Machine Protection

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FAIR - Facility for Antiproton and Ion Research

CERN Accelerator School: Introduction to Accelerator Physics
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Acknowledgment

This lecture is based on previous CAS lectures on Machine protection & Collimation by Rüdiger Schmidt (head of the machine protection at CERN)
The lecture is focused on protection of accelerators from consequences of beam losses

- Introduction
- Beam losses and consequences
- Regular beam losses
- Collimation system
- Accidental beam losses
- Beam loss detection
- Emergency extraction and dumping system
- Summary
# JAS course on Beam Loss and Accelerator Protection

**Joint International Accelerator School on Beam Loss and Accelerator Protection**

**November 5-14, 2014**

<table>
<thead>
<tr>
<th>Time</th>
<th>Wednesday Nov. 5</th>
<th>Thursday Nov. 6</th>
<th>Friday Nov. 7</th>
<th>Saturday Nov. 8</th>
<th>Sunday Nov. 9</th>
<th>Monday Nov. 10</th>
<th>Tuesday Nov. 11</th>
<th>Wednesday Nov. 12</th>
<th>Thursday Nov. 13</th>
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<tr>
<td>10:00</td>
<td>Rudiger Schmidt</td>
<td>Verena Kain</td>
<td>John Galambos</td>
<td>Jorg Wenninger</td>
<td>Rudiger Schmidt</td>
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<td>Verena Kain</td>
<td>Francesco Cerutti</td>
<td>Alessandro Bertarelli</td>
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<td>Enzo Carrone</td>
<td>Marc Ross</td>
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<td>Mike Plum</td>
<td>Nancy Leveson</td>
<td>Alessandro Bertarelli</td>
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<td>Tom Shea (2 hrs)</td>
<td>Howard Pfeffer</td>
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<td>18:30</td>
<td>Dinner, Registration and Talk</td>
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Introduction

- Particle beams produced by **large scale and powerful accelerators**
  - High **energy**: GeV/u – TeV/u
    (e.g. LHC: 7 TeV proton beam)
  - High **power**: kW – MW
    (e.g. PSI cyclotron: > 1.3 MW proton beam)
  - High **intensity**: $10^{13} – 10^{14}$ particles per beam
    (e.g. J-PARC Main Ring: > $3 \times 10^{14}$ particles in the proton beam)
  - High **beam density**: small beam size
    (e.g. LHC: transverse beam size < 1 mm)
  - High **beam stored energy**: kJ – MJ
    (e.g. LHC: > 360 MJ stored energy in proton beam)

- The energy stored in the beam and **power flow** have to be **under control**

- **Why?** Beam or its part can be lost

- **Beam losses** are the particles which deviate excessively from the reference trajectory and hit the aperture constraints (are no longer properly properly transported)
Beam losses and consequences

- **Beam losses**
  - Regular beam losses due to machine errors and beam dynamics processes
    - usually a few % of the beam
  - Accidental beam losses due to hardware failures (magnets, vacuum, ...)
    - can be the whole beam or a significant fraction
  - An uncontrolled energy release or power flow due to interaction of the lost particles with the accelerator structure can lead to serious consequences

- **Consequences** of the uncontrolled beam losses
  - Radiation damage of the accelerator components
  - Destruction or deformation of the accelerator components
  - Superconducting magnet quench
  - Residual activity induced in the accelerator structure
Why do we need protection for accelerators?

- **Ensure safe operation of the machine**
  - When a problem occurs the energy stored in the beam has to be safely disposed

- **Protect the equipment and devices**
  - Prevent radiation damage of the components
  - Prevent destruction or deformation of the components
  - Prevent superconducting magnet quenches

- **Protect the people and the environment**
  - Control residual activation - important for hands on maintenance (people who do installation or repair work in a close contact with the accelerator beam line)
  - High radiation in the area where a technical malfunction occurs → forbidden access → cannot fix the machine → loss of time for operation

Let’s take a closer look at the possible consequences of the beam losses to get better idea why do we need to protect the machine.
Radiation damage

