# Beam Losses and Machine Protection Issues

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CERN Accelerator School: Introduction to Accelerator Physics
Budapest, Hungary, 2016

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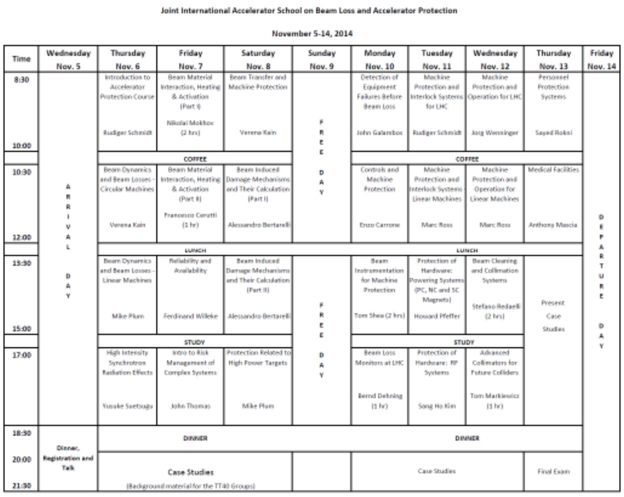
## Preface

- In 2014: *Joint International Accelerator School on Beam Loss and Accelerator Protection*
- The programme is presented below in order to give an overview of the topic and its scope



**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<br>10:00 | ARRIVAL DAY | Introduction to Accelerator Protection Course<br>Rudiger Schmidt | Beam Material Interaction, Heating & Activation (Part I)<br>Nikolai Mokhov (2 hrs) | Beam Transfer and Machine Protection<br>Verena Kain | FREE DAY | Detection of Equipment Failures Before Beam Loss<br>John Galambos | Machine Protection and Interlock Systems for LHC<br>Rudiger Schmidt | Machine Protection and Operation for LHC<br>Jorg Wenninger | Personnel Protection Systems<br>Sayed Rokni | DEPARTURE DAY |
|  |  | COFFEE |  |  |  | COFFEE |  |  |  |  |
| 10:30<br>12:00 |  | Beam Dynamics and Beam Losses - Circular Machines<br>Verena Kain | Beam Material Interaction, Heating & Activation (Part II)<br>Francesco Cerutti (1 hr) | Beam Induced Damage Mechanisms and Their Calculation (Part I)<br>Alessandro Bertarelli |  | Controls and Machine Protection<br>Enzo Carrone | Machine Protection and Interlock Systems - Linear Machines<br>Marc Ross | Machine Protection and Operation for Linear Machines<br>Marc Ross | Medical Facilities<br>Anthony Mascia |  |
|  |  | LUNCH |  |  |  | LUNCH |  |  |  |  |
| 13:30<br>15:00 |  | Beam Dynamics and Beam Losses - Linear Machines<br>Mike Plum | Reliability and Availability<br>Ferdinand Willeke | Beam Induced Damage Mechanisms and Their Calculation (Part II)<br>Alessandro Bertarelli | FREE DAY | Beam Instrumentation for Machine Protection<br>Tom Shea (2 hrs) | Protection of Hardware: Powering Systems (PC, NC and SC Magnets)<br>Howard Pfeffer | Beam Cleaning and Collimation Systems<br>Stefano Redaelli (2 hrs) | Present Case Studies |  |
|  |  | STUDY |  |  |  | STUDY |  |  |  |  |
| 17:00 |  | High Intensity Synchrotron Radiation Effects<br>Yusuke Suetsugu | Intro to Risk Management of Complex Systems<br>John Thomas | Protection Related to High Power Targets<br>Mike Plum |  | Beam Loss Monitors at LHC<br>Bernd Dehning (1 hr) | Protection of Hardware: RF Systems<br>Sang Ho Kim | Advanced Collimators for Future Colliders<br>Tom Markiewicz (1 hr) |  |  |
| 18:30 | Dinner, Registration and Talk | DINNER |  |  |  | DINNER |  |  |  |  |
| 20:00<br>21:30 |  | Case Studies<br>(Background material for the TT40 Groups) |  |  |  | Case Studies |  |  | Final Exam |  |

# Introduction

- Particle beams produced by large scale and powerful accelerators
  - High kinetic 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 > 3×10¹⁴ particles in the proton beam*)
  - High beam particle 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 the power flow have to be under control
- Why? The beam or a fraction of the beam particles can be lost
- The lost particles interact with the materials of accelerator components

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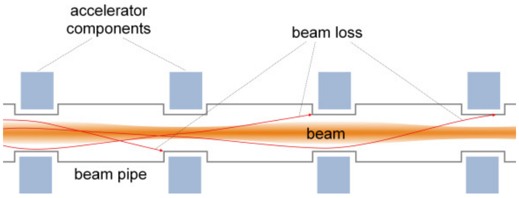
# Beam loss

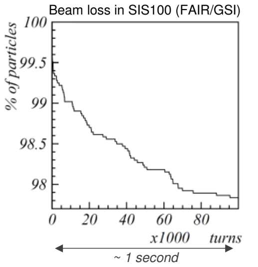
- Beam loss – the beam particles which deviate excessively from the reference trajectory and hit physical aperture constraints (are no longer properly transported)



- Causes (origins) of the beam loss – machine errors, beam instabilities and collective effects
  - Magnetic field errors and misalignments of the magnets
  - Nonlinear components of the magnetic field
  - Intrabeam scattering and Touschek effect
  - Space charge tune shift and resonances
  - Wake fields and impedances
  - Interaction of beam particles with residual gas atoms
  - Beam–beam effects (colliders)
  - Failure of magnets, RF cavities, vacuum systems, ...
  - . . .

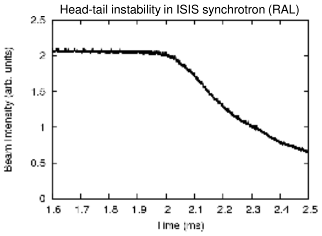
# Basic categorization of the beam losses

- Regular beam loss (common, continuous)
  - occurs in each cycle during the whole operation
  - usually a few % of the beam intensity
  - usually within the whole operational cycle (from injection to extraction)
  - usually caused by machine errors, imperfections (limited accuracy and precision) and collective effects



*[Ref] G. Franchetti et al., Proceedings of the PAC09, p 3242*

- Accidental beam loss (uncommon, occasional)
  - occurs only rarely, once in a while
  - can be lost the whole beam or a significant fraction of the beam particles
  - usually within a short period of the operational cycle (e.g. during injection, acceleration, extraction, ...)
  - usually caused by hardware failures and severe beam instabilities



*[Ref] V. Kornilov et al., Proceedings of the HB2014, p 240*

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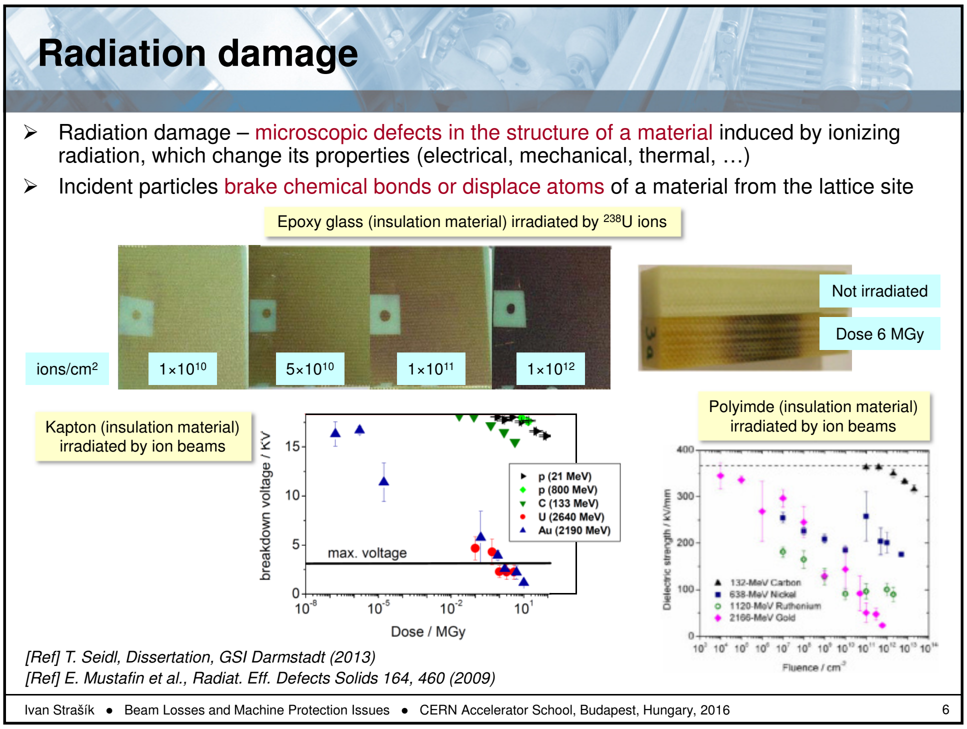
# Consequences of the beam loss

- An uncontrolled energy release or power flow due to interaction of the lost particles with the accelerator components can lead to serious consequences
- Consequences of the uncontrolled beam loss
  - Radiation damage of the accelerator components (microscopic defects)
  - Destructive damage or deformation of the accelerator components (macroscopic changes)
  - Quench of superconducting magnets (superconducting → normal conducting state)
  - Residual activation induced in the accelerator structure (radio-activation)
- The amount of beam loss has a direct impact on the time assigned to the accelerator operation (beam time) and also on the operating cost

