on a Major Machine Protection Event

MKBV FLASHOVER

Date of the Event: 14.07.2018
Machine: LHC

Abstract
This report summarises the high-voltage flashover of two vertical dilution kickers (MKBV) of Beam 2 during a regular beam dump on July, 14th 2018 at 6.5 TeV.
The event led to a reduced dilution pattern but did not cause an increased peak energy deposition in the dump block and windows because it occurred in the, less critical, vertical plane and only affected the end of the dilution sweep path. However, the event reconstruction revealed an unexpected behaviour that can potentially cause an increased peak energy deposition beyond the previously assumed worst-case scenario.

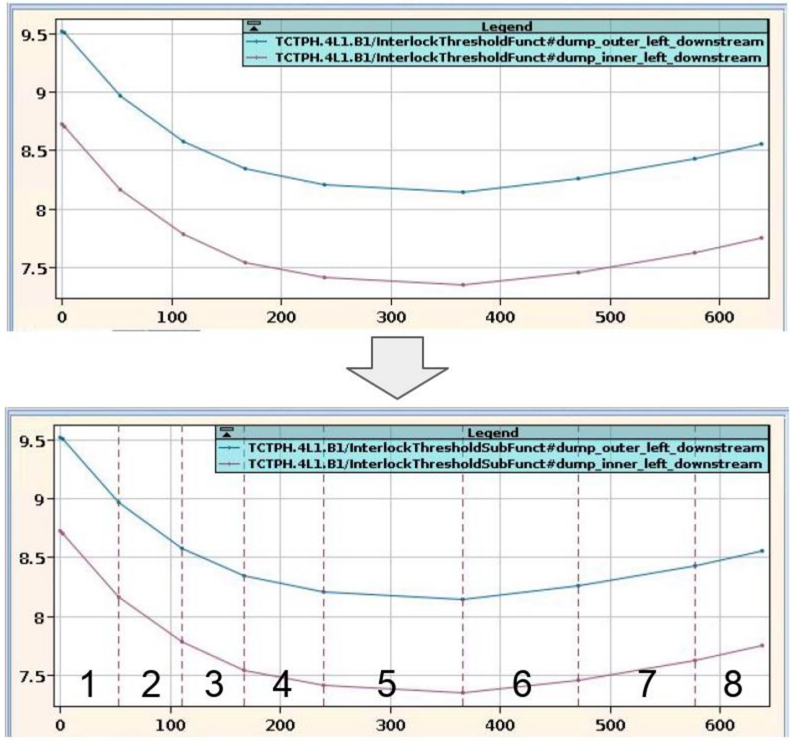
Prepared by:	*To be checked by:*	*To be approved by:*
Christoph Wiesner	**MPP** **Chiara Bracco** **Wolfgang Bartmann**	**Daniel Wollmann (for the MPP)** **Paul Collier (for the LMC)**

Machine-protection view on Run 3 (1/2)

- **Careful recommissioning and revalidation of all the machine-protection systems after LS2, and reestablishing safe operation with high-intensity beams required**

- **Extended use of luminosity levelling**
  - Increases operational complexity
  - Extended range of beta* levelling requires new approach of handling TCT interlock limits
  - Different options and their machine-protection implications investigated[1]
  - Proposed method for Run 3: pre-slice limit functions at matched points
  - Method to be tested in 2022 (reduced levelling range, TCT gaps constant) to gain experience and proposal for 2023 onwards to be developed (OP, MPP, COLL,…)

