# Machine & People Protection Issues

## *CAS Introduction to Accelerator Physics*

## Santa Susanna, 1st of October 2023

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

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# Introduction and Outline

**Reasons for machine protection:**

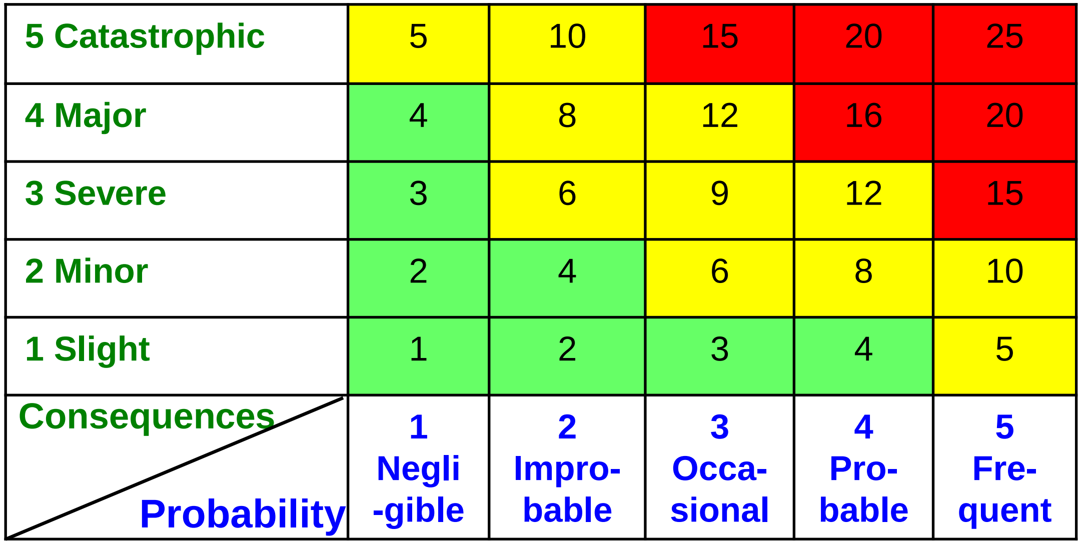
- **Protection of the environment:** Only necessary activation inside & outside of the facility should be produced
- **Protection of the accelerator:** Prevent for destruction of component, prevent for down-time, destruction & cost
- **Enable save operation:** Threshold values for reliable operation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

**Outline of this talk:**

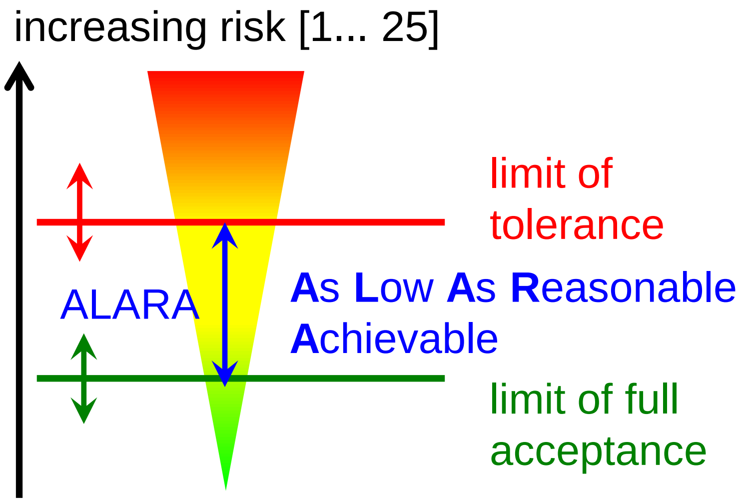
1. **Introduction to risk & destruction potential**
2. **Relevant atomic and nuclear physics**
3. **Collimation as passive protection**
4. **Measurements by Beam Loss Monitors**
5. **Design of Machine Protection System**
6. **Overview of personal safety**

# What Risk is acceptable?

## Risk is a factor to prepare for decisions, it is <u>not</u> a physical quantity:



| | | | | | |
|---|---|---|---|---|---|
| **5 Catastrophic** | 5 | 10 | 15 | 20 | 25 |
| **4 Major** | 4 | 8 | 12 | 16 | 20 |
| **3 Severe** | 3 | 6 | 9 | 12 | 15 |
| **2 Minor** | 2 | 4 | 6 | 8 | 10 |
| **1 Slight** | 1 | 2 | 3 | 4 | 5 |
| **Consequences** / **Probability** | **1 Negli-gible** | **2 Impro-bable** | **3 Occa-sional** | **4 Pro-bable** | **5 Fre-quent** |



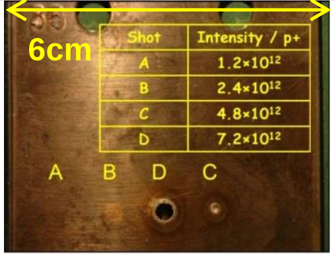
**Risk** = **probability** of an accident x **consequences**

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 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***)

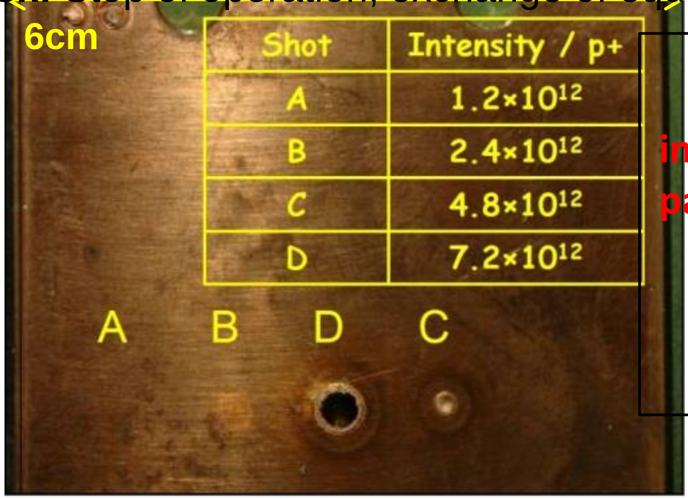
⇒ **Consequence:** Permanent activation ⇒ pollution, human access hindered

⇒ **Type of risk:** Maintenance impossible, expensive disposal

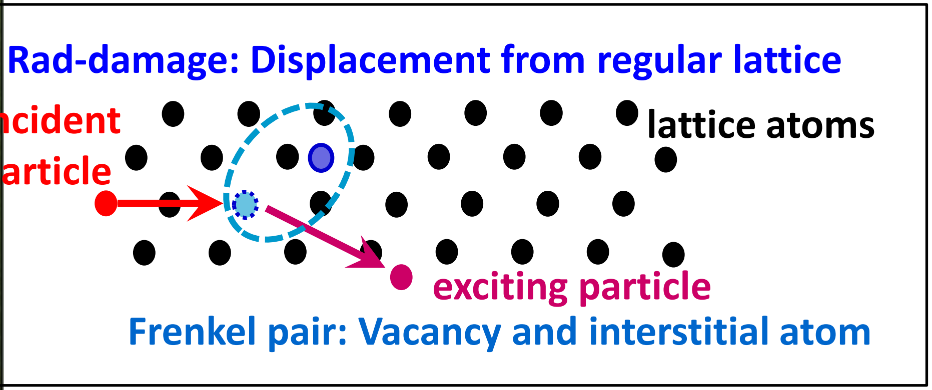
- **Radiation damage:** Displacement of lattice atoms, destruction of molecules (***atomic physics***)

⇒ **Consequence:** Degradation of material properties, faulty electronics

⇒ **Type of risk:** Stop of operation, exchange of equipment

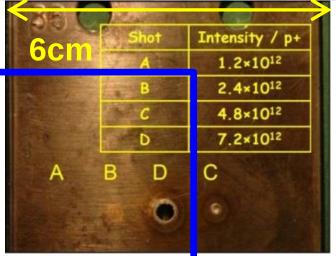


| Shot | Intensity / p+ |
|---|---|
| A | $1.2\times10^{12}$ |
| B | $2.4\times10^{12}$ |
| C | $4.8\times10^{12}$ |
| D | $7.2\times10^{12}$ |



# What is the Risk for an Accelerators?

## Categories of destruction, consequences and risk:

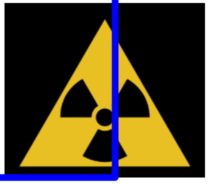


➢ **Heating:** Lost beam heat the surrounding by its energy loss (by ***atomic physics***)

⇒ **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***)

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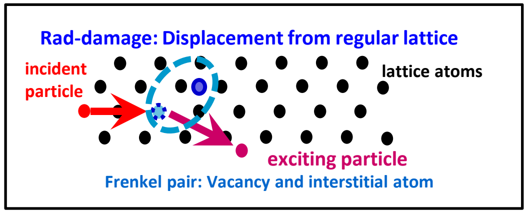


➢ **Financial aspects:** High cost of additional radiation shield

⇒ **Consequence:** Reconstruction of buildings

⇒ **Type of risk:** Insufficient budget, loss of operation permit

➢ **User requirements:** Less beam available for users

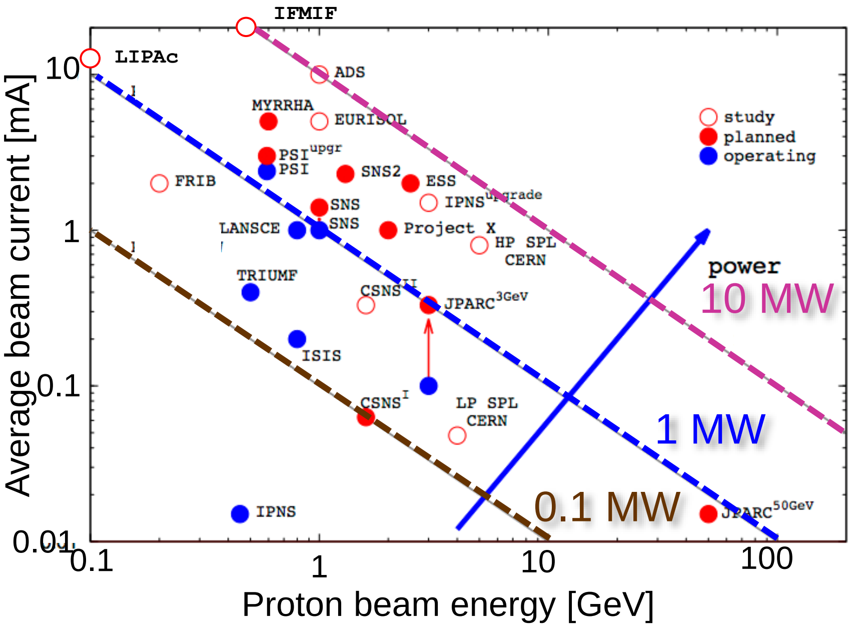
⇒ **Consequence:** Angry or disappointed users

⇒ **Type of risk:** Cancel financial support for accelerator facility

# Stored Beam Energy at Accelerators

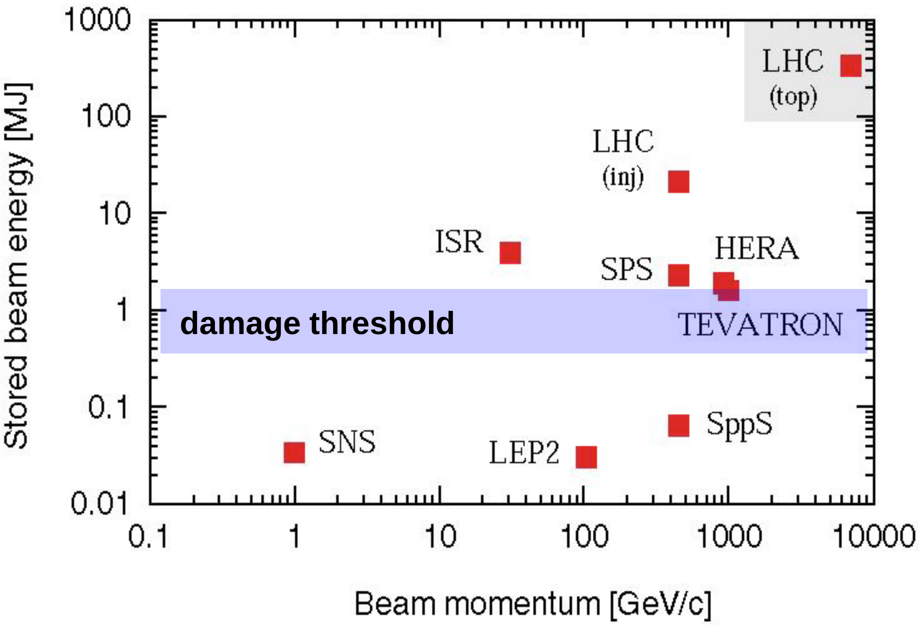
## Beam power on fixed target proton accelerator:

LINACs, cyclotrons or extraction from synchrotrons



## Stored beam energy within a synchrotron:

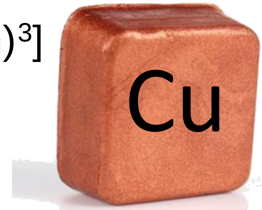
Mainly large circular collider



## Examples: Energy of 1MJ correspondence:

- 1 MJ is the kinetic energy of 2600 kg with an velocity of 100 km/h
- 1 MJ can heat and melt 1.5 kg of copper [equals cube $(5.5\ \mathrm{cm})^3$]
- 1 MJ is liberated by the explosion of 0.25 kg TNT

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



$T_{melt}$=1080 $^0$C

$\rho$ = 8.9 g/cm$^3$

Courtesy M. Lindroos & R. Schmidt, JIAS 2014 on beam loss, CERN-2016-002

# Outline

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# Overview: Interaction of Particles and Photons with Matter

## Interaction with matter

### General:

- Charged particles interacts with electrons
  $\Rightarrow$ shorter range
- Neutrons ionizes only indirectly
  $\Rightarrow$ 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**: $r_{Bohr} = 0.053$ nm

$$\sigma_{geo}^{atom} = \pi\,(r_{Bohr})^2 = 8{,}8\,\cdot 10^{-17}\ \mathrm{cm}^2$$
$$\approx 10^{-16}\mathrm{cm}^2$$

- Size of **nucleus**: $r_{nucl} \approx 3$ fm

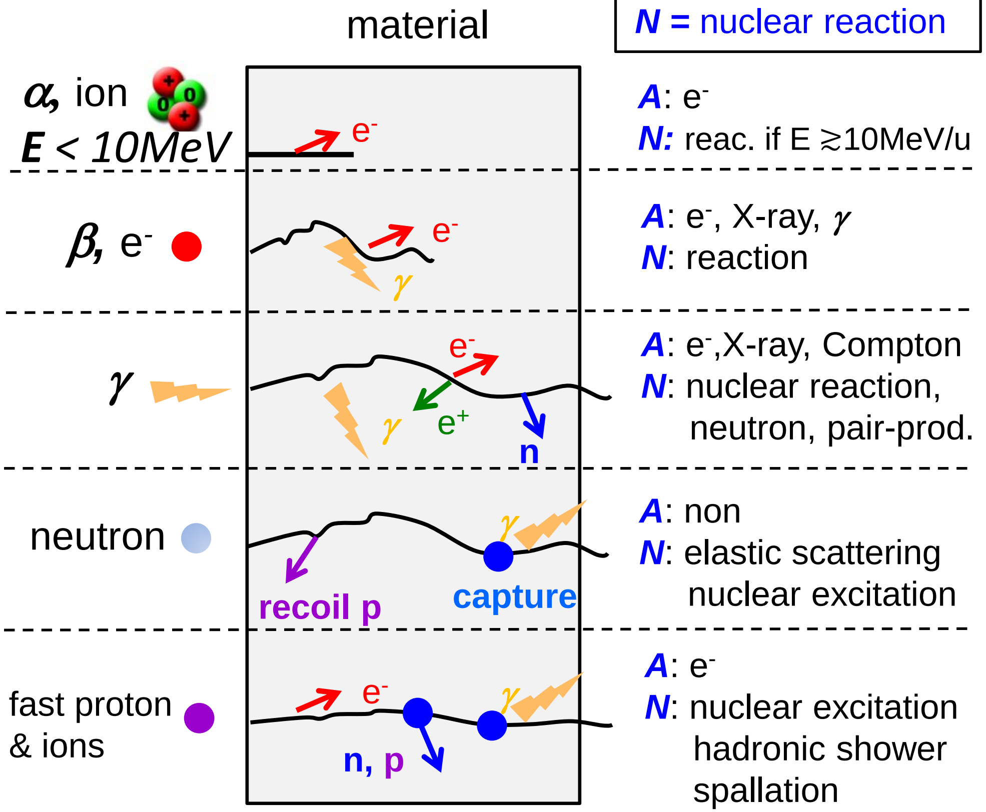
$$\sigma_{geo}^{nucl} = \pi\,(2 \cdot r_{nucl})^2$$
$$\approx 10^{-24}\mathrm{cm}^2 \equiv \mathbf{1\ barn}$$

**factor $10^8$**

**Mean free path:** $\lambda = \dfrac{1}{n \cdot \sigma} = \dfrac{M}{\rho N_A \cdot \sigma}$

$n$ target atom density [$\mathrm{cm}^{-3}$], $M$ molar mass, $\rho$ density, $N_A$ Advogadro number

**A = atomic reaction**
**N = nuclear reaction**



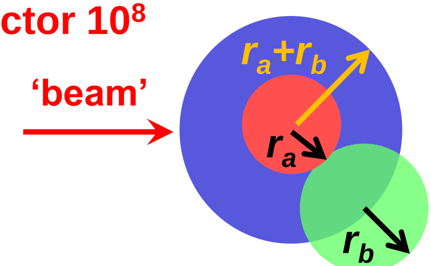
**A**: $e^-$
**N:** reac. if E ≳10MeV/u

**A**: $e^-$, X-ray, $\gamma$
**N**: reaction

**A**: $e^-$,X-ray, Compton
**N**: nuclear reaction, neutron, pair-prod.

**A**: non
**N**: elastic scattering nuclear excitation

**A**: $e^-$
**N**: nuclear excitation hadronic shower spallation



Hard balls’ ‘geometrical‘ cross section:

$\sigma_{geo} = \pi\,(r_a + r_b)^2$ for **any** ‘reaction’

# Energy Loss of Ions in Copper

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

(simplest formulation)

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**

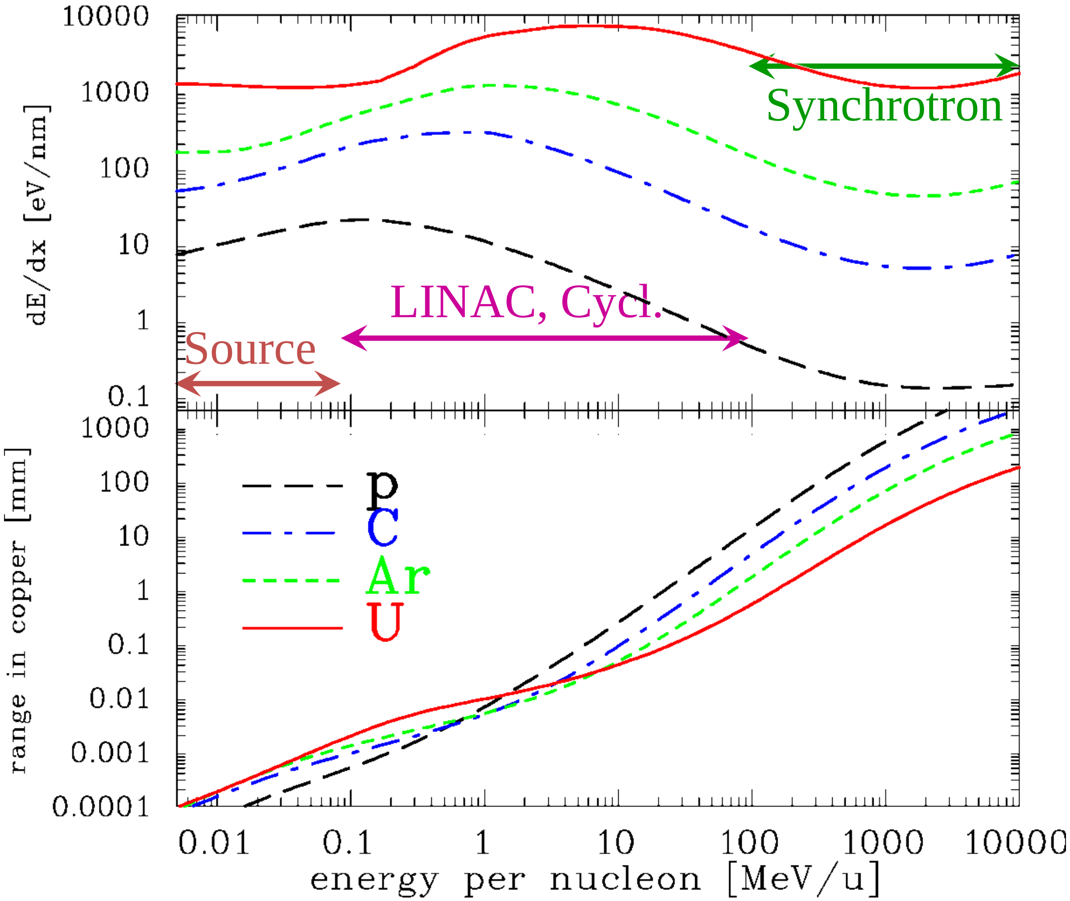
with semi-empirical model e.g. SRIM

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

**This is an atomic physics process:**

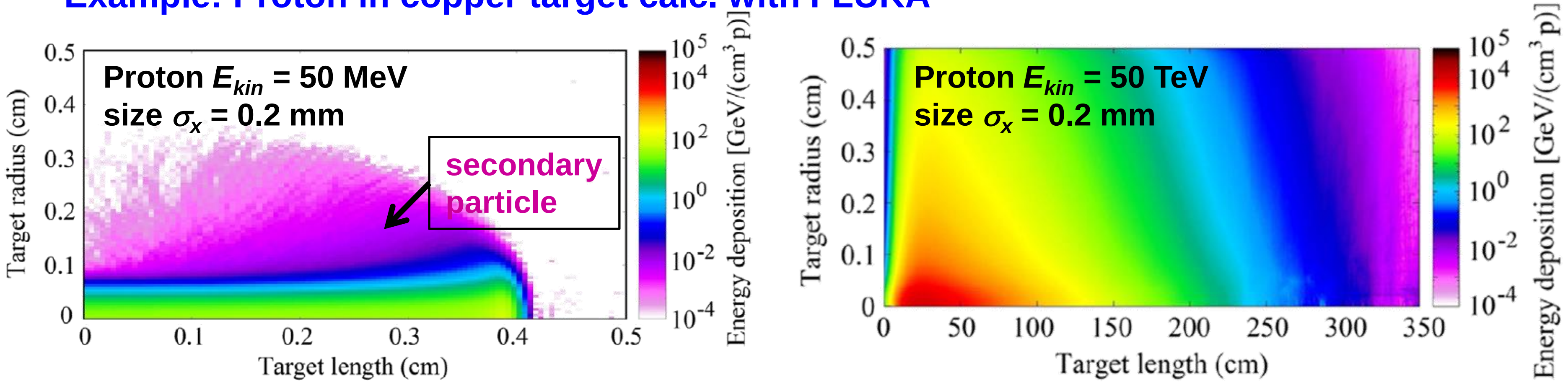
1. Projectile ions liberates fast electrons
2. Thermalization by collisions
   with further electrons
3. Transfer of energy to lattice (phonon)