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



# Radiation damage

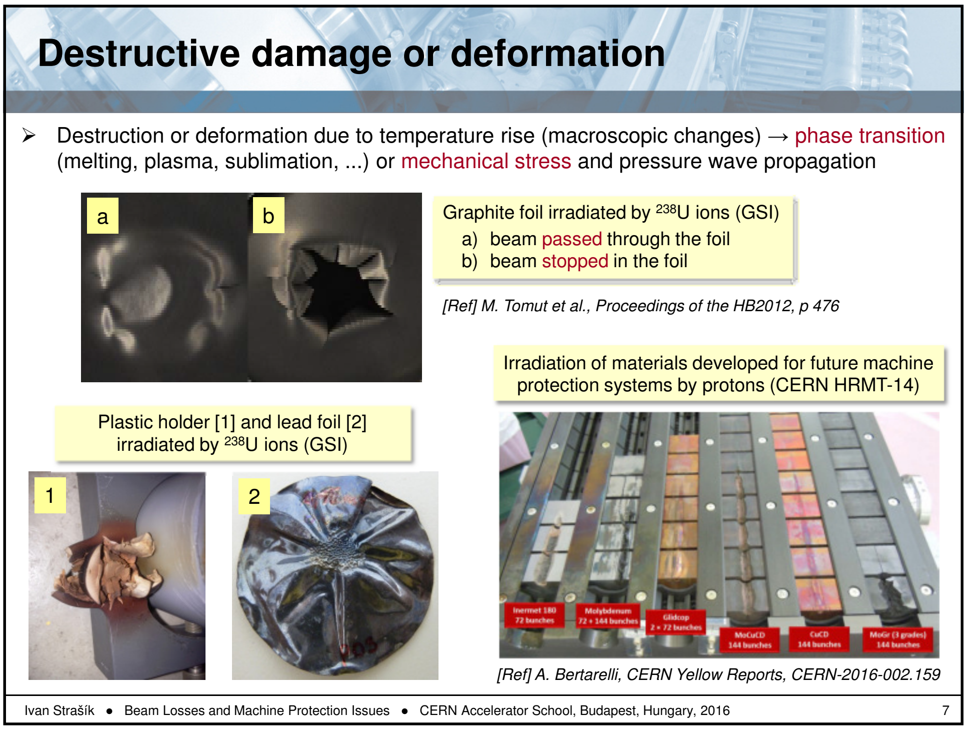
- Radiation damage – microscopic defects in the structure of a material induced by ionizing radiation, which change its properties (electrical, mechanical, thermal, …)
- Incident particles brake chemical bonds or displace atoms of a material from the lattice site

Epoxy glass (insulation material) irradiated by $^{238}$U ions

Kapton (insulation material) irradiated by ion beams

Polyimde (insulation material) irradiated by ion beams

*[Ref] T. Seidl, Dissertation, GSI Darmstadt (2013)*
*[Ref] E. Mustafin et al., Radiat. Eff. Defects Solids 164, 460 (2009)*



# Destructive damage or deformation

- Destruction or deformation due to temperature rise (macroscopic changes) → phase transition (melting, plasma, sublimation, ...) or mechanical stress and pressure wave propagation

Graphite foil irradiated by $^{238}$U ions (GSI)
a) beam passed through the foil
b) beam stopped in the foil

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

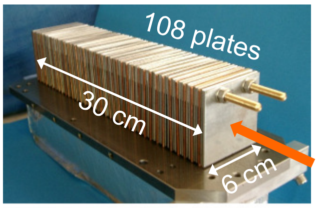
Irradiation of materials developed for future machine protection systems by protons (CERN HRMT-14)

Plastic holder [1] and lead foil [2] irradiated by $^{238}$U ions (GSI)

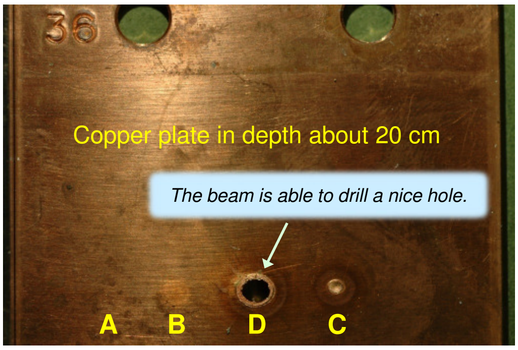
*[Ref] A. Bertarelli, CERN Yellow Reports, CERN-2016-002.159*

# Material damage test at CERN

- Experiment - impact of the 450 GeV proton beam from SPS synchrotron with the 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 | $1.2\times10^{12}$ |
| B | $2.4\times10^{12}$ |
| C | $4.8\times10^{12}$ |
| D | $7.2\times10^{12}$ |



Copper plate in depth about 20 cm

*The beam is able to drill a nice hole.*

*[Ref] V. Kain et al., Proceedings of the PAC'05, 1607 (2005)*
*[Ref] R. Schmidt et al., New J. Phys. 8, 290 (2006)*

# Energy loss and energy deposition

- Energy loss – Bethe formula

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

*[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
$\rho$ – density of the absorber material
$\beta$ and $\gamma$ – 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

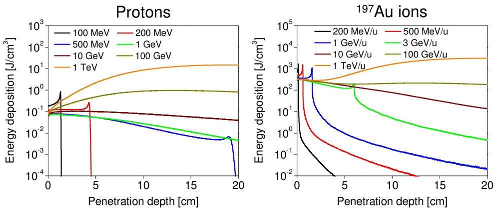
- Energy deposition

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

$N$ – number of particles
$A$ – cross-sectional area

Energy deposition of the proton and $^{197}$Au ion beams in copper target

Beam parameters
- $10^{10}$ particles
- Gaussian distribution
- 1 cm diameter ≈ 2 σ



*Other effects play also an important role: scattering, nuclear interactions, fragmentation, secondary particles, delta rays, ...*

- Temperature rise

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

$\rho$ – material density
$c_p$ – specific heat capacity

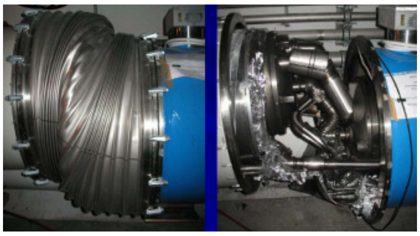
# Superconducting magnet quench

- Superconducting quench – transition from the superconducting to the normal conducting state
- Superconducting magnets store a large amount of energy and they need to be protected from being damaged when a quench occurs

LHC incident involving superconducting magnets in 2008
*(shown to demonstrate a risk of operation with superconducting magnets)*

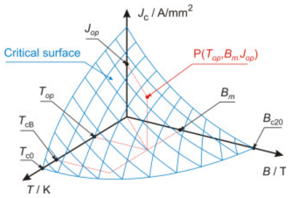
- The incident was NOT caused by a magnet quench
- The cause of the incident was a faulty electrical connection between two magnets
- An electric arc was produced which damaged the cryostat
- It resulted in a release of helium into the tunnel and consequently a pressure wave propagation
- Vacuum pipe polluted, some magnets displaced by several centimeters and over 50 had to be repaired
- The machine was out of operation for more than 1 year

Damage of the LHC beamline due to the incident



*[Ref] R. Schmidt, arXiv:1601.05207v1*
*[Ref] J. Wenninger, JAS Course on Beam Loss and Accelerator Protection*

- When a quench occurs, machine operation is interrupted for some time even if nothing is damaged
- Quench can be caused by increase of the (a) temperature, (b) current density or (c) magnetic field in the superconductor above the critical value



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# Quench level

- Quench induced by a beam loss – 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 above the critical value and consequently to induce quench
- The quench level can be expressed in case of the fast beam loss (transition state) in mJ/cm$^3$ and in case of the slow beam loss (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 loss 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*

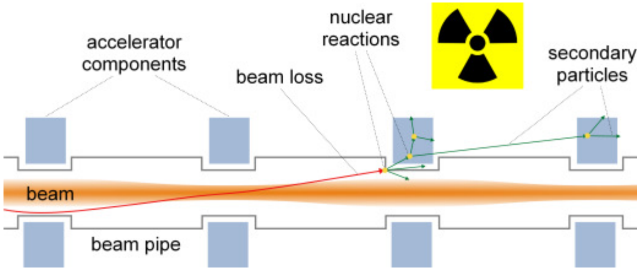
| Beam energy [TeV] | Quench level [particles/m] | Damage level [particles/m] |
|---|---|---|
| 0.45 | $10^9$ | $10^{12}$ |
| 7 | $10^6$ | $10^{10}$ |

*For comparison: total beam intensity ≈ $3 \times 10^{14}$*

*[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 accelerator components due to interaction with high energy particles



- Activation process – various types of nuclear reactions
  - spallation reactions (the most relevant to high energy accelerators)
  - radiative capture of low-energy neutrons
  - photonuclear reactions

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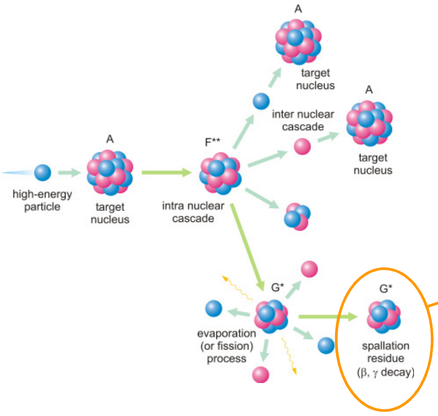
# Nuclear reactions and radionuclide production

