

A FAILURE CATALOGUE FOR THE LHC

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Abstract

The operation of the LHC involves the risk of incidents leading to machine damage. In order to protect the investment of several billion CHF, a complex Machine Protection System (MPS) ensures safe LHC operation by reducing the risk for machine damage to an acceptable level. The protection system was designed based on a large number of possible failures of LHC equipment. So far, the knowledge of these failures, and the related machine protection functions implemented in the MPS, is distributed over the different teams involved in the design and operation of the LHC. A newly started project aims at bringing together this knowledge in a common failure catalogue. This paper introduces the approach and presents the first experience.

INTRODUCTION

The LHC was built for studying subatomic particles on a new scale. The function of the LHC can be divided into two parts, 1) colliding two particle beams in the required conditions and 2) collecting data on particles emerging from these collisions.

The functionality of the machine involves technical characteristics that come along with a significant potential for equipment failures leading to machine damage. Without machine protection measures, the risk associated with LHC operation for the machine is high. The occurrence of damage beyond repair resulting in an early termination of operation is likely, (Fig. 1).

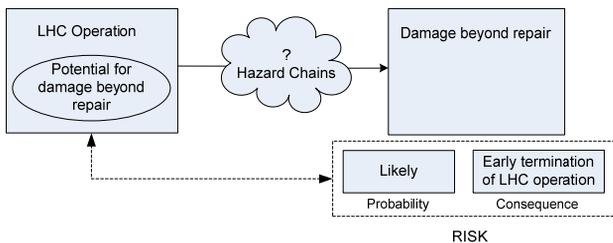


Figure 1: Risk associated with LHC operation (without machine protection measures).

In order to define appropriate machine protection functions for reducing the risk, a profound knowledge on failures and fault conditions potentially leading to machine damage (below referred to as *hazard chains*) is required. Accordingly, the claim ‘LHC operation is safe’ requires proof about 1) the identification of all critical hazard chains and 2) the implementation of appropriate machine protection functions.

This paper in the first part introduces a failure analysis approach for the building of a failure catalogue that allows for both the systematic collection of known hazard chains and the deduction of potentially unknown chains.

The second part provides an overview on the different MPS subsystems and their protection functions.

The third part finally illustrates an example of a general hazard chain with MPS subsystems assigned as a means for assessing the protection coverage.

FAILURE ANALYSIS

For a comprehensive failure analysis addressing hazard chains, a bottom-up approach starting with equipment failures is not advisable due to the number of components and the complexity of the LHC. Instead, a top-down approach is chosen, assuming any damage to be caused by *equipment* being exposed to an *impact* (Fig. 2).

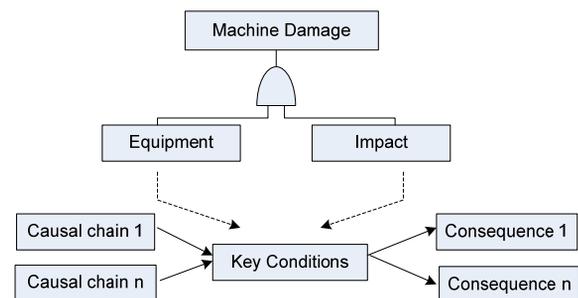


Figure 2: Top-down approach for failure analysis.

The following two sections introduce the equipment and impact considered to be the most critical in the LHC.

Critical Equipment

The following equipment is regarded to be most critical in terms of being damaged:

- Magnets (superconducting and normal conducting)
- Experiments (detectors)
- RF system

The criterion applied is the effort in terms of time and costs for equipment repair or replacement.

Critical Impact

The following sources of impact are regarded to be the most critical in terms of causing damage:

- Energy stored in the beam (up to 360 MJ per beam)
- Energy stored in the main dipole magnet powering circuits (up to 1.1 GJ per circuit)
- Energy stored in helium (cryogenics)

The criterion applied is the related risk taking into account the likelihood of causing damage and the potential extent of damage.

The next step is the identification of key conditions potentially leading to machine damage.

