Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

The unexpected

Summary
Accelerators, as all other technical systems, must respect some general principles with respect to safety:

- Protect the people (legal requirements).
- Protect the environment (legal requirements).
- Protect the equipment (asset management).
  - Without beam: superconducting magnets, high power equipment, power cables, normal conducting magnets, RF systems, etc.
  - With beam: damage caused by beams.

Those 3 aspects may be coupled in some circumstances!

This presentation on “Machine Protection” is focused on equipment protection from damage caused by beams.
All major accelerator projects are pushed to new records.

- **Higher beam energy and intensity:**
  - Hadron colliders – LHC.
  - Linear e+e- colliders.
  - CERN Future Circular Colliders study.

- **Higher power and brightness:**
  - Neutron spallation sources.
  - Neutrino physics.
  - Synchrotron light sources (synchrotron light power).

>> the energy (density) stored in the beams increases!

In many modern projects machine protection aspects have a large impact on (or may even dominate) design and operation.

Frequent mixing of superconducting magnets/RF and high power beams
Modern accelerators

- High power accelerators - from some 10 kW to above 1 MW.
  - Neutron spallation sources (SNS, ISIS).
  - High power/high duty cycle machines (PSI cyclotron, JPARC).

- High energy hadron colliders and synchrotrons.
  - LHC and its upgrades.
  - Synchrotrons for fixed target experiments (SPS).

- e+e- colliders.
  - B-factories (KEKB, super-KEKB).

- Synchrotron light sources.
  - High power photon beams.

- Linear colliders/ Free Electron Lasers (FEL).
  - SLAC linac, ILC, CLIC, FLASH, XFEL.

- Energy recovery linacs.

- Medical accelerators.
  - The patients!
Protection is required since there is some risk.

Risk = probability of an accident
\[ \times \text{consequences (in Euro, downtime, radiation doses)}. \]

> Probability of an uncontrolled beam loss:
  > What are the failures that lead to beam loss into equipment?
  > What is the probability for the failure modes?

Consequences:
  > Damage to equipment.
  > Downtime of the accelerator for repair.
  > Activation of material, dose to personnel.

>> The higher the risk, the more protection becomes important!
Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

The unexpected

Summary
Relevant parameters for MPS

- Momentum of the particle
- Particle type
  - Activation is mainly an issue for hadron accelerators.
- Energy stored in the beam
  - 1 MJ can heat and melt 1.5 kg of copper.
  - 1 MJ = energy stored in 0.25 kg of TNT.
- Beam power
- Beam size
- Time structure of beam

Key factor: how easily and how fast the energy is released!!

One LHC beam = 360 MJ = ?

The kinetic energy of a 200 m long train at 155 km/hour

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate
LHC design : 360 MJ
4 TeV record : ~140 MJ

LHC beams become really dangerous in the SPS
Beam loss in materials

- Lost particles induced particle cascades in materials they traverse.
  - The peak energy deposition can be deep in the material at the maximum of the hadron / electromagnetic shower.
  - Particle showers from hadrons with energies of 100’s of GeV to some TeV have a penetration depth of some meters.

- The energy deposition leads to a temperature increase, and for very fast losses to shock waves and to plastic deformation.
  - Material can melt, vaporize, deform or lose its mechanical properties.
  - Limited risk for some 10 kJ, large risk for some MJ.
  - Equipment becomes activated due to beam losses.
  - Superconducting magnets can quench (become normal-conducting).
A real case from the 2008 SPS run!
- Impact on the vacuum chamber of a 400 GeV beam of \(3 \times 10^{13}\) protons (2 MJ).
- Event is due to an insufficient coverage of the SPS MPS (known!).
- Vacuum chamber to atmospheric pressure, downtime ~ 3 days.

Risk = (3 days downtime + dose to workers) \(\times\) (1 event / 5-10 years)
In the past decade a lot of effort was invested to better understand the interaction of high energy / high density beams with matter.

Experiments:
  - *Ad-hoc experiments for the LHC*,
  - *Construction of a dedicated test facility at CERN (HiRadMat @ SPS)*.

Modeling and comparison with tests.
  - *Many matter phases (solid, liquid, plasma), ‘hydro-codes’*.