- Spallation reactions
  - Nuclear cascades
  - Evaporation or fission process
  - Shower of the secondary particles



Radionuclides detected in the accelerator construction materials

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

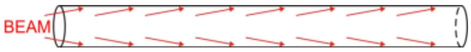
*[Ref] I. Strasik et al., NIMB 266, 3443 (2008)*
*[Ref] V. Chetvertkova et al., NIMB 269, 1336 (2011)*

# Tolerable beam loss 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.*

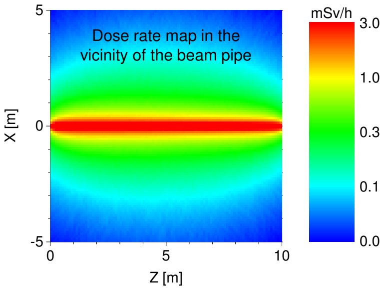
- 1 W/m ≈ $6\times10^9$ protons/(m·s) of energy 1 GeV (uniformly distributed)

Simulation of the 10 m long steel beam pipe residual activity induced by beam loss of 1 W/m



Irradiation time: 100 days
Cooling time: 4 hours

Effective dose rate at 30 cm is about 1 mSv/h



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

*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 |

- Tolerable beam loss for heavy ions with $E_k$ < 1 GeV/u is higher: e.g. 1 GeV/u $^{238}$U → 5 W/m

# 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 quench of the superconducting magnets
- Protect the people and the environment
  - Control of the 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 the operation time (beam time)

## Beam loss and machine protection

- Prevent uncontrolled regular beam loss
  - Cause: machine errors, beam instabilities and collective effects → beam halo
  - Consequences: superconducting magnet quench, residual activation
  - Cure: halo collimation system (beam cleaning)

- Prevent uncontrolled accidental beam loss
  - Cause: hardware failures and severe beam instabilities
  - Consequences: radiation damage, destructive damage, superconducting magnet quench
  - Cure: beam loss detection, beam extraction & dumping system, stop beam operation, beam interlock system, collimators and absorbers for a passive protection

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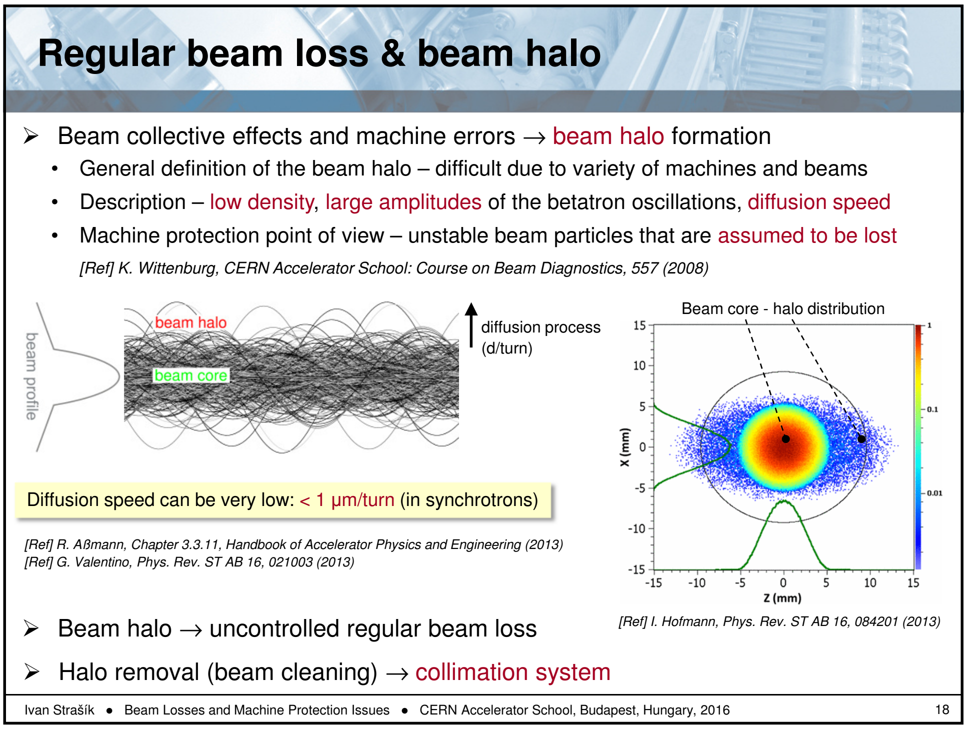
## Simulation tools for machine protection

- Beam dynamics and particle motion in an accelerator
  - Prediction of the beam instabilities and simulation of the collective effects
  - Particle tracking, beam loss distribution along the beamline, halo collimation
  - Simulation tools: MAD-X, SixTrack, STRUCT, PyORBIT, Micromap, Elegant, …

- Interaction and transport of particles in matter
  - Energy loss and energy deposition of the particles in construction materials
  - Scattering and particle fluence passing through the accelerator components
  - Inelastic nuclear interaction and production of the secondary particles
  - Simulation tools: FLUKA, GEANT4, MARS15, PHITS, MCNP6, …

- Material response to the interaction with the particles
  - Radiation damage of the accelerator components
  - Residual activation of the accelerator beamline
  - Quench of the superconducting magnets
  - Simulation tools: ANSYS, BIG2, LS-DYNA, FLUKA, SPQR, Quench, …

- Coupling of the simulation codes
  - Simulation tools: SixTrack & FLUKA coupling, MMBLB (MARS & MAD), BDSIM (Geant4 & C++ routines)



# Regular beam loss & beam halo

- Beam collective effects 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
  - Machine protection point of view – unstable beam particles that are assumed to be lost

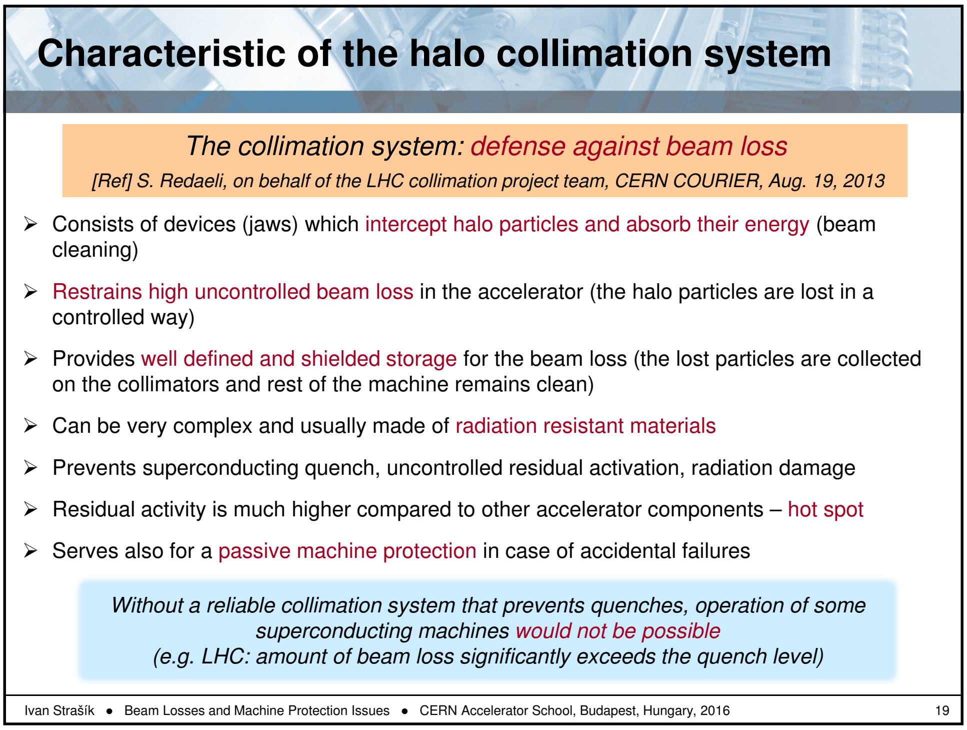
  *[Ref] K. Wittenburg, CERN Accelerator School: Course on Beam Diagnostics, 557 (2008)*

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)*

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

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



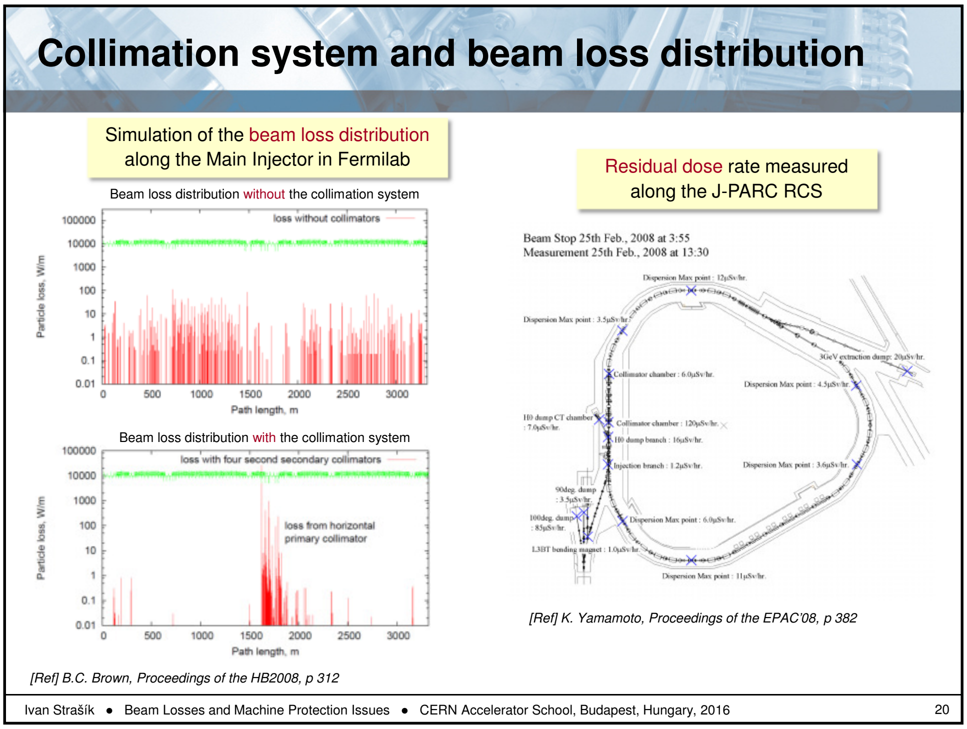
# Characteristic of the halo collimation system