$\Rightarrow$ **Heating of target**



# Energy Loss and Heating: Calculations

## Example: Proton in copper target calc. with FLUKA



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

secondary particle

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

Y. Nie et al., Phys Rev AB 20, 081001 (2017)

## General method of calculation (simplified):

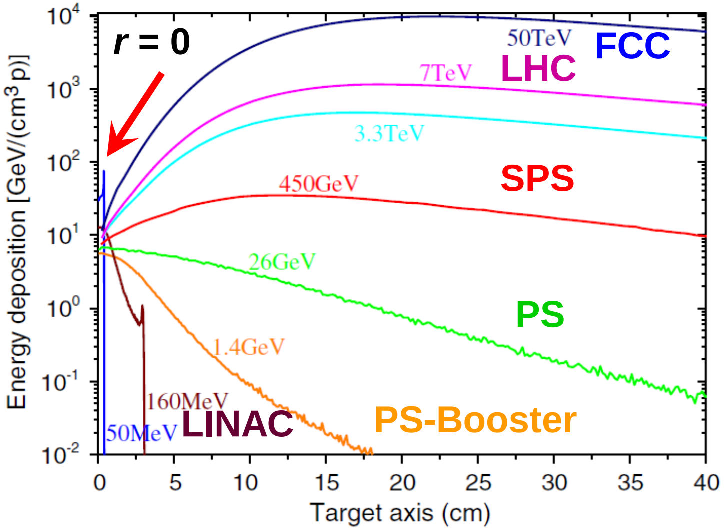
1. **Differential *energy loss:*** *by Bethe-Bloch* $\frac{dE}{dx}(x)$ *via codes like SRIM, LISE, FLUKA, MARS...*
2. **Energy deposition:** $\frac{dE}{dV} = -\frac{dE}{dx} \cdot \frac{N}{A}$ $\left[\frac{\mathrm{J}}{\mathrm{cm}^3}\right]$ with *N*: number of particles , *A*: beam cross section
3. **Temperature rise:** $\Delta T = \frac{dE}{dV} \cdot \frac{1}{\rho\, c_p}$ $[\mathrm{K}]$ 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**

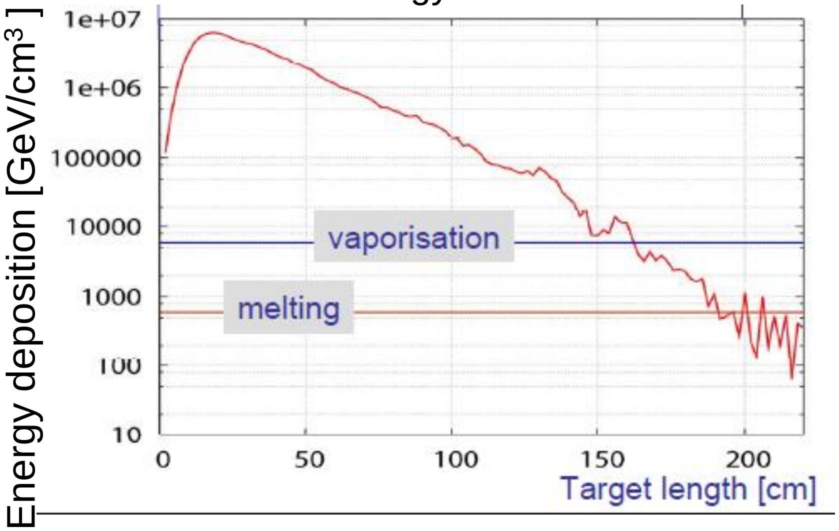
Energy deposition per protons



**Nominal LHC parameters for protons:**

$E_{kin}$ = 7 TeV, 2808 bunch

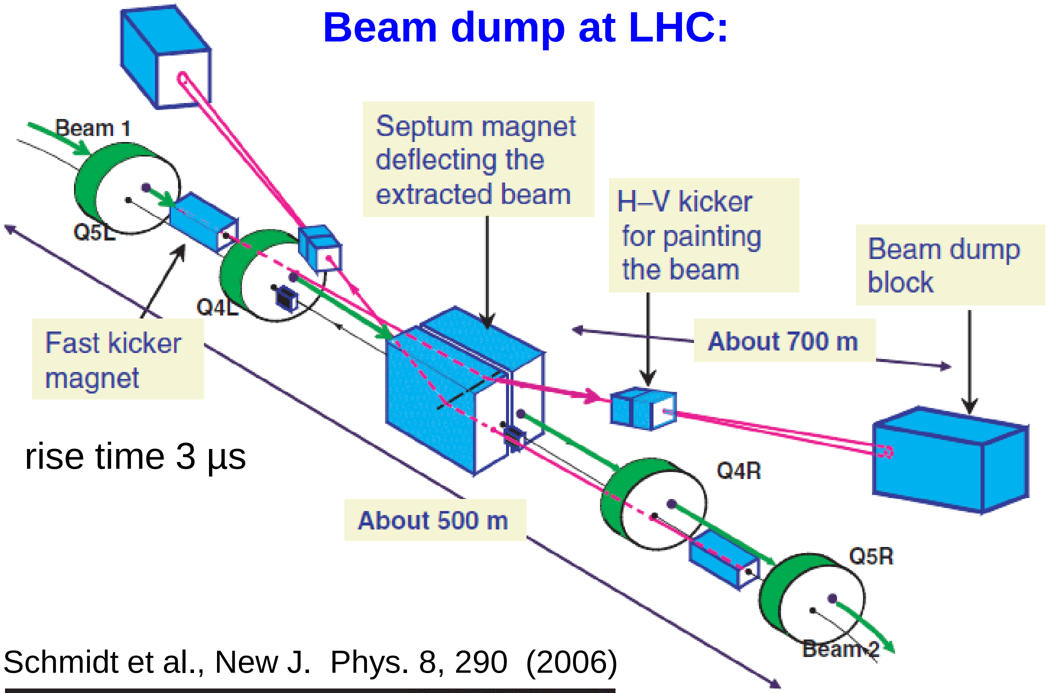
⇒ 380 MJ energy at center $r$ = 0



**Remark:** Low energetic proton have large energy deposition at short range e.g. $E_{kin}$ = 50 MeV

# Beam Dump for high Intensity Beams

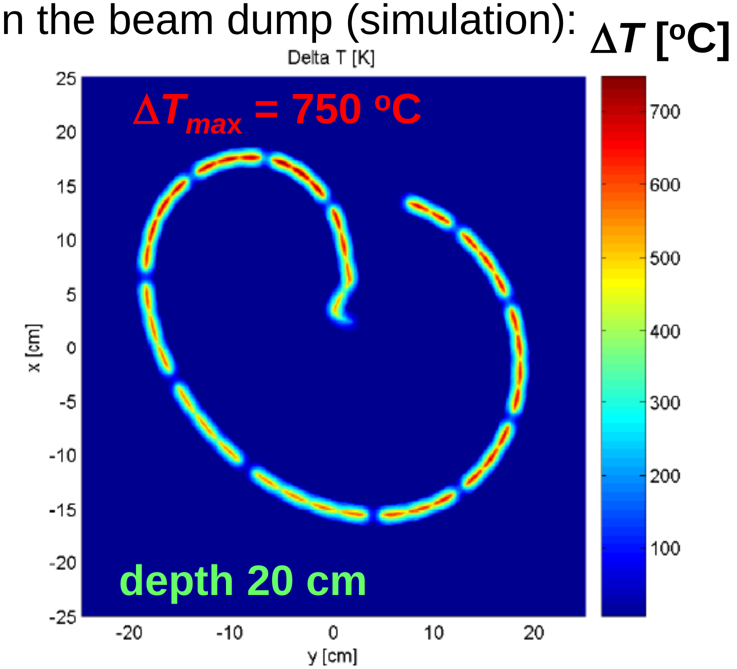
**Beam dump at LHC:**

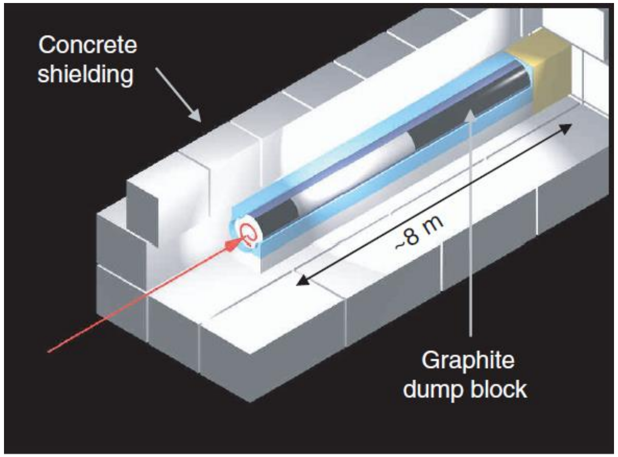


Fast kicker magnet rise time 3 µs

R. Schmidt et al., New J. Phys. 8, 290 (2006)

Extraction of LHC within **one** turn 86 µs on the beam dump (simulation):





**Beam dump at LHC:**

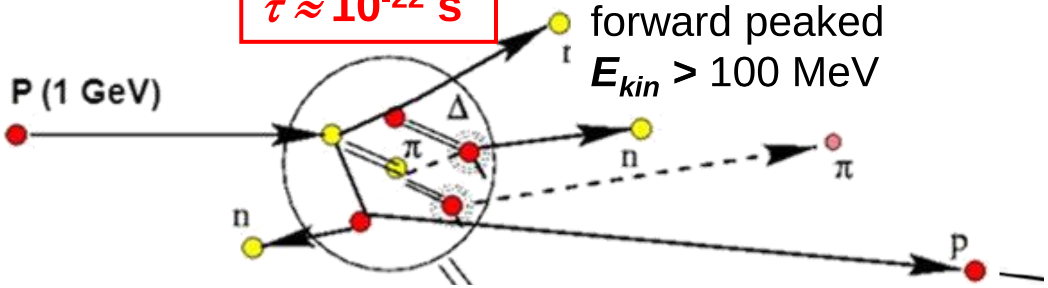
7m long, ∅ 0.7 m, graphite

900 tons of concrete shielding

# Nuclear Physics Processes for Protons

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

- Pre-equilibrium phases: π-exchange within ≈ $10^{-22}$ s with $E_{kin} > 20$ MeV ⇒ hadronic shower



$\tau \approx 10^{-22}$ s

forward peaked
$E_{kin} > 100$ MeV

## General properties:

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

D. Kiselev, CAS 2011

# Nuclear Physics Processes for Protons

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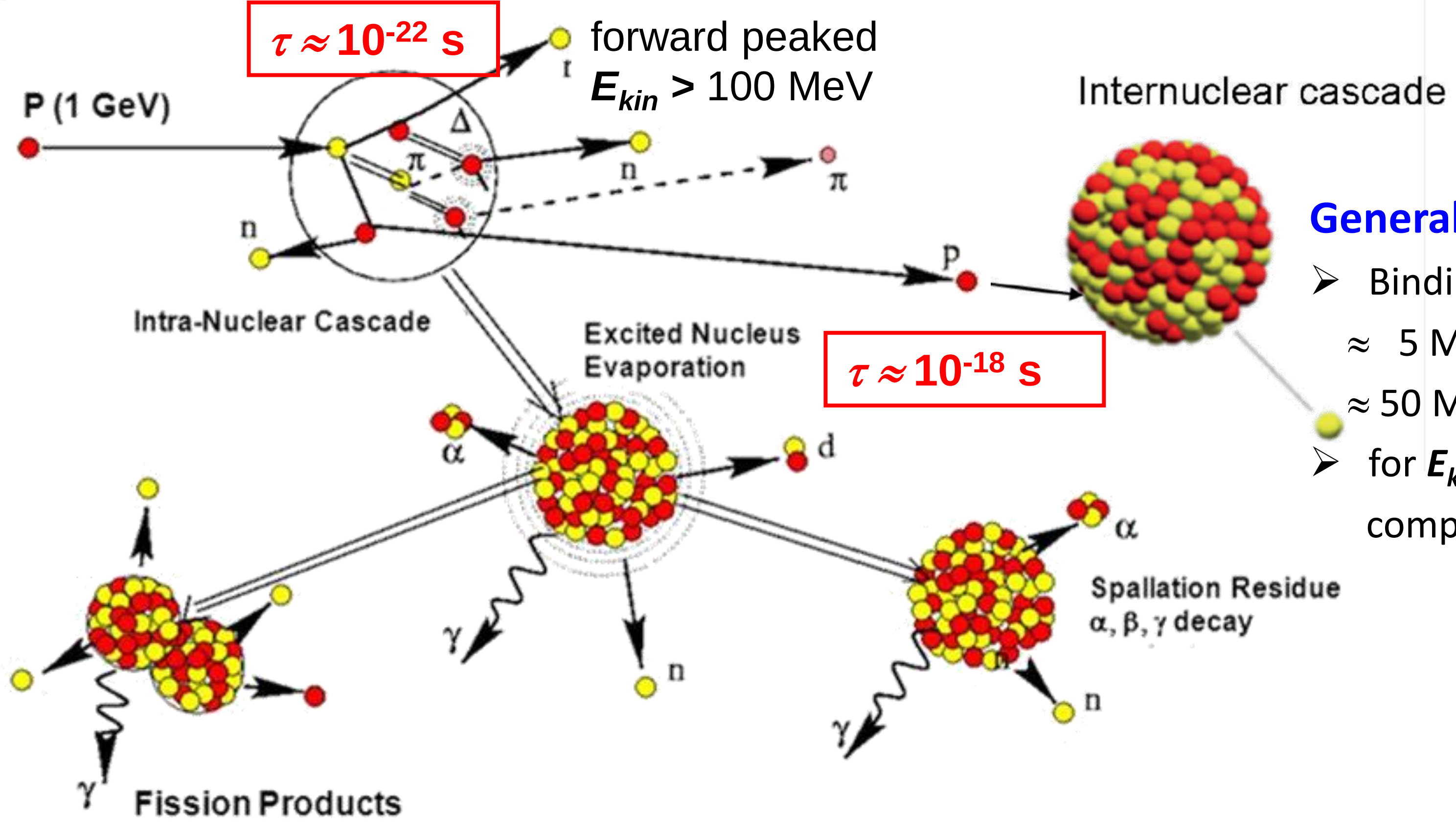
- Inter-nuclear cascade: Evaporation of n, p, d, α within ≈ $10^{-18}$ s with $E_{kin} \approx 1 - 10$ MeV
- Fission for heavy nuclei
- $\beta$ & γ decay of nuclei with long lifetime $\tau \gg 10^{-9}$ s



$\tau \approx 10^{-22}$ s

forward peaked

$E_{kin} > 100$ MeV

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**General properties:**

- Binding energy:
  ≈ 5 MeV outer nucleons
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  comparable $\sigma$ for n & p

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

D. Kiselev, CAS 2011

# Nuclear Physics Processes for Protons

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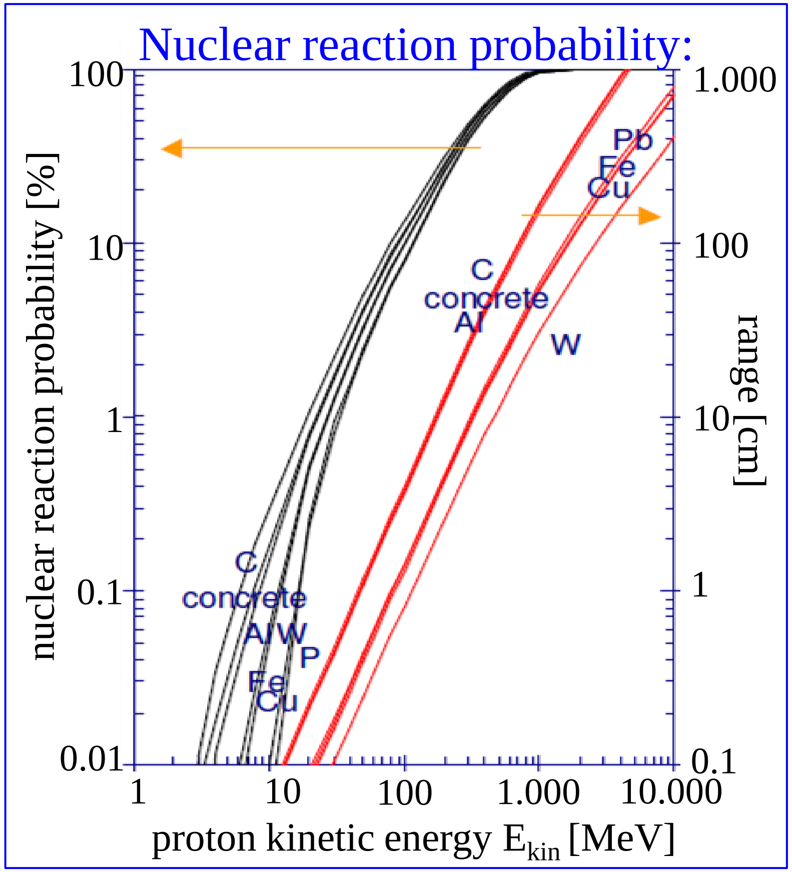
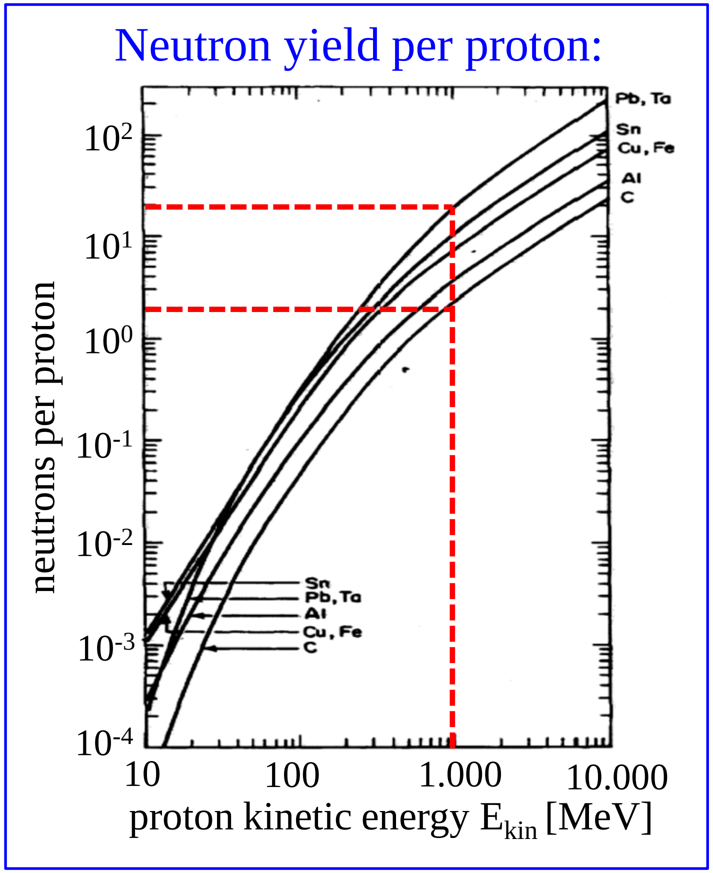


Nuclear reaction probability:



Neutron yield per proton:

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

R.H. Thomas, in Handbook on Acc. Phy. & Eng.

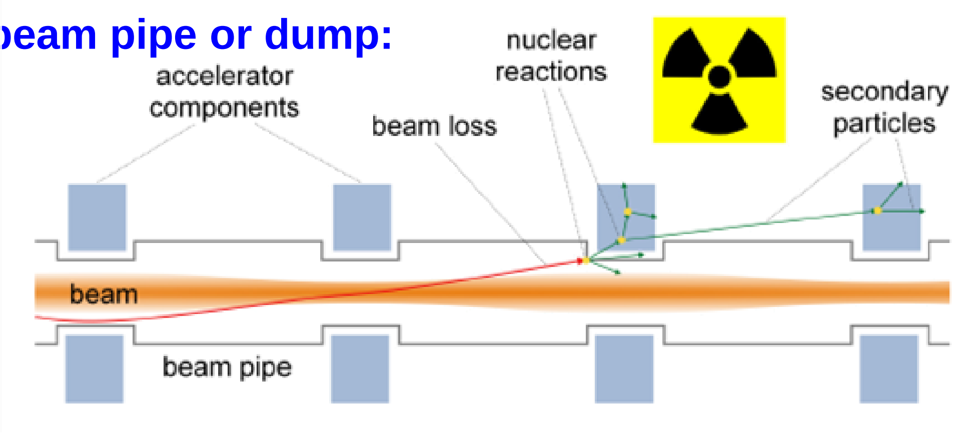
# Nuclear Physics Processes for Protons

Two slides

## 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’



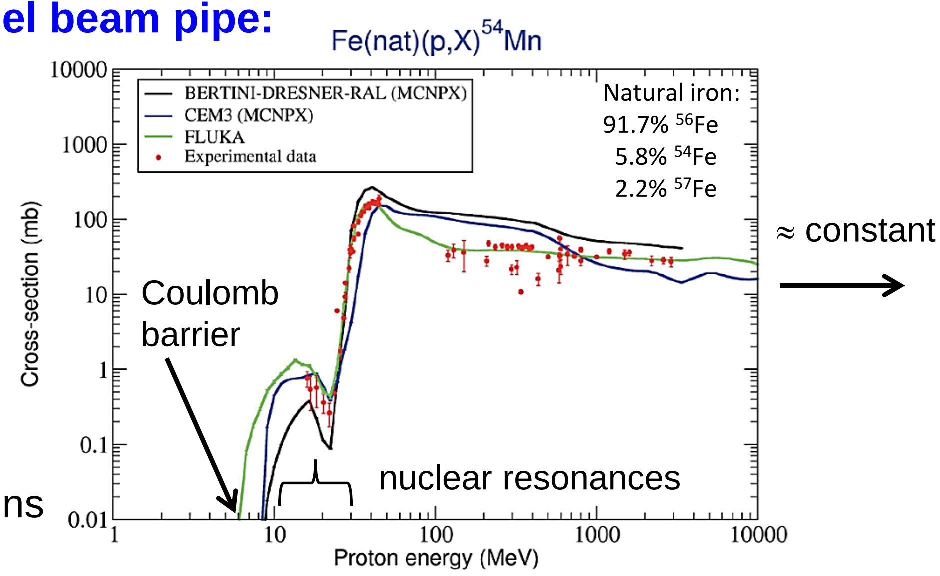
Courtesy I. Strasik

## Example of cross section for protons on steel beam pipe:

- Reaction: Fe + p → $^{54}$Mn + something
  [ 100 mb ≈ $\frac{1}{10}\,\sigma_{geo}$ ]
- $^{54}$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

⇒ **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 ≃ 5 fm

D. Kiselev, CAS 2011

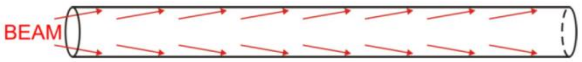
# Tolerable Beam Losses

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

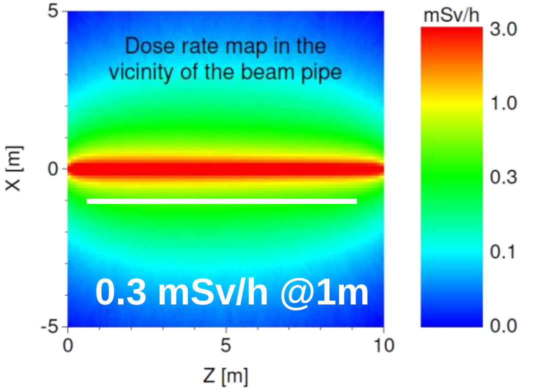
**'Beam loss below 1 W/m enables hands-on maintenance'**

