Machine & People Protection Issues

CAS Introduction to Accelerator Physics

Vysoké Tatry, 19th of September 2019

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Lecture based on previous CAS & JUAS contributions by Daniela Kiselev, Xavier Queralt, Rüdiger Schmidt, Ivan Strasik, Markus Zerlauth...

Challenging accelerator in the sky:
Machine protection warns you before the accelerator will fall down!
Introduction and Outline

Reasons for machine protection:

- **Protection of the environment:** Only necessary activation inside & outside of the facility should be produced
- **Protection of the accelerator:** Prevent for destruction of component, prevent for down-time, destruction & cost
- **Enable save operation:** Threshold values for reliable operation
- **Protection of people:** Important for workers and general public, following laws

Outline of this talk:

1. Introduction to risk & destruction potential
2. Important atomic and nuclear physics
3. Definition of loss categories, passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
What Risk is acceptable?

The risk is a factor to prepare for decisions:

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Catastrophic</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4 Major</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3 Severe</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>2 Minor</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>1 Slight</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Risk = **probability** of an accident x **consequences**

measured in terms of e.g. money, manpower, accelerator downtime, radiation pollution, ...

- Intolerable or acceptable depends on e.g. maintenance access, destruction level, operation
- Different accelerator facilities allows different risks e.g. medical ↔ research facilities
- Risk must be weighted to foreseen usage, goals and possible achievements
What is the Risk for an Accelerators?

Categories of destruction, consequences and risk:

- **Heating**: Lost beam heat the surrounding by its energy loss (by *atomic physics*)
- **Consequence**: Material is melted and deformed ⇒ proper functionality hindered
- **Risk**: Stop of operation
- **Example**: Destroyed insertions, leak in vacuum chamber, quench of superconducting magnet

- **Activation**: Nuclear reaction by beam particles (*nuclear physics*)
- **Consequence**: Permanent activation ⇒ pollution, human access hindered
- **Risk**: Maintenance impossible, expensive disposal

- **Radiation damage**: Displacement of lattice atoms, destruction of molecules (*atomic physics*)
- **Consequence**: Degradation of material properties, faulty electronics
- **Risk**: Stop of operation, exchange of equipment

![Image of lattice damage and Frenkel pair]
What is the Risk for an Accelerators?

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- **Financial aspects**: High cost of additional radiation shield
  - **Consequence**: Reconstruction of buildings
  - **Risk**: Insufficient budget, loss of operation permit

- **User requirements**: Less beam available for users
  - **Consequence**: Angry od disappointed users
  - **Risk**: Cancel financial support for accelerator facility
Stored Beam Energy at Accelerators

**Beam power on fixed target proton accelerator:**
LINACs, cyclotrons or extraction from synchrotrons.

**Examples: Energy of 1MJ correspondence:**
- 1 MJ is the kinetic energy of 2 600 kg with a velocity of 100 km/h
- 1 MJ can heat and melt 1.5 kg of copper [equals cube (5.5 cm)^3]
- 1 MJ is liberated by the explosion of 0.25 kg TNT

LINAC: 1 MW delivered within 1 s equals to 1MJ

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Stored beam energy within a synchrotron:
Mainly large circular collider

![Graph showing stored beam energy within a synchrotron](image)

Courtesy M. Lindroos & R. Schmidt
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Interaction with matter

General:

- Charged particles interact with electrons
  ⇒ shorter range
- Neutral particles ionize only indirectly
  ⇒ longer range
- Atomic processes have larger cross section than nuclear processes

‘Geometrical‘ cross section:

Cross section \( \sigma_{geo} \) comparable to size:

- Size of atom: \( r_{Bohr} = 0.053 \text{ nm} \)
  \[ \sigma_{geo}^{atom} = \pi (r_{Bohr})^2 = 8,8 \cdot 10^{-17} \text{ cm}^2 \]
  \( \approx 10^{-16} \text{ cm}^2 \)
- Size of nucleus: \( r_{nucl} \approx 3 \text{ fm} \)
  \[ \sigma_{geo}^{nucl} = \pi (2 \cdot r_{nucl})^2 \]
  \( \approx 10^{-24} \text{ cm}^2 \equiv 1 \text{ barn} \)

⇒ very probable reactions have \( \approx \sigma_{geo} \)

Mean free path: \( \lambda = \frac{1}{n \cdot \sigma} = \frac{M}{\rho N_A \cdot \sigma} \)

\( n \) target atom density [cm\(^{-3}\)], \( M \) molar mass, \( \rho \) density, \( N_A \) Avogadro number

\( A = \text{atomic physics} \)
\( N = \text{nuclear physics} \)

\( A: e^- \)
\( N: \text{reac. if } E>10\text{MeV/u} \)

\( A: e^-, X\text{-ray, } \gamma \)
\( N: \text{reaction} \)

\( A: e^-, X\text{-ray, Compton} \)
\( N: \text{nucl. reactions, neutron, pair-prod.} \)

\( A: \text{non} \)
\( N: \text{nucl. excitation elastic scat.} \)

\( A: e^- \)
\( N: \text{nucl. excitation hadronic shower spallation} \)

\( \sigma_{geo} = \pi (r_a + r_b)^2 \) for any ‘reaction’
Energy Loss of Ions in Copper

Bethe-Bloch formula: \[
\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \cdot \frac{Z_t}{A_t} \rho_t Z_p^2 \frac{1}{\beta^2} \left( \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I^2} - \beta^2 \right)
\]

(simplest formulation)

Range: \[
R = \int_{0}^{E_{\text{max}}} \left( \frac{dE}{dx} \right)^{-1} dE
\]
with approx. scaling \( R \propto E_{\text{max}}^{1.75} \)