standard interlock functions



"segmented" interlock functions

[1] see M.Hostettler, MPP workshop 2019, COLLWG #260

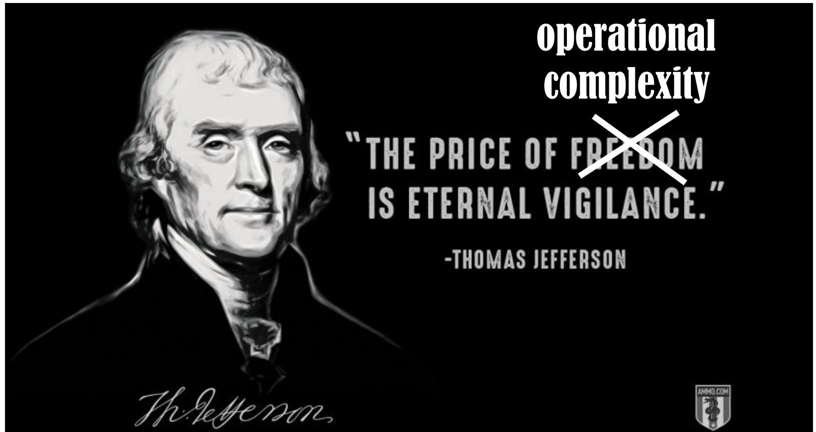
M. Hostettler, COLLWG #260

Machine-protection view on Run 3 (2/2)

- **Higher bunch intensity and stored beam intensity**
  - Bunch intensity will increase to 1.8×10^{11} ppb, leading to stored beam energies above 500 MJ per beam
  - Criticality of (fast) beam failures increases while protection strategy remains valid
  - BCCM will provide an additional safety net from 2023 on
- **Long Range Beam-Beam Compensator Wire (BBCW)**
  - BBCW will be used as operational device and interlocked via WIC (193rd MPP)
  - Full commissioning required
  - Draft commissioning procedure (EDMS #2384198) to be finalized
- **No impact for a possible 1-year extension to Run 3 identified**

Conclusions and outlook

- On track for the 2022 commissioning: procedures for the machine-protection systems reviewed in the MPP and applied for beam test → updates to be finalized before end of January 2022
- MPP proposal for intensity ramp-up 2022 developed, based on successful strategy in Run 2
- Bunch intensity limit in Run 3 is 1.8×10^{11} protons (to be clarified for TDE core)
- Major Event Reports established for Run 3
- Run 3 will bring increased operational complexity: stay vigilant!
- Run 1&2 brought us UFOs, ULOs, Gruffalos…
  Surprises in Run 3 to be expected…
- No damage occurred at the LHC in Run 2 due to the diverse redundancy in the machine protection systems, the vigilant hardware and machine-protection experts and OP teams… ***Let's keep it up for Run 3!***



https://ammo.com/articles/founding-fathers-quotes

https://www.keepcalmandposters.com/poster/5871552_keep_calm_and_expect_the__unexpected

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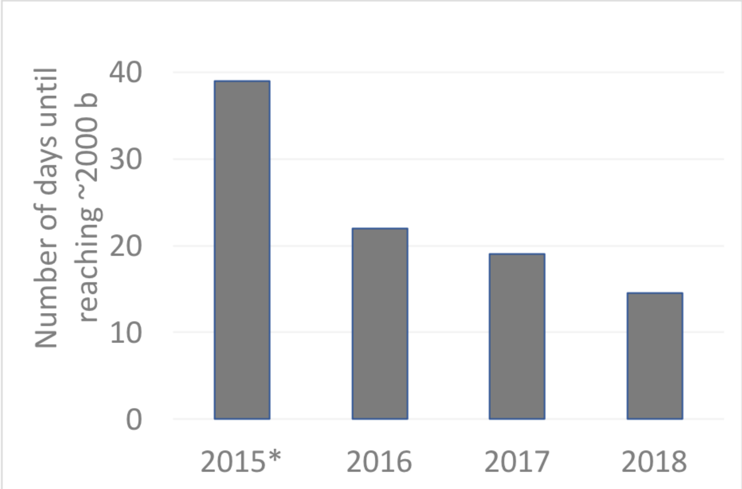
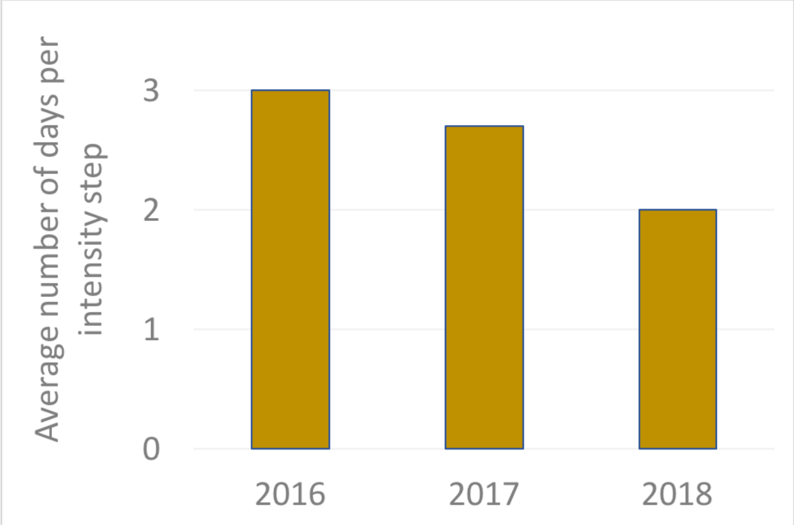
Durations of intensity ramp-ups in Run 2