- **Radiation damage** – microscopic defects in the structure of a material induced by ionizing radiation, which change its properties (mechanical, thermal, electrical, …)

**Insulation material (epoxy glass)** irradiated by uranium ions

\[ ^{238}\text{U ions/cm}^2 \]

1\times10^{10} \quad 5\times10^{10} \quad 1\times10^{11} \quad 1\times10^{12}


Change of the insulation material (kapton) breakdown voltage after irradiation

**Note the difference between protons and heavy ions!**


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Ivan Strašík  ●  Machine Protection  ●  CAS, Prague, Czech Republic, 2014
Destruction or deformation

- Destruction or deformation – phase transition (melting, vaporization, sublimation)

Graphite foil

Irradiation by uranium beam (E < 10 MeV/u)
- a) beam **passed** through the foil
- b) beam **stopped** in the foil


Plastic holder

Lead foil

Irradiation by **uranium beam** (E = 200 – 500 MeV/u)
Material damage test at CERN

- **Experiment**: impact of the 450 GeV proton beam from SPS with transverse beam size 1 mm on the target which consists of metal plates
- Carried out to validate the simulation codes

<table>
<thead>
<tr>
<th>Shot</th>
<th>Proton beam intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$1.2 \times 10^{12}$</td>
</tr>
<tr>
<td>B</td>
<td>$2.4 \times 10^{12}$</td>
</tr>
<tr>
<td>C</td>
<td>$4.8 \times 10^{12}$</td>
</tr>
<tr>
<td>D</td>
<td>$7.2 \times 10^{12}$</td>
</tr>
</tbody>
</table>

[Copper plate in depth about 20 cm]

The beam is able to drill a nice hole.

Energy deposition and temperature rise

**Energy loss – Bethe formula**

\[
\frac{dE}{dx} = \frac{4\pi N_A r_e^2 m_e c^2 Z^2 Z \rho}{A \beta^2} \left[ \frac{1}{2} \ln \left( \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{l^2} \right) - \beta^2 - \frac{\tau(\beta \gamma)}{2} \right] 
\]

- light ions
- 0.1 < \beta \gamma < 1000
- Intermediate Z materials
- accuracy of a few %


**Energy deposition**

\[
\frac{dE}{dV} = \frac{dE}{dx} \frac{N}{A} \\
\frac{dE}{dV} \left[ \frac{J}{\text{cm}^3} \right] \\
N - \text{number of particles} \\
A - \text{beam cross-sectional area [cm}^2\text{]}
\]

**Temperature rise**

\[
\Delta T = \frac{dE}{dV} \frac{1}{\rho c_p} \\
\rho \left[ \frac{\text{g}}{\text{cm}^3} \right] \\
c_p \left[ \frac{\text{J}}{\text{g} \cdot \text{K}} \right] \\
\Delta T [\text{K}]
\]

- \rho – material density
- \(c_p\) – specific heat capacity
Performance of various materials

Material parameters

<table>
<thead>
<tr>
<th>material</th>
<th>graphite</th>
<th>aluminium</th>
<th>iron</th>
<th>copper</th>
<th>tungsten</th>
</tr>
</thead>
<tbody>
<tr>
<td>density $\rho$ [g/cm$^3$]</td>
<td>1.7 – 2.3</td>
<td>2.7</td>
<td>7.87</td>
<td>8.92</td>
<td>19.25</td>
</tr>
<tr>
<td>heat capacity $c_p$ [J/(g·K)]</td>
<td>0.71</td>
<td>0.9</td>
<td>0.45</td>
<td>0.39</td>
<td>0.13</td>
</tr>
<tr>
<td>melting or sublimation [K]</td>
<td>3800</td>
<td>933</td>
<td>1811</td>
<td>1358</td>
<td>3695</td>
</tr>
</tbody>
</table>

Example (simulation):
- Irradiation of the materials by 1 GeV proton beam
- Transverse beam size (diameter): 1 cm
- Simulation code: FLUKA (particle transport in matter)
- Energy deposition in a cylinder 1 cm in diameter

