Machine Protection and Activation

CERN Accelerator School
Beam Injection, Extraction, and Transfer

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Machine Protection – A Term, A System, A Strategy?

Machine Protection is a **strategy** that research facilities can embrace/utilize to achieve **high operational availability**.

- What means availability?
- How could we describe availability?
- Why could high availability be more and more important nowadays?
- What could “strategy” mean in this context?

What could possibly go wrong?

Some examples

Accident Example I

SPS, CERN:

In 2004, during extraction tests in the SPS extraction line with 450 GeV/c protons, **beam with** an energy of **2 MJ was deflected** with grazing incidence **into a vacuum chamber.** This happened after the failure of a septum magnet.

The **vacuum chamber was cut along a length of 25 cm**. A magnet further downstream was damaged due to beam losses.

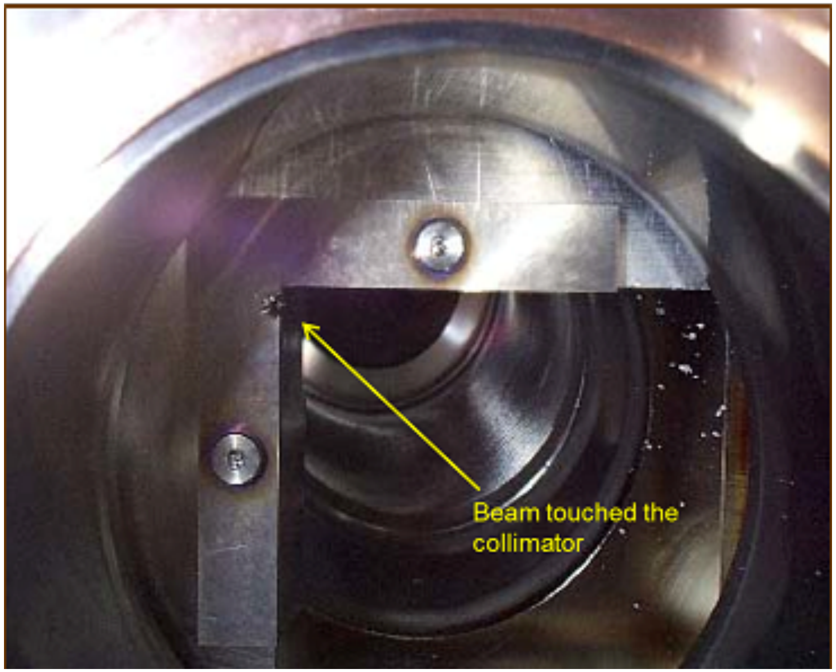
Condensed drops of steel were visible on the opposite side of the vacuum chamber.

Vacuum chamber and the damaged magnet needed to be **replaced**.

Courtesy of R. Schmidt, CERN

Accident Example II

Tevatron, Fermilab:



Roman pot moved into the beam.

Particle showers generated by the Roman pot **quenched superconducting magnets**.

The **beam** moved by 0.005 mm/turn,
and eventually **touched a collimator jaw** surface after about 300 turns.

The entire beam was lost, mostly on the **collimator** that was **damaged**.

Courtesy of R. Schmidt, CERN

Accident Example III

SNS, Oakridge:

Equipment operating at high voltage (RFQ, cavities) can be very sensitive to beam losses (surface quality degradation). Then operation at the same voltage is not possible and probability for arcing is increased.

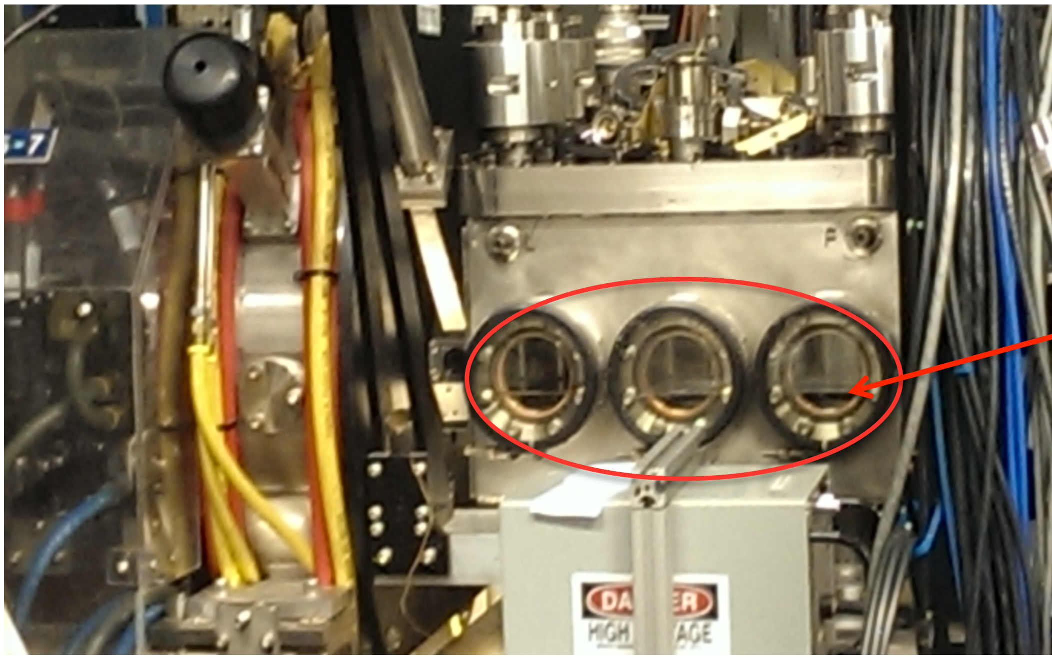
At SNS, errant beam losses led to degradation of a superconducting cavity. Beam current monitors (BCMs) measured **beam losses during a few μs**. After such errant beams, sometimes the cavity gradient needed to be lowered. Conditioning after warm-up helped in most cases, but in one case a complete **cryo-module had to be exchanged**.

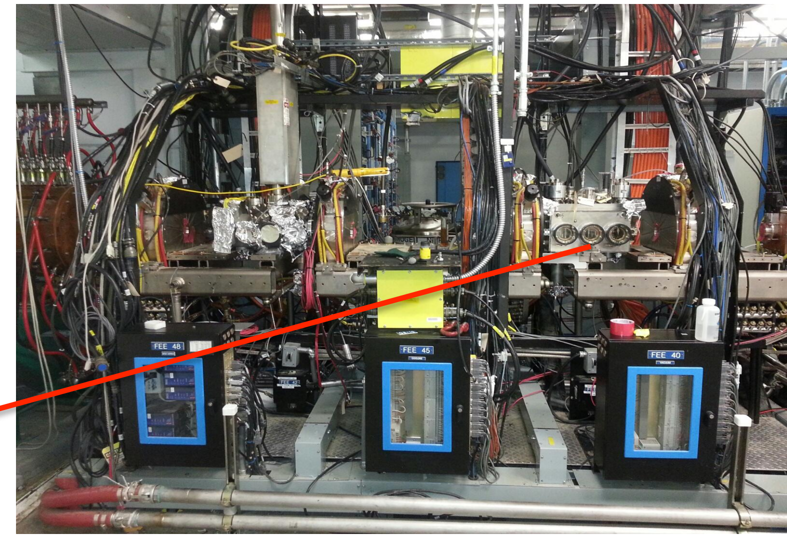
The energy of **beam losses** is about **10-100 J**. The damage mechanisms are not fully understood; it is assumed that some beam hitting the cavity desorbs gas or particulates (= small particles) creating an environment for arcing.

Courtesy of D. Curry, SNS

Accident Example IV

SNS, Oakridge:





Courtesy of D. Curry, SNS

2014: Water cooling of the **MEBT chopper absorber failed** and water entered the MEBT, causing several weeks of downtime. Luckily this happened during a maintenance period (gate valves were closed and **water** was "**stopped**" in the DTL section). The absorber was not interlocked and not periodically checked until this accident happened.

