Machine & People Protection Issues

CAS Introduction to Accelerator Physics
Santa Susanna, 1st of October 2023

Peter Forck
Gesellschaft für Schwerionenforschung (GSI)
p.forck@gsi.de

Lecture based on previous CAS & JUAS contributions by Daniela Kiselev, Xavier Queralt, Rüdiger Schmidt, Ivan Strasik, Markus Zerlauth...
Copyright statement and speaker’s release for video publishing

The author consents to the photographic, audio and video recording of this lecture at the CERN Accelerator School. The term “lecture” includes any material incorporated therein including but not limited to text, images and references.

The author hereby grants CERN a royalty-free license to use his image and name as well as the recordings mentioned above, in order to post them on the CAS website.

The material is used for the sole purpose of illustration for teaching or scientific research. The author hereby confirms that to his best knowledge the content of the lecture does not infringe the copyright, intellectual property or privacy rights of any third party. The author has cited and credited any third-party contribution in accordance with applicable professional standards and legislation in matters of attribution.
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. Relevant atomic and nuclear physics
3. Collimation as passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
What Risk is acceptable?

Risk is a factor to prepare for decisions, it is not a physical quantity:

\[
\text{Risk} = \text{probability of an accident} \times \text{consequences}
\]

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 Accelerators?

**Categories of destruction, consequences and risk:**

- **Heating:** Lost beam heats the surrounding by its energy loss (by *atomic physics*)
  - **Consequence:** Material is melted and deformed ⇒ proper functionality hindered
  - **Type of 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
  - **Type of risk:** Maintenance impossible, expensive disposal

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

---

**Table:**

<table>
<thead>
<tr>
<th>Shot</th>
<th>Intensity / p+</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>

---

**Figure:**

- Rad-damage: Displacement from regular lattice
- Frenkel pair: Vacancy and interstitial atom
- Incident particle
- Lattice atoms
- Exciting particle
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
  ⇒ **Type of 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
  ⇒ **Type of risk:** Maintenance impossible, expensive disposal

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

➢ **Financial aspects:** High cost of additional radiation shield
  ⇒ **Consequence:** Reconstruction of buildings
  ⇒ **Type of risk:** Insufficient budget, loss of operation permit

➢ **User requirements:** Less beam available for users
  ⇒ **Consequence:** Angry or disappointed users
  ⇒ **Type of 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 2600 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

Stored beam energy within a synchrotron:
Mainly large circular collider

Courtesy M. Lindroos & R. Schmidt, JIAS 2014 on beam loss, CERN-2016-002
Outline of this talk:
1. Introduction to risk & destruction potential
2. Relevant atomic & nuclear physics
3. Collimation as passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
Overview: Interaction of Particles and Photons with Matter

Interaction with matter

General:
- Charged particles interacts with electrons ⇒ shorter range
- Neutrons ionizes only indirectly ⇒ longer range
- Atomic processes have larger cross section than nuclear processes

‘Geometrical’ cross section:
Very probable reactions have $\approx \sigma_{geo}$
Cross section $\sigma_{geo}$ comparable to size:
- Size of atom: $r_{Bohr} = 0.053 \text{ nm}$
  
  \[
  \sigma_{geo,\text{atom}} = \pi (r_{Bohr})^2 = 8.8 \cdot 10^{-17} \text{ cm}^2 
  \approx 10^{-16} \text{ cm}^2
  \]
- Size of nucleus: $r_{nucl} \approx 3 \text{ fm}$
  
  \[
  \sigma_{geo,\text{nucl}} = \pi (2 \cdot r_{nucl})^2 
  \approx 10^{-24} \text{ cm}^2 \equiv 1 \text{ barn}
  \]

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

$A = \text{atomic reaction}$
$N = \text{nuclear reaction}$

$A: e^-$
$N: \text{reaction}$

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

$A: e^-X\text{-ray, Compton}$
$N: \text{nuclear reaction, neutron, pair-prod.}$

$A: \text{non}$
$N: \text{elastic scattering}$

$A: e^-\text{, nuclear excitation}$
$N: \text{hadronic shower}$

$A = \text{atomic reaction}$
$N = \text{nuclear reaction}$

$A: e^-, X\text{-ray}$
$N: \text{reaction}$

$A: e^-, X\text{-ray}$
$N: \text{reaction}$

$A: e^-, X\text{-ray}$
$N: \text{reaction}$
Energy Loss of Ions in Copper

**Bethe-Bloch formula:**
(simplest formulation)

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

Range: 
\[ R = \int_0^{E_{max}} \left( \frac{dE}{dx} \right)^{-1} dE \]

with approx. scaling \( R \propto E_{max}^{1.75} \)

