MACHINE PROTECTION SYSTEM: AVAILABILITY & PERFORMANCE 2010-2012

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Abstract

This paper presents the results of studies into the availability and performance of the LHC Machine Protection System (**MPS**) from 2010 to 2012.

The first section outlines the availability and performance as recorded from the operations viewpoint for all three years of LHC operation.

For 2012, a more detailed examination of MPS equipment is introduced, with failure rates, failure modes, and Mean Time To Repair (**MTTR**) identified for the MPS equipment having the biggest impact on LHC availability.

Conclusions are drawn and proposals made using an availability matrix, which directly compares and contrasts failure modes, failure rates and MTTR of MPS equipment. This work results in four suggestions (**S1-4**) and one recommendation (**R1**) to be considered by MPS experts.

OPERATIONAL VIEWPOINT 2010-2012

The operations viewpoint considers availability as the impact on the LHC's ability to produce physics. Therefore the causes of beam aborts are a key indicator of availability. Every abort leads to the creation of a post-mortem event and corresponding post-mortem database entry. Analysis of these events reveals most of the impact the MPS has on the LHC availability as seen from the operations viewpoint. This is not an exhaustive analysis, as other events, such as parallel faults involving MPS, are not considered.

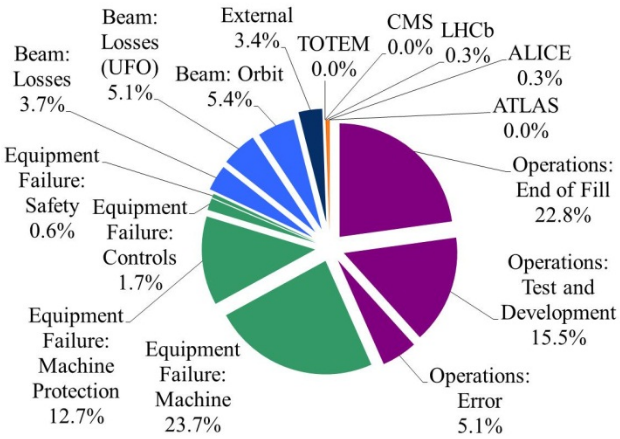

Figure 1: Distribution of Beam Aborts in 2010 (total 355)

Post-Mortem Dump Cause Evolution 2010-2012

Considering only beam aborts that took place above injection energy, between March and November, then classifying dump cause into five categories (external, beam, equipment, operations or experiment) leads to the following distribution of beam aborts for 2010 [1]:

The same analysis for 2012 [2]:

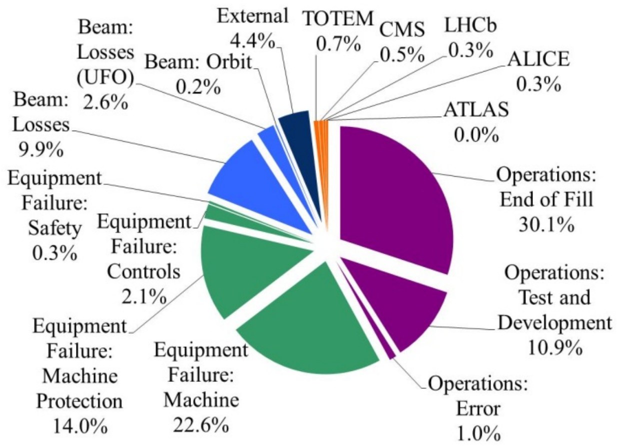

Figure 2: Distribution of Beam Aborts in 2012 (total 585)

Details of MPS Dump Causes

The analysis shown in figures 1 and 2 has been carried out for 2011 [3], leading to the following table of physics fills, and dump cause counts due to "Equipment Failure: Machine Protection" e.g. MPS Failure [4]:

Table 1: Beam Aborts Induced by MPS Failure 2010-2012

	2010	2011	2012	Total
Qualifying Fills [#]	355	503	585	**1443**
MPS Failure [#]	43	71	82	**196**
MPS Failure [%]	12.7	14.1	14.0	**13.6**
Quench Protection	24	48	56	**128**
Beam Loss Monitors	4	4	18	**26**
Beam Dump	9	11	4	**24**
Software Interlocks	4	2	4	**10**
Powering Interlocks	-	5	-	**5**
Beam Interlocks	2	1	-	**3**

This table indicates that between 2010 and 2012, from the operational viewpoint:

- There has been a slight increase in the ratio of beam aborts due to failures of the MPS from 12.7% to 14.0%.
- Only six sub-systems of the MPS have been responsible for beam aborts.
- The largest contribution of beam aborts has been the Quench Protection System (**QPS**)

For the year 2012, only four MPS sub-systems contributed to loss of LHC availability as seen from the operation viewpoint.

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EQUIPMENT VIEWPOINT 2012

In contrast to the operation viewpoint, the equipment viewpoint is not restricted by beam aborts or by machine fill, rather all system faults for the whole year are considered, in order to determine sub-system reliabilities.