Number of particles needed for temperature rise of 1K at maximum energy deposition

<table>
<thead>
<tr>
<th>material</th>
<th>graphite</th>
<th>aluminium</th>
<th>iron</th>
<th>copper</th>
<th>tungsten</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of particles</td>
<td>$1.5 \times 10^{12}$</td>
<td>$2.0 \times 10^{12}$</td>
<td>$1.0 \times 10^{12}$</td>
<td>$8.9 \times 10^{11}$</td>
<td>$3.4 \times 10^{11}$</td>
</tr>
</tbody>
</table>

Compare this with the CERN damage test and you will see how important are the beam size and beam energy.
Superconducting magnet quench

- **Superconducting quench** – sudden transition from the superconducting to the normal conducting state
- Caused by the increase of the temperature, current density or magnetic field in the superconductor above the critical value

Consequences LHC quench accident CERN, 2008
*(quench NOT induced by beam losses)*

Quench level

- **Quench induced by beam losses** – lost particles interact with the superconducting material and deposit energy which leads to the temperature rise.

- **Quench level** – minimal deposited energy to the superconducting wire which is able to rise the temperature to the critical value and consequently to induce quench.

- The quench level can be expressed in case of fast losses (transition state) in mJ/cm$^3$ and in case of slow losses (steady state) in mW/cm$^3$.

- It can be in order of a few mJ/cm$^3$ or a few mW/cm$^3$.

The amount of uncontrolled beam losses per 1 m of beam line arose in a short time (< 1 ms), which is able to
a) induce quench and b) cause damage in the LHC dipole magnet.

<table>
<thead>
<tr>
<th>Beam energy [TeV]</th>
<th>Quench level [particles/m]</th>
<th>Damage level [particles/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>$10^9$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>7</td>
<td>$10^6$</td>
<td>$10^{10}$</td>
</tr>
</tbody>
</table>


For comparison: total beam intensity: $3 \times 10^{14}$
Residual activation

- **Residual activation** – production of radioactive nuclei in construction materials of an accelerator due to interaction with high energy particles

**Activation process:** nuclear reactions
- spallation reactions (the most important for high energy accelerators)
- radiative capture of low-energy neutrons
Nuclear reactions and radionuclide production

- Spallation reactions
  - Nuclear cascades
  - Shower of the secondary particles

Radionuclides detected in the accelerator construction materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Radionuclides</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon, plastic</td>
<td>$^7$Be, $^{11}$C</td>
<td>53.1 days, 20.4 minutes</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Above plus: $^{22}$Na, $^{24}$Na</td>
<td>2.6 years, 15.0 hours</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Above plus: $^{43}$K, $^{46}$Sc, $^{48}$V, $^{51}$Cr, $^{52}$Mn, $^{54}$Mn, $^{56}$Co, $^{57}$Co, $^{58}$Co, $^{59}$Fe, $^{60}$Co</td>
<td>22.3 hours, 83.8 days, 16.0 days, 27.7 days, 5.6 days, 312.3 days, 77.3 days, 271.8 days, 70.9 days, 44.5 days, 5.3 years</td>
</tr>
<tr>
<td>Copper</td>
<td>Above plus: $^{65}$Ni, $^{64}$Cu, $^{65}$Zn</td>
<td>2.5 hours, 12.7 hours, 244.3 days</td>
</tr>
</tbody>
</table>

[Ref] I. Strasik et al., NIMB 266, 3443 (2008)
[Ref] V. Chetvertkova et al., NIMB 269, 1336 (2011)
Tolerable beam losses and radiation protection

"average beam loss of 1 W/m in the uncontrolled area should be a reasonable limit for hands-on maintenance."


