Machine & People Protection Issues

CAS Introduction to Accelerator Physics

Chavannes de Bogis, 30th of September 2021

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...

Introduction and Outline

Reasons for machine protection:

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

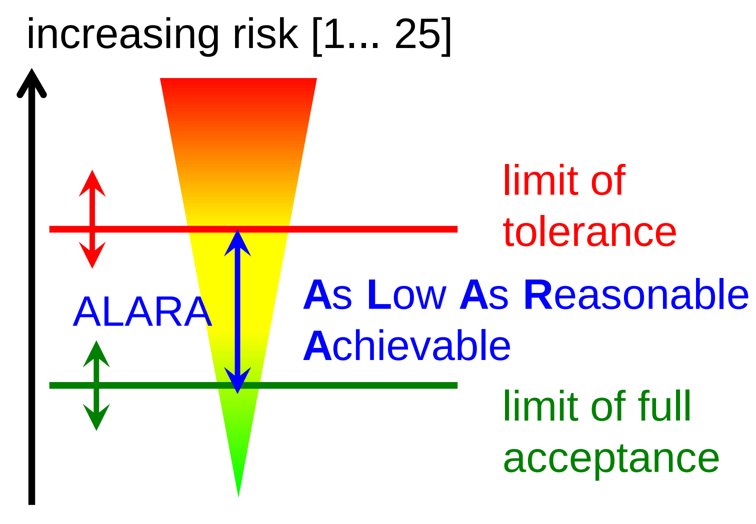
Outline of this talk:

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

What Risk is acceptable?

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

Consequences / Probability	1 Negli-gible	2 Impro-bable	3 Occa-sional	4 Pro-bable	5 Fre-quent
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



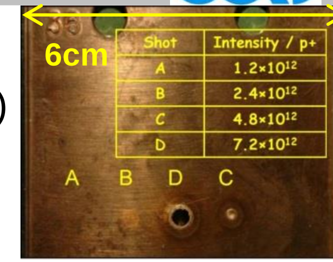
Risk = **probability** of an accident x **consequences**

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

- Intolerable or acceptable depends on e.g. maintenance access, destruction level, operation
- Different accelerator facilities allows different risks e.g. medical ↔ research facilities

⇒ Risk must be weighted to foreseen usage, goals and possible achievements

What is the Risk for an Accelerators?



Categories of destruction, consequences and risk:

- **Heating:** Lost beam 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***)

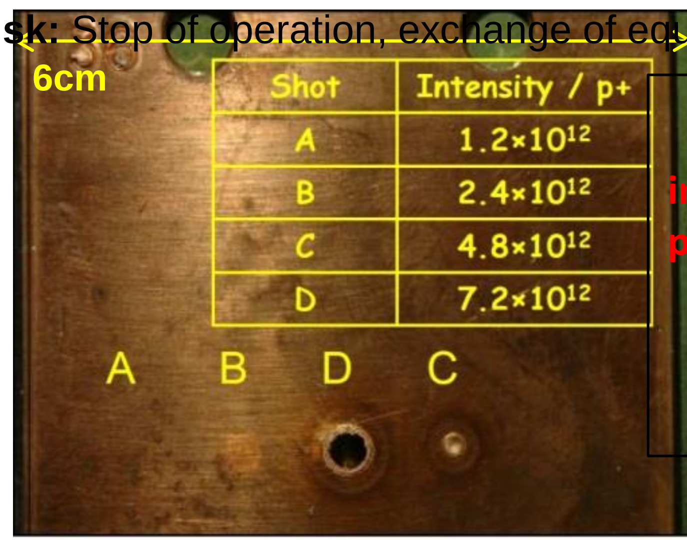
⇒ **Consequence:** Permanent activation ⇒ pollution, human access hindered

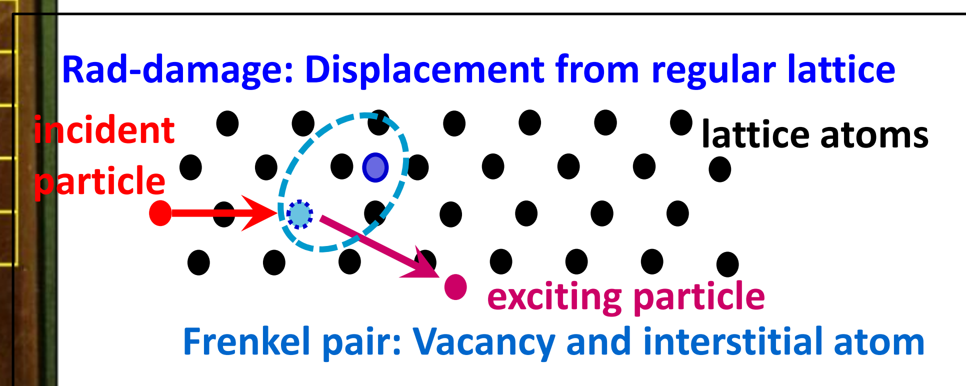
⇒ **Type of risk:** Maintenance impossible, expensive disposal

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

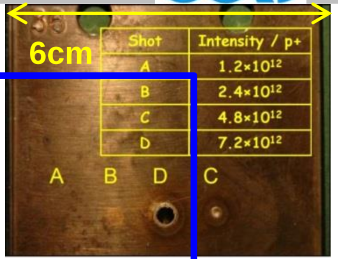
⇒ **Consequence:** Degradation of material properties, faulty electronics

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





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***)

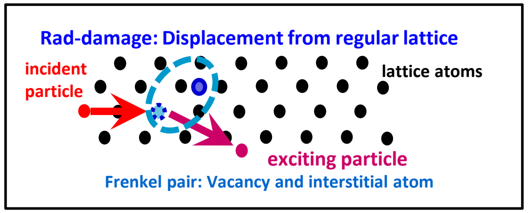
⇒ **Consequence:** Permanent activation ⇒ pollution, human access hindered

⇒ **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

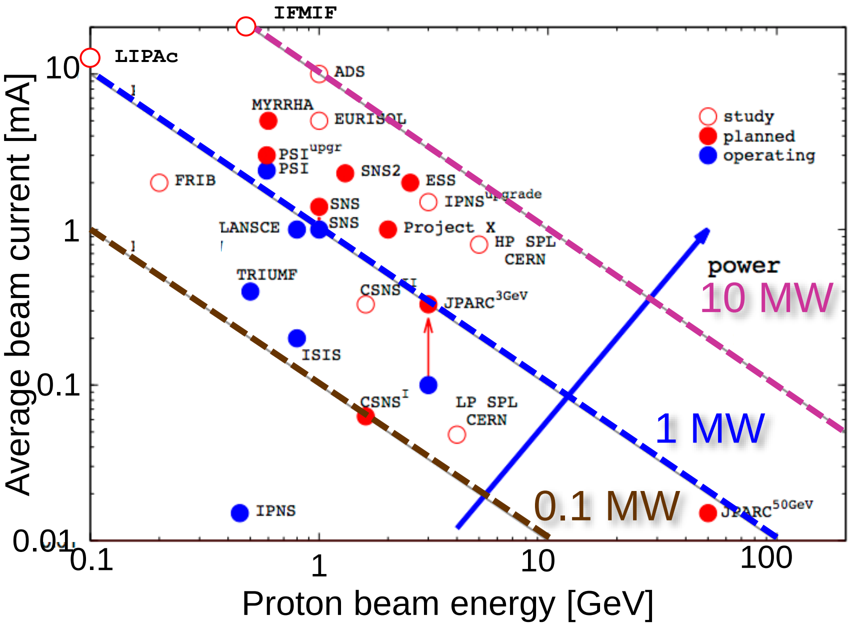
- **User requirements:** Less beam available for users

⇒ **Consequence:** Angry or disappointed users

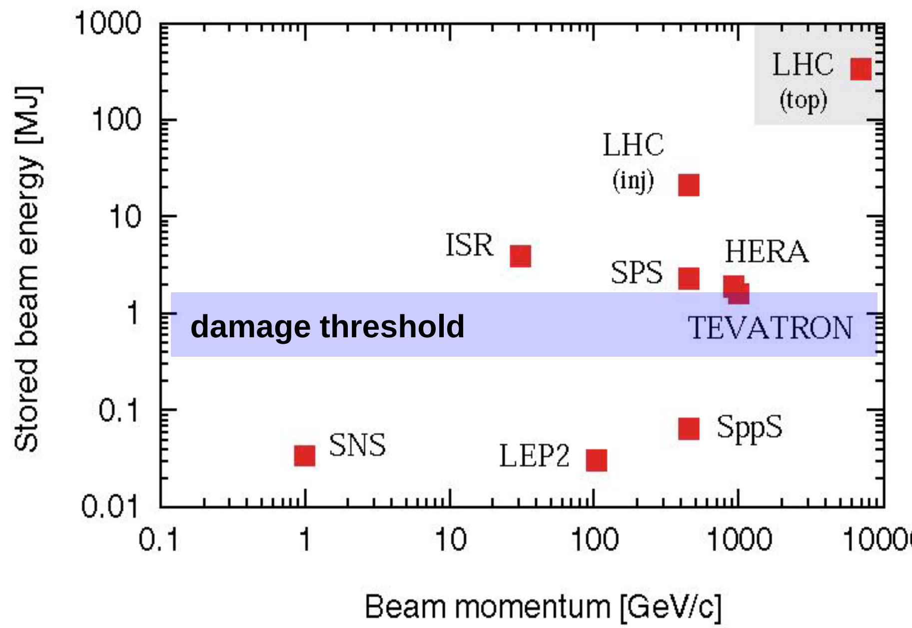
⇒ **Type of risk:** Cancel financial support for accelerator facility

Stored Beam Energy at Accelerators

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



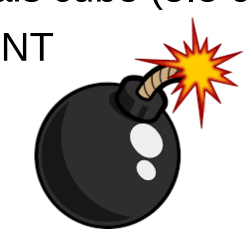
Stored beam energy within a synchrotron:
Mainly large circular collider



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 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

ρ = 8.9 g/cm^3

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

Outline

Outline of this talk:

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

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:

Cross section σ_{geo} comparable to size:

- Size of **atom**: r_{Bohr} = 0.053 nm

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

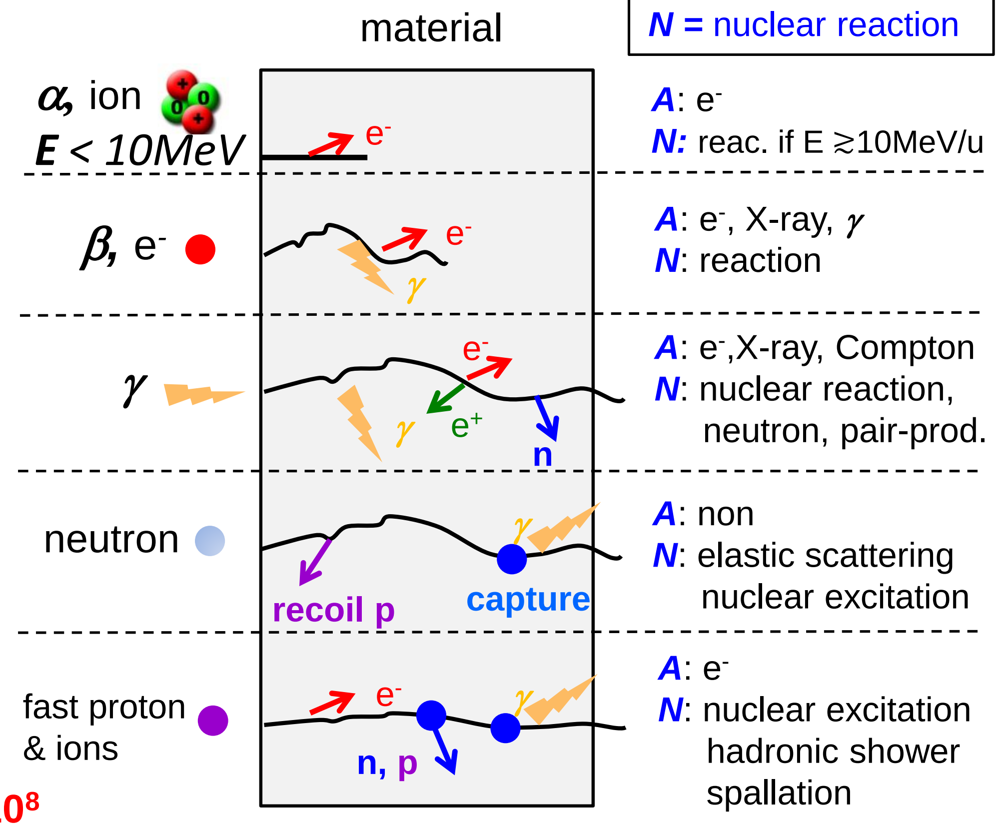
- Size of **nucleus**: $r_{nucl} \approx 3$ fm

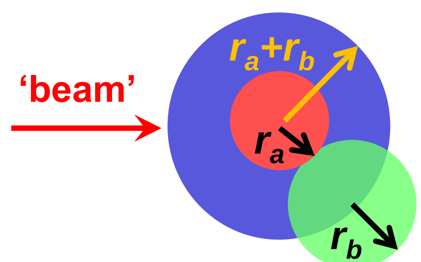
$$\sigma_{geo}^{nucl} = \pi\,(2\cdot r_{nucl})^2$$
$$\approx 10^{-24}\mathrm{cm}^2 \equiv \mathbf{1\ barn}$$

factor 10^8

$\Rightarrow$ very probable reactions have $\approx \sigma_{geo}$

A = atomic reaction
N = nuclear reaction





Hard balls' 'geometrical' cross section:

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

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

n target atom density [cm^{-3}], M molar mass, ρ density, N_A Advogadro number

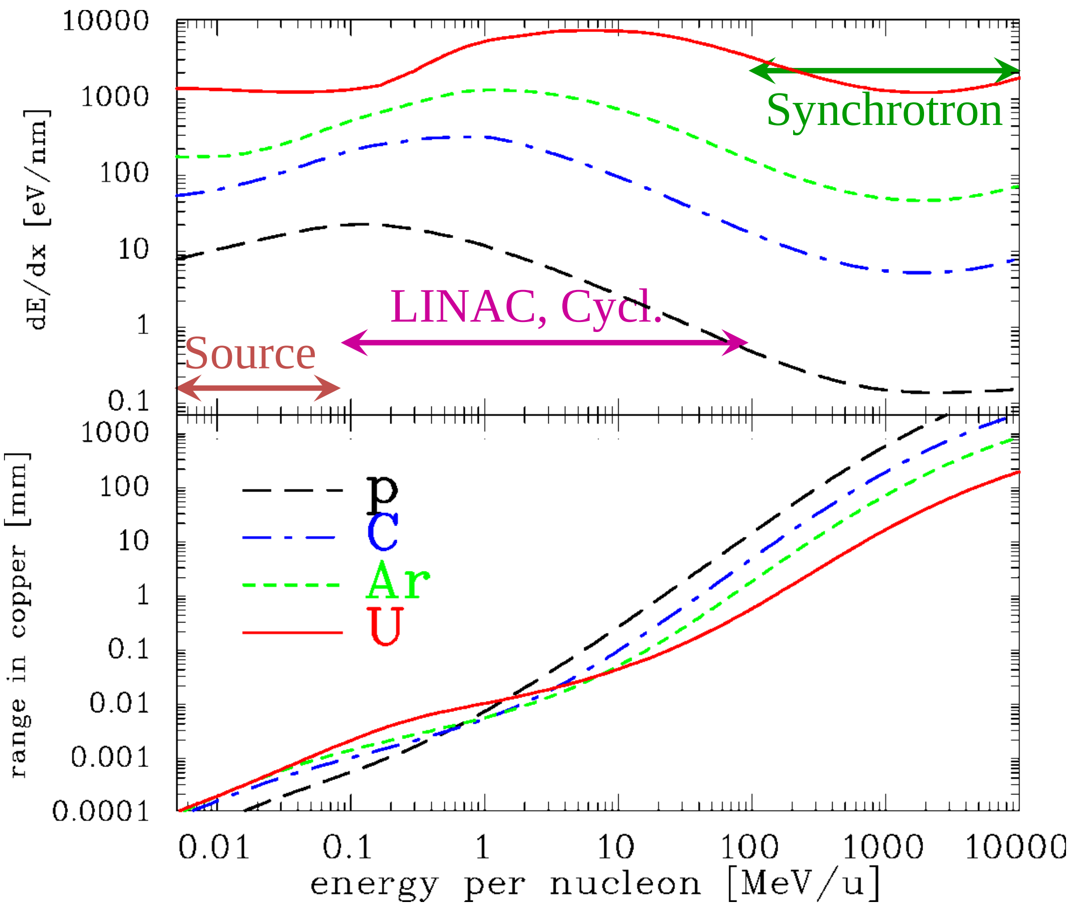
Energy Loss of Ions in Copper

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

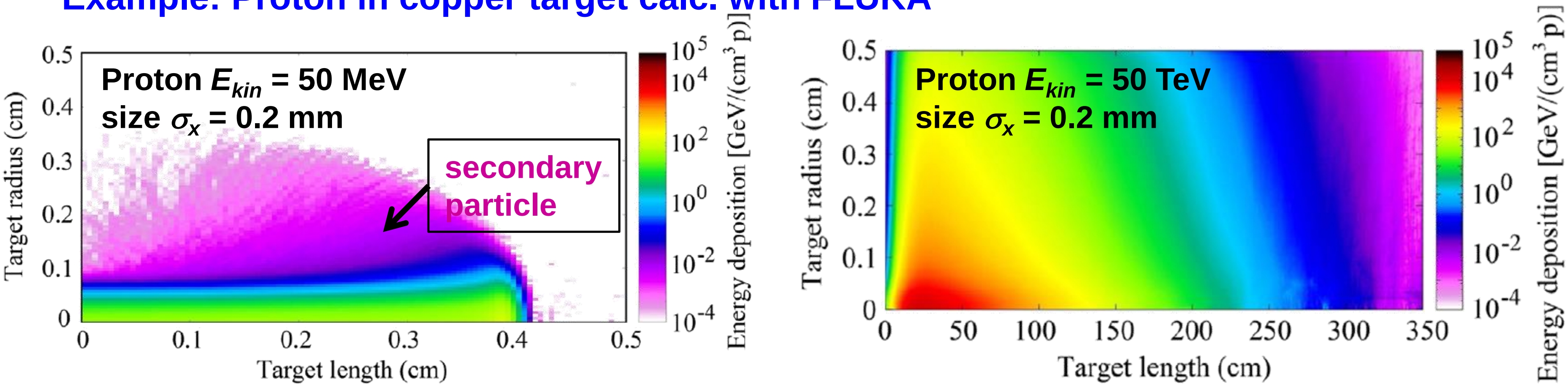
This is an atomic physics process:

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

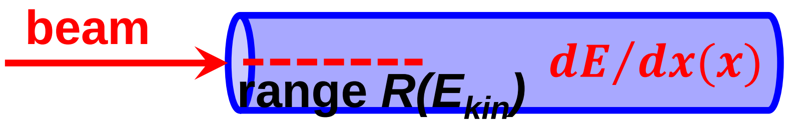
⇒ **Heating of target**

Energy Loss and Heating: Calculations

Example: Proton in copper target calc. with FLUKA



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

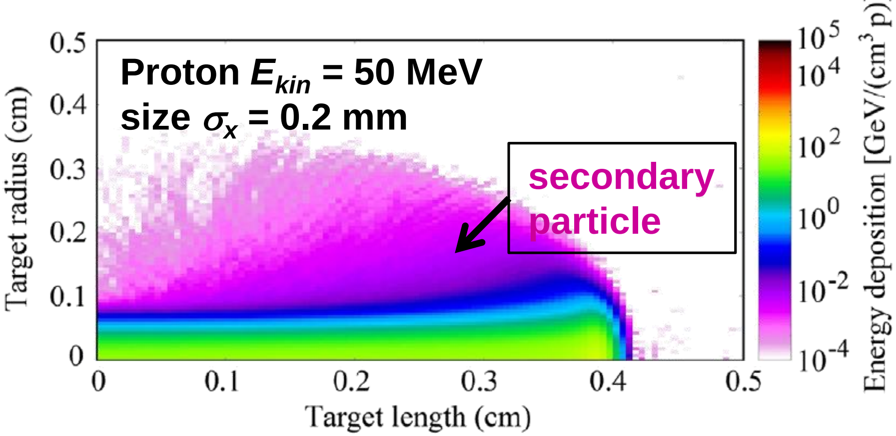


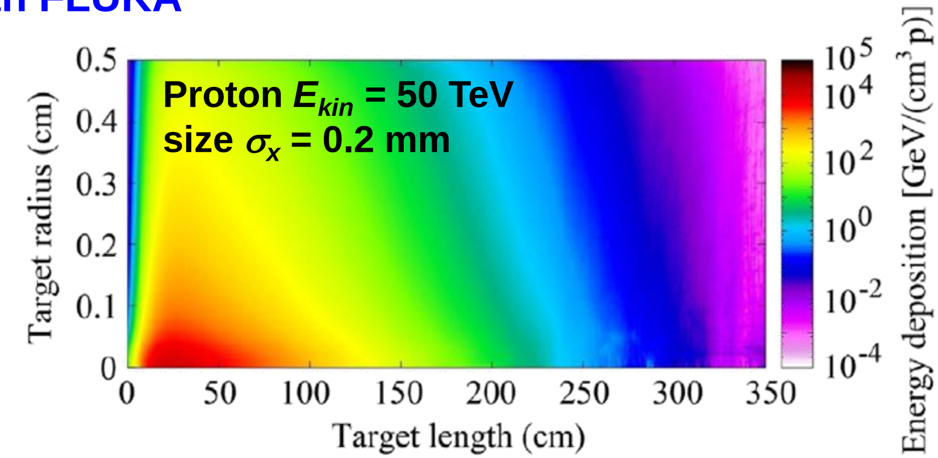
General method of calculation (simplified):

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

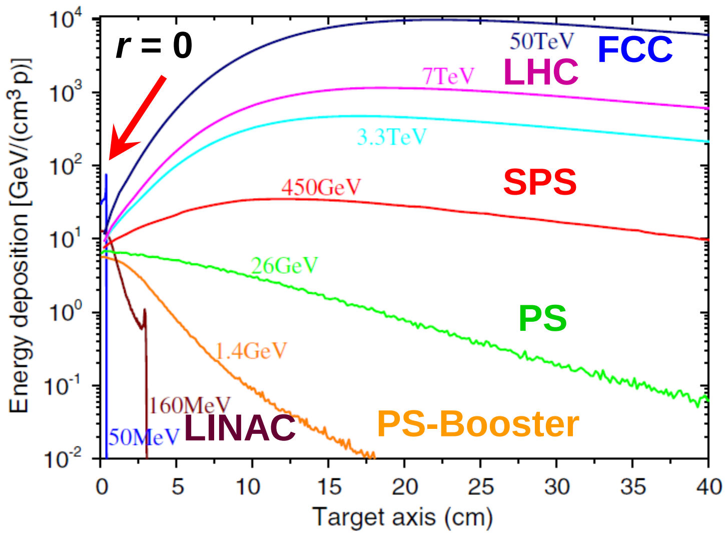
Example: Proton in copper target calc. with FLUKA