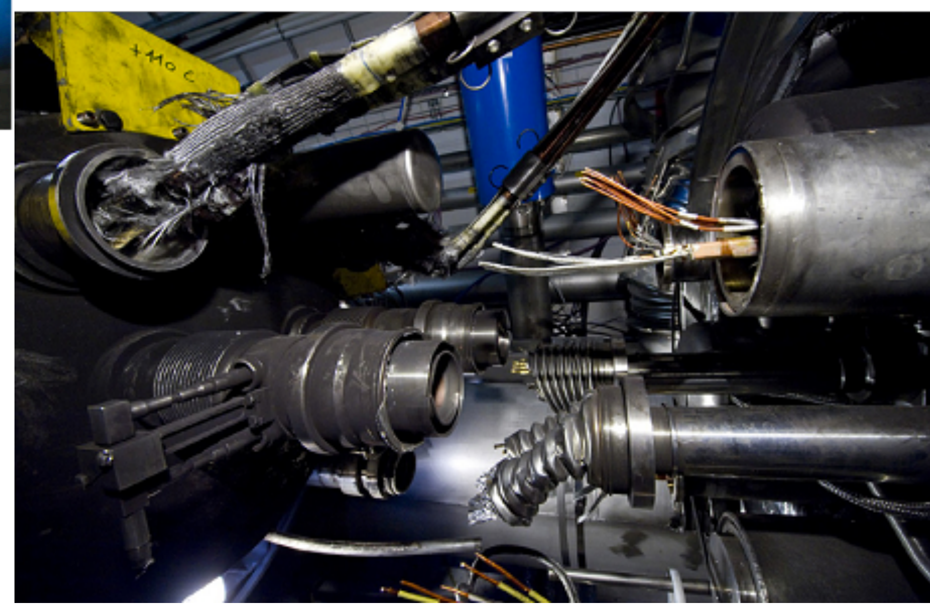
Accident Example V

LHC, CERN:

Quench accident 2008 (no beam!)

Quench:

Sudden transition from the superconducting state to the normal conducting state. Can be caused by increase of temperature, current density or magnetic field above the critical values.



Courtesy of R. Schmidt, CERN

Whom of you has seen a Quench?

“Controlled/Intended” quench of an LHC dipole (prototype) magnet*:

https://www.youtube.com/watch?v=PR2j1IMgOkQ

Shown is a Quench during the magnet training at the CAST experiment (CERN Axion Solar Telescope), located at LHC point 8, to the left & around the corner of LHCb entrance hall

* The only one currently operated at 13 kA [9 Tesla], but “filled” with dark matter, not with beam ☺

What are the **consequences of accidents** like the ones mentioned?

The bad:

- Unplanned **downtime/**no time for science
- Additional **cost** for repair or replacement of damaged equipment
- Unnecessary **beam losses** leading to unnecessary **activation** of equipment

The good:

- **Boost** for **awareness** and **establishment of** a **safety culture**

How could we **describe Machine Protection**?

Check the ‘goals’ on the next slide

Machine Protection Goals

Machine protection shall, in that order, **prevent and mitigate damage** to the machine, be it beam-induced or from any other sources, **in accordance with** beam and facility related **availability requirements**.

Machine protection shall protect the machine **from unnecessary beam-induced activation** having a potential to cause long-term damage to the machine or increase maintenance times, **in accordance with** beam and facility related **availability requirements**.

Some Important Definitions

Functional Safety Term	Functional Protection Term	Definition
Overall safety function	Overall protection function (OPF)	Generic function that protects from a hazard
Safety function	Protection function (PF)	Technology specific function that is part in fulfilling an OPF, containing a sensor, logic, actuator, timing and protection integrity requirement
Safety Integrity	Protection Integrity	Average probability for satisfactorily performing the required PF under the stated conditions
Safety Integrity Level (SIL)	Protection Integrity Level (PIL)	Discrete level for the Protection Integrity Level requirements of the PF.

Term	Definition
Risk	Combination of the frequency of occurrence of damage and the severity of that damage
Risk category	A discrete category specifying the level of Risk for a certain damage event
Damage	A device being affected by external factors in such a way that it (partly or entirely) cannot perform its intended task
Failure	A device being affected by internal factors in such a way that it (partly or entirely) cannot perform its intended task
Hazard	Potential source of damage
Protection	State of being protected against damage
Damage Event	A specific event that damages a device, including the source of damage and the risk category

How can we know if we **need protection** for a specific machine?

What **criteria** are to be considered?

- Damage potential of beam
- Level of expected beam losses (continuous and accidental)
- Delicacy of equipment (failure modes, state of the art, spares, etc)
- Means to inject, stop, or extract beam
- Availability requirements
- Environment: location of equipment (radiation, temperature, humidity)
- Prepare for the unknown, if you operate at unprecedented energy, power etc.

Damage Potential of Beam

To know about **heating of material** or **damage to material** due to beam, we need:

Momentum of the particle,

Particle **type**,

Energy stored in the beam,

Beam **power**,

Beam **size**,

Beam **power/energy density** (J/mm^2, W/mm^2),

Time structure of the beam,

Cooling conditions.

In order to estimate the **order of magnitude for possible damage**:

One MJ can heat and **melt ~1.5 kg of copper**;

One MJ corresponds to the energy stored in ~**0.25 kg of TNT**;

One MW during one second **corresponds to one MJ**.

Beam Losses

Continuous beam losses: inherent during operation of accelerators.

Accidental beam losses: transient losses with time scales from ns to many seconds due to a multitude of failure mechanisms.

'**Machine protection**' protects equipment from **damage, activation, downtime** due to **accidental beam losses**. Machine protection includes a **large variety of systems**.

Example:

For 1 MW, a loss of 1% corresponds to 10 kW, not to be lost along the beam line to avoid activation of material, heating, etc.

Assuming a length of 200 m, such losses would correspond to 50 W/m.

However: 1W/m is a reasonable limit for hands-on maintenance (see next slide).

Activation – Hands-On Maintenance

An average beam loss of **1W/m** should be a reasonable **limit for hands-on maintenance.**

1W/m corresponds to 6×10^9 protons/[m·s] of energy 1 GeV (uniformly distributed)

Simulations show the following:

If the irradiation time of a steel beam pipe with 1W/m beam losses is 100 days and cool down time is 4 hours, then the effective dose rate at 30cm distance from the beam pipe is about 1mSv per hour.

Courtesy of N.V. Mokhov and W. Chou, 7th ICFA workshop on High intensity high brightness hadron beams, USA, 1999

Delicacy of Equipment/What If?

In order to know **how** and **what** to protect against what kind of failures, its vital to set up a **failure catalogue** of your machine.

There are a lot of different **risk/hazard/failure analysis methods** on the market. AND…None of these is able to give you the ultimate answer ☺

Some advise:

Absolutely **avoid** performing only a "silo-**system**" **component failure** analysis, Consider also the **functions** relevant for operations that a certain system shall provide.

Focus on the **complexity and also** the **interplay of several systems performing one specific function**!

Risk Matrix

Create a **risk matrix** that helps you to categorize the failures based on consequences and severity (delicate and not so easy in fact).

Align the risk levels **with availability goals** of the facility/machine.

Such matrix can be used to understand the risk reduction needs and to prioritize.

Get this matrix **approved by upper management**.