Some outcomes:
  - Validation of LHC carbon collimator robustness,
  - Validation of damage thresholds for LHC injection energy,
  - Validation of simulation codes,
  - Search for more robust material.
SPS experiment: damage at 450 GeV

Controlled SPS experiment / protons.
- Energy 450 GeV,
- Beam area $\sigma_x \times \sigma_y = 1.1 \times 0.6 \text{ mm}^2$,
- Damage limit for copper at $2 \times 10^{12}$ p.
- No damage to stainless steel.

Damage limit is $\sim 200 \text{ kJ}$, < 0.1 % of a nominal LHC beam.

Impact D: ~1/3 of nominal LHC injection.
HiRadMat tests – new materials

*Courtesy A. Bertarelli (EN)*

- **Inermet 180, 72 bunches**
- **Molybdenum, 72 & 144 bunches**
- **Glidcop, 72 bunches (2 x)**
- **Copper-Diamond 144 bunches**
- **Molybdenum-Copper-Diamond 144 bunches**
- **Molybdenum-Graphite (3 grades) 144 bunches**
## Inermet: comparison between simulation and experiment

<table>
<thead>
<tr>
<th>Case</th>
<th>Bunches</th>
<th>p/bunch</th>
<th>Total Intensity</th>
<th>Beam Sigma</th>
<th>Specimen Slot</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>60</td>
<td>1.5e11</td>
<td>9.0e12 p</td>
<td>2.5 mm</td>
<td>9</td>
<td>316 m/s</td>
</tr>
<tr>
<td>Experiment</td>
<td>72</td>
<td>1.26e11</td>
<td>9.0e12 p</td>
<td>1.9 mm</td>
<td>8 (partly 9)</td>
<td>~275 m/s</td>
</tr>
</tbody>
</table>

*Courtesy A. Bertarelli (EN)*
Small…but dangerous

- Damage @ Linac4 with a 3 MeV beam – vacuum leak.

- Failure combination:
  - Beam misaligned,
  - Unlucky magnet setting,
  - Aperture limitation at bellow.

At such low energies, the local energy loss per proton is very high
⇒ Damage after some integration time
The 2008 LHC accident happened during test runs without beam. A magnet interconnect was defect and the circuit opened. An electrical arc provoked a He pressure wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km.

53 magnets had to be repaired.
Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

The unexpected

Summary
Modern Machine Protection System : \(P^3\)

- **Protect the machine**
  - Highest priority is to avoid damage of the accelerator.

- **Protect the beam**
  - Complex protection systems reduce the availability of the accelerator, the number of “false” interlocks stopping operation must be minimized.
  - Trade-off between protection and operation.

- **Provide the evidence**
  - Clear (post-mortem) diagnostics must be provided when:
    - the protection systems stop operation,
    - something goes wrong (failure, damage, but also ‘near miss’).
In accelerators, particles are lost due to a variety of reasons: beam gas interaction, losses from collisions, losses of the beam halo, …

- Some (continuous) beam losses are inherent to the operation of accelerators.
  - Taken into account during the design of the accelerator.
  - Max. loss rates may be given by the design:
    - Prevent magnet quenches (LHC).
    - Allow maintenance (residual contact radiation).

- Accidental beam losses are due to a multitude of failures mechanisms.

Analysis and structure required!
Failure classification

- **Failure type:**
  - **Hardware failure** (power converter trip, magnet quench, AC distribution failure, object in vacuum chamber, vacuum leak, RF trip, ...).
  - **Controls failure** (wrong data, wrong magnet current function, trigger problem, timing system, feedback failure, ...).
  - **Operational failure** (chromaticity / tune / orbit errors, ...).
  - **Beam instability** (high beam / bunch current).

- **Failure parameters:**
  - **Damage potential.**
  - **Probability** for the failure.
  - **Time constant** for beam loss.

- **Machine state (when failure occurs):**
  - Linac, beam transfer, injection and extraction (single pass).
  - Stored beam.

*Mixture defines the risk and the criticality for MP*
MPS design strategy

- Avoid a failure by design – if you can.
- Detect a failure at the hardware (equipment) level and stop operation – first protection layer.
- Detect the consequences of the failure on beam parameters (orbit, tune, losses etc) and stop operation – second protection layer.

- Stop beam operation.
  - *Inhibit injection*,
  - *Send beam to a dump*,
  - *Stop the beam by collimators / absorbers*.