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

Example: Proton in copper target at central path



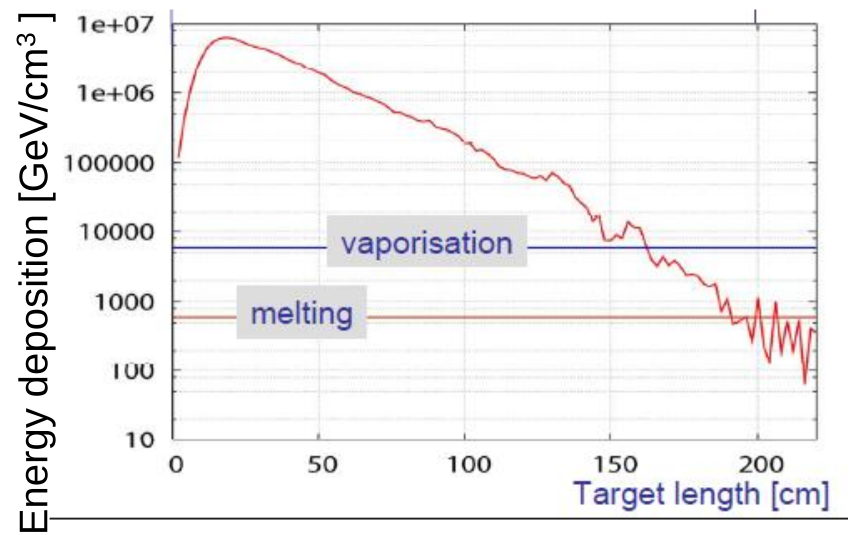
Proton:

E_{kin} = 7 TeV

2808 bunch

380 MJ energy

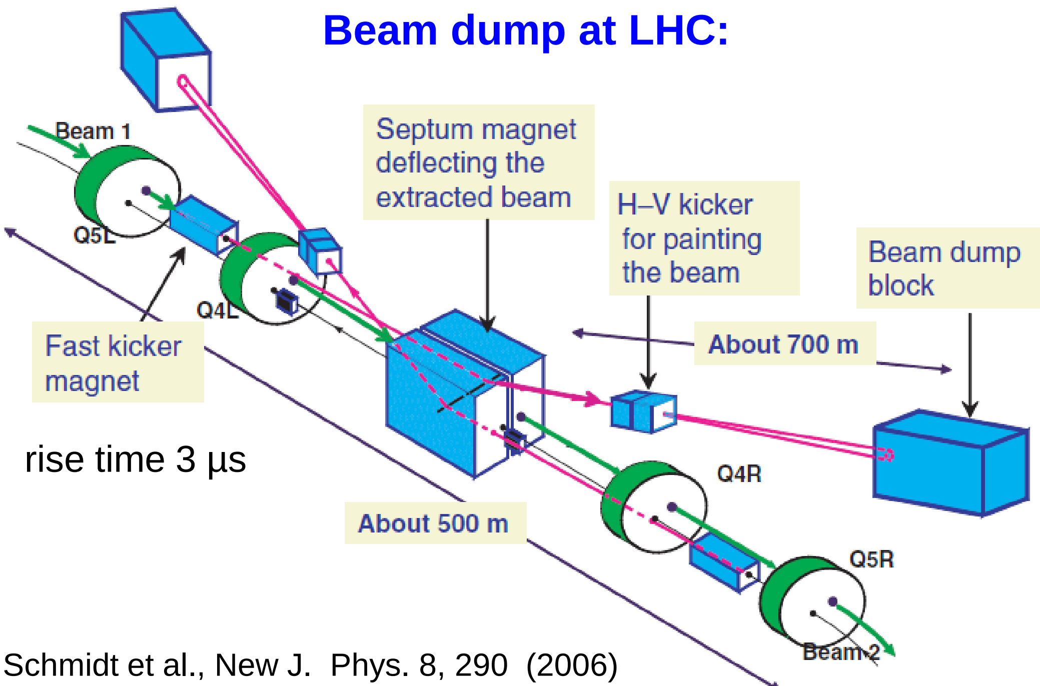
at center r = 0



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

Beam Dump for high Intensity Beams

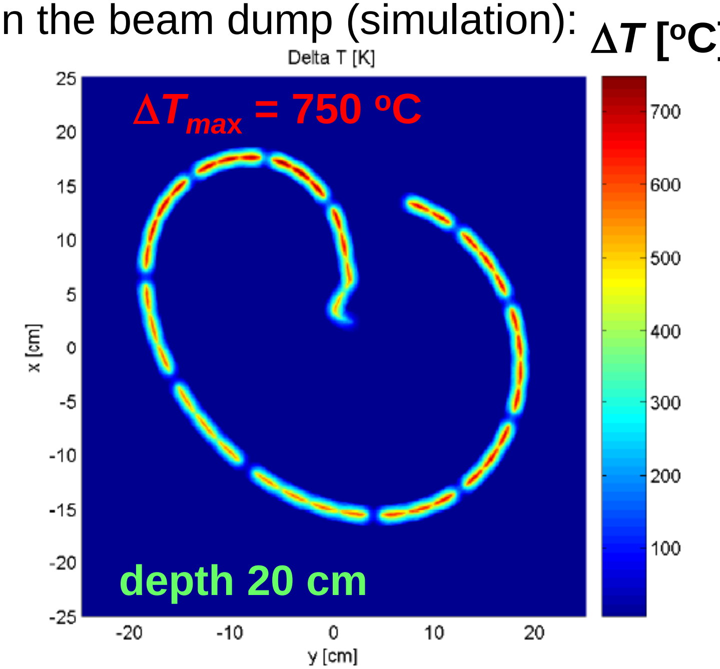
Beam dump at LHC:

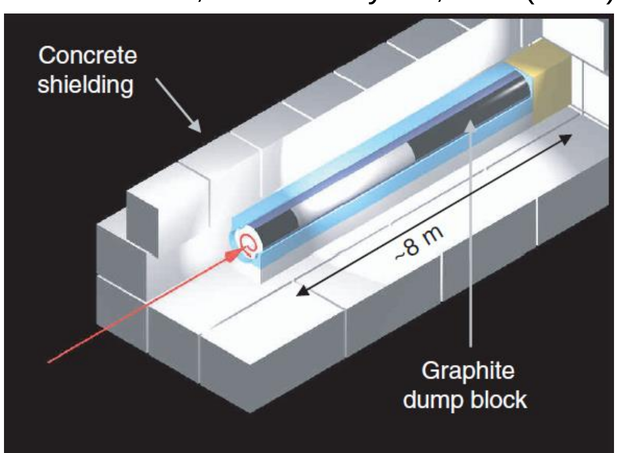


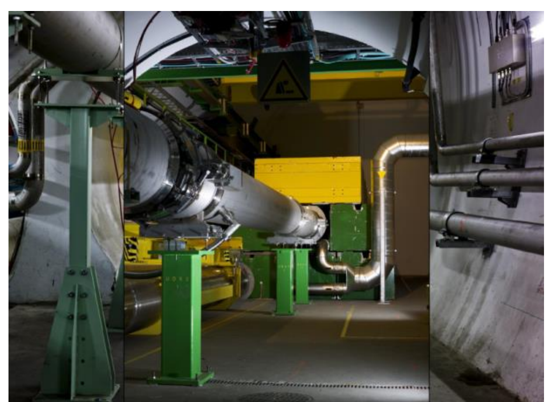
rise time 3 µs

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:

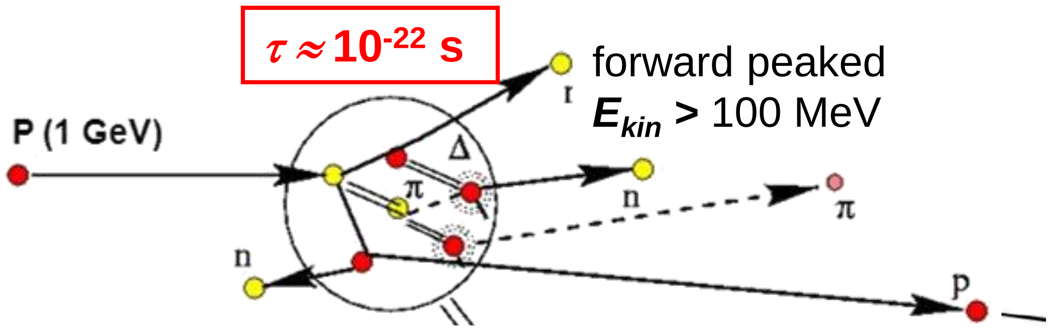
7m long, ∅ 0.7 m, graphite

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



General properties:

- Binding energy:
  ≈ 5 MeV out nucleons
  ≈ 50 MeV inner nucleons
- for E_{kin} >> 100 MeV
  comparable σ for n & p

D. Kiselev, CAS 2011

Nuclear Physics Processes for Protons

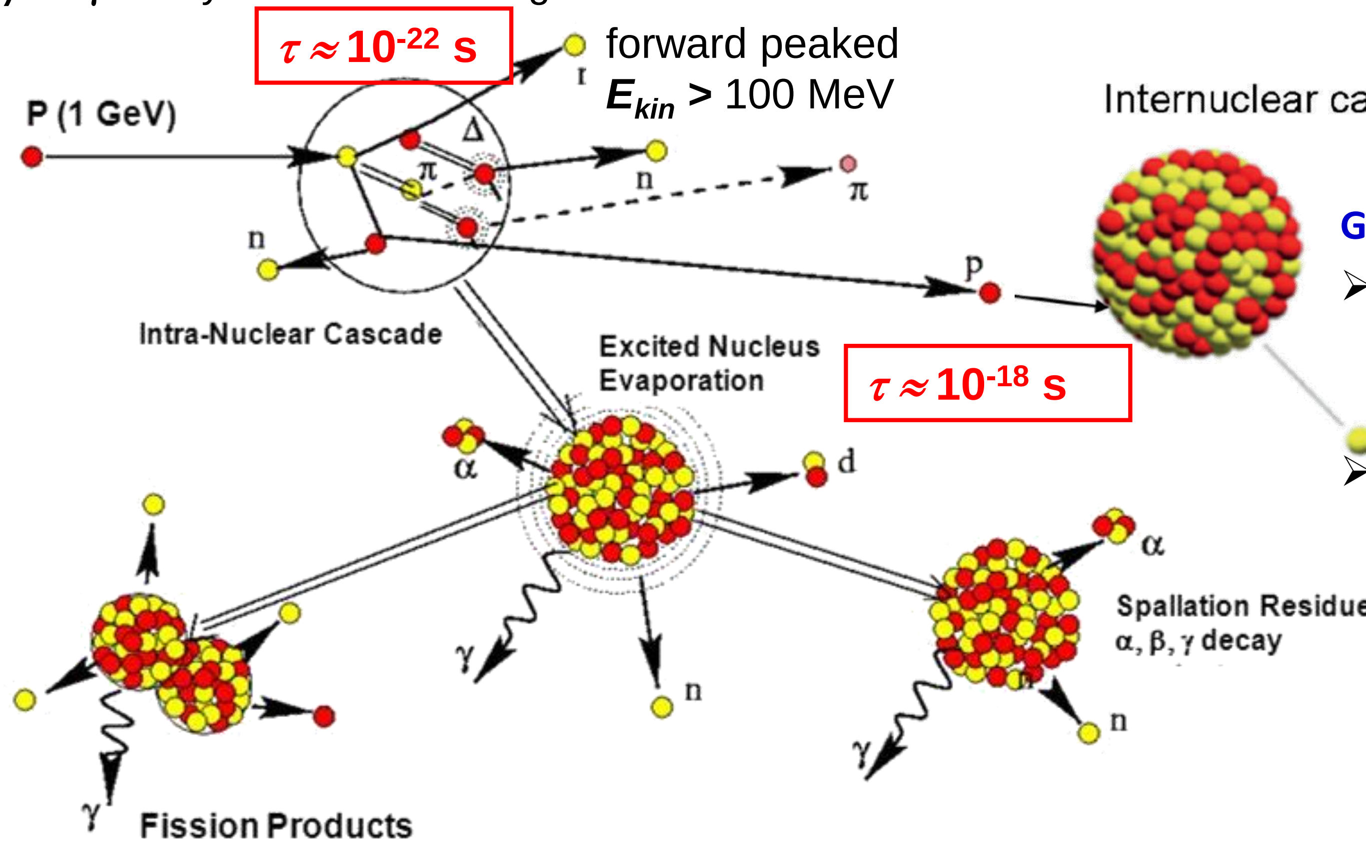
Nuclear reactions via spallation for protons with $E_{kin} \geq 1$ GeV (simplified):

- Pre-equilibrium phases: π-exchange within $\approx 10^{-22}$ s with $E_{kin} > 20$ MeV $\Rightarrow$ hadronic shower
- Inter-nuclear cascade: Evaporation of n, p, d, α within $\approx 10^{-18}$ s with $E_{kin} \approx 1 - 10$ MeV
- Fission for heavy nuclei
- β & γ decay of nuclei with long lifetime $\tau \gg 10^{-9}$ s

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

forward peaked
$E_{kin} > 100$ MeV

$\tau \approx 10^{-18}$ s



General properties:

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

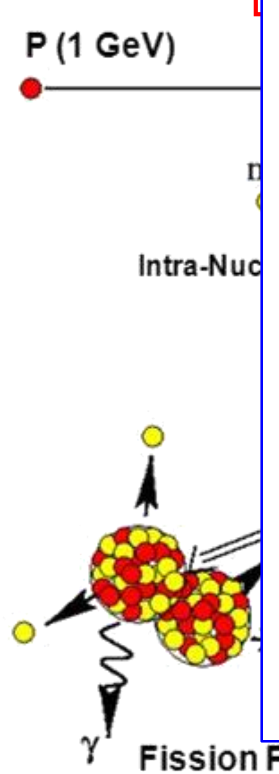
Result on long term $t > 1$ ms: Radioactive nuclei = activation

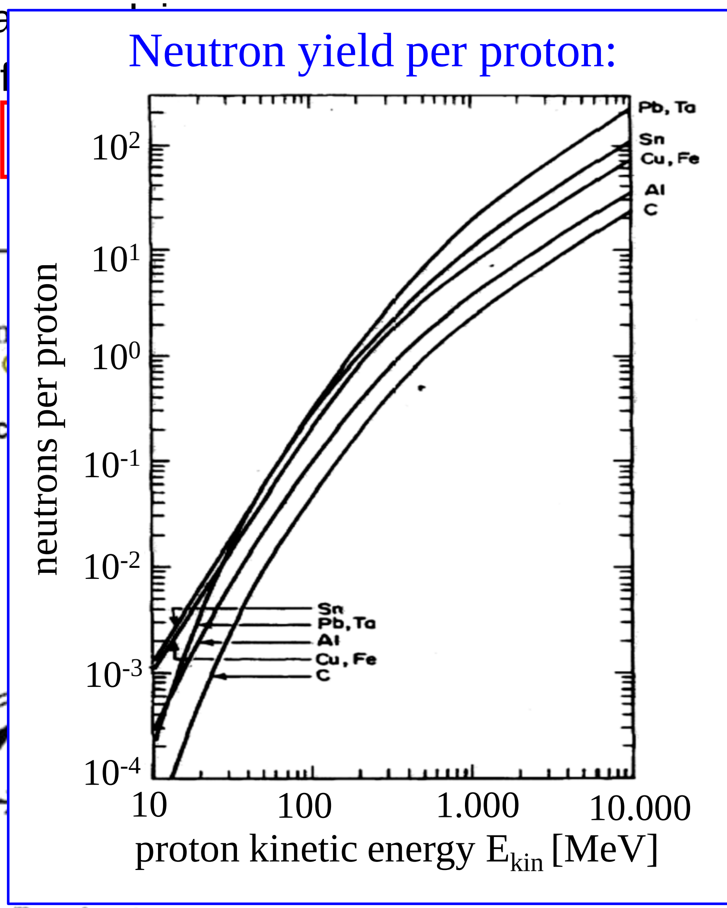
D. Kiselev, CAS 2011

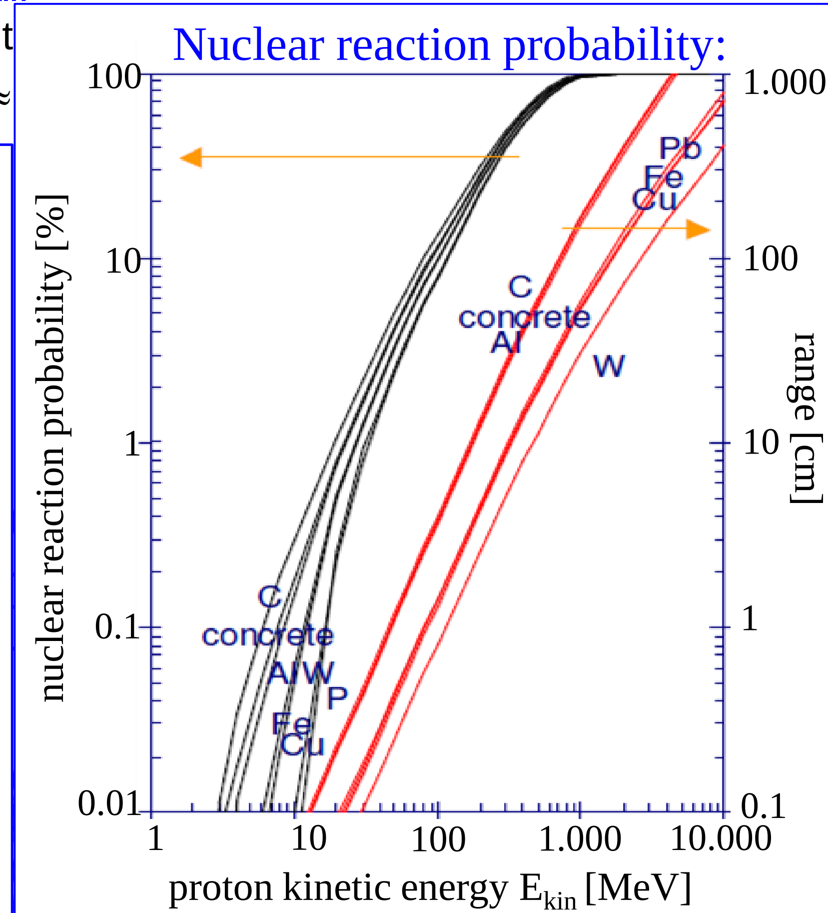
Nuclear Physics Processes for Protons

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

- Pre-equilibrium phases: π-exchange within ≈ 10^{-22} s wit
- Inter-nuclear cascade: Evaporation of n, p, d, α within ≈
- Fission for hea
- β & γ decay of







Thick target:

Penetration depth comparable to range

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

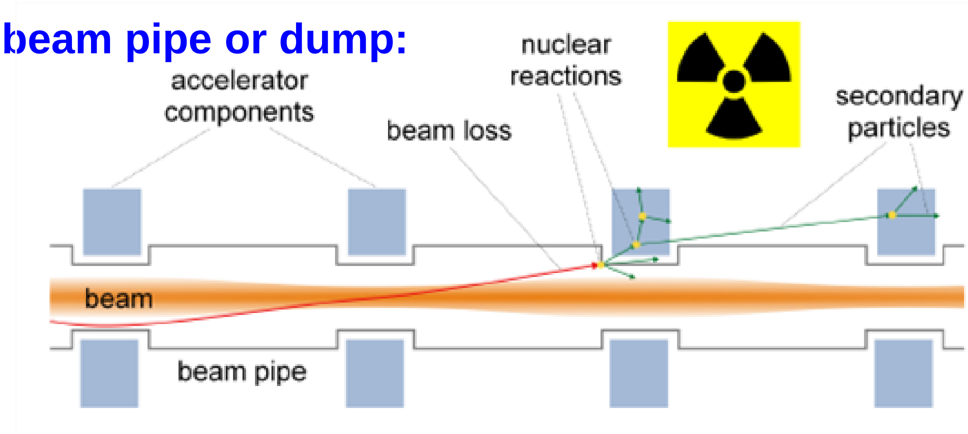
R.H. Thomas, in Handbook on Acc. Phy. & Eng.

Nuclear Physics Processes for Protons

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

- Hadronic shower
- Beam fragmented nuclei, secondary nuclei
- Fast and slow n, p, d, α ...
- β & γ decay of target nuclei
  on long time scale

Vacuum pipe might by 'thick target'
due to gracing incident



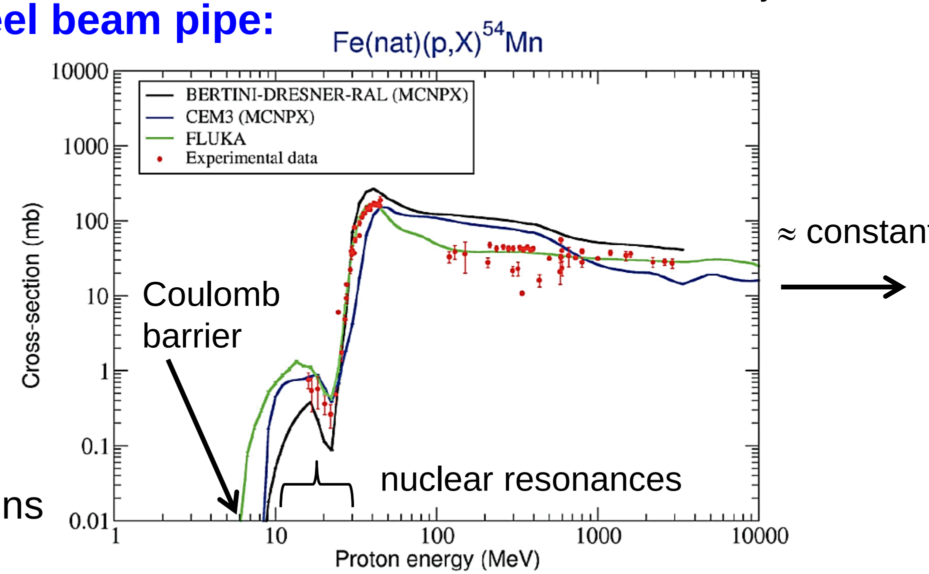
Courtesy I. Strasik

Example of cross section for protons on steel beam pipe:

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

$\Rightarrow$ **activation of beam pipe**

Remark: Comparable cross section for fast neutrons



Coulomb barrier:

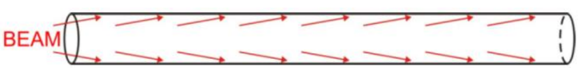
Kinetic energy required to overcome the electric potential to reach a distance for nuclear force $\simeq$ 5 fm

D. Kiselev, CAS 2011

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

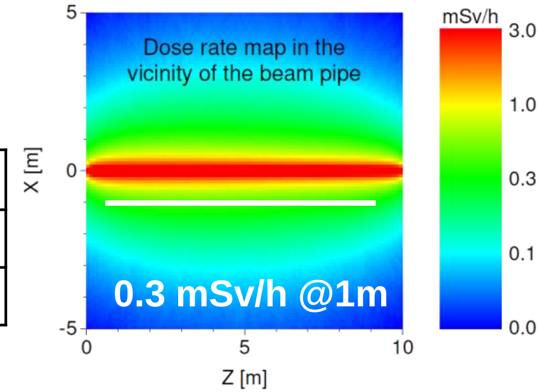
'Beam loss below 1 W/m enables hands-on maintenance'

- **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



Natural background	≈ 1 mSv/a
Medical X-ray CT	≈ 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'

