Accelerator Technology Challenges
(Part 3: Accelerator operation and design challenges)

Lecture I

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With contributions from many CERN colleagues

Summer student lecture

July 24$^{\mathrm{th}}$, 2018

Beam losses ...

... concern all accelerators ...

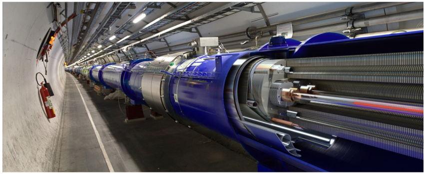
medical accelerators

synchroton light sources

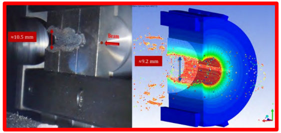
spallation sources

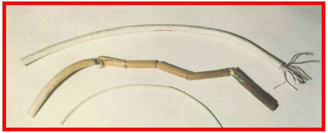
high energy (hadron/lepton) colliders

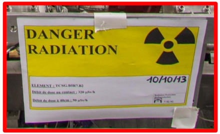
...

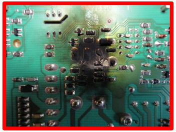


... and they can have many negative consequences









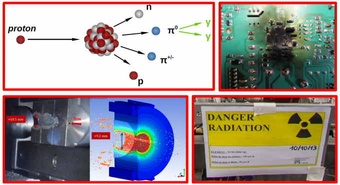
etc.

different machines → different challenges

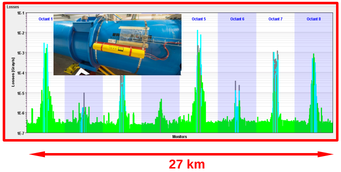
Outline

These lectures: how to cope with beam losses in high-energy colliders (main focus: circular hadron colliders - LHC)

- **Lecture I**
  - **Beam losses in circular hadron colliders**
  - **Particle-matter interactions (high-energy hadrons)**
  - **Consequences of beam losses**

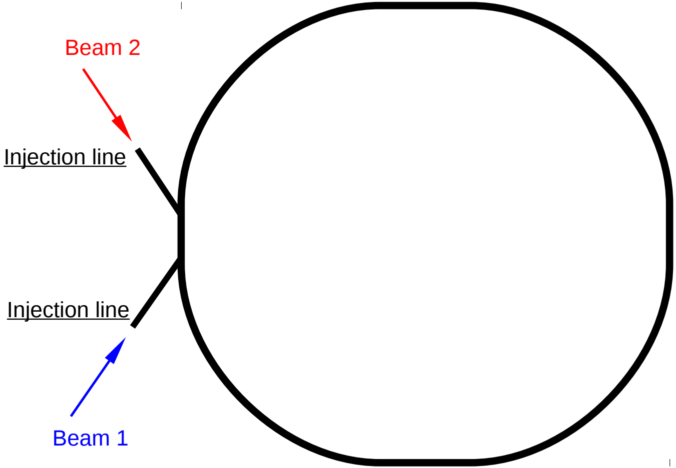


- **Lecture II**
  - Regular and irregular beam losses in the LHC
  - How to safely dump the 300 MJ LHC beams
  - Beam loss simulations (shower simulations)