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

Simulation for 1 GeV proton irradiation: Stainless steel beam pipe after 1 W/m beam loss for 100 days & 4 h 'cool down'



| | |
|---|---|
| Natural background | ≈ 1 mSv/a |
| Medical X-ray CT | ≈ 3 mSv |
| Max. for rad. workers | 20 mSv/a |

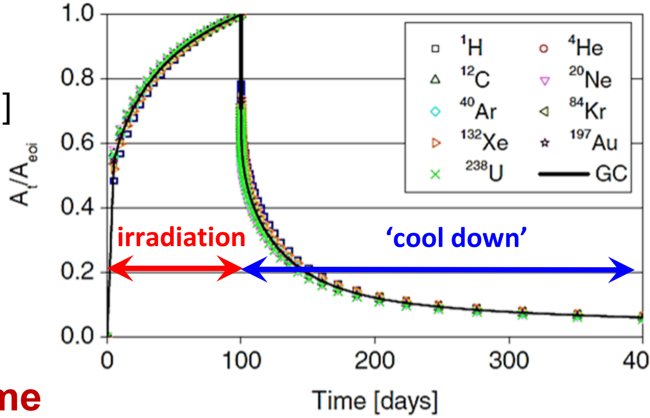


I. Strasik et al., Phys Rev AB 13, 071004 (2010)

**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:
  ≈ 10% after ≈ 1 year
- Isotope mixture same for all ions

⇒ **highly activated material needs significant 'cool down' time**



**Rule of thumb: Light targets (C, Al ...) have lower activation for impact of same # particles**

# Secondary Particle Production for Electron Beams

## 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 $E_\gamma = 5\text{-}50$ MeV

$\Rightarrow \gamma \to e^+ + e^-$ or $\mu^\pm$ .. $\to$ electro-mag. showers

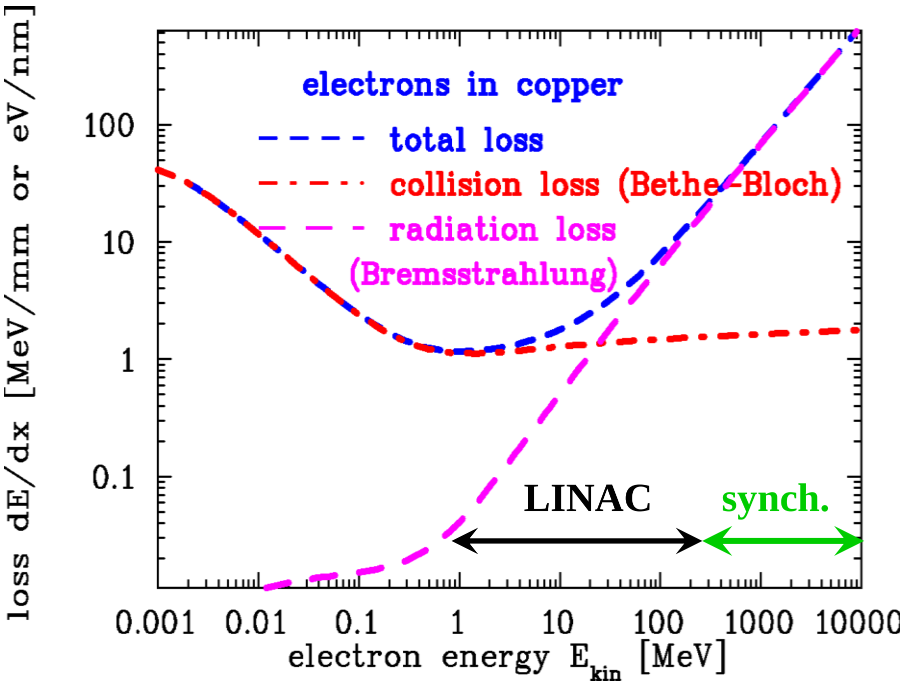
$\Rightarrow$ Excitation of giant resonances $E_{res} \approx 10\text{-}30$ MeV

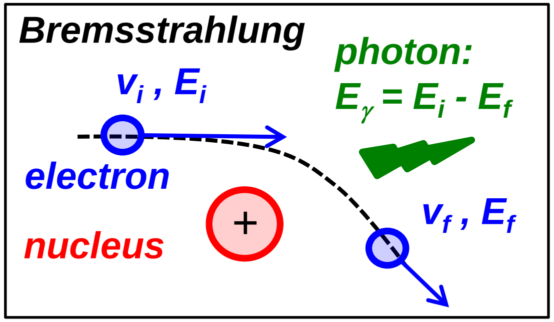
via ($\gamma$, n), ($\gamma$, p) or ($\gamma$, np) with $\sigma_{giant} \approx \frac{1}{10} \sigma_{geo}$

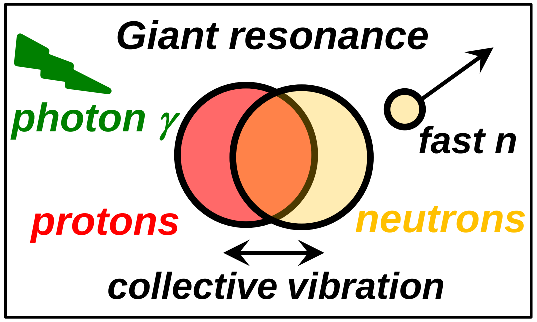
→ Fast neutrons emitted (by nuclear interaction)

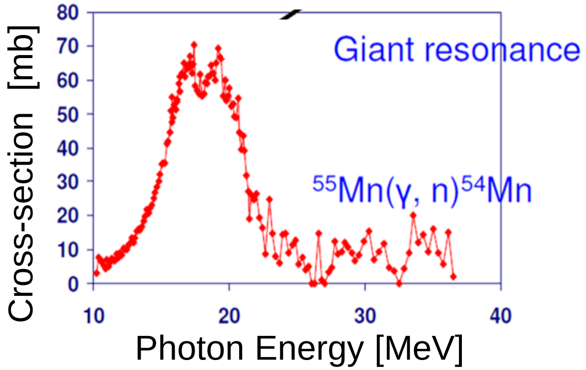
→ Neutrons: Long ranges in matter

$\Rightarrow$ **Neutrons at electron accelerators!**





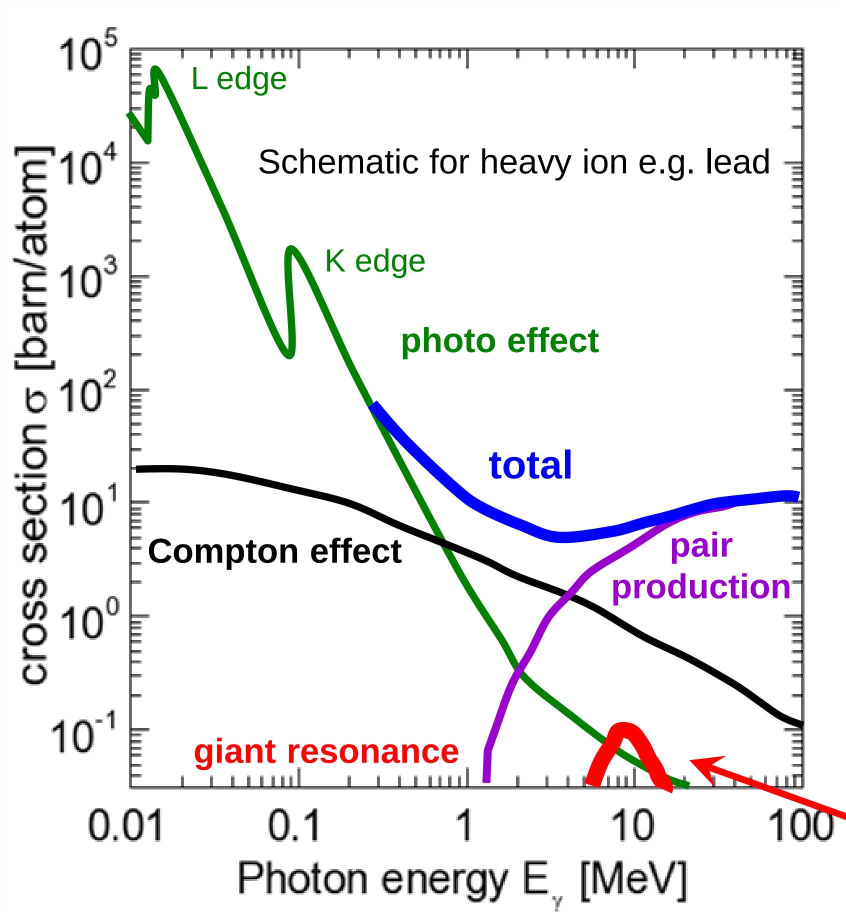




# Interaction of high Energy γ

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

***Example:*** Absorption in lead



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

$\rho$ *density,* $N_A$ Advogadro const., $A$ atomic mass

Courtesy C. Grupen, Xavier Queralt, JUAS

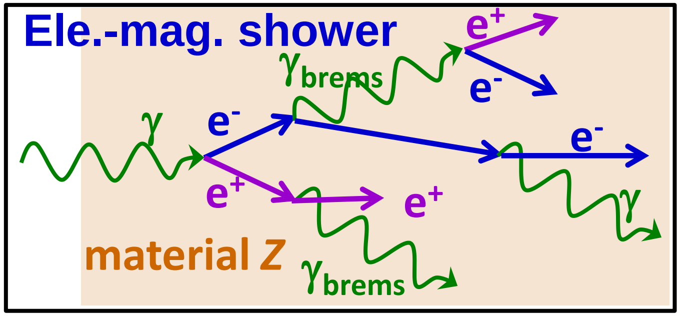
***Atomic physics*** (***Z*** = target nuclear charge)**:**

***Photo-effect:*** $\gamma$ + atom → $e^-$ + $\text{atom}^+$
approx. material scaling $\sigma_{photo} \propto Z^4$

***Compton-effect:*** $\gamma$ + atom → $\gamma'$ + $e^-$ + $\text{atom}^+$
approx. material scaling $\sigma_{Comp} \propto Z$

***Pair production:*** $\gamma$ + nucleus → $e^-$ + $e^+$ + nucleus
approx. material scaling $\sigma_{pair} \propto Z^2$

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



***Nuclear physics:***

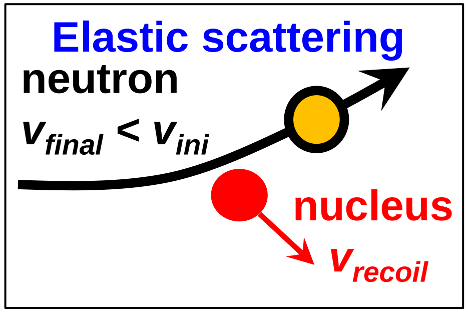
***Giant resonance:*** $\gamma$ + nucleus → n + nucleus'
small cross section but create free neutrons

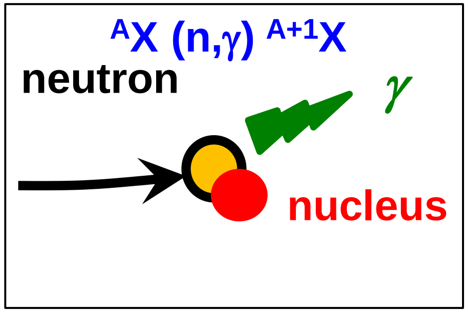
# Interaction of Neutrons

**Neutrons don’t interaction with electrons**

**Only nuclear physics processes:**

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





***Example:*** Neutron on chromium ${}^{50}$Cr (4.3% natural abundance, in stainless steel)

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

**Absorption**: Large cross section at resonances
γ emission and activation

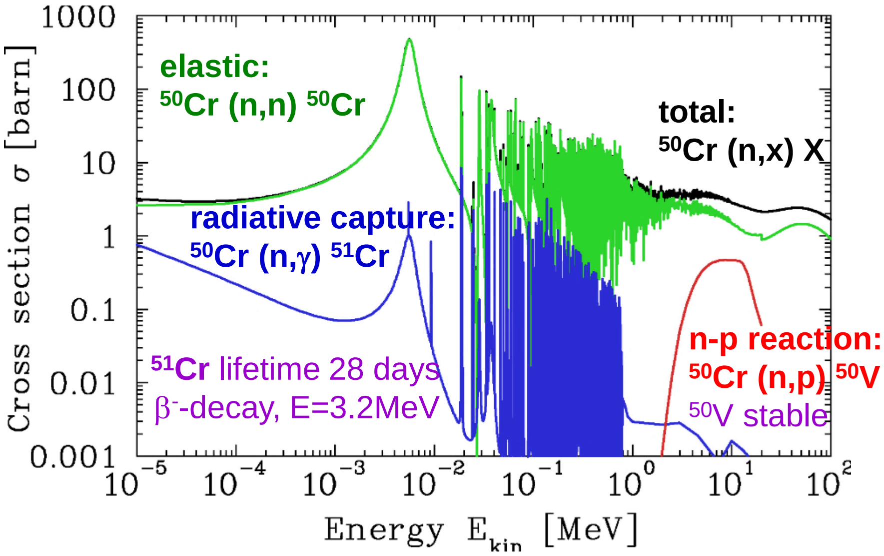
For ***E*** >> 100 MeV comparable cross section as proton

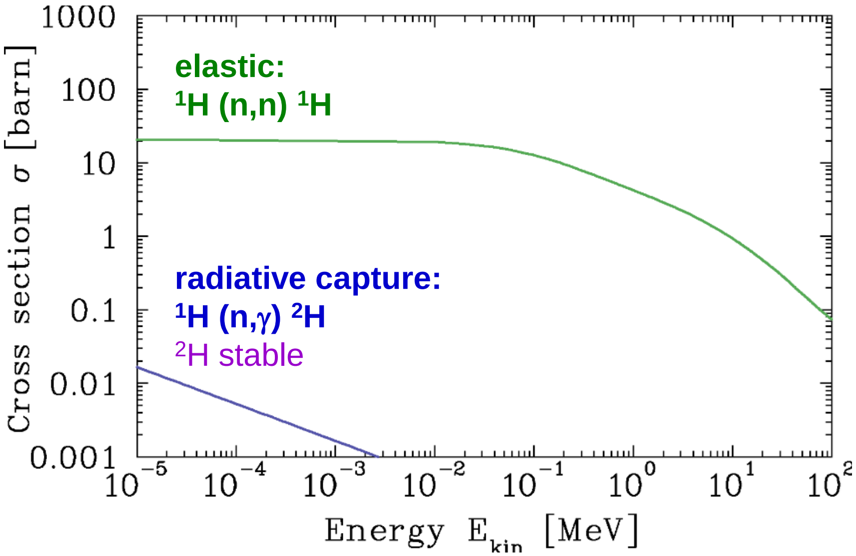
***Example:*** Neutrons on H with ≈ 10 $\sigma_{geo}$

e.g. organic materials, $H_2O$

→ effective moderator due to equal masses

→ no activation





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

https://t2.lanl.gov/nis/data/endf/ & https://www.nndc.bnl.gov/

# Outline

**Outline of this talk:**

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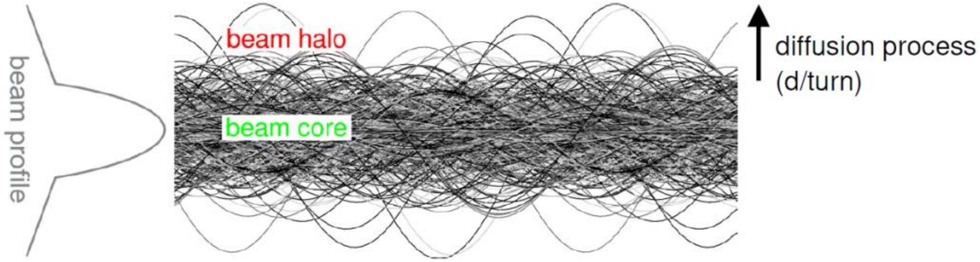
2. **Relevant atomic and nuclear physics**
3. **Collimation as passive protection**
4. **Measurements by Beam Loss Monitors**
5. **Design of Machine Protection System**
6. **Overview of personal safety**

# 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

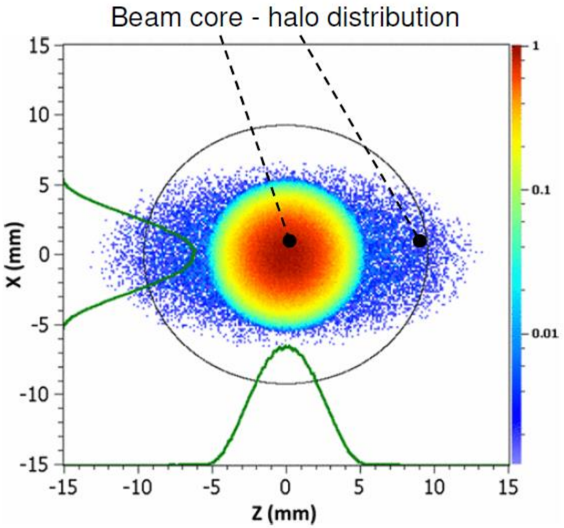
- ➢ **Warm synchrotron**: Protection of sensitive insertions (e.g. septum)
  Concentration of loss at few locations
- ➢ **Super-conduction synch:** + quench protection of sc magnets
- ➢ **Collider:** + well defined condition for detector at IP
  ⇔ min. exp. background
  Cleaning of collisional halo particles

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

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

**Goal:** Quench protection of sc civilities

Courtesy I. Strasik CAS 2016



Remark:

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

# Quench Protection for superconducting Magnets

**Superconducting magnets:**

Beam particles energy loss

$\Rightarrow$ 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:** $\frac{dE}{dV} = -\frac{dE}{dx} \cdot \frac{N}{A} \quad \left[\frac{\mathrm{J}}{\mathrm{cm}^3}\right]$

***N:*** number of particles , *A*: cross section

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

$\rho$: mat. density, $c_p$ specific heat

**Temperature dependent specific heat:**

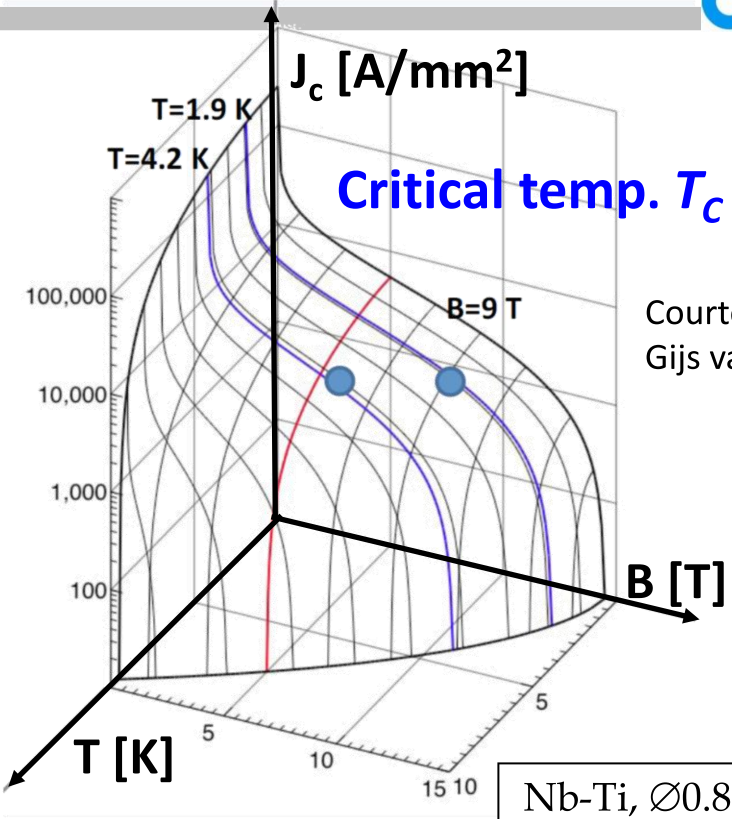
**Insulator:** $c_{phonon}(T) \propto T^3$

**Normal conductor:** $c_{NC}(T) \propto \alpha T + \beta T^3$

**Superconductor:** $c_{SC}(T) \propto T_C\, e^{-\gamma T/T_C}$

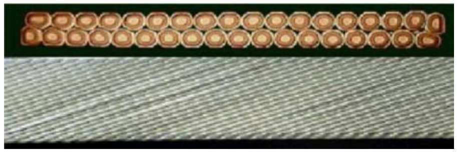
$\alpha, \beta, \gamma$ material constants

See lecture 'Superconducting Magnets' by Gijs van Rijk

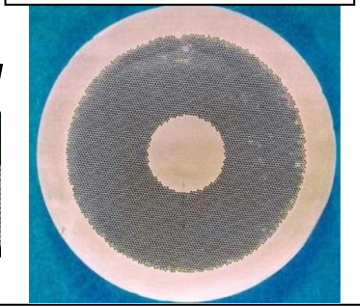


Courtesy Gijs van Rijs

*'Rutherford' cable strand*



Nb-Ti, ∅0.85mm

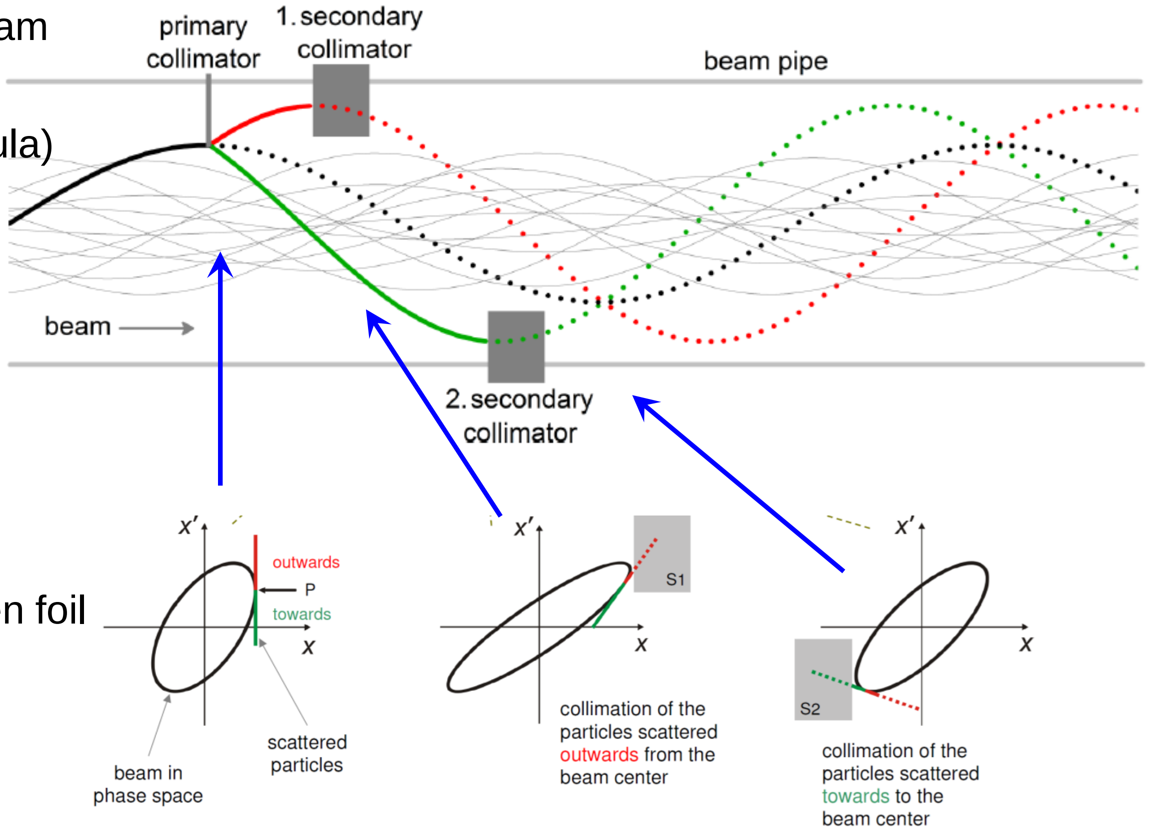


J ~ 1500-2000 A/mm$^2$
I ~ 400 A, B = 8-9 T

# Two Stage Betatron Collimation System = active Collimation

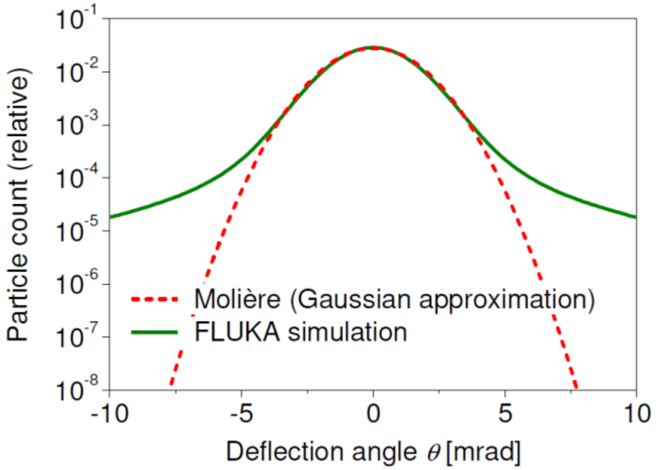
## General functionality of cleaning:

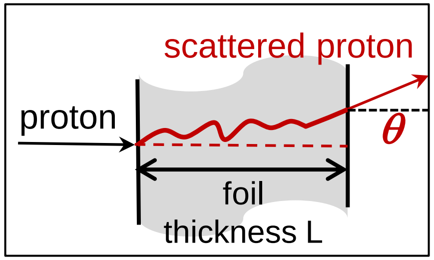
- Primary stage as **thin** foil **close** to beam
  $\Rightarrow$ scattering of halo particles
  (Coulomb scattering by Moliere formula)
- Betatron amplitude increases
- Max. extension after
  $\mu \approx 90^0$ or $270^0$ betatron phase
- Secondary collimator as absorber
  more distant to beam



Example:

4.7 GeV scattering in L=1 mm Tungsten foil





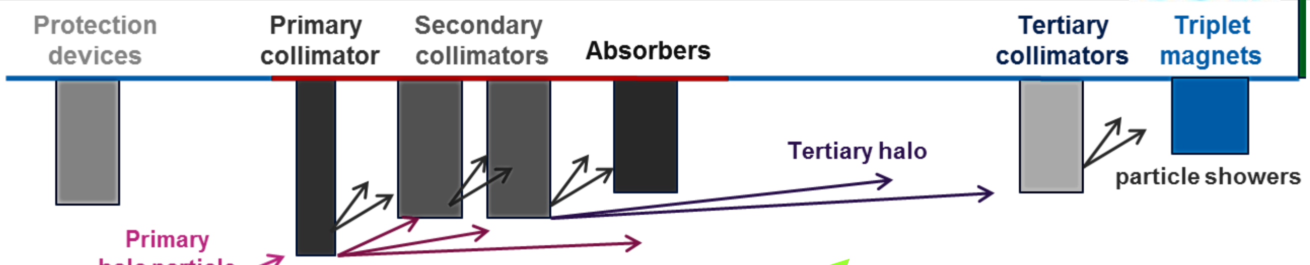
Courtesy I. Strasik CAS 2016

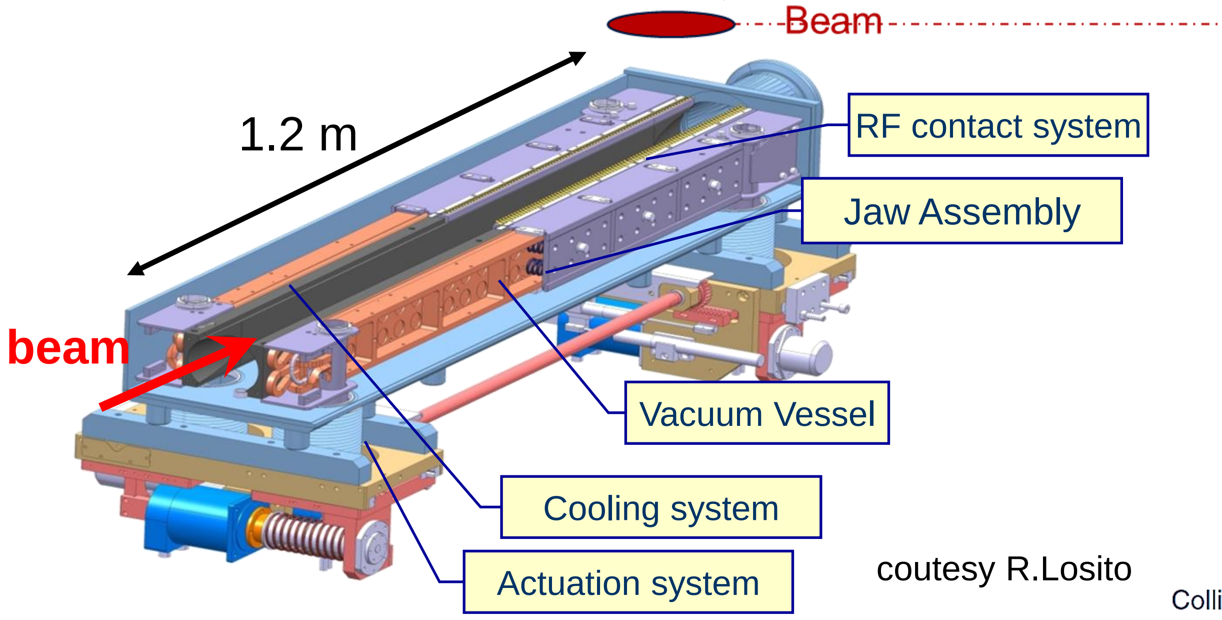
# LHC Collimator Hardware

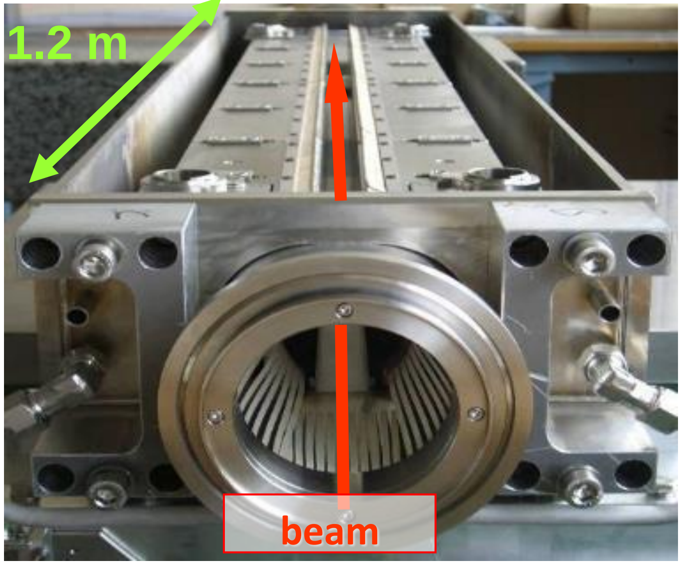
## LHC Collimator system:

- Primary stage
- Secondary & tertiary stage
- Absorbers

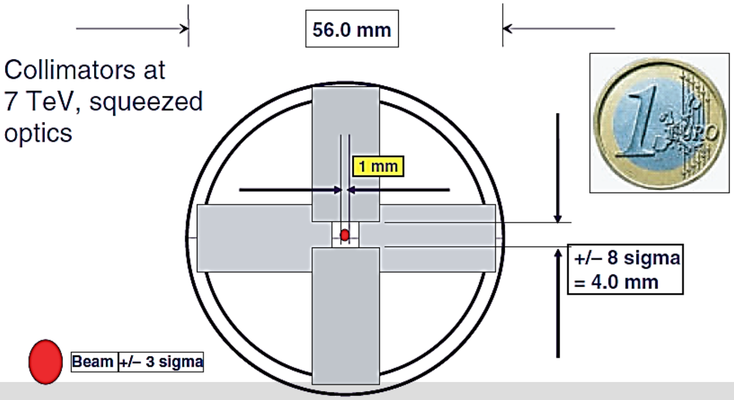
in total 110 movable devices







coutesy R.Losito



## LHC maximal losses for 6.5 TeV protons:

- Total stored power 300 MJ
- Max. energy deposition in sc magnet: 0.1 J/cm$^2$
- Corresponding to 6x10$^7$ protons
- Or 2x10$^{-7}$ of the stored beam of 3x10$^{14}$ protons

# LHC Collimator System

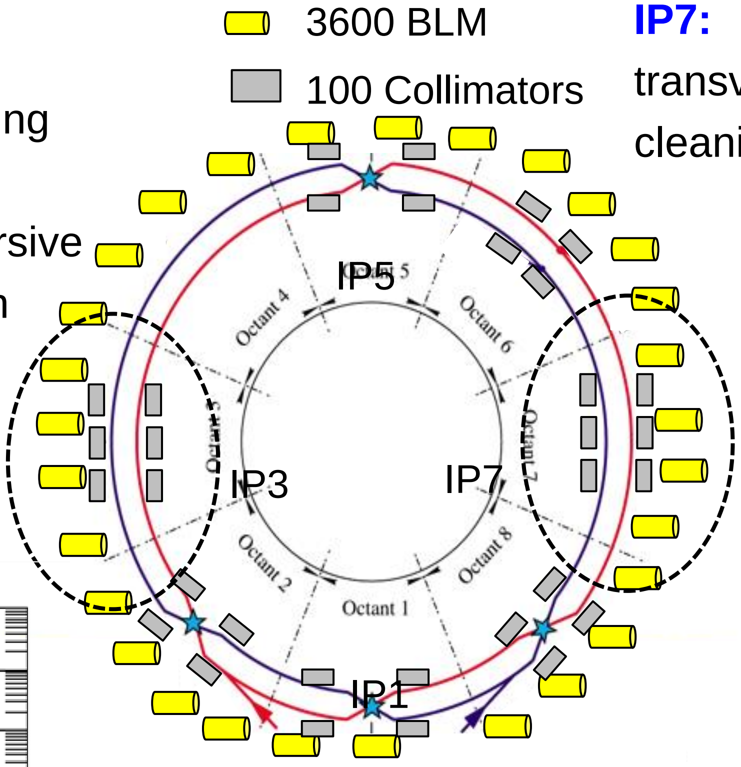
**LHC Collimator system:**

- Primary stage as close as $\approx 5\sigma_{beam} \approx 1$ mm
- Secondary & tertiary stage made of carbon
- Absorbers made of tungsten alloy

→ in total 110 movable devices

moving e.g. from injection r = 5 mm → 1 mm

**IP3:** long. cleaning at dispersive region



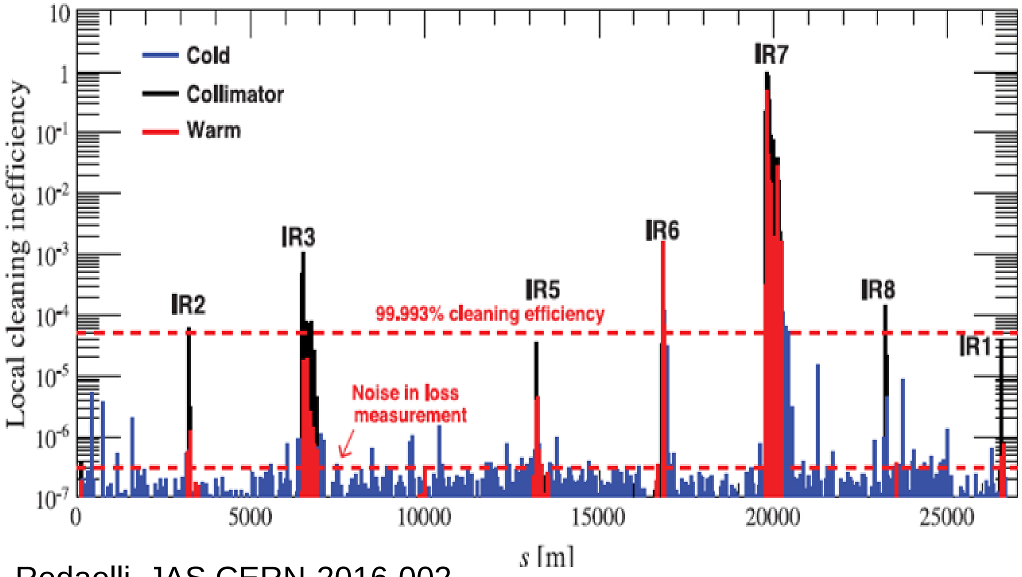
**IP7:** transverse cleaning

**Test of functionality:**

- Loss concentrated at collimators

**Experimental verification**: Single bunch excitation

**Result:** Main losses concentrated at collimators



S. Redaelli, JAS CERN-2016-002

Cleaning efficiency:

$\eta$ = (protons lost at collimator) / (total beam loss)

Result: $\eta$ = 99.8 % reached

Courtesy M. Zerlauth, CAS 2018

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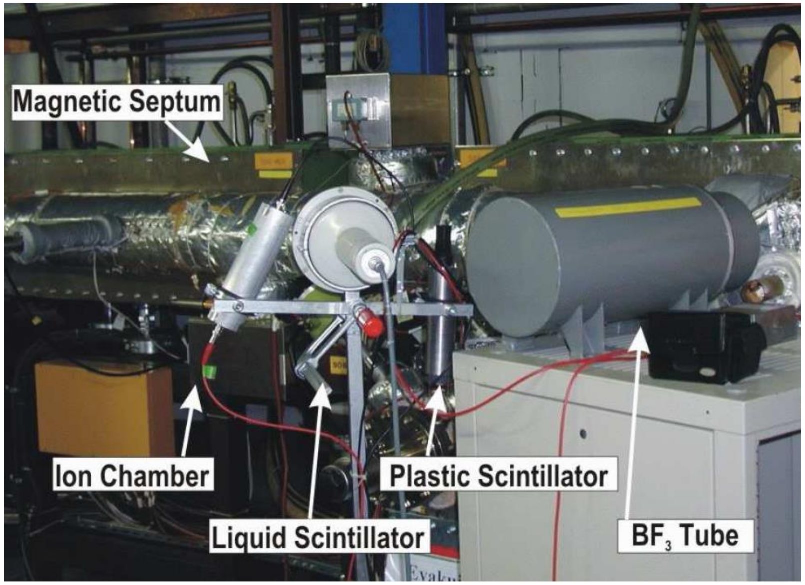


# Basic Idea of Beam Loss Monitors

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

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

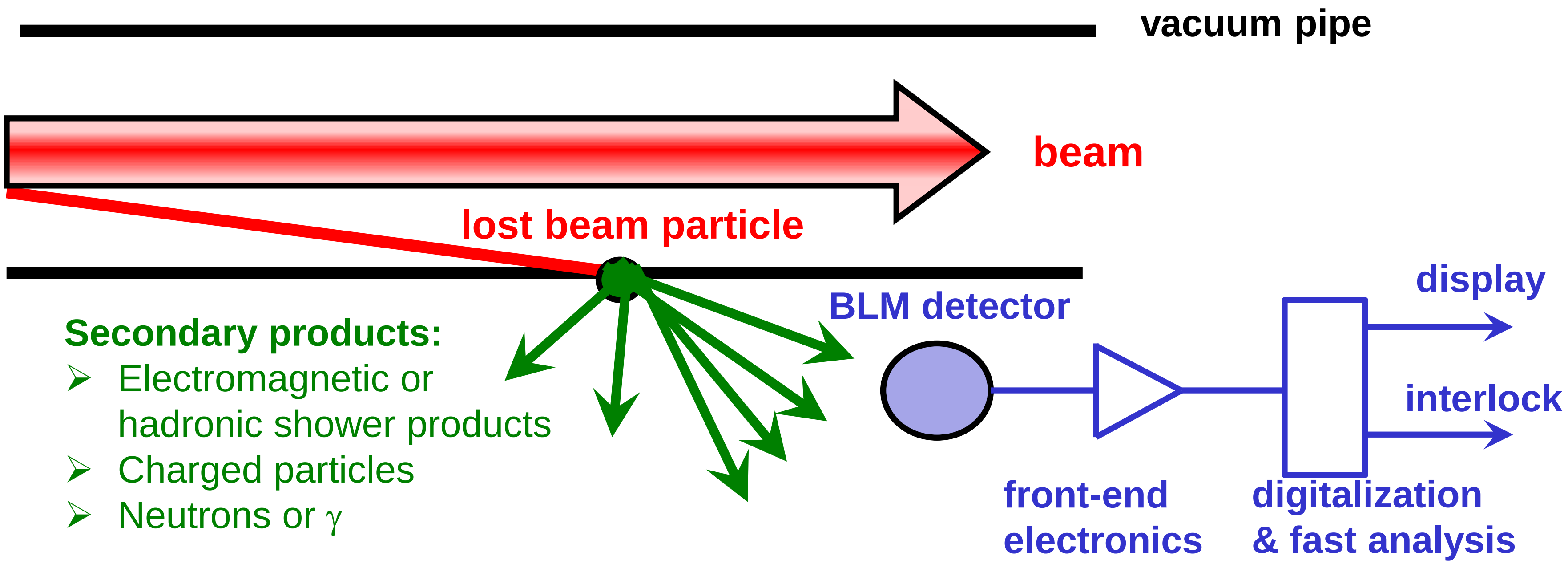
⇒ Interaction leads to some shower particle:

$e^-$, $\gamma$, 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 $\gamma$

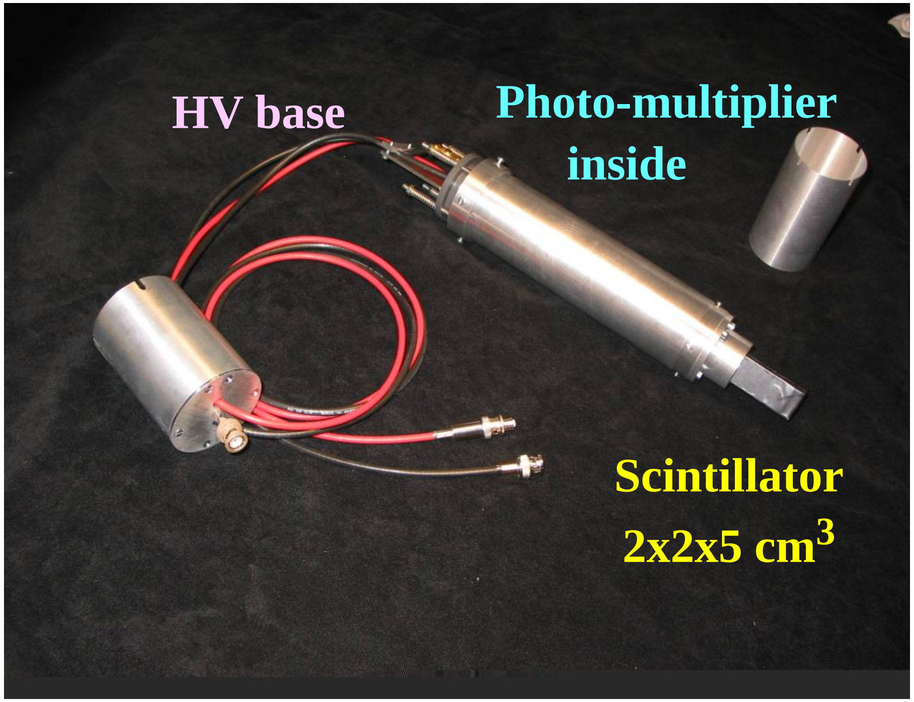
# Scintillators as Beam Loss Monitors

**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:**

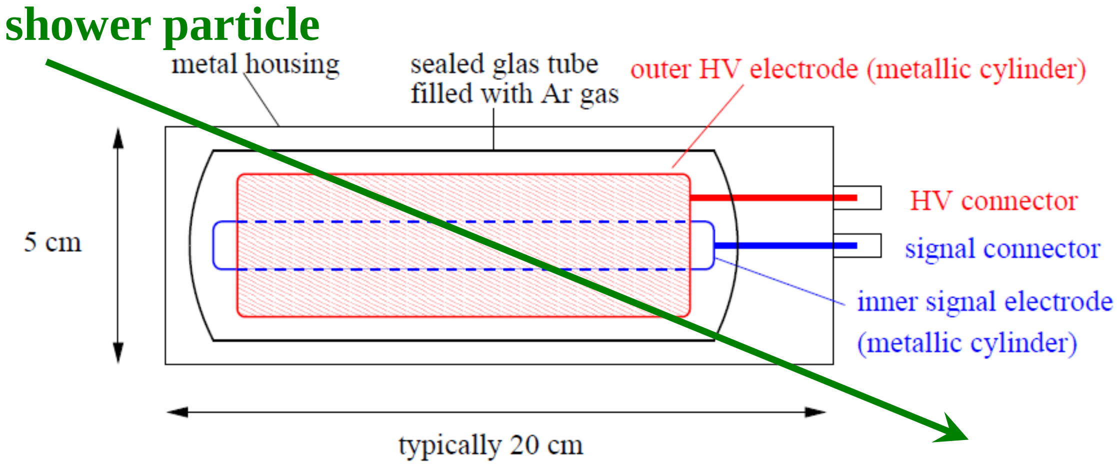
counting (large PMT amplification)
or analog voltage ADC (low PMT amplification)
Radiation hardness:
plastics 1 Mrad = $10^4$ Gy
liquid 10 Mrad = $10^5$ Gy



# Ionization Chamber as Beam Loss Monitors

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

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

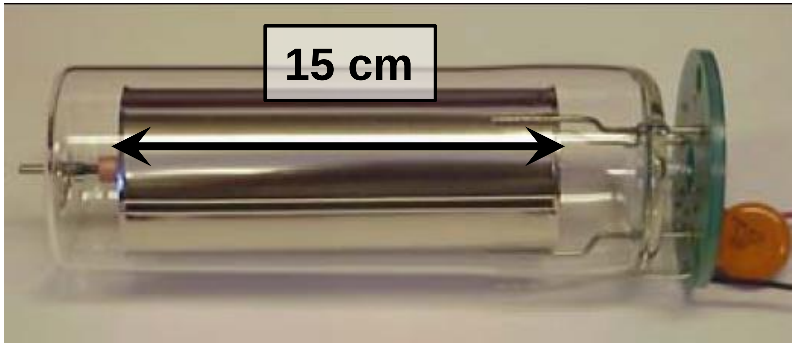


*W* is average energy for creation for one $e^-$ -ion pair:

| Gas | Ionization Pot. [eV] | W-Value [eV] |
|---|---|---|
| Ar | 15.7 | 26.4 |
| $N_2$ | 15.5 | 34.8 |
| $O_2$ | 12.5 | 30.8 |
| Air | | 33.8 |

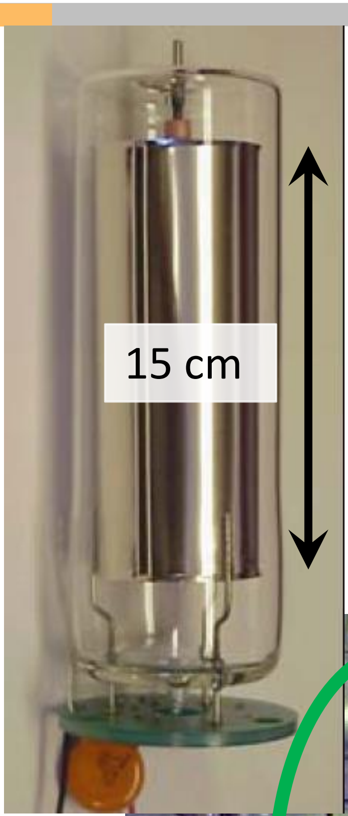
**Sealed tube Filled with Ar or $N_2$ gas:**

- Creation of $Ar^+$-$e^-$ pairs, average energy ***W*** = 32 eV/pair
- measurement of this current
- Slow time response due to ≈ 10 μs drift time of $Ar^+$.