Failure modes, failure rates, Total Time To Repair (**TTTR**) and MTTR were considered for seven sub-systems of the MPS. Failures have been categorised as follows:

- External – failure due to a system dependency.
- Random Hardware – failure due to a random in time failure of hardware.
- Radiation Hardware – failure due to radiation induced effects on hardware.
- Exploitation – failure due to the manner in which the system was setup, or being operated.

*Software Interlock System (**SIS**)*

The post-mortem database indicated **4 beam aborts** due to the SIS. However, in 2012 the SIS did not fail. All actions carried out by the system were due to real conditions requiring an interlock. Table 2 shows records for typical causes and ratios for interlocks generated by the SIS [5].

Table 2: SIS Dump Causes and Ratios

Cause	Ratio [%]
CMW Failure	20
Orbit Feedback Crash	20
Power Converter Fault	15
Beam Position Measurement	10
Beam Loss Monitor High Voltage	10
Others…	25

*Fast Magnet Current Change (**FMCM**)*

The post-mortem database indicated **0 beam aborts** due to the FMCM, with equipment experts indicating **one failure**, which occurred four times while being diagnosed, as shown in Table 3 [6]:

Table 3: FMCM Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Earth Cable Intermittent	1	5.8	5.8
combined	**1**	**5.8**	**5.8**

*Powering Interlock Controllers (**PIC**)*

The post-mortem database indicated **0 beam aborts** due to the PIC, with equipment experts indicating **one failure**, as shown in Table 4 [7]:

Table 4: PIC Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Ethernet Switch Fault	1	1	1
combined	**1**	**1**	**1**

*Warm Magnet Interlock Controllers (**WIC**)*

The post-mortem database indicated **0 beam aborts** due to the WIC, with equipment experts indicating **one failure mode**, occurring twice, as shown in Table 5 [8]:

Table 5: WIC Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Power Converter Trigger	2	11	5.5
combined	**2**	**11**	**5.5**

*Beam Interlock System (**BIS**)*

The post-mortem database indicated **0 beam aborts** due to the BIS, with equipment experts indicating several failure modes as shown in Table 6 [9]:

Table 6: BIS Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
User Side Powering	3	6	2
User Side Infrastructure	2	40	20
User Interface Powering	2	4	2
Monitoring Corruption	1	1	1
Power PC Failure	1	1	1
Reference Database Fault	1	1	1
combined	**10**	**53**	**5.3**

The User Side Infrastructure failure mode was an intermittent failure being complex to diagnose. The input to the BIS was disabled whilst system experts from both sides investigated. This prevented the failure from having an impact on LHC availability.

*LHC Beam Dumping System (**LBDS**)*

The post-mortem database indicated **4 beam aborts** due to the LBDS. However, for the same period, equipment experts identified **9** such events. The total system characteristics are shown in Table 7 [10]:

Table 7: LBDS Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Slow Surveillance Fault	10	4	0.4
Vacuum Fault	5	3	0.6
Power Electronics Fault	4	8	2
PM / Arming Problem	4	0.5	0.1
Beam Interlocks Failure	4	3.5	0.9
Control Hardware Error	4	1	0.3
Energy Tracking Hardware	1	1	1
combined	**33**	**27**	**0.8**

*Beam Loss Monitors (**BLM**)*

The post-mortem database indicated **18 beam aborts** due to the BLM. The overall system characteristics are shown in Table 8 [11]:

Table 8: BLM Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Optical Link – Surface	15	45	3
CMW	14	14	1
SEM Connectivity	10	20	2
Optical Link – Tunnel	6	30	5
LIC Connectivity	5	10	2
High Voltage Droop	4	12	3
IC Connectivity	3	9	3
VME Power Supply	1	3	3
Programmable Logic	1	1	1
combined	**59**	**146**	**2.5**

Middleware (**CMW**) faults are approximately 50% due to failure of the Management of Critical Settings (**MCS**) and 50% due to failure of communication with front-end computers. Some of the failures listed are designed to allow the current mission to complete, but then inhibit the next mission to force correction of the faulty state.

As BE/BI has no dedicated piquet service, a best-effort system is in place, this may cause an increase in the MTTR.

Quench Protection System (QPS)

The post-mortem database indicated **56 beam aborts** due to the QPS. The overall system characteristics are shown in Table 9 [12]:

Table 9: QPS Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Radiation Induced	39	35	0.9
Internal Communications	25	15.5	0.6
Spurious Signal	23	23	1.0
Power Converter	13	13	1.0
WorldFIP Fault	12	17	1.4
DFB / Current Lead	9	18	2.0
Mains Perturbation	8	9	1.1
600A Energy Extraction	7	13	1.9
13kA Energy Extraction	6	11	1.8
EM Interference	2	3	1.5
CMW	1	0.5	0.5
13kA Power Supply Fault	1	2.5	2.5
Others	9	6	0.7
combined	**155**	**166.5**	**1.1**

The QPS system will be significantly consolidated and upgraded during the LS1 period.