Numerical calculation for ions with semi-empirical model e.g. SRIM

Main modification \( Z_p \rightarrow Z_{\text{eff}}(E_{\text{kin}}) \)

This is an atomic physics process:
1. Projectile ions liberates fast electrons
2. Thermalization by collisions with further electrons
3. Transfer of energy to lattice (phonon) \( \Rightarrow \) heating of target
Energy Loss and Heating: Calculations

Example: Proton in copper target calc. with FLUKA

General method of calculation (simplified):

1. Differential energy loss: by Bethe-Bloch $\frac{dE}{dx}(x)$ via codes like SRIM, LISE, FLUKA, MARS...

2. Energy deposition: $\frac{dE}{dV} = -\frac{dE}{dx} \cdot \frac{N}{A} \left[ \frac{J}{cm^3} \right]$ with $N$: number of particles, $A$: cross section

3. Temperature rise: $\Delta T = \frac{dE}{dV} \cdot \frac{1}{\rho c_p} \left[ K \right]$ for short bunches; $\rho$: mat. density, $c_p$ specific heat

4. Further material response: Melting, evaporation, pressure and stress .... via e.g. ANSYS

5. Secondary particles: Nuclear reactions, fragmentation, spallation, shower.... → discussed later

Proton $E_{kin} = 50$ MeV
size $\sigma_x = 0.2$ mm

Proton $E_{kin} = 50$ TeV
size $\sigma_x = 0.2$ mm

Y. Nie et al., Phys Rev AB 20, 081001 (2017)
Energy Loss and Heating: Calculations

Example: Proton in copper target calc. with FLUKA

Proton $E_{\text{kin}} = 50$ MeV
size $\sigma_x = 0.2$ mm

Example: Proton in copper target at central path

$r = 0$

Proton: $E_{\text{kin}} = 7$ TeV
2808 bunch
380 MJ energy
at center $r = 0$

Remark: Low energetic proton have large energy deposition at short range e.g. $E_{\text{kin}} = 50$ MeV
Beam Dump for high Intensity Beams

Extraction of LHC within one turn 86 µs on the beam dump (simulation): $\Delta T [^\circ C]$


Beam dump at LHC:
7m long, $\varnothing$ 0.7 m, graphite
900 tons of concrete shielding
Nuclear Physics Processes for Protons

Nuclear reactions via spallation for protons with $E_{\text{kin}} > 100$ MeV (simplified):

- Pre-equilibrium phases: $\pi$-exchange within $\approx 10^{-22}$ s with $E_{\text{kin}} > 20$ MeV $\Rightarrow$ hadronic shower
- Inter-nuclear cascade: Evaporation of n, p, d, $\alpha$ within $\approx 10^{-18}$ s with $E_{\text{kin}} \approx 1 – 10$ MeV
- Fission for heavy nuclei

General properties:

- Binding energy:
  $\approx 5$ MeV out nucleons
  $\approx 50$ MeV inner nucleons
- for $E_{\text{kin}} >> 100$ MeV comparable $\sigma$ for n & p

D. Kiselev, CAS 2011
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- $\beta$ & $\gamma$ decay of nuclei with long lifetime $\tau >> 10^{-9}$ s

Result on long term $t > 1$ ms: Radioactive nuclei = activation

D. Kiselev, CAS 2011
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Nuclear Physics Processes for Protons

**Impact of protons with $E_{\text{kin}}>100$ MeV at beam pipe or dump:**
- Hadronic shower
- Beam fragmented nuclei, secondary nuclei
- Fast and slow n, p, d, $\alpha$ ...
- $\beta$ & $\gamma$ decay of target nuclei on long time scale

Vacuum pipe might by ‘thick target’ due to gracing incident

**Example of cross section for protons on steel beam pipe:**
- Reaction: Fe + p $\rightarrow$ $^{54}$Mn + something
  \[ 100 \text{ mb} = \frac{1}{10} \sigma_{\text{geo}} \text{ for iron} \]
- $^{54}$Mn lifetime $t_{1/2} = 312$ days
- Electron capture $E = 1.3$ MeV to $^{54}$Cr (excited) with X-ray emission of $E_\gamma = 0.54$ MeV
- $^{54}$Cr decay via $\gamma$ emission $E_\gamma = 0.83$ MeV
  $\Rightarrow$ activation of beam pipe

Remark: Comparable cross section for fast neutrons

D. Kiselev, CAS 2011
Tolerable Beam Losses

Rule of thumb for proton beam with $E_{\text{kin}} > 100$ MeV:

‘Beam loss below 1 W/m enables hands-on maintenance’

- Example: 1 W/m $\approx 6 \times 10^9$ protons/(m·s) at 1 GeV
- Care: Most energy is lost by atomic process, while activation depends on nuclear physics
  $\Rightarrow$ dependence on projectile and target

Simulation for 1 W/m losses for 1 GeV/u impact:

- 100 days irradiation of stainless steel No. 304
  [Fe(70%), Cr(18%), Ni(10%), Mn(2%)]
- Decrease of activation: $\approx 10\%$ after 1 year
- Isotope mixture same for all ions
  $\Rightarrow$ highly activated material needs significant ‘cool down’ time
- Rule of thumb: Light targets (C, Al ...) have lower activation for impact of same # particles

Simulation for 1 GeV proton irradiation:

Stainless steel beam pipe after 1 W/m beam loss for 100 days & 4 h ‘cool down’

<table>
<thead>
<tr>
<th>Natural background</th>
<th>1 mSv/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical X-ray CT</td>
<td>$\approx 3$ mSv</td>
</tr>
<tr>
<td>Max. for rad. workers</td>
<td>20 mSv/a</td>
</tr>
</tbody>
</table>

Secondary Particle Production for Electron Beams

Processes for interaction of electrons

For $E_{\text{kin}} < 10$ MeV:
Mainly electronic stopping $\Rightarrow$ X-rays, slow $e^-$