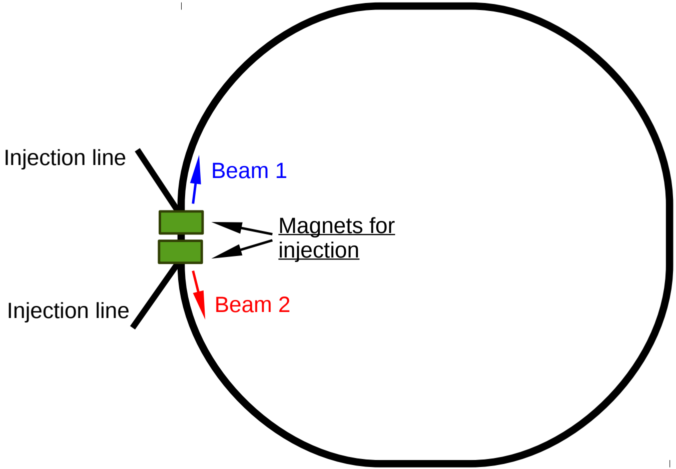


Circular colliders

two counter-rotating beams



Circular colliders



Injection line

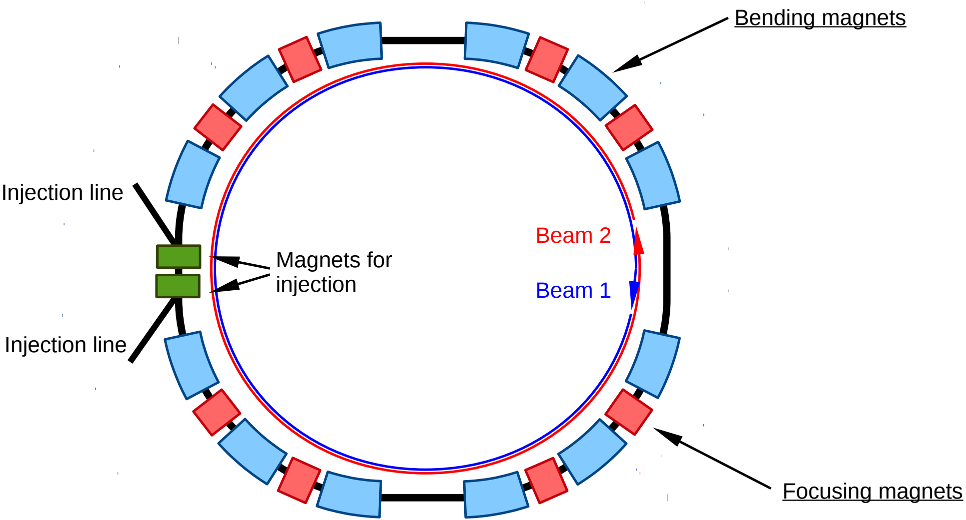
Beam 1

Magnets for injection

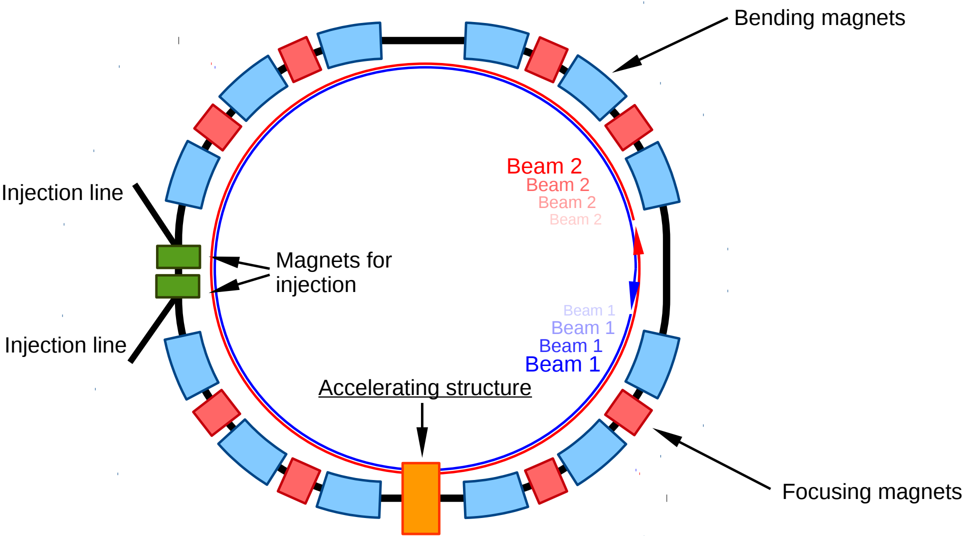
Beam 2

Injection line

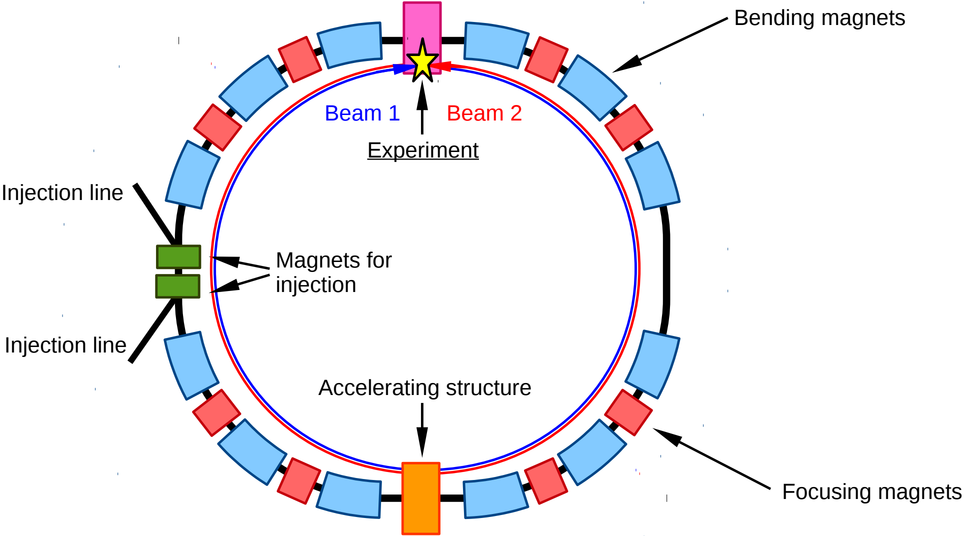
Circular colliders



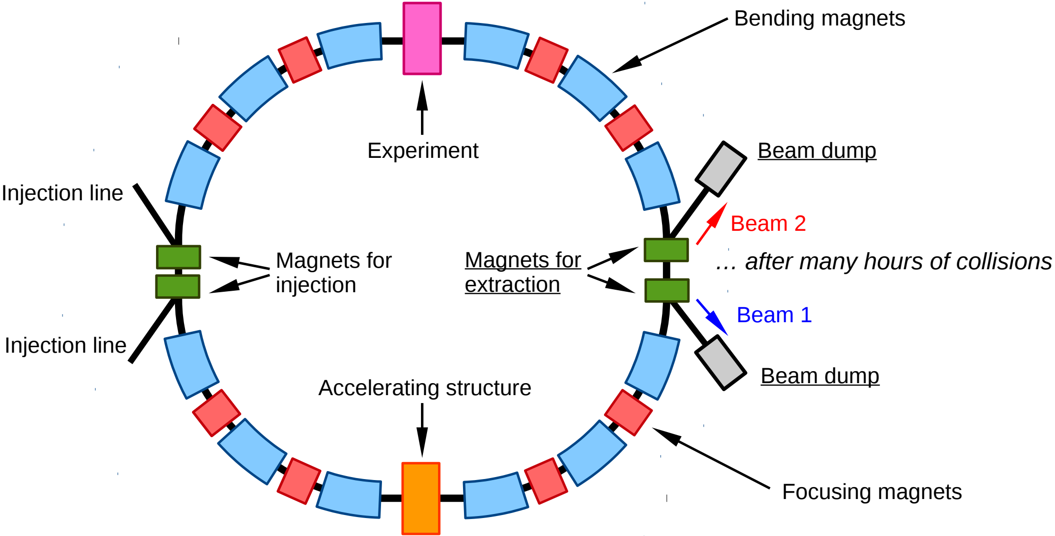
Circular colliders



Circular colliders

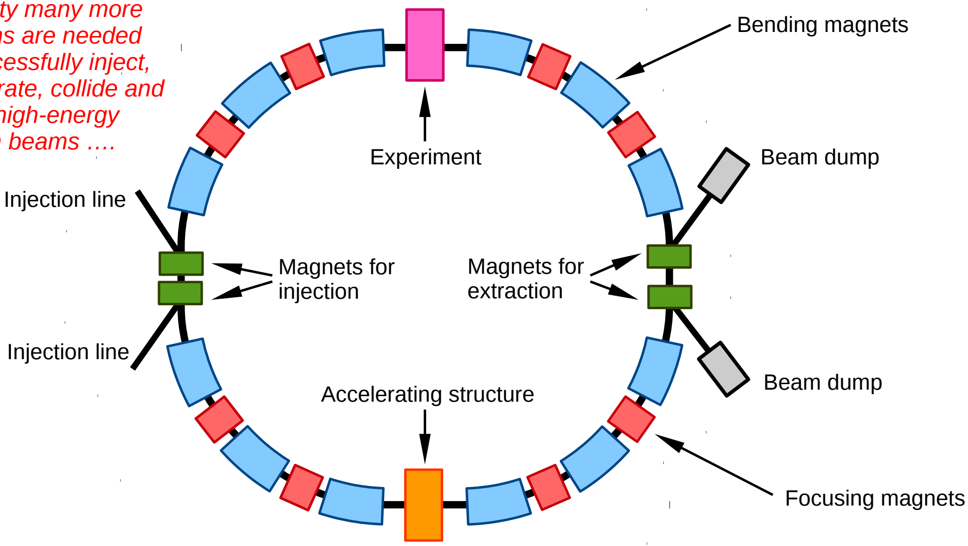