- 1 W/m → $6 \times 10^9$ protons/(m·s) of energy 1 GeV (uniformly distributed)

Simulation of the steel beam pipe residual activity induced by beam losses of 1 W/m

Simulation tool: FLUKA – MC code (particle transport in matter)
Irradiation time: 100 days
Cooling time: 4 hours

Effective dose rate at 30 cm is about 1 mSv per hour

For comparison

- Natural background radiation (annual dose) 2 mSv
- Medical radiation sources (e.g. CT scan) 10 - 20 mSv
- Limit for radiation workers (annual dose) 20 mSv


ALARA – As Low As Reasonably Achievable
Machine protection related to the beam losses

- Prevent uncontrolled regular beam losses
  - **Cause:** beam dynamics processes and machine errors → beam halo
  - **Consequences:** superconducting magnet quench, residual activation
  - **Cure:** collimation system (beam cleaning)

- Prevent uncontrolled accidental beam losses
  - **Cause:** machine failures
  - **Consequences:** radiation damage, material destruction, superconducting magnet quench
  - **Cure:** extraction & dumping system, collimation system for passive protection
Regular beam losses & beam halo

- **Beam dynamics** processes and machine errors → **beam halo** formation
  - General definition of the beam halo – difficult due to variety of machines and beams
  - Description – **low density**, **large amplitudes** of the betatron oscillations, **diffusion speed**


- Beam halo → **uncontrolled regular beam losses**
- Halo removal (beam cleaning) → **collimation system**


The collimation system: defense against beam loss

[Ref] S. Redaeli, on behalf of the LHC collimation project team, CERN COURIER, Aug. 19, 2013

- Consists of devices which intercept halo particles (future lost particles)
- Restrains high uncontrolled beam losses in the accelerator
- Provides well defined and shielded storing location for the beam losses
- Can be very complex and made of radiation resistant materials
- Prevents superconducting quench, uncontrolled activation, radiation damage
- Residual activity is much higher (hot spot) compared to other components

Without reliable collimation system that prevents quenches, operation of some superconducting machines would not be possible (e.g. LHC: amount of beam losses significantly exceed the quench level)!
Simple idea of the halo collimation

Naively, all particles that enter the collimator are stopped in the collimator.

However, that is usually not the case…

...most of the halo particles hit near edge (small impact parameter) and scatter out of the collimator!

Impact parameter is usually very small: tenths of nm - a few µm

Two stage betatron collimation system

- **Primary collimator** (thin foil) – scattering of the halo particles
- **Secondary collimators** (bulky blocks) – absorption of the scattered particles

- Particles have small impact parameter on the primary collimator
- The impact parameter on the secondary collimator is enlarged due to scattering

Very robust concept and well established in many accelerators.

Scattering in the primary collimator

Molière theory of multiple Coulomb scattering

\[ \theta_{\text{rms}} = \frac{13.6}{\beta c p} \sqrt{\frac{L}{L_R}} \left( 1 + 0.038 \times \ln \left( \frac{L}{L_R} \right) \right) \]

roughly Gaussian for small deflection angles


Protons and \(^{12}\)C\(^{6+}\) ions 0.1 – 10 GeV/u scattered in 1 mm thick tungsten foil

\[ p \] – momentum in MeV/c,
\[ \beta \] – relativistic parameter beta
\[ c \] – speed of light
\[ Z \] – atomic number of the incident particle
\[ L \] – thickness of the target
\[ L_R \] – the radiation length of the particle in the target material

Choice of the scattering foil material is important.

Scattering of 4 GeV protons

Thickness \(L\) needed to have the same angle \(\theta_{\text{rms}}\)

<table>
<thead>
<tr>
<th>Material</th>
<th>Graphite</th>
<th>Copper</th>
<th>Tungsten</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_{\text{rms}} ) [mrad]</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>(L) [mm]</td>
<td>52</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

But don’t forget to the radiation damage
Normalized phase space

Real phase space

\[ x'_\text{max} = \sqrt{\varepsilon \gamma} \]
\[ x_{\text{max}} = \sqrt{\varepsilon \beta} \]
\[ \text{Area} = \pi \varepsilon \]

\[ \varepsilon = \gamma x^2 + 2\alpha xx' + \beta x'^2 \]