*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 (jaws) which intercept halo particles and absorb their energy (beam cleaning)
- Restrains high uncontrolled beam loss in the accelerator (the halo particles are lost in a controlled way)
- Provides well defined and shielded storage for the beam loss (the lost particles are collected on the collimators and rest of the machine remains clean)
- Can be very complex and usually made of radiation resistant materials
- Prevents superconducting quench, uncontrolled residual activation, radiation damage
- Residual activity is much higher compared to other accelerator components – hot spot
- Serves also for a passive machine protection in case of accidental failures

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



# Collimation system and beam loss distribution

Simulation of the beam loss distribution along the Main Injector in Fermilab

Beam loss distribution without the collimation system

Beam loss distribution with the collimation system

[Ref] B.C. Brown, Proceedings of the HB2008, p 312

Residual dose rate measured along the J-PARC RCS

Beam Stop 25th Feb., 2008 at 3:55
Measurement 25th Feb., 2008 at 13:30

[Ref] K. Yamamoto, Proceedings of the EPAC'08, p 382

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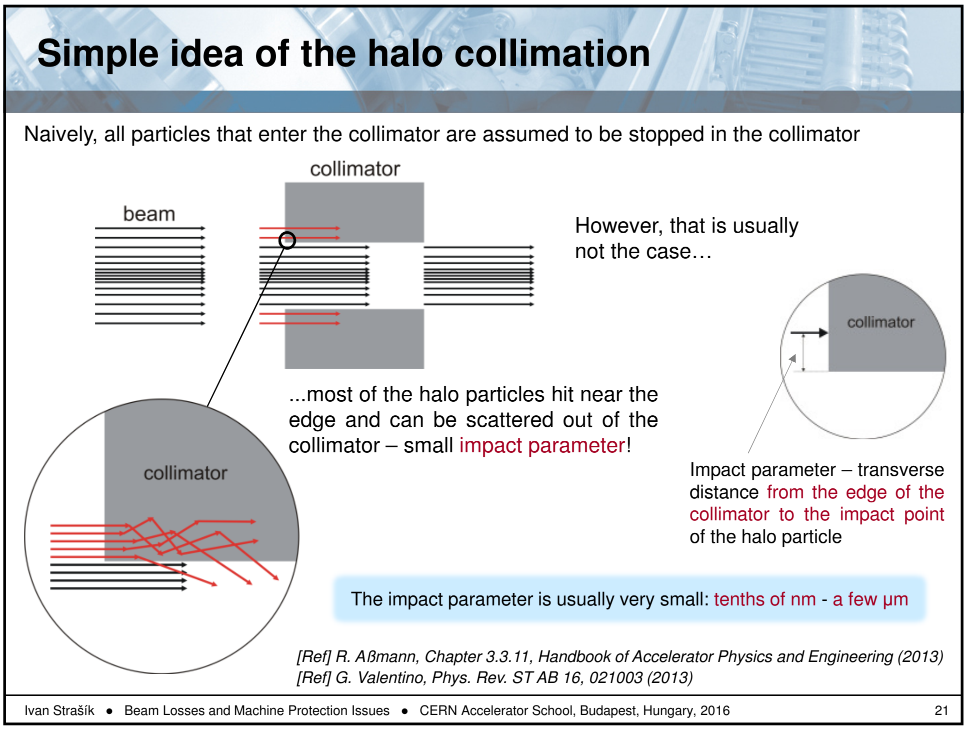


# Simple idea of the halo collimation

Naively, all particles that enter the collimator are assumed to be stopped in the collimator

However, that is usually not the case…

...most of the halo particles hit near the edge and can be scattered out of the collimator – small impact parameter!

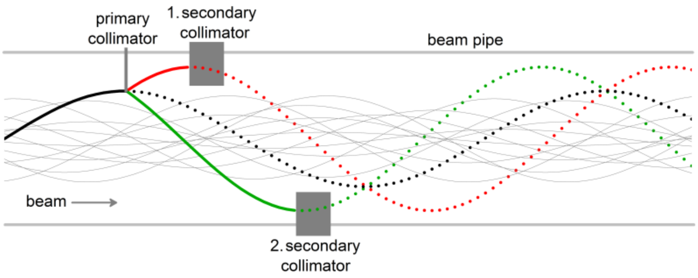
Impact parameter – transverse distance from the edge of the collimator to the impact point of the halo particle

The 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 halo particles



- Particles have a 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] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998)*

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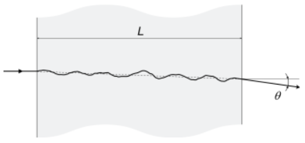
# Scattering in the primary collimator

- Molière theory of multiple Coulomb scattering



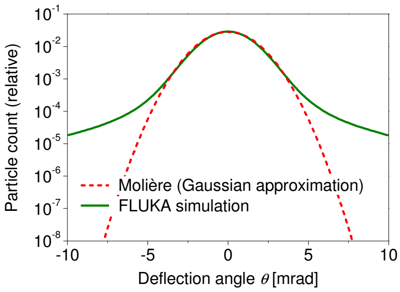
$$\theta_{rms} = \frac{13.6}{\beta c p} Z \sqrt{\frac{L}{L_R}} \left(1 + 0.038 \times \ln\left(\frac{L}{L_R}\right)\right)$$

$\theta_{rms}$ – projected deflection angles (rms)
$p$ – momentum in MeV/c
$\boldsymbol{\beta}$ – 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

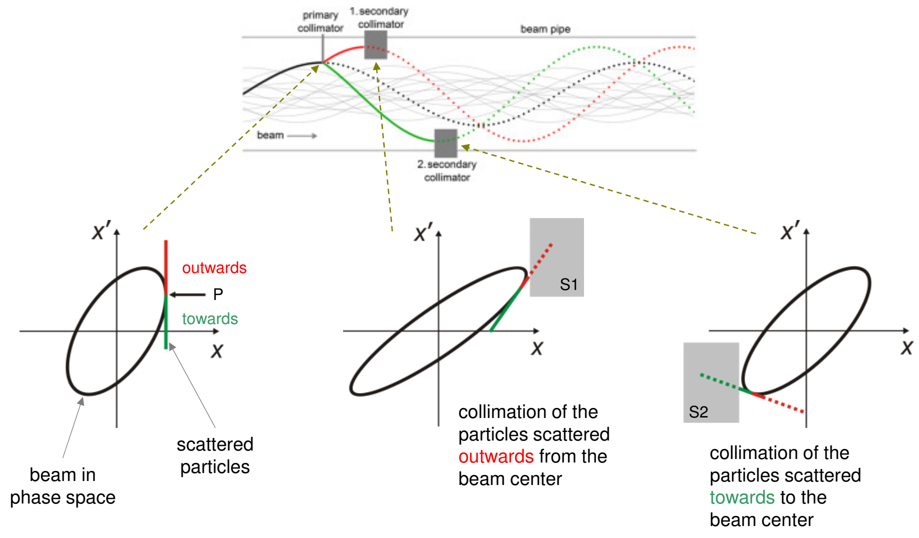
  - roughly Gaussian for small deflection angles

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

- Molière theory vs FLUKA Monte Carlo code
  - SIS100 (FAIR/GSI) collimation system
  - 4.5 GeV protons (injection energy)
  - 1 mm thick tungsten foil (primary collimator)



# Phase space plots at the collimators



outwards

towards

beam in phase space

scattered particles

collimation of the particles scattered outwards from the beam center

collimation of the particles scattered towards to the beam center

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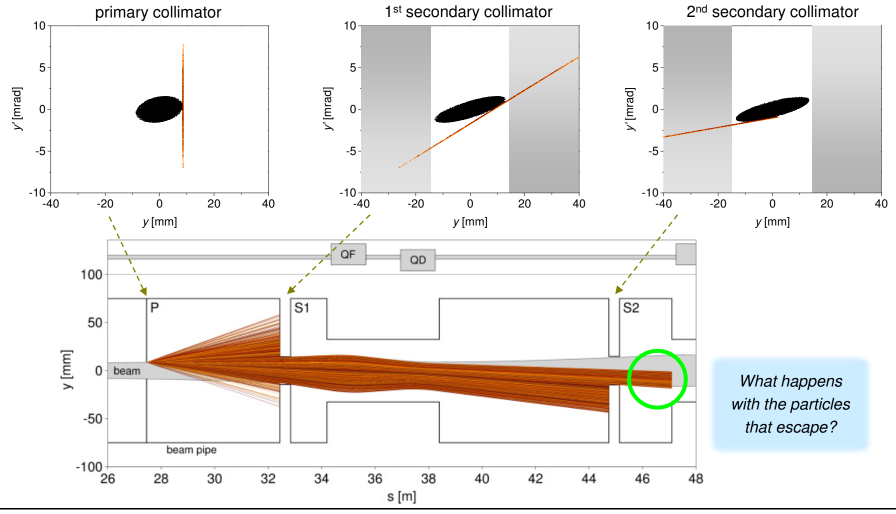
# Simulation of the singlepass halo collimation