Circular colliders

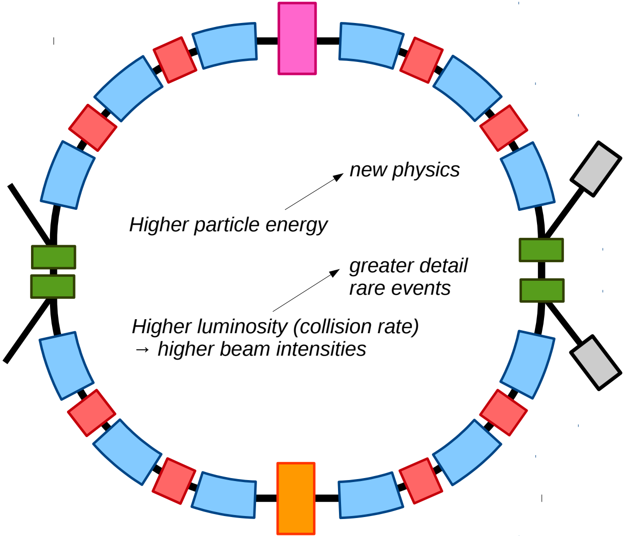


Circular colliders

In reality many more systems are needed to successfully inject, accelerate, collide and dump high-energy hadron beams ....



Key parameters



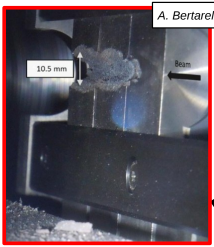
new physics

Higher particle energy

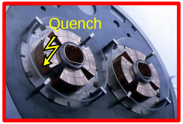
greater detail
rare events

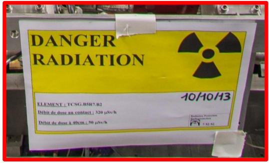
Higher luminosity (collision rate)
