Reports on Major Machine Protection Events

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Acknowledgment: W. Bartmann, C. Bracco, B. Mikulec, D. Nisbet, M. Widorski

Outline

- Introduction, procedure and criteria
- Contents and template
- Overview of major MP events 2018/19
- Example reports
- Conclusions and Outlook

Major MP Event Reports: Overview

- Follow-up from Evian 2019: Document major MP relevant events with “quality assurance and rigor” (P. Collier, Evian 2019) to learn for future events.

→ ***Proposal***:

- A *Report on a Major Machine Protection Event* is **requested by the MPP** and **reported to the LMC or IEFC**. The report is issued in close collaboration between the concerned system teams, the MPP members and the MP3 (for events in the powering system).
- The MPP requests a report, 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**.
- ~10 identified events during Run2 for LHC and injectors (no claim for completeness).

Major MP Events 2019*

Event	Damage	Down-time	Unexpected beam loss pattern	MP relevant malfunctioning/ unexpected system behaviour or non-conformity
Beam sent unintentionally towards the PSB during the Linac4 LBE run (8.11.2019)	No	10 min	Yes	No (however agreed to configure BIS in non-nominal way to allow for commissioning tests)

*no claim for completeness

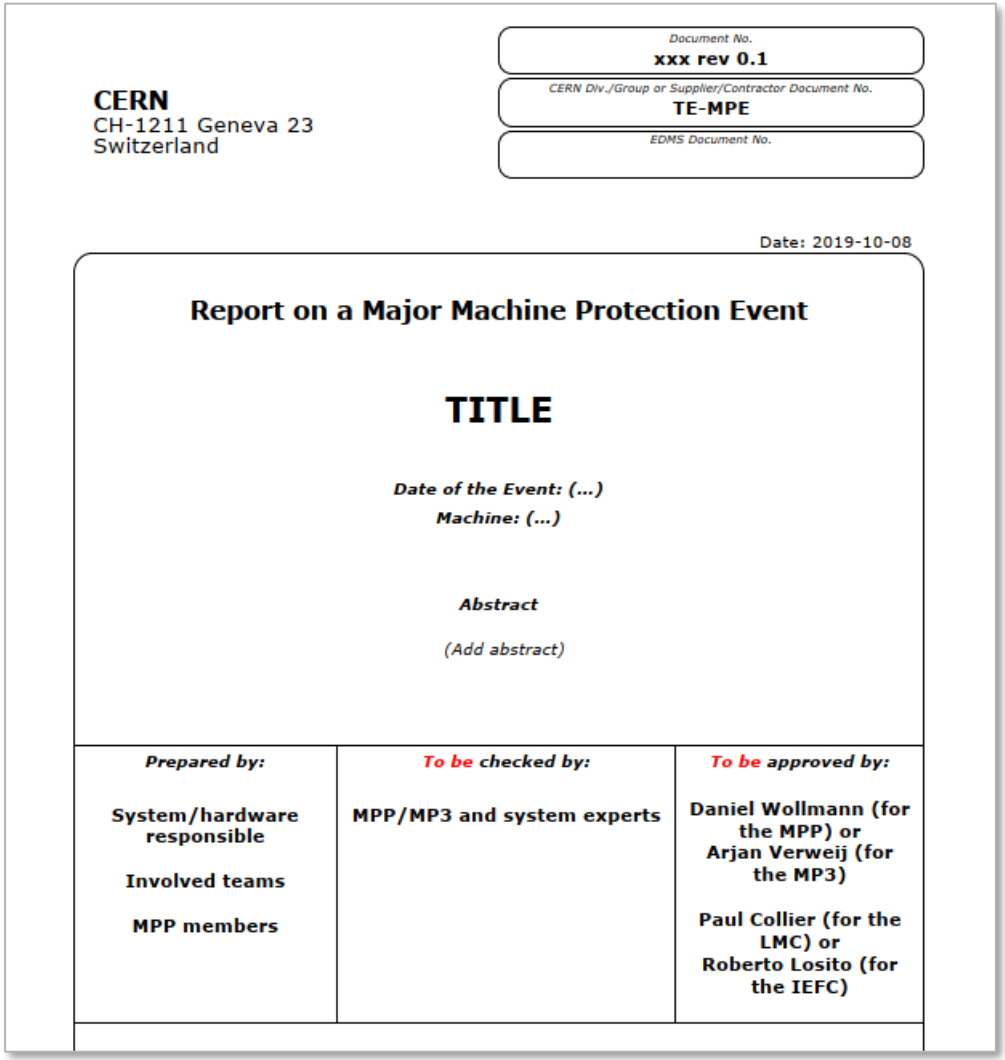
Major MP Events 2018*

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

Major MP Event Reports: Template

- The major event report should contain in a concise way (2-3 pages):
  - **Analysis of the event**, including the relevant timestamps, operational conditions, beam and system parameters, comparable past events.
  - **Description of the recovery and revalidation procedure**, if applicable.
  - The **lessons learnt** to prevent similar events in the future, including proposed actions, if any.
  - Links to **additional information** (presentations, Internal Reports, Non-Conformity Reports, …), if required.
- All major event reports will be stored on EDMS.