- **2015: commissioning year**
  - Two ramp-ups (50 ns & 25 ns operation); intensity increase until end of proton run
- **2016/17/18: 7 steps to reach 2000+ bunches**
  - 2016 → 2018: reduction of ramp-up duration by 35%
  - The 14.5 days achieved in 2018 are close to the theoretical minimum
- **44 intensity-ramp-up and scrubbing checklists issued during Run 2**



*2015: up to 1825 b (25 ns)



See D. Wollmann, Evian'19

Issues discovered during intensity ramp-ups

- **Establish cycle/beam commissioning:**
  - PM/XPOC: data missing or misaligned
  - BIS timing mis-aligned
  - Direct dump BLMs (IR6) – connected to LBDS of wrong beam
- **MP dominated:**
  - Orbit feedback: offsets due to BPM calibrations
  - UFO – 16L2 events causing beam dumps & quenches
  - Abort Gap cleaning not properly functioning
  - Screen unintentionally left in dumpline
- **Intensity dominated:**
  - TDI – vacuum issues and heating
  - Insufficient cooling of a collimator
  - Instabilities
- **Random occurrence:**
  - MKD and MKB erratics
  - Un-physical BLM readings in PM
  - PM event builder stuck

For full list: see D. Wollmann, Evian'19 and checklists for intensity ramp-up

Major MP Events 2018 at LHC/SPS*

Event	Dam-age	Down-time	Unexpected beam loss pattern	MP relevant malfunctioning/ unexpected system behaviour or non-conformity
Multiple injections of high intensity beam on crystal collimators (13./14.10.2018)	No	No	Yes	Insufficient procedural handling
SPS dipole issue (20.8.2018)	Yes	~2d	Yes	Yes
MKBV flashover (14.7.2018)	No	~11h	No	Accepted failure case, but unexpected behavior, revealing new worst case
Symmetric triplet quench with orbit drift (3.6.2018)	No	~5h	Yes (due to fast developing orbit offset in B1)	No (Correct behaviour of circuit protection verified)
Spurious firing of quench heaters due to injection beam losses (1.6.2018)	No	~few hours	No	Unexpected behavior of QPS (shown to be beam-loss related)

*no claim for completeness

Sample Report: MKBV flashover

→ EDMS

Document No.

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Document No.

Page 3 of 5

1. EVENT DESCRIPTION

On July, 14th 2018, a high-voltage flashover of two vertical dilution kickers (MKBV) of Beam 2 occurred during a regular beam dump with 2556 bunches at 6.5 TeV. The flashovers happened at 37 μs and 47 us after the firing of the extraction kickers. They reduced the vertical deflection at the end of the sweep path, but did not increase the peak energy deposition in the dump block and windows. However, the event reconstruction revealed an unexpected behaviour that can potentially cause an increased peak energy deposition beyond the previously assumed worst-case scenario.