- Collimation of the halo particles in the vertical plane of the SIS100 synchrotron (FAIR/GSI)
- The particles are tracked from the primary to the 2nd secondary collimator (singlepass)



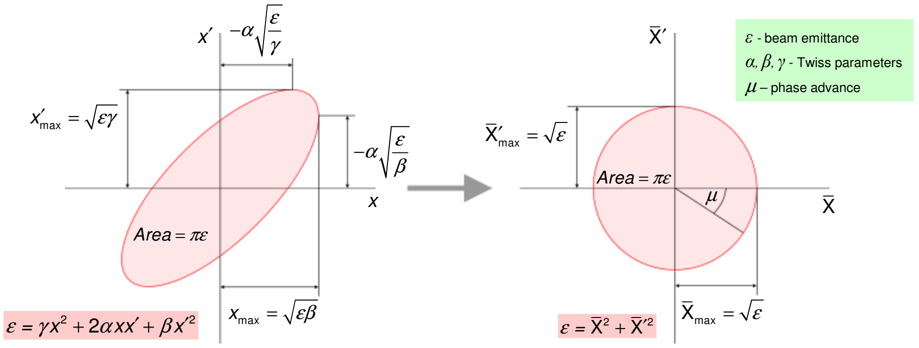
*What happens with the particles that escape?*

# Normalized phase space

- Let us find an optimal beam optical configuration of the two stage collimation system

Real phase space

Normalized phase space



$\varepsilon$ - beam emittance
$\alpha, \beta, \gamma$ - Twiss parameters
$\mu$ – phase advance

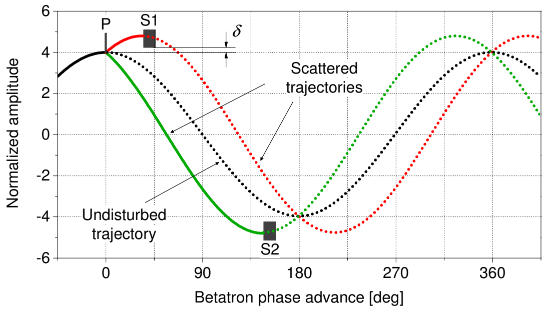
$\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2$

$\varepsilon = \bar{X}^2 + \bar{X}'^2$

Real to normalized coordinates: $\begin{pmatrix} \bar{X} \\ \bar{X}' \end{pmatrix} = \frac{1}{\sqrt{\beta}} \begin{pmatrix} 1 & 0 \\ \alpha & \beta \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$ → $\bar{X} = \frac{1}{\sqrt{\beta}} x \qquad \bar{X}' = \frac{1}{\sqrt{\beta}} \alpha x + \sqrt{\beta} x'$

Transport of the particles in the normalized phase space: $\begin{pmatrix} \bar{X}_{s_1} \\ \bar{X}'_{s_1} \end{pmatrix} = \mathrm{M} \begin{pmatrix} \bar{X}_{s_0} \\ \bar{X}'_{s_0} \end{pmatrix} \qquad \mathrm{M} = \begin{pmatrix} \cos\mu & \sin\mu \\ -\sin\mu & \cos\mu \end{pmatrix}$

# Normalized betatron oscillation amplitudes



$$n_P = \frac{d_P}{\sqrt{\varepsilon\beta_P}} \quad n_{S1} = \frac{d_{S1}}{\sqrt{\varepsilon\beta_{S1}}} \quad n_{S2} = \frac{d_{S2}}{\sqrt{\varepsilon\beta_{S2}}}$$

$$n_S = n_{S1} = n_{S2}$$

$n_P$, $n_S$ – normalized apertures of the primary and secondary collimators

$d_P$, $d_{S1}$, $d_{S2}$ – physical apertures of the primary and secondary collimators

$\varepsilon$ – rms beam emittance (1$\sigma$ beam)

$\beta_P$, $\beta_{S1}$, $\beta_{S2}$ – beta Twiss parameters at the collimators

$\sqrt{\varepsilon\beta_P}$, $\sqrt{\varepsilon\beta_{S1}}$, $\sqrt{\varepsilon\beta_{S2}}$ – rms transverse beam size (1$\sigma$ beam)

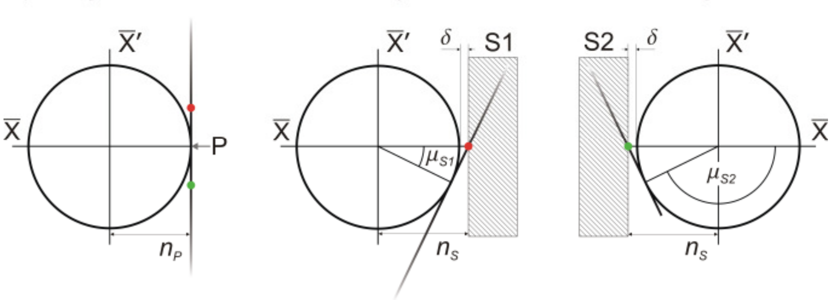
$$\delta = \frac{n_S}{n_P} - 1$$

$\delta$ – retraction distance

- By definition $n_P < n_S$, otherwise we break the hierarchy
- Typical normalized apertures of the collimators: $n_P$, $n_S > 4$ (e.g. LHC: $n_P = 6$, $n_S = 7$)
- Typical values of the retraction distance: $\delta = 0.1 – 0.3$

*[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998)*
*[Ref] M. Seidel, DESY Report (Dissertation), 94-103, (1994)*
*[Ref] R. Aßmann, in Handbook of Accelerator Physics, and Engineering (2013)*

# Normalized phase space plots at the collimators



$n_P$, $n_S$ – normalized aperture of the primary and secondary collimators $\delta$ – retraction distance
$\mu_{S1}$, $\mu_{S2}$ – 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 advance:

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

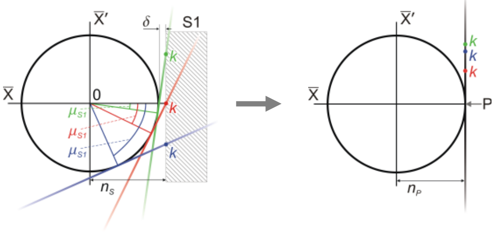
$$\mu_{S2} = \pi - \mu_{S1}$$

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

# Optimal phase advance and critical angle

- Critical angle $k$

*(minimal deflection angle under which a particle has to be scattered in order to be collimated).*



$$\begin{pmatrix}\bar{X}_{S1}\\ \bar{X}'_{S1}\end{pmatrix} = \begin{pmatrix}\cos\mu_{S1} & \sin\mu_{S1}\\ -\sin\mu_{S1} & \cos\mu_{S1}\end{pmatrix}\begin{pmatrix}\bar{X}_{P}\\ \bar{X}'_{P}\end{pmatrix}$$

$$\bar{X}_{S1} = \bar{X}_P\cos\mu_{S1} + \bar{X}'_P\sin\mu_{S1} \rightarrow n_S = n_P\cos\mu_{S1} + k\sin\mu_{S1} \rightarrow k = \frac{n_S - n_P\cos\mu_{S1}}{\sin\mu_{S1}}$$

$\bar{X}_P = n_P$ $\bar{X}'_P = k$ initial parameters
$\bar{X}_{S1} = n_S$ $n_S = n_{S1} = n_{S2}$

- Critical angle $k$ for the optimal phase advance $\mu_{S1}$ and $\mu_{S2}$

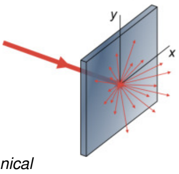
$$k = \frac{n_S - n_P\cos\mu_{S1}}{\sin\mu_{S1}} \rightarrow k = \sqrt{n_S^2 - n_P^2} \rightarrow k = n_P\sqrt{2\delta + \delta^2}$$

$\mu_{S1} = \arccos\frac{n_P}{n_S}$ optimal phase advance $n_S = n_P(\delta + 1)$

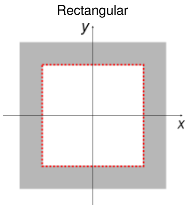
*[Ref] T. Trenkler and J.B. Jeanneret, Particle Accelerators 50, 287 (1995)*

# Design of 2D collimation system

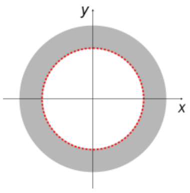
- ➢ Scattering of the halo particles in the primary occurs in both planes (horizontal and vertical)
- ➢ In order to reach the maximum collimation efficiency we need 2D approach
  - Collimators with a fixed aperture (rectangular, circular, ...)



Rectangular



Circular



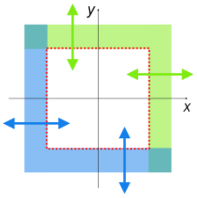
*Optimal for the maximum efficiency of the collimation system is circular aperture*

*Circular aperture → mechanical problems with movable aperture → octagonal approximation*

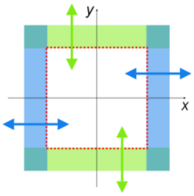
*[Ref] J.B. Jeanneret, Phys. Rev. ST Accel. Beams 1, 081001 (1998)*

- Collimators with a movable aperture (L-shape, H-shape, skewed, one or two sided, ...)