Normalised phase space

\[ \bar{x}'_{\text{max}} = \sqrt{\varepsilon} \]
\[ \bar{x}_{\text{max}} = \sqrt{\varepsilon} \]
\[ \text{Area} = \pi \varepsilon \]

\[ \varepsilon = \bar{x}^2 + \bar{x}'^2 \]

Real to normalized coordinates:

\[ \begin{pmatrix} \bar{x} \\ \bar{x}' \end{pmatrix} = \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ \alpha & \beta \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix} \]

\[ \begin{pmatrix} \bar{x} \\ \bar{x}' \end{pmatrix} = \frac{1}{\sqrt{\beta}} x \\ \bar{x}' = \frac{1}{\sqrt{\beta}} \alpha x + \sqrt{\beta} x' \]

Transport of the particles in the normalized phase space:

\[ \begin{pmatrix} \bar{x}_{s_1} \\ \bar{x}'_{s_1} \end{pmatrix} = M \begin{pmatrix} \bar{x}_{s_0} \\ \bar{x}'_{s_0} \end{pmatrix} \]

\[ M = \begin{pmatrix} \cos \mu & \sin \mu \\ -\sin \mu & \cos \mu \end{pmatrix} \]
Normalized phase space plots at the collimators

$n_P, n_S$ – normalized aperture of the primary and secondary collimators

$\mu_{S1}, \mu_{S2}$ – phase advances between the collimators

$\delta$ – retraction distance

Optimal phase advances:

$$\mu_{S1} = \arccos \frac{n_P}{n_S}$$

$$\mu_{S2} = \pi - \mu_{S1}$$

Particle transport through the collimation system

- Particles with **small deflection angle** escape from the collimation system in the single passage through the collimation system (primary → 2nd secondary collimator)

Simulation of the beam collimation using MAD-X (particle tracking code)

- P - primary collimator
- S1 – 1st secondary collimator
- S2 – 2nd secondary collimator

*What happens with the particles that escape?*
Multi stage collimation: LHC collimation system

“LHC employs the largest and most advanced cleaning system ever built for a particle accelerator”
[Ref] S. Redaelli, on behalf of the LHC collimation project team, CERN COURIER, Aug. 19, 2013

- Consists of more than 100 collimators (primary, secondary, tertiary collimators, absorbers)

Very robust and efficient system (cleaning efficiency > 99.99 % with stored beam)

\[
\text{Efficiency} = \frac{N_C}{N_L} \\
N_C - \text{collimated lost particles} \\
N_L - \text{amount of beam losses}
\]

Extremely high efficiency is required to prevent quench.

[Ref] LHC Collimation Project, R. Aßmann (former head), S. Redaelli (present head), {http://lhccollimation-project.web.cern.ch/lhc-collimation-project/}
Most of the LHC collimators consist of two parallel jaws about 1 m long.

Radiation resistant materials – only carbon based materials withstand direct LHC beam impact.

Top view, open collimator

Carbon composite jaw

Carbon composite jaw, front view

Beam passage through the collimator

Front view, open jaws

[Ref] LHC Collimation Project, R. Aßmann (former head), S. Redaelli (present head), {http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/}
Multiturn particle motion and beam loss maps

- Consider the motion in circular accelerators (synchrotrons)
- Particles scattered at a small angle in the primary collimator and are not further intercepted by the secondary collimators can be still collimated in the next turns

Example: LHC collimation of 3.5 TeV proton beam – simulation & measurement
Simulation tool: SixTrack (particle tracking code)
Measuring devices: Beam loss monitors (detection of the beam losses)

Advanced techniques: bent crystal channeling

- Crystal lattice constrains the path of a charged particle passed through a crystalline solid along the bent planes. This process is called **channeling**.

![Crystal lattice diagram](image)

- Critical angle $\theta_C$:
  \[
  \theta_C = \sqrt[2]{\frac{E_C}{p v}}
  \]

  - $E_C$ – critical energy (maximum value of the interplanar potential)
  - $p$ – momentum of the particle
  - $v$ – velocity of the particle

- In silicon, is the $E_C = Z_{\text{ion}}16$ eV, where $Z_{\text{ion}}$ is the charge state of the ion

- For 100 GeV protons, the $\theta_C \approx 19 \mu$rad

- Equivalent dipole magnetic field: 1000 T (or even more)!