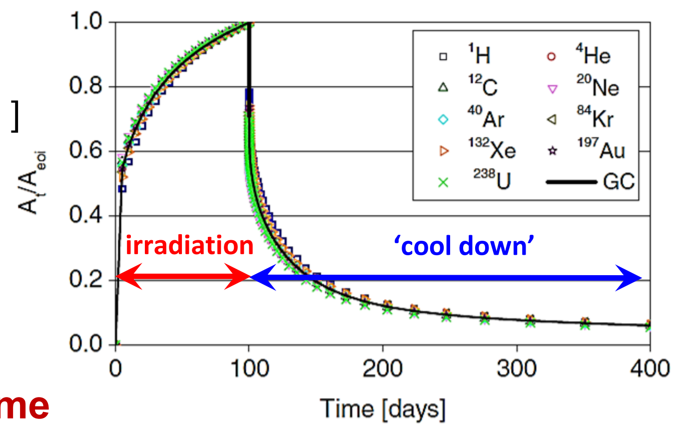


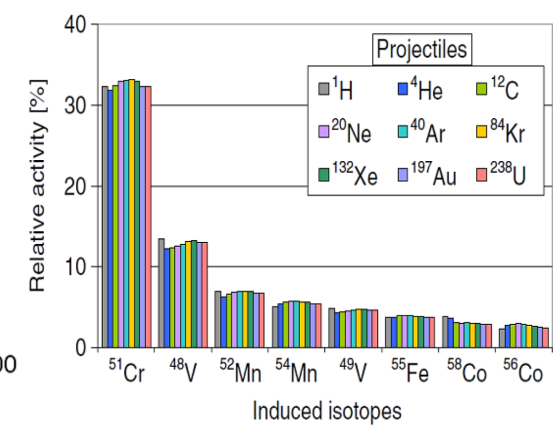
Simulation for 1 W/m losses for 1 GeV/u impact:

- 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**

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





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 ⇒ X-rays, slow e^-

For E_{kin} > 10 MeV:

Bremsstrahlungs-γ, forward peaked E_γ = 5-50 MeV

⇒ $\gamma \rightarrow e^+ + e^-$ 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

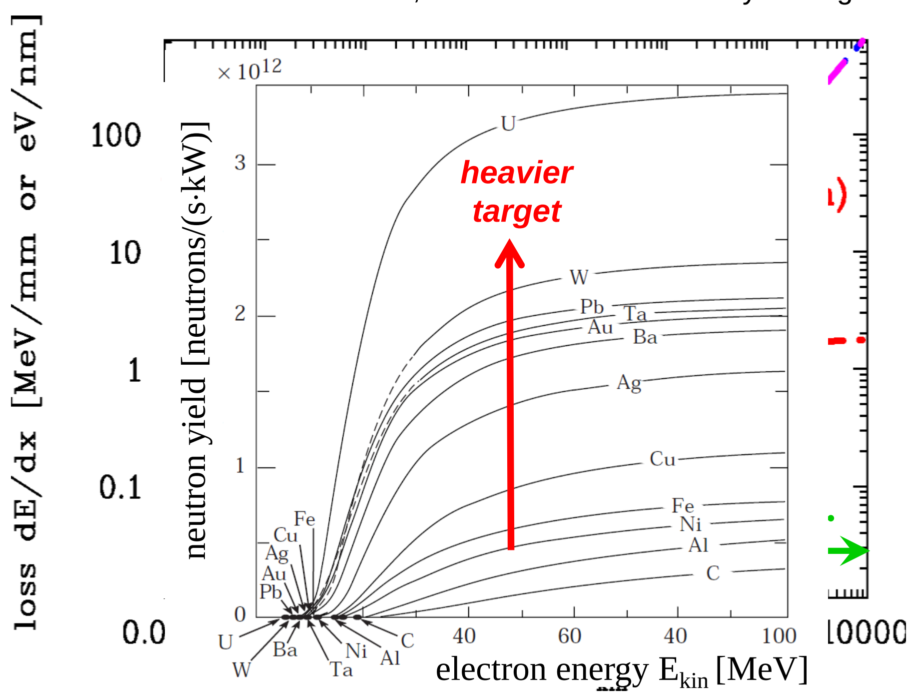
→ Neutrons: Long ranges in matter

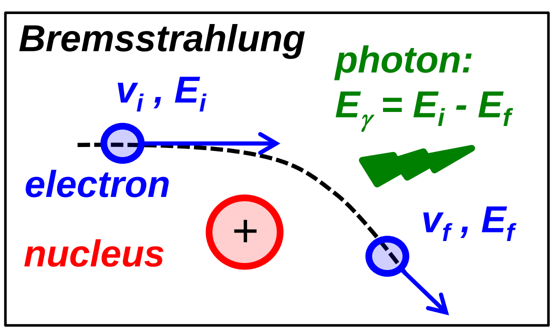
no ele.-mag. interaction but nuclear reactions

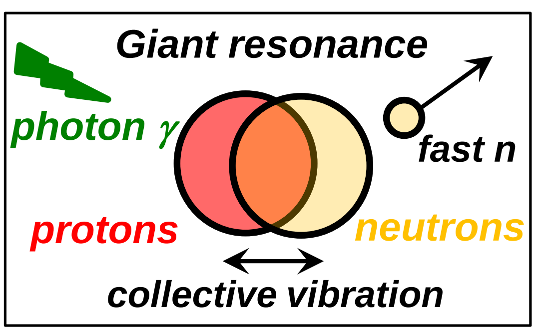
Photo-Pion reaction: d (γ,π^0) pn or d (γ,π^-) pp

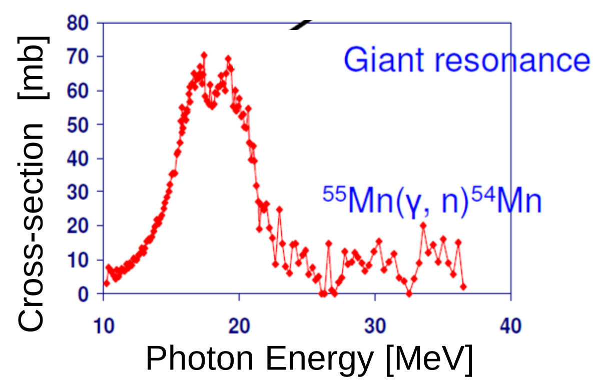
⇒ activation at electron accelerators

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





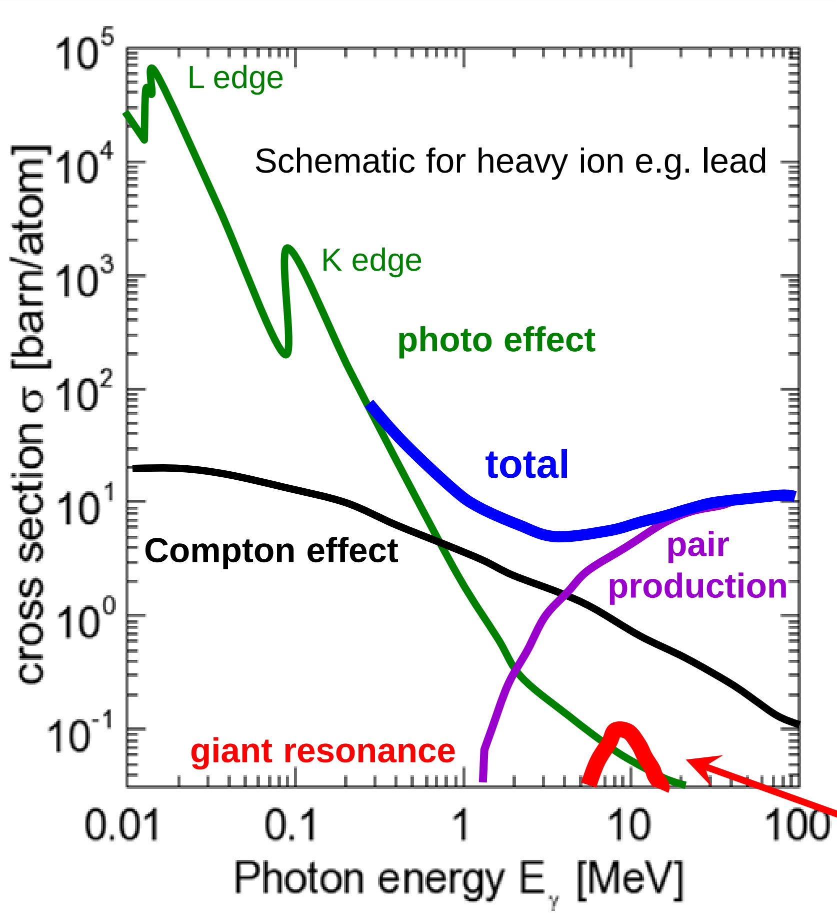




Interaction of high Energy γ

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

Example: Absorption in lead



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

ρ *density,* N_A Advogadro const., A atomic mass

Courtesy C. Grupen, Xavier Queralt, JUAS

Atomic physics **(*Z*=target nucl. charge):**

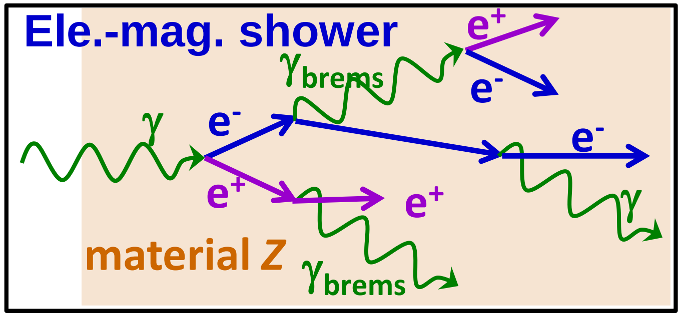
Photo-effect: γ + atom $\rightarrow$ e^- + atom$^+$
approx. material scaling $\sigma_{photo} \propto Z^4$

Compton-effect: γ + atom $\rightarrow$ γ' + e^- + atom$^+$
approx. material scaling $\sigma_{Comp} \propto Z$

Pair prod.: γ + nucleus $\rightarrow$ e^- + e^+ + nucleus
approx. material scaling $\sigma_{pair} \propto Z^2$

Ele.-mag. shower: for high E_γ

$\gamma \rightarrow (e^-e^+) \rightarrow \gamma'_{brems} \rightarrow (e^-e^+)' \rightarrow \gamma''_{Brems} \rightarrow$ ....



Nuclear physics:

Giant resonance: γ + nucleus $\rightarrow$ n + nucleus'

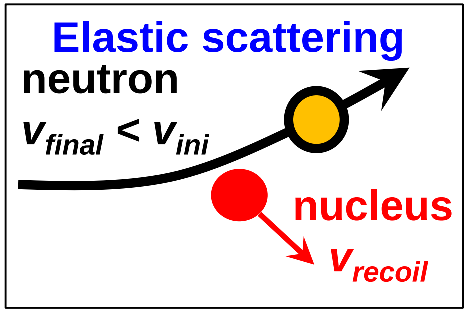
small cross section but create free neutrons

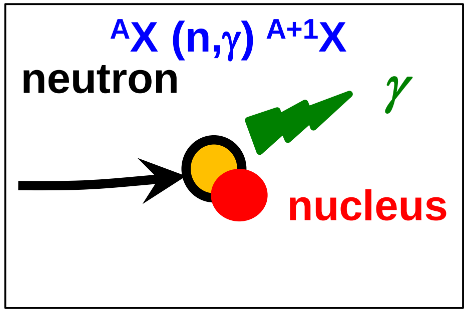
Interaction of Neutrons

Neutrons don't interaction with electrons

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 copper ^{63}Cu

Elastic scattering: Large cross section for thermal n

Absorption: Large cross section at resonances

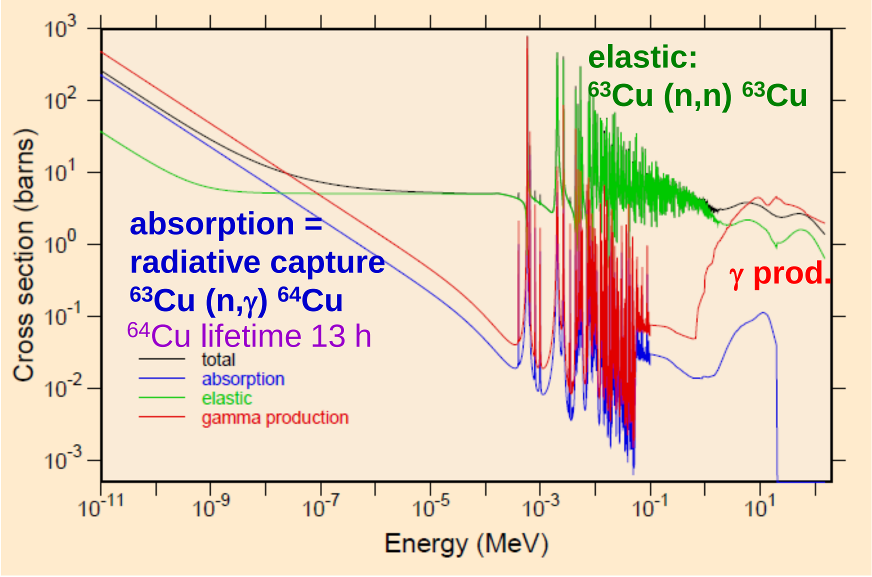
γ- emission and activation

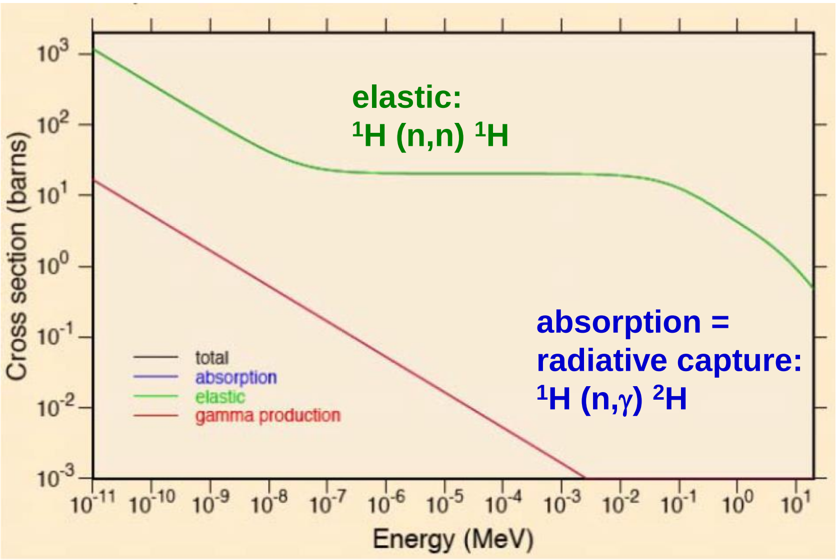
For ***E*** >> 100 MeV comparable cross section as proton

Example: Neutrons on H

e.g. H_2O, organic materials

→ effective moderator due to equal masses





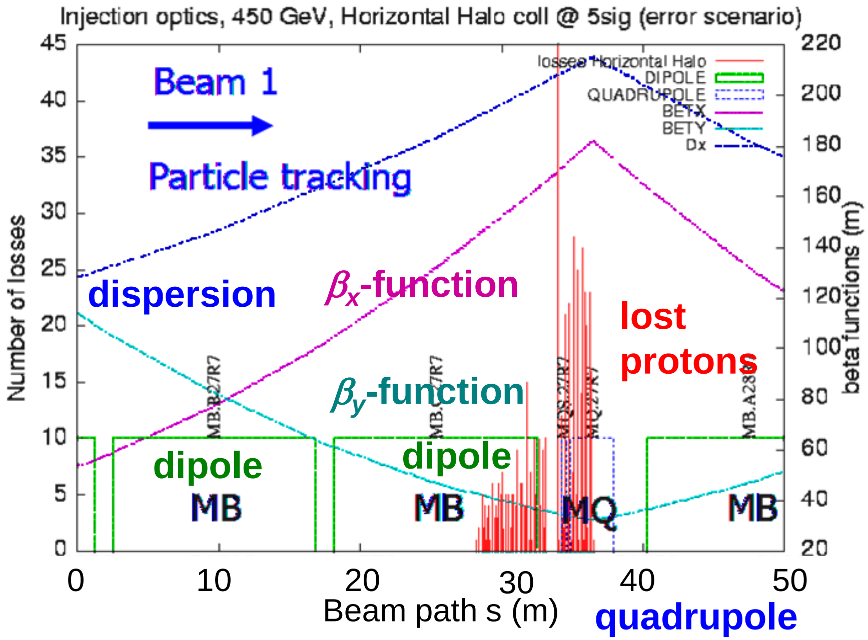
Remark: Shielding of n by plastic ('paraffin') or concrete

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

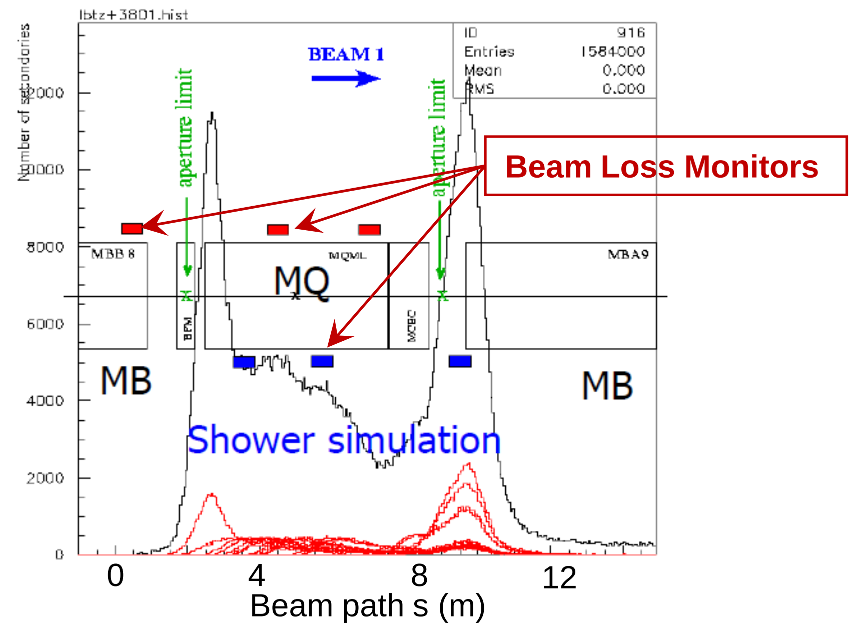
Secondary particles and shower produces are emitted within a forward cone
(in rest-frame isotopically but due to Lorentz-transformation forward in lab-frame .

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*** & β_x maximum



Example: Simulation of number
of shower particles



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

Outline of this talk:

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

Relevant Losses for Machine Protection

Types of losses:

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

- Caused by lifetime inside synchrotron (residual gas scattering or charge exchange, Touschek ...)
- Caused by halo-formation and cleaning, aperture limitation, imperfections, machine errors
- Caused by multi-turn injection, slow extraction,....→ known loss mechanism

⇒ Occurs in each cycle at characteristic times and/or beam parameters

⇒ Usually a few % of the beam intensity

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

2. *Irregular losses* or fast losses by malfunction → avoidable losses, **see below**

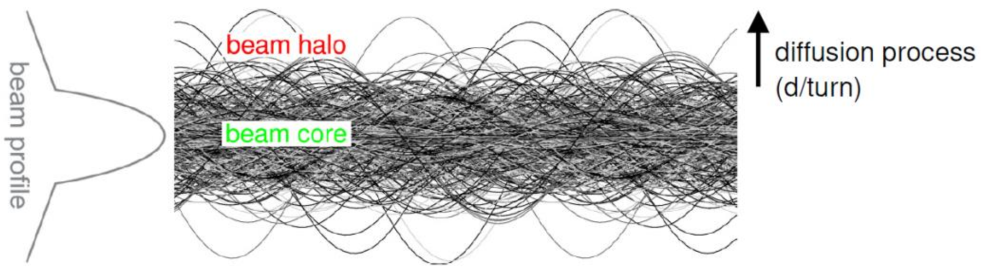
Halo formation at synchrotrons:

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

⇒ **unstable particles are lost**

Beam loss terminology: 'uncontrolled regular loss'

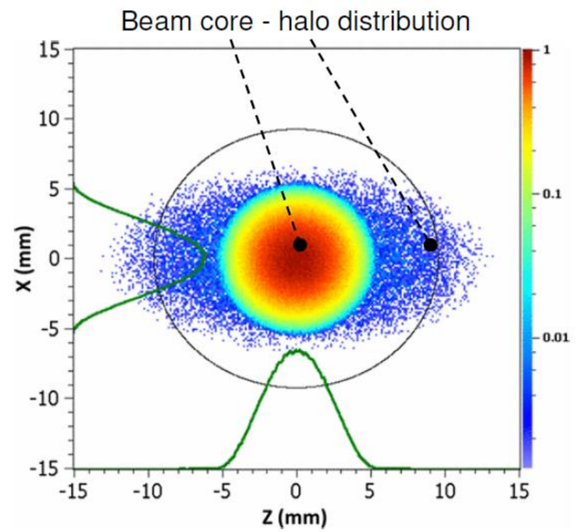
⇒ Beam halo collimation system at a synchrotron



Goal: Low impurity beam

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

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



LINAC: Halo generation by long. and trans. mismatch

Goal: Quench protection of sc civilities

Remark:

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

Courtesy I. Strasik CAS 2016

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 ΔT:

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

ρ: mat. density, c_p specific heat

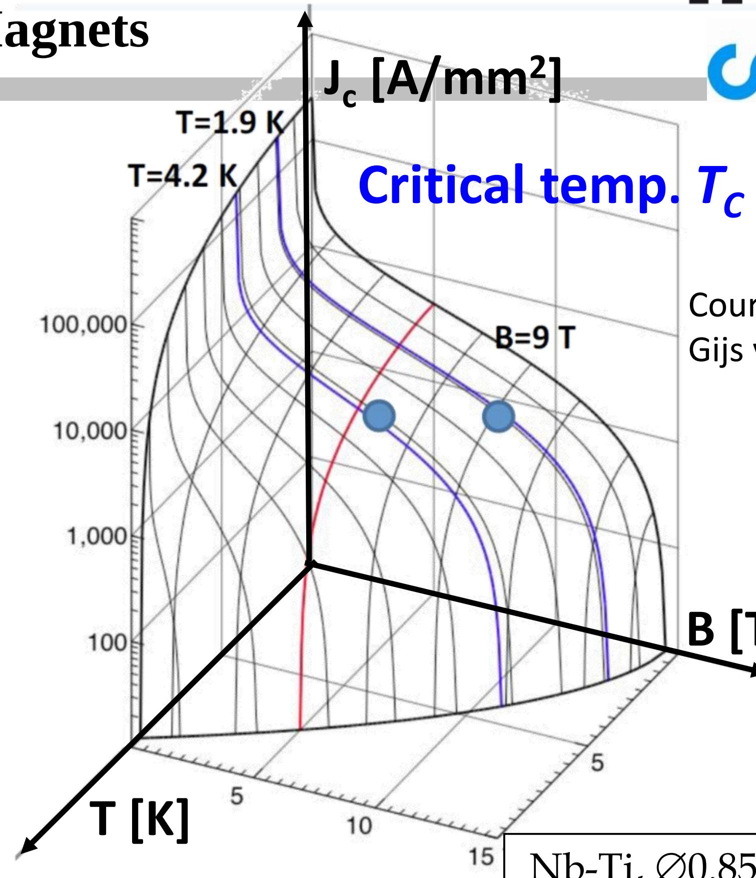
Temperature dependent specific heat:

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

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

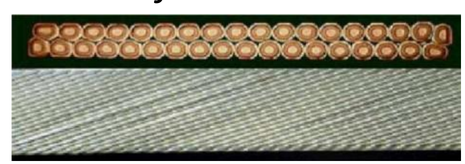
Insulator: $c_{phonon}(T) \propto T^3$ $\quad \alpha, \beta, \gamma$ mat. const.

