Machine Protection

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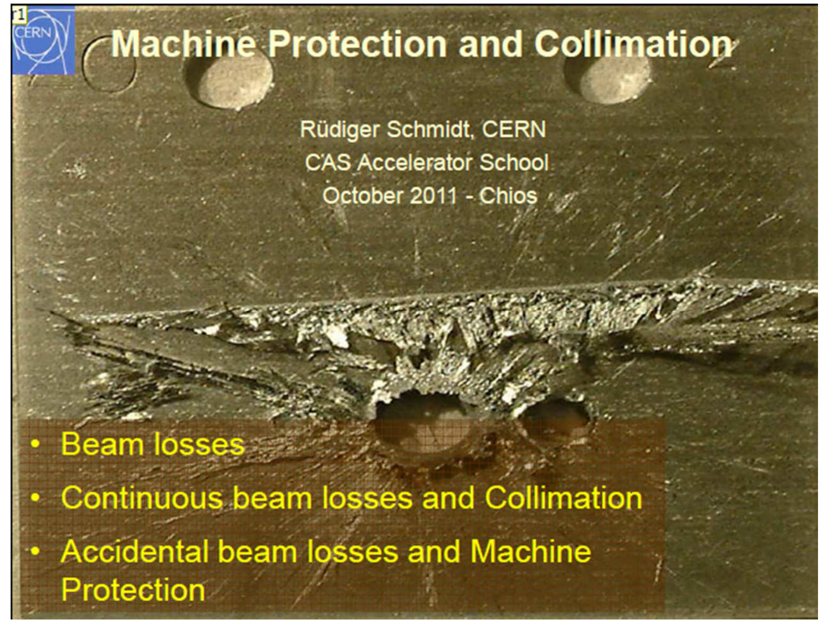
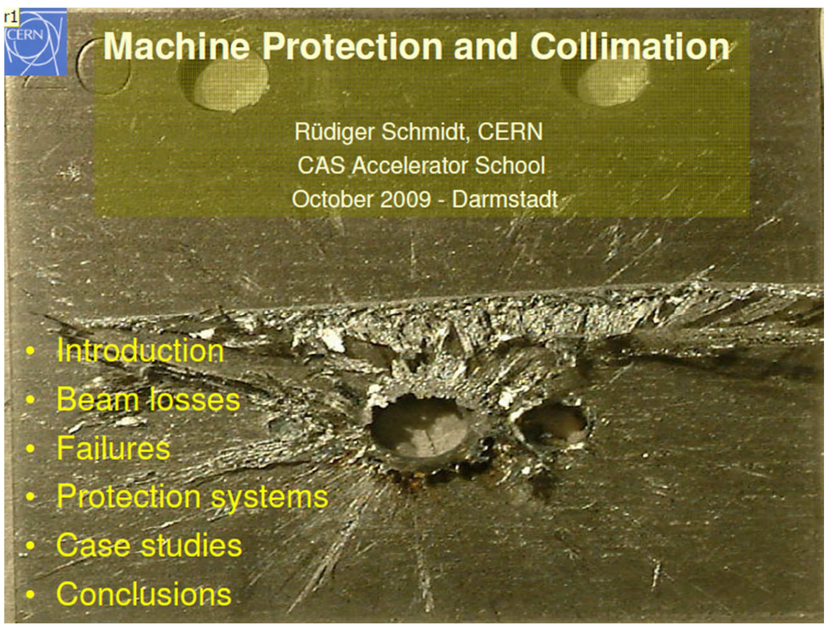
CERN Accelerator School: Introduction to Accelerator Physics

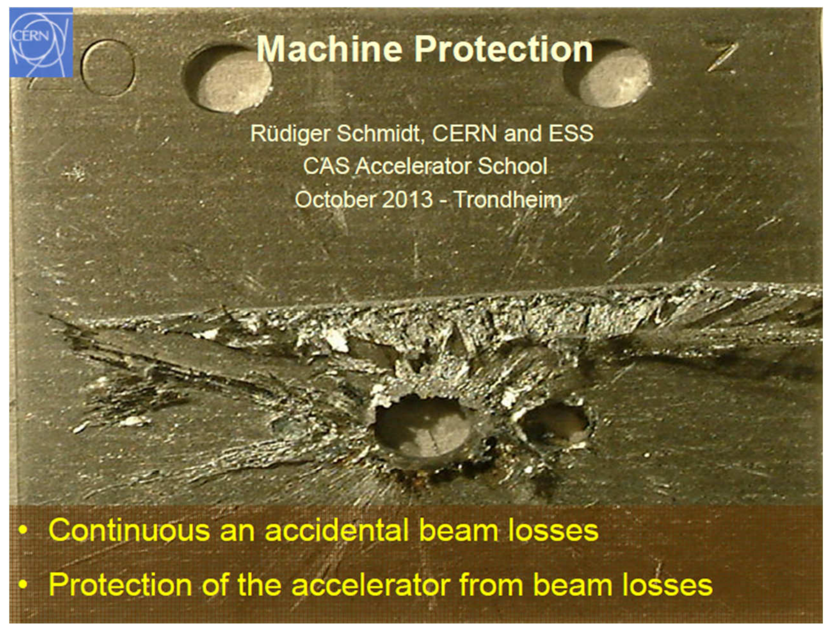
Prague, Czech Republic, 2014

Acknowledgment

This lecture is based on previous CAS lectures on Machine protection & Collimation by Rüdiger Schmidt (head of the machine protection at CERN)







Overview

The lecture is focused on protection of accelerators from consequences of beam losses

- Introduction
- Beam losses and consequences
- Regular beam losses
- Collimation system
- Accidental beam losses
- Beam loss detection
- Emergency extraction and dumping system
- Summary

JAS course on Beam Loss and Accelerator Protection

Joint International Accelerator School on Beam Loss and Accelerator Protection

November 5-14, 2014

Time	Wednesday Nov. 5	Thursday Nov. 6	Friday Nov. 7	Saturday Nov. 8	Sunday Nov. 9	Monday Nov. 10	Tuesday Nov. 11	Wednesday Nov. 12	Thursday Nov. 13	Friday Nov. 14
8:30 10:00	ARRIVAL DAY	Introduction to Accelerator Protection Course Rudiger Schmidt	Beam Material Interaction, Heating & Activation Nikolai Mokhov (2 hrs)	Beam Transfer and Machine Protection Verena Kain	FREE DAY	Detection of Equipment Failures Before Beam Loss John Galambos	Machine Protection and Interlock Systems - Circular Machines Jorg Wenninger	Practical Design Principles for Protection Systems: LHC Rudiger Schmidt	Personnel Protection Systems Sayed Rokni	DEPARTURE DAY
		COFFEE				COFFEE				
10:30 12:00		Beam Dynamics and Beam Losses - Circular Machines Verena Kain	Beam Material Interaction, Heating & Activation Francesco Cerutti (1 hr)	Beam Induced Damage Mechanisms and Their Calculation (Part I) Alessandro Bertarelli		Controls and Machine Protection Enzo Carrone	Machine Protection and Interlock Systems - Linear Machines Marc Ross	Practical Design Principles for Protection Systems: Linear Colliders Marc Ross	Medical Facilities TBD	
		LUNCH				LUNCH				
13:30 15:00		Beam Dynamics and Beam Losses - Linear Machines Mike Plum	Intro to Risk Management of Complex Systems Nancy Leveson	Beam Induced Damage Mechanisms and Their Calculation (Part II) Alessandro Bertarelli		Beam Instrumentation for Machine Protection Tom Shea (2 hrs)	Protection of Hardware: Powering Systems (PC, NC and SC Magnets) Howard Pfeffer	Beam Cleaning and Collimation Systems Stefano Redaelli (2 hrs)	Present Case Studies	
		STUDY				STUDY				
17:00		High Intensity Synchrotron Radiation Effects Yusuke Suetsugu	Reliability and Availability Nancy Leveson	Protection Related to High Power Targets Mike Plum		Beam Loss Monitors at LHC Bernd Dehning (1 hr)	Protection of Hardware: RF Systems Sang Ho Kim	Advanced Collimators for Future Colliders Tom Markiewicz (1 hr)		
18:30	Dinner, Registration and Talk	DINNER				DINNER				
20:00 21:30		Case Studies				Case Studies			Final Exam	

Introduction

- Particle beams produced by large scale and powerful accelerators
  - High energy: GeV/u – TeV/u
    (*e.g. LHC: 7 TeV proton beam*)
  - High power: kW – MW
    (*e.g. PSI cyclotron: > 1.3 MW proton beam*)
  - High intensity: 10^{13} – 10^{14} particles per beam
    (*e.g. J-PARC Main Ring > 3×10^{14} particles in the proton beam*)
  - High beam density: small beam size
    (*e.g. LHC: transverse beam size < 1 mm*)
  - High beam stored energy: kJ – MJ
    (*e.g. LHC: > 360 MJ stored energy in proton beam*)
- The energy stored in the beam and power flow have to be under control
- Why? Beam or its part can be lost
- Beam losses are the particles which deviate excessively from the reference trajectory and hit the aperture constraints (are no longer properly transported)

Beam losses and consequences

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

- Consequences of the uncontrolled beam losses
  - Radiation damage of the accelerator components
  - Destruction or deformation of the accelerator components
  - Superconducting magnet quench
  - Residual activity induced in the accelerator structure

Why do we need protection for accelerators?

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

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

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

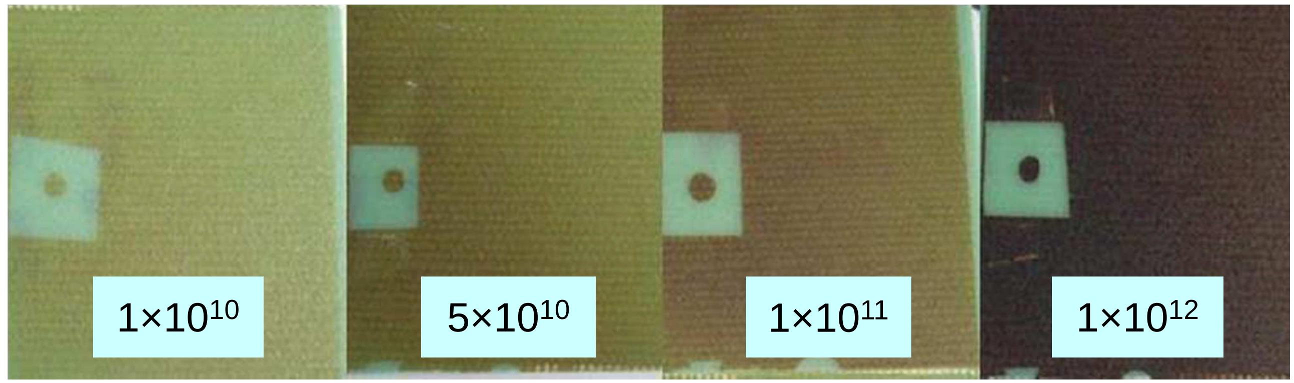
Let's take a closer look at the possible consequences of the beam losses to get better idea why do we need to protect the machine.

Radiation damage

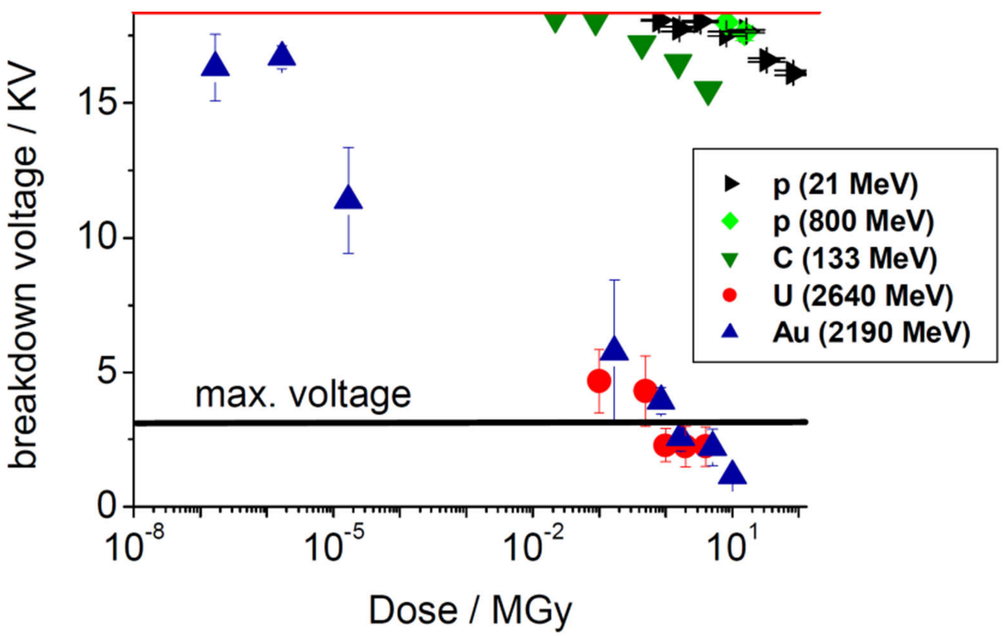
- Radiation damage – microscopic defects in the structure of a material induced by ionizing radiation, which change its properties (mechanical, thermal, electrical, …)

Insulation material (epoxy glass) irradiated by uranium ions

^{238}U ions/cm^2



[Ref] E. Mustafin et al., Radiat. Eff. Defects Solids 164, 460 (2009)



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

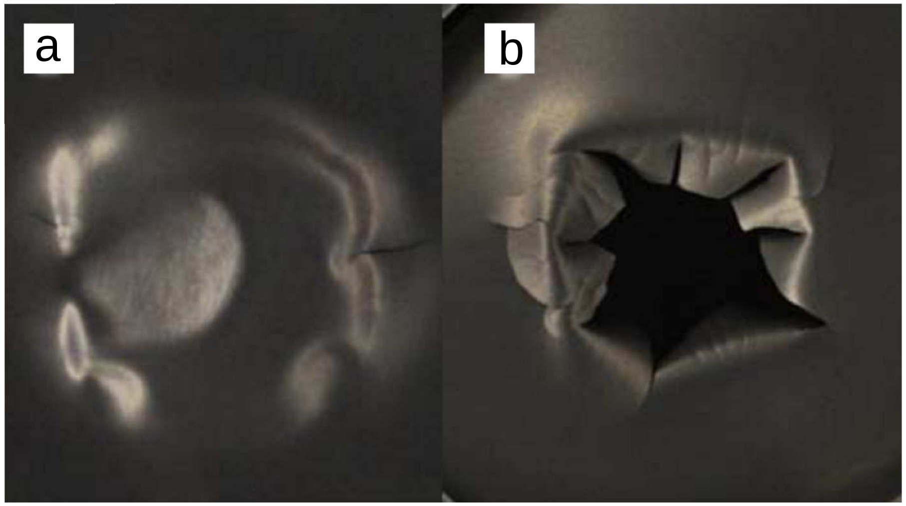
Note the difference between protons and heavy ions!