Key Conditions

The general key condition is an accidental release of stored energy (due to impact ‘meeting’ equipment or vice

versa). For the energy stored in the beams, this can be caused by

- Unstable beam, i.e. the beam in a condition which cannot be controlled and without further measures leads to non-nominal beam loss
- Equipment in the path of the beam

For the energy stored in the powering circuits, accidental energy release is caused by

- Quench, i.e. the transition from superconducting (sc) to normal conducting (nc), entailing local heat generation due to electrical resistance.

Based on these conditions, a failure catalogue is built, covering all identified impact and equipment categories.

Building a Failure Catalogue

Starting from the key conditions, hazard chains are deduced, identifying causing equipment failures and consequences, i.e. the extent of damage (Fig.2). The different hazard chains are then systematically collected in a failure catalogue.

The subsequent steps for the development of appropriate protection functions are introduced by Todd et al [1]. For an existing system like the LHC, the next step is the assignment of existing protection systems in order to assess whether all the failures are covered.

The following section provides an overview on the different LHC MPS subsystems.

MACHINE PROTECTION SYSTEM

The LHC MPS represents a mixed system based on *active* and *passive protection* [2].

Active Protection

During LHC operation, thousands of parameters are monitored and in case a non-nominal condition is detected, appropriate measures are triggered. Depending on whether the monitoring relates to equipment or beam conditions, the active protection can be divided into equipment-based and beam-based systems.

Table 1 shows equipment-based monitoring systems with the monitored equipment and parameters. It is to be noted that only systems monitoring machine equipment are included. The self-monitoring of the control system as well as monitoring related to personal safety is not included. Table 2 shows the beam-based systems and the monitored parameters.

As for the triggered measures, the following are the most essential (representing the controlled release of stored energy):

- *Emergency beam dump*, i.e. beam extraction from the LHC ring onto the absorber blocks
- Energy extraction from the main dipole magnet powering circuits

The above measures directly intervene on the present beam or equipment condition in order to achieve a safe state in the current operational cycle. The continuation of operation, i.e. the start of a new cycle, requires the restoration of nominal equipment conditions. That means

that the causes for non-nominal parameters have to be identified and eliminated.

Table 1: Equipment-based Monitoring Systems (not exhaustive)

System	Equipment	Parameter
Kicker Surveillance	Injection, extraction, aperture, tune, AC dipole kicker	Charge, switch, timing
PC Controls	Power converter	Power converter current, faults
FMCM	nc magnet system	Fast current change
WIC	nc magnet system	Temperature
QPS	sc magnet system	Voltage
UPS control	Power supply	Condition
CRYO Interlock	sc magnet system	Temperature, (helium) pressure
Vacuum Interlock	Vacuum valves, vacuum sector	Valve position, vacuum pressure
RF Interlock	RF system	Voltage, frequency, power, temperature
Collimation Interlock	Cleaning collimators	Position, temperature
Experiments Interlock	Experimental magnets, detectors, moveable devices	Current, condition, position

Table 2: Beam-based Monitoring Systems

System	Parameter
BLM	Beam loss
BPM	Beam position
FBCM	Beam intensity (under develop.)
BCM	Beam loss in experiments
Screen, Mirror, Wire scanner, BSRT	Beam profile

In certain cases, direct intervention, in particular on the beams, is not feasible, e.g. due to time constraints inherent to beam injection and extraction. Still, the detection of non-nominal conditions results in the inhibition of a new operational cycle, requiring passive protection for the current cycle.

Passive Protection

Passive protection refers to elements protecting the equipment in cases (e.g. single turn beam losses during beam injection and extraction) that cannot be covered by active protection (Tab.3). In addition, they can represent a (limited) backup in case of insufficient performance of active protection.

The collimators and absorbers in the table relate to elements that are explicitly installed for protection reasons in case of failures.

Table 3: Beam-based Passive Protection Elements

Element	Function
Collimators	Absorb beam particles with non-nominal trajectory
Absorbers	Absorb entire beam

It is to be noted that the mentioned monitoring systems and protection elements in turn can fail and are (self-)monitored.

EXAMPLE

Figure 3 illustrates a general hazard chain for beam-induced damage. The arrows are to be read as ‘may lead to’. The monitoring systems are assigned downstream (arrow-wise) of the failures which they react on. They are considered to interrupt the causal chain.