For $E_{\text{kin}} > 10$ MeV:
Bremsstrahlungs-$\gamma$, forward peaked $E_\gamma = 5$-50 MeV
$\Rightarrow \gamma \rightarrow e^+ + e^-$ or $\mu^\pm .. \Rightarrow$ electro-mag. showers
$\Rightarrow$ Excitation of giant resonances $E_{\text{res}} \approx 10$-30 MeV
via $(\gamma, n)$, $(\gamma, p)$ or $(\gamma, np)$
$\rightarrow$ Fast neutrons emitted
$\rightarrow$ Neutrons: Long ranges in matter
no ele.-mag. interaction but nuclear reactions
Photo-Pion reaction: $d \ (\gamma, \pi^0)$ pn or $d \ (\gamma, \pi^-)$ pp
$\Rightarrow$ activation at electron accelerators

Interaction of Neutrons

Neutrons don’t interact with electrons

Nuclear physics processes:
- Elastic scattering: $X(n,n)X$ with $X$ receiving recoil momentum
- Radiative capture with $\gamma$ emission: $^A X (n,\gamma) ^{A+1} X$

**Example:** Neutron on copper $^{63}\text{Cu}$

**Elastic scattering:** Large cross section for thermal $n$

**Absorption:** Large cross section at resonances $\gamma$-emission and activation

For $E \gg 100 \text{ MeV}$ comparable cross section as proton

https://t2.lanl.gov/nis/data/endf/   and Zhukov, BIW 2010

Remark: Shielding of n by plastic (‘paraffin’) or concrete

Example: Neutrons on H

e.g. $\text{H}_2\text{O}$, organic materials

$\rightarrow$ effective moderator due to equal masses
Interaction of high Energy $\gamma$

At accelerators the $\gamma$ are originated from nuclear reactions or Bremsstrahlung for $e^{-}$.

**Example:** Absorption in lead

![Graph showing absorption cross-section vs. photon energy for lead.](image)

- **Atomic physics:**
  - **Photo-effect:** $\gamma + \text{atom} \rightarrow e^{-} + \text{atom}^+$
    - approx. material scaling $\sigma_{\text{photo}} \propto Z^4$
  - **Compton-effect:** $\gamma + \text{atom} \rightarrow \gamma' + e^{-} + \text{atom}^+$
    - approx. material scaling $\sigma_{\text{comp}} \propto Z$
  - **Pair prod.:** $\gamma + \text{nucleus} \rightarrow e^{-} + e^{+} + \text{nucleus}$
    - approx. material scaling $\sigma_{\text{pair}} \propto Z^2$

- **Ele.-mag. shower:** for high $E_\gamma$
  - $\gamma \rightarrow (e^{-}e^{+}) \rightarrow \gamma'_{\text{brems}} \rightarrow (e^{-}e^{+})' \rightarrow \gamma''_{\text{Brems}} \rightarrow \ldots$

- **Nuclear physics:**
  - **Giant resonance:** $\gamma + \text{nucleus} \rightarrow n + \text{nucleus'}$
    - small cross section but create free neutrons

Mass absorption coefficient $\mu = \frac{\rho N_A}{A} \cdot \sigma$

$p$ density, $N_A$ Avogadro const., $A$ atomic mass

Courtesy C. Grupen, Xavier Queralt, JUAS
Placement of Beam Loss Monitors

Secondary particles and shower produces are emitted within a forward cone (in rest-frame isotopically but due to Lorentz-transformation forward in lab-frame).

Position of detector at quadruples due to maximal beam size.

High energy particles leads to a shower in forward direction → Monte-Carlo simulation.

**Example:** Simulation of lost protons at LHC at 450 GeV of lost protons:
→ at focusing quad. $D$ & $\beta_x$ maximum

**Example:** Simulation of number of shower particles

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B. Dehning, JAS 2014, CERN-2016-002
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1. Introduction to risk & destruction potential
2. Important atomic and nuclear physics
3. Definition of loss categories, passive protection
4. Measurements by Beam Loss Monitors
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Relevant Losses for Machine Protection

Types of losses:

1. **Regular losses** or slow losses → **un**avoidable losses
   - Caused by lifetime inside synchrotron (residual gas scattering or charge exchange, Touschek...),
   - Caused by halo-formation and cleaning, aperture limitation, imperfections, machine errors
   - Caused by multi-turn injection, slow extraction,.....→ known loss mechanism
   - Occurs in each cycle at characteristic times and/or beam parameters
   - Usually a few % of the beam intensity

⇒ Protection of **sensitive** components, beam abortion only required **if** above a certain level

2. **Irregular losses** or fast losses by malfunction → **av**oidable losses, **see below**
Regular Losses from Halo

**Halo formation at synchrotrons:**
- Definition of halo: low density of particle with large betatron amplitude
- Caused by collective effect (e.g. space charge), resonances or machine errors
- Diffusion process (e.g. 1 µm per turn)

⇒ **unstable particles are lost**

Beam loss terminology: ‘uncontrolled regular loss’

⇒ Beam halo collimation system at a synchrotron

**Goal:** Low impurity beam

- **Warm synchrotron:** Protection of sensitive insertions (e.g. septum)
  Concentration of loss at few locations
- **Super-conduction synch:** + quench protection of sc magnets
- **Collider:** + well defined condition for detector at IP
  ⇔ min. exp. background
  Cleaning of collisional halo particles

⇒ Concentration of loss at dedicated locations i.e. ‘controlled losses’

**LINAC:** Halo generation by long. and trans. mismatch

**Goal:** Quench protection of sc civilities

Remark:
- Halo might have other distribution than core
- Halo formation and its mitigation is an actual topic