→ higher beam intensities

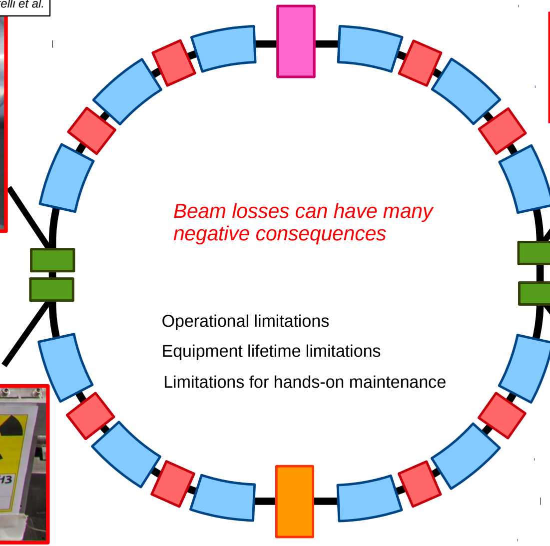
Effects of beam losses



A. Bertarelli et al.





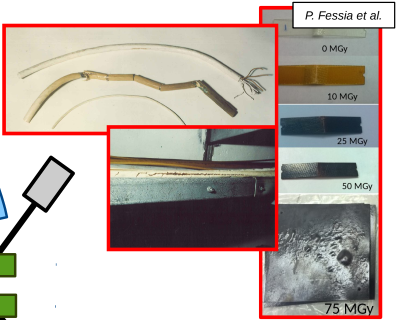


Beam losses can have many negative consequences

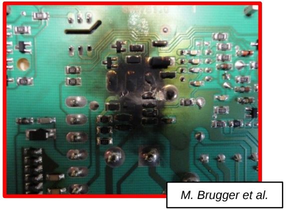
Operational limitations

Equipment lifetime limitations

Limitations for hands-on maintenance



P. Fessia et al.

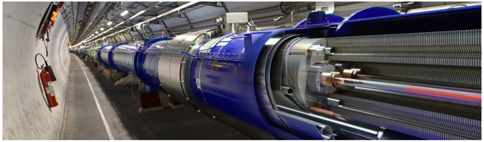


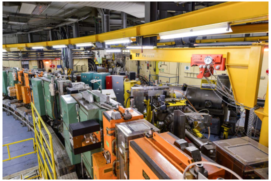
M. Brugger et al.