Table 1: Classification of the event

Characteristic Event Name	High-voltage flashover of MKBV magnets
Machine	LHC
Date or timestamp	14/07/2018, 03h00m23s
Did the event caused damage to the machine? *If yes, describe below the damage that occurred.*	No
Did the event led to machine downtime? *If yes, specify how long and insert details below.*	Yes, 11 hours (AFT).
Did the event cause an unexpected beam loss pattern? *If yes, insert details below.*	No. The event occurred during a regular OP dump at the end of a PHYSICS fills and the beam was regularly extracted from the LHC.
Did a machine-protection relevant system not fulfill its function or show an unexpected behavior or non-conformity? *If yes, insert details below.*	Yes. MKB flashover is a well-known, accepted failure case, but during the event an unexpected behaviour (delayed propagation of the flashover and only slowly decaying magnetic field) was observed, which can potentially lead to an increased peak energy deposition on the dump block and windows.

Table 2: Main machine and beam parameters at the time of the event

Accelerator Mode	PROTPHYS
Beam Mode	Stable Beams
Beams concerned by the event	Beam 2
Particle type	Protons
Beam Energy	6.5 TeV
Total beam intensity	1.7e14 p+
Number of bunches	2556
Optics	Collisions
Observed orbit change	No
Main MP-relevant systems concerned	Vertical dilution kickers (MKBV) of Beam 2. The first flashover occcured at MKBV.C and propagated to MKBV.D with a delay of ~10 μs.
Other relevant information	-
Link to logbook	http://elogbook.cern.ch/eLogbook/eLogbook.jsp?shiftId=1100199

1.1 DAMAGE

No damage occurred.

Sample Report: MKBV flashover

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1.2 DOWNTIME

A downtime of the LHC of ~11 hours was caused, which includes event analysis, recovery and revalidation measures (AFT).

1.3 UNEXPECTED BEAM LOSS PATTERN

No unexpected beam loss pattern was observed.

1.4 MACHINE-PROTECTION RELEVANT MALFUNCTIONING, UNEXPECTED BEHAVIOUR OR NON-CONFORMITY

An MKB flashover is a well-known and accepted failure case. However, the detailed reconstruction of the event on July 14th 2018 revealed the following unexpected behaviour:

- The high-voltage flashover propagated to the adjacent magnet within the same vacuum tank with an unexpected long delay of approximately 10 µs.
- The current and thus the field inside the magnets persisted after the flashover. This effect partially cancelled out the deflection of the remaining kickers. During the given event, the flashover of two MKBV led to a reduced dilution at the end of the sweep path that would be equivalent to the loss of nearly three MKBV.

For the given event, the expected peak energy density in the dump did not increase because the flashovers occurred relatively late (at 37 µs and 47 us after the firing of the extraction kickers) and in the vertical plane. However, a flashover at the horizontal dilution kickers with an unfavourable timing could lead to an increased peak energy deposition on the dump block and windows. Consequently, the analysis of the event has led to a newly defined worst-case dilution failure scenario when compared to the previous worst case scenario which accounted for the missing kick of two dilution kickers (i.e. 2oo4 for horizontal, respectively 2oo6 kickers for vertical). More details can be found in [1-2].

1.5 COMPARABLE EVENTS IN THE PAST

No flashover in the dilution kickers has been observed since the start of LHC beam operation. However, during the initial commissioning phase, a flashover occurred that propagated to adjacent magnets [7, Slide 17].

2. DESCRIPTION OF THE RECOVERY AND REVALIDATION PROCEDURE

After the event, the External Post-Operational Check (XPOC) of the dump system latched and the MKB status went to faulty. The kicker piquet and the dump experts were called, correctly diagnosed the flashover and initated the following recovery and revalidation measures:

- Magnet re-conditioning campaign
- Dry dumps to verify correct MKB behaviour

For details see [3].