[Ref] T. Seidl et al., GSI Scientific Report (2008)

Destruction or deformation

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

Graphite foil



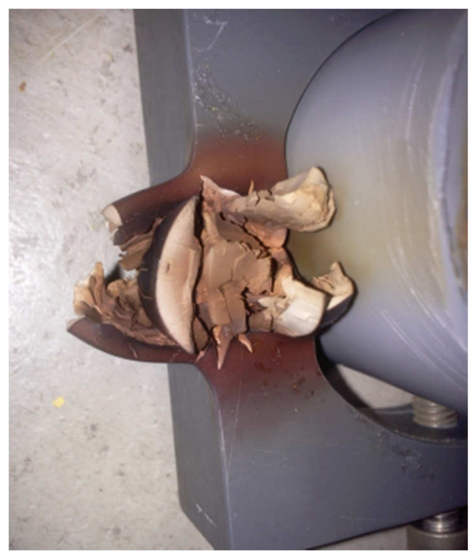
Irradiation by uranium beam (E < 10 MeV/u)

a) beam passed through the foil
b) beam stopped in the foil

[Ref] M. Tomut et al., Proceedings of the HB2012, p 476

Irradiation by uranium beam (E = 200 – 500 MeV/u)

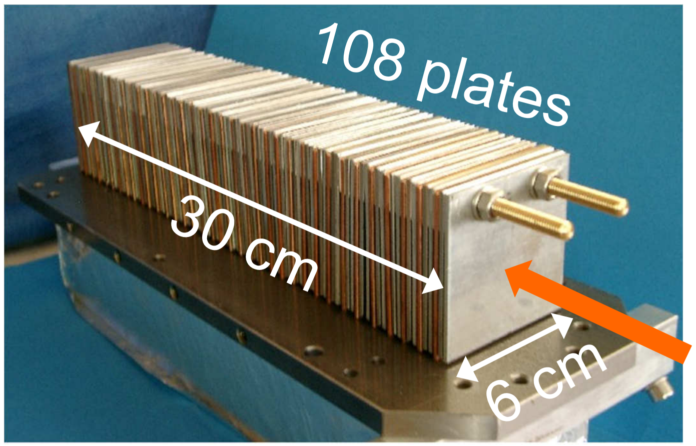
Plastic holder



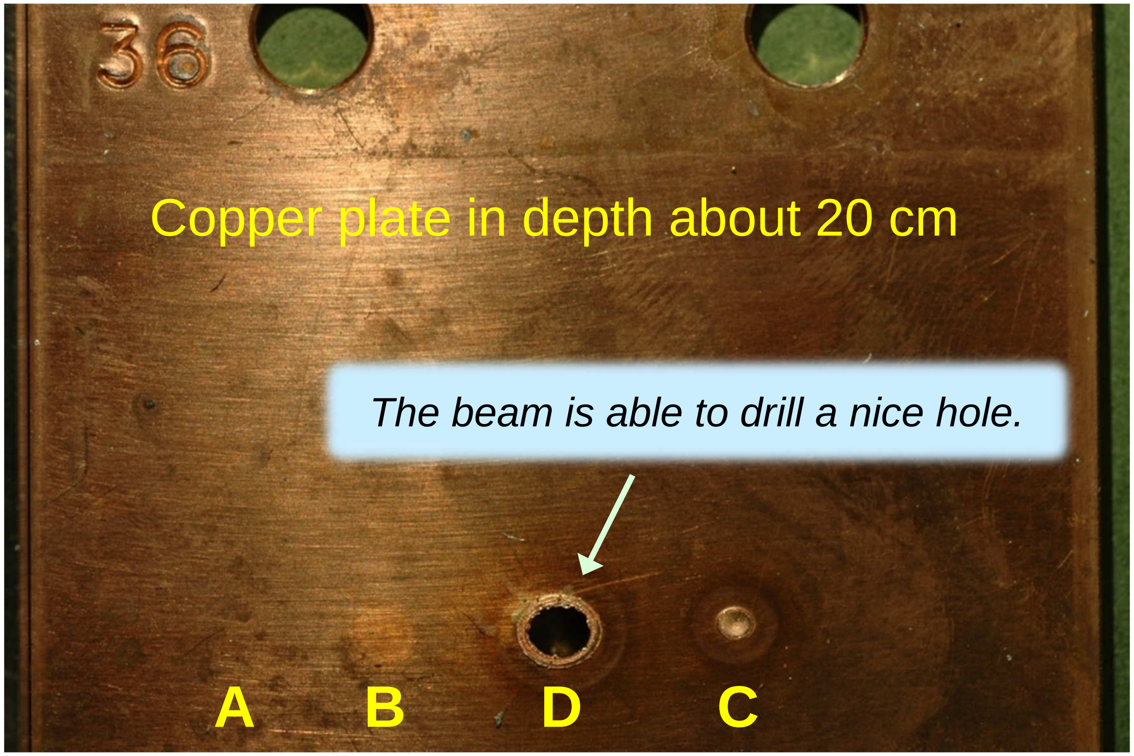
Lead foil

Material damage test at CERN

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



Shot	Proton beam intensity
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}



[Ref] R. Schmidt et al., New J. Phys. 8, 290 (2006)
[Ref] J. Wenninger, LNF Spring School (2010)

Energy deposition and temperature rise

- Energy loss – Bethe formula

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

$$-\frac{dE}{dx}\left[\frac{\text{J}}{\text{cm}}\right]$$

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

[Ref] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

N_A – Avogadro constant
r_e – classical electron radius
m_e – electron mass
c – speed of light
z – charge number of the incident particle
Z *and* A – atomic and mass number of the absorber
ρ – density of the absorber material
β and γ – relativistic parameters of the particle
T_{max} – maximum kinetic energy imparted to a free electron in a single collision
I – mean excitation energy
$\tau(\beta\gamma)$ – density effect correction term

- Energy deposition

$$\frac{dE}{dV}=-\frac{dE}{dx}\cdot\frac{N}{A}$$

$$\frac{dE}{dV}\left[\frac{\text{J}}{\text{cm}^3}\right]$$

N – number of particles
A – beam cross-sectional area [cm^2]

- Temperature rise

$$\Delta T=\frac{dE}{dV}\cdot\frac{1}{\rho c_p}$$

$$\rho\left[\frac{\text{g}}{\text{cm}^3}\right] \qquad c_p\left[\frac{\text{J}}{\text{g}\cdot\text{K}}\right] \qquad \Delta T\,[\text{K}]$$

ρ – material density
c_p – specific heat capacity

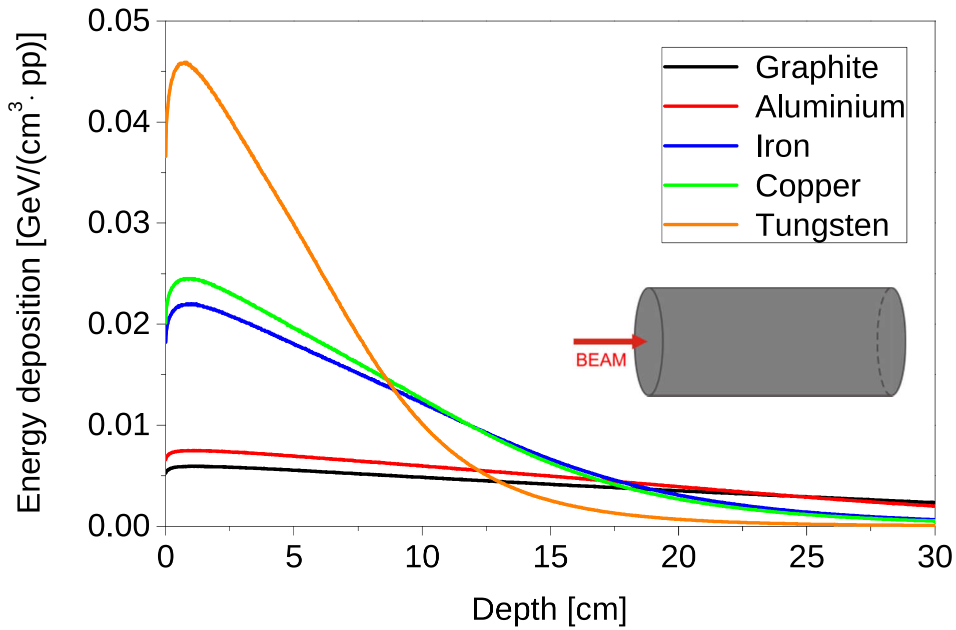
Performance of various materials

Material parameters

material	graphite	aluminium	iron	copper	tungsten
density ρ [g/cm^3]	1.7 – 2.3	2.7	7.87	8.92	19.25
heat capacity c_p [J/(g·K)]	0.71	0.9	0.45	0.39	0.13
melting or sublimation [K]	3800	933	1811	1358	3695

Example (simulation):

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



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

material	graphite	aluminium	iron	copper	tungsten
number of particles	1.5×10^{12}	2.0×10^{12}	1.0×10^{12}	8.9×10^{11}	3.4×10^{11}

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

Superconducting magnet quench

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

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

[Ref] R. Schmidt, CERN Accelerator School: Machine Protection and Collimation (2011)

Quench level

- Quench induced by beam losses – lost particles interact with the superconducting material and deposit energy which leads to the temperature rise
- Quench level – minimal deposited energy to the superconducting wire which is able to rise the temperature to the critical value and consequently to induce quench
- The quench level can be expressed in case of fast losses (transition state) in mJ/cm^3 and in case of slow losses (steady state) in mW/cm^3
- It can be in order of a few mJ/cm^3 or a few mW/cm^3

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

Beam energy [TeV]	Quench level [particles/m]	Damage level [particles/m]
0.45	10^9	10^{12}
7	10^6	10^{10}

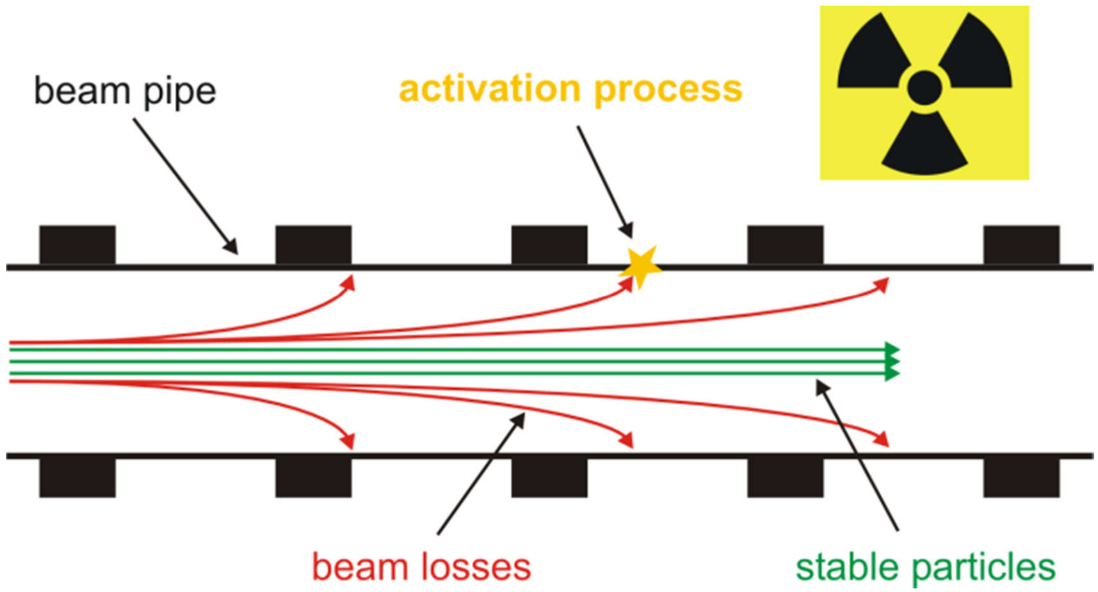
For comparison: total beam intensity : 3×10^{14}

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

[Ref] J. Wenninger, LNF Spring School (2010)

Residual activation

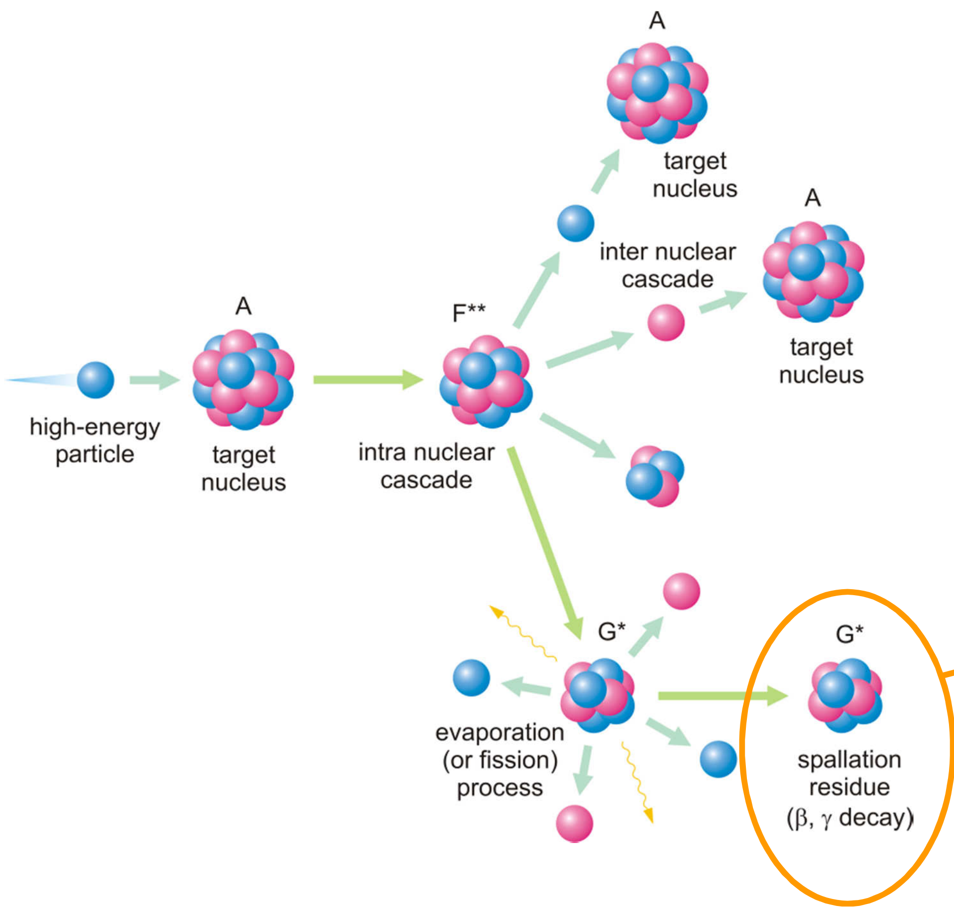
- **Residual activation** – production of radioactive nuclei in construction materials of an accelerator due to interaction with high energy particles



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

Nuclear reactions and radionuclide production

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



Radionuclides detected in the accelerator construction materials

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

[Ref] I. Strasik et al., NIMB 266, 3443 (2008)
[Ref] V. Chetvertkova et al., NIMB 269, 1336 (2011)

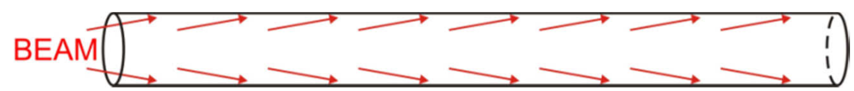
Tolerable beam losses and radiation protection

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

[Ref] N.V. Mokhov and W. Chou, The 7th ICFA Mini-workshop on High Intensity High Brightness Hadron Beams, USA, 1999.