The **two main criteria for the risk matrix for Machine Protection** are:

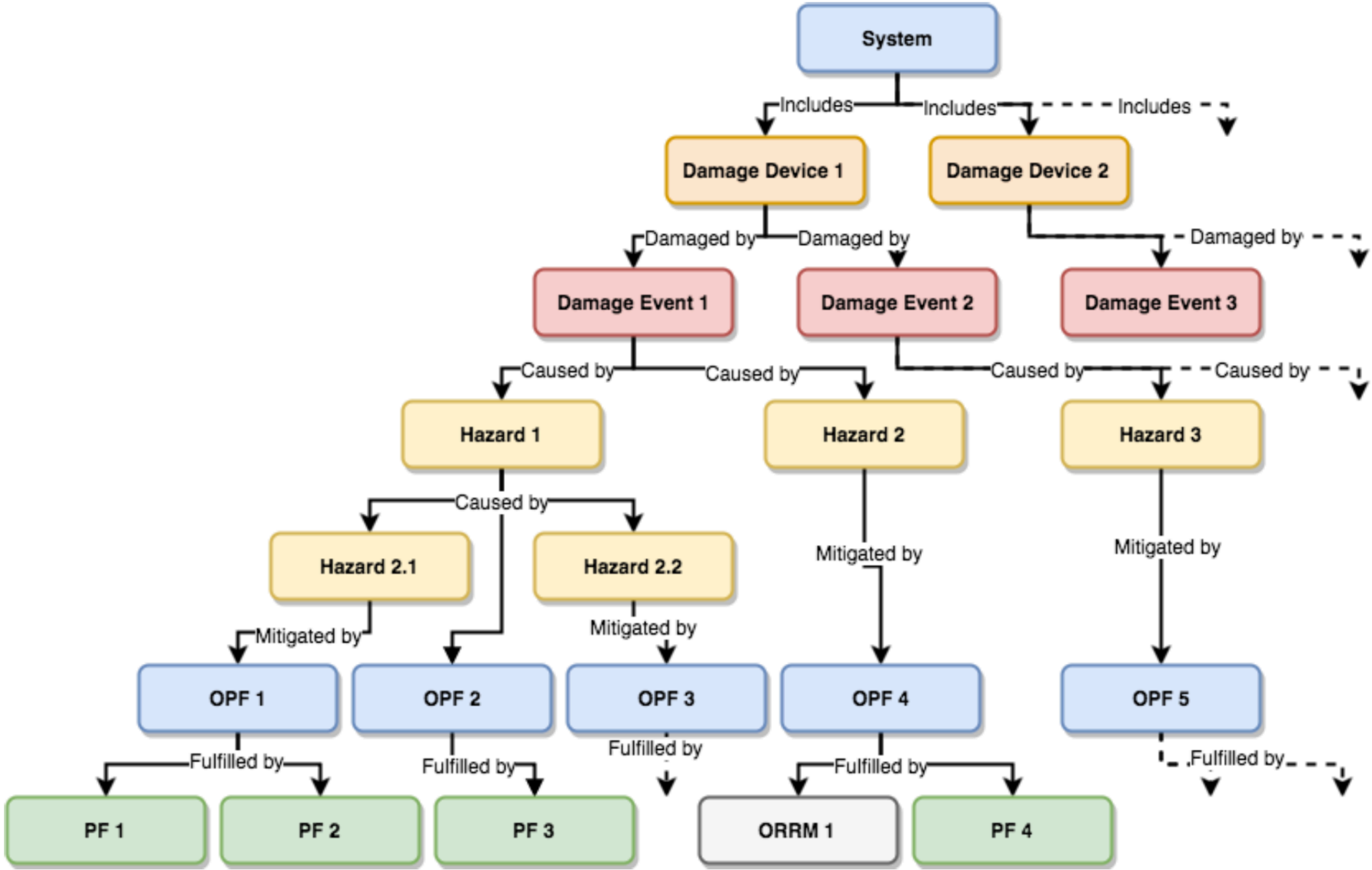
- **Downtime**
- **Cost to repair/replace the damaged equipment**

Risk Matrix as used for MP at ESS

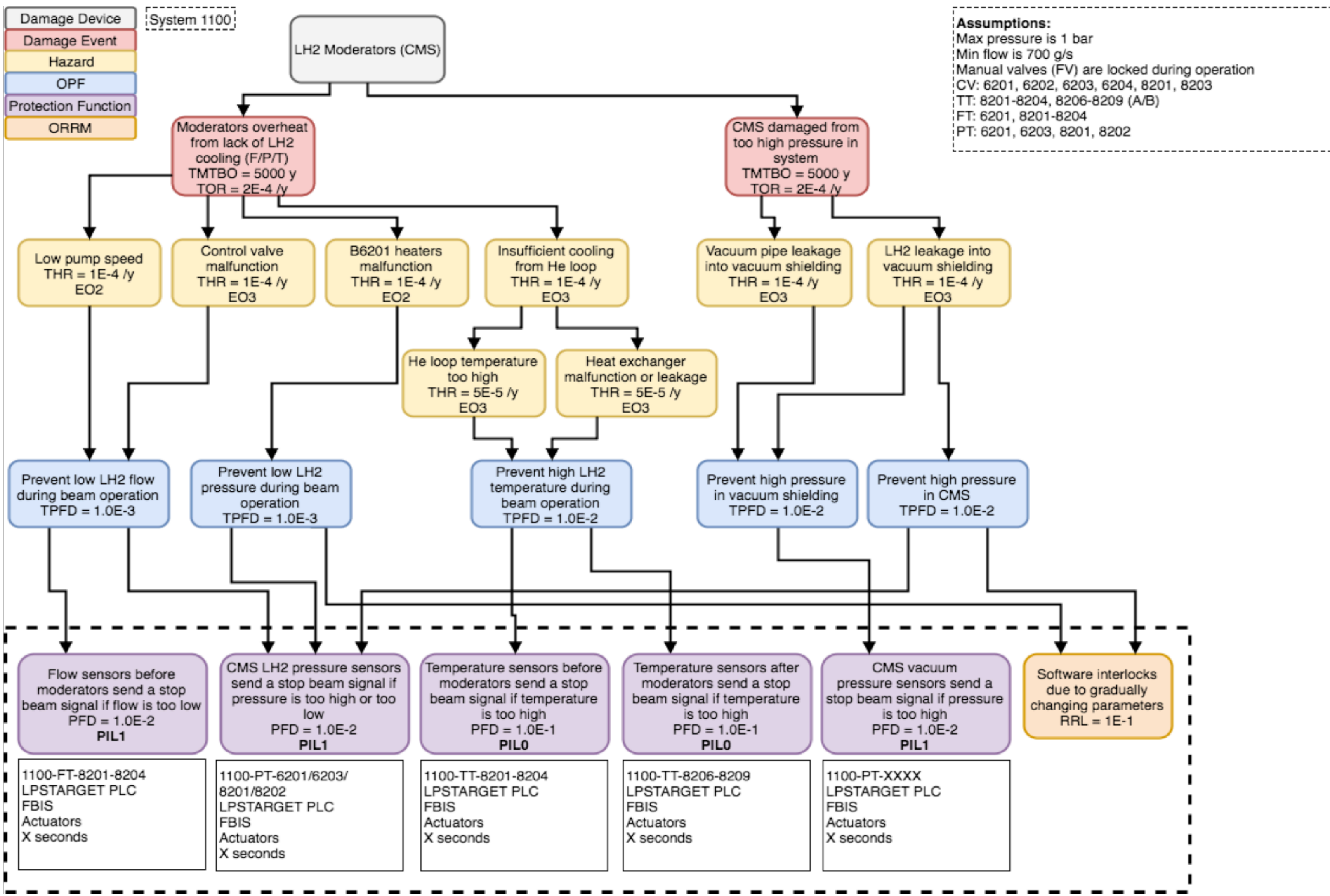
	Downtime				
Cost	< 1h	1h – 1d	1d – 14d	14d – 10m	> 10m
< 0.1M€	Minor	Moderate	Significant	Significant	Severe
0.1M€ – 1M€	Moderate	Moderate	Significant	Significant	Severe
1M€ – 5M€	Significant	Significant	Significant	Severe	Severe
>5M€	Severe	Severe	Severe	Severe	Severe

	Consequence			
Mean Time Between Occurrences	Minor	Moderate	Significant	Severe
> 5000 y				
> 500 y				
> 50 y				
> 5 y				