**Per definition: Direct measurement of dose !**

# Ionization Chamber as BLM: TEVATRON and CERN Type

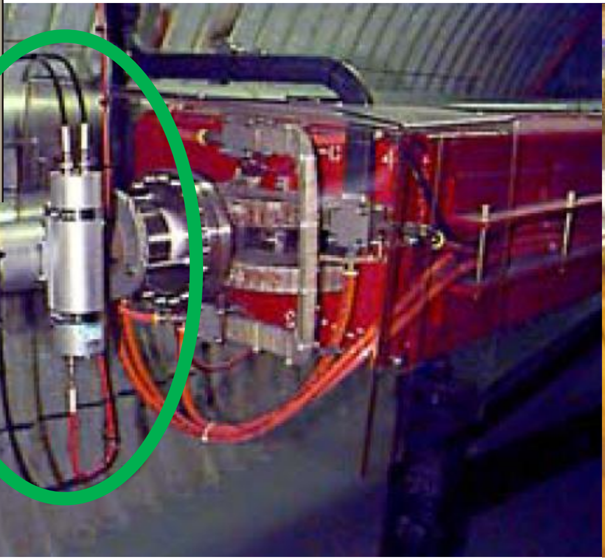


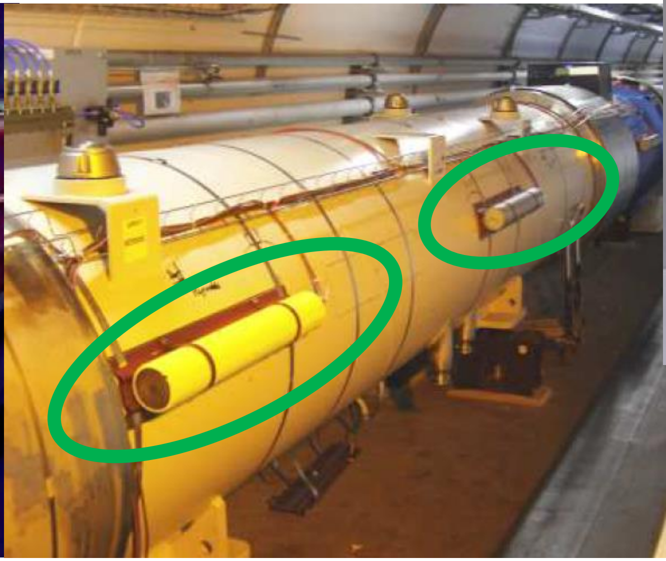
| Parameter | TEVATRON, RHIC | CERN type |
|---|---|---|
| Size | 15cm, ∅ 6 cm | 50 cm, ∅ 9 cm |
| Gas | Ar at 1.1 bar | $N_2$ at 1.1 bar |
| # of electrodes | 3 | 61 |
| Voltage | 1000 V | 1500 V |
| Reaction time | 3 µs | 0.3 µs |

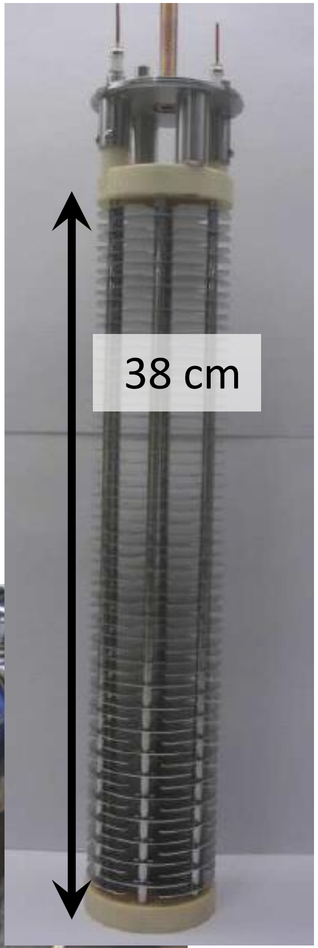
**4000 BLMs at LHC⇔ each ≈ 6m**

**TEVATRON, RHIC type**

**CERN type**







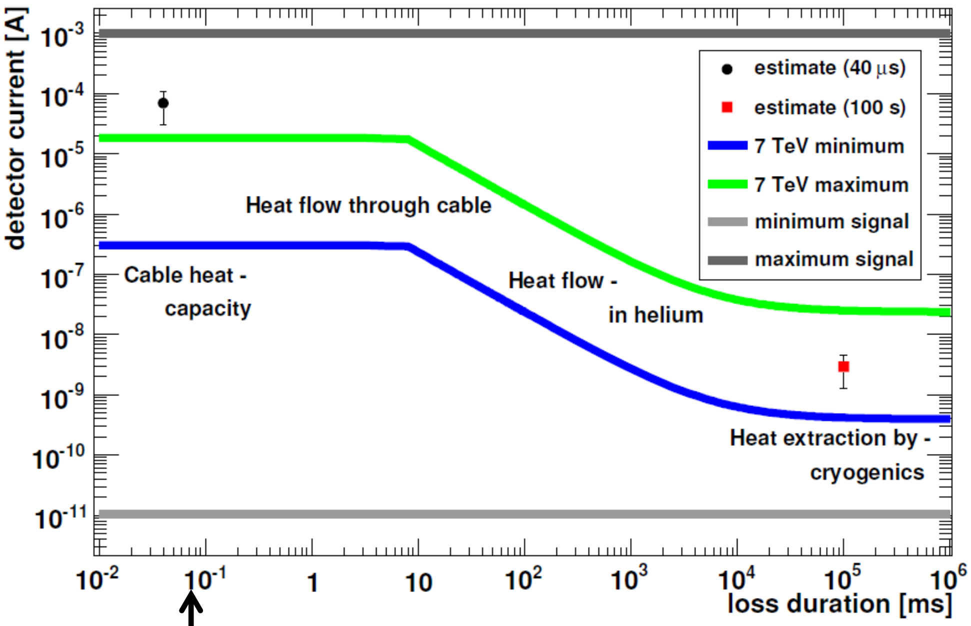
# Ionization Chamber as BLM: CERN Type

**Simulation of det. efficiency by Geant4:**

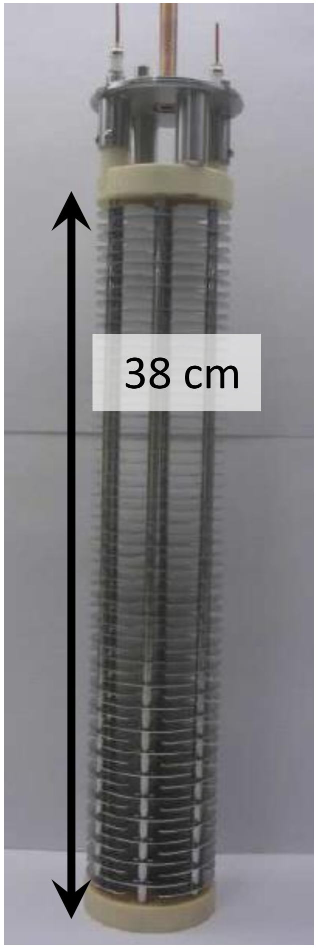
- Most sensitive to protons, electrons & high energy $\gamma$
- Low sensitive to neutrons

⇒ Calculation of lost protons by integrating of shower composition

⇒ **Quench limit estimation**

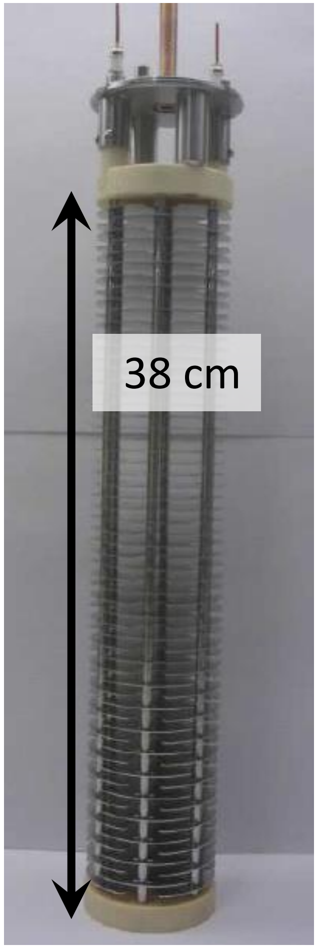


one turn



M. Stockner: PhD-Thesis, Tech. Uni. Vienna
A. North et al., HB 2010

# 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 γ, eff, no neutron detection),

  - Sometimes slow, ion drift time 10 ... 100 μs

  ⇒ Often used at **proton** accelerators

- **Scintillator, Cherenkov detector:**

  **Advantage:**

  - Fast current reading or particle counting

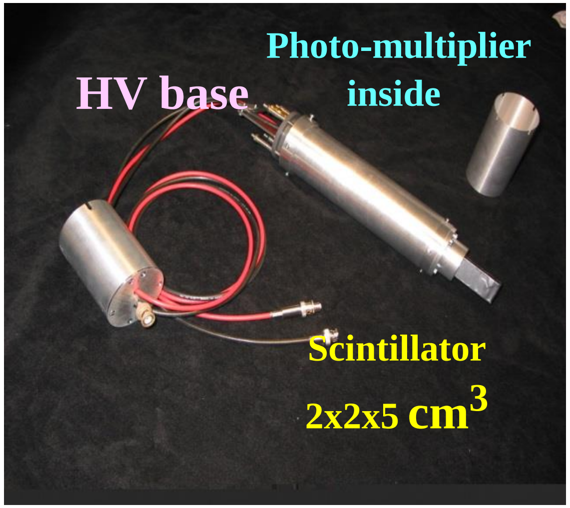
  - Can be fabricated in any shape, cheap

  **Disadvantage:**

  - Need calibration in many cases

  - Might suffer from radiation

  ⇒ Often used at **electron** accelerators



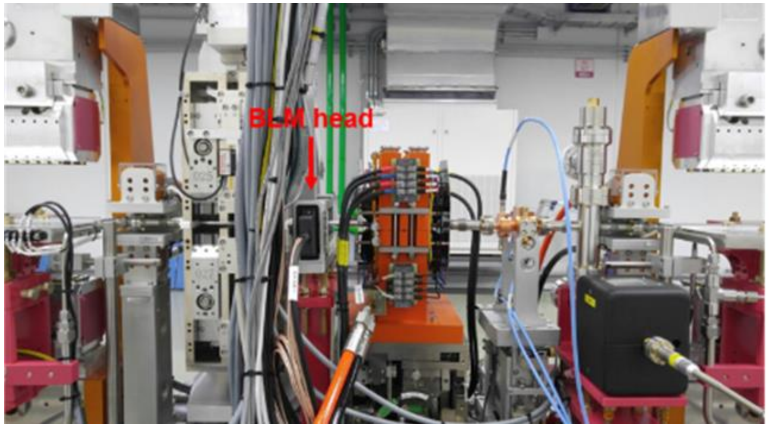
# Cherenkov Light Detectors as Beam Loss Monitors

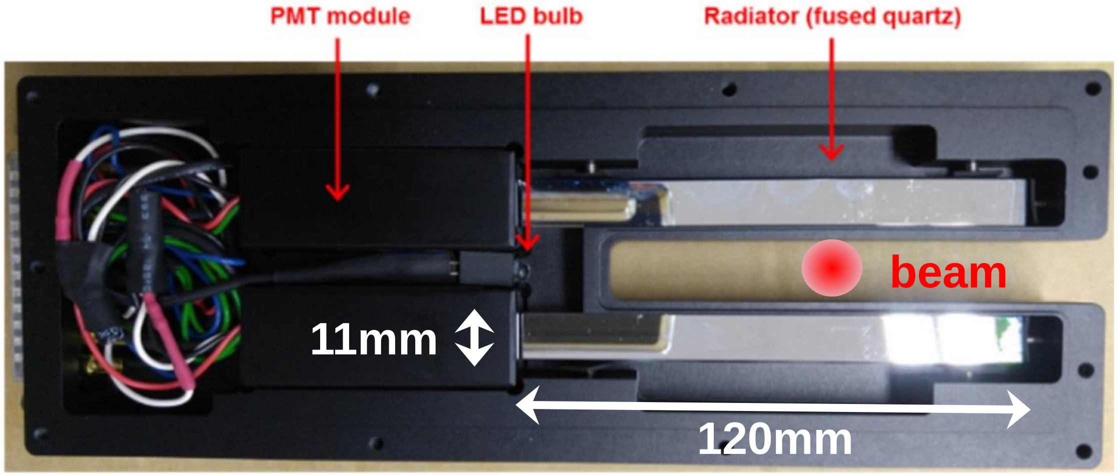
## Cherenkov detectors:

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

**Technical:** Quartz rod $n=1.5$ & photomultiplier

Example: Korean XFEL behind undulator



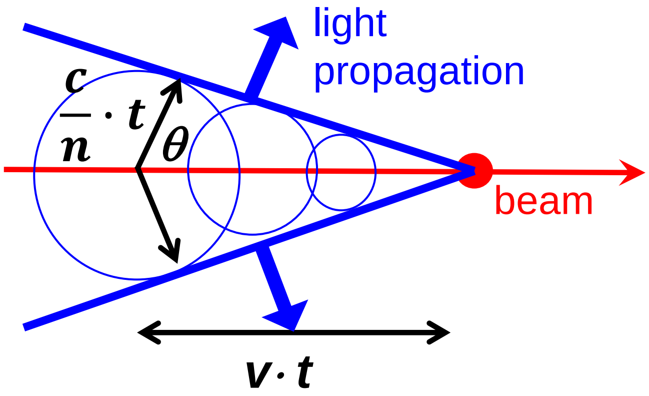


## Cherenkov light emission:

For $v > c_{medium} = c/n$

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

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# Relevant Losses for Machine Protection

***Type of losses:***

***1. Regular losses*** or slow losses ⇔ **un**avoidable 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

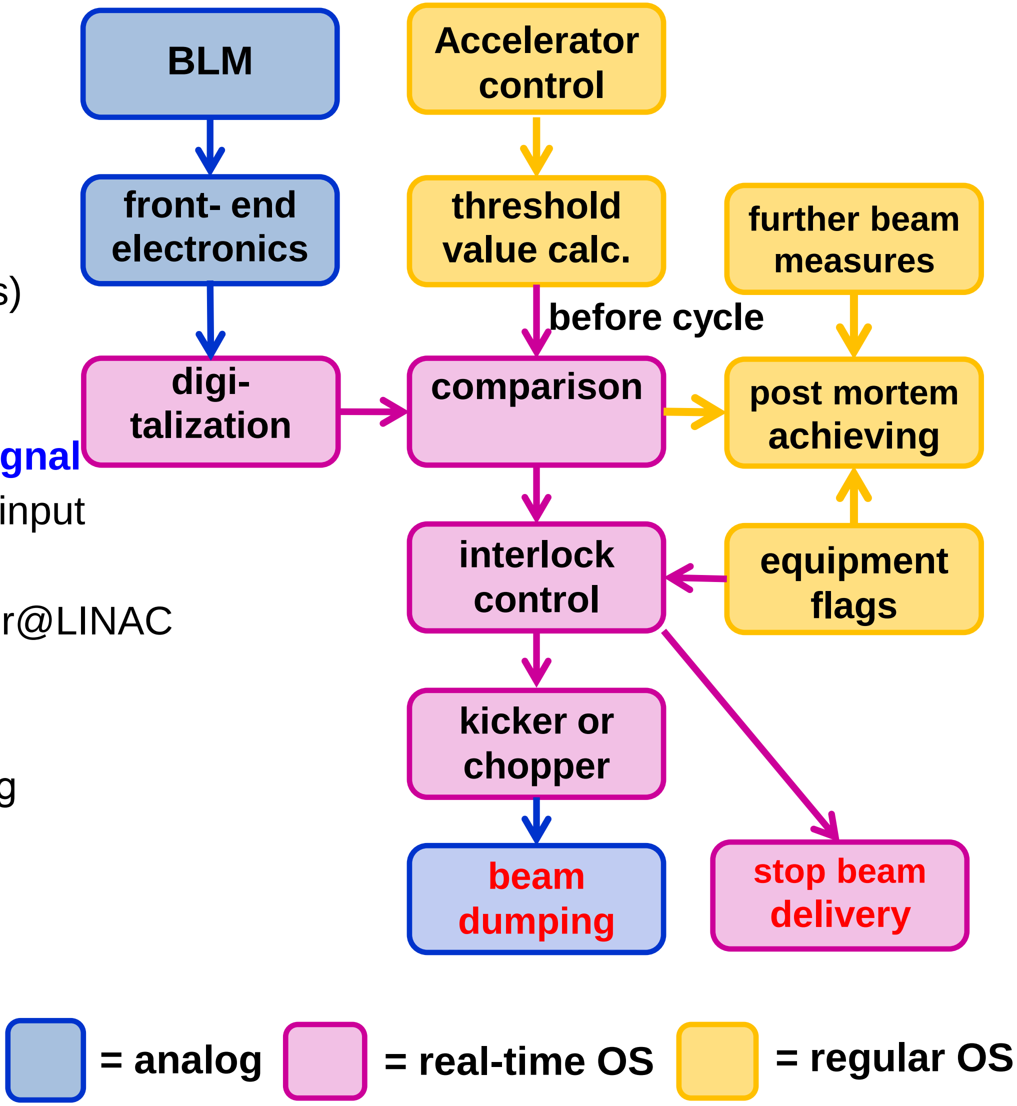
⇒ **Control system watchdog for all important devices**

**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:

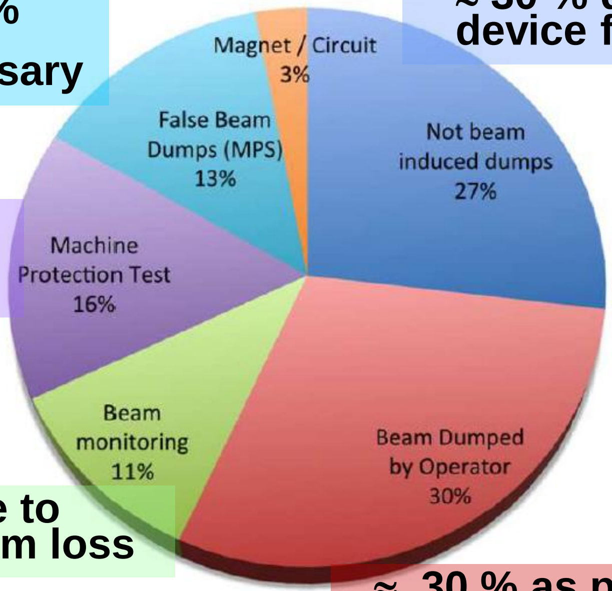
- **BLM detector & analog front-end**
  low input signal under regular losses
  large dynamic range for irregular losses
  e.g. current-frequency converter
- **Digitalization**
  high time resolution (e.g. LHC 1 turn = 89 µs)
- **Comparison to threshold values**
  fast, real-time calculation (FPGA, DSP)
- **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**



# Statistics for Interlock Generation

**Beam dump statistics at LHC in year 2015 and 2012 (above injection):**

**Beam dump LHC year 2015**



**≈ 15 %**
**unnecessary**

**≈ 30 % due to**
**device failure**

**≈ 15 % by**
**≈ MPS tests**

**≈ 15 % due to**
**increasing beam loss**

**≈ 30 % as planned**
**after ≈ 10 h**

**Sum: 442 dumps**

B. Todd et al., CERNACC- 2014-0041
D. Wollmann et al., IPAC 2016, Busan, p. 4203 (2016)

→ conclusion

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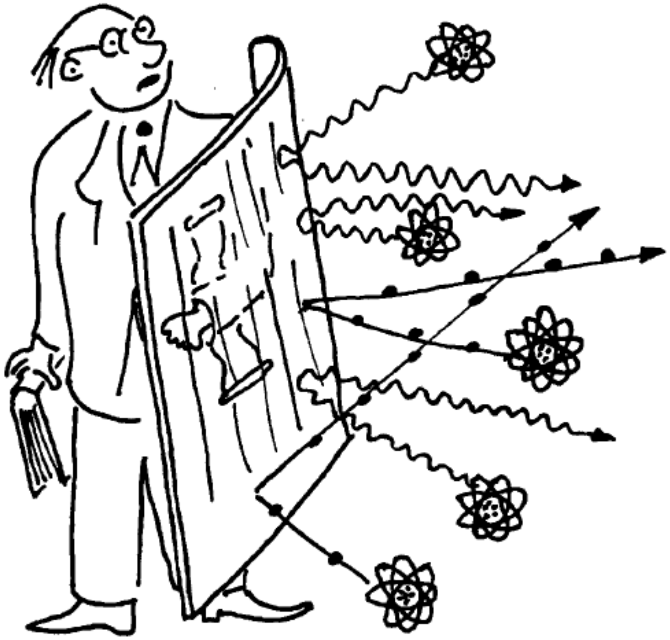
5. **Design of Machine Protection System**
6. **Overview of personal safety**



"Radiation Protection"

© by Claus Grupen

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:** $D_{R,T} = \frac{1}{m}\int_{V_T}\frac{dE_R}{dV}\cdot dV$

  (physical quantity) $= \left[\frac{\text{J}}{\text{kg}}\right] = [\text{Gy}] = [100\text{rad}]$

  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 $\Leftrightarrow \sum_T w_T = 1$

| Rad. type *R* | $w_R$ |
|---|---|
| γ all energies | 1 |
| $e^-$ , $e^+$ , $\mu^\pm$ all energies | 1 |
| Protons E > 2 MeV | 5 |
| α, heavier nuclei | 20 |
| Neutrons: E < 10 keV | 5 |
| 10 keV < E < 100 keV | 10 |
| 100 keV < E < 2 MeV | 20 |
| 2 MeV < E < 20 MeV | 10 |
| E > 20 MeV | 5 |

Neutrons: Since 2007 smooth function

| Example: Organ or tissue | Sensi. | $w_T$ |
|---|---|---|
| Gonads | High | 0.20 |
| Lung, stomach, colon, lens, hematopoietic &lymphatic system | Inter-mediate | 0,12 |
| Liver, esophagus, chest, skin, muscle, hart, bone surface | Low | 0.05 to 0.01 |

# Shielding of Accelerators

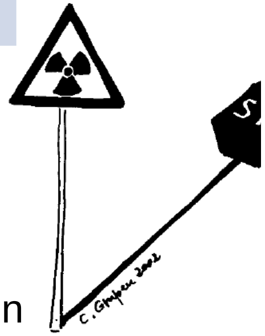
## Shielding of accelerator by <u>rough</u> rule of thumb:

Estimation of shielding by 10th-value $\lambda_{10}$

with $H(l) = H_0 10^{-l/\lambda_{10}}$

(disregarding any secondary particle transport)

| Material | ρ $[\frac{g}{cm^3}]$ | $\lambda_{10}$ [cm] |
|---|---:|---:|
| Earth | 1.8 | 128 |
| Concrete | 2.4 | 100 |
| Heavy concrete | 3.2 | 80 |
| Iron | 7.4 | 41 |
| Lead | 11.3 | 39 |



© by Clau

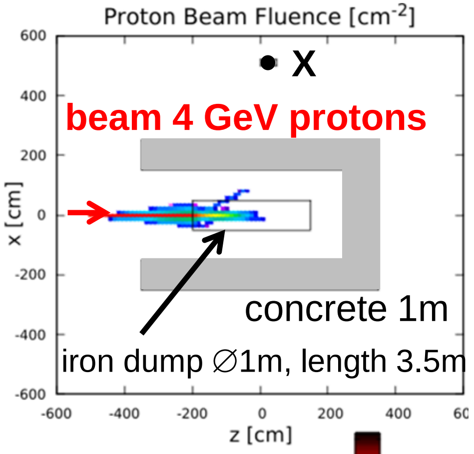
## Further <u>rough</u> rule of thumb:

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

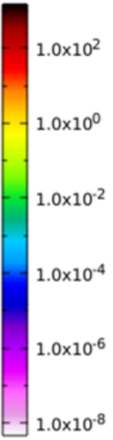
# Simplified Model Shielding of Accelerators

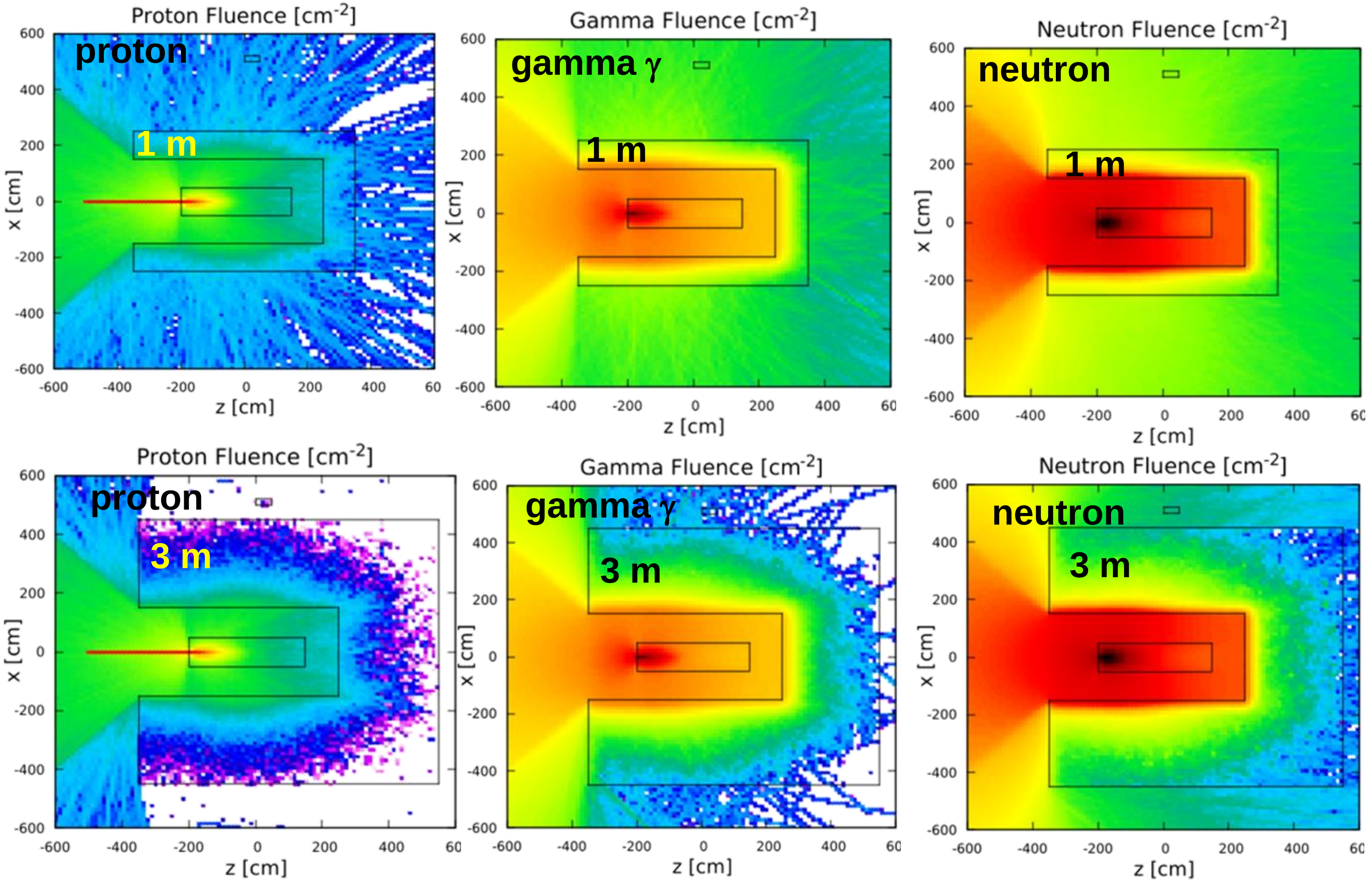
**Simplified FLUKA calculation:** 4GeV protons, iron beam dump ∅1m, l=3.5m, concrete 1 & 3 m, 5·$10^5$ particles

Courtesy S. Udrea



Particle flux [cm$^{-2}$]





**Result:**
Mainly neutrons and μ 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 ≈ $10^{-3}$ attenuation at X
- ➢ **Neutrons** produced, scattered at wall ≈ $10^{-3}$ atten. at X by distance & concrete
- ➢ 'Leakage' through opening

- ➢ **Protons** stopped in wall
- ➢ $\gamma$ well shielded
- ➢ **Neutrons** at X ≈ 0.3% of 1m.

# Realistic Example for Shielding of Accelerators

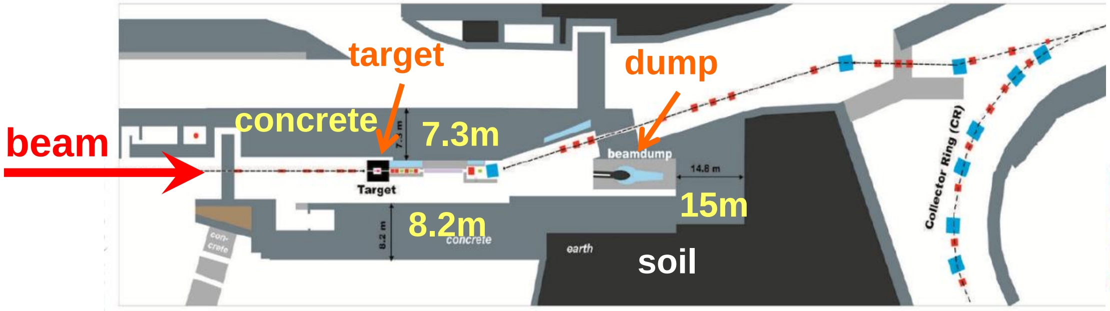
**Example shielding of accelerator:** Proton beam of 29 GeV for anti-proton production

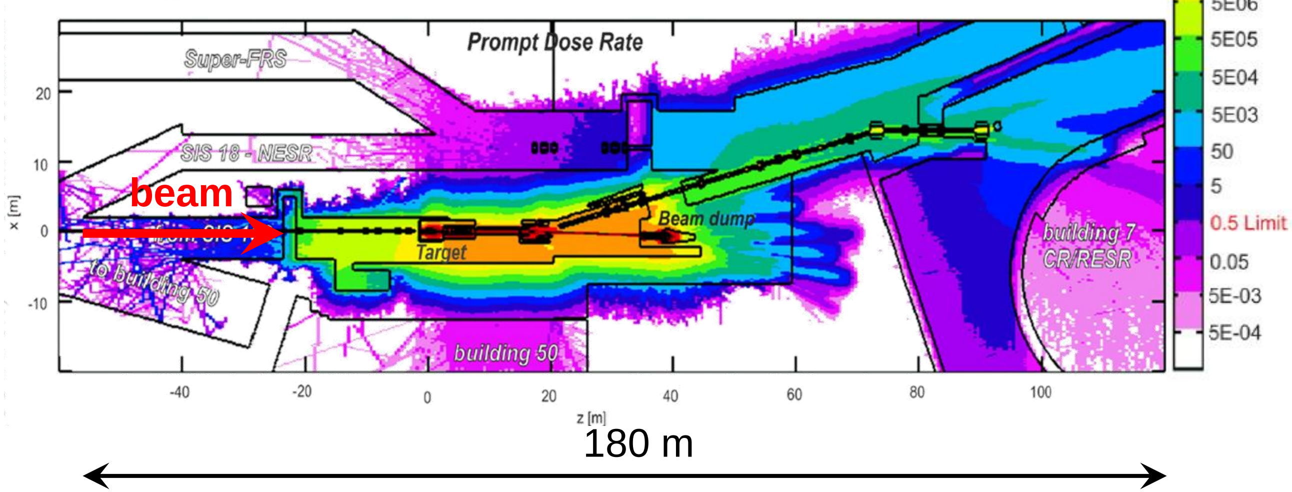
Assumtion 2.5 · $10^{13}$ protons on 11cm long copper target

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

Concrete ≈ 8 m around beam pipe

Goal: Free access region outside i.e. equivalent dose rate ***H / t*** < 0.5 µSv/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 µSv/h**

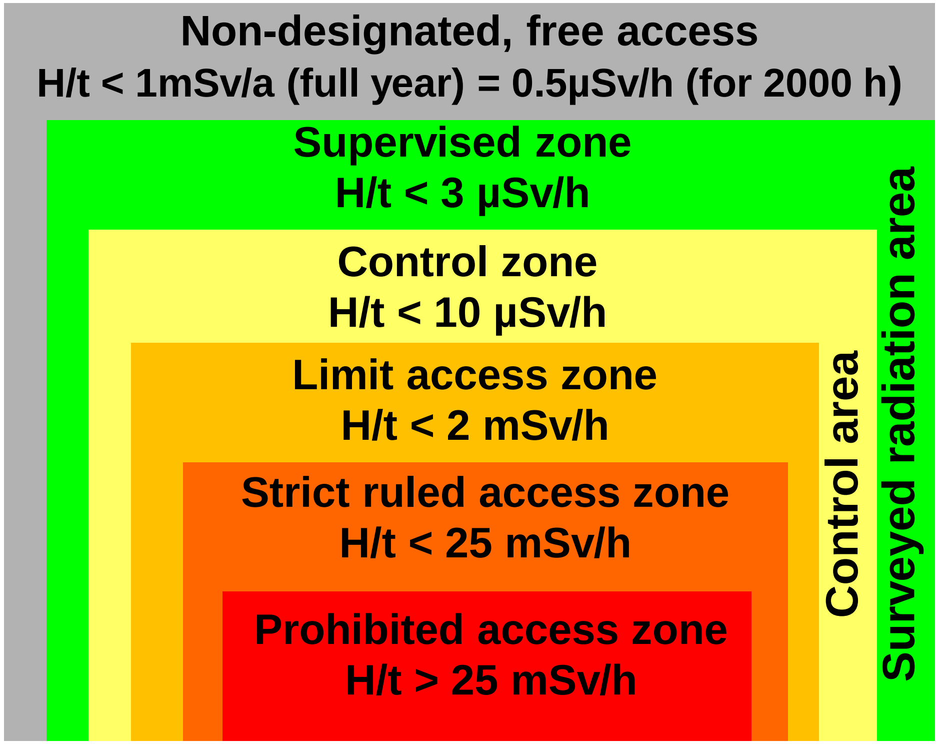
K.. Knie et al., IPAC 2012

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 < 1mSv/a (full year) = 0.5µSv/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**

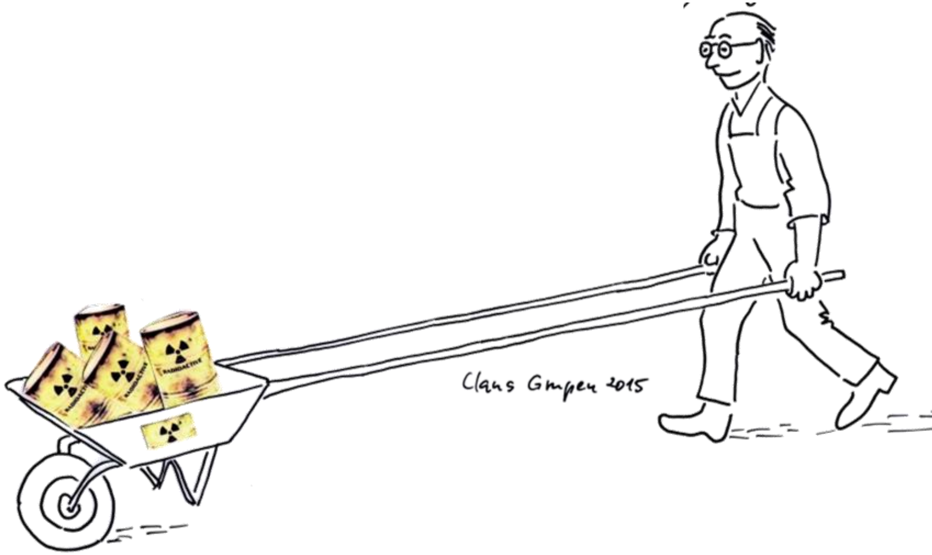
**Prohibited access zone**
**H/t > 25 mSv/h**

**Control area**

**Surveyed radiation area**

**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

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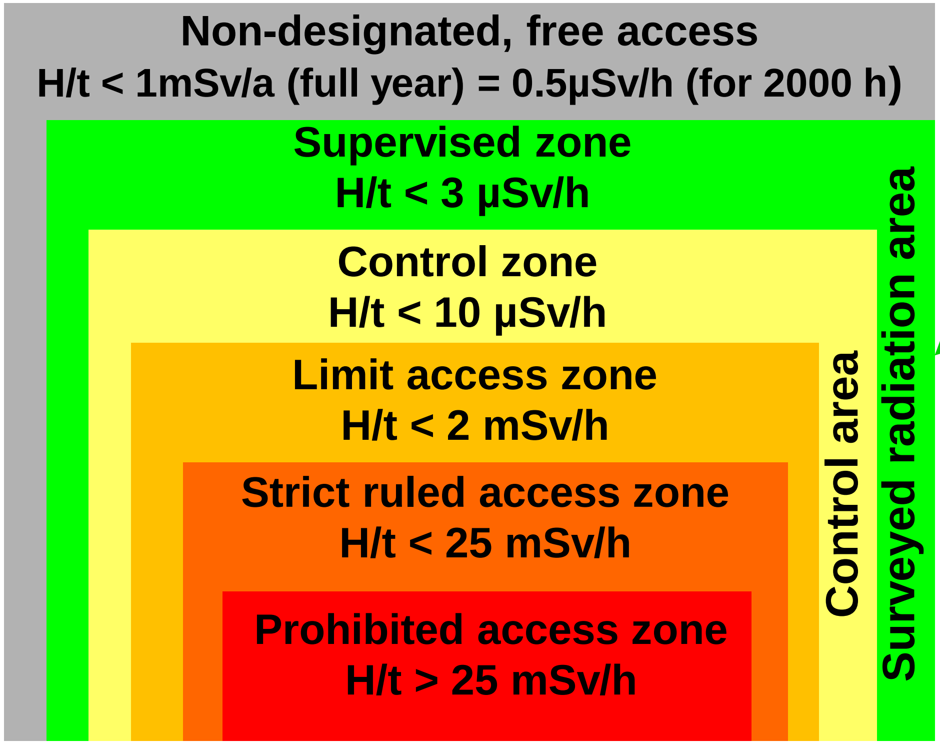
For workers: Assumption 2000 h/a of access



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**Supervised zone**
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**H/t < 25 mSv/h**

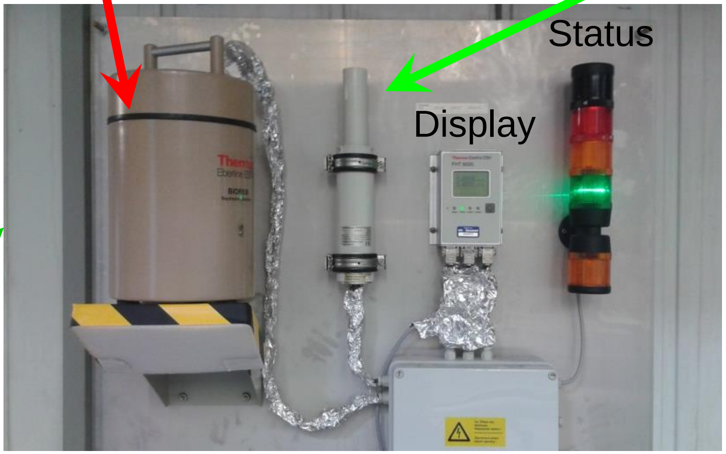
**Prohibited access zone**
**H/t > 25 mSv/h**

**Control area**

**Surveyed radiation area**

Moderated prop. tube for n
1 eV < $E_n$ < 20 MeV

Proportional tube for $\gamma$:
30 keV < $E_{ph}$ < 1.3 MeV



Moderated thermo-luminescence detector for passive n-detection

**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)**

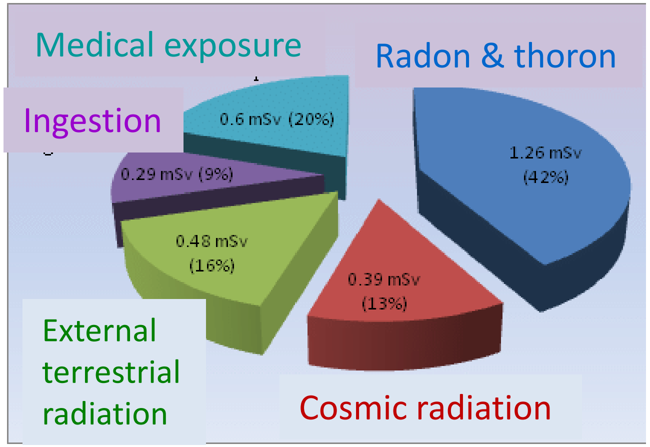
**Remark:** Actual limits are given by national laws.

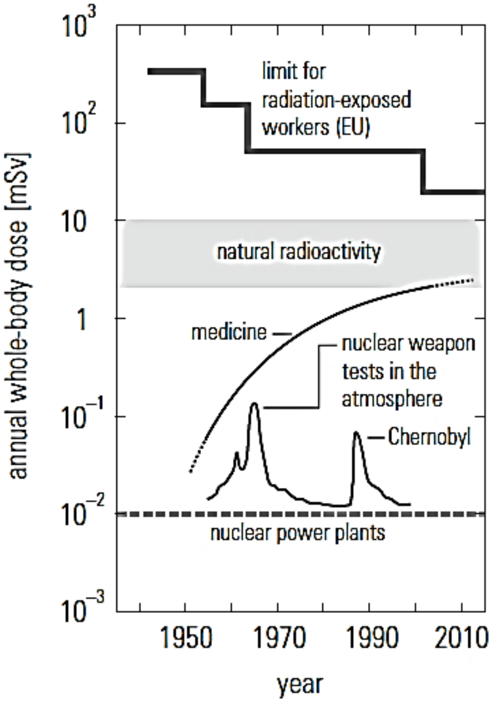
→ conclusion

# Natural Radiation Exposure

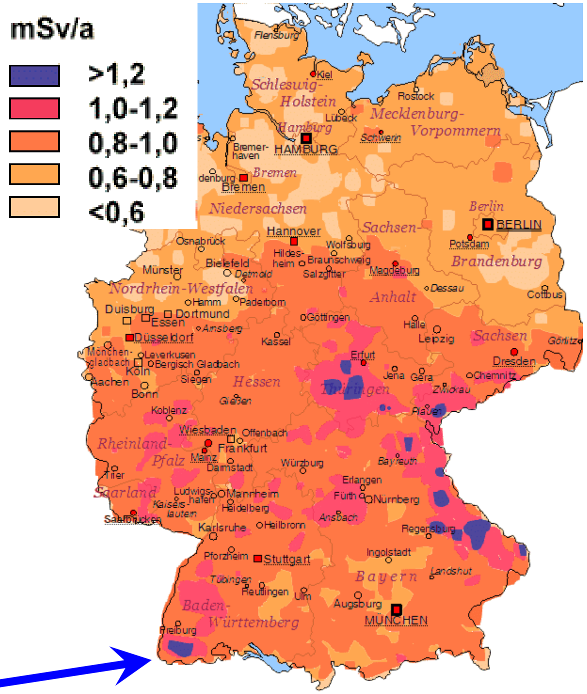
## Example of radiation level:

- **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:**





Natural dose in Germany:

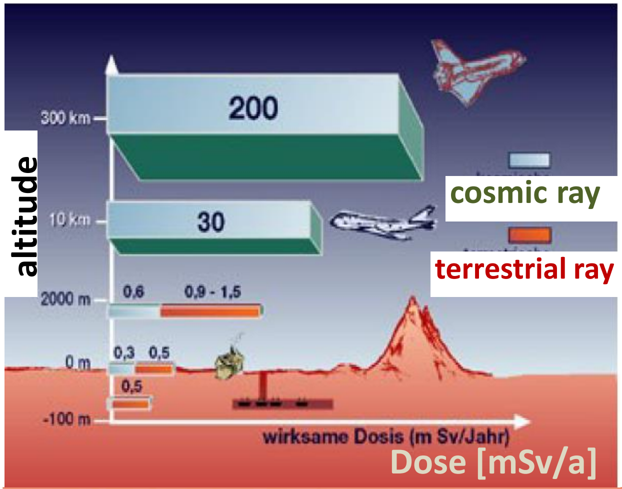


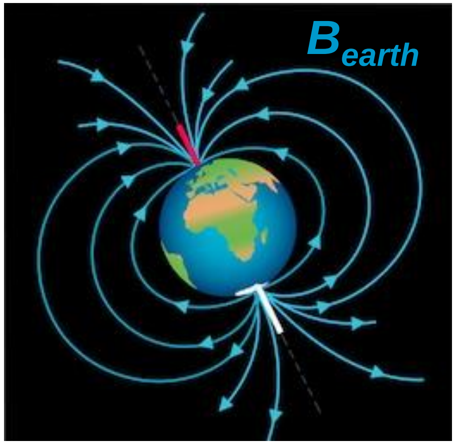
Source: German Bundesamt für Strahlenschutz
C. Grupen, Introduction to Radiation Protection

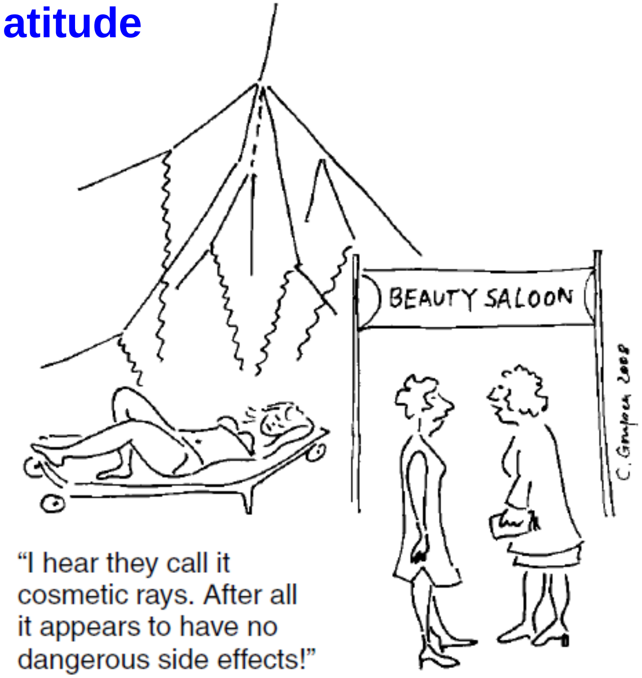
→ conclusion

# Avoidable, but wildly accepted Radiation Exposure

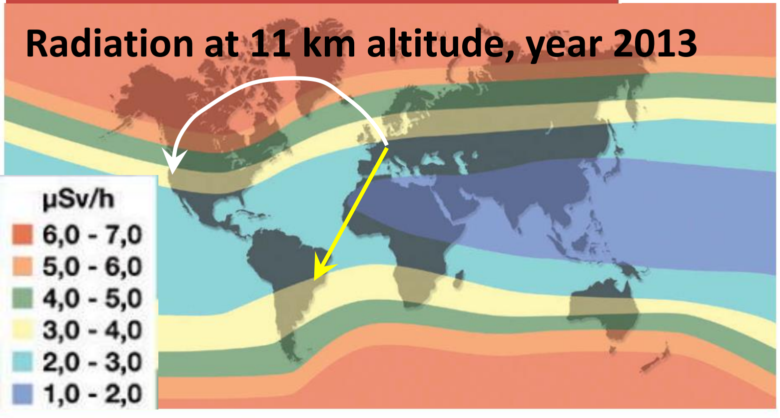
## Cosmic ray based radiation effects depend on altitude and latitude





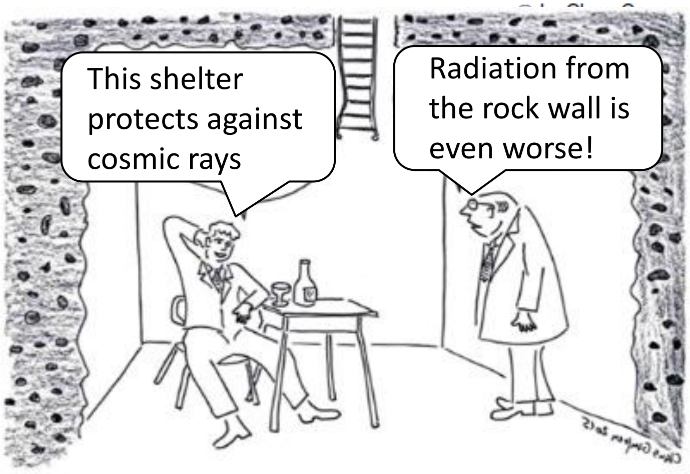


"I hear they call it cosmetic rays. After all it appears to have no dangerous side effects!"