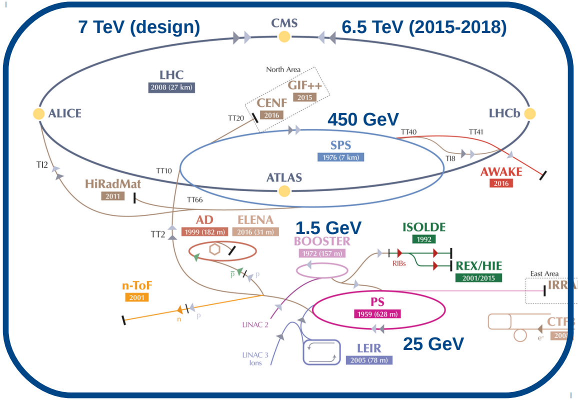
Large Hadron Collider

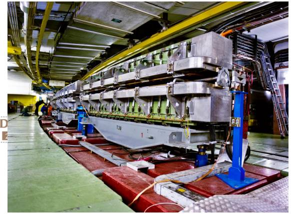
$1\ \mathrm{eV} = 1.60218 \times 10^{-19}\ \mathrm{J}$

$1\ \mathrm{TeV} = 10^{12}\ \mathrm{eV}$









All pictures: CERN

Large Hadron Collider - stored beam energy

Stored beam energy = particle energy x beam intensity

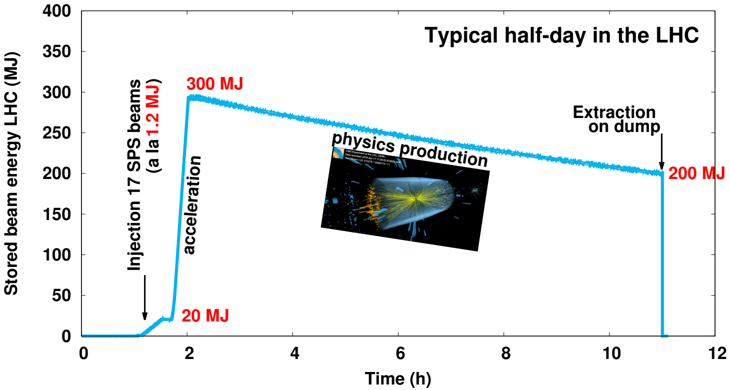
Usually specified in ***Joules (kJ, MJ)***

Usually specified in ***eV (keV, MeV, GeV, TeV)***

particles

Pre-LHC era: ***few MJ*** (HERA, Tevatron, SPS)

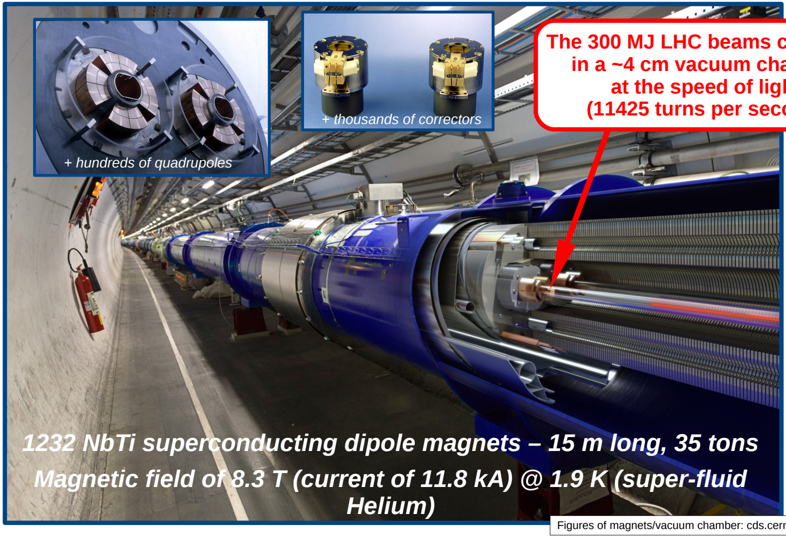
LHC: ***360 MJ*** (design) 2018 → ***~300 MJ***



300 MJ =
kinetic energy
of a ~400 t train
travelling at a
speed of 140 km/h


S. Terfloth, Wikipedia, CC BY-SA 3.0

Large Hadron Collider



+ hundreds of quadrupoles

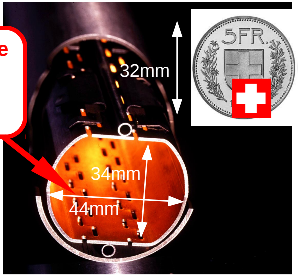
+ thousands of correctors

The 300 MJ LHC beams circulate in a ~4 cm vacuum chamber at the speed of light (11425 turns per second)

1232 NbTi superconducting dipole magnets – 15 m long, 35 tons

Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)

Figures of magnets/vacuum chamber: cds.cern.ch



Full beam lost → enormous damage potential!