See lecture 'Superconducting Magnets by Gijs an Rijk

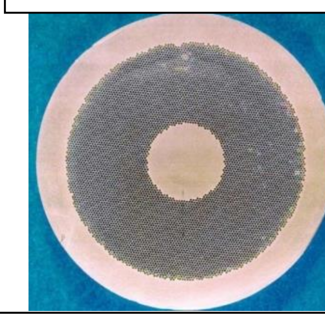


Courtesy Gijs van Rijs

'Rutherford' cable strand



Nb-Ti, ∅0.85mm

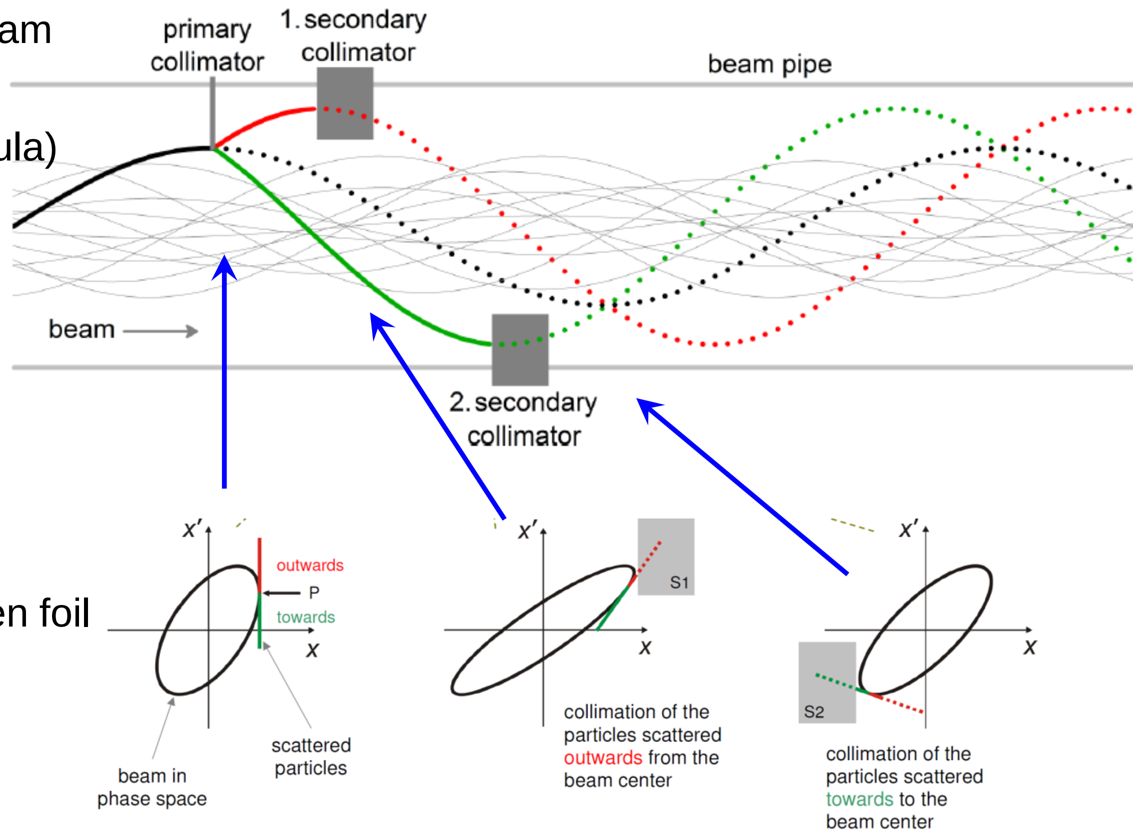


J ~ 1500-2000 A/mm²
I ~ 400 A, B = 8-9 T

Two Stage Betatron Collimation System = active Collimation

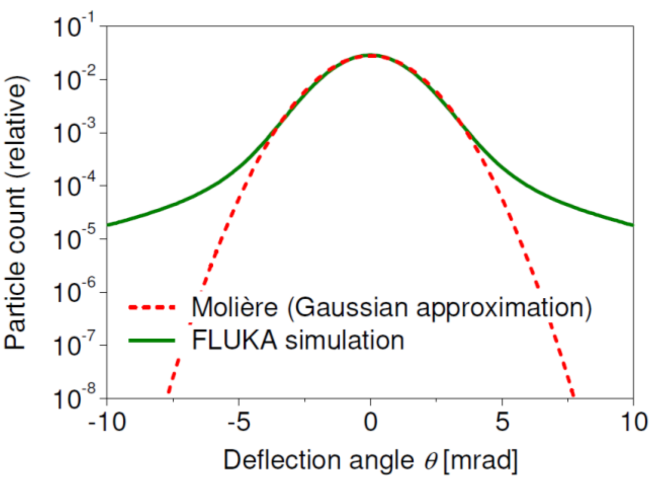
General functionality of cleaning:

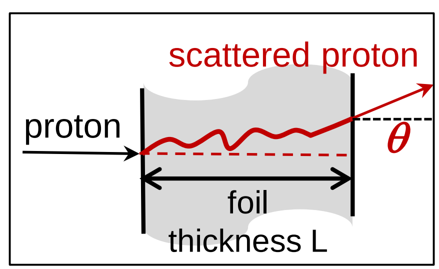
- Primary stage as **thin** foil **close** to beam
  $\Rightarrow$ scattering of halo particles
  (Coulomb scattering by Moliere formula)
- Betatron amplitude increases
- Max. extension after
  $\mu \approx 90^0$ or 270^0 betatron phase
- Secondary collimator as absorber
  more distant to beam



Example:

4.7 GeV scattering in L=1 mm Tungsten foil





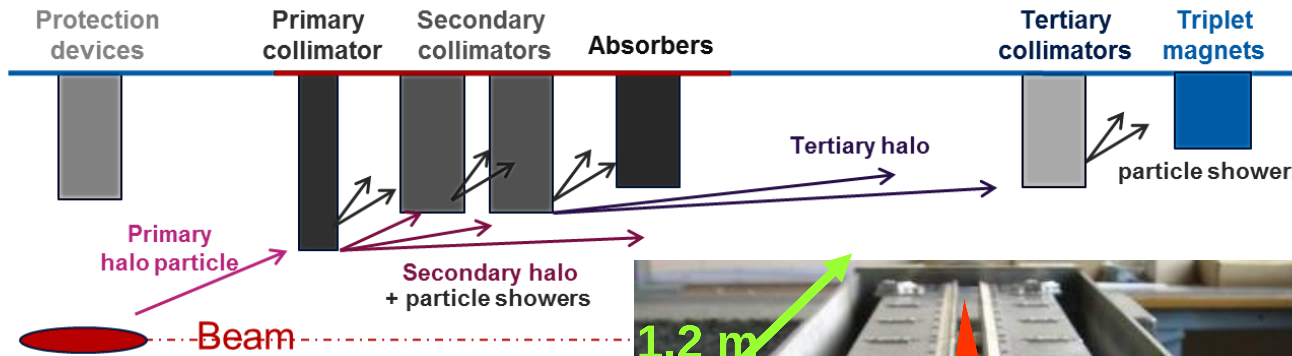
Courtesy I. Strasik CAS 2016

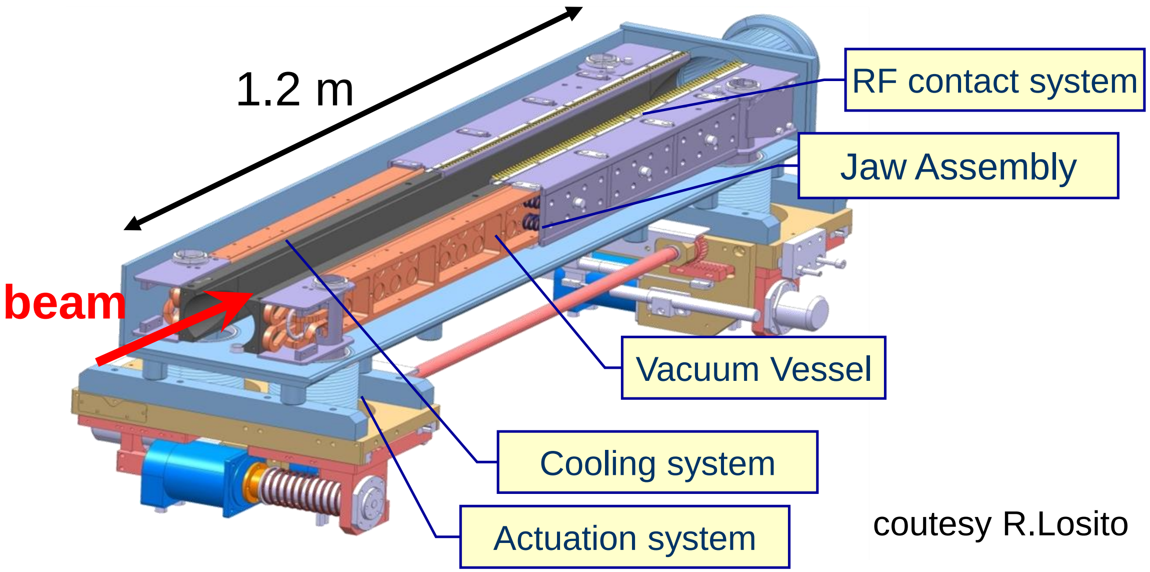
LHC Collimator Hardware

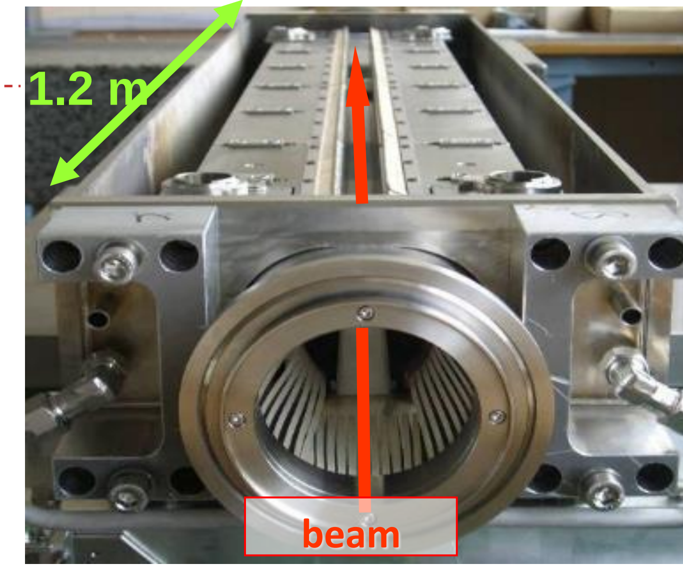
LHC Collimator system:

- Primary stage
- Secondary & tertiary stage
- Absorbers

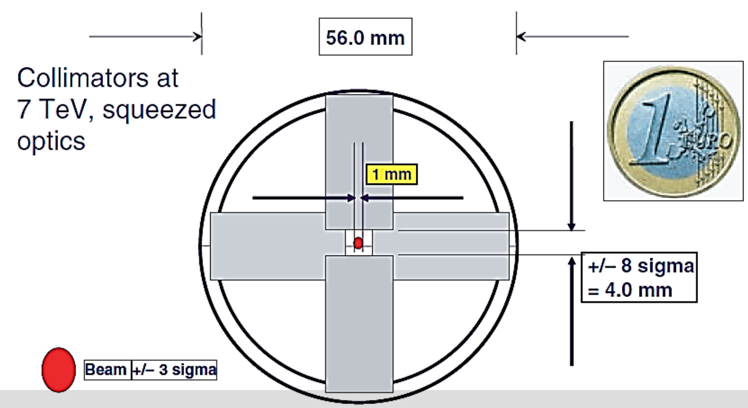
in total 110 movable devices







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

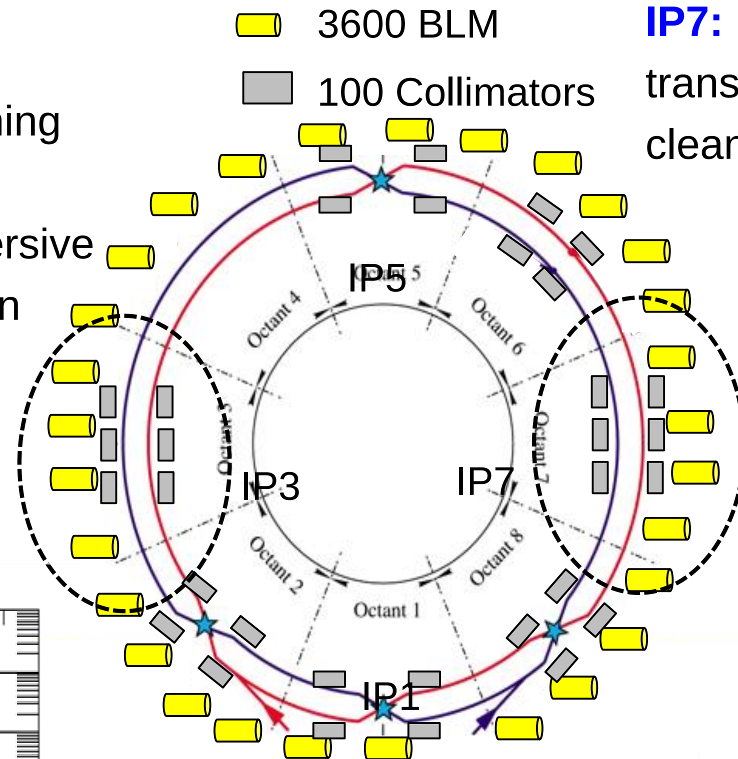
LHC Collimator system:

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

$\rightarrow$ in total 110 movable devices
moving e.g. from injection r = 5 mm $\rightarrow$ 1 mm

IP3: long. cleaning at dispersive region

IP7: transverse cleaning

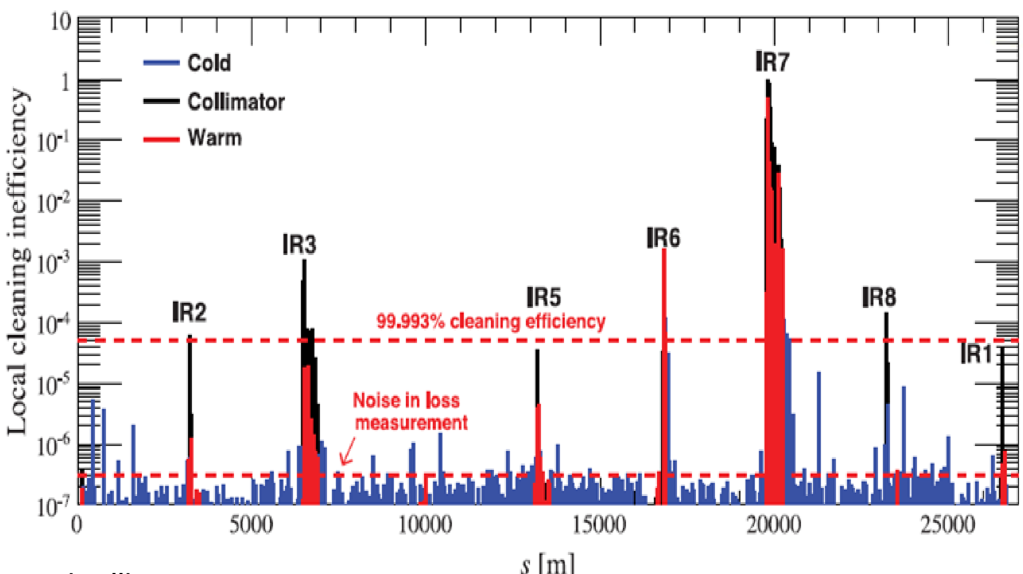


Test of functionality:

- Loss concentrated at collimators

Experimental verification: Single bunch excitation

Result: Main losses concentrated at collimators



S. Redaelli, JAS CERN-2016-002

Cleaning efficiency:
η = (protons lost at collimator) / (total beam loss)
Result: η = 99.8 % reached

Courtesy M. Zerlauth, CAS 2018

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

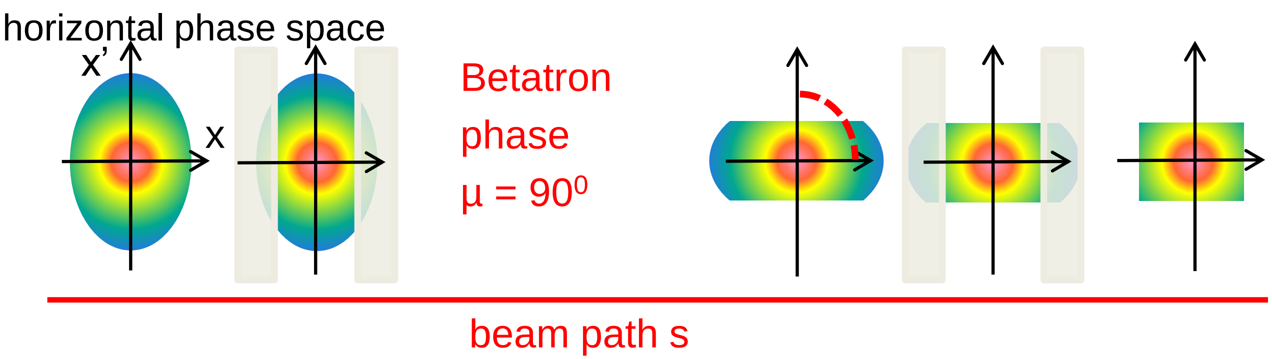
Goal: Halo cutting at low energy to prevent for activation

Collimators:

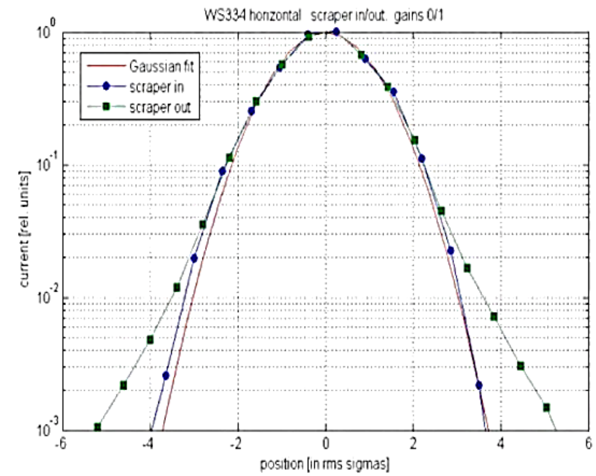
Cut the beam tail in space

μ = 90⁰ or μ = 45⁰ betatron phase to cut angle

⇒ at least two locations required



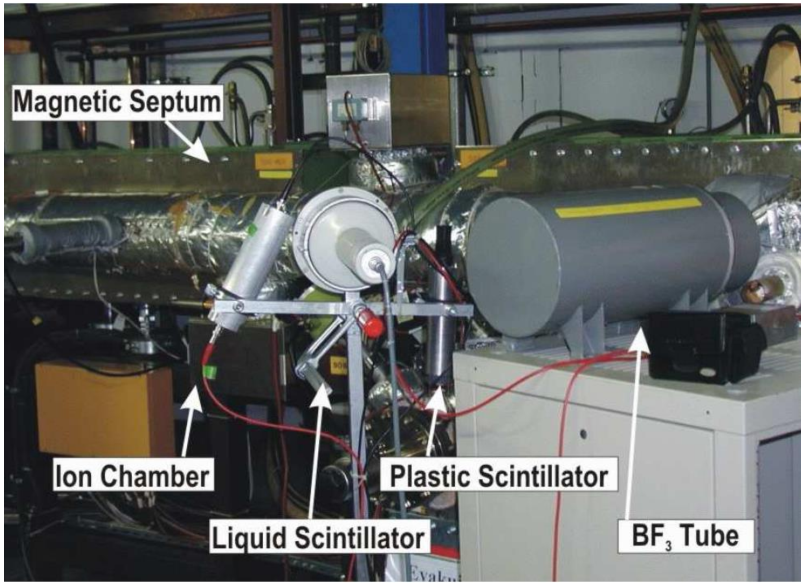
i.e. phase space distribution is not completely cut



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

Outline of this talk:

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



Basic idea for Beam Loss Monitors B LM:

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

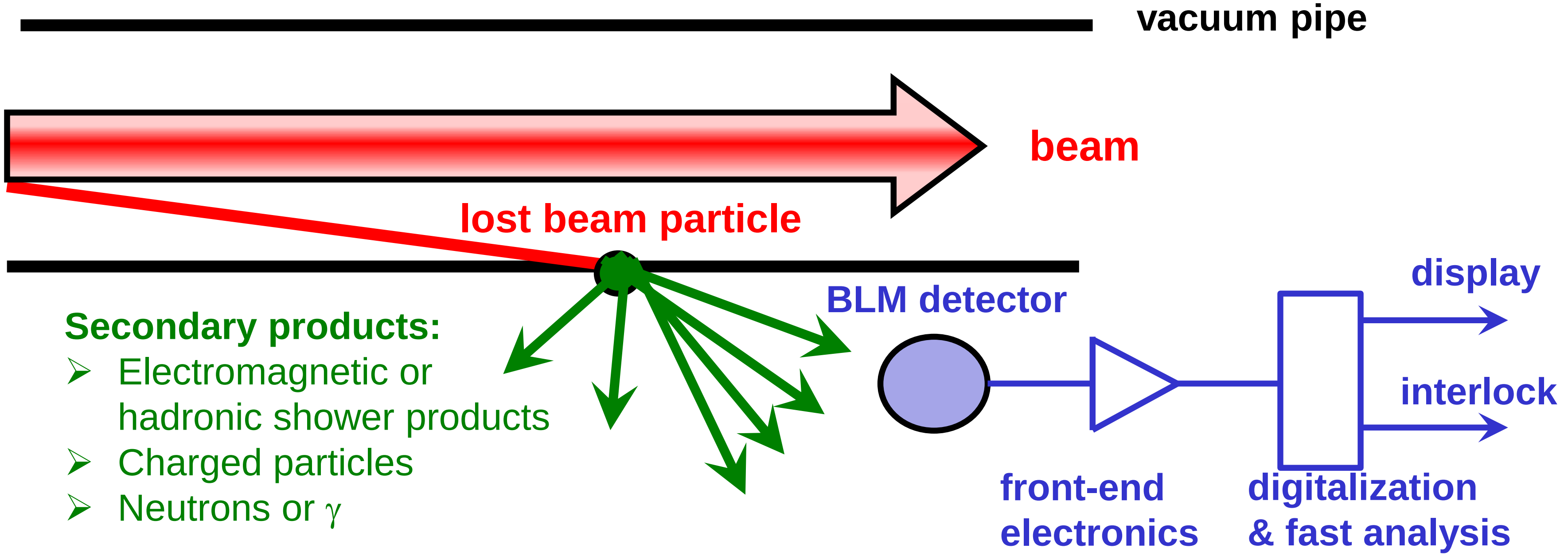
⇒ Interaction leads to some shower particle:

e^-, γ, 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'

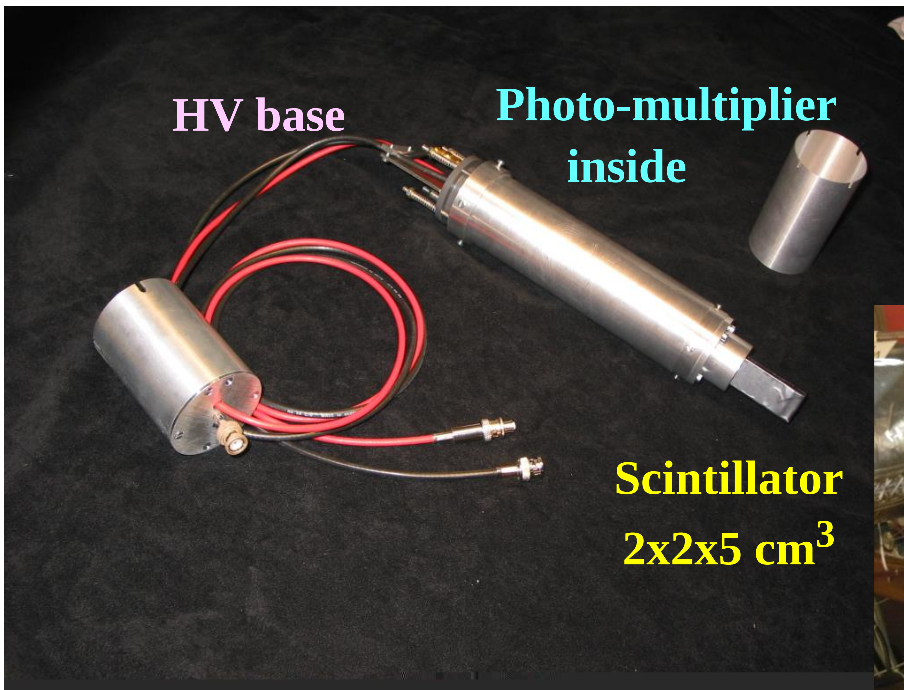


Plastics or liquids are used:

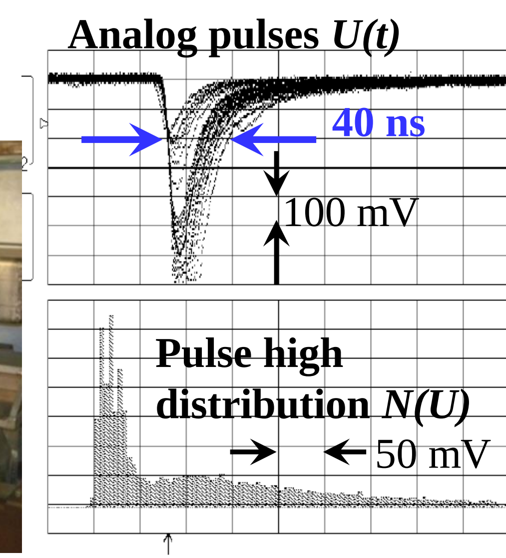
- Detection of **charged particles** by electronic stopping
- Detection of **neutrons** by elastic collisions n on p in plastics and fast p electronic stopping.