Zonen mit unterschiedlicher Höhenstrahlung [11 km Höhe, Ende 2013, Mikrosievert pro Stunde]

| 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

→ conclusion

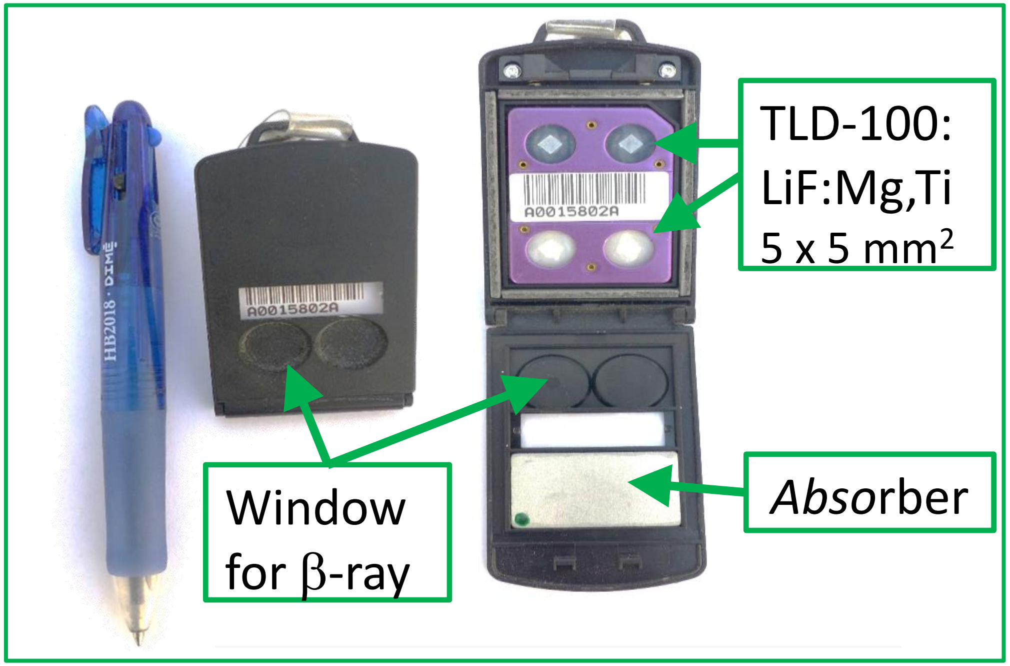
# Passive Film Badge Dosimeter and TLD

**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 ${}^{6}$Li(n,$\alpha$)T

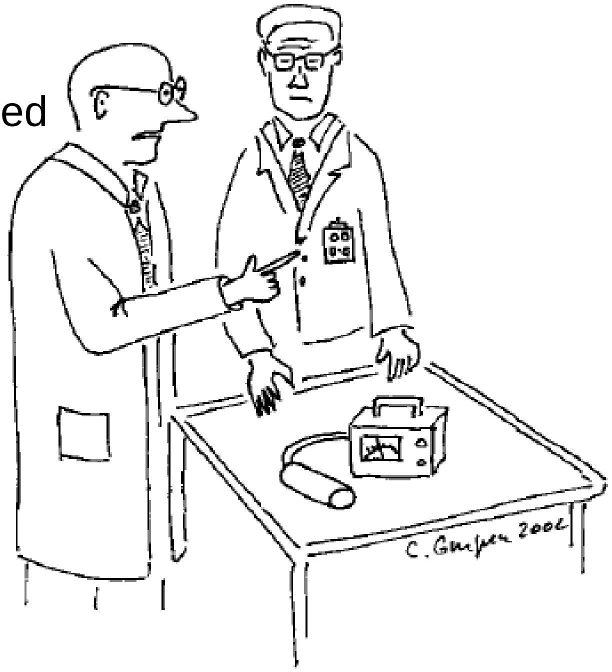
**Sensitivity for $\beta$ & $\gamma$:** 0.1 mSv to 10 Sv



TLD-100:
LiF:Mg,Ti
5 x 5 mm$^2$

Window
for $\beta$-ray

*Absorber*



"And these bagdes are supposed to protect us effectively from radiation?"

© by Claus Grupen

**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:**

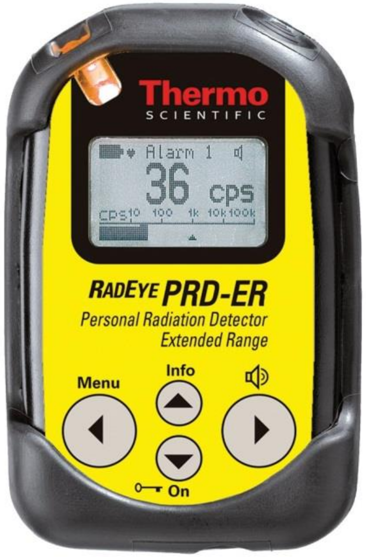
Alternative: PIN-diode solid state detector

Photons: typ. 10 keV... 10 MeV

$\beta^{\pm}$ : 0.25 .... 1.5 MeV

**Sensitivity for β & γ:** 0.05 µSv/h to 1 Sv/h

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



**'Pocket meter' for γ-rays:**

Scintillator NaI(Tl) + photo-multiplier for γ detection

photons (typ. 60 keV... 1.5 MeV)

**Sensitivity for γ:** 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 & $\gamma$ 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

- R. Schmidt (Ed.), *Beam Loss and Accelerator Protection,* Proc. Joint International Accelerator School CERN-2016-002
- 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*
- A. Zhukov, *BLMs: Physics, Simulation and Application in Accelerator,* Proc. BIW 2010, www.jacow.org
- *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

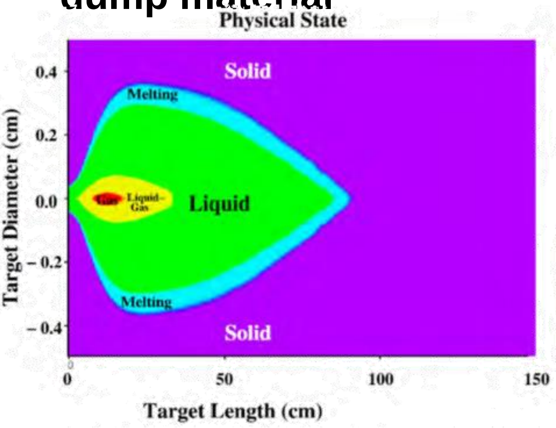
**Verification of material interaction by 440 GeV protons:**

Destruction of material due to temperature rise

- ➢ melting, sublimation plasma formation
- ➢ mechanical stress

⇒ verification of simulation

⇒ **finding proper dump material**

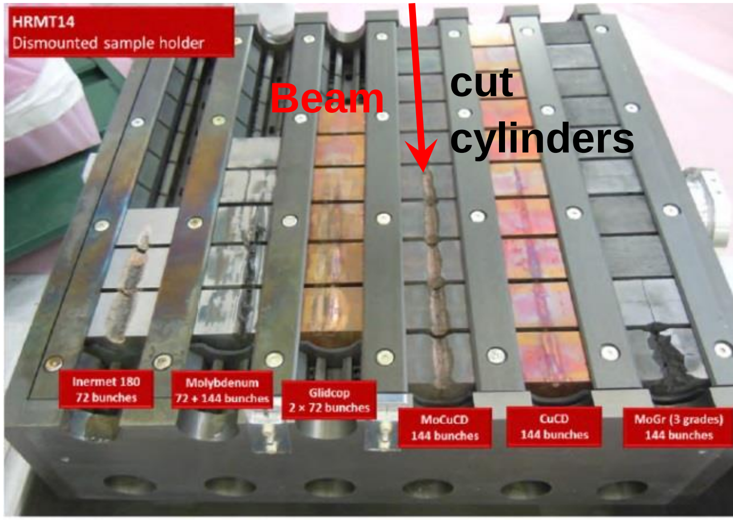


HiRadMat facility at CERN SPS

**Beam:** 440 GeV ≈ $10^{13}$ protons,

$\sigma_x = \sigma_y \approx$ 2 mm within $t$ = 50 µs

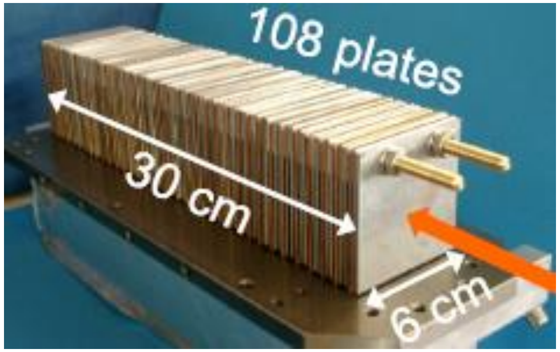
$\Rightarrow E_{tot} \approx$ 1 MJ

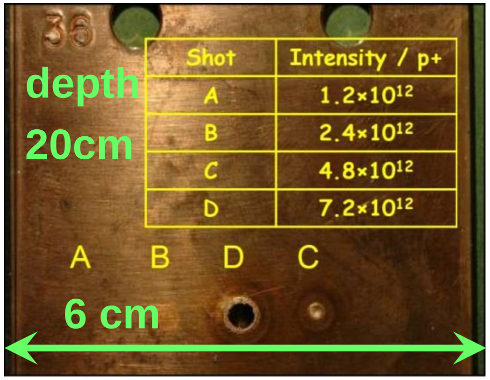


A. Bertarelli, JAS CERN-2016-002.

**Experiment with 450 GeV protons:**

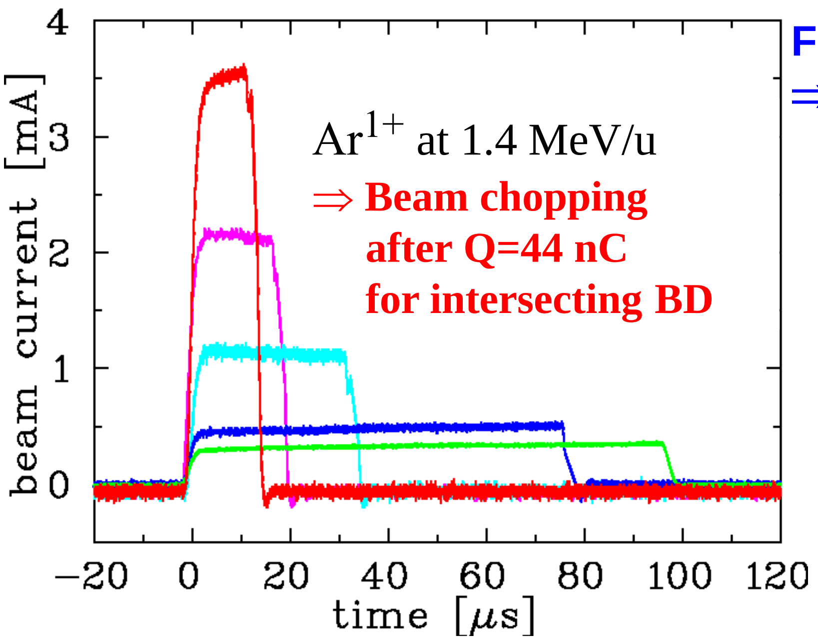
V. Kain et al.,
PAC'05, 1607 (2005)





| Shot | Intensity / p+ |
|---|---|
| A | $1.2 \times 10^{12}$ |
| B | $2.4 \times 10^{12}$ |
| C | $4.8 \times 10^{12}$ |
| D | $7.2 \times 10^{12}$ |

# Dynamic Machine Protection by Transmission Measurement



**For E > 50 MeV protons: nuclear $\sigma_{nucl}$ 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.

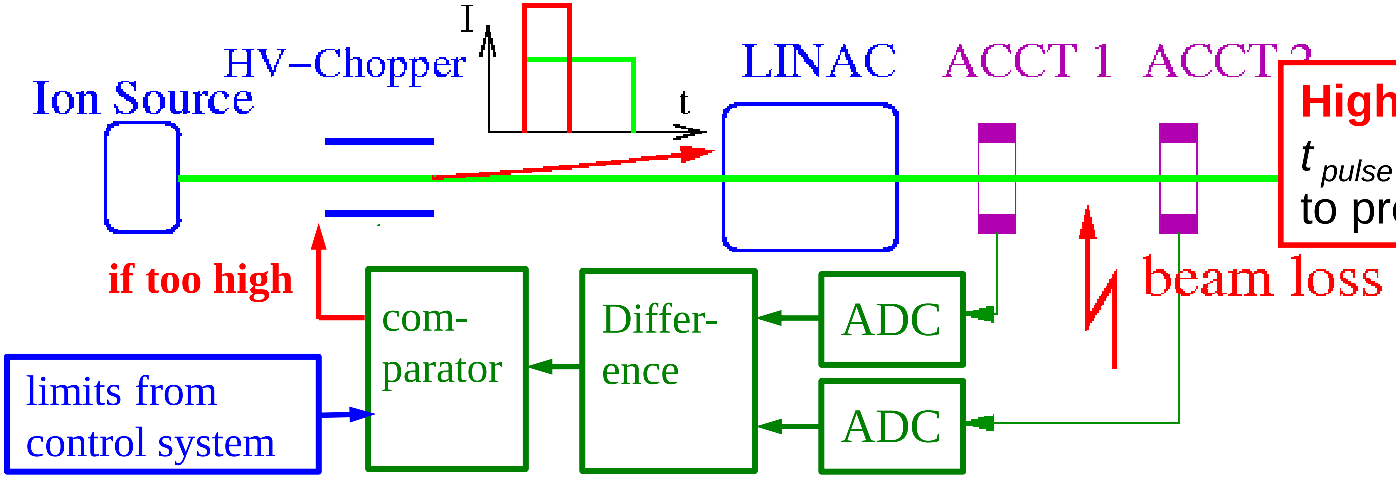
***FPGA-electronics:***

→ ADC digitalization

→ calculation of difference

→ digital comparator

→ chopper control in case of threshold overshoot



**High current:**
$t_{pulse}$ < 10 μs only
to prevent from damage!

H. Reeg (GSI) et al., Proc. EPAC’06

# Neutron Energy Spectrum

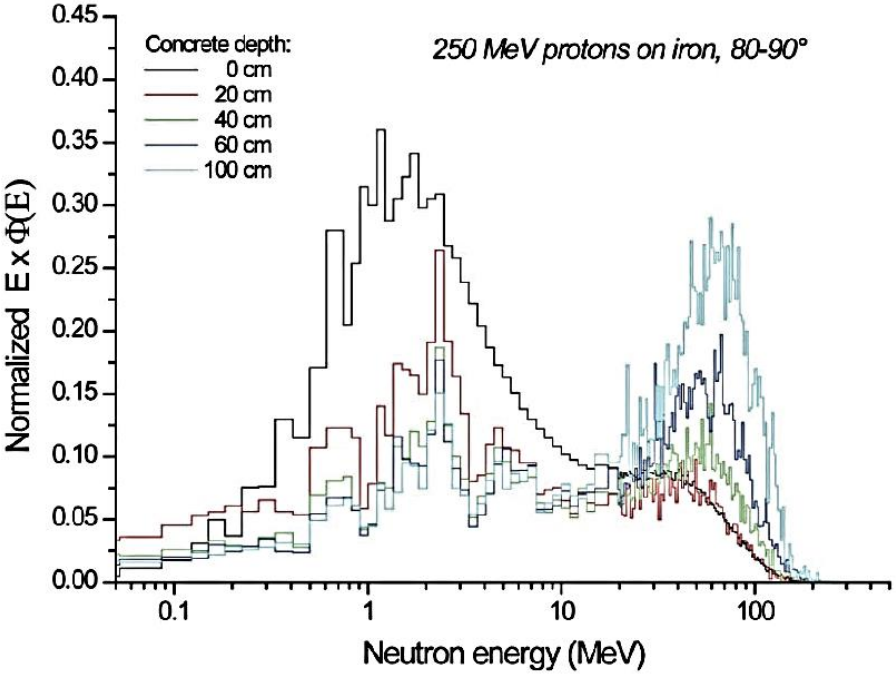


**Fig. 6:** Neutron energy distributions $E\Phi(E)$ in the transverse direction generated by 250 MeV protons impinging on an iron target thicker than the proton range. The distributions are for source neutrons and behind concrete shields of thicknesses ranging from 20 cm to 1 m. The distributions have 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 $E_{kin}$ > 100 MeV nearly equal cross section

Electronic stopping range

Large capture cross section results in recoil energy

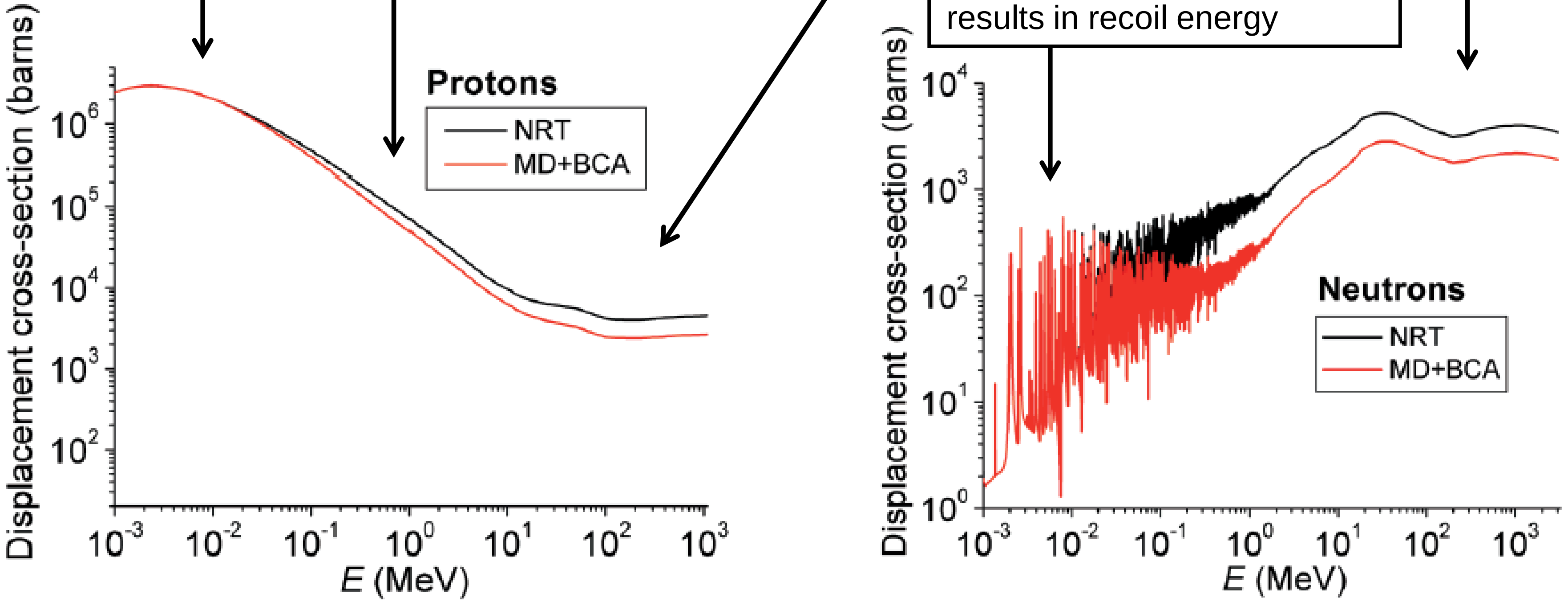


**Fig. 12:** Displacement cross-sections of protons (left) and neutrons (right) in copper obtained by two different approaches (see legend).