- Elements of protection:
  - Equipment and beam monitoring,
  - Collimators and absorbers,
  - Beam dumps,
  - Interlock system linking different systems.
Passive and active protection

Passive protection
- Collimators.
- Masks.
- Absorbers.
- Dumps.

Obstacles to absorb the energy

Active protection
- Equipment surveillance.
- Beam observation.
- Extraction (dump) kickers.

Detection of a failure directly on the equipment or by its effects on the beam.

Modern MP systems usually require both passive and active protection to cover all failure cases.
Failure time scales – circular machines

- **Single turn (single-passage) beam loss**
  - Failures of kicker magnets (injection, extraction kicker magnets).
  - Transfer failures between two accelerators or from an accelerator to a target station.

- **Very fast beam loss (μs - ms)**
  - Multi turn beam losses in rings.
  - Large variety of possible failures, mostly in the magnet powering system, with a typical time constant of some 10 turns to many seconds.

- **Fast beam loss**
  
- **Slow beam loss**
  
**Time scale**

- High reliability
  - Passive protection
    - ns - μs

- Active Protection
  - Passive protection
    - μs - ms

- 10 ms - s
- many s
Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

The unexpected

Summary
The LHC

IR4: RF + Beam instrumentation
IR5: CMS
IR1: ATLAS
IR2: ALICE
IR8: LHC-B
Injection
Beam loss monitoring

- Ionization chambers are used to detect beam losses:
  - Very fast reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- ~3600 chambers (BLMS) are distributed over the LHC to detect beam losses and trigger a beam abort!
- BLMs are good for almost all failures as long as they last ~ a few turns (few 0.1 ms) or more!
LHC

3600 x

IR5: CMS

IR4: RF + Beam instrumentation

IR2: ALICE

IR1: ATLAS

IR8: LHC-B

Injection

Injection
The LHC requires a complex multi-stage collimation system to operate at high intensity.

- Previous hadron machines used collimators only for experimental background conditions.

Almost **100 collimators**, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam.

140 MJ in each beam versus few mJ to quench a magnet.
To be able to absorb the energy of the protons, the collimators are staged – primary, secondary, tertiary – multi-stage system.

The system worked perfectly – also thanks to excellent beam stabilization and machine reproducibility – only one setup / year.

- ~99.99% of the protons that were lost from the beam were intercepted.
- *No magnet was quenched in operation at 3.5/4 TeV.*
LHC

IR4: RF + Beam instrumentation

IR5: CMS

IR1: ATLAS

IR2: ALICE

IR3: Momentum Collimation

IR7: Betatron Collimation

IR8: LHC-B

3600 x

100 x

Opening

7 Feb 2014
The BLM signals near the experiments are almost as high at the collimators (steady losses) due to the luminosity.

- At the experiments the BLM record collision debris – in fact the physics at small angles not covered by the experiments!!
LHC beam dumping system

When it is time to get rid of the beams (also in case of emergency!), the beams are ‘kicked’ out of the ring by a system of *kicker magnets* and send into a dump block!

15 fast ‘kicker’ magnets deflect the beam to the outside

10 kicker magnets dilute the beam

15 septum magnets deflect the beam vertically

≈ 900 m

≈ 500 m

beam dump block

Ultra-high reliability system
LHC dump line
The LHC dump block

The dump block is the only LHC element capable of absorbing the nominal beam.
The dump is the only LHC element capable of absorbing the nominal beam.

*Beam swept over dump surface to lower the power density.*

- A beam screen installed in front of the dump provides monitoring of the dump execution.

*The shape of the beam impact is checked against prediction at each dump!*

30 cm
Let us pick an example for the LHC

- **Step 1:** Figure out what can go wrong…
  - Requires good understanding of *accelerator physics*: how does a given element affect the beam?
  - Requires good understanding of the *hardware*: time scales, failure modes?
  - Requires a complete *overview* of all machine equipment that affect the beam.
  - The analysis must be done systematically for every system, from bottom up – including the software/controls.
Failure analysis process – step (2)

- Step 2: Identify a critical element – the D1’s.

LHC room temperature (normal conducting) separation/recombination dipoles (‘D1’) around ATLAS and CMS.

Those magnets are very strong (large deflections) and they are fast –> good candidates
Step 3: Simulate the failure.

- 12 magnets are powered in series.
- Large betatron function when squeezed ($\beta > 2000$ m) $\Rightarrow$ large orbit changes.
- Short time constant $\tau = 2.5$ seconds ($B$ is the magnetic field):

$$B(t) = B_0 e^{-t/\tau}$$

Simulated orbit change along the LHC ring a few milliseconds after failure.