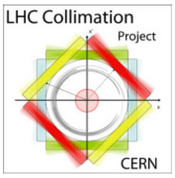
L-shape



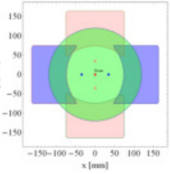
H-shape



LHC octagonal shape



CSNS/RCS design



*[Ref] Hong-Fei Ji et al, arXiv:1603.09020*

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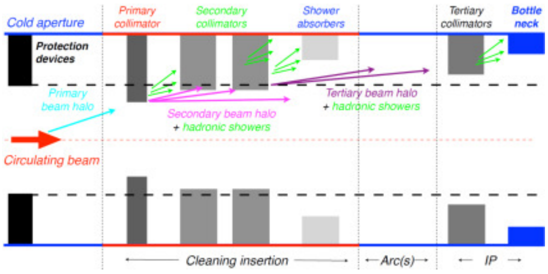
# Multi stage collimation: LHC collimation system

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

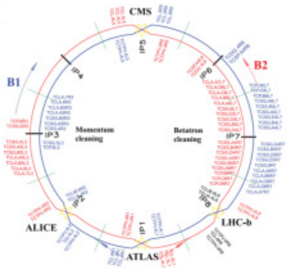
*[Ref] S. Redaeli, on behalf of the LHC collimation project team, CERN COURIER, Aug. 19, 2013*

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

Hierarchy of the LHC collimaton system



LHC collimaton system layout



- ➢ 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 loss

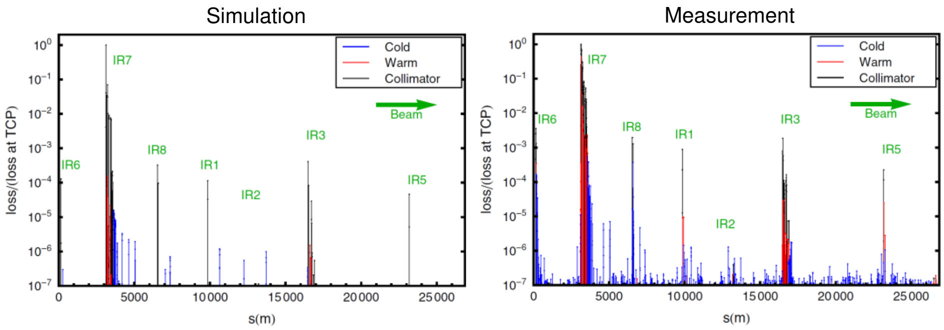
*Extremely high efficiency is required to prevent quench*

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

# Multiturn particle motion and collimation

- 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 and interaction with materials)
Measuring devices: Beam loss monitors (detection of the beam loss)



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

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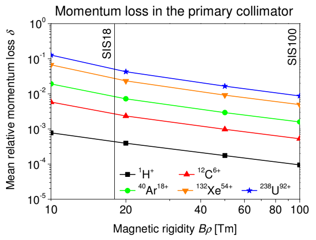
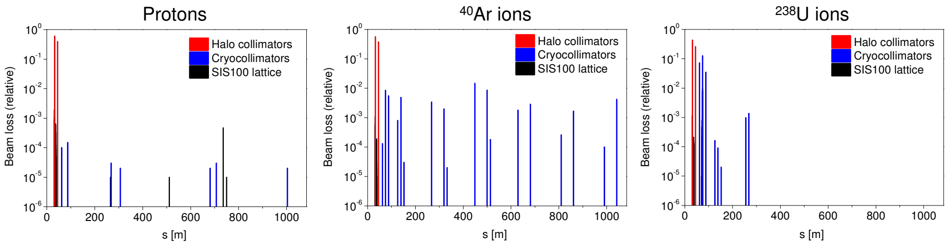
# Collimation of heavy ions

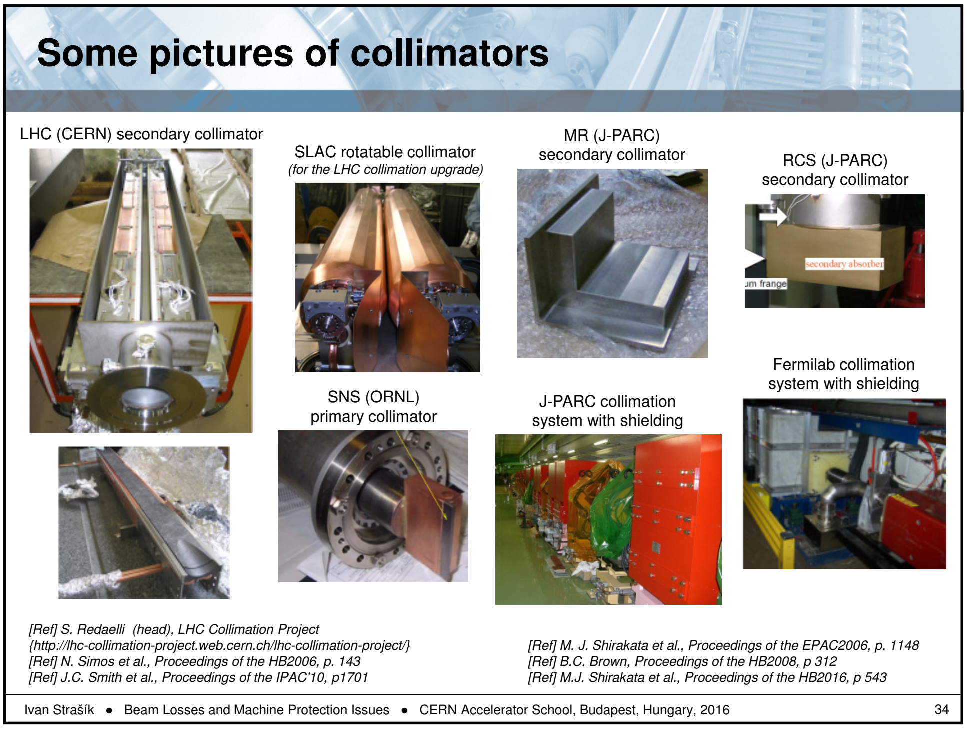
- Issues of the heavy ion collimation
  - Significantly higher momentum loss in the primary collimator than for protons: $-\Delta p \propto z^2$ (see Bethe formula)
  - Nuclear fragmentation of the ions in the primary collimator → change of the rigidity



Collimation in SIS100 (FAIR/GSI)



*[Ref] I. Strasik et al., Phys. Rev. ST AB 18, 081001 (2015)*



# Some pictures of collimators

LHC (CERN) secondary collimator

SLAC rotatable collimator
*(for the LHC collimation upgrade)*

MR (J-PARC)
secondary collimator

RCS (J-PARC)
secondary collimator

Fermilab collimation
system with shielding

SNS (ORNL)
primary collimator

J-PARC collimation
system with shielding

*[Ref] S. Redaelli (head), LHC Collimation Project*
*{http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/}*
*[Ref] N. Simos et al., Proceedings of the HB2006, p. 143*
*[Ref] J.C. Smith et al., Proceedings of the IPAC'10, p1701*

*[Ref] M. J. Shirakata et al., Proceedings of the EPAC2006, p. 1148*
*[Ref] B.C. Brown, Proceedings of the HB2008, p 312*
*[Ref] M.J. Shirakata et al., Proceedings of the HB2016, p 543*

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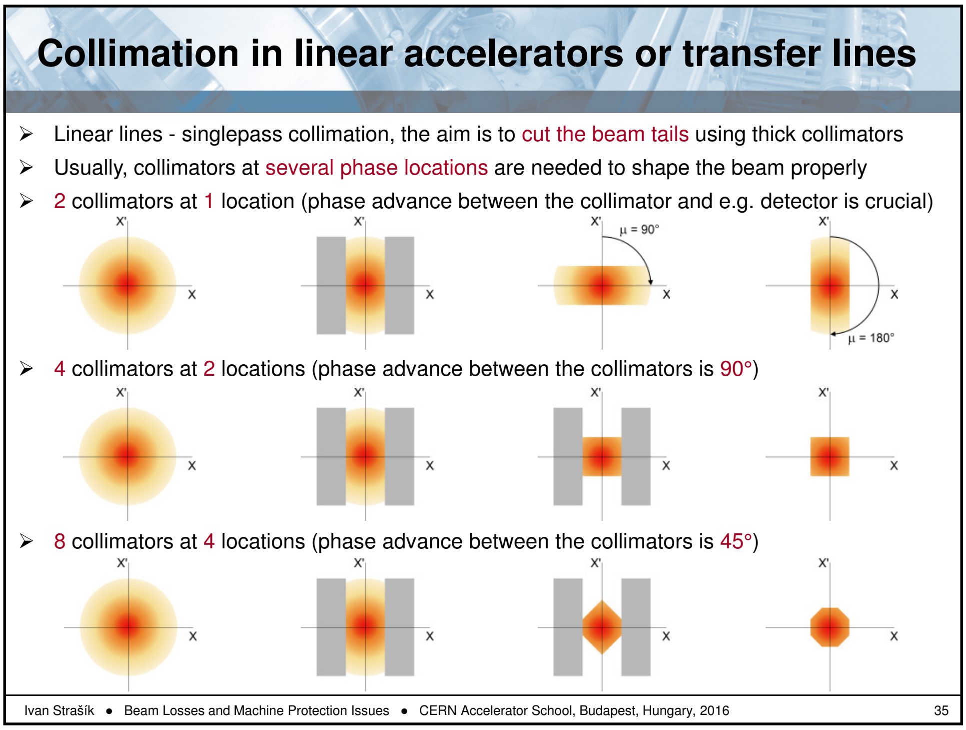