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TE-MPE

EDMS Document No.

Date: 2019-10-08

Report on a Major Machine Protection Event

TITLE

Date of the Event: (…)
Machine: (…)

Abstract

(Add abstract)

Prepared by:	*To be checked by:*	*To be approved by:*
System/hardware responsible Involved teams MPP members	MPP/MP3 and system experts	Daniel Wollmann (for the MPP) or Arjan Verweij (for the MP3) Paul Collier (for the LMC) or Roberto Losito (for the IEFC)

Report template: EDMS

Example Report: MKBV flashover

→ EDMS

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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)**

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.

Example Report: MKBV flashover

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:

- 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/

Example Report: Linac4 LBE Run

→ EDMS

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Report on a Major Machine Protection Event

BEAM SENT UNINTENTIONALLY TOWARDS THE PSB DURING THE LINAC4 LBE RUN

Date of the event: 8/11/2019
Installation: Linac4 / PSB

Abstract

For the LBE tests, the LTB.BHZ40 dipole deflects the beam towards the LBE line. Due to an unannounced intervention on the related power converter this magnet was switched off during the beam tests, resulting in two shots towards the PSB, hitting the temporary shielding. Radiation alarms occurred inside the PSB shielding. Both the Personnel Safety System and the Machine Protection System performed correctly, according to their specific configurations allowing for this during LS2. As an immediate mitigation, the MPS configuration was changed to avoid any further beam extraction towards the PSB during further Linac4 commissioning tests.

Prepared by:	***To be checked by:***	***To be approved by:***
Jan Uythoven	**MPP** **David Nisbet** **Markus Widorski**	**Daniel Wollmann (for the MPP)** **Roberto Losito (for the IEFC)**

1. EVENT DESCRIPTION

During the LBE tests the beam is bent by the LTB.BHZ40 dipole magnets towards the LBE line. Due to an unannounced intervention on the power converter, this magnet was unintentionally switched off, resulting in two shots towards the PSB destination (as the default beam destination), hitting the temporary shielding. As part of the intervention, the power converter was moved some 30 seconds after the start of the intervention to the fault state, which finally caused the WIC and the BIS to inhibit further beam extractions.

Radiation alarms occurred inside the PSB shielding. Both the Personnel Safety system and the Machine Protection performed correctly according to the agreed special configuration allowing for this stage of Linac4 commissioning during LS2. As an immediate mitigation, both the power converter interlocking (requiring now zero current and status ON to be TRUE and the BIS configuration (removed the jumpers of the PSB slave BICs) were changed following the event. There were also changes on the SIS level to avoid operation with zero current in the BHZ40 magnet. As the measured radiation levels were higher than expected, additional shielding was installed, covering a gap between the tunnel wall and the installed shielding.

There was no relevant exposure of personnel in the PSB to radiation.

In the future and in the final nominal configuration, there will be no operation of the LT/LTB/LBE lines possible while the booster is accessible.

Table 1: Classification of the event

Characteristic Event Name	Beam sent unintentionally towards the PSB during the Linac4 LBE run.
Machine	Linac4 / PSB
Date or timestamp	8/11/2019, 15h15m11s
Did the event cause damage to the machine? *If yes, describe below the damage that occurred.*	No
Did the event cause machine downtime? *If yes, specify how long and insert details below.*	10 minutes, fault assigned to power converter (AFT).
Did the event cause an unexpected beam loss pattern? *If yes, insert details below.*	Yes, triggering a radiation alarm within the PSB area (PAXB102)
Did a machine-protection relevant system not fulfill its function or show an unexpected behavior or non-conformity? *If yes, insert details below.*	No. It was, however, decided to operate with the MPS configured in a non-nominal way to allow for commissioning tests during LS2.

Example Report: Linac4 LBE Run

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

Accelerator Mode	LINAC 4 LBE running
Beam Mode	-
Beams concerned by the event	-
Particle type	H^-
Beam Energy	160 MeV
Total beam intensity	Two cycles of 5.9e12 H^- each.
Number of bunches	
Optics	-
Observed orbit change	-
Main MP-relevant systems concerned	Beam Interlock System, Power converter, Operational Procedures.
Link to logbook	http://elogbook.cern.ch/eLogbook/event_viewer.jsp?eventId=2748257

1.1 DAMAGE

None.