It does not fit!
The simulations indicate absence of redundancy (we only have beam loss monitors) and very short reaction times for BLMs → we want an extra-layer of protection at the equipment level.

This analysis triggered the development of so-called FMCMs (Fast Magnet Current change Monitor) that provide protection against fast magnet current changes after powering failures - CERN - DESY/Hamburg collaboration.

Very fast detection (< 1 ms) of voltage changes on the circuit. Tolerances of ~ 10^{-4} on ΔI/I are achievable.
Step 5: Test failure of PC and FMCM reaction.

- *Switch off D1 PC – simulated failure.*
Failure analysis process – step (6)

- Step 6: Real test with beam – no FMCM
  - Low intensity (‘safe’) test beam.
  - Switch off D1 PC – simulated failure.
  - Beams dumped by the LHC BLMs when beams hit the collimators.

From the LHC Post-Morten system

Beam dump!
Step 7: Real test with beam – with FMCM

- Low intensity (‘safe’) test beam.
- Switch off D1 PC – simulated failure.
- Beam dumped by FMCM.

Orbit change in mm

Beam dump!

No measurable orbit change

From the LHC Post-Morten system

LHC turn number
Timescales @ LHC

- **1 turn** = 89 μs
  - Kicker magnets
  - Transverse feedback
  - NC magnet powering failures

- **10 turns**
  - Operation 'mistakes'

- **100 turns**
  - Quenches

- **1000 turns**
  - Quench protection
  - Power converter interlocks

- **10000 turns**
  - Operational 'mistakes'

- **Time**
  - Absorbers
  - BLMs
  - BPMs
  - FMCM
The beam’s gone immediately isn’t it?

- Unfortunately even the best failure detection takes some time, the signal must be propagated to the dumping system, the dumping system must synchronize to the beam.

  - Unavoidable delay to fire the dump!

At the LHC the delay can be up to ~3 turns – ~300 μs.
It took more than a year of commissioning and tuning (e.g. BLM thresholds) to reach the maximum intensity at 3.5/4 TeV.
Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

The unexpected

Summary
Very fast and localized beam losses were observed as soon as the LHC intensity was increased in 2010.

The beam losses were traced to dust particles falling into the beam – ‘UFO’.

If the losses are too high, the beams are dumped to avoid a magnet quench.

– ~20 beams dumped / year due to UFOs.
– We observe conditioning of the UFO-rate from ~10/hour to ~2/hour.

In one accelerator component UFOs were traced to Aluminum oxide particles.

UFOs could become an issue at 7 TeV!
10000 turns = 0.89 s
1000 turns
100 turns
10 turns
1 turn = 89 μs

Thanks to the broad coverage of the LHC MPS, UFOs are not a problem (for protection !)
Incidents happen

JPARC home page – January 2014

2013.07.26 Message from Director of J-PARC Center

We have been working together to investigate the causes of the accident and to develop the efficient safety management system to prevent recurrence of similar accidents since the radioactive material leak accident at the Hadron Experimental Facility (HD Facility) on May 23.

>>> more
Due to a power converter failure, a slow extraction was transformed into a fast extraction.

- *Extraction in milliseconds instead of seconds.*

As a consequence of the high peak power a target was damaged and radio-isotopes were released into experimental halls.

>> machine protection coupled to personnel protection !

Investigations and protection improvements delayed the restart of the JPARC complex for ~7-8 months. JPARC is just restarting.

One insufficiently covered failure case had major consequences !
Machine protection:

- requires a comprehensive overview of all aspects of the accelerator (accelerator physics, operation, equipment, instrumentation),
- requires understanding the different failure types that could lead to uncontrolled beam loss,
- affects many aspects of accelerator construction and operation,
- must be an integral part of the machine design,
- is becoming increasingly important for future projects, with increased beam power / energy density and increasingly complex machines.
Stored energies – the future

Energy stored in the beam [MJ]

Momentum [GeV/c]

2015

2023

>2035 ?

VHE-LHC

HL-LHC

LHC ions

TEVATRON

LEP2

PS LHC beam

RHIC proton

SPS ppbar

LEP

SPS transfer to LHC

LHC at injection

LHC 4 TeV

LHC 7 TeV

LHC magnets