# Collimation in linear accelerators or transfer lines

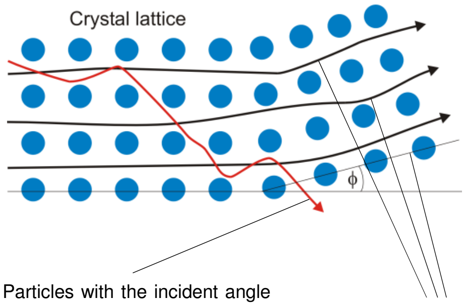
- Linear lines - singlepass collimation, the aim is to cut the beam tails using thick collimators
- Usually, collimators at several phase locations are needed to shape the beam properly
- 2 collimators at 1 location (phase advance between the collimator and e.g. detector is crucial)

- 4 collimators at 2 locations (phase advance between the collimators is 90°)

- 8 collimators at 4 locations (phase advance between the collimators is 45°)

# Advanced techniques: bent crystal channeling

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



Critical angle $\theta_C$ : $\theta_C = \sqrt{\frac{2E_C}{pv}}$

$E_C$ – 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

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

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)*

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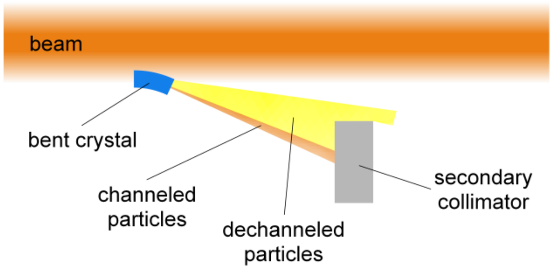
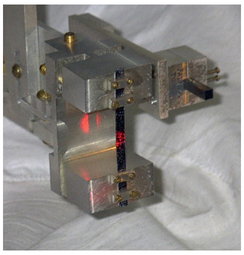
# Bent crystal collimation

- 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



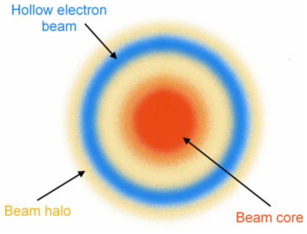
Dechanneling – caused by scattering of the channeled particle due to interaction with electrons, nuclei and lattice defects

*[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)*

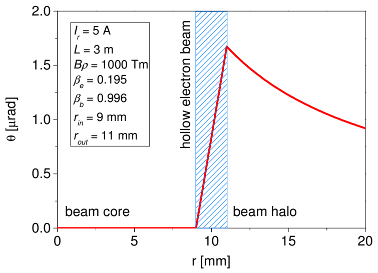
# Advanced techniques: hollow electron beam

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



$$\theta_r = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2 I_r L \left(1 \pm \beta_e \beta_b\right)}{r \beta_e \beta_p c^2 \left(B\rho\right)_b} \begin{cases} 0 & r < r_{in} \\ \dfrac{r - r_{in}}{r_{out} - r_{in}} & r_{in} \le r \le r_{out} \\ \dfrac{r_{out}}{r} & r > r_{out} \end{cases}$$

$I_r$ – enclosed electron current
$L$ – length of the e-lens
$r$ – radial distance
$r_{in}$ – inner radius
$r_{out}$ – outer radius
$\beta_e$, $\beta_b$ – beta rel. parameters
$B\rho$ – magnetic rigidity



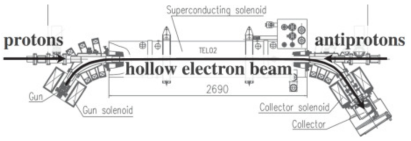
- Enhances diffusion speed of the halo particles → larger impact parameter
- No nuclear fragmentation of heavy ions and no material damage in the collimator

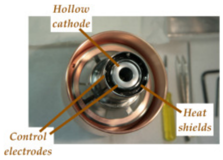
*[Ref] G. Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)*
*[Ref] V. Shiltsev, Electron Lenses for Super-Colliders (book), ISBN 978-1-4939-3317-4*

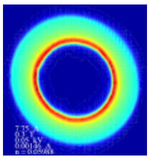
# Collimation using the hollow electron beam

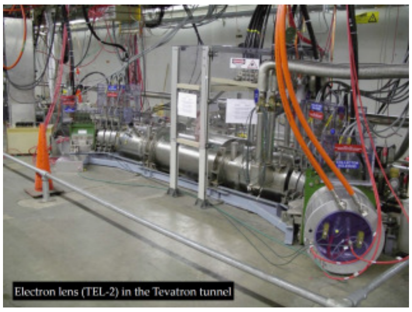
- Current density profile of the electron beam is shaped by electrode geometry and maintained by strong solenoidal fields
- The hollow electron beam collimation was developed for Tevatron in Fermilab and is going to be applied in LHC for future upgrade of the collimation system

Hollow electron beam collimation in Tevatron (Fermilab)









*[Ref] G. Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)*
*[Ref] V. Shiltsev, Electron Lenses for Super-Colliders (book), ISBN 978-1-4939-3317-4*

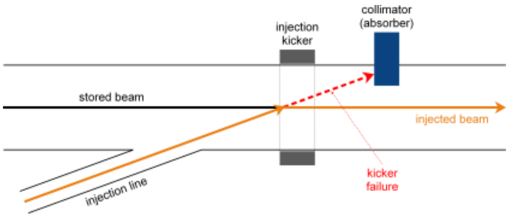
# Accidental beam loss and machine protection

- Caused by hardware failures, severe beam instabilities, and treated by an active or a passive machine protection
- Usually faster and quantitatively higher than the regular beam loss (lost is significant fraction of the beam particles or the whole beam in the time range of µs – s)
- Active machine protection
  - The beam loss is monitored using detectors and the available response time is long enough
  - When a predefined loss threshold is exceeded, the system activates an emergency extraction of the beam to the beam dump and interrupts the injection
  - Interconnection of the detectors and protection systems is ensured by the beam interlock
- Passive machine protection
  - In case of specific failures when the available response time is too short
  - The active protection (detection and reaction) is not possible
  - The passive protection relies on properly located collimators and absorbers
- Categorized from slow (beam lifetime longer than 1 second) up to ultra fast or singlepass (the beam is lost in 1 turn or in a line)

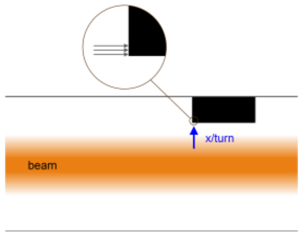
*[Ref] R. Schmidt et al., New J. Phys. 8, 290 (2006)*
*[Ref] S.C. Wagner, Dissertation, CERN (2010)*

# Categories of the accidental beam loss

- The ultra fast (singlepass) beam loss occurs usually in linear accelerators or transfer lines (e.g. can be caused by failures of magnets)



- Other categories of the accidental beam loss except the ultra fast (from fast to slow) occur usually in circular accelerators during at least several turns with various diffusion speed typically of the order of micrometers per turn (e.g. caused by beam instabilities)



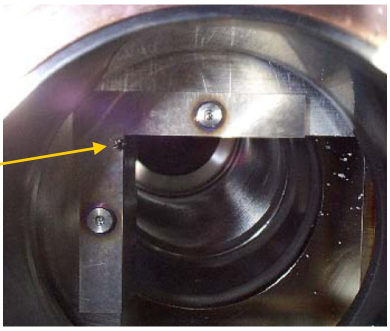
- The all categories of the beam loss, except the ultra fast, can be detected using diagnostik devices mostly Beam Loss Monitors (BLM)

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

# Example of the accidental beam loss

- Tevatron collimator accident in Fermilab
  - A diagnostic device (Roman pot) was moved accidentally towards the beam
  - Due to interaction with the beam particles a shower of secondary particles was produced and this induced a superconducting quench
  - The beam became unstable and the particles started to move in the transverse direction towards the collimator with the diffusion speed several µm per turn
  - First particles touched the collimator after 300 turns, the entire beam was lost in 400 turns and damaged the halo collimator

Damage of the halo collimator (made of tungsten) designed for the regular beam loss



*[Ref] N.V. Mokhov, Proceedings of the HB2006, p 205*

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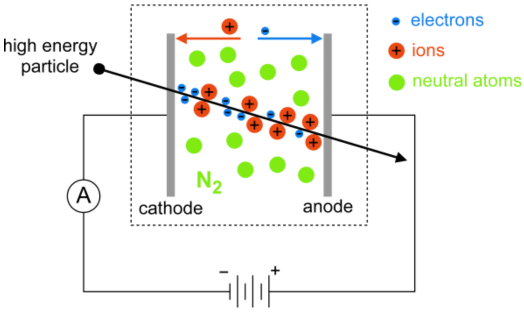
# Beam loss monitors

- Beam loss monitor (BLM) – a ionization chamber to detect the beam loss
- BLM provide a current signal proportional to the intensity of the particle shower passing through the chamber
- Very short reaction time (80 µs) and very large dynamic range (> $10^6$)