Beam-induced damage is preceded by unstable beam or equipment in the path of the beam, which in turn is caused by an incorrect magnetic field, RF or vacuum, or incorrect mechanical aperture respectively. Two of the possible events leading to incorrect RF are RF voltage or frequency failures. With regard to incorrect magnetic

fields, one can distinguish between kicker magnets, nc and sc magnets.

The basic failures leading to a nc magnet failure are a powering or a cooling failure. Accordingly, for the sc magnet it is a power converter or a cooling failure, or a quench.

The presented hazard chain intends to exemplify the approach and is not exhaustive. It is being further developed. The relevant ‘branches’ to be considered for a certain failure case, as well as the assessment of its protection coverage, depends on a number of additional parameters to be taken into account, in particular:

- Type and location of failing element
- Operational mode (injection, circulating beam, extraction)
- Beam parameters (e.g. energy, intensity)

The above parameters define the time constraints required for (active) protection and as such allow assessing the coverage through the indicated monitoring systems. As mentioned above, for some failure cases the active monitoring by definition can only intervene on the subsequent operational cycle (e.g. Kicker surveillance, BPM, Screens, Mirrors, Wire Scanners, BSRT, Fig. 3).

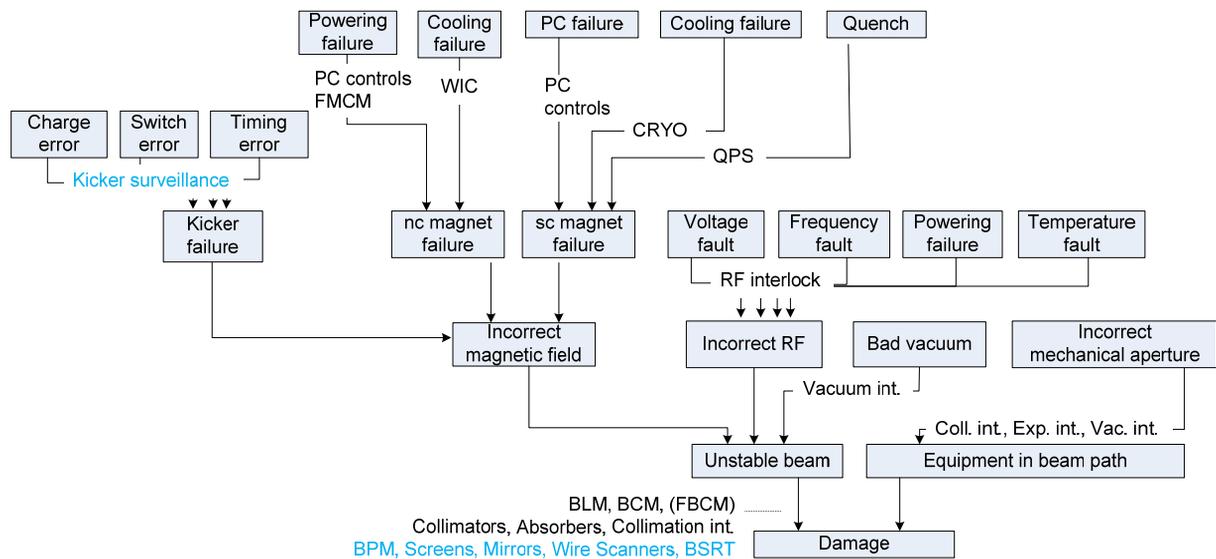


Figure 3: General hazard chain for beam-induced damage (not exhaustive).

CONCLUSIONS

The paper presents an approach to build a failure catalogue for the LHC. It introduces the required failure analysis and machine protection comprehension and provides a general hazard chain for beam-induced damage, as an illustration of failure catalogue content.

The completion of the failure catalogue is ongoing. The implementation of an appropriate database, different from an existing Excel table, is being considered. The aim is to create a database that is easily useable and maintainable and customised to the potential users within the

organisation, both in terms of including and extracting data.

REFERENCES

- [1] B. Todd et al., “Machine Protection of the Large Hadron Collider”, 6th IET International System Safety Conference 2011, Birmingham, UK (accepted).
- [2] R. Schmidt et al., “Protection of the CERN Large Hadron Collider”, New Journal of Physics 8, 290 (2006) p. 31.