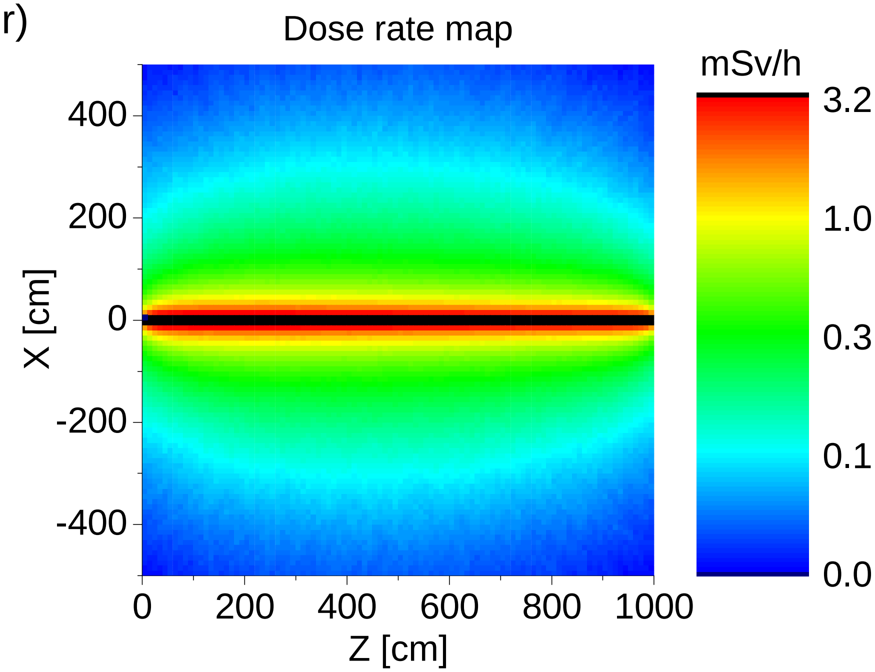
- 1 W/m → 6×10^9 protons/(m·s) of energy 1 GeV (uniformly distributed)

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



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

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



For comparison

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

[Ref] I. Strasik et al., Phys. Rev. ST AB 13, 071004 (2010)

- ALARA – As Low As Reasonably Achievable

Machine protection related to the beam losses

➢ Prevent uncontrolled regular beam losses

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

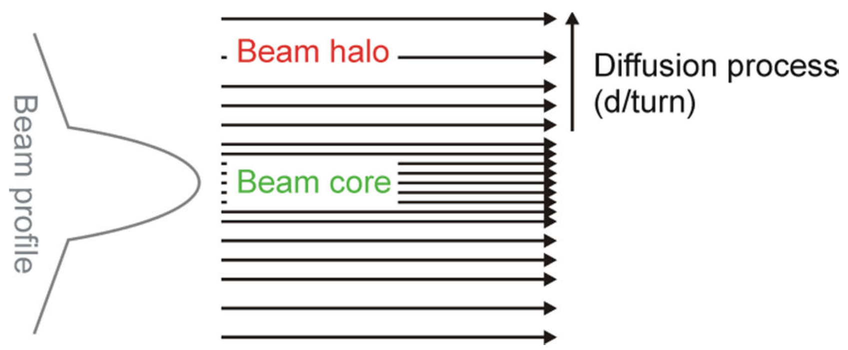
➢ Prevent uncontrolled accidental beam losses

- Cause: machine failures
- Consequences: radiation damage, material destruction, superconducting magnet quench
- Cure: extraction & dumping system, collimation system for passive protection

Regular beam losses & beam halo

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

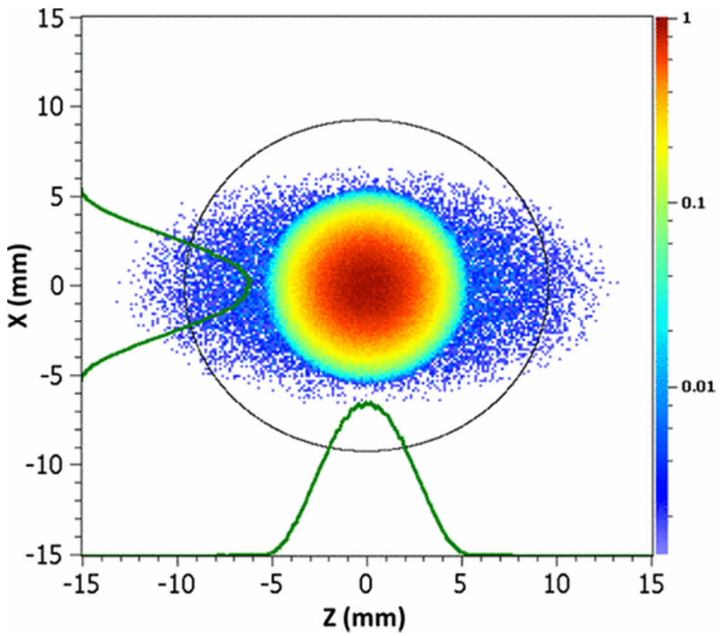
[Ref] K. Wittenburg, CERN Accelerator School: Course on Beam Diagnostics, 557 (2008).



Diffusion speed can be very low: < 1 μm/turn (in synchrotrons)

[Ref] R. Aßmann, Chapter 3.3.11, Handbook of Accelerator Physics and Engineering (2013)
[Ref] G. Valentino, Phys. Rev. ST AB 16, 021003 (2013)

Beam core-halo distribution



[Ref] I. Hofmann, Phys. Rev. ST AB 16, 084201 (2013)

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

Collimation system for machine protection

The collimation system: defense against beam loss

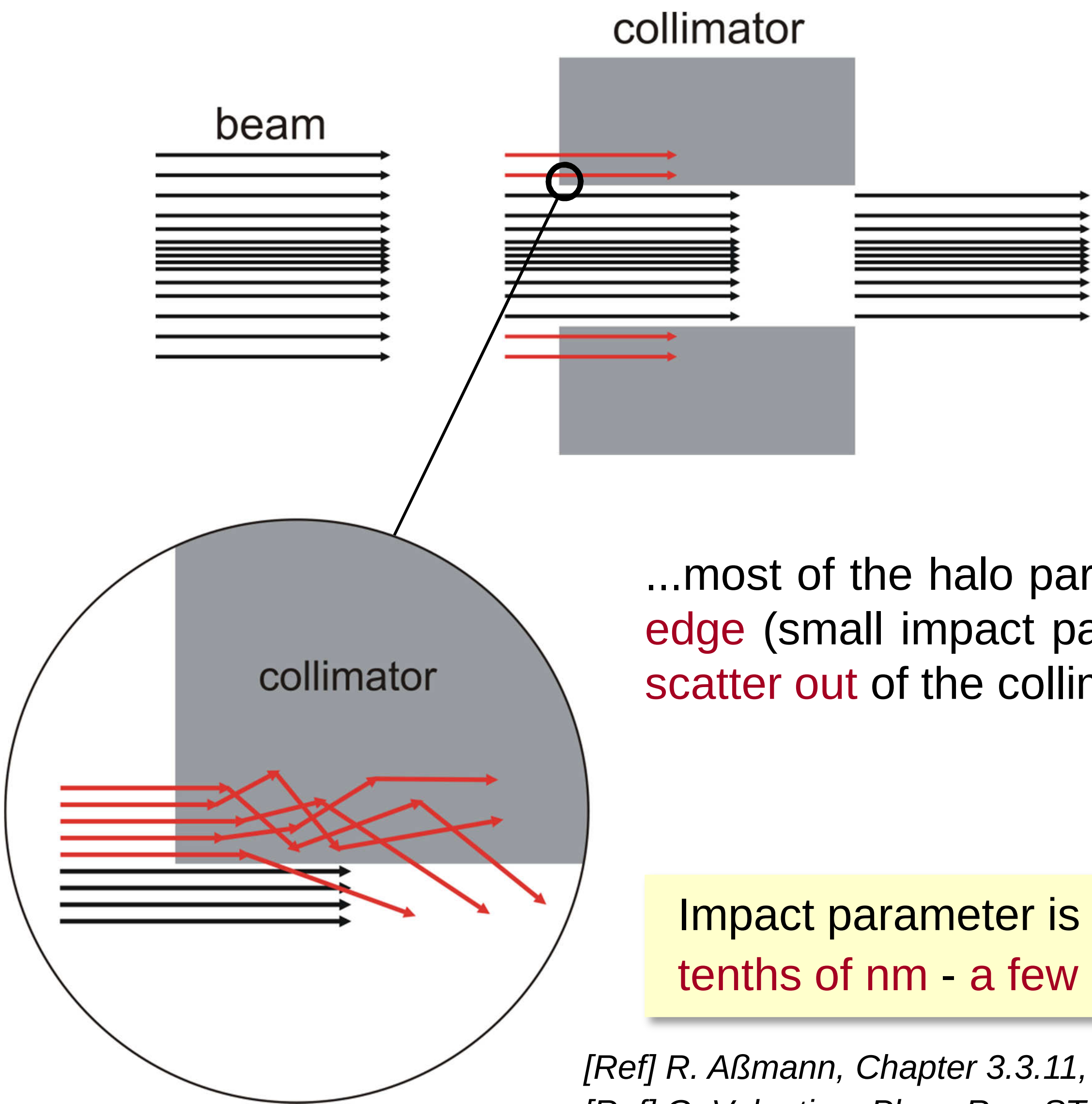
[Ref] S. Redaeli, on behalf of the LHC collimation project team, CERN COURIER, Aug. 19, 2013

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

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

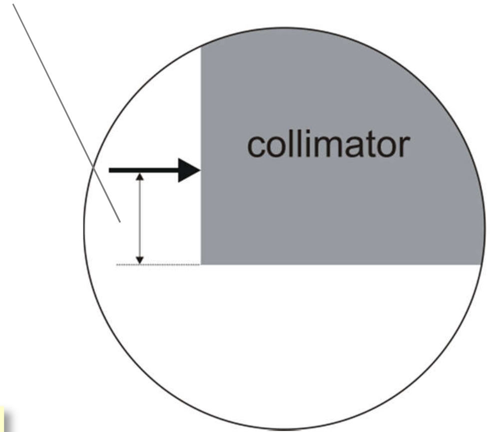
Simple idea of the halo collimation

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



However, that is usually not the case…

Impact parameter – transverse distance from the edge of the collimator to the impact point of the halo particle



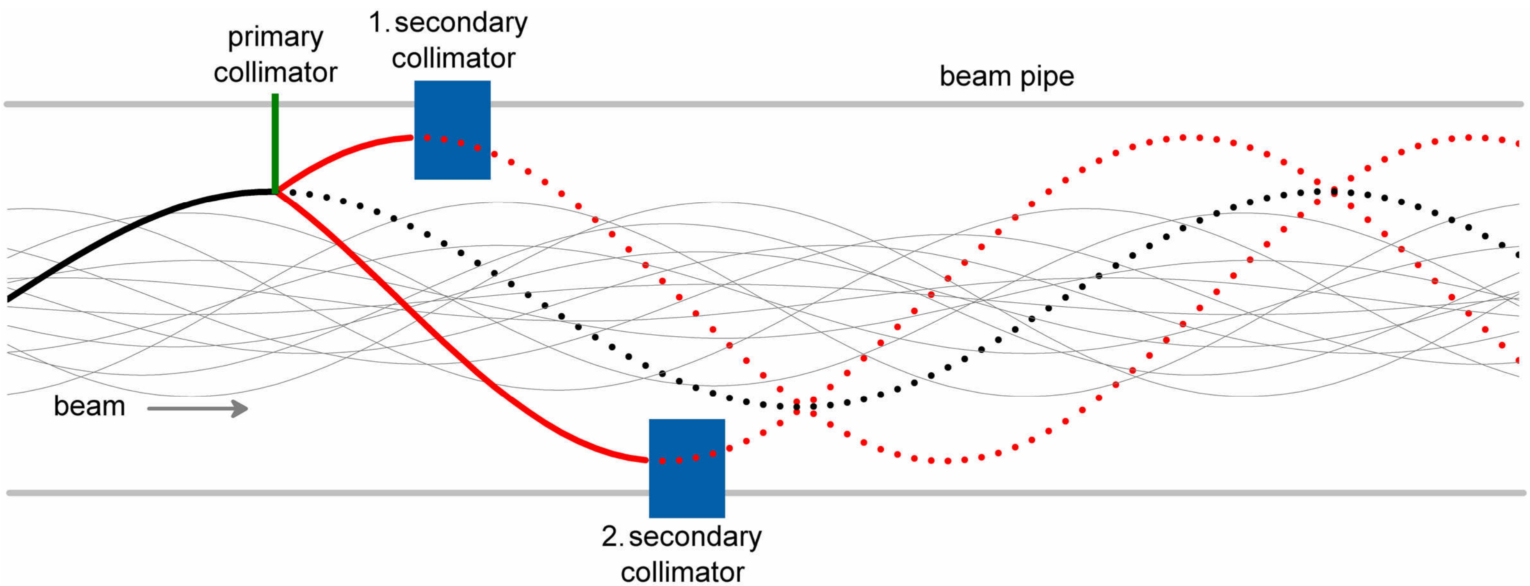
...most of the halo particles hit near edge (small impact parameter) and scatter out of the collimator!

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

[Ref] R. Aßmann, Chapter 3.3.11, Handbook of Accelerator Physics and Engineering (2013)
[Ref] G. Valentino, Phys. Rev. ST AB 16, 021003 (2013)

Two stage betatron collimation system

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



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

Very robust concept and well established in many accelerators.