Courtesy I. Strasik CAS 2016
Two Stage Betatron Collimation System

**General functionality of cleaning:**
- Primary stage as **thin foil close** to beam
  - scattering of halo particles
    (Coulomb scattering by Moliere formula)
- Betatron amplitude increases
- Max. extension after
  - \( \mu \approx 90^0 \) or \( 270^0 \) betatron phase
- Secondary collimator as absorber more distant to beam

Example:
4.7 GeV scattering in \( L=1 \) mm Tungsten foil

![Diagram of the collimation system](diagram.png)

Courtesy I. Strasik CAS 2016
LHC Collimator Hardware

LHC Collimator system:
- Primary stage
- Secondary & tertiary stage
- Absorbers
in total 110 movable devices

LHC maximal losses for 6.5 TeV protons:
- Total stored power 300 MJ
- Max. energy deposition in sc magnet: 0.1 J/cm²
- Corresponding to $6 \times 10^7$ protons
- Or $2 \times 10^{-7}$ of the stored beam of $3 \times 10^{14}$ protons
LHC Collimator System

**LHC Collimator system:**
- Primary stage as close as \( \approx 5\sigma_{beam} \approx 1 \text{ mm} \)
- Secondary & tertiary stage made of carbon
- Absorbers made of tungsten alloy
- In total 110 movable devices moving e.g. from injection \( r = 5 \text{ mm} \rightarrow 1 \text{ mm} \)

**Test of functionality:**
- Loss concentrated at collimators

**Experimental verification:** Single bunch excitation

**Result:** Main losses concentrated at collimators

Cleaning efficiency:
\[ \eta = \frac{\text{protons lost at collimator}}{\text{total beam loss}} \]

Result: \( \eta = 99.8\% \) reached

Courtesy M. Zerlauth, CAS 2018

S. Redaelli, JAS CERN-2016-002
Collimation at LINACs

**Halo development at LINACs caused by**
- higher order magnet fields (e.g. aberration)
- transverse mis-match
- off-momentum particles due to wrong acceleration
- space charge forces

**Goal:** Halo cutting at low energy to prevent for activation

**Collimators:**
Cut the beam tail in space
\( \mu = 90^0 \) or \( \mu = 45^0 \) betatron phase to cut angle
⇒ at least two locations required

**Example:** SNS LINAC
Scraping at 3 MeV
profile measurement at 40 MeV
M. Plum, CERN-2016-002
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Basic Idea of Beam Loss Monitors

**Basic idea for Beam Loss Monitors B LM:**

A loss beam particle must collide with the vacuum chamber or other insertions

⇒ Interaction leads to some shower particle:

   - $e^-$, $\gamma$, protons, neutrons, excited nuclei, fragmented nuclei

⇒ Detection of these secondaries by an appropriate detector outside of beam pipe

⇒ Relative cheap detector installed at many locations

Remark: Due to grazing angle a thin vacuum chamber might be a ‘thick target’
Scintillators as Beam Loss Monitors

**Plastics or liquids are used:**
- Detection of **charged particles** by electronic stopping
- Detection of **neutrons** by elastic collisions $n$ on $p$ in plastics and fast $p$ electronic stopping.

**Scintillator + photo-multiplier:**
- Counting (large PMT amplification)
- Or analog voltage ADC (low PMT amplification)
- Radiation hardness:
  - Plastics: 1 Mrad = $10^4 \text{ Gy}$
  - Liquid: 10 Mrad = $10^5 \text{ Gy}$

**Example:** Analog pulses of plastic scintillator:
- Broad energy spectrum due to many particle species and energies.

![Image of Scintillator with HV base, Photo-multiplier inside, and 2x2x5 cm$^3$ scintillator.](image)

**Analog pulses $U(t)$**
- Pulse high distribution $N(U)$
- 40 ns
- 100 mV
- 50 mV

20 ns/div and 100 mV/div
Cherenkov Light Detectors as Beam Loss Monitors

Cherenkov detectors:
Passage of a charged particle $v$ faster than propagation of light $v > c_{\text{medium}} = c / n$

Technical: Quartz rod $n=1.5$ & photomultiplier

Example: Korean XFEL behind undulator

Cherenkov light emission:
For $v > c_{\text{medium}} = c / n$
light wave-front like a wake broadband light emission

Advantage:
- Detection of fast electrons only not sensitive to $\gamma$ & synch. photons
- No saturation effects
- Prompt light emission

Usage: Mainly at FELs for short and intense pulses

H. Yang, D.C. Shin, FEL Conf. 2017
Ionization Chamber as Beam Loss Monitors

Energy loss of charged particles in gases → electron-ion pairs → current meas.

\[ I_{\text{sec}} \propto \frac{1}{W} \cdot \frac{dE}{dx} \Delta x \]

Shower particle

- Sealed tube filled with Ar or N\textsubscript{2} gas:
  - Creation of Ar\textsuperscript{+}-e\textsuperscript{-} pairs,
    - average energy \( W = 32 \text{ eV/pair} \)
  - measurement of this current
  - Slow time response
    - due to \( \approx 10 \mu\text{s} \) drift time of Ar\textsuperscript{+}

Per definition: Direct measurement of dose!