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



Example: Analog pulses of plastic scintillator:
⇒ broad energy spectrum
due to many particle species and energies.



20 ns/div and 100 mV/div

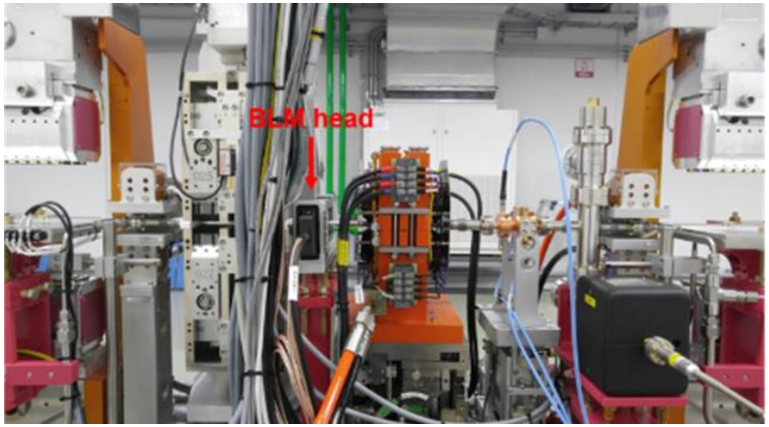
Cherenkov Light Detectors as Beam Loss Monitors

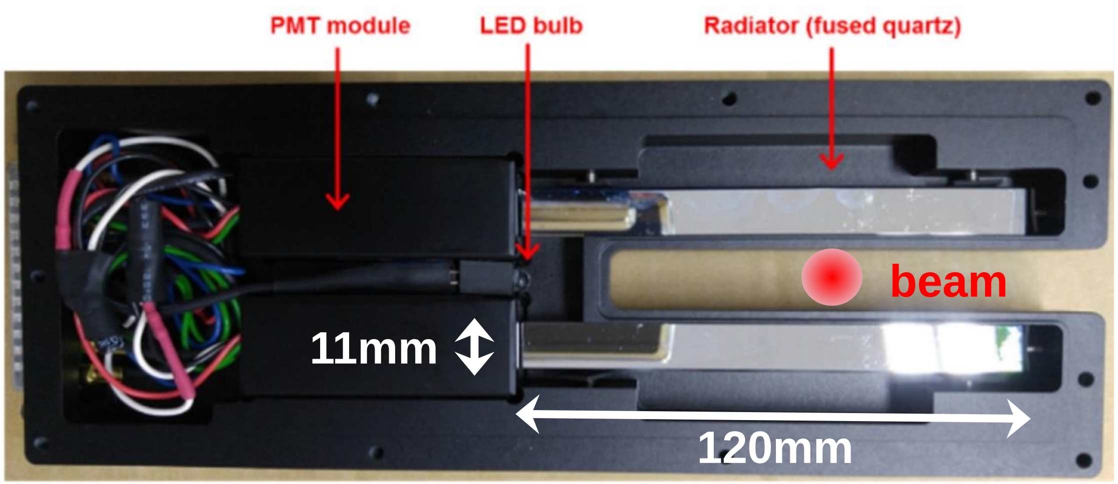
Cherenkov detectors:

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

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

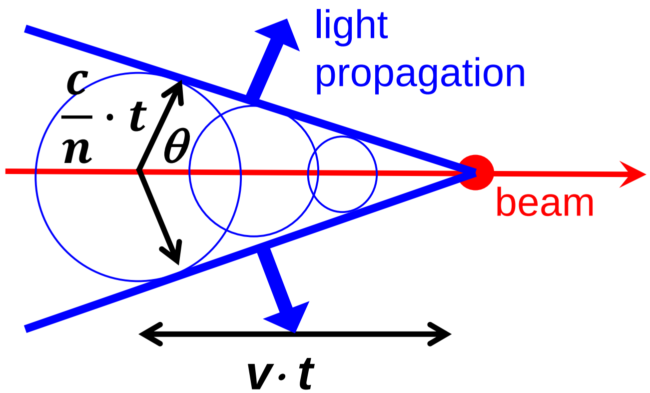
Example: Korean XFEL behind undulator





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 γ & synch. photons
- No saturation effects
- Prompt light emission

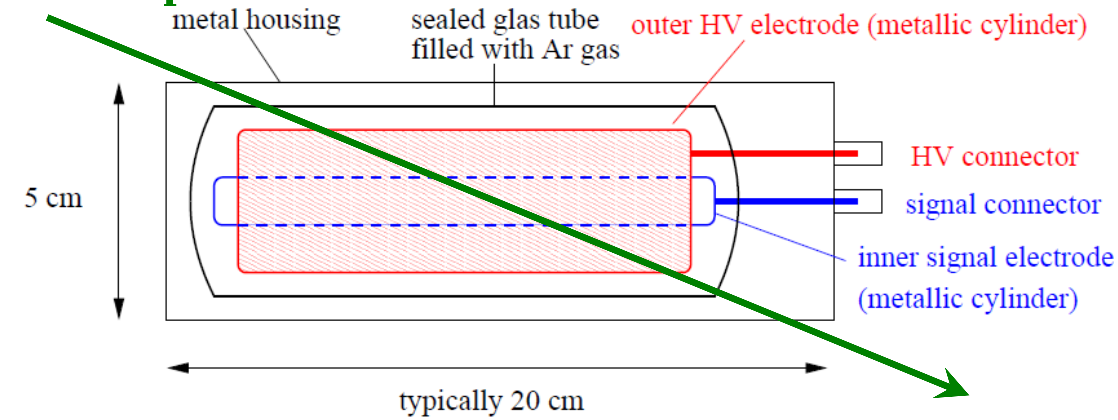
Usage: Mainly at FELs for short and intense pulses

H. Yang, D.C. Shin, FEL Conf. 2017

Ionization Chamber as Beam Loss Monitors

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

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

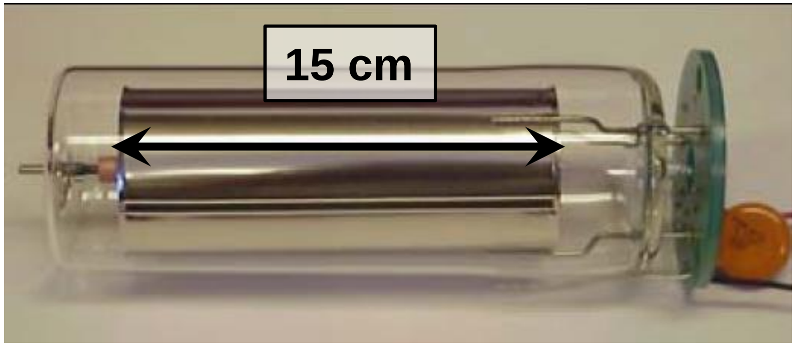


W is average energy for creation for one e⁻ -ion pair:

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

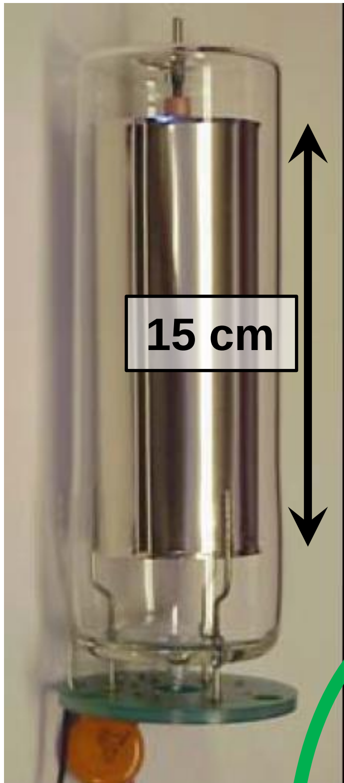
Sealed tube Filled with Ar or N_2 gas:

- 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^+.

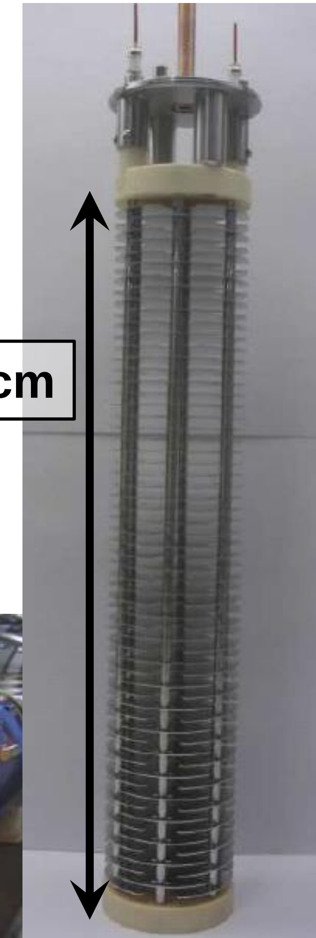


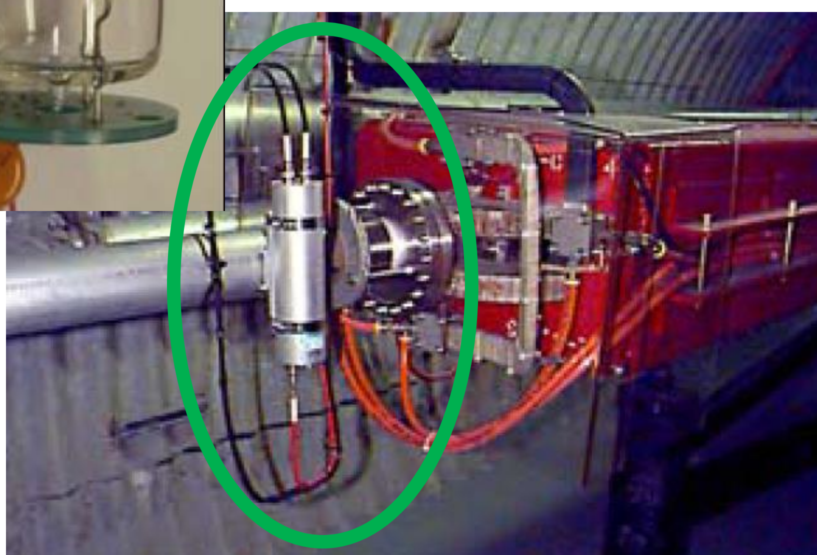
Per definition: Direct measurement of dose !

Ionization Chamber as BLM: TEVATRON and CERN Type



TEVATRON, RHIC type		CERN type
15cm, ∅ 6 cm	**size**	50 cm, ∅ 9 cm
Ar at 1.1 bar	**gas**	N_2 at 1.1 bar
3	**# of electrodes**	61
1000 V	**voltage**	1500 V
3 µs	**reaction time**	0.3 µs
	# at the synchr.	≈ 4000 at LHC
	aver. distance	1 BLM each ≈ 6 m





Ionization Chamber as BLM: CERN Type

Simulation of det. efficiency by Geant4:

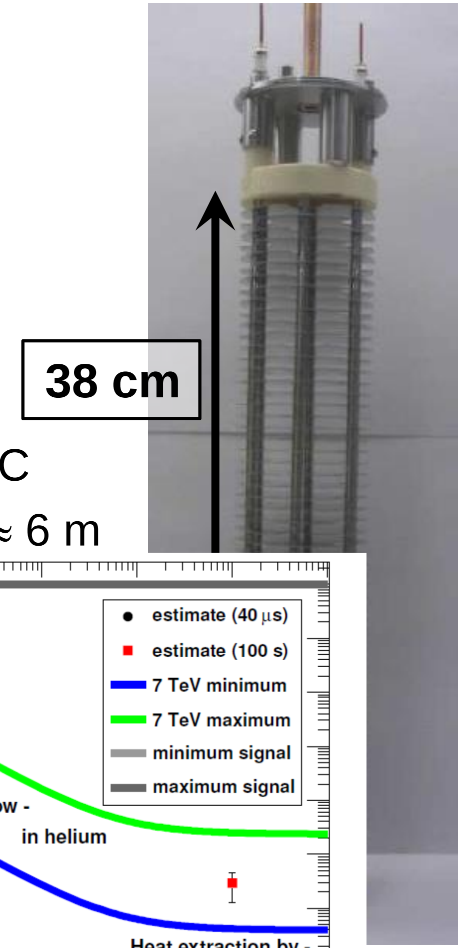
- Most sensitive to protons, electrons & high energy γ
- Low sensitive to neutrons

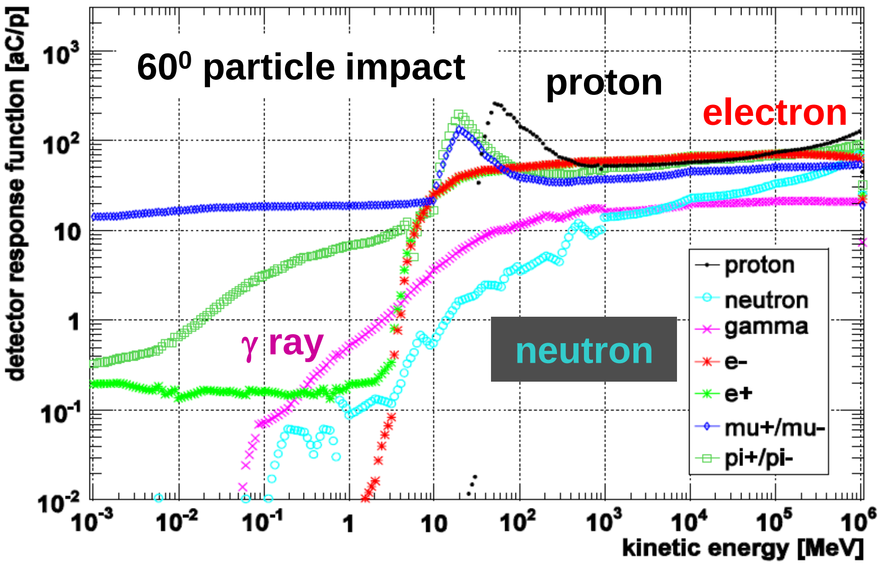
⇒ Calculation of lost protons by integrating of shower composition

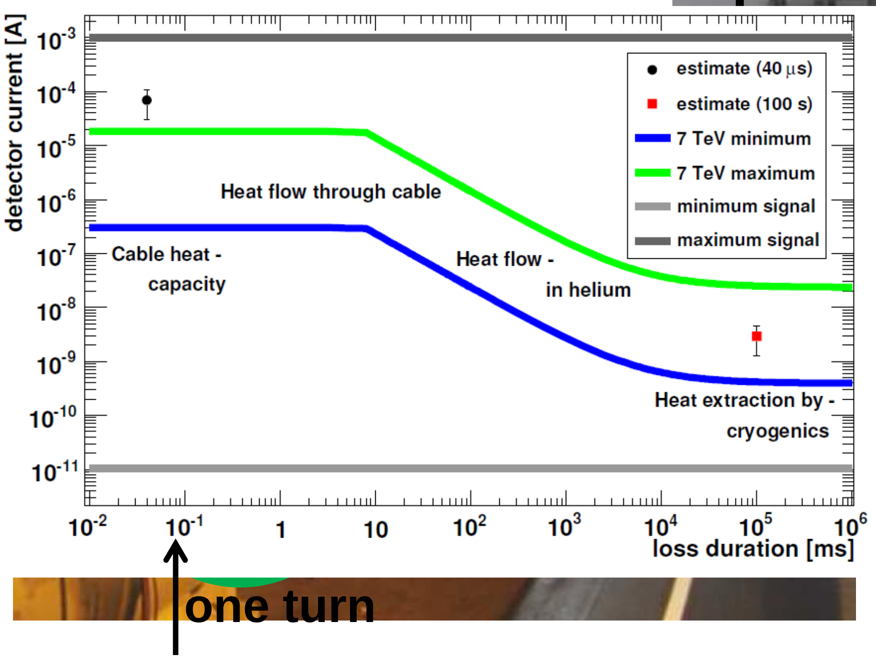
⇒ **Quench limit estimation**

CERN type

size	50 cm, ∅ 9 cm
gas	N_2 at 1.1 bar
# of electrodes	61
voltage	1500 V
reaction time	0.3 μs
# at the synchr.	≈ 4000 at LHC
aver. distance	1 BLM each ≈ 6 m

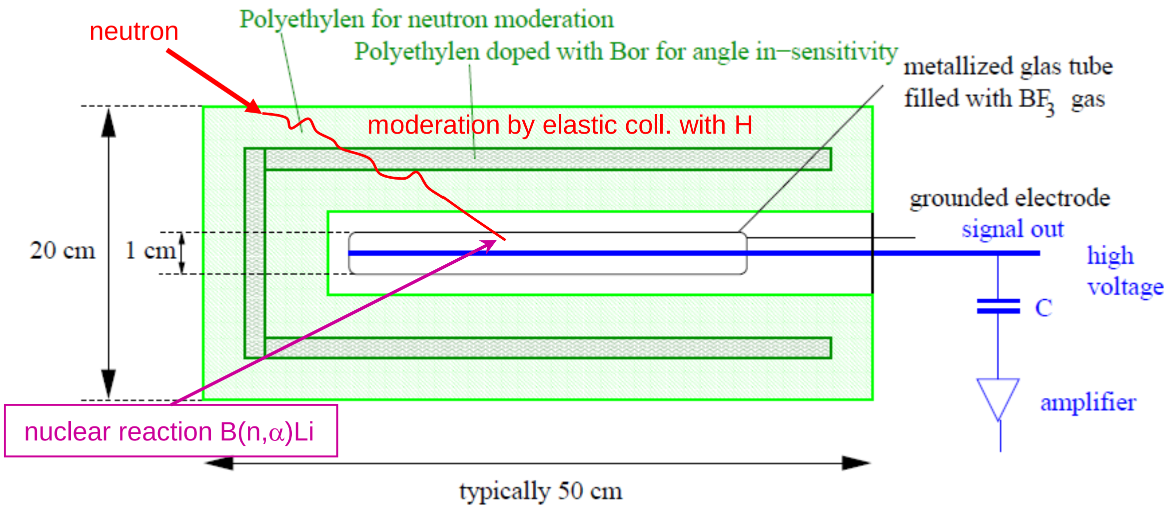


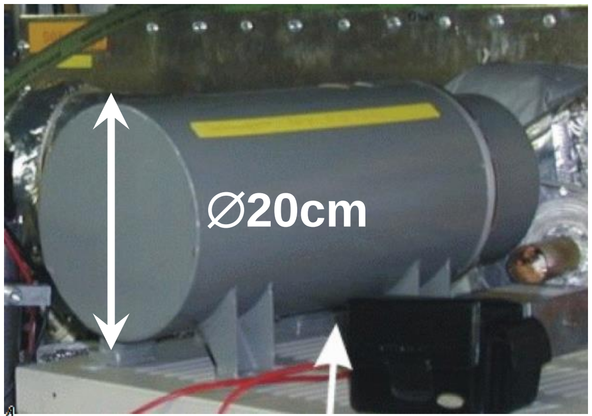


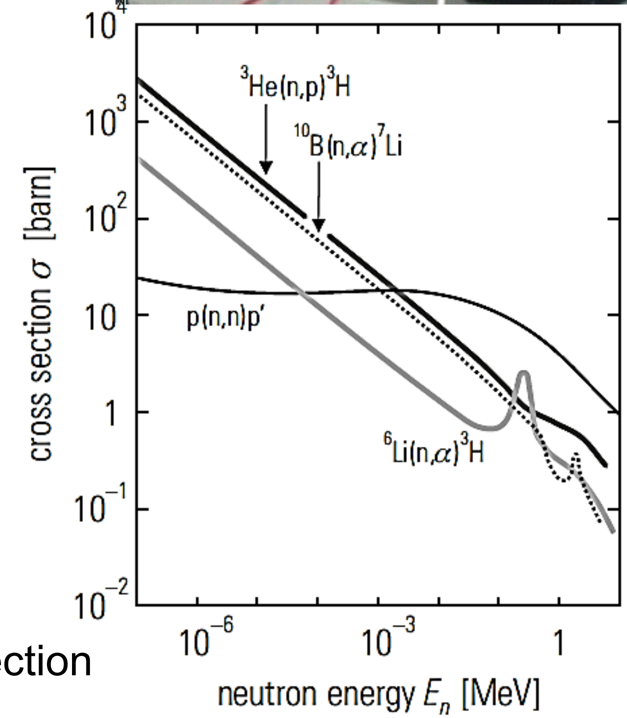


M. Stockner: PhD-Thesis, Tech. Uni. Vienna
A. North et al., HB 2010

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:

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

3. Electronic stopping of ^{7}Li and α 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

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

  $\Rightarrow$ Often used at proton accelerators

- **Scintillator, Cherenkov detector:**

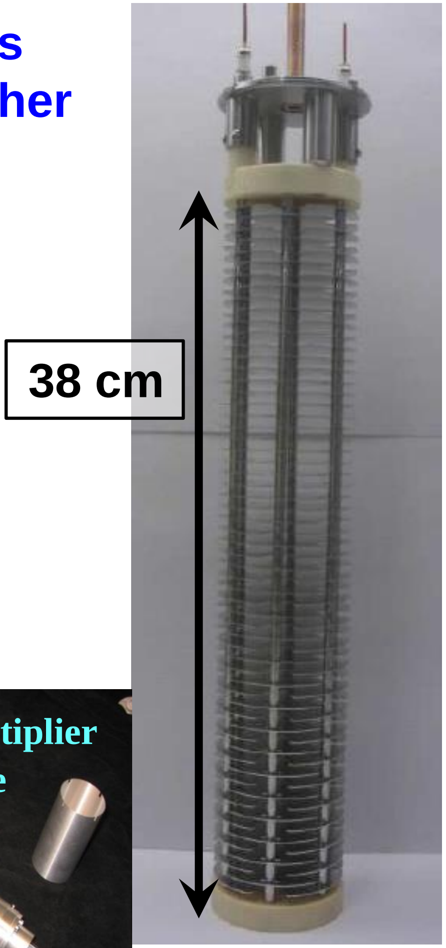
  Advantage:

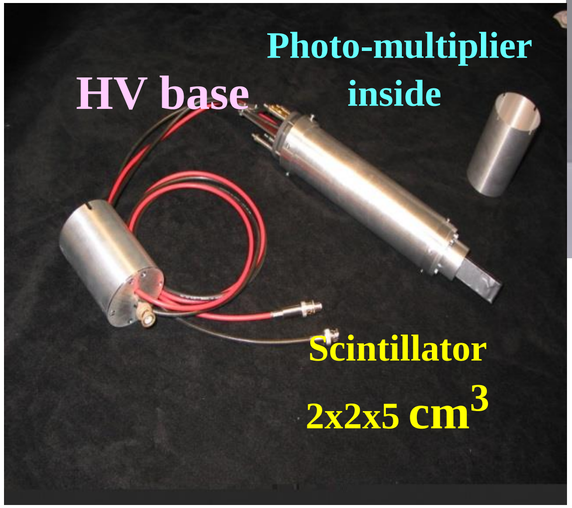
  - Fast current reading or particle counting
  - Can be fabricated in any shape, cheap

  Disadvantage:

  - Need calibration in many cases
  - Might suffer from radiation

  $\Rightarrow$ Often used at electron accelerators





Outline

Outline of this talk:

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

Relevant Losses for Machine Protection

Types of losses:

1. *Irregular losses* or fast losses by malfunction → avoidable losses

- Occurs only seldom i.e. have low probability
- The whole beam or a significant fraction is lost
- Usually within a short period of the operational cycle (e.g. injection, acceleration, extraction, ...)
  ⇒ Requirement for detector system: large dynamic range
- Usually caused by
  - Hardware failures, inaccurate settings or control errors (magnets, cavities ...)
  - Beam instabilities (wake-fields, resonances, ...)
  - Manually initialized improper beam alignment

⇒ Beam abortion required to prevent for destruction via **interlock generation**

2. Regular losses or slow losses → **un**avoidable losses, ***discussed above***

- Caused by lifetime inside synchrotron (residual gas, Touschek ...),
- Caused by aperture limitation, beam manipulations .....
- Usually a few % of the beam intensity

Remark:

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

Machine protection: Appropriate BLMs, device specific loss threshold → might be more complex

General Layout of a Machine Protection System: Design

Design criteria for a Machine Protection System:

1. Beam based: *Choice of BLM detector type*

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

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

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

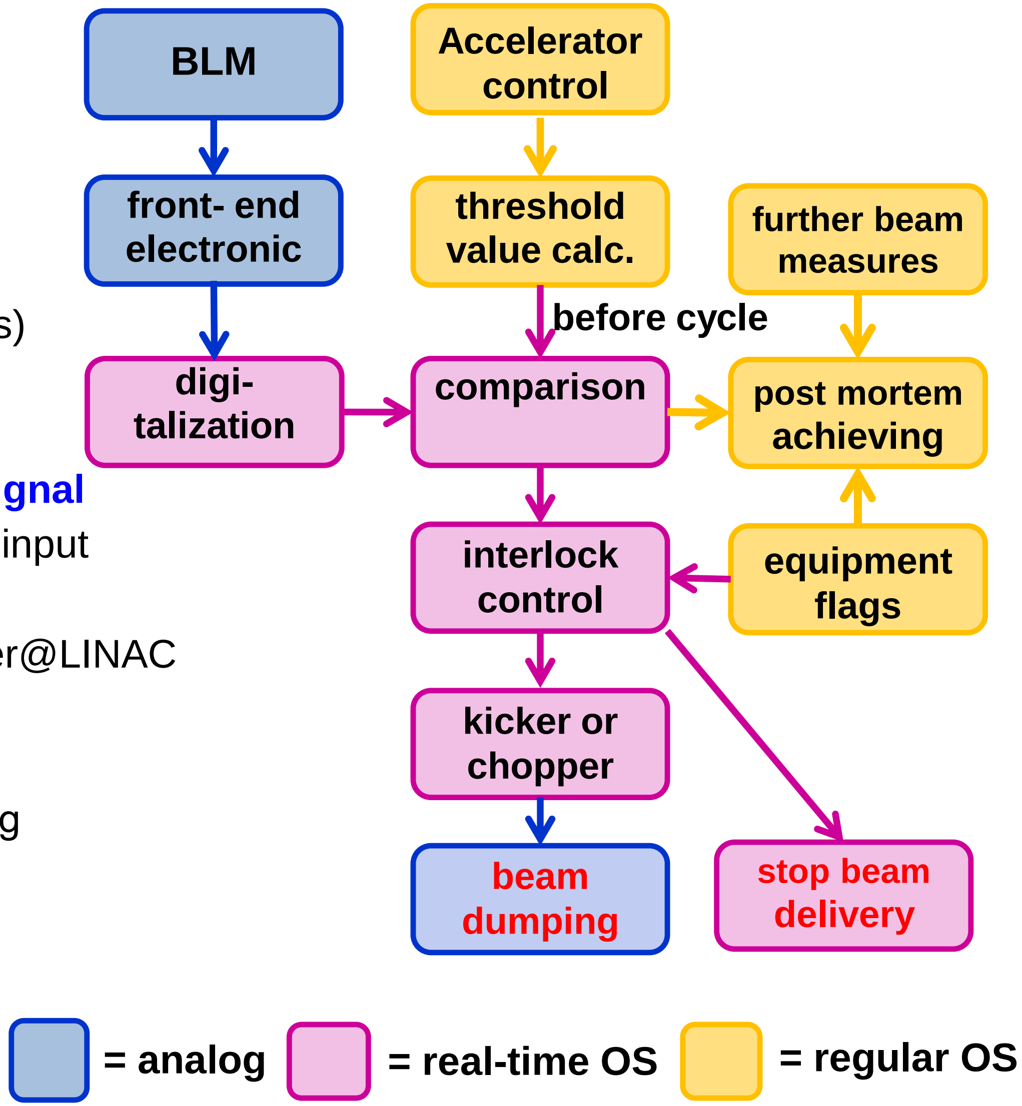
2. Equipment based: Functionality of any relevant device must be guarantied

- Magnet power supplier
- rf-generators, cavity properties
- Super-conducting state of magnet or cavity
- Vacuum conditions
- Relevant diagnostics instruments
- Control system watchdog
- ...

Remark: In exceptional cases an interlock-source can be masked to allow for acc. operation

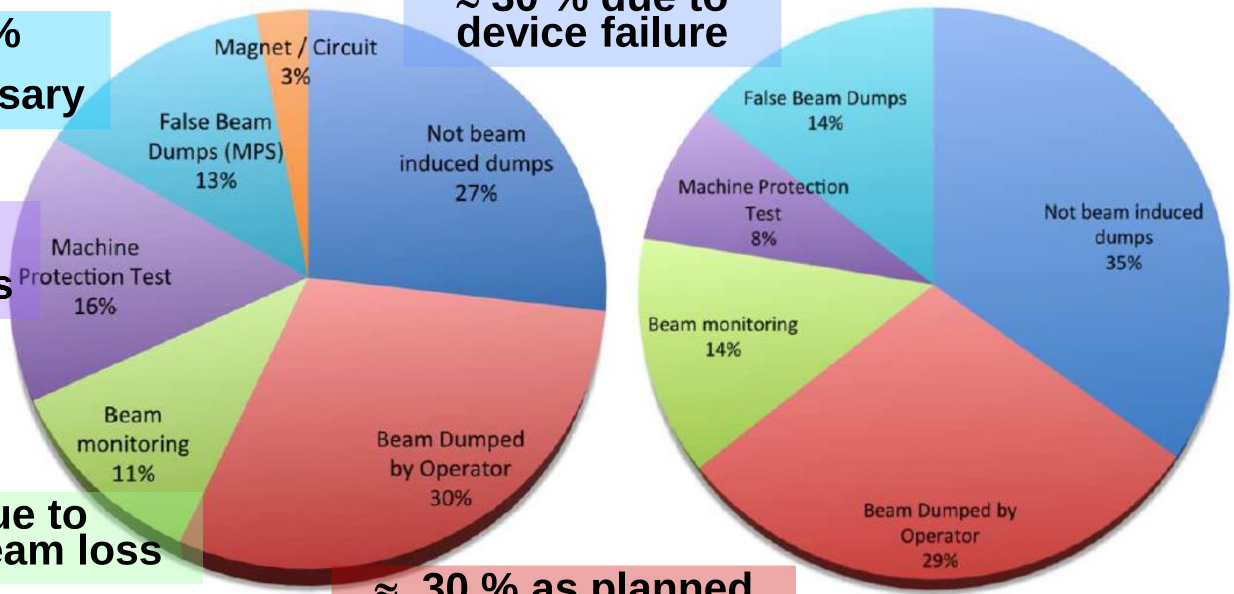
Design of a protection system:

- **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



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

Beam dump LHC year 2015 **Beam dump LHC year 2012**



≈ 15 % unnecessary

≈ 30 % due to device failure

≈ 15 % by MPS tests

≈ 15 % due to increasing beam loss

≈ 30 % as planned after ≈ 10 h

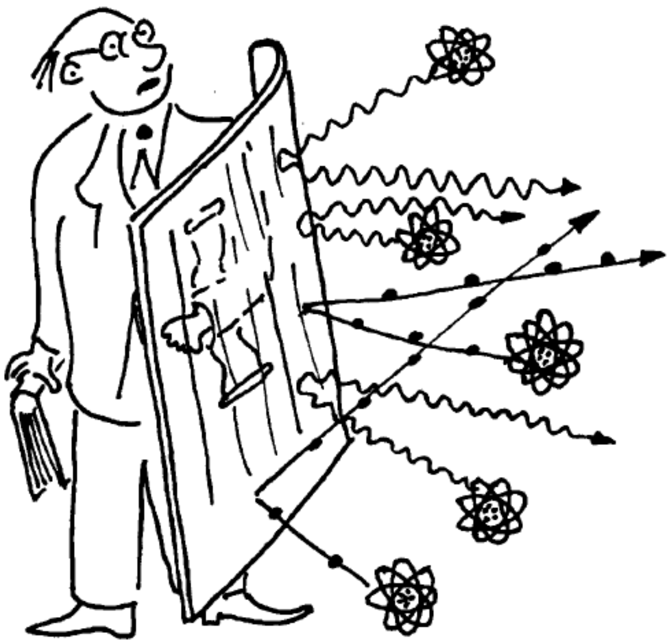
Sum: 442 dumps **Sum:536 dumps**

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

⇒ conclusion

Outline of this talk:

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



"Radiation Protection"

© by Claus Grupen

Cartoons from C. Grupen
Introduction to Radiation Protection,
Springer Verlag 2010

Radiological Quantities and Units

Basic quantities & units for personal safety:

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

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

for each radiation type ***R*** and each tissue ***T***

- **Equivalent Dose:** $H_T = \sum_R w_R D_{R,T} = [\mathrm{Sv}] = [100\mathrm{rem}]$

  with weight factor w_R for the radiation type ***R***

- **Effective Dose:** $E = \sum_T w_T H_T = [\mathrm{Sv}] = [100\mathrm{rem}]$

  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 10 keV < E < 100 keV 100 keV < E < 2 MeV 2 MeV < E < 20 MeV E > 20 MeV	5 10 20 10 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 - 0.01

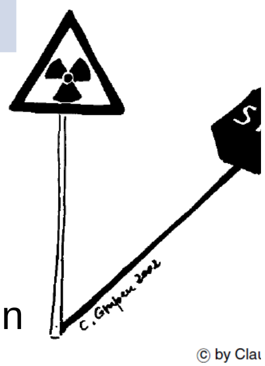
Shielding of accelerator by rough rule of thumb:

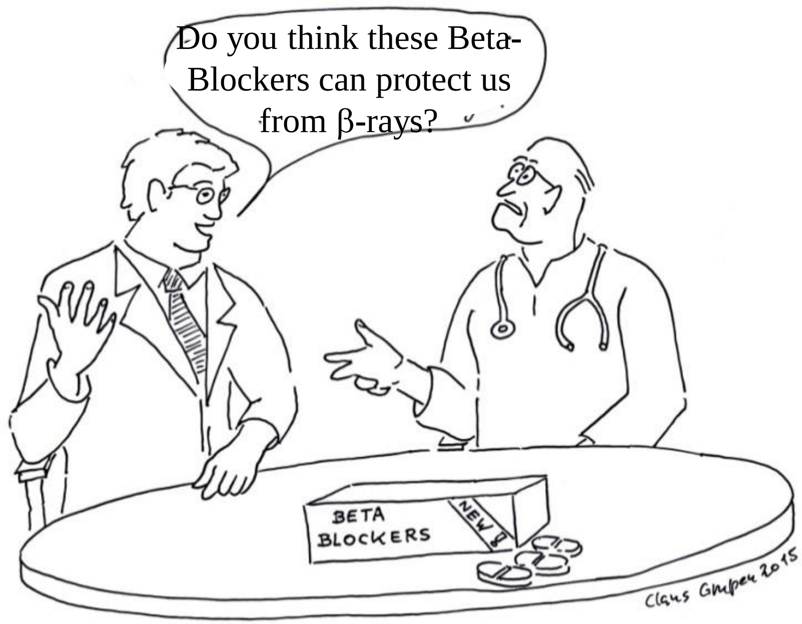
Estimation of shielding by 10th-value λ_{10}
with $H(l) = H_0 10^{-l/\lambda_{10}}$
(disregarding any secondary particle transport)

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

Further rough rule of thumb:

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

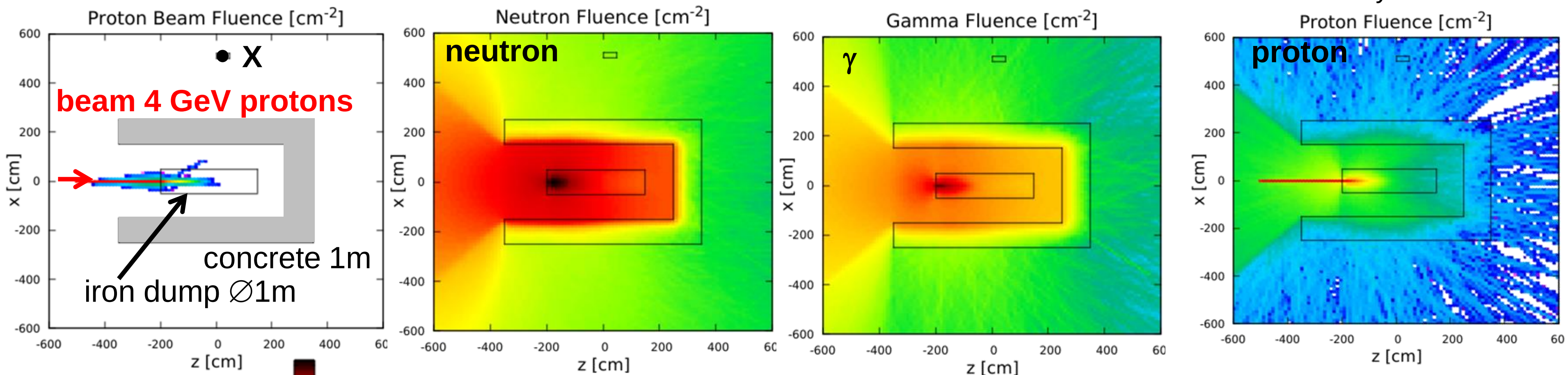




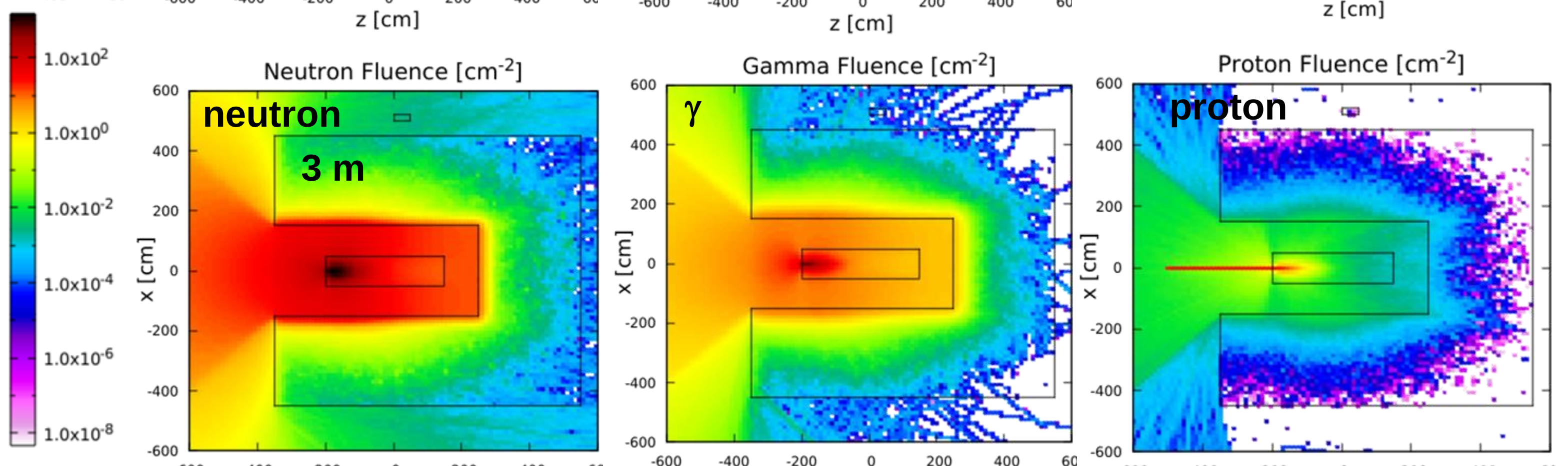
Simplified Model Shielding of Accelerators

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

Courtesy S. Udrea



Result:
Mainly neutrons and μ behind thick shield



Results:

- Primary protons are stopped in dump
- **Neutrons** produced, scattered at wall ≈ 10^{-3} atten. at X by distance & concrete
- 'Leakage' through opening

- γ are from beam & neutrons in the wall ≈ 10^{-3} attenuation at X
- **Protons** produced from neutrons, but partly stopped in the wall

- **Neutrons** at X ≈ 0.3% of 1m.
- Equal 'leakage' of n, γ & p
- γ well shielded
- **Protons** stopped in wall

Realistic Example for Shielding of Accelerators

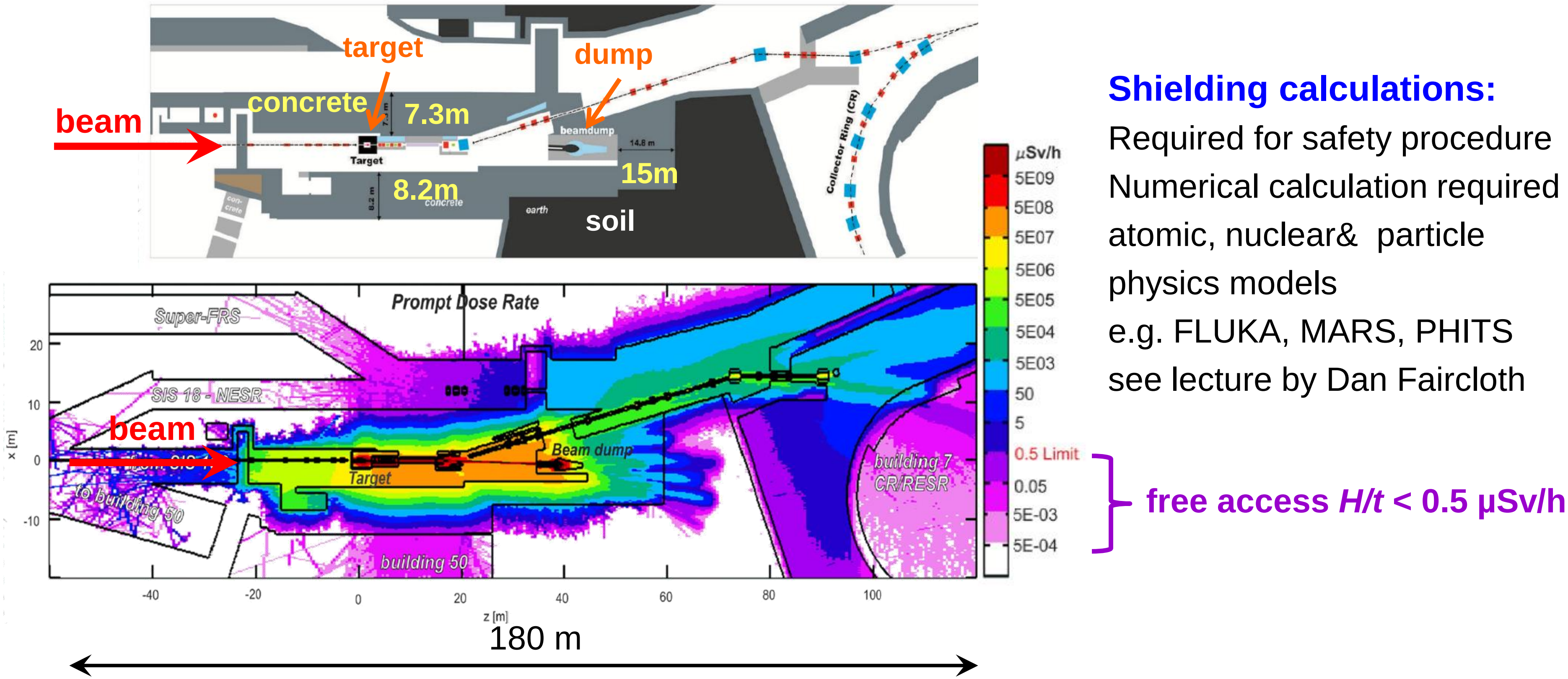
Example shielding of accelerator: Proton beam of 29 GeV for anti-proton production

Assumtion $2.5 \cdot 10^{13}$ 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

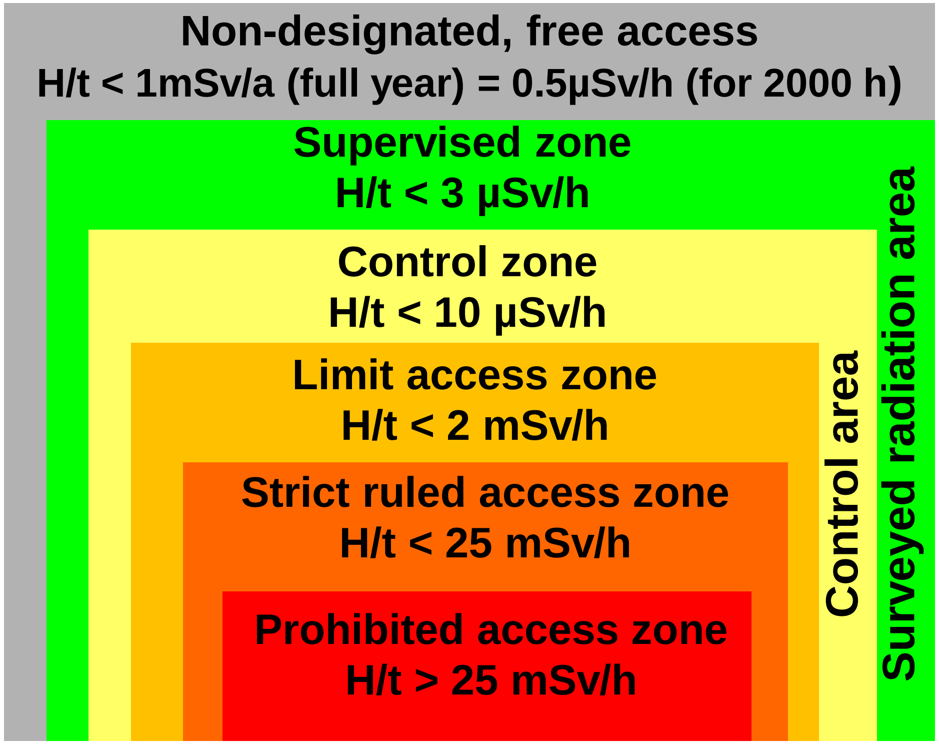
see lecture 'Secondary Beams and Targets' by K. Knie