[Ref] M. Seidel, DESY Report, 94-103, (1994)
[Ref] T. Trenkler and J.B. Jeanneret, Particle Accelerators 50, 287 (1995)
[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998)

Scattering in the primary collimator

Molière theory of multiple Coulomb scattering

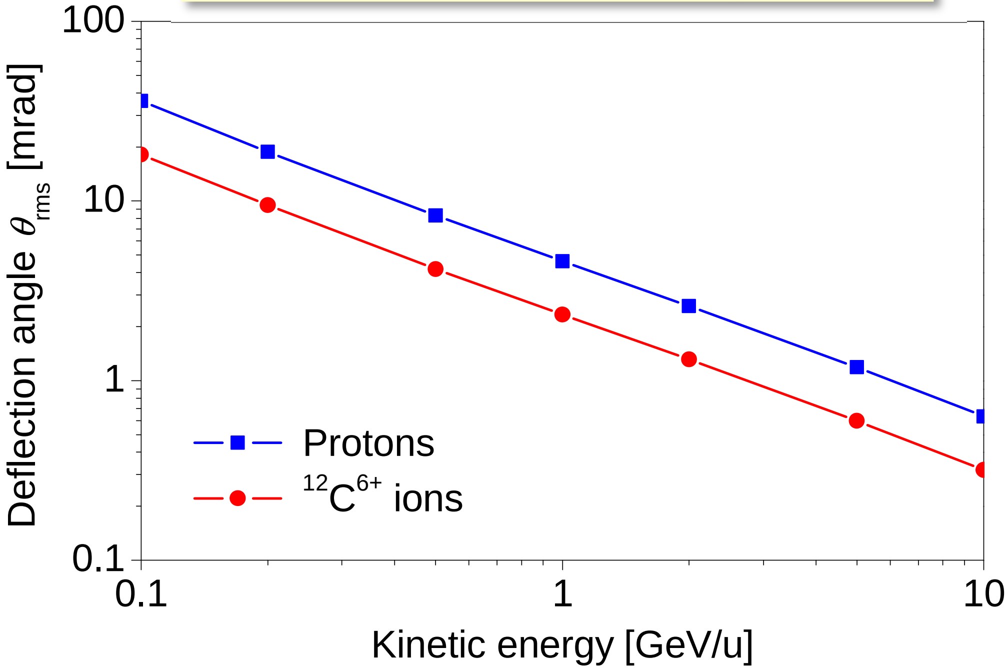
$$\theta_{rms} = \frac{13.6}{\beta c p} Z \sqrt{\frac{L}{L_R}} \left(1 + 0.038 \times \ln\left(\frac{L}{L_R}\right)\right)$$

roughly Gaussian for small deflection angles

[Ref] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

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

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



Choice of the scattering foil material is important.

Scattering of 4 GeV protons

Thickness L needed to have the same angle θ_{rms}

Material	Graphite	Copper	Tungsten
θ_{rms} [mrad]	1.5	1.5	1.5
L [mm]	52	4	1

But don't forget to the radiation damage

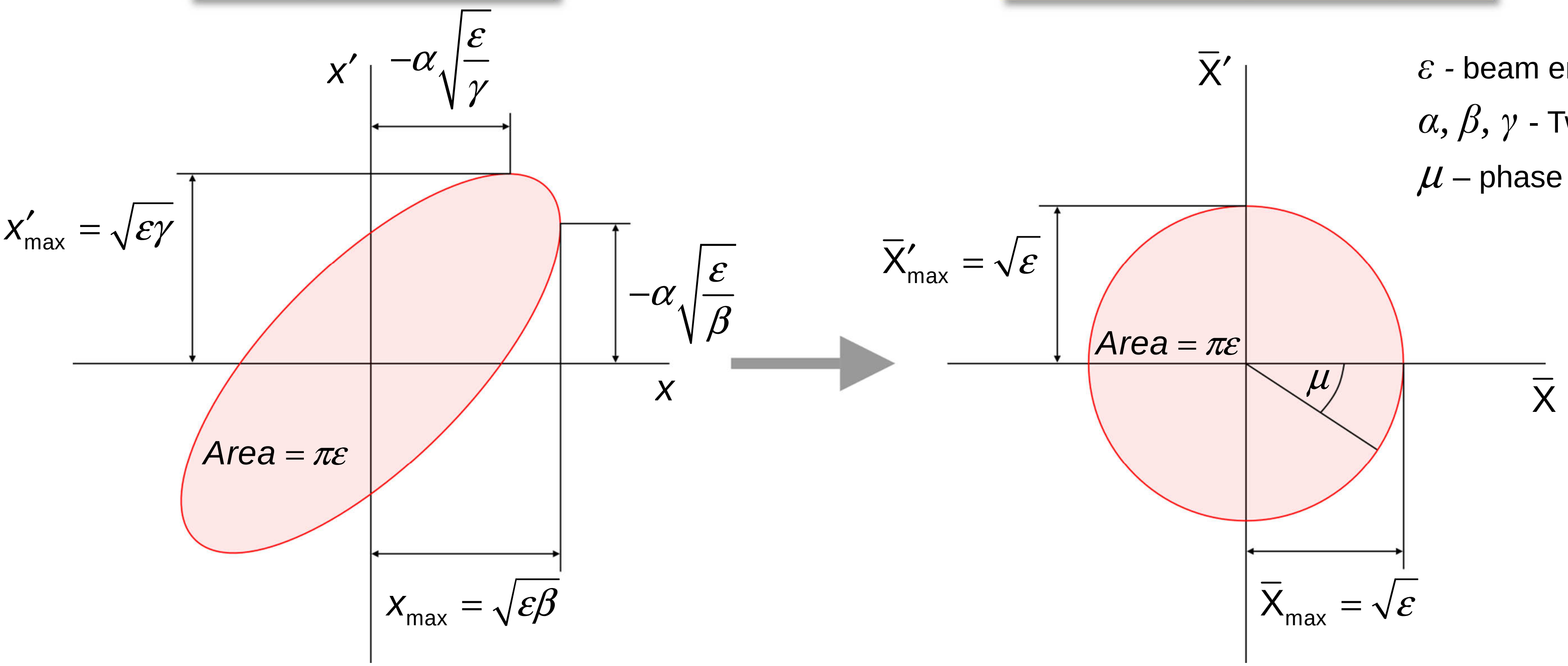
Normalized phase space

Real phase space | **Normalised phase space**

ε - beam emittance

α, β, γ - Twiss parameters

μ – phase advance



$$\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2 \qquad \varepsilon = \bar{X}^2 + \bar{X}'^2$$

Real to normalized coordinates:

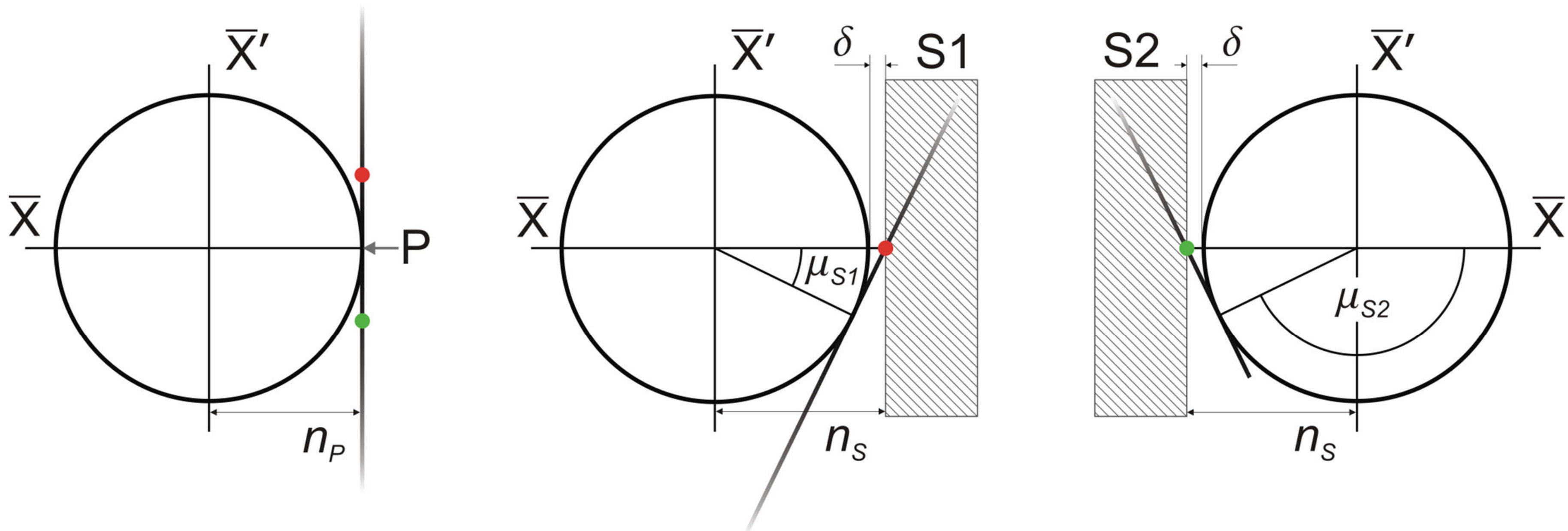
$$\begin{pmatrix} \bar{X} \\ \bar{X}' \end{pmatrix} = \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ \alpha & \beta \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix} \rightarrow \bar{X} = \frac{1}{\sqrt{\beta}} x \qquad \bar{X}' = \frac{1}{\sqrt{\beta}} \alpha x + \sqrt{\beta} x'$$

Transport of the particles in the normalized phase space:

$$\begin{pmatrix} \bar{X}_{s_1} \\ \bar{X}'_{s_1} \end{pmatrix} = M \begin{pmatrix} \bar{X}_{s_0} \\ \bar{X}'_{s_0} \end{pmatrix} \qquad M = \begin{pmatrix} \cos\mu & \sin\mu \\ -\sin\mu & \cos\mu \end{pmatrix}$$

Normalized phase space plots at the collimators

primary collimator | 1. secondary collimator | 2. secondary collimator



n_P, n_S – normalized aperture of the primary and secondary collimators δ – retraction distance

μ_{S1}, μ_{S2} – phase advances between the collimators

particle transport P → S1: $\begin{pmatrix} \bar{X}_{S1} \\ \bar{X}'_{S1} \end{pmatrix} = M_{S1} \begin{pmatrix} \bar{X}_P \\ \bar{X}'_P \end{pmatrix}$ $M_{S1} = \begin{pmatrix} \cos\mu_{S1} & \sin\mu_{S1} \\ -\sin\mu_{S1} & \cos\mu_{S1} \end{pmatrix}$

particle transport P → S2: $\begin{pmatrix} \bar{X}_{S2} \\ \bar{X}'_{S2} \end{pmatrix} = M_{S2} \begin{pmatrix} \bar{X}_P \\ \bar{X}'_P \end{pmatrix}$ $M_{S2} = \begin{pmatrix} \cos\mu_{S2} & \sin\mu_{S2} \\ -\sin\mu_{S2} & \cos\mu_{S2} \end{pmatrix}$

Optimal phase advances:

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

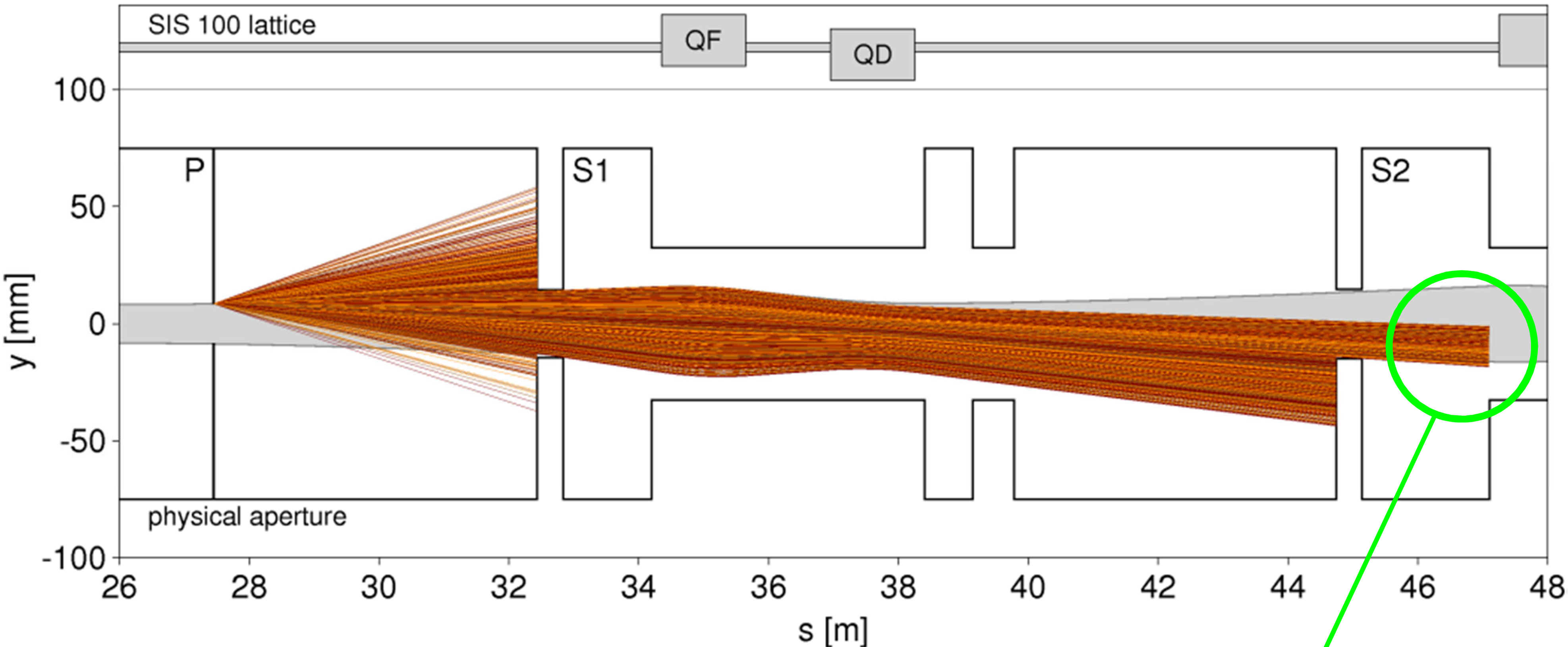
$$\mu_{S2} = \pi - \mu_{S1}$$

[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998)

Particle transport through the collimation system

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

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



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

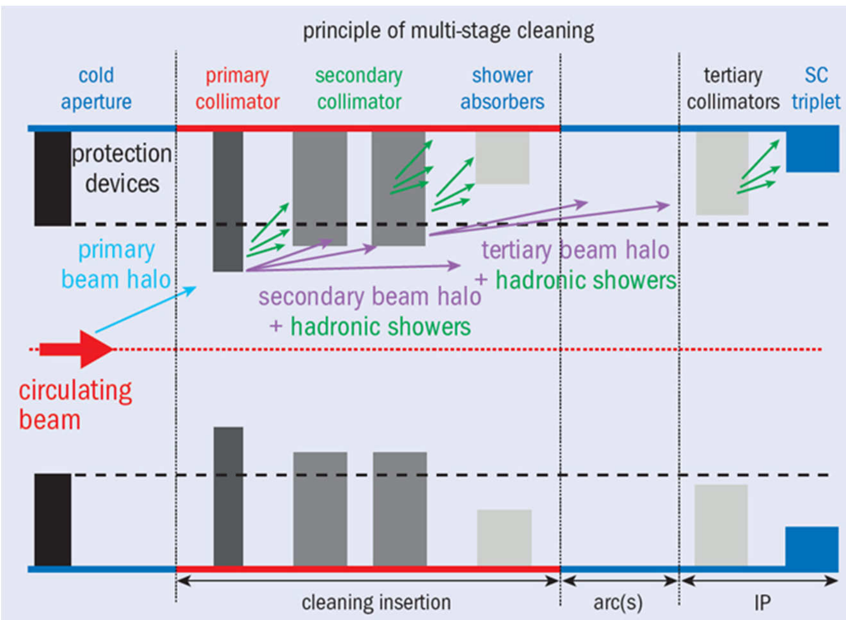
What happens with the particles that escape?