1.2 DOWNTIME

The event caused a downtime of ~10 minutes. The fault was assigned to the power converters (AFT).

1.3 ABNORMAL BEAM LOSS PATTERN

Instead of being transported to the LBE line, the beam travelled through the bending magnet without being deflected and hit the temporary beam stopper installed in the BI line. The beam lost on the temporary beam stopper caused increased radiation levels within the PSB. The measured radiation levels were higher than expected due to an imperfect shielding.

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

The MPS functioned according to its configuration, with the PSB slave BICs jumpered out (forced to true) as was agreed upon between the operations and the BIS teams to allow for beam tests during LS2.

1.5 COMPARABLE EVENTS IN THE PAST

None.

2. DESCRIPTION OF THE RECOVERY AND REVALIDATION PROCEDURE

Operation continued 10 minutes after the event, without a good understanding of what had happened. The mitigation measures mentioned in Section 4 were put in place some days later, following a detailed analysis and discussion in the 184th MPP meeting [2].

3. LESSONS LEARNT

The configuration of the MPS for special operational conditions should have been discussed and agreed upon in a larger forum, which could have revealed this neglected failure mode during this special configuration.

The intervention on the power converter (which was in operation despite being in a long shutdown) should have been communicated to the CCC/operation crews.

Operation should not have continued without a better understanding of what had happened.

4. MITIGATION MEASURES AND REQUIRED ACTIONS

The following actions took place:

- The BHZ40 power converter was configured to give a false USER_PERMIT to the BIS for zero current and status OFF (to be undone for nominal configuration).
- The SIS was configured to request a beam abort for zero current of the BHZ40.
- The jumpers on the PSB slave BICs were removed (i.e. put to their nominal configuration), resulting in a USER_PERMIT = FALSE.
- This operational mode will not be possible anymore with access in the PSB.

5. COMMENTS AND ADDITIONAL INFORMATION

The event was discussed in the MPP injectors meeting [1] and the PS-CSAP [2].

6. REFERENCES

[1] D. Nisbet, "Recent PSB radiation alarm during LINAC4 LBE run: post-mortem analysis and actions", MPP injectors meeting, 22/11/2019. https://indico.cern.ch/event/863440/

[2] Markus Widorski, "Incident during Linac4 beam tests to LBE line on 8 November 2019" at the PS-CSAP 54 meeting, 5/12/2019. https://indico.cern.ch/event/864675/

Conclusions and Outlook

- Follow-up from Evian 2019 to prepare *Reports on Major Machine Protection Events.*
- Reports to be requested by MPP and reported to LMC/IEFC for events involving
  - damage of machine elements, OR
  - considerable downtime (>24h), OR
  - unexpected beam loss pattern, OR
  - machine-protection relevant malfunctioning, unexpected behaviour or non-conformity.
- Report template and example reports have been prepared and are stored on EDMS.
- Reports to be issued from Run3 onwards.

Thank you for your attention!

Evian 2019 - Discussion

"P. Collier commented on the list of machine-protection issues presented by D. Wollmann, and remarked that we need quality assurance and rigor in documenting these events. He suggested that, whenever we have an incident that the rMPP considers serious, we should issue a major event document that includes a clear analysis of what went wrong and of what has to be done to avoid the issue in the future. If necessary, this document should then be brought to the LMC for decision and action. D. Wollmann agreed that this should be done."
https://indico.cern.ch/event/751857/sessions/296634/attachments/1815369/2966754/2019_01_28_Evian_Minutes.pdf

Major MP Events 2017*

Event	Dam-age	Down-time	Unexpected beam loss pattern	MP relevant malfunctioning/ unexpected system behaviour or non-conformity
Injection into Abort Gap (4.9.2017)	No	~few hours	No	Yes
16L2 dumps (5.6.2017)	No	Turn-around	Yes, for first occurrence(s)	No

*no claim for completeness

Major MP Events 2016*

Event	Dam-age	Down-time	Unexpected beam loss pattern	MP relevant malfunctioning/ unexpected system behaviour or non-conformity
MKI erratic with quench of triplet in IP2 (2.9.2016)	No	~few hours	Losses higher than ususal (due to grazing impact on TDI)	No
Intermittent inter-turn short in MB.A31L2 (10.8.2016)	(Yes)	>24h	No	Risk of magnet damage in case of quench or fast power abort
TDE leak (2016)	No	Paused high-intensity operation	No	Non-nominal operation conditions

*no claim for completeness