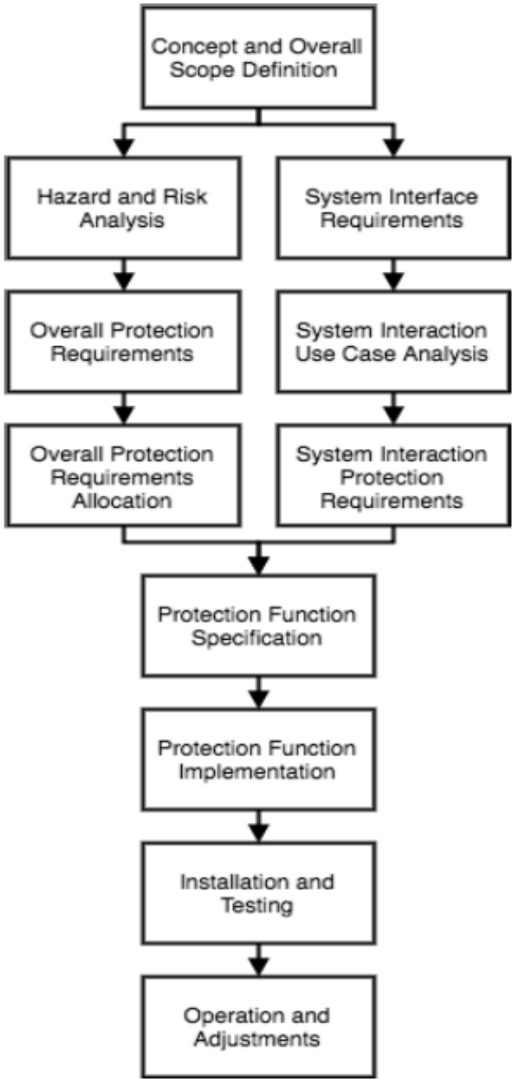
Analysis as done at ESS

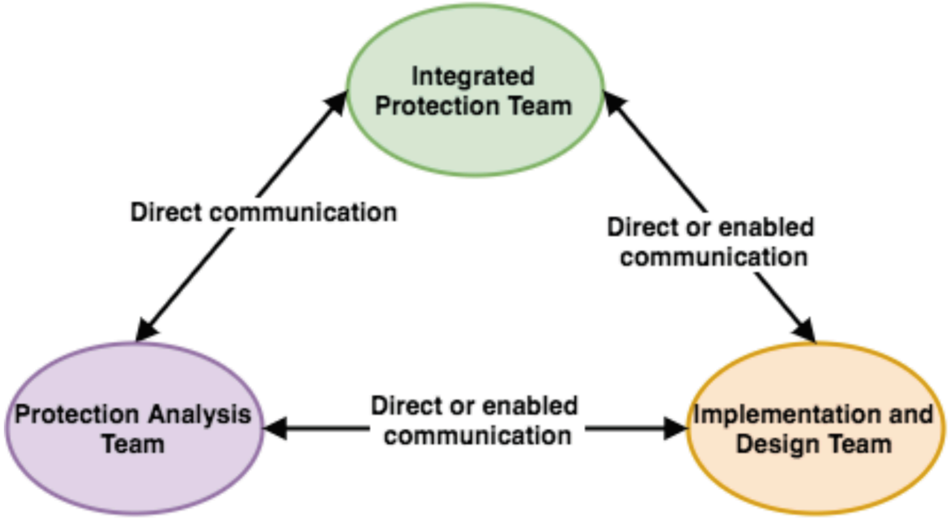


Analysis Example: ESS Neutron Moderator System



Functional Protection Lifecycle at ESS





Further Categorization of Failures

Categorize the **failures not only based on severity**, but also according to, e.g.:

beam induced,

non-beam induced,

locally but impacting on beam,

locally but no effect on beam performance

Very important is also to **understand** the **time evolution of failures**, like:

slow [days, hours, seconds],

fast [ms],

ultra-fast [ns, µs]

Means to Inject/Extract/Stop Beam

Understand how the **beam** is being **injected** into your machine.

Understand how **beam** can be **extracted** or **stopped**, for example by using:

Kicker magnets and extracting beam to a dump

Choppers to deflect beam to an absorber

Switch off the **source** or inhibit further extraction from source

Availability Requirements

Understand the **availability requirements** of your facility/machine.

User and medical facilities usually have very strict availability requirements.

Why?

How can we define these requirements?

Ideas?

Environment of Your Equipment

Understand where the equipment will be located

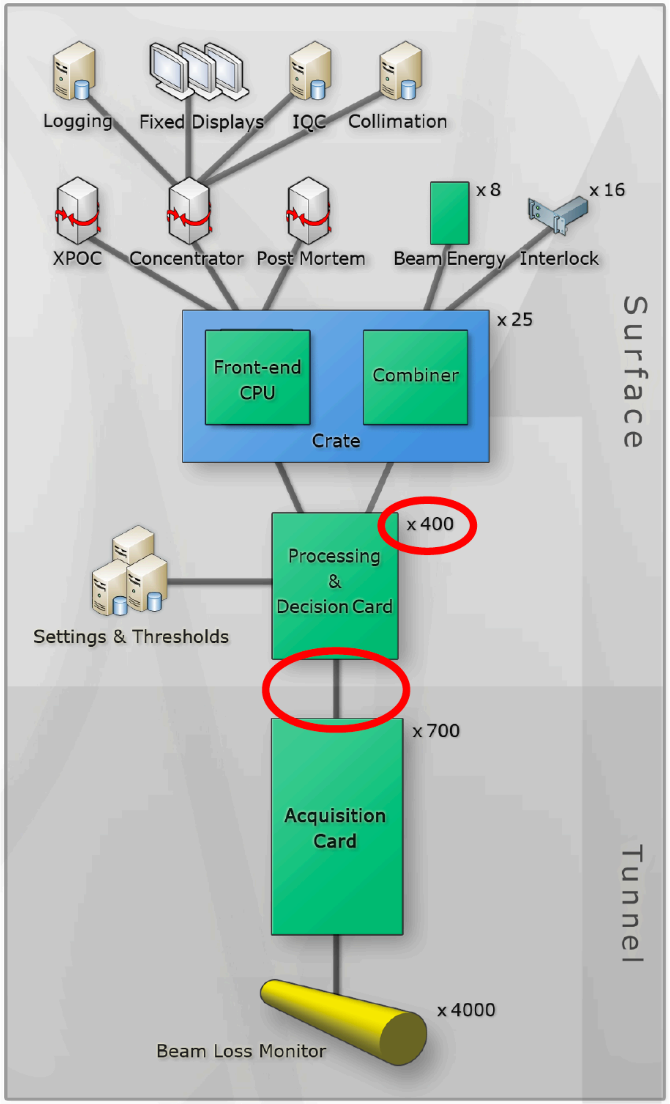
This also contributes in achieving high availability and high reliability

Examples:

Avoid electronics in an radiation area (single event upsets)
Avoid high temperatures and high humidity
Avoid exposure to water, fire, etc.
Always try to equip with rich diagnostics for efficient failure tracking