Multi stage collimation: LHC collimation system

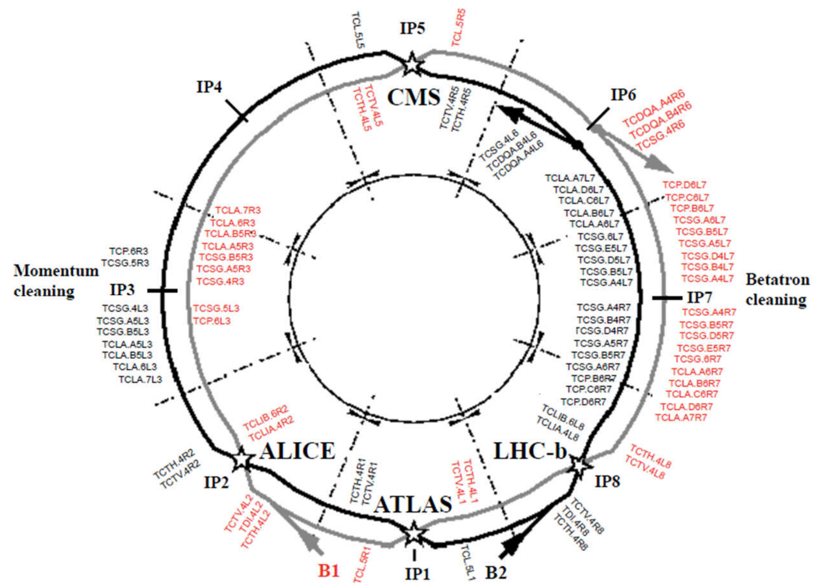
“LHC employs the largest and most advanced cleaning system ever built for a particle accelerator”

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

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



LHC collimaton system layout



[Ref] C. Bracco, CERN-THESIS-2009-031 (2009)

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

$$Efficiency = \frac{N_C}{N_L}$$

N_C – collimated lost particles
N_L – amount of beam losses

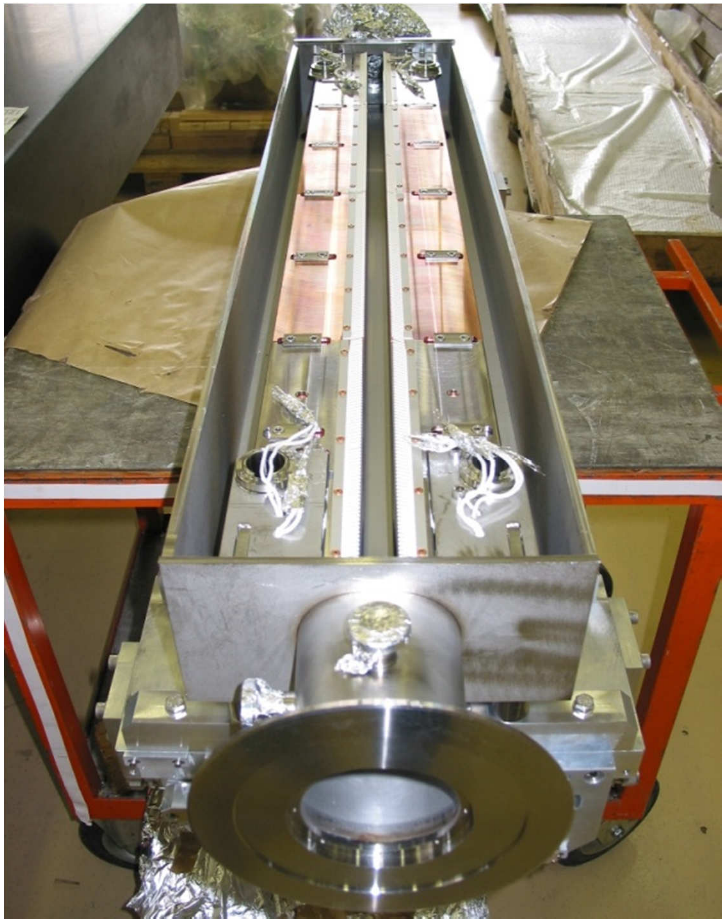
Extremely high efficiency is required to prevent quench.

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

Pictures of LHC collimators

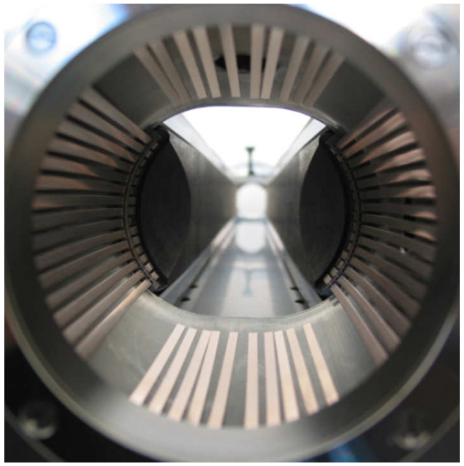
- Most of the LHC collimators consist of two parallel jaws about 1 m long
- Radiation resistant materials – only carbon based materials withstand direct LHC beam impact

Top view, open collimator

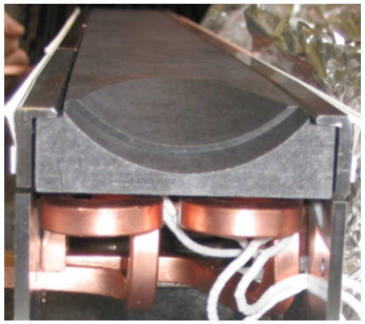


Carbon composite jaw

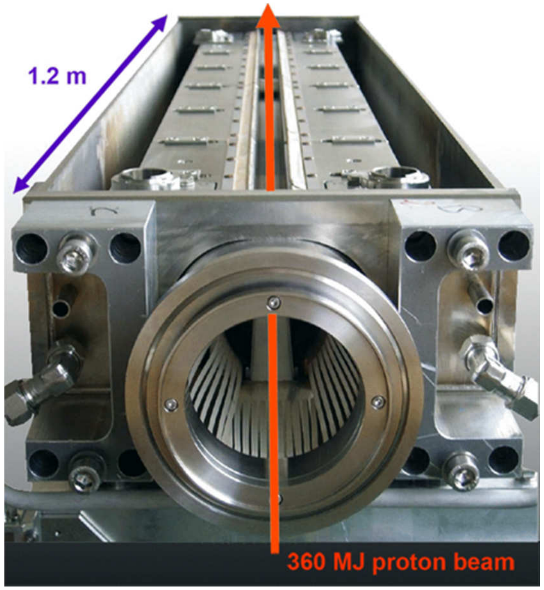
Front view, open jaws



Carbon composite jaw, front view



Beam passage through the collimator



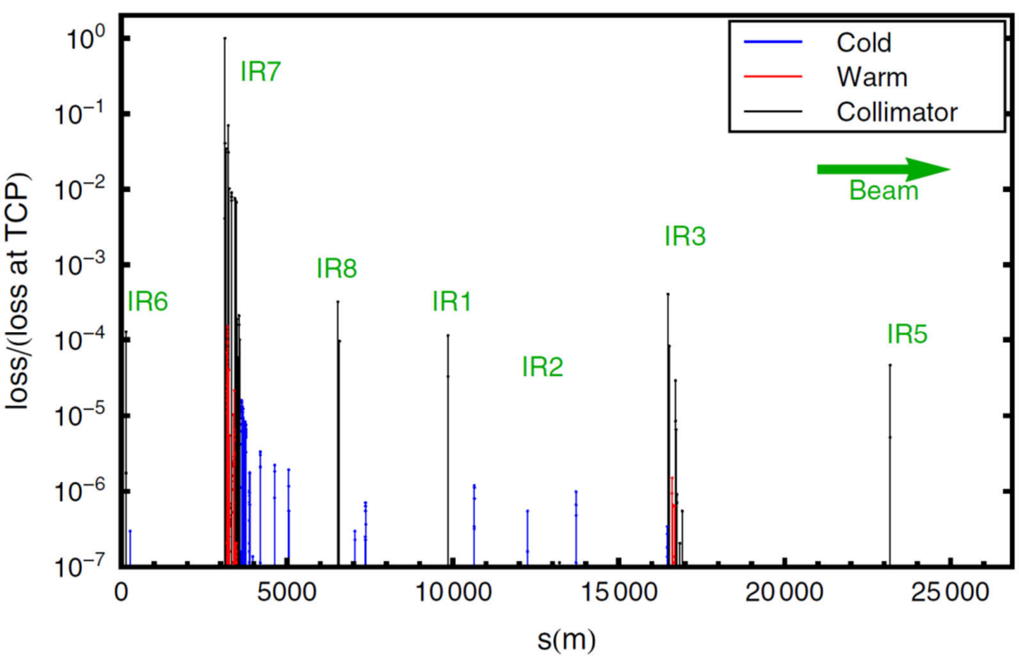
[Ref] LHC Collimation Project, R. Aßmann (former head), S. Redaelli (present head), {http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/}

Multiturn particle motion and beam loss maps

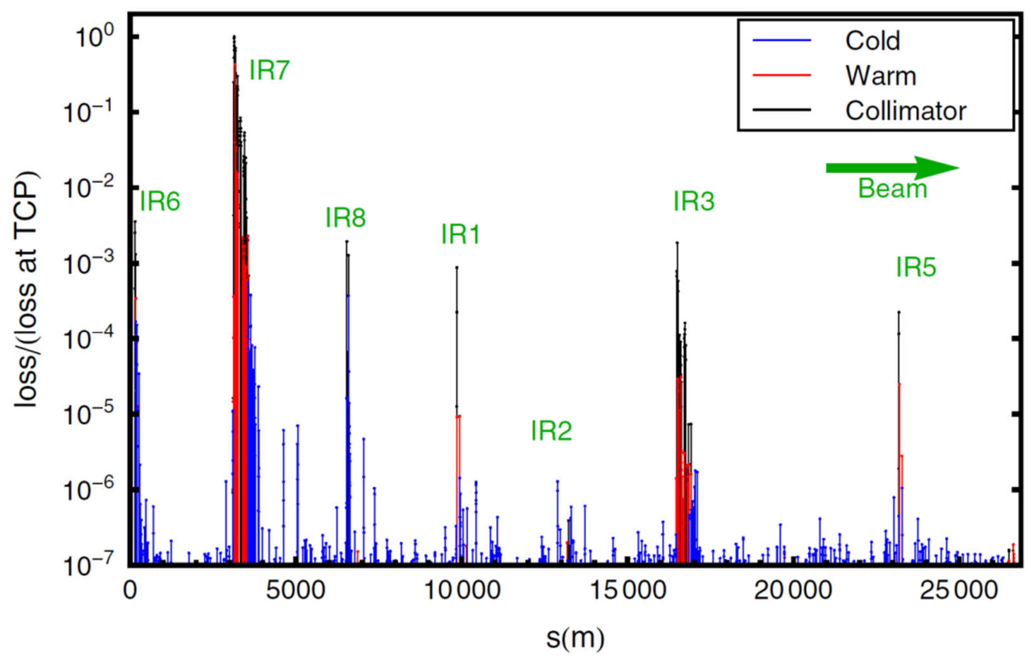
- Consider the motion in circular accelerators (synchrotrons)
- Particles scattered at a small angle in the primary collimator and are not further intercepted by the secondary collimators can be still collimated in the next turns

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

Simulation



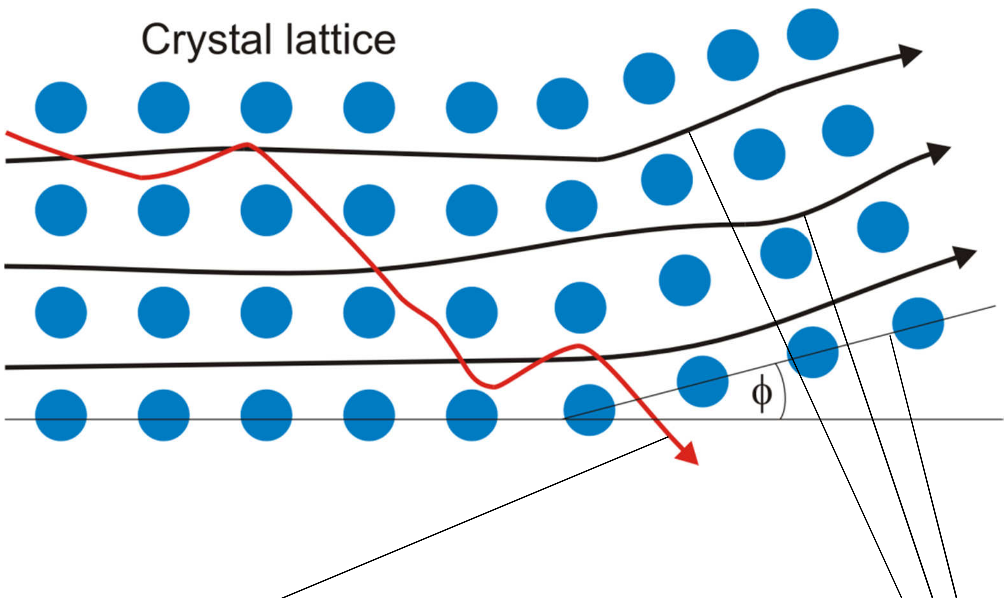
Measurement



[Ref] R. Bruce et al., Phys. Rev. ST AB 17, 081004 (2014)

Advanced techniques: bent crystal channeling

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



Particles with the incident angle greater than critical angle are scattered through the crystal.

Particles with the incident angle smaller than critical angle are properly channeled.