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

Main modification \( Z_P \rightarrow Z_P^{eff} (E_{kin}) \)

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

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

beam

range \( R(E_{\text{kin}}) \)

**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:** \( \frac{dE}{dV} = -\frac{dE}{dx} \cdot \frac{N}{A} \left[ \frac{J}{\text{cm}^3} \right] \) with \( N: \) number of particles, \( A: \) beam cross section

3. **Temperature rise:** \( \Delta T = \frac{dE}{dV} \cdot \frac{1}{\rho \cdot c_p} \left[ \text{K} \right] \) 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
Energy Loss and Heating: Calculations

Example: Proton in copper target calc. with FLUKA

Proton beam at the CERN accelerators
Energy deposition per protons

Nominal LHC parameters for protons:
\[ E_{\text{kin}} = 7 \text{ TeV}, \text{2808 bunch} \]
\[ \Rightarrow 380 \text{ MJ energy at center } r = 0 \]

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

**Beam dump at LHC:**
- Septum magnet deflecting the extracted beam
- H–V kicker for painting the beam
- Beam dump block
- Fast kicker magnet
- About 700 m
- Rise time 3 µs

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


**Beam dump at LHC:**
- 7 m long, $\varnothing$ 0.7 m, graphite
- 900 tons of concrete shielding

Depth 20 cm
Nuclear Physics Processes for Protons

Nuclear reactions via spallation for protons with $E_{kin} \geq 1$ GeV (simplified):

- Pre-equilibrium phases: $\pi$-exchange within $\approx 10^{-22}$ s with $E_{kin} > 20$ MeV $\Rightarrow$ hadronic shower

General properties:

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

D. Kiselev, CAS 2011
Nuclear Physics Processes for Protons

Nuclear reactions via spallation for protons with $E_{\text{kin}} \geq 1$ GeV (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
- $\beta$ & $\gamma$ decay of nuclei with long lifetime $\tau >> 10^{-9}$ s

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

D. Kiselev, CAS 2011
Nuclear Physics Processes for Protons

Nuclear reactions via spallation for protons with $E_{\text{kin}} \geq 1$ GeV (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

**Thick target:** Penetration depth comparable to range

Impact of protons with $E_{kin} > 100$ MeV at beam pipe or dump:

- Emission of n, p, d, $\alpha$, nucl. fragment ...
- $\beta$ & $\gamma$ decay of target nuclei on long time scale

Gracing incident: vacuum pipe is ‘thick target’

Example of cross section for protons on steel beam pipe:

- Reaction: Fe + p $\rightarrow ^{54}\text{Mn} +$ something
  [ $100$ mb $\approx \frac{1}{10} \sigma_{geo}$ ]
- $^{54}\text{Mn}$ lifetime $t_{1/2} = 312$ days
- Electron capture $E = 1.3$ MeV to $^{54}\text{Cr}$ (excited) with X-ray emission $E_\gamma = 0.54$ MeV
- $^{54}\text{Cr}$ decay via $\gamma$ emission $E_\gamma = 0.83$ MeV

$\Rightarrow$ activation of beam pipe

Remark: Comparable cross section for fast neutrons

Coulomb barrier:

Kinetic energy required to overcome the electric potential to reach a distance for nuclear force $\approx 5$ fm

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 $\approx 1$ 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

---

**Natural background** $\approx 1$ mSv/a

**Medical X-ray CT** $\approx 3$ mSv

**Max. for rad. workers** 20 mSv/a

---

Simulation for 1 GeV proton irradiation:

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

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

For $E_{kin} > 10$ MeV:
Bremsstrahlungs-$\gamma$, forward peaked $E_{\gamma} = 5$-50 MeV
$\Rightarrow \gamma \rightarrow e^+ + e^- \text{ or } \mu^\pm \ldots \rightarrow$ electro-mag. showers
$\Rightarrow$ Excitation of giant resonances $E_{res} \approx 10$-30 MeV
via $(\gamma, n), (\gamma, p)$ or $(\gamma, np)$ with $\sigma_{giant} \approx \frac{1}{10} \sigma_{geo}$
$\Rightarrow$ Fast neutrons emitted (by nuclear interaction)
$\Rightarrow$ Neutrons: Long ranges in matter
$\Rightarrow$ **Neutrons at electron accelerators!**
Interaction of high Energy $\gamma$