Environment Example: LHC BLM System I

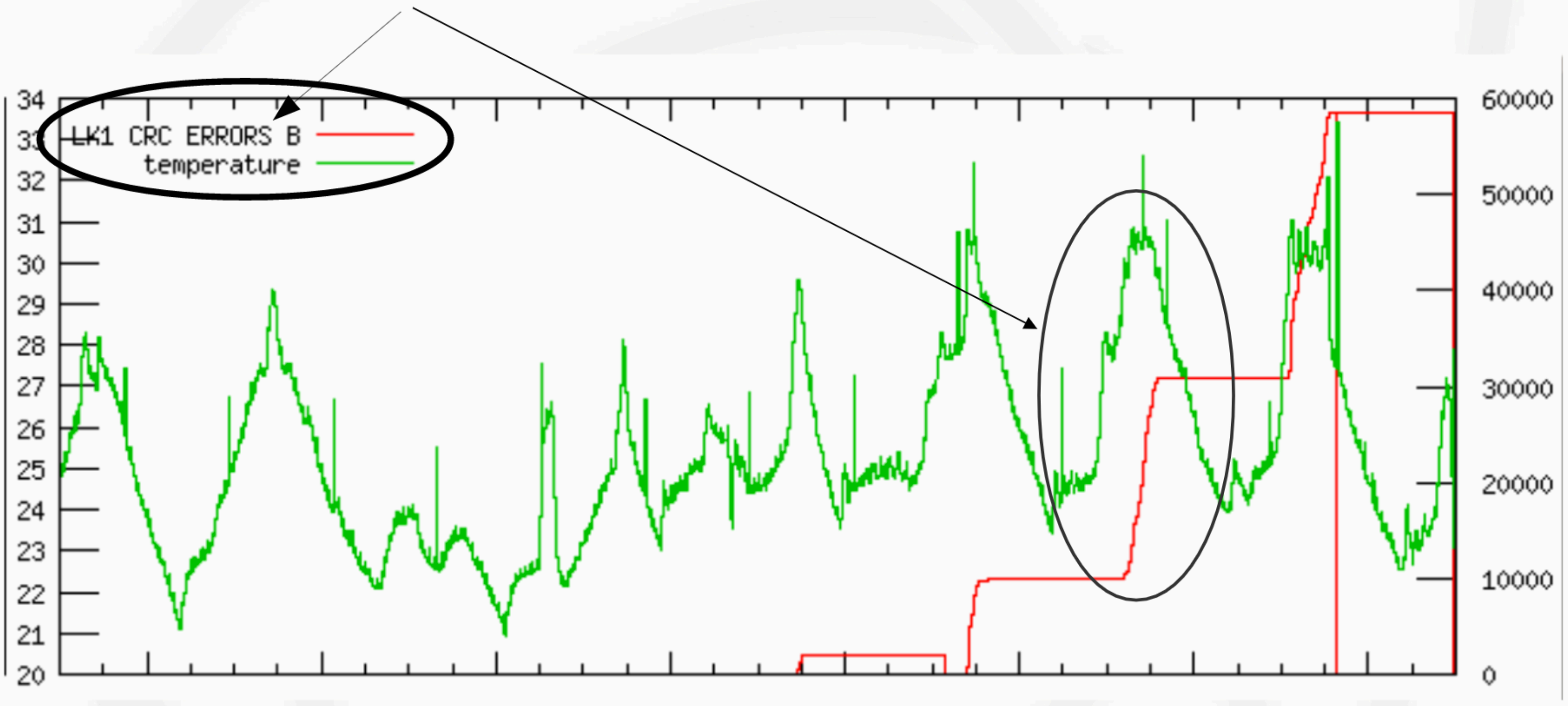
- 25.000 data packets/second/link and 1600 links!
- Continuous checks on data transmission (FPGA level)
- In 14 cases lost packets can induce an LHC beam dump
- Automatic offline monitoring and survey on lost packets (check of 12 variables):
  - Nr of CRC comparison errors between links,
  - Nr of CRC comparison errors on links,
  - Nr of lost frames,
  - Nr of lost frame IDs.
- Correlation with temperature?



A cyclic redundancy check (**CRC**) is an error-detecting code commonly used in digital networks and storage devices to detect accidental changes to raw data. Blocks of data entering these systems get a short check value attached, based on the remainder of a polynomial division of their contents.

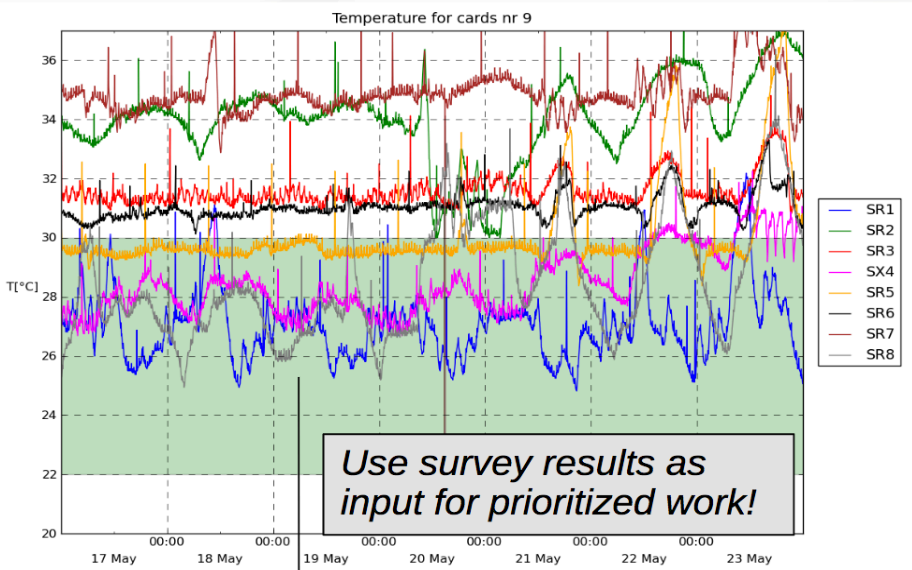
Environment Example: LHC BLM System II

Correlation of CRC error rate with temperature can be confirmed!



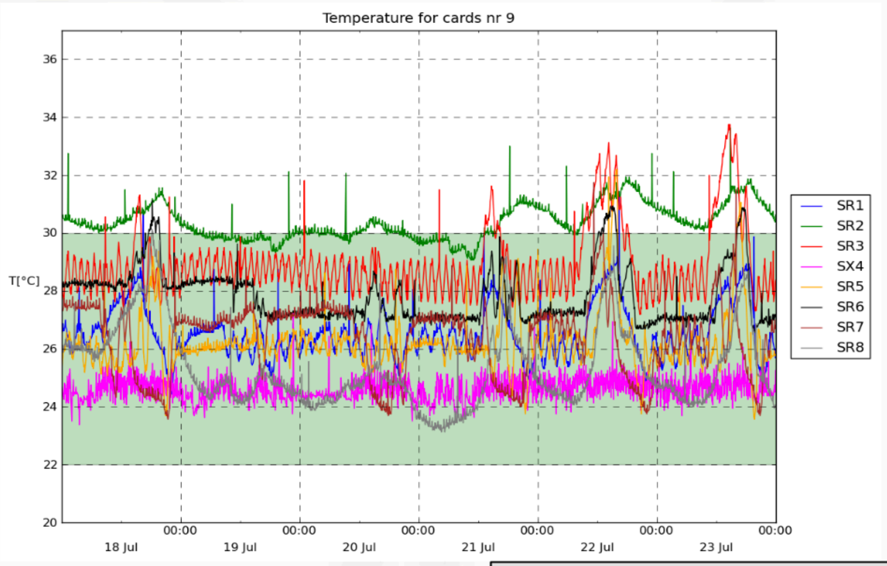
Environment Example: LHC BLM System III

Status temperatures: 2010

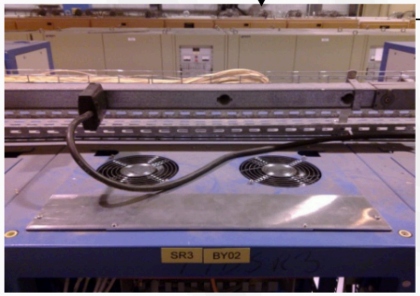


Use survey results as input for prioritized work!