Critical angle θ_C :

$$\theta_C = \sqrt{\frac{2E_C}{pv}}$$

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

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

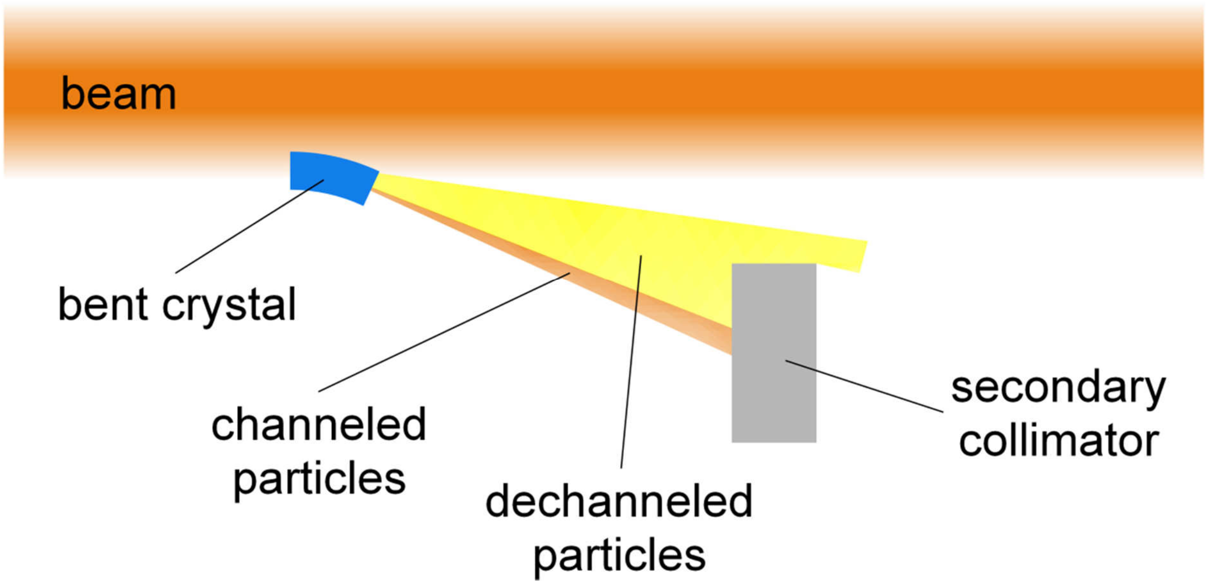
For 100 GeV protons, the $\theta_C \approx 19$ µrad

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

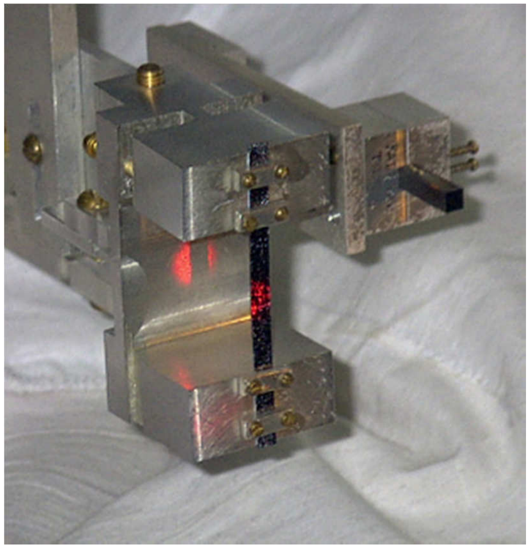
[Ref] W. Scandale et al., Phys. Rev. Lett. 102, 084801 (2009)
[Ref] R. P. Fliller et al., Phys. Rev. ST Accel. Beams 9, 013501 (2006)

Bent crystal collimation

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



silicon crystal



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

Dechanneling length L_D : $L_D \propto p$

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

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

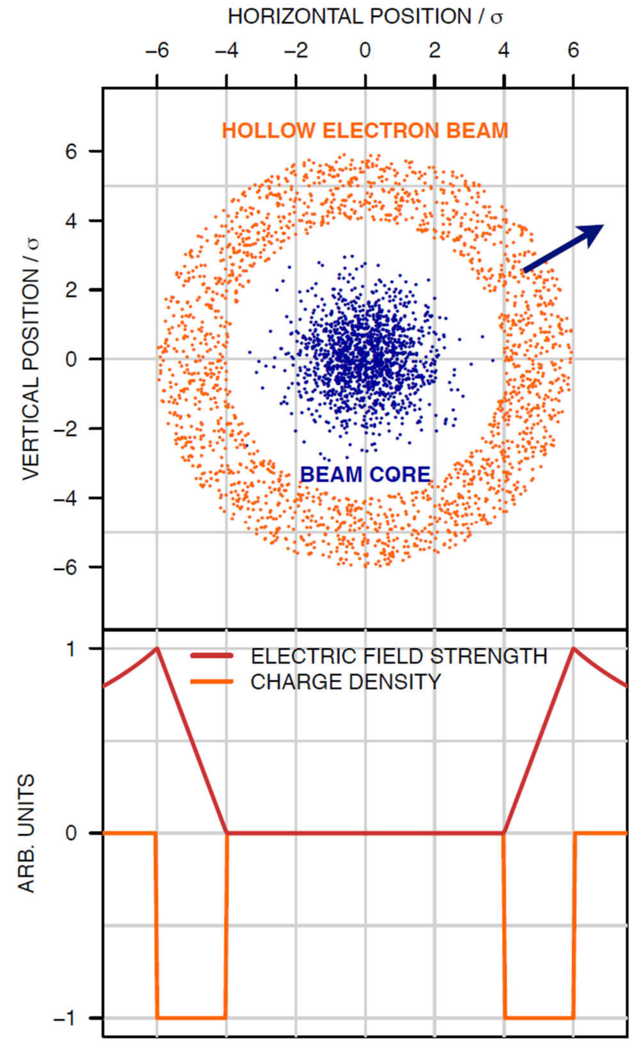
Advanced techniques: hollow electron beam

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

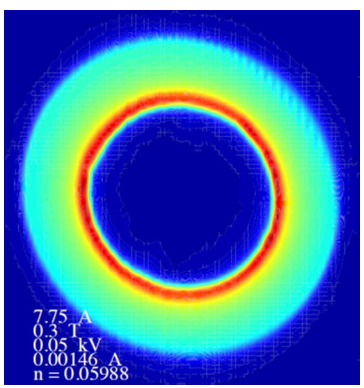
$$\theta_r = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2 I_r L \left(1 \pm \beta_e \beta_p\right)}{r\,\beta_e \beta_p c^2 \left(B\rho\right)_p}$$

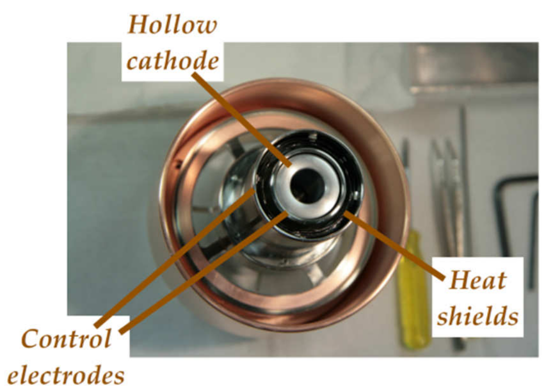
I_r – electron current
L – length of the interaction region
r – radial distance
β_e, β_p – beta relativistic parameters
$B\rho$ – magnetic rigidity

For 980 GeV protons, the $\theta_r \approx 0.3$ μrad



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



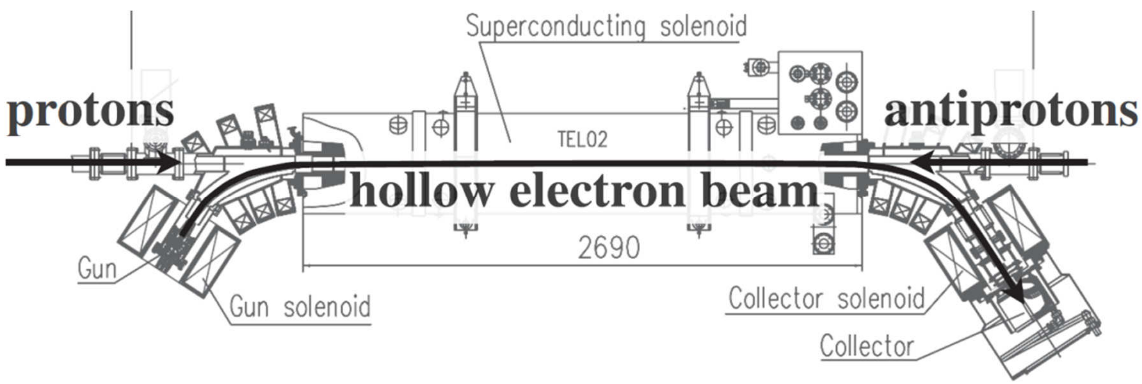


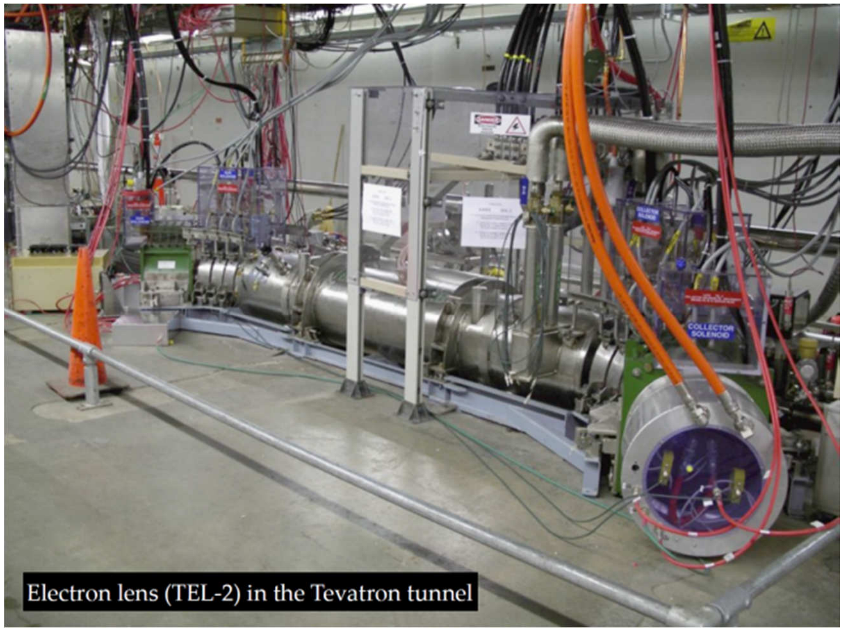
[Ref] G. Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)
[Ref] V. Shiltsev et al., Phys. Rev. ST Accel. Beams 11, 103501 (2008)

Collimation using hollow electron beam

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

Hollow electron beam collimation in Tevatron (Fermilab)





[Ref] G. Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)
[Ref] V. Shiltsev et al., Phys. Rev. ST Accel. Beams 11, 103501 (2008)

Accidental beam losses

- Caused by hardware failures (magnets, cavities, control systems, ...)
- Usually faster and quantitatively higher than the regular beam losses (lost is significant part or the whole beam in the time range of μs – s)
- When detected, the beam require an immediate emergency extraction to the beam dump in order to prevent component damage or magnet quenches
- Categorized from slow (beam lifetime longer than 1 second) up to ultra fast or singlepass (beam is lost in 1 turn)
- The all categories except the ultra fast losses can be detected using the Beam Loss Monitor (BLM) system
- The ultra fast losses, which are caused e.g. by failures of the magnets are beyond the capabilities of the active protection (emergency extraction) and are handled by the passive protection (e.g. collimators, absorbers,...)

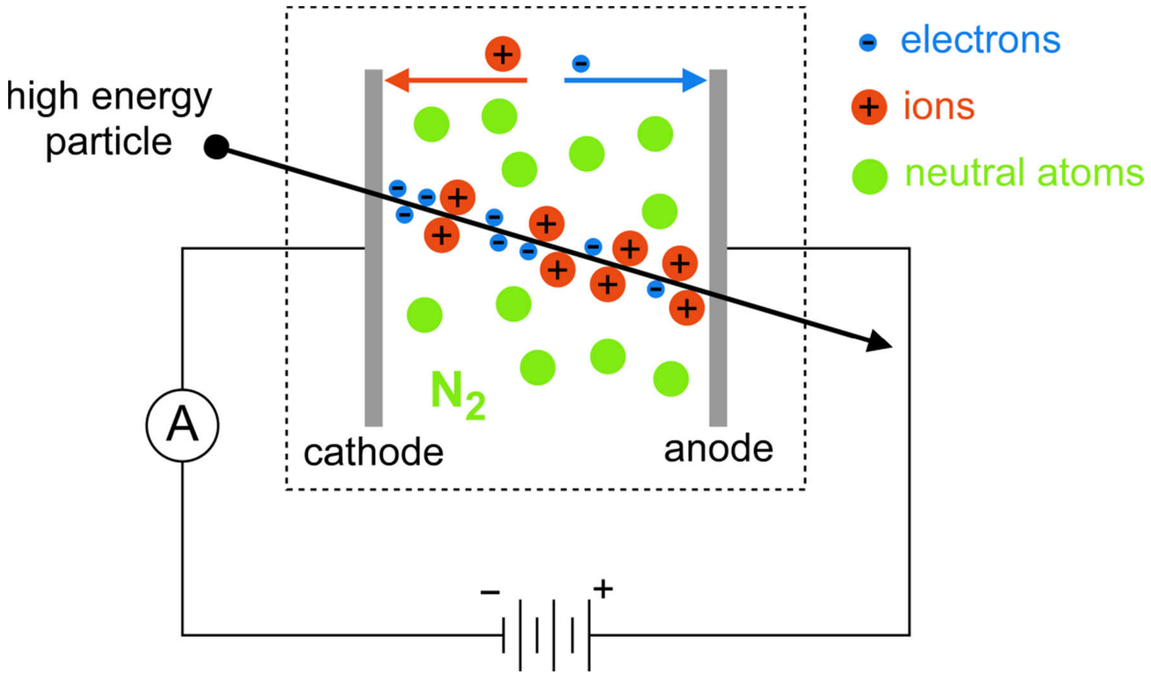
[Ref] S.C. Wagner, LHC Machine Protection System, Dissertation, (2010)

Beam loss monitors

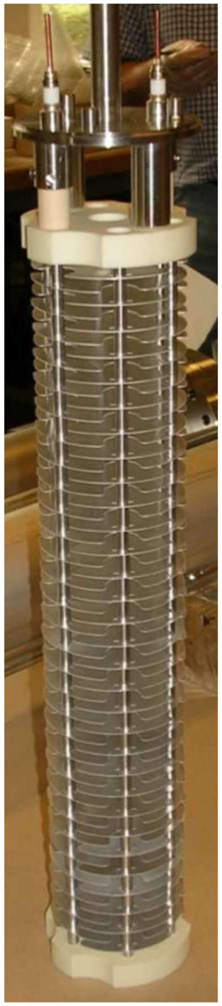
- Beam loss monitor (BLM) – ionization chamber to detect beam losses
- BLM provide a current signal proportional to the intensity of the particle shower passing through the chamber
- Very short reaction time (40 μs) and very large dynamic range (> 10^6)

[Ref] R. Schmidt, CERN Accelerator School: Machine Protection and Collimation (2011)

Principle of the ionization chamber



Inside of the BLM:
(LHC type)



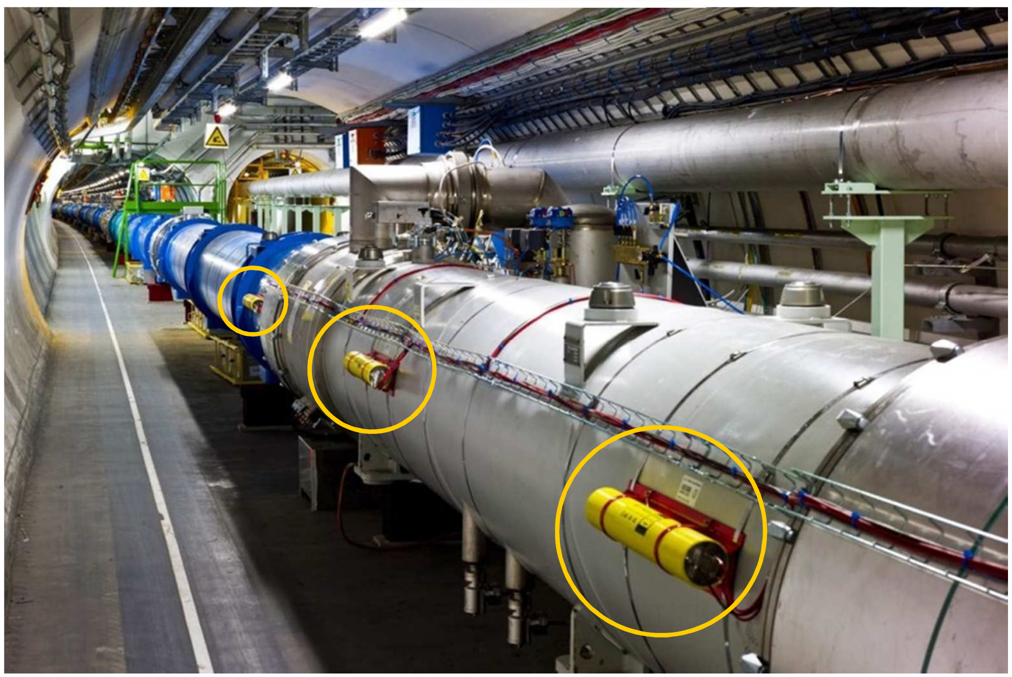
Parameters of the BLM (LHC type):