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

**Example**: Absorption in lead

**Atomic physics** ($Z = \text{target nuclear charge}$):

**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 production**: $\gamma + \text{nucleus} \rightarrow e^- + e^+ + \text{nucleus}$  
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
Interaction of Neutrons

Neutrons don’t interact with electrons
Only 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 chromium $^{50}\text{Cr}$ (4.3% natural abundance, in stainless steel)

**Elastic scattering:** Cross section $\approx \sigma_{\text{geo}}$

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

For $E >> 100$ MeV comparable cross section as proton

- For $E >> 100$ MeV comparable cross section as proton

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

Outline of this talk:
1. Introduction to risk & destruction potential
2. Relevant atomic and nuclear physics
3. Collimation as passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
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’

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

LINAC: Halo generation by long. and trans. mismatch

Goal: Quench protection of sc civilities

Courtesy I. Strasik CAS 2016
Quench Protection for superconducting Magnets

Superconducting magnets:
Beam particles energy loss
⇒ heat wires due to energy loss

Quench: Transition to normal-conducting phase

Goal: Beam dump prior to quench !!!

Simulation of temperature increase \( \Delta T \):
Energy deposition:
\[
\frac{dE}{dV} = - \frac{dE}{dx} \cdot \frac{N}{A} \left[ \frac{J}{cm^3} \right]
\]

\( N \): number of particles, \( A \): cross section

Temperature rise:
\[
\Delta T = \frac{dE}{dV} \cdot \frac{1}{\rho c_p(T)} \quad [K]
\]

\( \rho \): mat. density, \( c_p \): specific heat

Temperature dependent specific heat:
Insulator: \( c_{\text{phonon}}(T) \propto T^3 \)
Normal conductor: \( c_{\text{NC}}(T) \propto \alpha T + \beta T^3 \)
Superconductor: \( c_{\text{sc}}(T) \propto T_C e^{-\gamma T/T_C} \)

\( \alpha, \beta, \gamma \): material constants

See lecture ‘Superconducting Magnets’ by Gijs van Rijk

J ~ 1500-2000 A/mm²
I ~ 400 A, B = 8-9 T

'\text{Rutherford}’ cable strand

Courtesy Gijs van Rijs
Two Stage Betatron Collimation System = active Collimation

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 \( \mu \approx 90^0 \text{ or } 270^0 \) betatron phase
- Secondary collimator as absorber more distant to beam

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

Courtesy I. Strasik CAS 2016
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 6x10⁷ protons
- Or 2x10⁻⁷ of the stored beam of 3x10¹⁴ protons

courtesy R. Losito
LHC Collimator System

**LHC Collimator system:**
- Primary stage as close as \( \approx 5 \sigma_{\text{beam}} \approx 1 \text{ mm} \)
- Secondary & tertiary stage made of carbon
- Absorbers made of tungsten alloy
  → in total 110 movable devices moving e.g. from injection \( r = 5 \text{ mm} \) → 1 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
Outline of this talk:
1. Introduction to risk & destruction potential
2. Important atomic and nuclear physics
3. Collimation as passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
**Basic Idea of Beam Loss Monitors**

**Basic idea for Beam Loss Monitors BLM:**
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’

---

**Secondary products:**
- Electromagnetic or hadronic shower products
- Charged particles
- Neutrons or $\gamma$

---

**Diagram:**
- Beam
- Lost beam particle
- BLM detector
- Front-end electronics
- Digitalization & fast analysis
- Display
- Interlock

---

Machine & People Protection Issues
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 $1 \text{ Mrad} = 10^4 \text{ Gy}$
  - liquid $10 \text{ Mrad} = 10^5 \text{ Gy}$

![HV base](image1.png)

![Photo-multiplier inside](image2.png)

![Scintillator](image3.png)

![2x2x5 cm$^3$](image4.png)
Ionization Chamber as Beam Loss Monitors

Energy loss of charged particles in gases $\rightarrow$ electron-ion pairs $\rightarrow$ current meas.