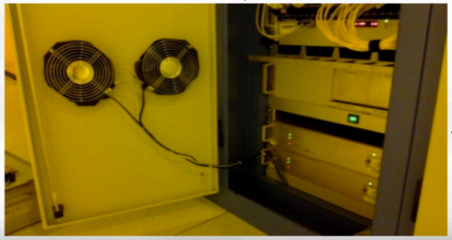
Status temperatures: 2011



Result:
Improved cooling and
Less optical link errors



Install additional ventilation



Environment Example: LHC BLM System IV

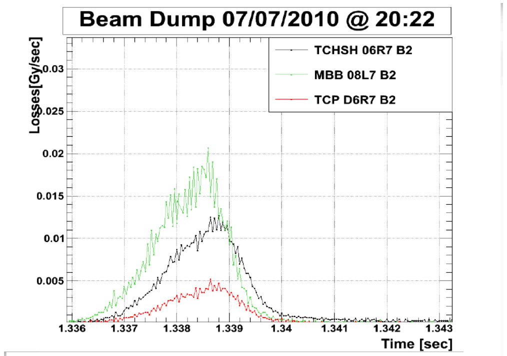
The **key message** from this example is:

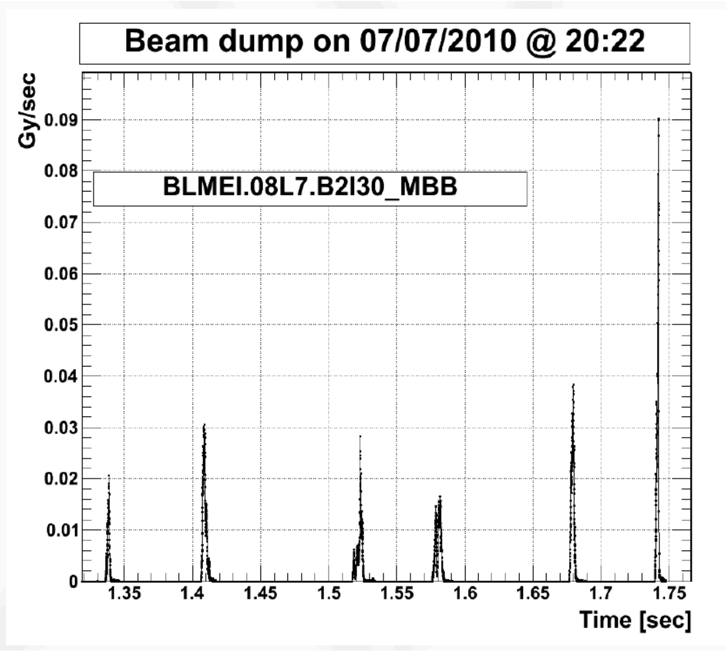
Equip the system with **rich diagnostics**, like e.g. with temperature and humidity sensors (here: directly on electronics level)

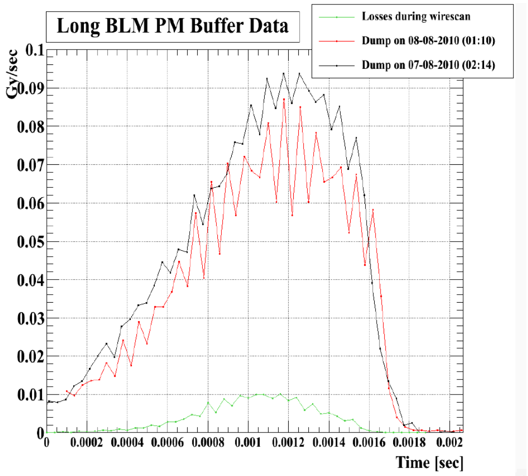
Archive the data and make it available (in an easy way) for further analysis

Optimize performance by reducing false trips

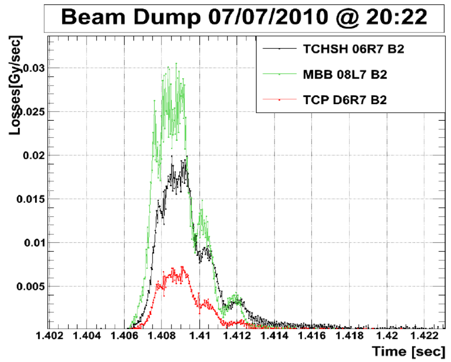
UFOs in LHC?

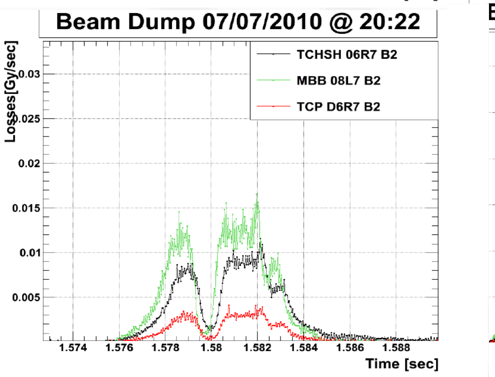


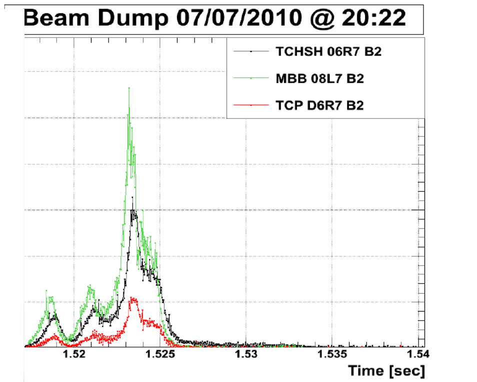


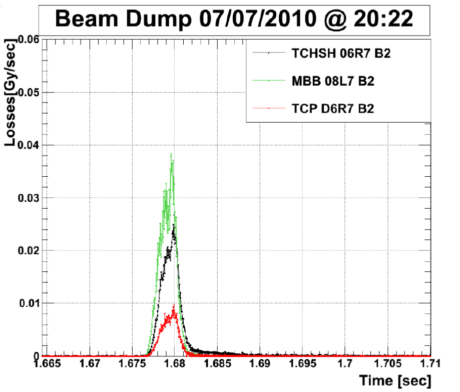


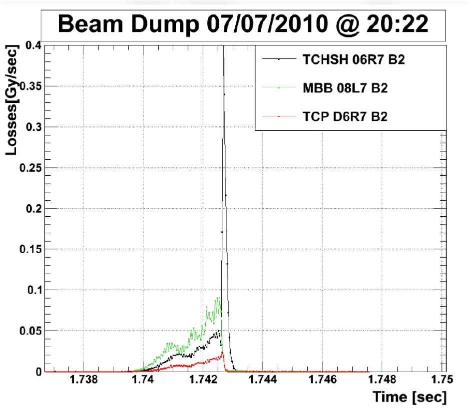
Compare with wire scan losses











Mission Impossible?

Very tough to foresee and prepare for some features, like e.g. the UFOs in LHC

It is certainly very helpful to have highly **reliable beam instrumentation systems**, with a **large dynamic range**:

> do not focus only on the huge beam loss detection but also allow on detection and analysis of very small beam losses

Archive data with high quality/resolution and allow for quick correlation of different data sets from different systems (synchronized time stamping can be helpful too)

Equip vital systems with a lot of diagnostics and make measurements accessible

Summarizing what has been said and defining some basic MP requirements

We could write down the following

Means to Achieve Machine Protection

- Designing and operating the **equipment** under control (EUC) **with high inherent reliability** and overall low damage potential,

- Minimization of the mean down time (MDT) of EUC by introducing **dedicated technical systems** preventing and **mitigating damage**,

- Minimization of the MDT of EUC systems by introducing dedicated **operational and preventive maintenance procedures** reducing the probability for (unscheduled) corrective maintenance,

- **Supporting systems** dedicated to reducing MDT. These include **analysis, management and recovery tools** addressing operational activities related to machine protection (e.g. for post-mortem analysis).

Machine Protection General Requirements I

Machine protection functions shall be implemented:

- **with timing and protection integrity levels** in accordance with damage risk reduction requirements.
- such that the **probability of spurious trips is reduced** in accordance with availability and damage risk reduction requirements.

Machine Protection General Requirements II

Machine protection shall:

- **transmit all necessary information to** the responsible staff allowing them to take adequate actions to resume facility operation within a minimum amount of time.
- **record all information** about detected off-nominal states and performed prevention and mitigation actions to allow for a-posteriori event reconstruction and analysis.
- **support operation** during all foreseen lifecycle phases of the machine, including, but not limited to assembly and installation, commissioning, tuning, operation, fault-finding, maintenance, and dismantling.