Length: 50 cm
Diameter: 9 cm
Gas: N_2

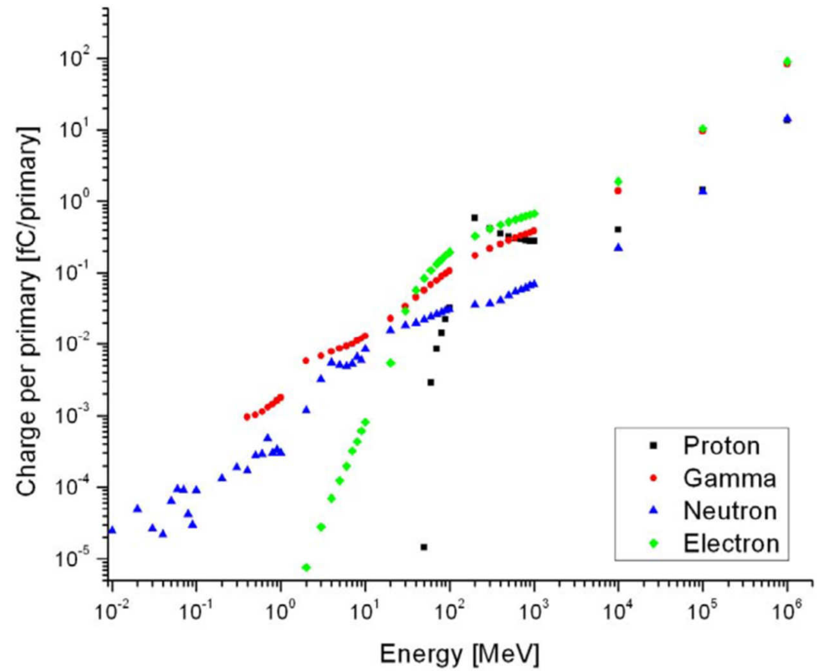
Beam loss monitors (LHC type)

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

BLMs @ LHC:



Simulation using FLUKA particle transport code



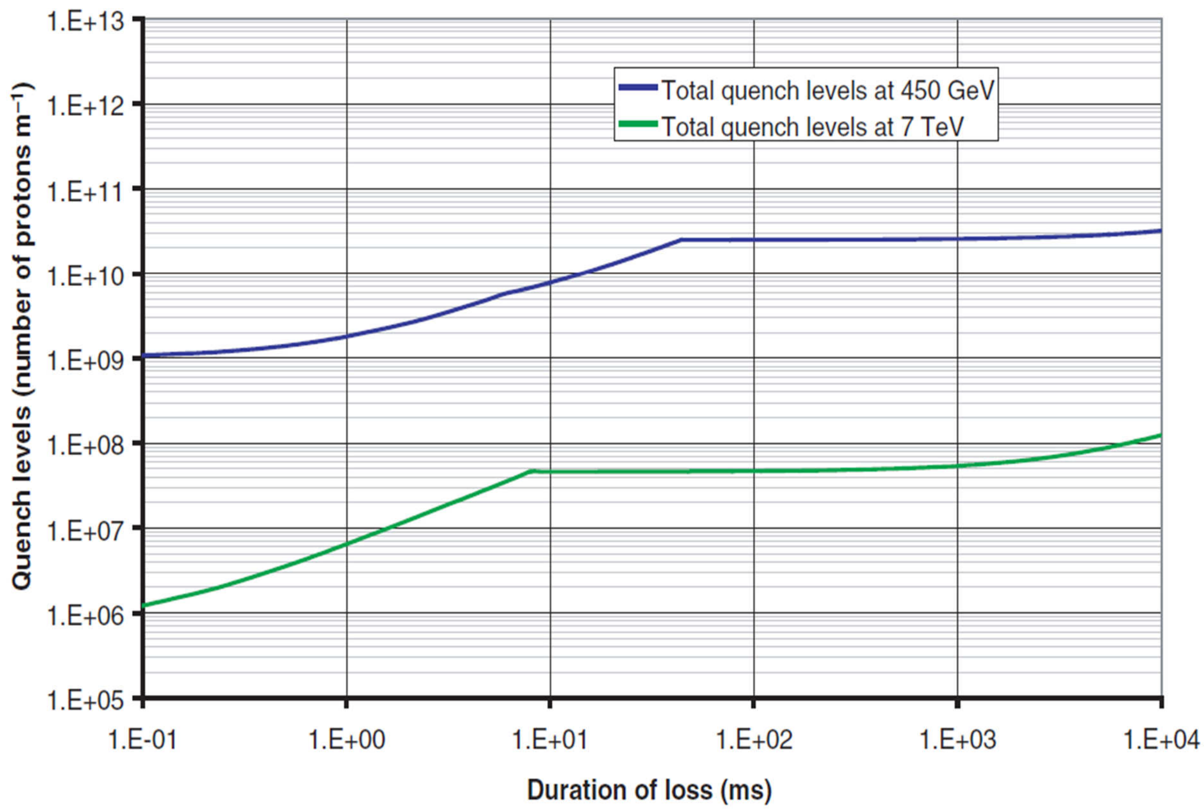
[Ref] V. Lavrik, BLM study @ GSI, 2nd Fluka Advanced Course and Workshop (2012)

[Ref] R. Schmidt, CERN Accelerator School: Machine Protection and Collimation (2011)

Beam loss monitors and quench level

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

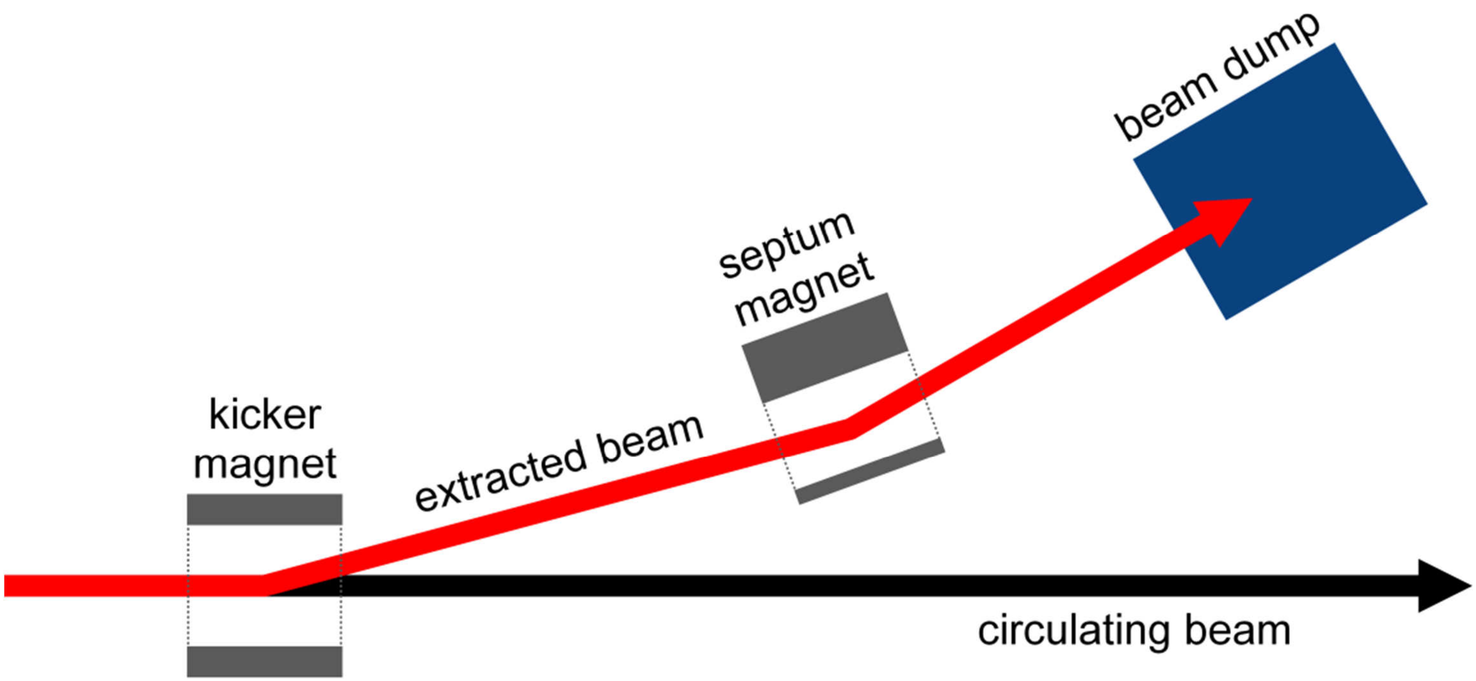
Expected quench levels for LHC superconducting magnets as a function of the beam loss duration



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

Emergency extraction

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



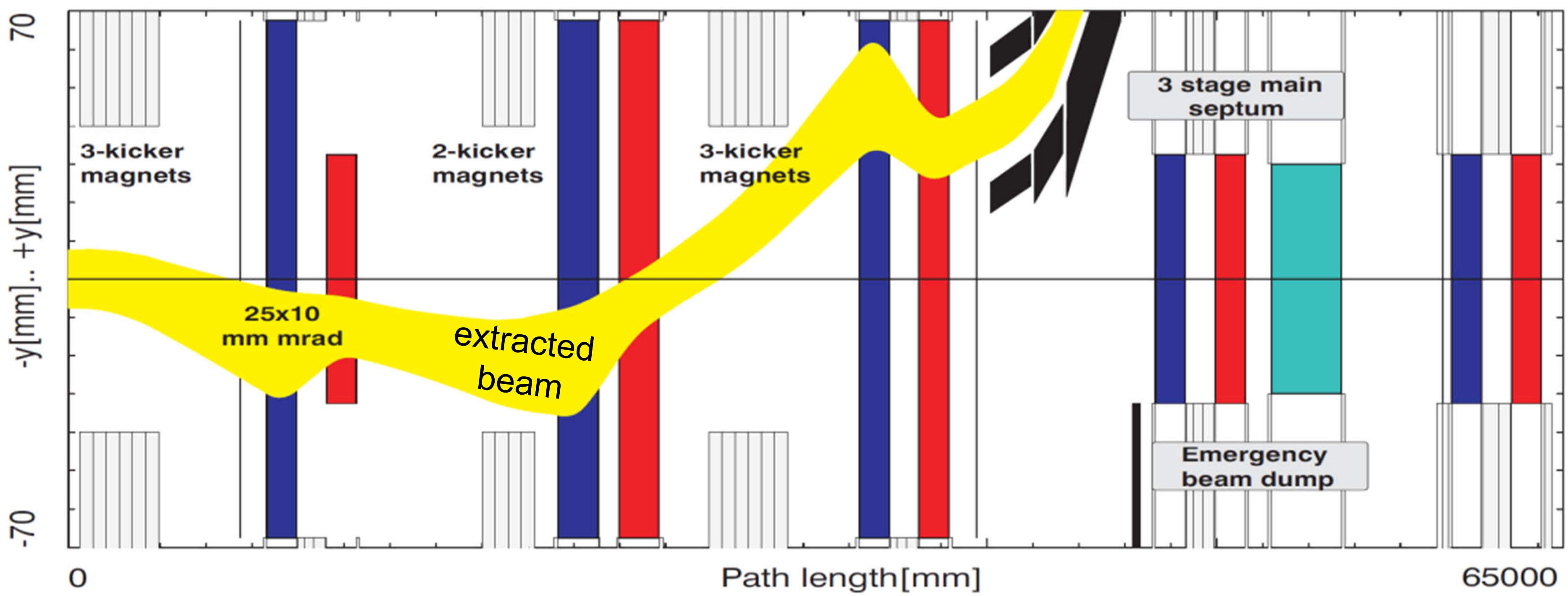
[Ref] M.J. Barnes et al., CERN Accelerator School: Specialised Course on Magnets, 141 (2009)

Extraction from the accelerator (example)

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

Simulation of the extraction from SIS100 synchrotron (FAIR@GSI)

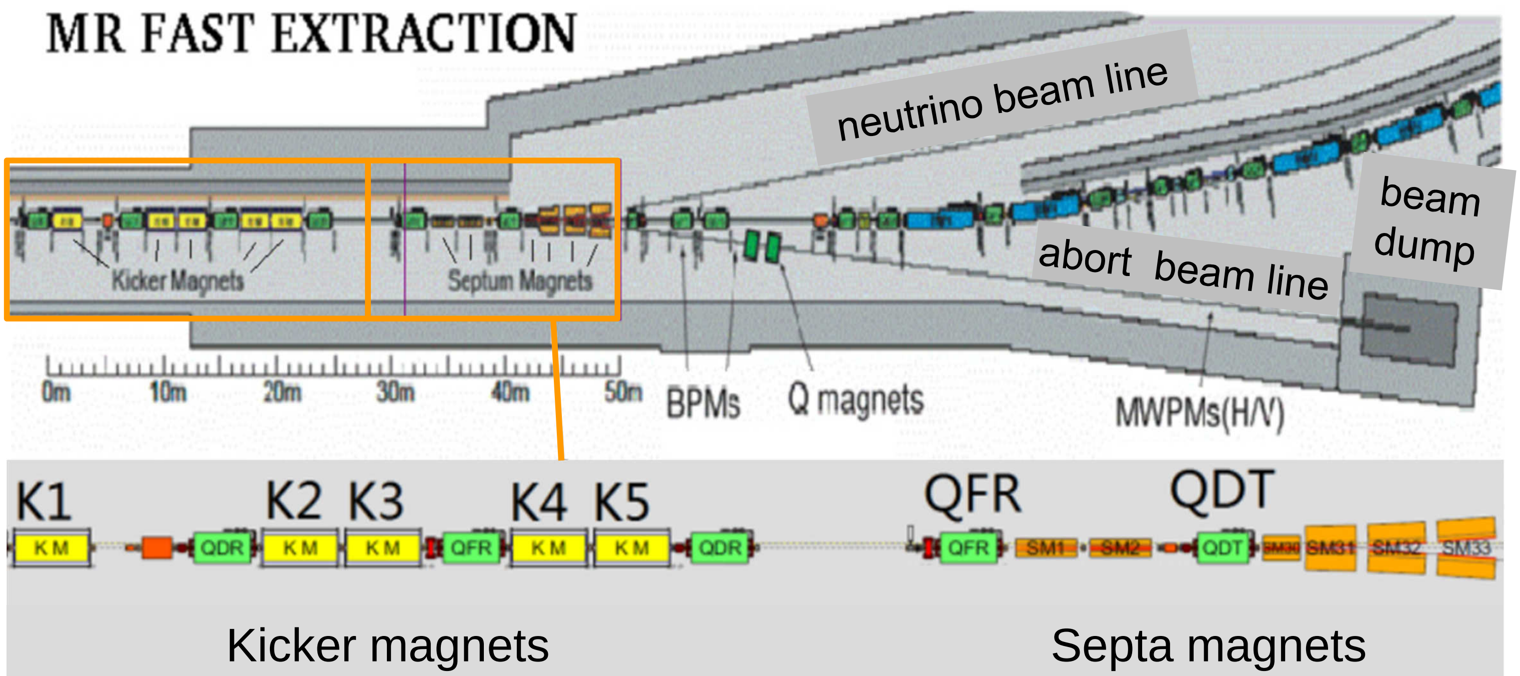
Simulation tool: MIRKO (code for accelerator design and beam optics)