CONCLUSIONS

On Availability

Combining the information from the previous section allows failure rates, modes and repair times to be compared. In total, for the seven sub-systems, there were over **250 faults** identified, split into around **36 failure modes**, having a total repair time of over **360 hours**. An *availability matrix* has been created, with impact on the y-axis, and repair time on the x-axis. Failure Modes are plotted as coordinate points. Three options can be exploited to improve LHC availability:

1. Move a failure mode left on the x-axis, by **decreasing the MTTR**. This can be done by improving maintenance plans, or moving equipment to areas that are accessed more quickly.
2. Move a failure mode lower on the y-axis, by **decreasing the failure rate**. This can be done by building systems out of more reliable components, or by more advanced techniques such as redundancy.
3. **Removing a failure mode** altogether. This can be done by redesigning or redeploying systems.

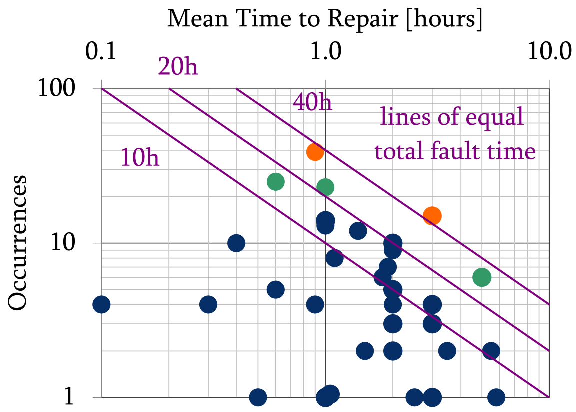

Figure 3: 2012 Availability Matrix

For the systems studied, there are five failure modes which stand out: (frequency, MTTR)

1. BLM: Optical Link Failure – Surface (15, 3.0)
2. QPS: Radiation Induced Fault (39, 0.9)
3. QPS: Internal Communications Fault (25, 0.6)
4. QPS: Spurious Signal (23, 1.0)
5. BLM: Optical Link Failure – Tunnel (6, 5.0)

Changes should be made during LS1 to address failure modes such as these, leading to an improved availability post-LS1.

S1. Study planned changes to systems in LS1 to predict the expected availability post-LS1.

On Fault Tracking

The information presented in the paper has been the result of many days work data mining the various log books and sources throughout the various equipment and operations groups. More robust conclusions require a more robust collection of raw failure rate information.

R1. Consider a fault tracker to improve data collection and analysis post LS1.

On the SIS

The SIS has been identified as a source of several premature beam aborts in 2012. In each case the beam abort was justified, but the root cause of the beam abort beyond the SIS was not recorded in the PM database.

S2. PM Events that are labelled as SIS should be expanded to include root cause information.

Potential Dormant Failures

In studying the behaviour of the BIS, it was revealed that several of the input channels have not been activated since the beginning of LHC operation in 2010. Internal test modes have been used to verify functionality internal to the BIS but not beyond that to the user system.

S3. Infrequently activated inputs to interlock systems should be periodically tested to reduce the risk of dormant unsafe failures.

Defence in Depth and Hazard Chains

The MPS ensures that the LHC operates with an acceptable risk, based on a two-step approach: *prevent* hazardous situations from occurring, *protect* the machine if they do. A significant proportion of activations of the MPS are occurring in the *protect* phase, indicating that hazardous situations are occurring, as evidenced by the dump events labelled with a root cause of "Beam Losses".

S4. MPS abort events which are triggered by Beam Loss interlocks should be investigated to try and identify new hazard chains.

ACKNOWLEDGMENTS

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REFERENCES

[1] PM database. Extracted from 23rd March to 6th December 2010, only for fills >450.1 GeV, ignoring entries marked as "no input change".

[2] PM database. Extracted from 1st March to 6th December 2012, only for fills >450.1 GeV, ignoring entries marked as "no input change".

[3] PM database. Extracted from 17th February to 13th December 2011, only for fills >450.1 GeV, ignoring entries marked as "no input change".

[4] Sort [3] by MPS Dump Cause, Discarding EOF, MD and MPS Test. Identify only those events caused by "MPS Equipment Failure"

[5] Courtesy L. Ponce, J. Wenninger. PM database, filter by SIS, extract labelled events and generalise.

[6] Courtesy S. Gunther, I. Romera. Extracted from TE-MPE-COMS "FMCM" Issue Tracker

[7] Courtesy S. Gunther, I. Romera. Extracted from TE-MPE-COMS "PIC" Issue Tracker

[8] Courtesy P. Dahlen, S. Gunther, I. Romera. Extracted from TE-MPE-COMS "WIC" Issue Tracker, ignoring "SPS/TL" events

[9] Courtesy C. Martin. Extracted from personal records, and TE-MPE-COMS "BIS" Issue Tracker.

[10] Courtesy R. Filippini. Extracted from TE-ABT logbook, LHC-OP logbook, and expert personal records

[11] Courtesy C. Zamantzas. Extracted from BI-BLMS Issue Tracker and expert personal records

[12] Courtesy K. Dahlerup-Petersen, R. Denz, S. Gunther & I. Romera. Extracted from TE-MPE-COMS "QPS" Issue Tracker