Machine Protection General Requirements III

Machine protection shall support:

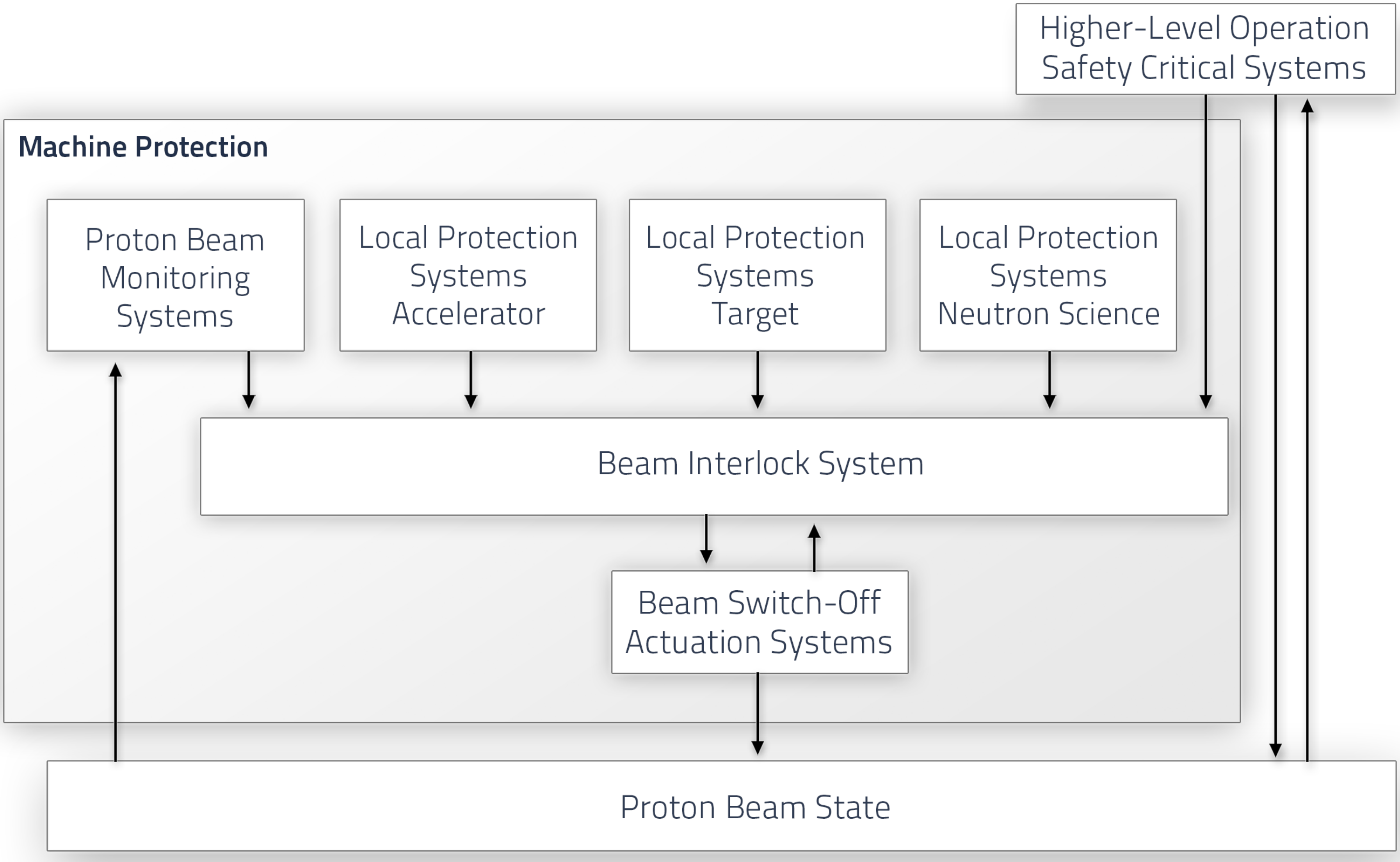
- **all** foreseen **operating modes** of the machine, including but not limited to beam up to intermediary targets, beam with reduced beam power or alternative beam envelopes, beam with alternative duty cycles.
- **operation in case of degraded mode** of operation of equipment under control, if required for reaching the availability goals and if compatible with damage risk reduction requirements.
- **operation in case of degraded protection functions**, if required for reaching the availability goals, and still be compatible with damage risk reduction requirements.

Machine Protection SoS Architectural Framework

Machine Protection can be recognized as **System-of-Systems (SoS)**.
Composed of **five classes** of constituent systems:

1. Local MP-related systems,
2. MP-related beam monitoring systems,
3. Beam Interlock System,
4. MP-related beam switch-off actuation systems,
5. MP management systems.

Functional MP-SoS Architecture Concept at ESS



Local MP Related Systems I

The **local MP-related systems implement** the needed **local protection functions to**:

- **keep the local system protected from non-beam-induced damage**,
- **prevent beam** from being switched on/injected **if the local system is not ready** to support beam operation,
- If a local damage risk gets detected, these local protection functions will result in a **locally protected** state for the affected system,
- **If such** an **action** has a potential to negatively **influence** the state of the **beam**, the local protection functions **additionally trigger a switch-off** of the **beam**.

Local MP Related Systems II

- If the local system is not ready to support beam production, the local protection functions will not permit beam.

- If other systems depends on the operation, then necessary actions will need to be taken to prevent damage to that other system.

Local MP-related systems can implement a:

- **LOCAL-PERMIT**: state variable that is internal to the system and represents whether it is correctly functioning or an off-nominal state has been detected.

- **BEAM-PERMIT:** communicated to the Beam Interlock System and tells whether the system is in a state where beam production is safe or not.

Proton Beam Monitoring Systems

MP related Proton Beam Monitoring Systems:

- The MP-related proton-beam monitoring systems detect any off-nominal states of the beam itself that might cause damage to or unnecessary activation of any equipment.
- The corresponding protection functions will trigger a switch-off of the beam by means of a BEAM-PERMIT signal transmitted to the Beam Interlock System.

MP related Beam Monitoring Local Protection Systems:

- detect off-nominal states that might lead to damage to the beam instrumentation itself,
- detect states where the monitoring systems are not ready for beam operation

Beam Interlock System

- The **Beam Interlock System evaluates the BEAM-PERMIT signals** from all local MP-related systems and MP-related beam monitoring systems.

- **If required, the Beam Interlock System initiates the switch-off of the beam** by triggering a set of MP-related beam switch-off actuation systems in a specific sequence, allowing for a **painless** recovery to normal operation.

- **The BIS will verify the correct reaction of the actuation systems** and, in case beam is not switched-off, an emergency sequence disregarding any recovery requirements will be triggered.

- **After an interlock**, beam production will only be allowed to resume once all relevant BEAM-PERMIT input signals are in the expected state and **all affected MP-related systems as well as the Beam Interlock System have been actively reset**.

Implementation of Machine Protection

Machine Protection cannot be implemented by a single group of people or a single work package.

A **common effort across many divisions is needed** to ensure the right level of protection.

Team work is vital for implementing machine protection!

Awareness, openness, global thinking as well as understanding the impact and consequences of certain decisions on a global (machine wide) level is **highly important.**

Thank You for Listening!

Special thanks to:

CERN teams:
R. Schmidt et al.
B. Dehning et al.
B. Goddard et al.

ZHAW team:
C. Hilbes et al.

SNS teams:
D. Curry et al.
M. Plum et al.