The idea for the crystal collimation is to use a bent crystal as the primary collimator for deflection of the halo particles by the channeling towards the secondary collimator.

Dechanneling — caused by scattering of the channeled particle due to interaction with electrons, nuclei and lattice defects.

Dechanneling length $L_D: \quad L_D \propto p$

[Ref] W. Scandale et al., Annual Workshop on Crystal Collimation (2010)

[Ref] V.M. Biryukov et al., Crystal channeling and its applications at high-energy accelerators, Springer (1997)
Advanced techniques: hollow electron beam

- Based on electromagnetic field generated by the hollow electron beam.
- Halo particles experience nonlinear transverse kicks.

\[ \theta_r = \frac{1}{4\pi\varepsilon_0} \frac{2I_r L (1 \pm \beta_e \beta_p)}{r \beta_e \beta_p c^2 (B\rho)_p} \]

- \( I_r \) – electron current
- \( L \) – length of the interaction region
- \( r \) – radial distance
- \( \beta_e, \beta_p \) – beta relativistic parameters
- \( B\rho \) – magnetic rigidity

For 980 GeV protons, the \( \theta_r \approx 0.3 \) µrad

- Current density profile of the electron beam is shaped by electrode geometry and maintained by strong solenoidal fields

Collimation using hollow electron beam

- Hollow electron lens *enhances diffusion speed* of the halo particles → *larger impact parameter* on the collimator.
- No nuclear fragmentation of heavy ions and no material damage.

Hollow electron beam collimation in Tevatron (Fermilab)

Accidental beam losses

- Caused by hardware failures (magnets, cavities, control systems, ...)

- Usually faster and quantitatively higher than the regular beam losses (lost is significant part or the whole beam in the time range of μs – s)

- When detected, the beam require an immediate emergency extraction to the beam dump in order to prevent component damage or magnet quenches

- Categorized from slow (beam lifetime longer than 1 second) up to ultra fast or singlepass (beam is lost in 1 turn)

- The all categories except the ultra fast losses can be detected using the Beam Loss Monitor (BLM) system

- The ultra fast losses, which are caused e.g. by failures of the magnets are beyond the capabilities of the active protection (emergency extraction) and are handled by the passive protection (e.g. collimators, absorbers,...)

Beam loss monitors

- Beam loss monitor (BLM) – ionization chamber to detect beam losses
- BLM provide a current signal proportional to the intensity of the particle shower passing through the chamber
- Very short reaction time (40 µs) and very large dynamic range (> 10^6)


Principle of the ionization chamber

Inside of the BLM: (LHC type)

Parameters of the BLM (LHC type):
Length: 50 cm
Diameter: 9 cm
Gas: N₂
Beam loss monitors (LHC type)

- BLM system is a powerful diagnostic tool which monitors the beam losses along the beam line.
- About 4000 BLMs installed around the LHC at the locations where the losses are predicted.
- When the BLM system detects an excessive beam losses it triggers the beam abort (emergency extraction and dumping of the beam).

**BLMs @ LHC:**

*Simulation using FLUKA particle transport code*


[Ref] V. Lavrik, BLM study @ GSI, 2nd Fluka Advanced Course and Workshop (2012)
Beam loss monitors and quench level

- Threshold of the BLM signal is adjusted in order to request emergency extraction and beam dump before the beam losses cause the quench of the superconducting magnet.
- The electronics integrates the signal from the BLMs over different integration intervals.
- The integrated value in each interval is compared with predefined thresholds.
- When the threshold is exceeded, the system immediately requests emergency extraction.

Expected quench levels for LHC superconducting magnets as a function of the beam loss duration.

Emergency extraction

- A combination of **kicker** and **septa magnets** is frequently used to extract the beam.
- Kicker magnets: **fast rise times**, the **field strength is relatively low**.
- Septa magnets: **slow pulsed**, the **field is relatively strong**.
- The kicker deflects the beam into the septum.
- The septum deflects the kicked beam into the transfer line.
- In the emergency extraction the beam is delivered to the **beam dump**.