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

**shower particle**

![Diagram of sealed tube filled with Ar or N$_2$ gas]

Sealed tube Filled with Ar or N$_2$ gas:
- Creation of Ar$^+$-e$^-$ pairs, average energy $W = 32$ eV/pair
- Measurement of this current
- Slow time response due to $\approx 10$ $\mu$s drift time of Ar$^+$.

**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$_2$</td>
<td>15.5</td>
<td>34.8</td>
</tr>
<tr>
<td>O$_2$</td>
<td>12.5</td>
<td>30.8</td>
</tr>
<tr>
<td>Air</td>
<td></td>
<td>33.8</td>
</tr>
</tbody>
</table>
### Ionization Chamber as BLM: TEVATRON and CERN Type

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TEVATRON, RHIC</th>
<th>CERN type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>15cm, ø 6 cm</td>
<td>50 cm, ø 9 cm</td>
</tr>
<tr>
<td>Gas</td>
<td>Ar at 1.1 bar</td>
<td>N₂ at 1.1 bar</td>
</tr>
<tr>
<td># of electrodes</td>
<td>3</td>
<td>61</td>
</tr>
<tr>
<td>Voltage</td>
<td>1000 V</td>
<td>1500 V</td>
</tr>
<tr>
<td>Reaction time</td>
<td>3 µs</td>
<td>0.3 µs</td>
</tr>
</tbody>
</table>

**4000 BLMs at LHC ↔ each ≈ 6m**
Simulation of det. efficiency by Geant4:

- Most sensitive to protons, electrons & high energy γ
- Low sensitive to neutrons

⇒ Calculation of lost protons by integrating of shower composition
⇒ Quench limit estimation

A. North et al., HB 2010

Peter Forck, CAS 2023, Santa Susanna
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 (low $\gamma$, eff, no neutron detection),
  - Sometimes slow, ion drift time 10 ... 100 $\mu$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
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
Outline of this talk:
1. Introduction to risk & destruction potential
2. Relevant atomic and nuclear physics
3. Collimation as passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety
Relevant Losses for Machine Protection

Type of losses:
1. Regular losses or slow losses ⇔ unavoidable losses
   - Caused by lifetime inside synchrotron (residual gas, Touschek ...),
   - Caused by aperture limitation, beam manipulations ..... 
   - Usually a few % of the beam intensity

2. Irregular losses or fast losses by malfunction ⇔ avoidable losses
   - Occurs only seldom
   - A significant fraction of the beam 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

Remark:
Machine protection: Appropriate BLMs, device specific loss threshold → might be more complex
Personal safety system: Simple devices, reliable technology → based on dose threshold [Gy/s]
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!

   - **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 for all important devices**

**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-safe system required!
  - challenge: large dynamic range

- **= analog**
- **= real-time OS**
- **= regular OS**
Beam dump statistics at LHC in year 2015 and 2012 (above injection):

Sum: 442 dumps

≈ 30 % as planned after ≈ 10 h

≈ 15 % by MPS tests

≈ 15 % due to increasing beam loss

≈ 15 % unnecessary

≈ 30 % due to device failure

B. Todd et al., CERNACC- 2014-0041
D. Wollmann et al., IPAC 2016, Busan, p. 4203 (2016)
Outline of this talk:
1. Introduction to risk & destruction potential
2. Relevant atomic and nuclear physics
3. Collimation as passive protection
4. Measurements by Beam Loss Monitors
5. Design of Machine Protection System
6. Overview of personal safety

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

Basic quantities & units for personal safety:

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

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

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

### Example: Organ or tissue

<table>
<thead>
<tr>
<th>Example: Organ or tissue</th>
<th>Sensi.</th>
<th>( w_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>High</td>
<td>0.20</td>
</tr>
<tr>
<td>Lung, stomach, colon, lens, hematopoietic &amp; lymphatic system</td>
<td>Intermediate</td>
<td>0.12</td>
</tr>
<tr>
<td>Liver, esophagus, chest, skin, muscle, heart, bone surface</td>
<td>Low</td>
<td>0.05 to 0.01</td>
</tr>
</tbody>
</table>