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ionization Pot. [eV]</th>
<th>W-Value [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>15.7</td>
<td>26.4</td>
</tr>
<tr>
<td>N\textsubscript{2}</td>
<td>15.5</td>
<td>34.8</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>12.5</td>
<td>30.8</td>
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<tr>
<td>Air</td>
<td>33.8</td>
<td></td>
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</table>
### Ionization Chamber as BLM: TEVATRON and CERN Type

<table>
<thead>
<tr>
<th>TEVATRON, RHIC type</th>
<th>CERN type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>50 cm, Ø 9 cm</td>
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<tr>
<td>Gas</td>
<td>38 cm</td>
</tr>
<tr>
<td># of electrodes</td>
<td>61</td>
</tr>
<tr>
<td>Voltage</td>
<td>1500 V</td>
</tr>
<tr>
<td>Reaction time</td>
<td>0.3 µs</td>
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<tr>
<td># at the synchr.</td>
<td>≈ 4000 at LHC</td>
</tr>
<tr>
<td>Aver. distance</td>
<td>1 BLM each ≈ 6 m</td>
</tr>
</tbody>
</table>
Ionization Chamber as BLM: CERN Type

Simulation of det. efficiency by Geant4:

- Most sensitive to protons, electrons & high energy $\gamma$
- Low sensitive to neutrons

$\Rightarrow$ Calculation of lost protons by integrating of shower composition

$\Rightarrow$ Quench limit estimation

<table>
<thead>
<tr>
<th>CERN type</th>
<th>size</th>
<th>50 cm, $\varnothing$ 9 cm</th>
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<tbody>
<tr>
<td>gas</td>
<td>$\text{N}_2$ at 1.1 bar</td>
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<td># of electrodes</td>
<td>61</td>
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A. North et al., HB 2010

60° particle impact

- proton
- electron
- $\gamma$ ray
- neutron

A. North et al., HB 2010
BF3 Proportional Tubes as BLM and for personal Protection

Detection of neutrons **only** with a ‘REM-counter’:

![Diagram of BF3 proportional tube](image)

**Physical processes of signal generation:**

1. Slow down of fast neutrons by elastic collisions with p
2. Nuclear reaction inside BF3 gas in tube:
   \[
   ^{10}\text{B} + n \rightarrow ^{7}\text{Li} + \alpha \quad \text{with} \quad Q = 2.3 \text{ MeV.}
   \]
3. Electronic stopping of \(^7\text{Li}\) and \(\alpha\) leads to signal.

**Remark:** ‘REM-counters’ are frequently used for neutron detection outside of the concrete shield & in nuclear power plants.

C. Grupen, Introduction to Radiation Protection

Peter Forck, CAS 2019, Vysoké Tatry
Comparison of different Types of BLMs

Different detectors are sensitive to various physical processes very different count rate, but basically proportional to each other

Typical choice of the detector type:

- **Ionization Chamber:**
  - **Advantage:**
    - Measurement of absolute dose
  - **Disadvantage:**
    - Low signal \((\text{low } \gamma, \text{eff}, \text{no neutron detection})\),
    - Sometimes slow, ion drift time \(10 \ldots 100 \mu\text{s}\)
  \(\Rightarrow\) Often used at proton accelerators

- **Scintillator, Cherenkov detector:**
  - **Advantage:**
    - Fast current reading or particle counting
    - Can be fabricated in any shape, cheap
  - **Disadvantage:**
    - Need calibration in many cases
    - Might suffer from radiation
  \(\Rightarrow\) Often used at electron accelerators
Outline of this talk:

1. Introduction to risk & destruction potential
2. Important atomic and nuclear physics
3. Definition of loss categories, passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
Relevant Losses for Machine Protection

**Types of losses:**

1. **Irregular losses** or fast losses by malfunction → avoidable losses
   - Occurs only seldom i.e. have low probability
   - The whole beam or a significant fraction is lost
   - Usually within a short period of the operational cycle (e.g. injection, acceleration, extraction, ...)
   ⇒ Requirement for detector system: large dynamic range
   - Usually caused by
     - Hardware failures, inaccurate settings or control errors (magnets, cavities ...)
     - Beam instabilities (wake-fields, resonances, ...)
     - Manually initialized improper beam alignment
   ⇒ Beam abortion required to prevent for destruction via interlock generation

2. **Regular losses** or slow losses → unavoidable losses, *discussed above*
   - Caused by lifetime inside synchrotron (residual gas, Touschek ...),
   - Caused by aperture limitation, beam manipulations .....  
   - Usually a few % of the beam intensity

**Remark:**

**Personal safety system:** Simple devices, reliable technology → based on dose threshold [Gy/s]

**Machine protection:** Appropriate BLMs, device specific loss threshold → might be more complex
General Layout of a Machine Protection System: Design

Design criteria for a Machine Protection System:

1. Beam based: Choice of BLM detector type
   - Main type of radiation (protons, neutrons, electrons, muons.....)
   - Expected radiation level at foreseen location
   - Required time response (fast particle counts or short beam delivery ↔ medium fast IC ↔ slow IC)
   - Required dynamic range to detect irregular losses e.g. 6 orders of magnitude!
   - Required reliability & fail safe

Proton accelerators: Most often IC are used for interlock-generation
   & particle counters for relative measurements (after calibration suited for interlock generation)

Electron accelerators: Scintillators and Cherenkov counters (partly due to short pulse operation)

2. Equipment based: Functionality of any relevant device must be guarantied
   - Magnet power supplier
   - rf-generators, cavity properties
   - Super-conducting state of magnet or cavity
   - Vacuum conditions
   - Relevant diagnostics instruments
   - Control system watchdog
   - ...