K.. Knie et al., IPAC 2012

Categories of Locations & maximal Doses

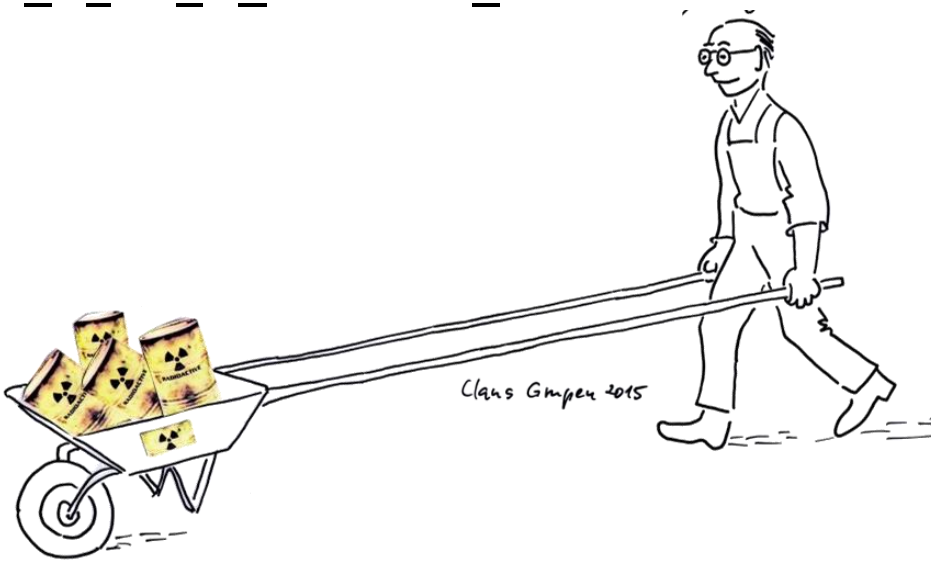
Simplified categories of radiation areas:

For workers: Assumption 2000 h/a of access



ALARA principle:

As **L**ow **A**s **R**easonable **A**chievable



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 < 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

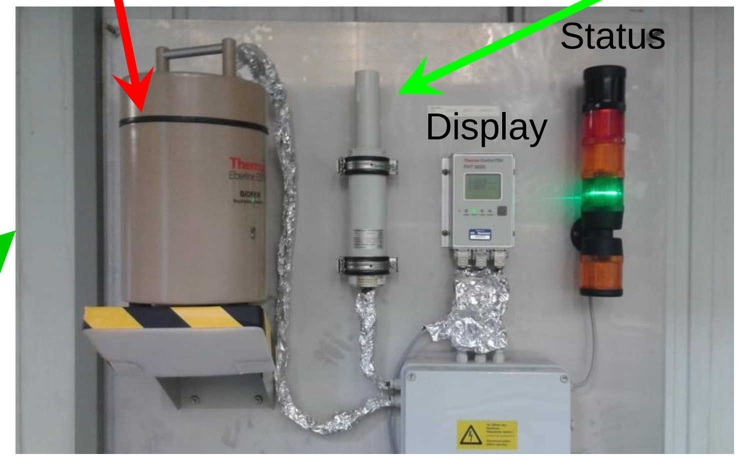
Prohibited access zone
H/t > 25 mSv/h

Control area

Surveyed radiation area

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

Proportional tube for γ:
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

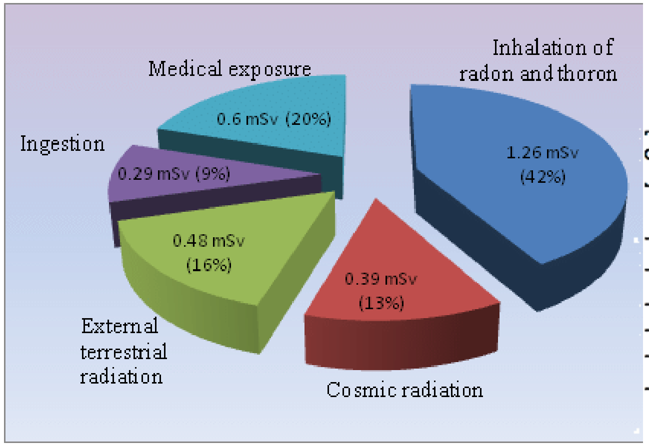
Natural Radiation Exposure

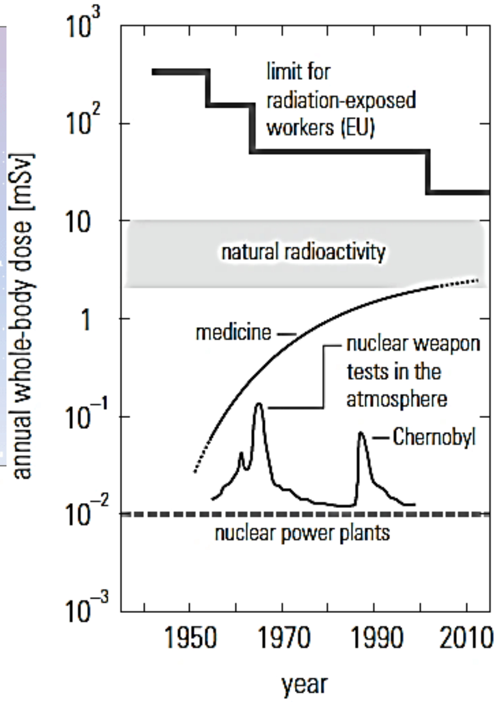
Example of radiation level:

- **Natural geological dose:**

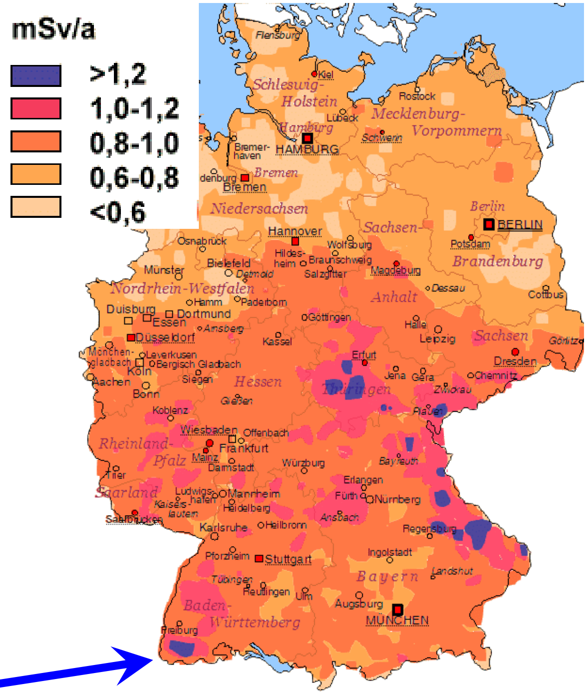
In some parts the dose can be up to some 10 mSv/a **without** significant increase of diseases

- **Typical dose composition:**





Natural dose in Germany:

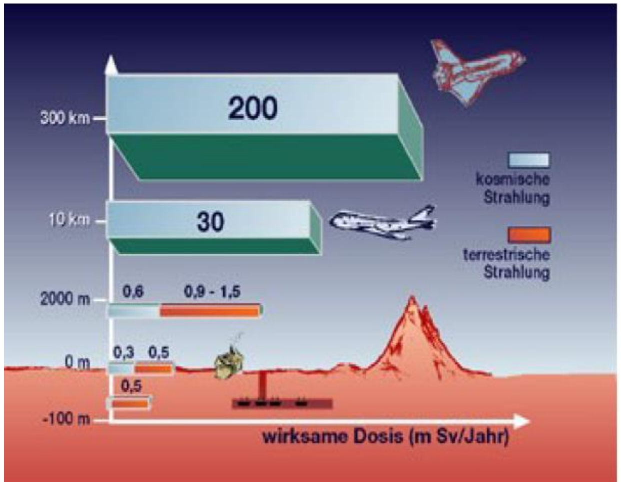


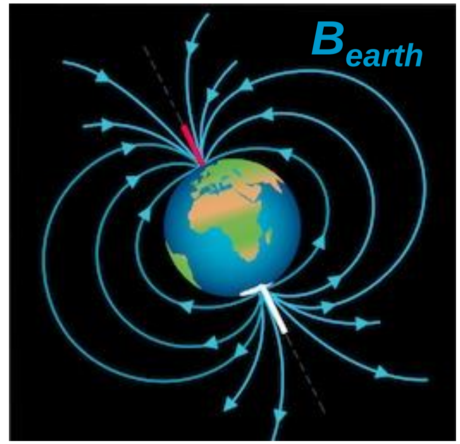
Source: German Bundesamt für Strahlenschutz
C. Grupen, Introduction to Radiation Protection

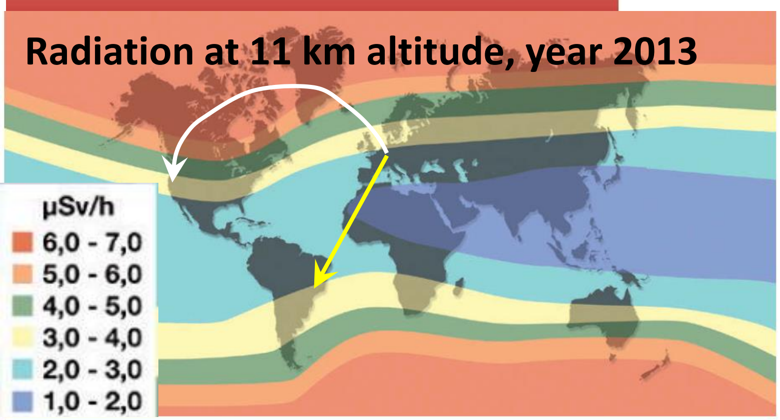
⇒ conclusion

Avoidable, but wildly accepted Radiation Exposure

Cosmic ray based radiation effects depend on altitude and latitude

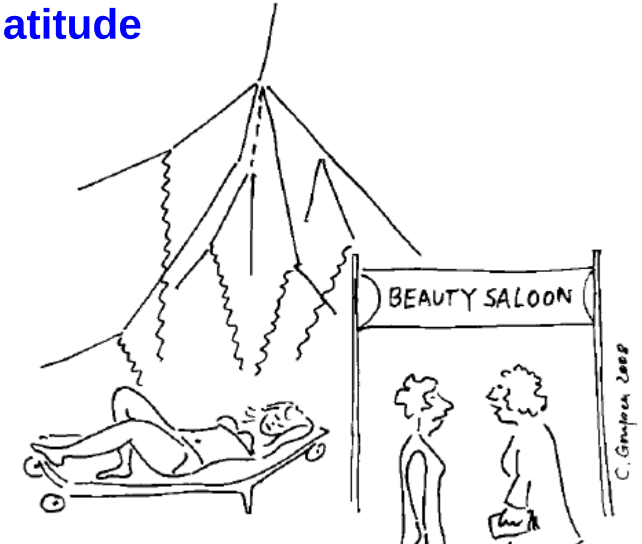






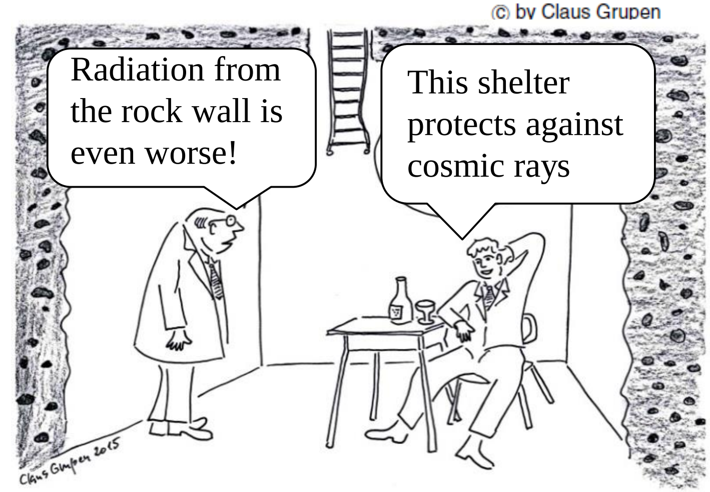
Zonen mit unterschiedlicher Höhenstrahlung [11 km Höhe, Ende 2013, Mikrosievert pro Stunde]

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



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

© by Claus Grupen



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

Passive Film Badge Dosimeter and TLD

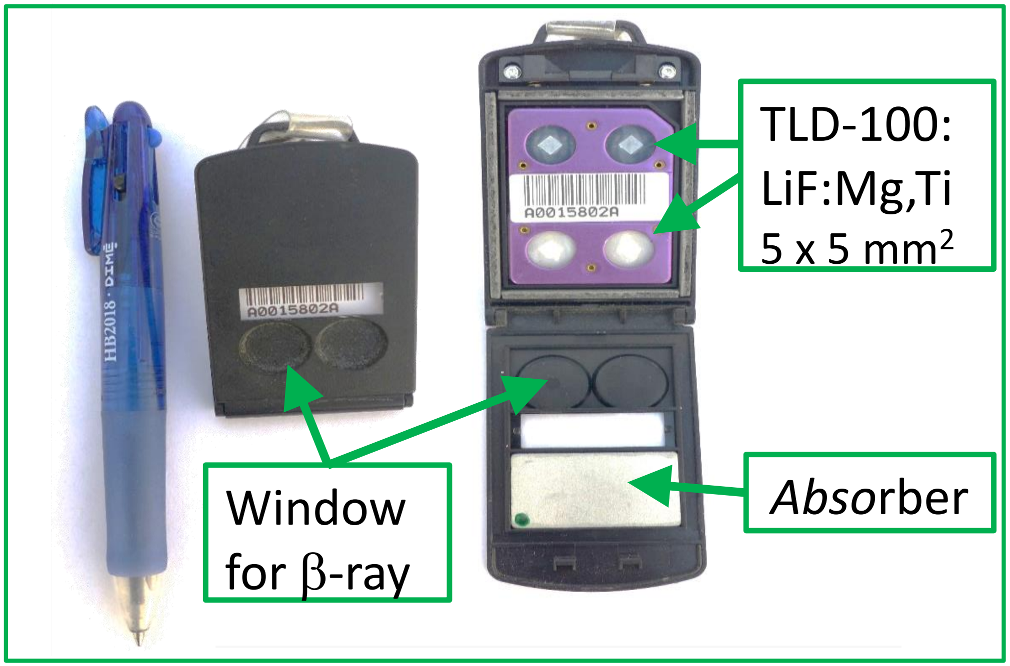
For personal safety a dosimeter should be worn!

Thermo-luminescence dosimeter TLD:

Crystal e.g. LiF is excited by radiation and emit light when heated

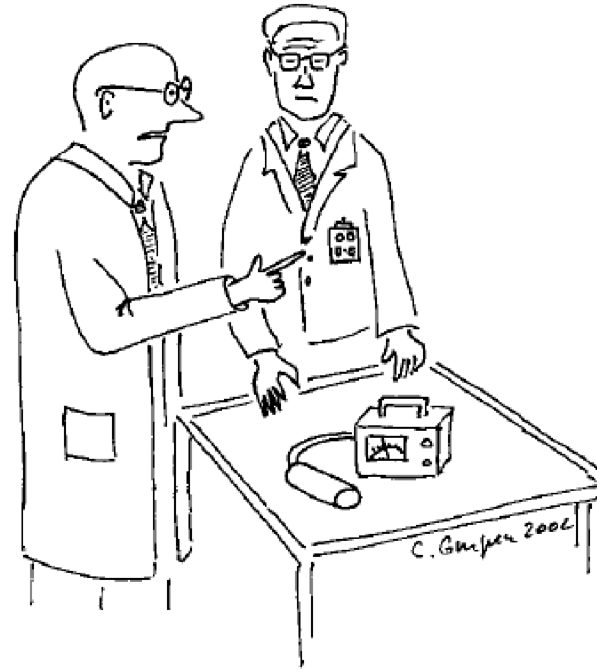
neutron sensitive via ${}^{6}Li(n,\alpha)T$

Sensitivity for β & γ: 0.1 mSv to 10 Sv



Advantage: Can be archived

Disadvantage: Limited sensitivity, **no** online display



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

© by Claus Grupen

Film badge: X-ray sensitive films

photons (typ. 5keV... 9MeV) &

$\beta^{\pm}$ (typ. > 0.3MeV)

Sensitivity for β & γ: 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

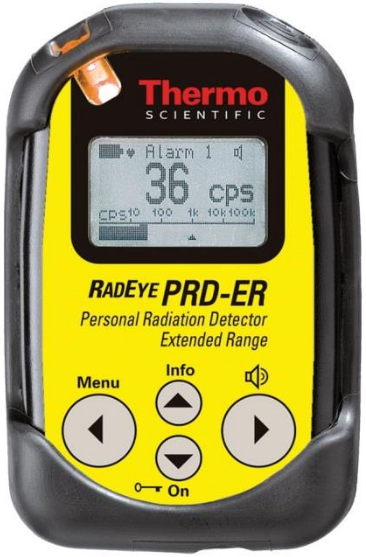
(TLD sensitivity: 100 µSv to 5 Sv, flight above pole: 45...110 µSv)

'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 <u>overheating</u> ('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 <u>activation</u> ('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!

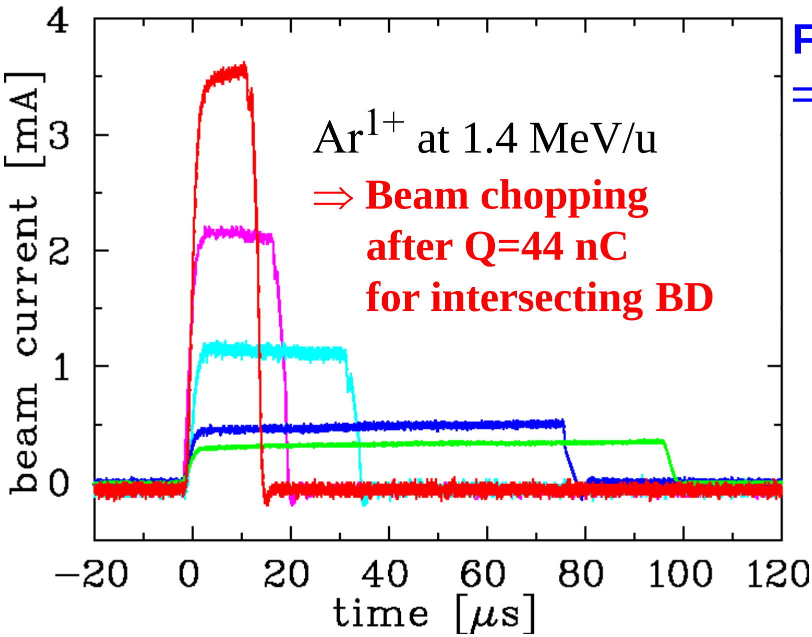
In my own purpose: We are looking for a PhD student for the topic of slow extraction.

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

Dynamic Machine Protection by Transmission Measurement



For E > 50 MeV protons: nuclear σ_{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.

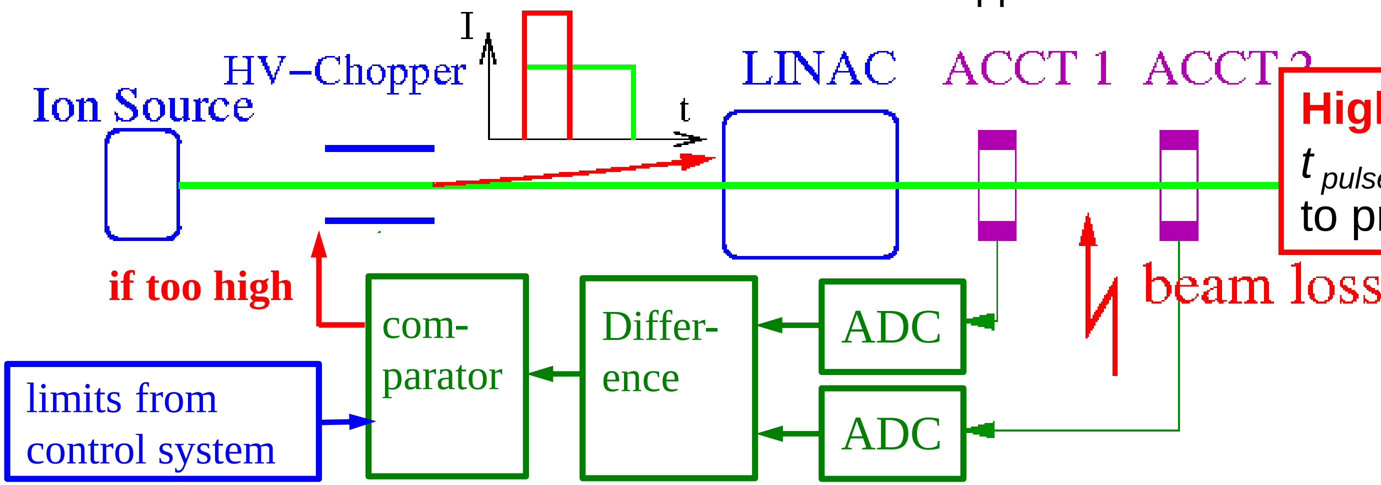
FPGA-electronics:

→ 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

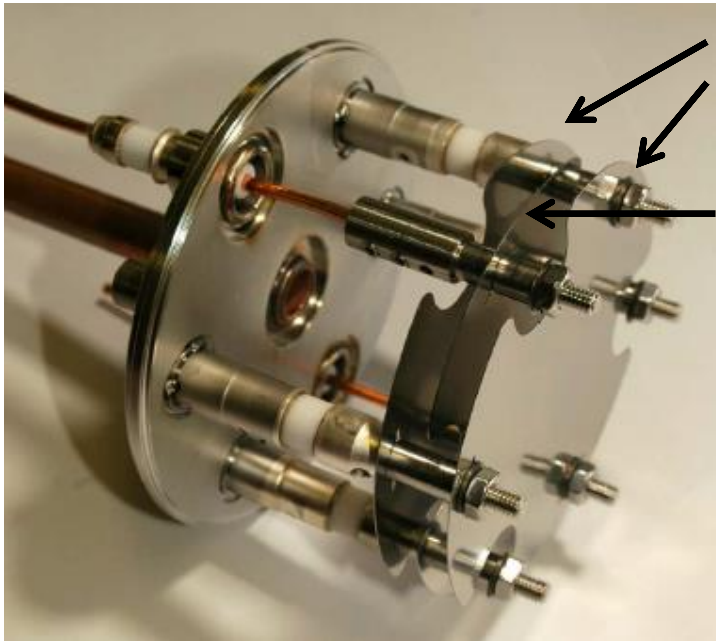
Secondary Electron Monitor as BLM

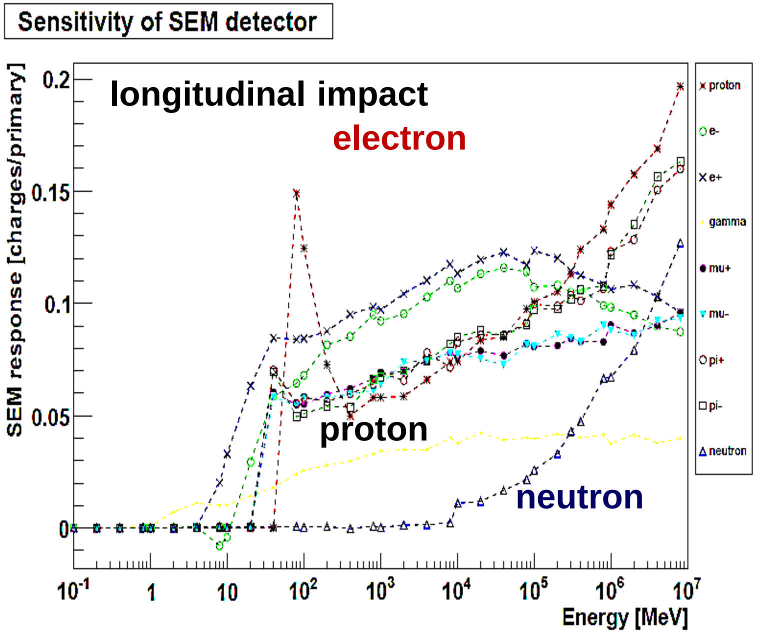
Ionizing radiation liberates secondary electrons from a surface.