### Rad. type \( R \) and weight factor \( w_R \)

<table>
<thead>
<tr>
<th>Rad. type ( R )</th>
<th>( w_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma ) all energies</td>
<td>1</td>
</tr>
<tr>
<td>( e^- ), ( e^+ ), ( \mu^\pm ) all energies</td>
<td>1</td>
</tr>
<tr>
<td>Protons ( E &gt; 2 \text{ MeV} )</td>
<td>5</td>
</tr>
<tr>
<td>( \alpha ), heavier nuclei</td>
<td>20</td>
</tr>
<tr>
<td>Neutrons: ( E &lt; 10 \text{ keV} )</td>
<td>5</td>
</tr>
<tr>
<td>( 10 \text{ keV} &lt; E &lt; 100 \text{ keV} )</td>
<td>10</td>
</tr>
<tr>
<td>( 100 \text{ keV} &lt; E &lt; 2 \text{ MeV} )</td>
<td>20</td>
</tr>
<tr>
<td>( 2 \text{ MeV} &lt; E &lt; 20 \text{ MeV} )</td>
<td>10</td>
</tr>
<tr>
<td>( E &gt; 20 \text{ MeV} )</td>
<td>5</td>
</tr>
</tbody>
</table>

Neutrons: Since 2007 smooth function
Shielding of Accelerators

**Shielding of accelerator by rough rule of thumb:**

Estimation of shielding by 10\textsuperscript{th}-value $\lambda_{10}$ with $H(l) = H_0 10^{-l/\lambda_{10}}$

(disregarding any secondary particle transport)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho \left[ \frac{g}{cm^3} \right]$</th>
<th>$\lambda_{10} \left[ cm \right]$</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 attenuated by heavy materials
- Neutrons are scattered by hydrogen due to same mass
  Concrete contains $\approx 10\%_{\text{weight}}$ $H_2O$
- Nuclear reactions produce further particles
Simplified Model Shielding of Accelerators

**Simplified FLUKA calculation:** 4GeV protons, iron beam dump Ø1m, l=3.5m, concrete 1 & 3 m, $5 \cdot 10^5$ particles

Result:
Mainly neutrons and $\mu$ behind thick shield

Results:
- Primary protons are stopped in dump
- **Protons** produced from neutrons, but partly stopped in the wall
- $\gamma$ are from beam & neutrons in the wall $\approx 10^{-3}$ attenuation at X
- **Neutrons** produced, scattered at wall $\approx 10^{-3}$ atten. at X by distance & concrete
- ‘Leakage’ through opening
- **Protons** stopped in wall
- $\gamma$ well shielded
- **Neutrons** at X $\approx 0.3\%$ of 1m.

Peter Forck, CAS 2023, Santa Susanna
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 11cm 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 & 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

see lecture ‘Secondary Beams and Targets’ by K. Knie
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) = 0.5 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

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

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

**ALARA principle:**
As Low As Reasonable Achievable

**Maximal dose for an radiation exposed worker:**
Maximum dose for one year: 20 mSv/a
Maximum total life dose: 400 mSv
(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) = 0.5 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

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

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

**Maximal dose for an radiation exposed worker:**

- 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 \(\gamma\):
- \(30\) keV \(< E_{\gamma} < 1.3\) MeV

Moderated prop. tube for n
- \(1\) eV \(< E_{n} < 20\) MeV

Moderated thermo-luminescence detector for passive n-detection

Remark: Actual limits are given by national laws.
Natural Radiation Exposure

Example of radiation level:

- **Natural geological dose up to 10 mSv/a:**
  Mainly due to noble gas radon from decay chain **without** significant increase of diseases

- **Typical dose natural and artificial composition:**

  ![Radiation Sources and Doses Diagram]

  - **Medical exposure**
  - **Radon & thoron**
    - Ingestion: 0.25 mSv (20%)
    - 0.48 mSv (16%)
    - 0.39 mSv (13%)
    - 1.25 mSv (42%)
  - External terrestrial radiation
  - **Cosmic radiation**

  ![Chart showing annual whole-body dose in mSv]

  - **Limit for radiation-exposed workers (EU):**
  - **natural radioactivity**
  - **nuclear power plants**
  - **radiation tests in the atmosphere**
  - **Chernobyl**

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

Radiation at 11 km altitude, year 2013

Departure | Arrival       | Duration | Dose     
-----------|---------------|----------|----------
Frankfurt  | San Francisco| 11.5 h   | 45 - 110 µSv 
Frankfurt  | Rio de Janeiro| 11.5 h   | 17 - 28 µSv  

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

Sensitivity for $\beta$ & $\gamma$: 0.1 mSv to 10 Sv

Advantage: Can be archived
Disadvantage: Limited sensitivity, no online display

Film badge: X-ray sensitive films photons (typ. 5keV... 9MeV) & $\beta^\pm$ (typ. > 0.3MeV)
Sensitivity for $\beta$ & $\gamma$: 0.1 mSv to 5 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
\(\beta^\pm: 0.25 \ldots 1.5\) 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
Many accelerator are built to produce radiation, some risk remains.