Remark: In exceptional cases an interlock-source can be masked to allow for acc. operation
General Layout of a Machine Protection System: Hardware

**Design of a protection system:**

- **BLM detector & analog front-end**
  - low input signal under regular losses
  - large dynamic range for irregular losses
  - e.g. current-frequency converter

- **Digitalization**
  - high time resolution (e.g. LHC 1 turn = 89 µs)

- **Comparison to threshold values**
  - fast, real-time calculation (FPGA, DSP)

- **Generation & broadcasting of interlock signal**
  - real-time operation required, equipment ok input

- **Beam permit**: if not ok:
  -beam abortion kicker@synchr. or chopper@LINAC
  - disable next beam production

- **Data logging**
  - detailed ‘post mortem ‘storage & archiving
  - error display

- **Generally**
  - robust & fail-save system required!
  - challenge: large dynamic range

- = analog
- = real-time OS
- = regular OS
Beam dump statistics at LHC in year 2012 (above injection, 582 dumps):

- Beam: Losses (UFO) 9.9%
- Beam: Losses 2.6%
- Equipment Failure: Safety 0.3%
- Equipment Failure: Machine Protection 14.0%
- Equipment Failure: Controls 2.1%
- Equipment Failure: Machine 22.6%
- TOTEM 4.4%
- CMS 0.5%
- LHCb 0.3%
- ALICE 0.3%
- ATLAS 0.0%
- Operations: End of Fill 30.1%
- Operations: Test and Development 10.9%
- Operations: Error 1.0%
- External e.g. by operators 4.4%
- due to experiment’s advice 0.2%
- equipment failure 0.7%

B. Todd et al., CERNACC-2014-0041
J. Wenninger, JAS 2014, CERN-2016-002
Outline

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Cartoons from C. Grupen
Introduction to Radiation Protection,
Springer Verlag 2010
Radiological Quantities and Units

Basic quantities & units for personal safety:

- **Absorbed dose:** \( D_{R,T} = \frac{1}{m} \int_{V_T} dE_R \cdot dV \) (physical quantity)  
  \[ = \left[ \frac{1}{\text{kg}} \right] = \text{[Gy]} = \text{[100rem]} \]
  for each radiation type \( R \) and each tissue \( T \)

- **Equivalent Dose:** \( H_T = \sum_R w_R D_{R,T} = \text{[Sv]} = \text{[100rem]} \)
  with weight factor \( w_R \) for the radiation type \( R \)

- **Effective Dose:** \( E = \sum_T w_T H_T = \text{[Sv]} = \text{[100rem]} \)
  with weight factor \( w_T \) for the absorption of each tissue \( T \)
  whole body irradiation \( \Leftrightarrow \sum_T w_T = 1 \)

- **Activity:** \( r = \left[ \frac{1}{s} \right] = \text{[Bq]} = \text{[27 pCi]} \)
  1 Ci = activity of 1 g radium \(^{226}\text{Ra}\)

Example: Organ or tissue | Sensi. | \( w_T \)
--- | --- | ---
Gonads | High | 0.20
Lung, stomach, colon, lens, Hematopoietic & lymphatic system | Intermediate | 0.12
Liver, esophagus, chest, skin, muscle, heart, bone surface | Low | 0.05

**Note:**
- Neutrons: Since 2007 smooth function
- 2 MeV < \( E < 20 \text{ MeV} \)
- \( E > 20 \text{ MeV} \)
- 10
- 5

Example: I will not eat this fish, it has \( 10^4 \text{ Bq} \)  
My fish is fine, it has 0.3 µCi
Shielding of Accelerators

**Shielding of accelerator by rough rule of thumb:**
Estimation of shielding by 10th-value $\lambda_{10}$
with $H(l) = H_0 \times 10^{-l/\lambda_{10}}$
(disregarding any secondary particle transport)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho \ [\text{g cm}^{-3}]$</th>
<th>$\lambda_{10} \ [\text{cm}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>1.8</td>
<td>128</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.4</td>
<td>100</td>
</tr>
<tr>
<td>Heavy concrete</td>
<td>3.2</td>
<td>80</td>
</tr>
<tr>
<td>Iron</td>
<td>7.4</td>
<td>41</td>
</tr>
<tr>
<td>Lead</td>
<td>11.3</td>
<td>39</td>
</tr>
</tbody>
</table>

**Further rough rule of thumb:**
- Protons, electrons & $\gamma$ are att. by heavy materials
- Neutrons are scattered by hydrogen due to same mass
  - Concrete contains $\approx 10\%_{\text{weight}} H_2O$
- Nuclear reactions produces further particles

I believe we need a better shielding.

Do you think these Beta-Blockers can protect us from $\beta$-rays?
Simplified Model Shielding of Accelerators

**Simplified FLUKA calculation:** 4GeV protons, iron beam dump Ø 1m l=3.5m, concrete 1 or 3 m, 5·10^5 particles

**Result:**
Mainly neutrons and μ behind thick shield

**Results:**
- Primary protons are stopped in dump
- Neutrons produced, scattered at wall
  - ≈ 10^{-3} atten. at X by distance & concrete
  - ‘Leakage’ through opening
- γ are from beam & neutrons in the wall
  - ≈ 10^{-3} attenuation at X
- Protons produced from neutrons, but partly stopped in the wall
- Neutrons at X ≈ 0.3% of 1m.
- Equal ‘leakage’ of n, γ & p
- γ well shielded
- Protons stopped in wall
Realistic Example for Shielding of Accelerators

**Example shielding of accelerator:** Proton beam of 29 GeV for anti-proton production

Assumption $2.5 \cdot 10^{13}$ protons on 11 cm long copper target

Shield: Iron (1.6 m downstream and 1 m transverse)

Concrete $\approx$ 8 m around beam pipe

Goal: Free access region outside i.e. equivalent dose rate $H/t < 0.5 \mu$Sv/h

**Shielding calculations:**
Required for safety procedure
Numerical calculation required
atomic, nuclear, and particle physics models
e.g. FLUKA, MARS, PHITS
see lecture by Dan Faircloth

free access $H/t < 0.5 \mu$Sv/h

K. Knie et al., IPAC 2012
Simplified categories of radiation areas:
For workers: Assumption 2000 h/a of access

- Non-designated, free access
  H/t < 1 mSv/a (full year) = 0.5 μSv/h (for 2000 h)