*[Ref] E.B. Holzer et al., Physics Procedia 37, 2055 (2012)*
*[Ref] B. Dehning, JAS Course on Beam Loss and Accelerator Protection (2014)*

Principle of the ionization chamber



Inside of the BLM: (LHC type)

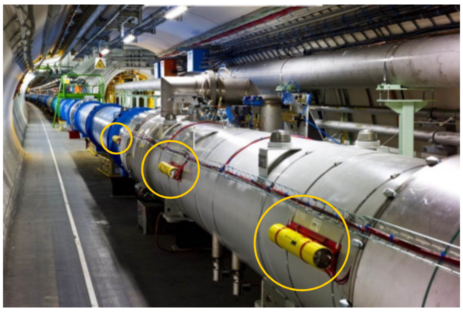
Parameters of the BLM (LHC type):

Length: 50 cm
Diameter: 9 cm
Gas: $N_2$

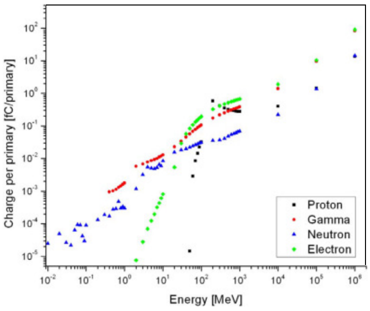
# Beam loss monitors and beam abort

- BLM system is a powerful diagnostic tool which monitors the beam loss along the beamline
- About 4000 BLMs installed around the LHC at the locations where the beam loss is predicted
- When the BLM system detects an excessive beam loss (exceed a predefined BLM signal threshold) then it triggers a beam abort (emergency extraction and dumping of the beam)

BLMs @ LHC:



Simulation using FLUKA code



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

*[Ref] E.B. Holzer et al., Physics Procedia 37, 2055 (2012)*
*[Ref] B. Dehning, JAS Course on Beam Loss and Accelerator Protection (2014)*

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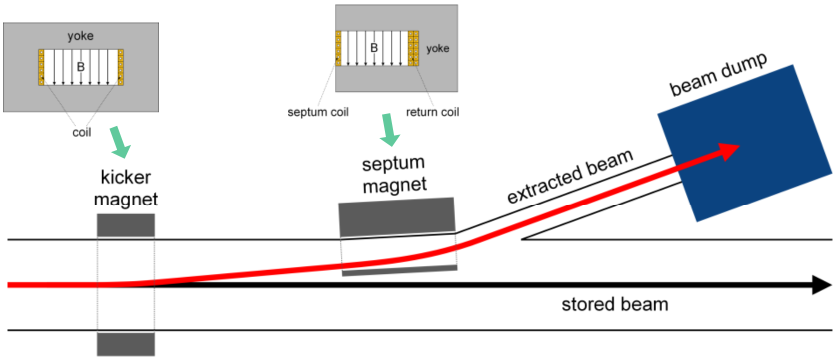
# Emergency extraction of the beam

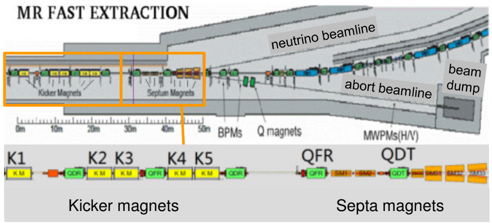
- Kicker and septa magnets combination is often used to extract the beam
- Kicker magnets – fast rise times, the field strength is relatively low
- Septa magnets – slow pulsed, the field is relatively strong
- The kicker deflects the beam into the septum
- The septum deflects the kicked beam into the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



# Regular and emergency extraction

- Beam extraction system can have two functions
  - Regular extraction during normal operation to the experimental area
  - Emergency extraction to the beam dump (stop of the operation in case of failure)
  - The same bipolar kicker magnets are used for both, regular and emergency extraction

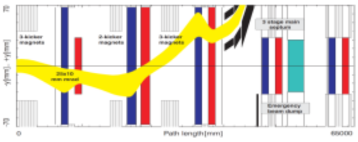
J-PARC Main Ring extraction system



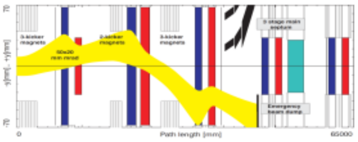
*[Ref] K. Fan et al., Proceedings of the IPAC'14, p. 821*
*[Ref] G.H. Wei et al., Proceedings of the IPAC'10, p. 3918*

SIS100 (FAIR/GSI) extraction system

Regular fast extraction



Emergency beam dumping



*[Ref] FAIR Technical Design Report (2008)*

# Beam dump

- Beam dump is an accelerator component designed to stop high energy primary particles (to absorb their kinetic energy) and it is crucial for the machine protection system
- 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 be very robust, highly reliable and withstand high thermal stress

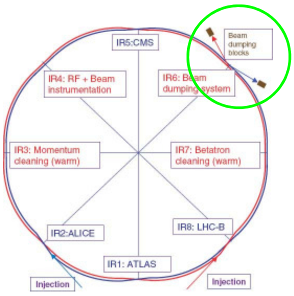
*[Ref] O. Aberle, Some reflection about beam dumping at CERN, (2012)*

Beam dump for SIS18 synchrotron at GSI
(made of iron 3×2×3 m with concrete shielding)

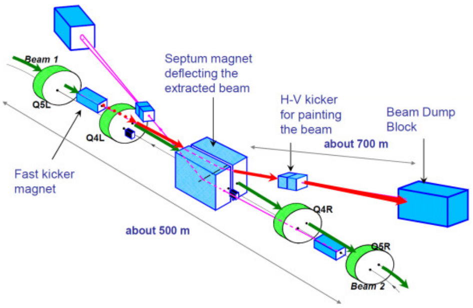
# LHC beam dumping system

- The system consists of two beam dumps, one for each colliding beam
- The beam dumps are the only components that can withstand a direct impact of the full LHC beam, other components would be damaged
- In case of a failure the LHC beams must always be extracted into the beam dump

Location of the beam dumps in LHC



Schematic layout of the LHC beam dumping system



*[Ref] B. Goddard et al., Proceedings of the PAC'03, 1646 (2003), and PAC'09, 1584 (2009)*
*[Ref] R. Schmidt et al., New J. Phys. 8, 290 (2006)*

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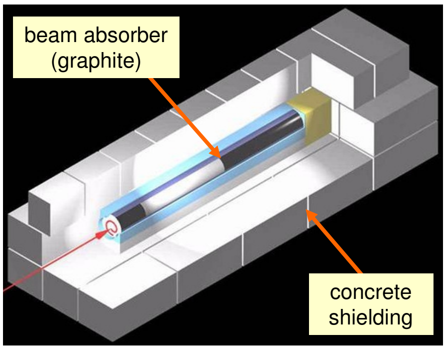
# LHC main beam dump

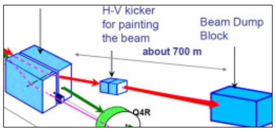
- Robust and failsafe design, made of resistant materials and with efficient cooling
- Parameters: 8 m long, 6 tons beam dump absorber, 900 tons shielding, to absorb > 360 MJ
- Beam dump absorber consist of 7 m long and 70 cm in diameter segmented graphite cylinder

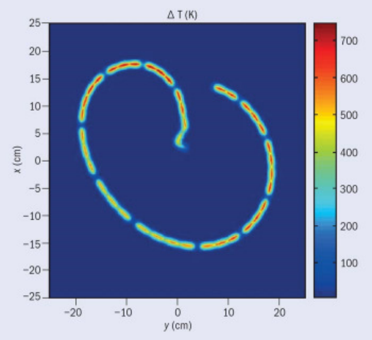


*[Ref] R. Schmidt et al., New J. Phys. 8, 290 (2006)*
*[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)*

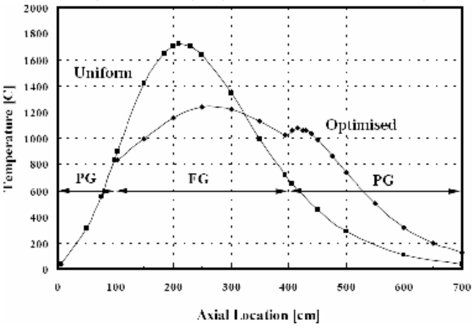
# Methods to minimize the temperature rise

- The extracted bunches of the beam are distributed in a spiral using h-v kicker magnets
- Density of the graphite absorber is graded





Temperature depth profile after the beam impact



PG ($\rho$ = 1.8 g/cm$^3$), FG ($\rho$ = 1.1 g/cm$^3$)

*Selection of the materials is important!*

*[Ref] O. Aberle, Some reflection about beam dumping at CERN, GSI (2012)*
*[Ref] R. Schmidt et al., New J. Phys. 8, 290 (2006)*

# Summary

- Machine protection systems deal with protection of equipment and devices as well as safety and environmental risks related to the accelerator operation
- Prevent uncontrolled beam loss (regular and accidental) and secure a well defined and shielded storage for the lost particles
- Regular beam loss is caused by machine imperfections, errors, beam collective effects and it is treated by using the halo collimation system
- Accidental beam loss is caused by hardware failures, severe beam instabilities and it is treated by using the emergency extraction and dumping system
- The systems 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, ...)
- Development of advanced materials for collimators and beam dumps is essential
- Machine protection is extremely important for future big accelerator projects (very high beam energy, beam power, beam intensity, ...), e.g FCC

Thank you for your attention