Accelerator components must be protected from overheating (‘atomic physics’) e.g. superconducting 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: Unnecessary 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
  http://uspas.fnal.gov/materials/17UCDavis/davis-machineprotection.shtml
- D. Kiselev, *Activation and radiation damage in the environment of hadron accelerators &
  D. Forkel-Wirth et al., Radiation protection at CERN in R. Bailey (Ed.) Proc. CAS CERN-2013-001
- 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
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 ≈ 10^{13} protons, \( \sigma_x = \sigma_y \approx 2 \text{ mm} \) within \( t = 50 \mu\text{s} \)
⇒ \( E_{\text{tot}} \approx 1 \text{ MJ} \)

HiRadMat facility at CERN SPS

Experiment with 450 GeV protons:

V. Kain et al., PAC'05, 1607 (2005)

A. Bertarelli, JAS CERN-2016-002.
Machine & People Protection Issues

Dynamic Machine Protection by Transmission Measurement

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

Determination of maximal loss between consecutive transformers by ‘differential current measurement’ → dynamic beam interruption in case of software-given threshold overshoot.

FPGA-electronics:
→ ADC digitalization
→ calculation of difference
→ digital comparator
→ chopper control in case of threshold overshoot

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

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

H. Reeg (GSI) et al., Proc. EPAC’06
**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

Rough estimation of maximal dose

<table>
<thead>
<tr>
<th>Material</th>
<th>Dose [Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon (PTEE)</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
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 quadrupoles 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
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:**

Bremsstrahungs-$\gamma$, forward peaked $E_\gamma = 5-50$ MeV
$\Rightarrow \gamma \rightarrow e^+ + e^-$ or $\mu^\pm \ldots \rightarrow$ electro-mag. showers
$\Rightarrow$ Excitation of giant resonances $E_{\text{res}} \approx 10-30$ MeV
via $(\gamma, n)$, $(\gamma, p)$ or $(\gamma, np)$ with $\sigma_{\text{giant}} \approx \frac{1}{10} \sigma_{\text{geo}}$
$\Rightarrow$ Fast neutrons emitted (by nuclear interaction)
$\Rightarrow$ Neutrons: Long ranges in matter

Photo-Pion reaction: $d (\gamma, \pi^0)$ pn or $d (\gamma, \pi^-)$ pp
$\Rightarrow$ activation at electron accelerators

**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**
  - Bremsstrahlung $\Rightarrow \gamma \rightarrow e^+ + e^-$ or $\mu^\pm \ldots \rightarrow$ electro-mag. showers
  - Excitation of giant resonances $E_{\text{res}} \approx 10-30$ MeV
    - via $(\gamma, n)$, $(\gamma, p)$ or $(\gamma, np)$ with $\sigma_{\text{giant}} \approx \frac{1}{10} \sigma_{\text{geo}}$
    - Fast neutrons emitted (by nuclear interaction)
    - Neutrons: Long ranges in matter
  - Photo-Pion reaction: $d (\gamma, \pi^0)$ pn or $d (\gamma, \pi^-)$ pp
    - Activation at electron accelerators
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

\[ \mu = 90^\circ \text{ or } \mu = 45^\circ \text{ betatron phase to cut angle} \]

\[ \implies \text{ at least two locations required} \]

Example: SNS LINAC

Scraping at 3 MeV

profile measurement at 40 MeV

M. Plum, CERN-2016-002
Secondary Electron Monitor as BLM

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.

B. Dehning et al., PAC 2007
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:

- $7.5 \times 20$ mm$^2$
- 0.1 mm thickness.
Detection of neutrons **only** with a ‘REM-counter’:

**Physical processes of signal generation:**

1. Slow down of fast neutrons by elastic collisions with p
2. Nuclear reaction inside BF$_3$ gas in tube:
   \[ {}^{10}\text{B} + n \rightarrow {}^{7}\text{Li} + \alpha \] with \( Q = 2.3 \text{ MeV} \).
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.