- Supervised zone
  H/t < 3 μSv/h

- Control zone
  H/t < 10 μSv/h

- Limit access zone
  H/t < 2 mSv/h

- Stricked ruled access zone
  H/t < 25 mSv/h

- Prohibited access zone
  H/t > 25 mSv/h

ALARA principle:
As Low As Reasonable Achievable

Maximum dose for one year: 20 mSv/a
Maximum total life dose: 400 mSv
(E lethal dose for short term exposure: ≈4000 mSv)

Remark: Actual limits are given by national laws.
**Categories of Locations & maximal Doses**

**Simplified categories of radiation areas:**
For workers: Assumption 2000 h/a of access

- **Non-designated, free access**
  - H/t < 1 mSv/a (full year) = 0.5µSv/h (for 2000 h)

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  - H/t < 2 mSv/h

- **Stricked ruled access zone**
  - H/t < 25 mSv/h

- **Prohibited access zone**
  - H/t > 25 mSv/h

- **Maximum dose for one year:** 20 mSv/a
- **Maximum total life dose:** 400 mSv
  (Lethal dose for short term exposure: \( \approx 4000 \) mSv)

Remark: Actual limits are given by national laws.

**Proportional tube for γ:**
- 30 keV < \( E_{ph} \) < 1.3 MeV

**Moderated prop. tube for n**
- 1 eV < \( E_n \) < 20 MeV

**Display Status**
- Moderated thermo-luminescence detector for passive n-detection
Natural Radiation Exposure

Example of radiation level:

- **Natural geological dose:**
  In some parts the dose can be up to some 10 mSv/a without significant increase of diseases

- **Typical dose composition:**

  - Medical exposure
  - Inhalation of radon and thoron
  - Ingestion
  - External terrestrial radiation
  - Cosmic radiation

  - Typical dose composition:

    - 0.6 mSv (20%)
    - 1.26 mSv (42%)
    - 0.48 mSv (13%)
    - 0.39 mSv (13%)

Source: German Bundesamt für Strahlenschutz
C. Grupen, Introduction to Radiation Protection

There have been rumors that Black Forest must be evacuated due to 6 mSv/a.
Avoidable, but wildly accepted Radiation Exposure

Cosmic ray based radiation effects depend on altitude and latitude

<table>
<thead>
<tr>
<th>Departure</th>
<th>Arrival</th>
<th>Duration</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frankfurt</td>
<td>San Francisco</td>
<td>11.5 h</td>
<td>45 - 110 µSv</td>
</tr>
<tr>
<td>Frankfurt</td>
<td>Rio de Janeiro</td>
<td>11.5 h</td>
<td>17 - 28 µSv</td>
</tr>
</tbody>
</table>

Source: German Bundesamt für Strahlenschutz

C. Grupen, Introduction to Radiation Protection
Passive Film Badge Dosimeter and TLD

**For personal safety a dosimeter should be worn!**

Film badge: X-ray sensitive films with different absorbers to determine the energy of photons (typ. 5keV... 9MeV) & $\beta^\pm$ (typ. > 0.3MeV)

**Sensitivity for $\beta$ & $\gamma$:** 0.1 mSv to 5 Sv

Thermo-luminescence dosimeter TLD:
Crystal e.g. LiF is excited by radiation and emit light when heated neutron sensitive via $^6\text{Li}(n,\alpha)T$

**Sensitivity for $\beta$ & $\gamma$:** 0.1 mSv to 10 Sv
Active personal Dosimeter

**Active dosimeters for online display**
Dose measurement with alarm function, has to be worn when entering a protected area

**Ionization chambers or proportional chambers:**
Alternative: PIN-diode solid state detector

- Photons: typ. 10 keV... 10 MeV
- $\beta^\pm$: 0.25 .... 1.5 MeV

**Sensitivity for $\beta$ & $\gamma$:** 0.05 µSv/h to 1 Sv/h

(TLD sensitivity: 100 µSv to 5 Sv, flight above pole: 45...110 µSv)

**‘Pocket meter’ for $\gamma$-rays:**
Scintillator NaI(Tl) + photo-multiplier for $\gamma$ detection photons (typ. 60 keV... 1.5 MeV)

**Sensitivity for $\gamma$:** 0.01 µSv/h to 100 mSv/h

Older versions: Proportional tube

**Advantage:** Alarm functionality, sensitive can be archived with some efforts

**Disadvantage:** Expensive
Summary

- Many accelerator are build to produce radiation, some risk remains
- Accelerator components must be protected from overheating (‘atomic physics’)
  - e.g. super-conducting magnet & cavities
    - Particles’ energy loss must be limited and/or steered to dedicated locations
    - Passive protection by collimators for protection or localizing
    - Active Machine Protection System based on Beam Loss Monitors
- Accelerator components must be protected from activation (‘nuclear physics’)
  - Losses must be limited to certain locations e.g. collimators & beam dump
  - ‘1 W/m criterion’ to limit activation for hand-on maintenance
- Shield of the accelerator required
  - p, ion & γ best shield by high density material, but care for nuclear reactions
  - e⁻ shield for light material (lower Bremsstrahlung)
  - n light material preferred
- ALARA principle: Radiation exposure to people should be avoided

Thank you for your attention!
General Reading on Machine Protection

- US Particle Accelerator School – Beam Loss & Machine Protection, January 2017
  [Website](http://uspas.fnal.gov/materials/17UCDavis/davis-machineprotection.shtml)
- C. Grupen, *Introduction to Radiation Protection*, Springer Verlag 2010
- Proceedings of several CERN Acc. Schools (introduction & advanced level, special topics).
- Contributions to conferences, in particular to IPAC & IBIC.
Backup slides
Dynamic Machine Protection by Transmission Measurement

For $E > 50$ MeV protons: nuclear $\sigma_{\text{nuc}}$ quite low
$
\Rightarrow \text{machine protection by active transmission control}
$

Determination of maximal loss between consecutive transformers by ‘differential current measurement’
$
\rightarrow \text{dynamic beam interruption in case of software-given threshold overshoot.}
$

**FPGA-electronics:**

$
\rightarrow \text{ADC digitalization}
$
$
\rightarrow \text{calculation of difference}
$
$
\rightarrow \text{digital comparator}
$
$
\rightarrow \text{chopper control in case of threshold overshoot}
$

For $E > 50$ MeV protons: nuclear $\sigma_{\text{nuc}}$ quite low
$
\Rightarrow \text{machine protection by active transmission control}
$

High current: $t_{\text{pulse}} < 10 \mu\text{s}$ only to prevent from damage!