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.**





B. Dehning et al., PAC 2007

Neutron Energy Spectrum

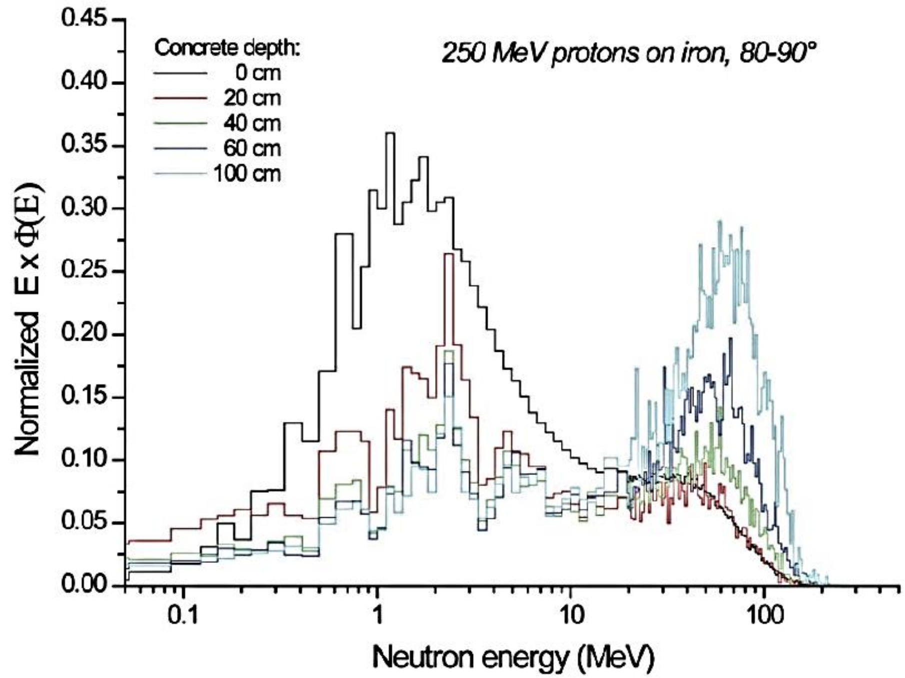


Fig. 6: Neutron energy distributions $E\Phi(E)$ in the transverse direction generated by 250 MeV protons impinging on an iron target thicker than the proton range. The distributions are for source neutrons and behind concrete shields of thicknesses ranging from 20 cm to 1 m. The distributions have been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

60

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

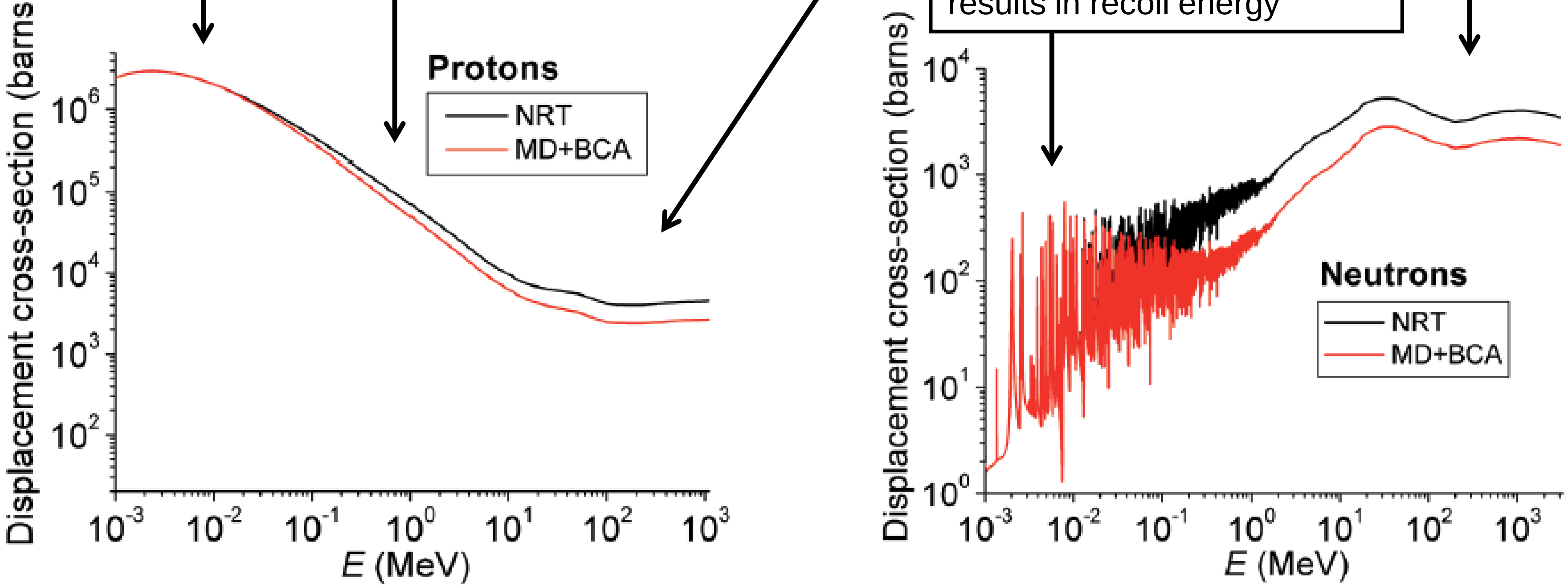


Fig. 12: Displacement cross-sections of protons (left) and neutrons (right) in copper obtained by two different approaches (see legend).

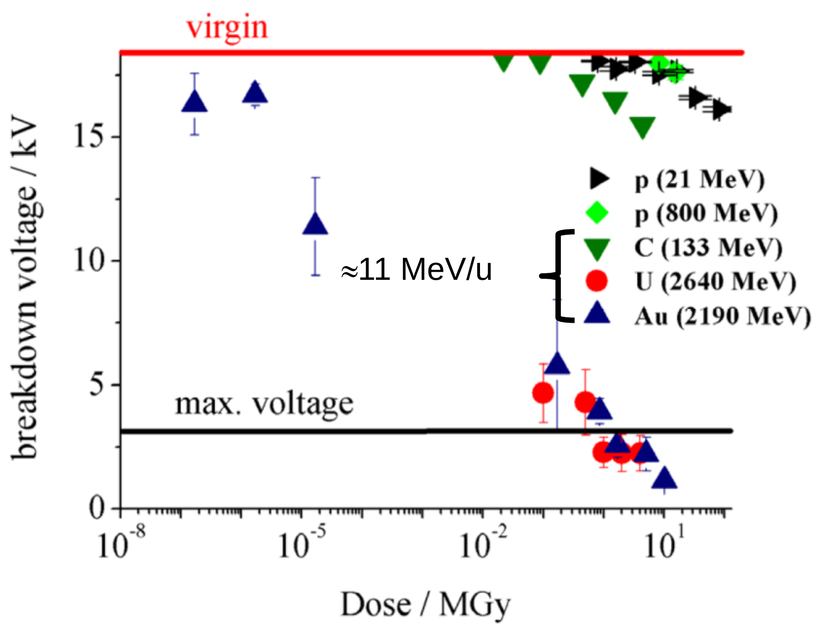
D. Kiselev, CAS 2011, CERN-2013-001

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

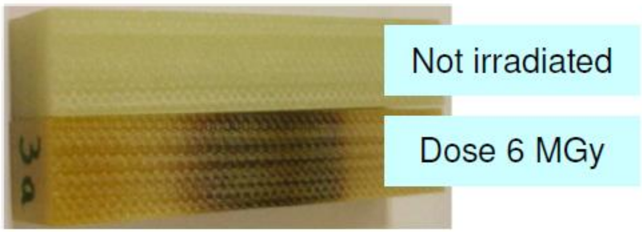
Example: Kapton foil of 125 µm thickness
Direct irradiation by ion beam's
energy loss dE/dx increases for heavy ions



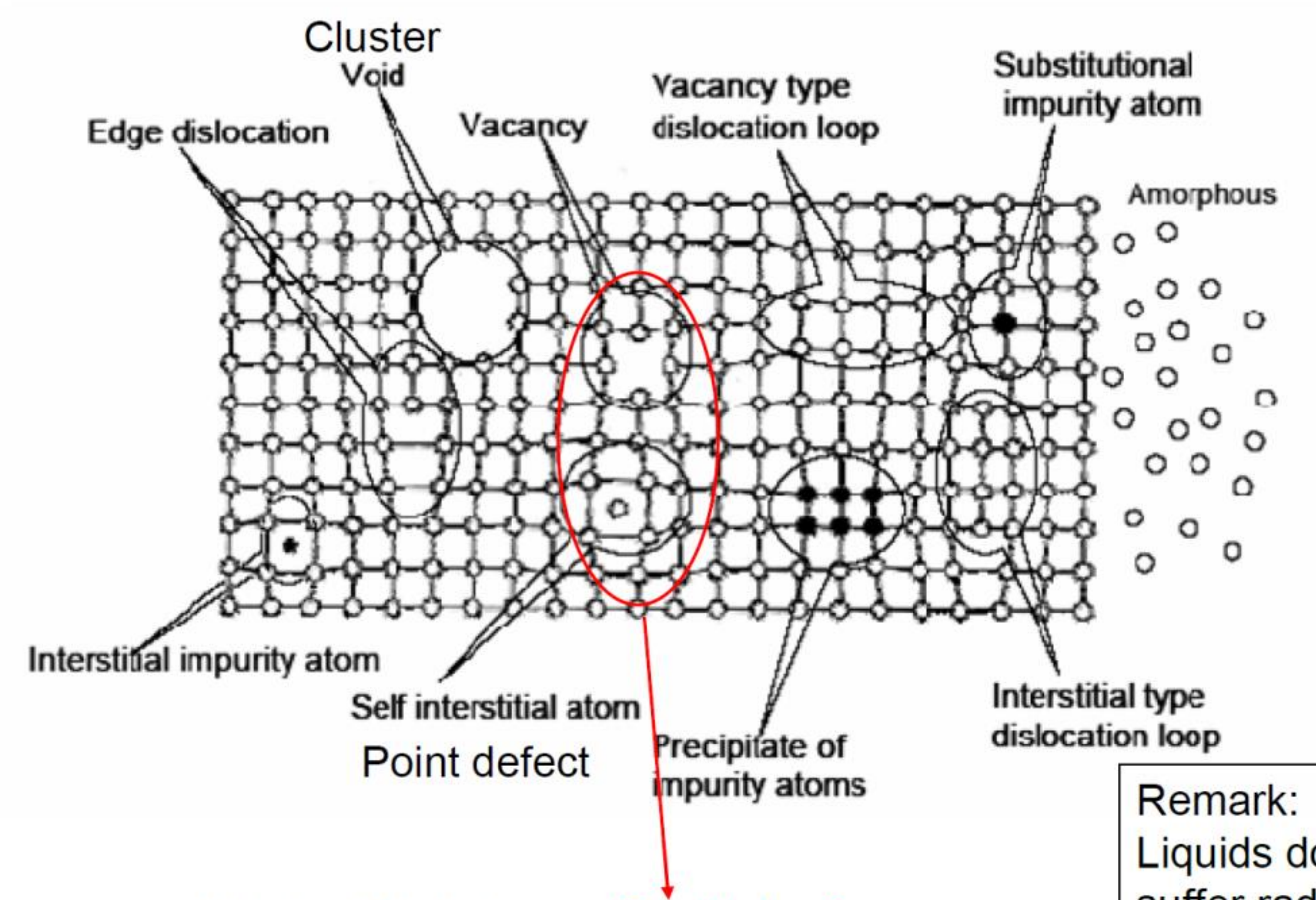
T. Seidl et al, HB 2010

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



Microscopic Damage of structural Materials



vacancy + self-interstitial atom = Frenkel pair.

Remark:
Liquids do not suffer radiation damage

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

Energy Loss and Heating: Experiment

Verification of material interaction by 440 GeV protons:

Destruction of material due to temperature rise

- ➢ melting, sublimation plasma formation
- ➢ mechanical stress

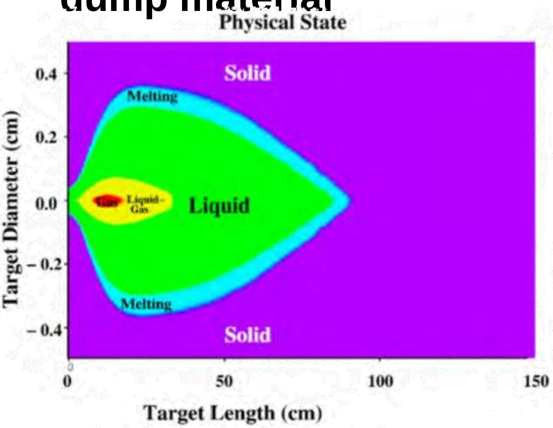
⇒ verification of simulation

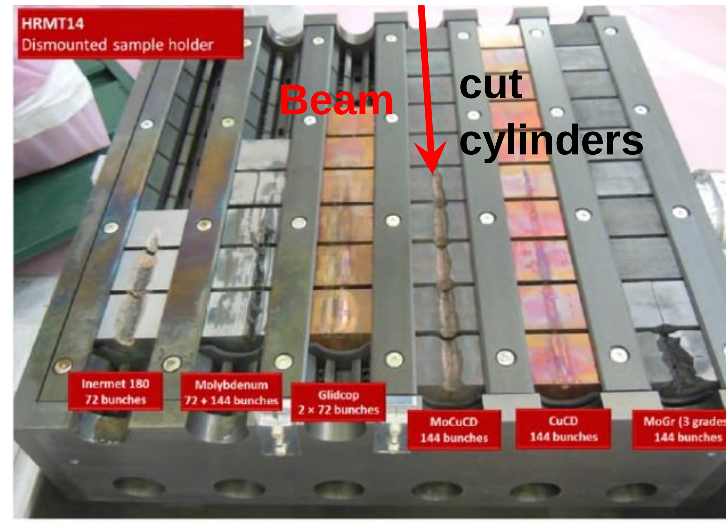
⇒ **finding proper dump material**

Beam: 440 GeV $\approx 10^{13}$ protons,

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

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

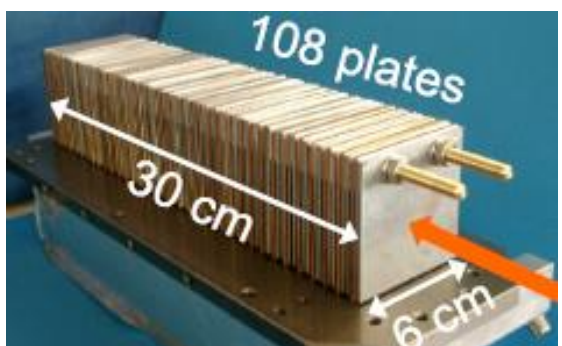


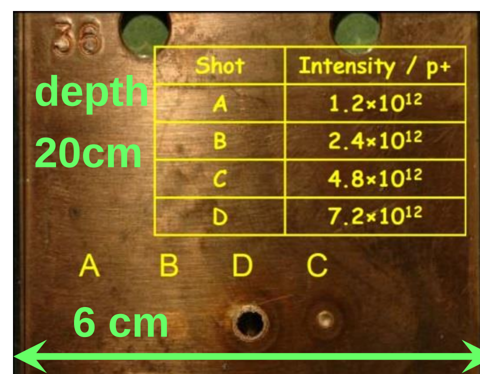


A. Bertarelli, JAS CERN-2016-002.

Experiment with 450 GeV protons:

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





PIN-Diode (Solid State Detector) as BLM

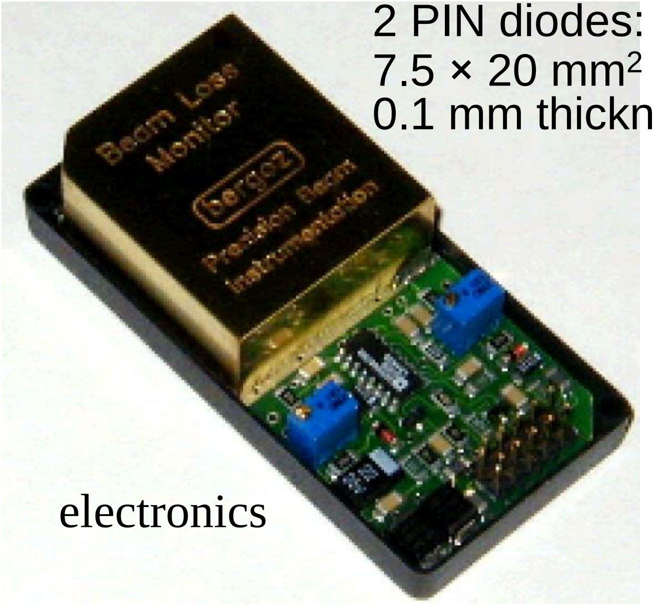
Solid-state detector: Detection of charged particles.

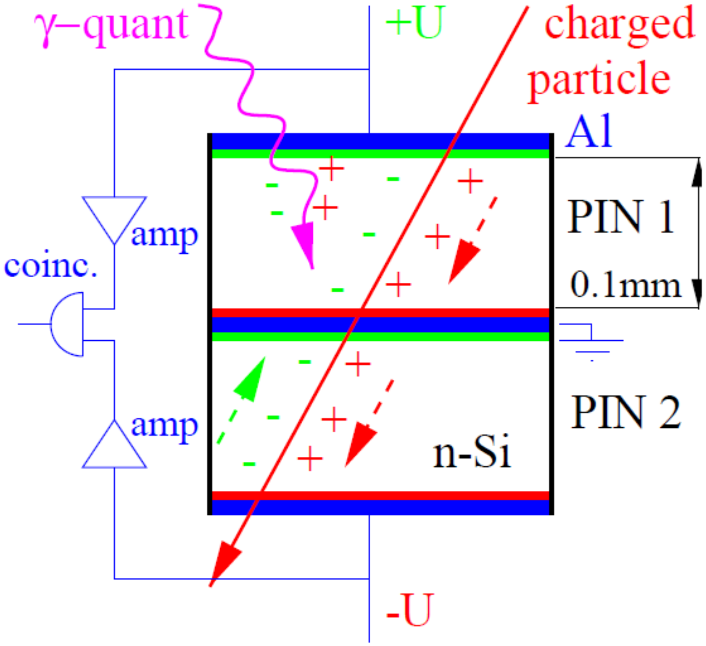
Working principle

- 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 mm²
0.1 mm thickness.





Collimation at LINACs

Halo development caused by

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

Goal: Halo cutting at low energy to prevent for activation

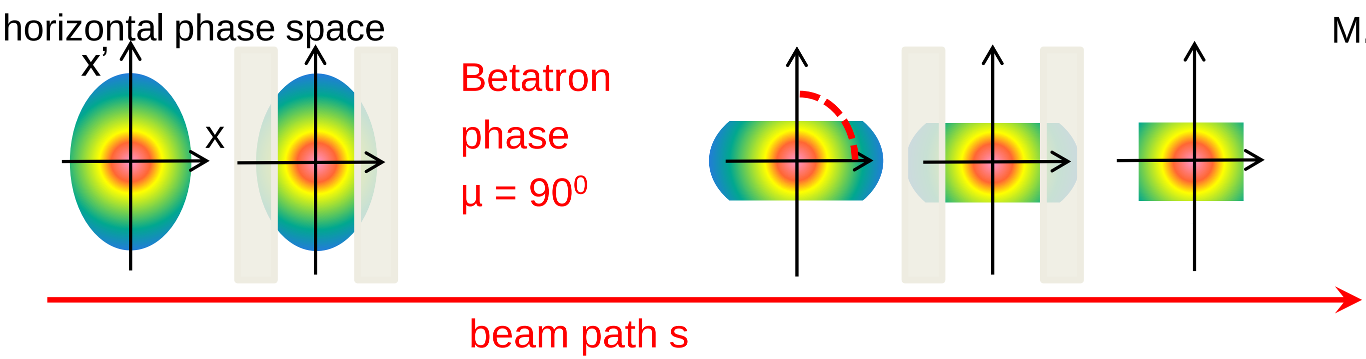
Collimators:

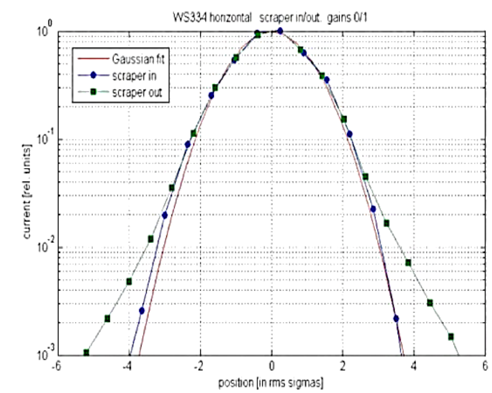
Cut the beam tail in space

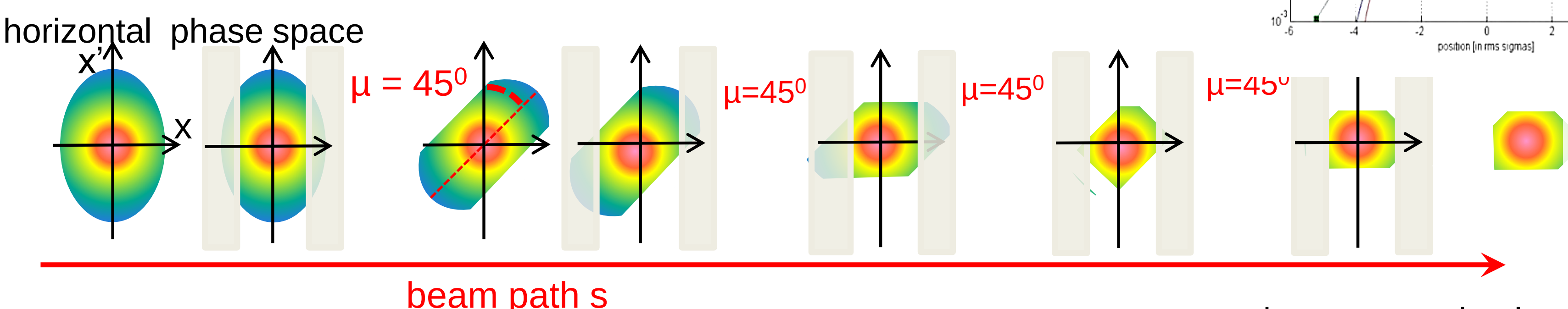
$\mu = 90^0$ or $\mu = 45^0$ betatron phase to cut angle

$\Rightarrow$ at least two locations required

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







i.e. not completely cut...