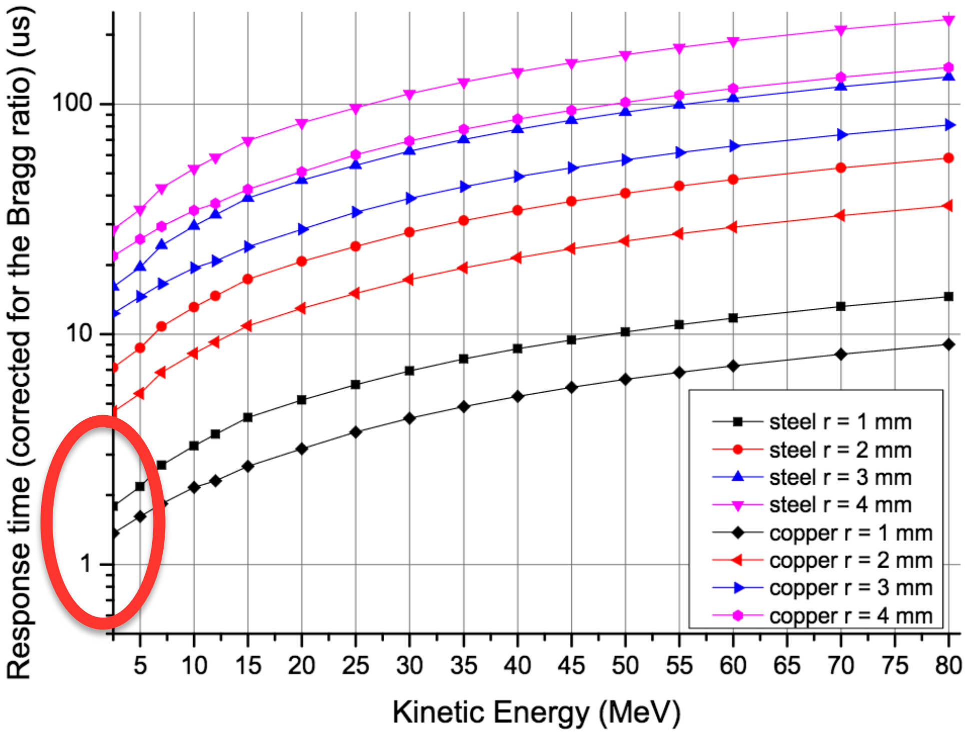
ESS teams:
M. Eshraqi et al.
T. Shea et al.
E. Bargallo, A. Vergara

Example Beam Loss Studies

at European Spallation Source, ESS

The Time Needed to Melt Copper or Steel

Assuming perpendicular beam impact, 1 mm beam size at 1MeV, then melting **WOULD** start in 1 μs!



Courtesy of L. Tchelidze, ESS

But can it really happen and how?

Yes it Can Happen

Simulations have shown that 90° beam impact is possible in the MEBT scrapers.

Fastest reaction time required to stop proton beam is **1-5µs.**

This includes detecting, processing and actual stopping of the proton beam.

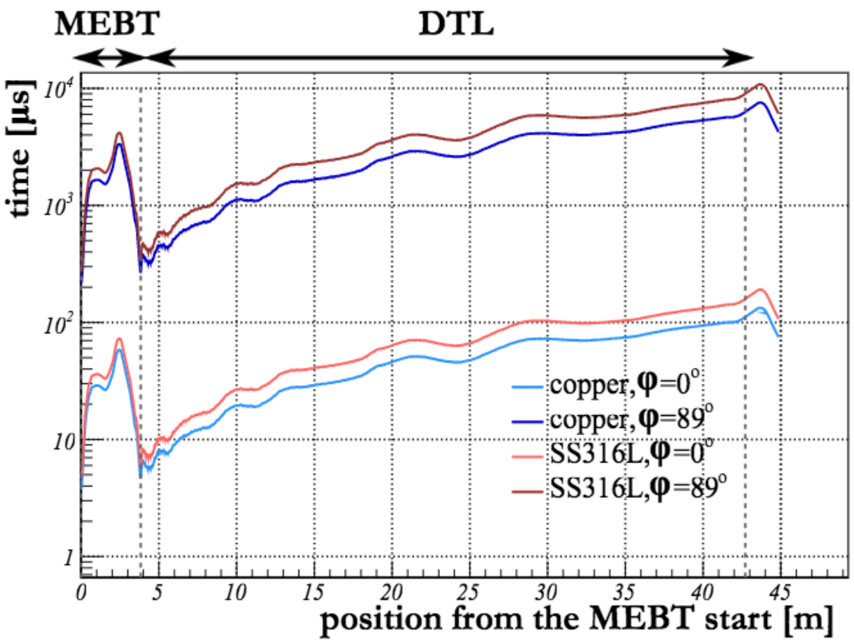
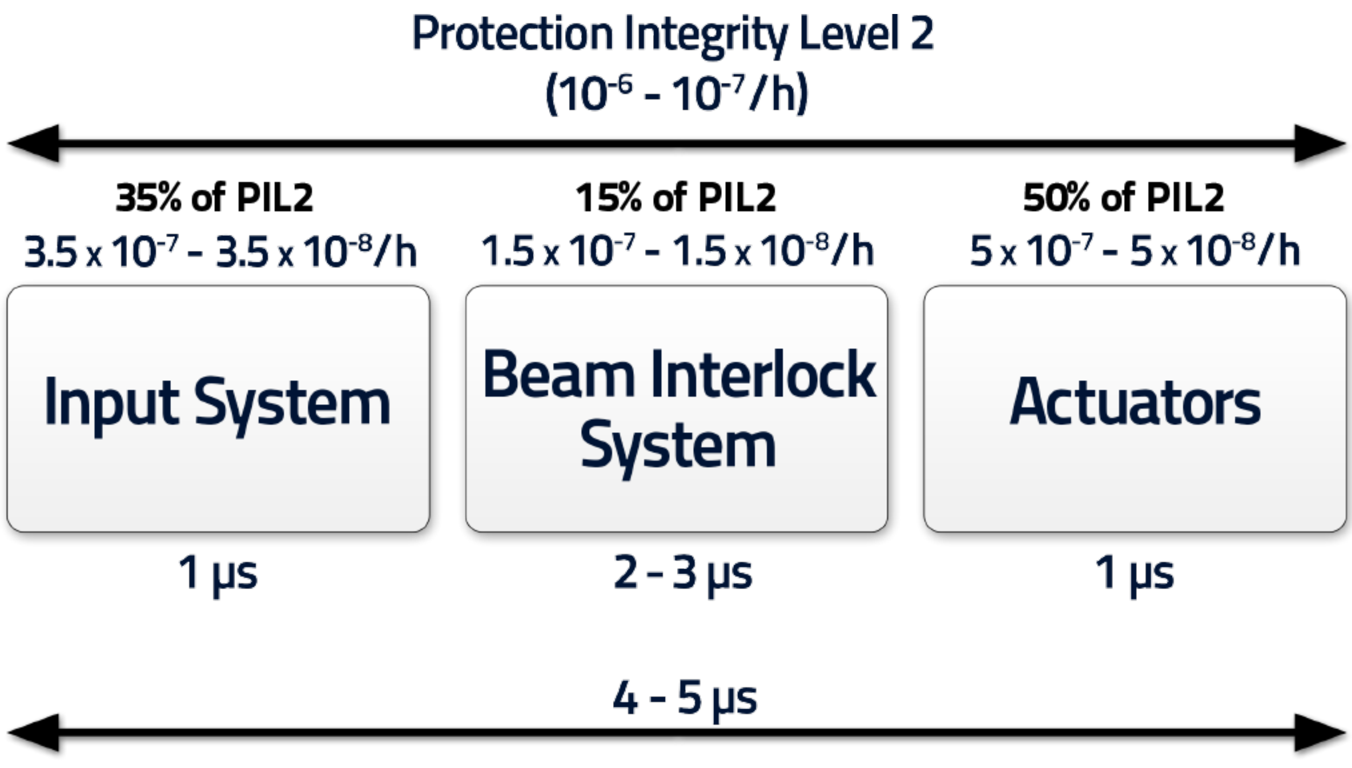


Figure 3: Time to melt a block of copper (blue) or stainless steel (red) under constant irradiation with a proton beam under perpendicular incidence (φ=0°) or a very shallow angle.

Courtesy of I. Kittelmann/ HB2016 THAM6Y01

How Fast/How Reliable/Example ESS

Based on preliminary risk
analysis (IEC61508, IEC61511)



Requirements at ESS