H. Reeg (GSI) et al., Proc. EPAC’06
Ionizing radiation liberates secondary electrons from a surface.

**Working principle:**
- Three plates mounted in a vacuum vessel (passively NEG pumped)
- Outer electrodes: biased by $U \approx +1$ kV
- Inner electrode: connected for current measurement (here current-frequency converter)

→ small and cheap detector, very insensitive.

![HV electrodes and electrode for measured current](image)

**Sensitivity of SEM detector**

![Energy response curves for proton, electron, and neutron](image)

B. Dehning et al., PAC 2007
Fig. 6: Neutron energy distributions $E\Phi(E)$ in the transverse direction generated by 250 MeV protons impinging on an iron target thicker than the proton range. The distributions are for source neutrons and behind concrete shields of thicknesses ranging from 20 cm to 1 m. The distributions have been normalized to unit area in order to show better the change in the shape of the spectrum with increasing shield thickness.

D. Forkel-Wirth et al., CAS 2011, CERN-2013-001
Radiation Damage Displacements of Atoms

Low energy protons: Nuclear stopping (collision of protons with target nucleus results in recoil energy above binding energy to stopping)

For $E_{\text{kin}} > 100$ MeV nearly equal cross section

Electronic stopping range

Large capture cross section results in recoil energy

Fig. 12: Displacement cross-sections of protons (left) and neutrons (right) in copper obtained by two different approaches (see legend).

D. Kiselev, CAS 2011, CERN-2013-001
Radiation Damage of organic Materials

Radiation damage in plastic by ionizing radiation:

- Brake of chemical bonds and displacement of atoms
- Microscopic defects in the chemical bonds
- Displacement of atoms in the structural material

**Example:** Kapton foil of 125 µm thickness

Direct irradiation by ion beam’s energy loss $dE/dx$ increases for heavy ions

<table>
<thead>
<tr>
<th>Material</th>
<th>Dose [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon (PTFE)</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Mylar</td>
<td>$5 \cdot 10^4$</td>
</tr>
<tr>
<td>Cable insulation</td>
<td>$5 \cdot 10^4$</td>
</tr>
<tr>
<td>Magnet coil insul.</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Kapton (Polyamide)</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

T. Seidl et al, HB 2010
Microscopic Damage of structural Materials

D. Kiselev, CAS 2011, CERN-2013-001

vacancy + self-interstitial atom = Frenkel pair.

Remark: Liquids do not suffer radiation damage
Energy Loss and Heating: Experiment

Verification of material interaction by 440 GeV protons:
Destruction of material due to temperature rise
- melting, sublimation plasma formation
- mechanical stress
⇒ verification of simulation
⇒ finding proper dump material

Beam: 440 GeV \approx 10^{13} \text{ protons},
\sigma_x = \sigma_y \approx 2 \text{ mm within } t = 50 \mu\text{s}
⇒ \mathcal{E}_{\text{tot}} \approx 1 \text{ MJ}

HiRadMat facility at CERN SPS

A. Bertarelli, JAS CERN-2016-002.

Experiment with 450 GeV protons:

V. Kain et al.,
PAC’05, 1607 (2005)
PIN-Diode (Solid State Detector) as BLM

Solid-state detector: Detection of charged particles.

**Working principle**
- About $10^4$ e⁻-hole pairs are created by a Minimum Ionizing Particle (MIP).
- A coincidence of the two PIN reduces the background due to low energy photons.
- A counting module is used with threshold value comparator for alarming.

→ small and cheap detector.

2 PIN diodes:
- $7.5 \times 20$ mm²
- 0.1 mm thickness.
Application of BLMs for slow Extraction

BLM can be installed at several locations and determine local, regular losses:

- Losses during acceleration
- Losses at ele. septum
- Momentum dependent extraction current
  ⇒ change of extraction angle
  ⇔ time-dependent losses at mag. septum
  ⇒ used for optimization of time-dep. extraction angle

Example at SIS synchr. using quadrupole variation for slow extraction cycle time 3s:

- Losses during acceleration
- Losses at ele. septum
- Momentum dependent extraction current
  ⇒ change of extraction angle
  ⇔ time-dependent losses at mag. septum

BLM can be installed at several locations and determine local, regular losses:

- dc transformer
- BLM at ele. septum
- IC at experiment
- BLM at synch. quadrupole
- BLM at mag. septum
- IC at experiment

The diagram illustrates the temporal changes in acceleration and extraction processes, highlighting the data acquisition points from various locations within the synchrotron.
Collimation at LINACs

Halo development caused by
- higher order magnet fields (e.g. aberration)
- transverse mis-match
- off-momentum particles due to wrong focusing
- space charge forces

**Goal:** Halo cutting at low energy to prevent for activation

Collimators:
Cut the beam tail in space
μ = 90° or μ = 45° betatron phase to cut angle
⇒ at least two locations required

Example: SNS LINAC
Scraping at 3 MeV
profile measurement at 40 MeV
M. Plum, CERN-2016-002

i.e. not completely cut...