3. LESSONS LEARNT

The event analysis led to an improved understanding of the flashover behaviour in the LHC dilution kickers, which allowed identifying a new worst-case dilution failure (see 1.3).

4. MITIGATION MEASURES AND REQUIRED ACTIONS

The following mitgation measures were taken:

- As a short-term mitigation, the voltage at the two affected MKBV was reduced by 20% following the incident [4].

The following mitgation measures are planned or under discussion:

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- The visual inspection of the magnets during Long Shutdown (LS) 2 did not lead to conclusive results on the flashover cause. The proposed strategy for LS2, thus, aims to reduce the voltage stress on the MKBs by increasing the internal capacitor value and matching the oscillation frequencies of the vertical and horizontal systems [8]. Additional hardware changes (insulation of high-voltage conductors, geometrical modifications) are under study for implementation in LS3 or during a YETS in Run3 [8].
- As long-term mitigation, the installation of two additional horizontal kickers per beam during Long Shutdown 3 has been proposed [4]. This would reduce the expected worst-case peak temperature in the dump core for a flashover of two horizontal dilution kickers from 3200°C to 2900°C. [1] More importantly, it would allow to lower the voltage of the individual MKBH magnets to 72% of its present value. It would, thus, significantly decrease the probability of a flashover, while keeping the same total dilution at the higher operational beam energy of 7 TeV.
- A major upgrade of the dump blocks and windows is under study to ensure the mechanical stability of the dump vessel and the material integrity of the core also for HL-LHC beams [6].

5. COMMENTS AND ADDITIONAL INFORMATION

Additional information about the event can be found in references [1-5].

6. REFERENCES

[1] C. Wiesner et al., "Machine Protection Aspects of High-Voltage Flashovers of the LHC Beam Dump Dilution Kickers", in Proc. IPAC'19, Melbourne, Australia, May 2019, pp. 2418-2421, WEPMP040, http://accelconf.web.cern.ch/AccelConf/ipac2019/papers/wepmp040.pdf.

[2] C. Wiesner et al., "Summary of MKBV flashover (14.7.2018) and implications for the LHC dilution failure cases", 170th SPS and LHC Machine Protection Panel Meeting, Geneva, Switzerland, 28.09.2018, https://indico.cern.ch/event/760267/

[3] W. Bartmann, "Update on understanding of MKB dilution kicker fault and planned mitigations", LHC Machine Committee (LMC), 1.8.2018, https://indico.cern.ch/event/747798/

[4] C. Bracco et al., "LBDS: Setting the Scenes", LHC Beam Dump System Review and its readiness for the Run3 and HL-LHC operation, Geneva, Switzerland, 05.02.2019, https://indico.cern.ch/event/784431/contributions/3263912/attachments/1790381/2916630/LBDS_Review.pptx

[5] C. Bracco et al., "LHC dilution kicker flash-overs and impact to the HL-LHC upgrade plans and needs", 59th HL-LHC TCC, 04.10.2018, https://indico.cern.ch/event/761078/contributions/3158082/attachments/1723639/2792742/MKBFlashOver.pptx

[6] M. Calviani et al., "TDE upgrade needs and future prospects for HL-LHC", LHC Beam Dump System Review and its readiness for the Run3 and HL-LHC operation, Geneva, Switzerland, 05.02.2019, https://indico.cern.ch/event/784431/contributions/3263989/attachments/1790450/2917807/mc__LBDS__5Feb2019_v6.pptx

[7] J. Uythoven, "LHC Risk Review: Kicker Magnet Reliability", LHC Risk Review, 5.3.2009, https://indico.cern.ch/event/53467/contributions/1204064/attachments/974645/1384919/LHC_Risk_Review_kickers.pptx

[8] V. Senaj, "New MKB Generators", 187th Machine Protection Panel Meeting, Geneva, Switzerland, 3.4.2020, https://indico.cern.ch/event/893576/