[Ref] M.J. Barnes et al., CERN Accelerator School: Specialised Course on Magnets, 141 (2009)
Extraction from the accelerator (example)

- In reality a more complicated system of the kicker and septa magnets is needed

Simulation of the extraction from SIS100 synchrotron (FAIR@GSI)
Simulation tool: MIRKO (code for accelerator design and beam optics)

Fast extraction system in J-PARC MR has two functions:

- to **extract the beam to the experimental area** (regular extraction to the neutrino beam line)
- to **abort the beam operation in case of failure** (emergency extraction to the beam dump)

The same (**bipolar**) kicker magnets are used.

[Ref] K. Fan et al., *Proceedings of the IPAC’14*, p. 821
[Ref] G.H. Wei et al., *Proceedings of the IPAC’10*, p. 3918
Beam dump

- Beam dump is an accelerator component designed to stop high energy primary particles (to absorb their kinetic energy)
- Kinetic energy of the primary beam particles is transferred to the kinetic energy of the secondary particles, heat or mechanical stress
- Secondary particles are either stopped directly by the beam dump or slowed down and then absorbed by the surrounding shielding (usually concrete)
- Beam dumps in high power accelerator have to withstand the high thermal stress


Beam dump for SIS18 synchrotron at GSI: (made of iron, 3×2×3 m)
The beam is extracted from LHC, the peak energy density has to be first diluted to avoid high temperature rise and then absorbed in the beam dump.

Location of the beam dumps in LHC

Schematic layout of the LHC beam dumping system:

[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)
LHC main beam dump

- Robust and failsafe design, proper material choice and efficient cooling
- **Parameters**: 8 m long, 6 tons (beam dump absorber), 900 tons (shielding), to absorb > 360 MJ
- **Beam dump absorber** consist of 7 m long and 70 cm in diameter segmented graphite cylinder

[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)
Methods to minimize the temperature rise

- The extracted bunches of the beam are distributed in a spiral using h-v kicker magnets.
- Density of the graphite is graded in order to minimize the temperature rise.

Temperature depth profile after the beam impact

\[
\Delta T (K) = \begin{cases} 
25 & \text{if } \rho = 1.8 \text{ g/cm}^3 \\
15 & \text{if } \rho = 1.1 \text{ g/cm}^3 
\end{cases}
\]

[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)
Tools for machine protection & collimation design

- **Particle tracking through the accelerator lattice** and beam dynamics simulations
  - Prediction of the **beam halo formation**
  - Calculation of the **beam loss distribution**
  - Simulation tools: MAD-X, SixTrack, STRUCT, ORBIT, TRANSPORT, …

- **Particle transport in matter** (beam interaction with construction materials)
  - Calculation of the **energy deposition** to the material
  - **Scattering** of the particles interacting with the material
  - **Nuclear interaction**, secondary particles and residual activity
  - Simulation tools: FLUKA, GEANT4, MARS, PHITS, MCNP, …

- **Impact of the particle interaction** on the material properties
  - Deformation, melting, sublimation, vaporization, material properties
  - Simulation tools: ANSYS, BIG2, …

- **Coupling** between the particle tracking and particle interaction with materials
Summary

- Machine protection & collimation systems deal with protection of equipment and devices as well as safety and environmental risks related to the accelerator operation.

- Prevent uncontrolled beam losses (regular and accidental) and secure a well defined and shielded storing location for the lost particles.

- Regular, continuous beam losses are caused by beam instabilities and treated using the collimation system.

- Accidental beam losses are caused by machine failures and treated using the emergency extraction and dumping system.

- Include very complex and complicated technical solutions.

- Require understanding of many aspects of the accelerators and physics in general (beam dynamics, operation, instrumentation, particle interaction with materials, ...).

- Extremely important for future big accelerator projects (higher beam energy, beam power, beam intensity, ...).
Thank you for your attention