[Ref] FAIR Technical Baseline Report (2006)

Regular and emergency extraction

➢ Extraction from J-PARC Main Ring synchrotron



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

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

The same (bipolar) kicker magnets are used

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

Beam dump

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

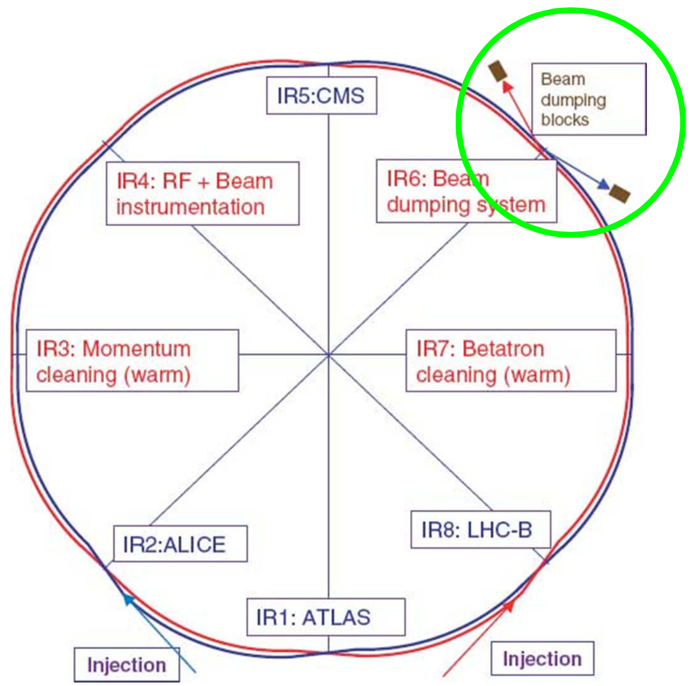
[Ref] O. Aberle, Some reflection about beam dumping at CERN, (2012)

Beam dump for SIS18 synchrotron at GSI:
(made of iron, 3×2×3 m)

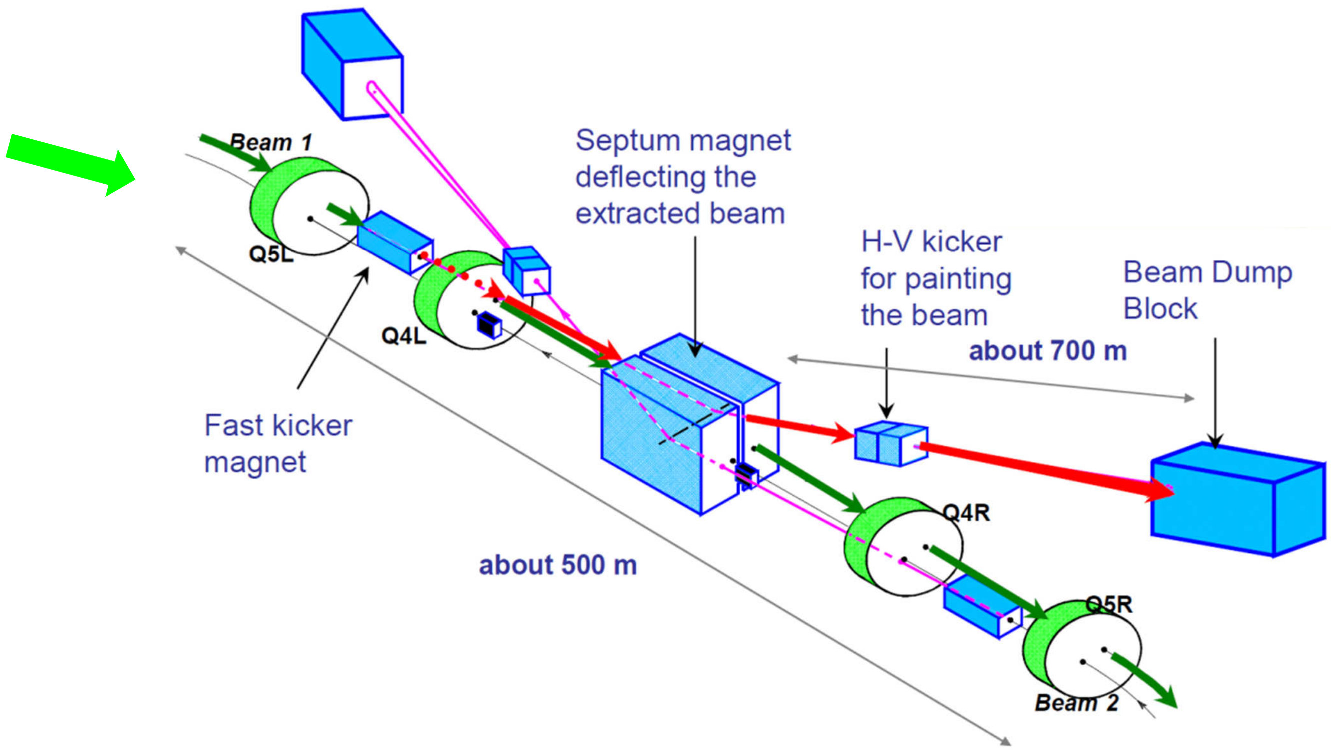
LHC beam dumping

- The beam is extracted from LHC, the peak energy density has to be first diluted to avoid high temperature rise and then absorbed in the beam dump

Location of the beam dumps in LHC



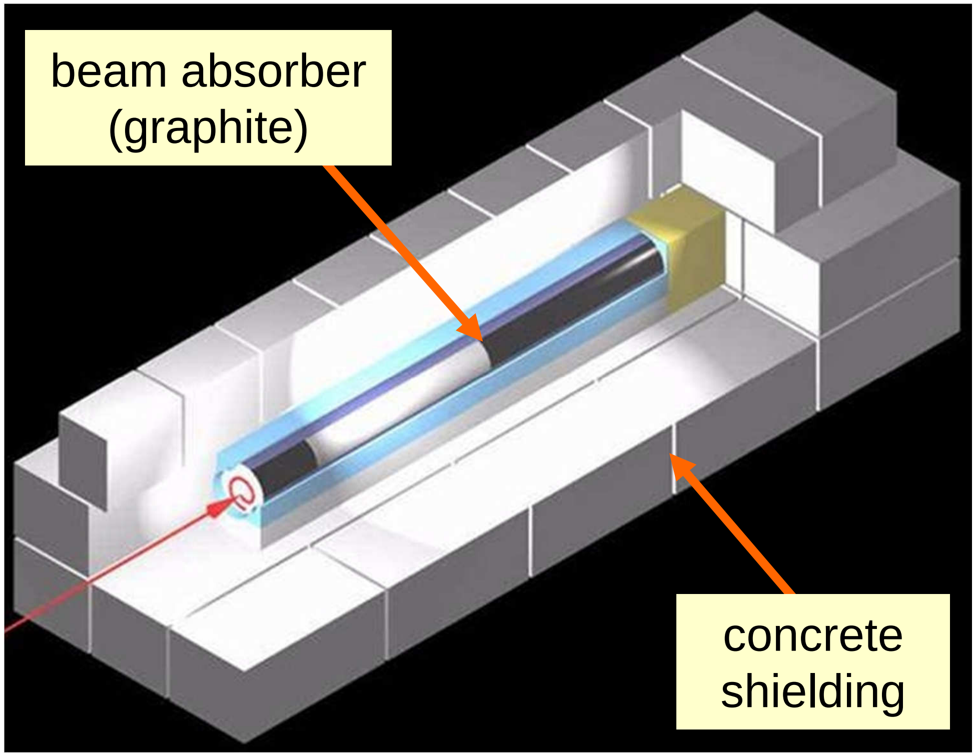
Schematic layout of the LHC beam dumping system:



[Ref] R. Schmidt, CERN Accelerator School: Machine Protection and Collimation (2011)
[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)

LHC main beam dump

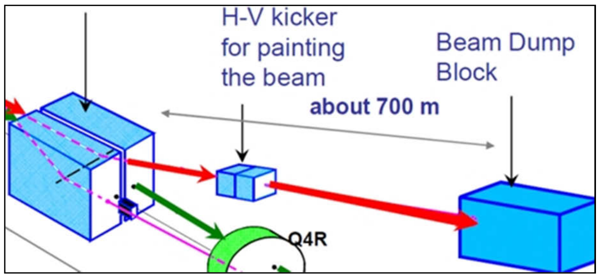
- Robust and failsafe design, proper material choice and efficient cooling
- Parameters: 8 m long, 6 tons (beam dump absorber), 900 tons (shielding), to absorb > 360 MJ
- Beam dump absorber consist of 7 m long and 70 cm in diameter segmented graphite cylinder

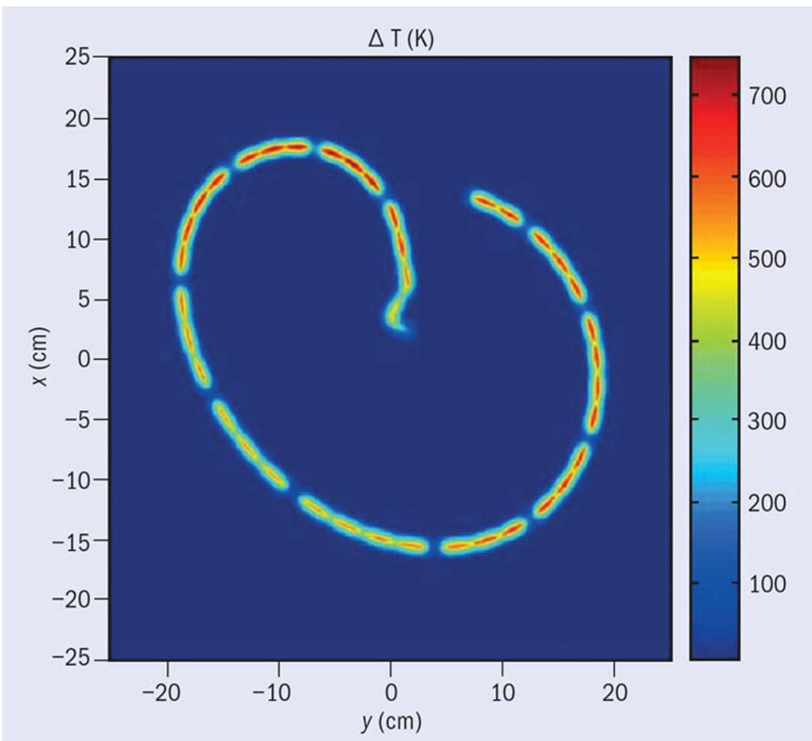


[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)
[Ref] J. Wenninger, LNF Spring School (2010)

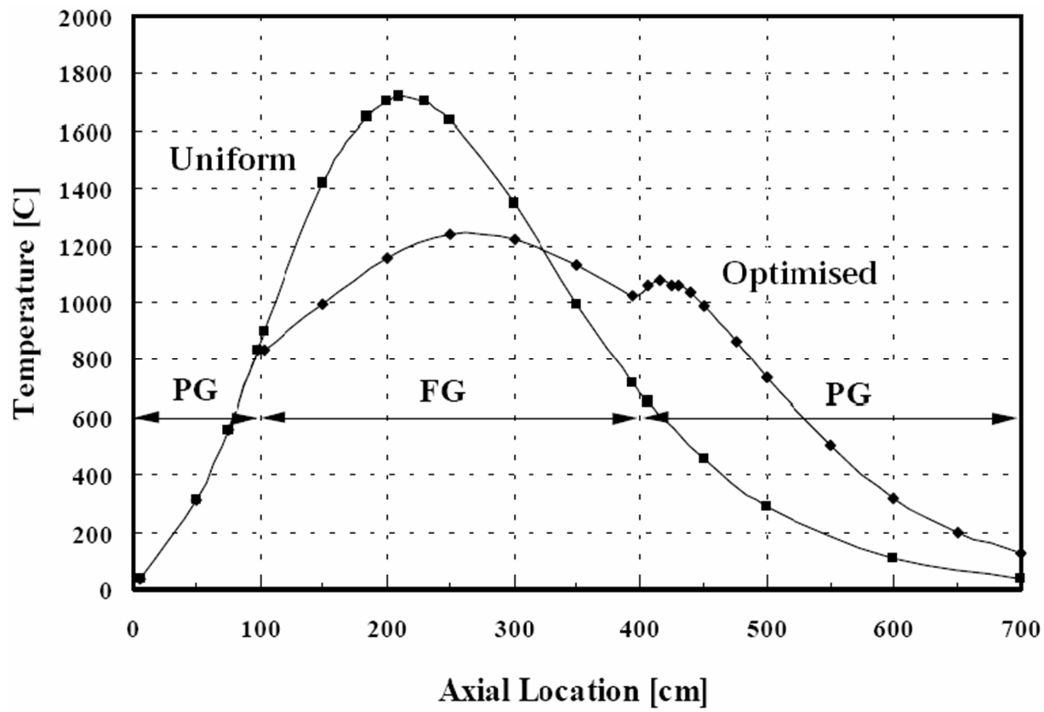
Methods to minimize the temperature rise

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





Temperature depth profile after the beam impact



PG (ρ = 1.8 g/cm^3), FG (ρ = 1.1 g/cm^3)

[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)
[Ref] J. Wenninger, LNF Spring School (2010)

Tools for machine protection & collimation design

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

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

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

- Coupling between the particle tracking and particle interaction with materials

Summary

- Machine protection & collimation systems deal with protection of equipment and devices as well as safety and environmental risks related to the accelerator operation
- Prevent uncontrolled beam losses (regular and accidental) and secure a well defined and shielded storing location for the lost particles
- Regular, continuous beam losses are caused by beam instabilities and treated using the collimation system
- Accidental beam losses are caused by machine failures and treated using the emergency extraction and dumping system
- Include very complex and complicated technical solutions
- Require understanding of many aspects of the accelerators and physics in general (beam dynamics, operation, instrumentation, particle interaction with materials, ...).
- Extremely important for future big accelerator projects (higher beam energy, beam power, beam intensity, ...).

Thank you for your attention