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

# Radiation Damage of organic Materials

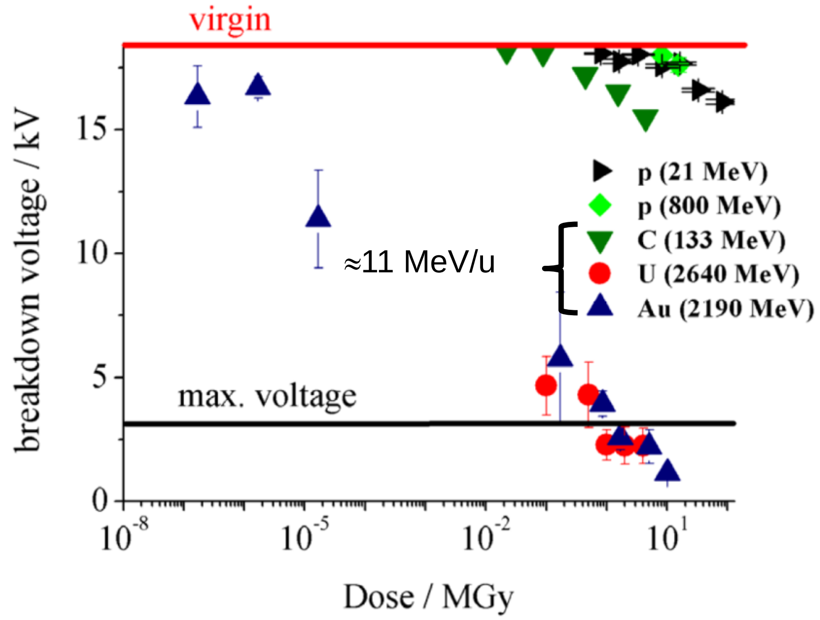
## Radiation damage in plastic by ionizing radiation:

- 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

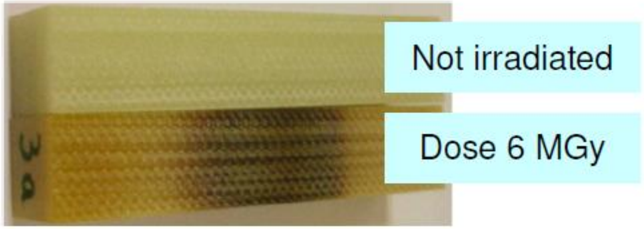
energy loss dE/dx increases for heavy ions



T. Seidl et al, HB 2010

Rough estimation of maximal dose

| Material | Dose [Gy] |
|---|---|
| Teflon (PTEE) | $10^3$ |
| Mylar | $5{\cdot}10^4$ |
| Cable insulation | $5{\cdot}10^4$ |
| Magnet coil insul. | $10^6$ |
| Kapton (Polyamide) | $10^7$ |

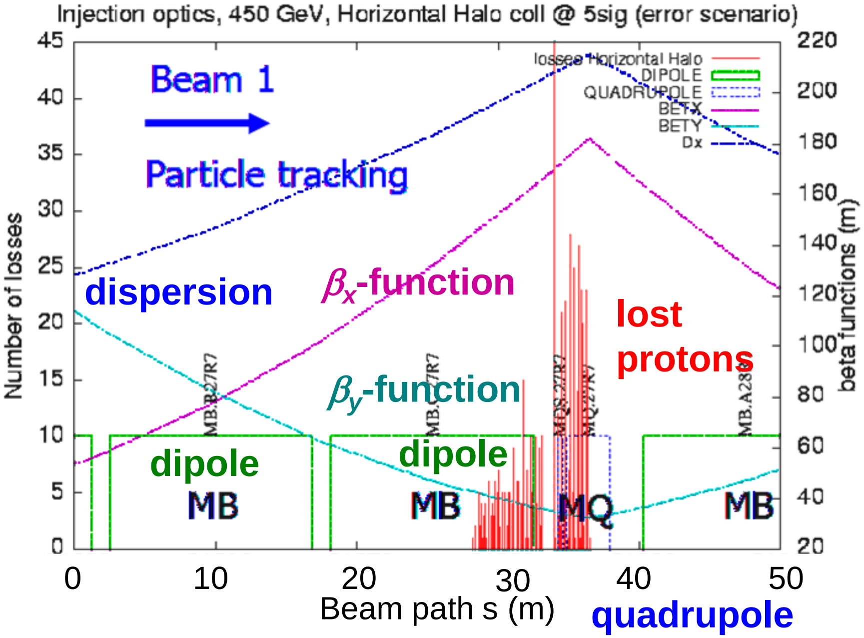


# Placement of Beam Loss Monitors

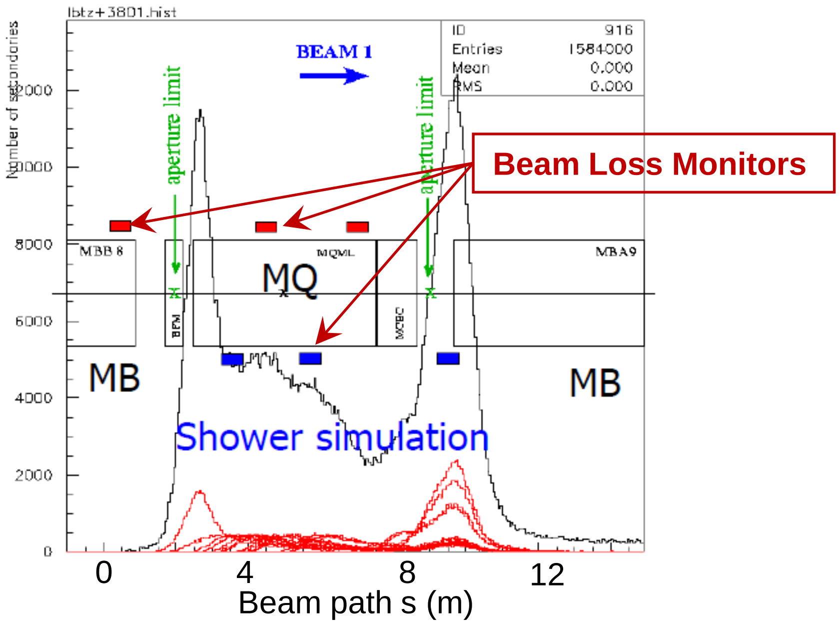
Secondary particles and shower produces are emitted within a forward cone
(in rest-frame isotopically but due to Lorentz-transformation forward in lab-frame .

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



B. Dehning, JAS 2014, CERN-2016-002

# Secondary Particle Production for Electron Beams

## Processes for interaction of electrons

**For $E_{kin}$ < 10 MeV:**

Mainly electronic stopping ⇒ X-rays, slow $e^-$

**For $E_{kin}$ > 10 MeV:**

Bremsstrahlungs-γ, forward peaked $E_\gamma$ = 5-50 MeV

⇒ $\gamma \to e^+ + e^-$ or $\mu^\pm$ .. → electro-mag. showers

⇒ Excitation of giant resonances $E_{res} \approx$ 10-30 MeV

via (γ, n), (γ, p) or (γ, np) with $\sigma_{giant} \approx \frac{1}{10}\sigma_{geo}$

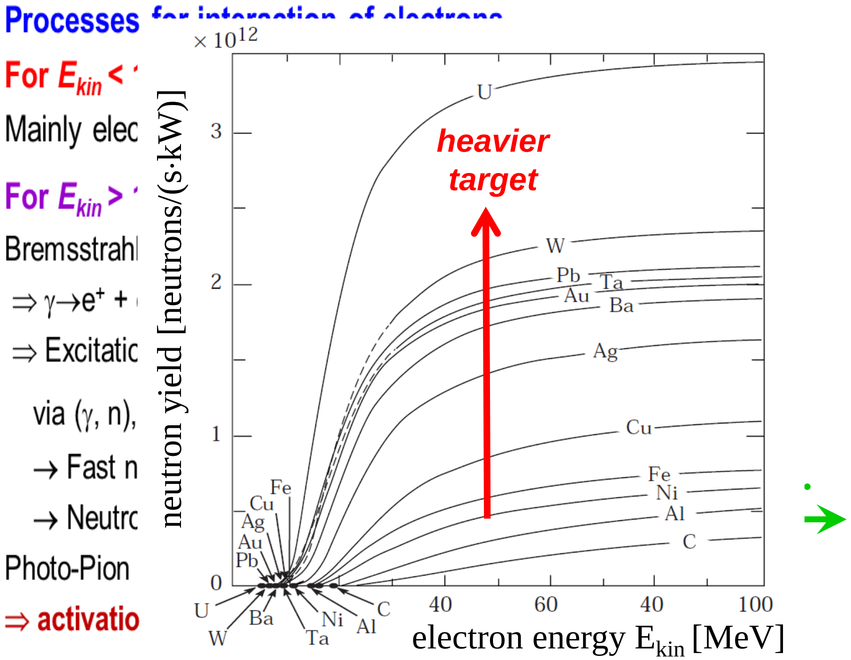
→ Fast neutrons emitted (by nuclear interaction)

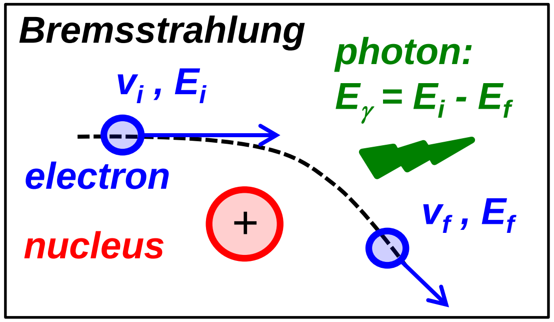
→ Neutrons: Long ranges in matter

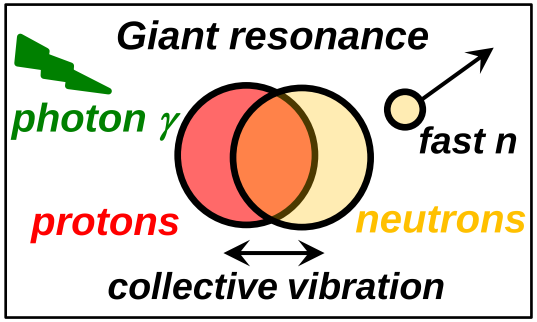
Photo-Pion reaction: d $(\gamma,\pi^0)$ pn or d $(\gamma,\pi^-)$ pp

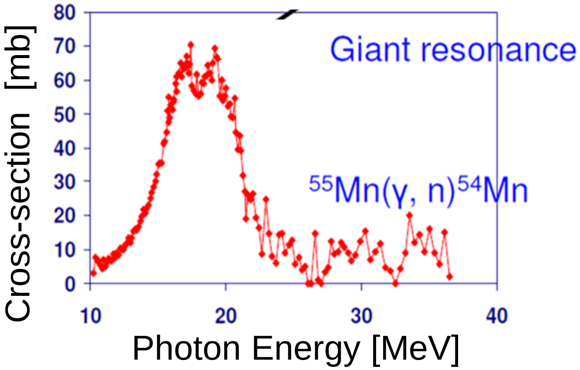
**⇒ activation at electron accelerators**

R.H. Thomas, in Handbook on Acc. Phy. & Eng.







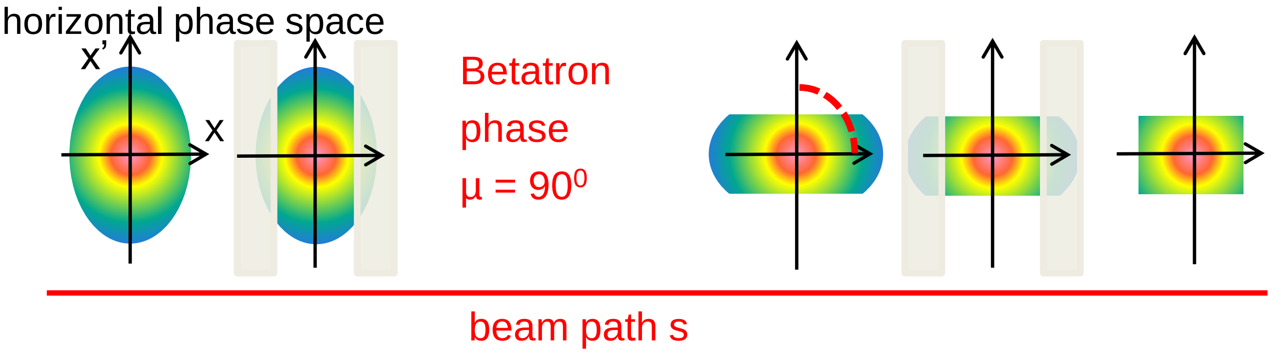


# Collimation at LINACs

**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



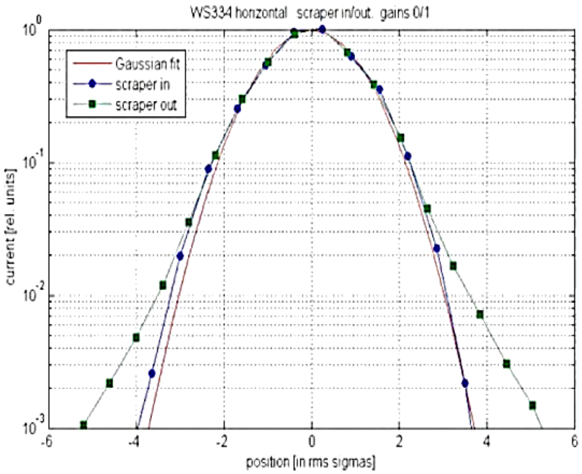
i.e. phase space distribution is not completely cut

**Collimators:**

Cut the beam tail in space

$\mu = 90^0$ or $\mu = 45^0$ betatron phase to cut angle

$\Rightarrow$ at least two locations required



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

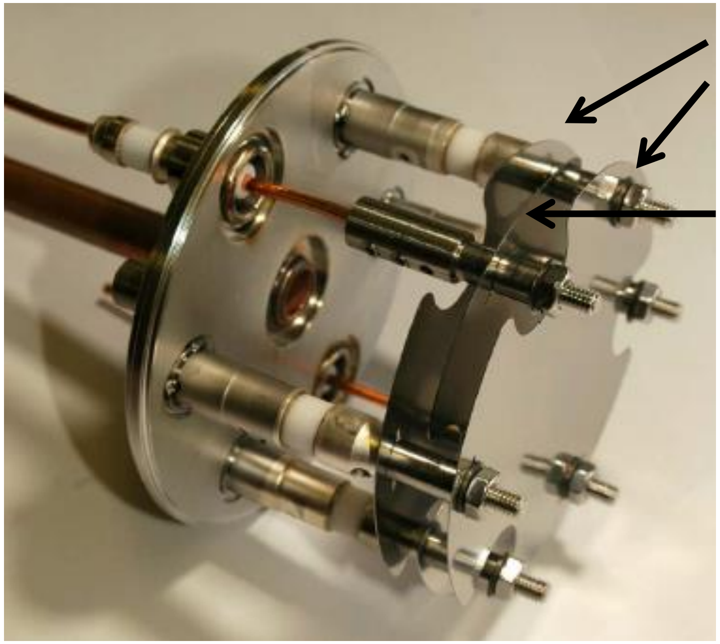
# Secondary Electron Monitor as BLM

**Ionizing radiation liberates secondary electrons from a surface.**

Working principle:

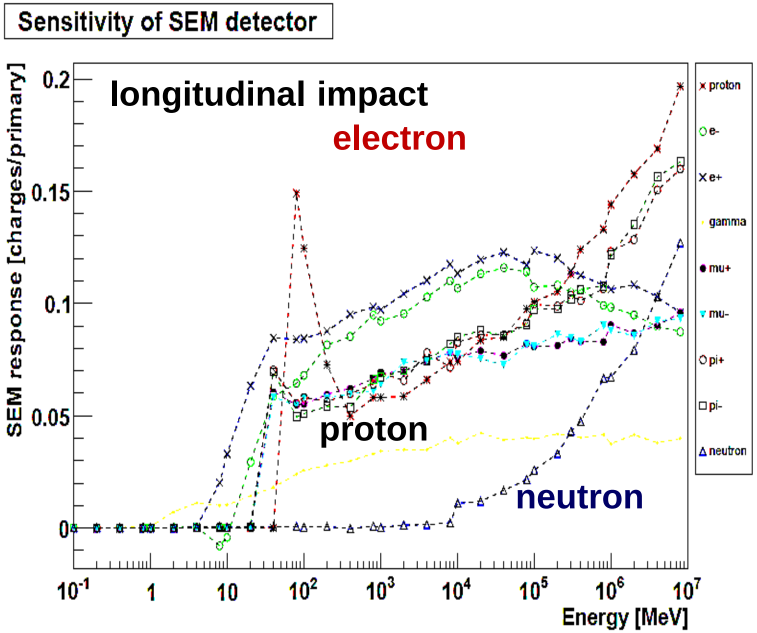
- ➢ Three plates mounted in a vacuum vessel (passively NEG pumped)
- ➢ Outer electrodes: biased by ***U*** ≈ +1 kV
- ➢ Inner electrode: connected for current measurement (here current-frequency converter)

→ **small and cheap detector, very insensitive.**



HV electrodes

Electrode for measured current



*B. Dehning et al., PAC 2007*

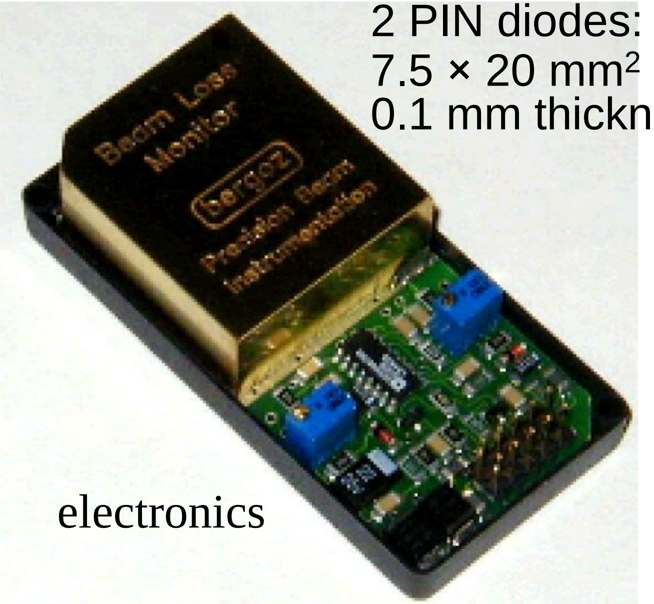
# PIN-Diode (Solid State Detector) as BLM

## Solid-state detector: Detection of charged particles.

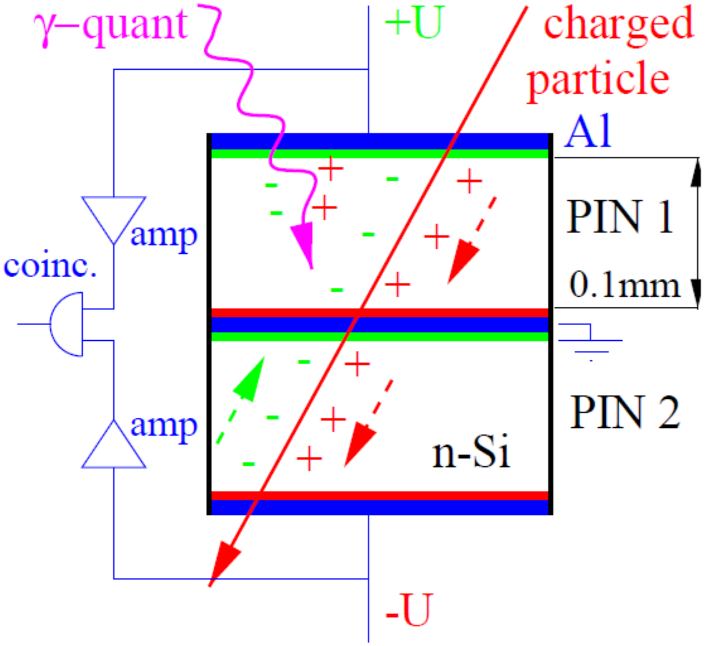
### Working principle

- 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.**

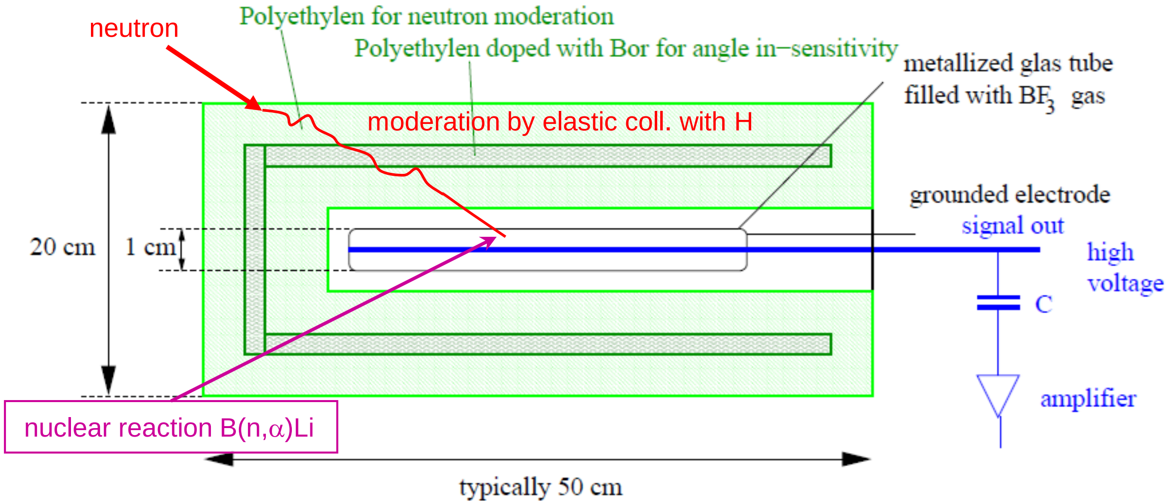


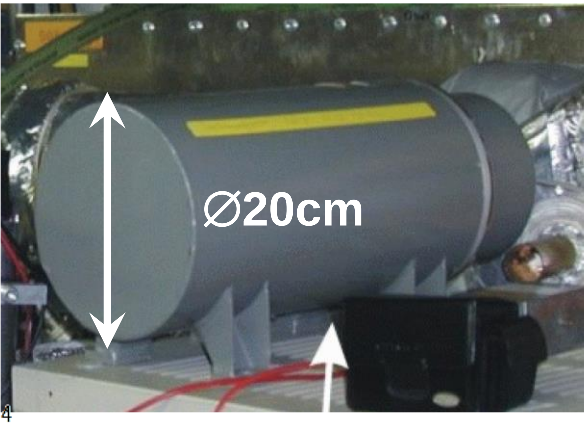
2 PIN diodes:
7.5 × 20 mm$^2$
0.1 mm thickness.



# $BF_3$ Proportional Tubes as BLM and for personal Protection

## Detection of neutrons **only** with a 'REM-counter':



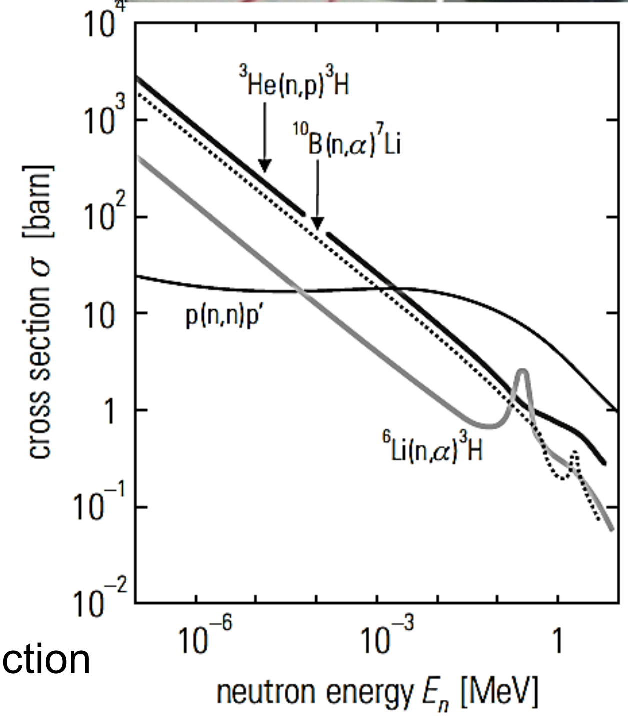


### Physical processes of signal generation:

1. Slow down of fast neutrons by elastic collisions with p
2. Nuclear reaction inside $BF_3$ gas in tube:

$$^{10}\mathrm{B} + \mathrm{n} \rightarrow {}^{7}\mathrm{Li} + \alpha \quad \text{with} \quad Q = 2.3\ \text{MeV}.$$

3. Electronic stopping of $^7$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