Monitoring essential:

- *beam (position, losses, etc.)*
- *equipment (magnet current etc.)*

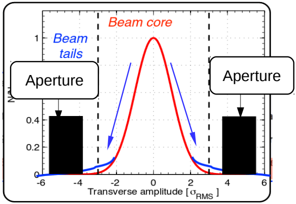
Something out of norm → beam extracted on dump

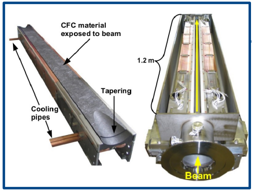
Beam losses in circular colliders

Regular beam losses

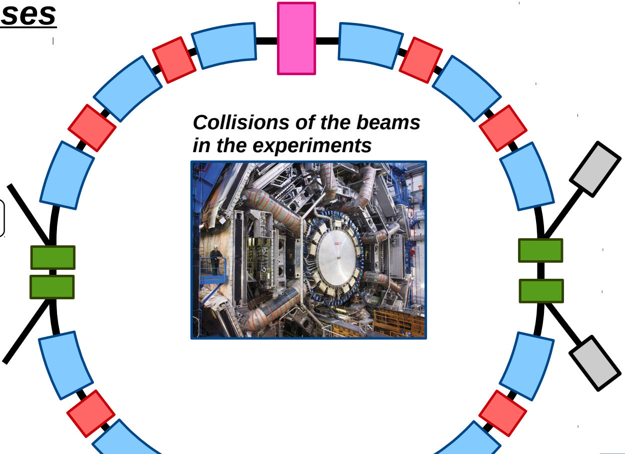
Beam halo losses → various sources

(intra-beam scattering, Touscheck effect, RF noise, collective effects, transition crossing, field errors ...)



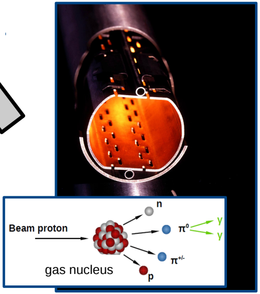


Typically continuous losses



Collisions of the beams in the experiments

Collisions of the beams with residual gas atoms in the vacuum chamber



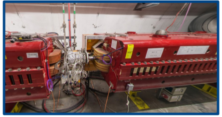
Unavoidable, hence minimize impact on equipment, personnel and operation

(→ collimators, shielding, material choices etc.)

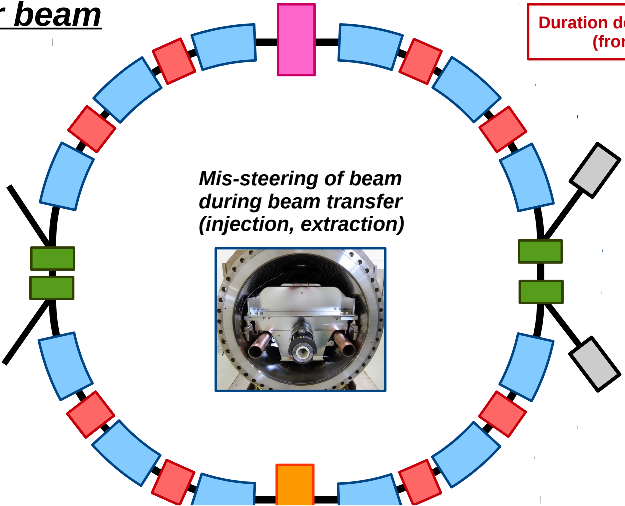
Beam losses in circular colliders

Possible irregular beam losses

Powering failures of magnets



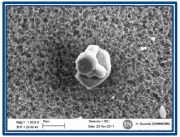
Operational mistakes



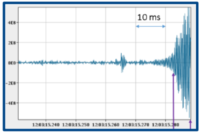
Mis-steering of beam during beam transfer (injection, extraction)

Duration depends on loss mechanism (from single turn to sec)

Macroparticles falling into the beam

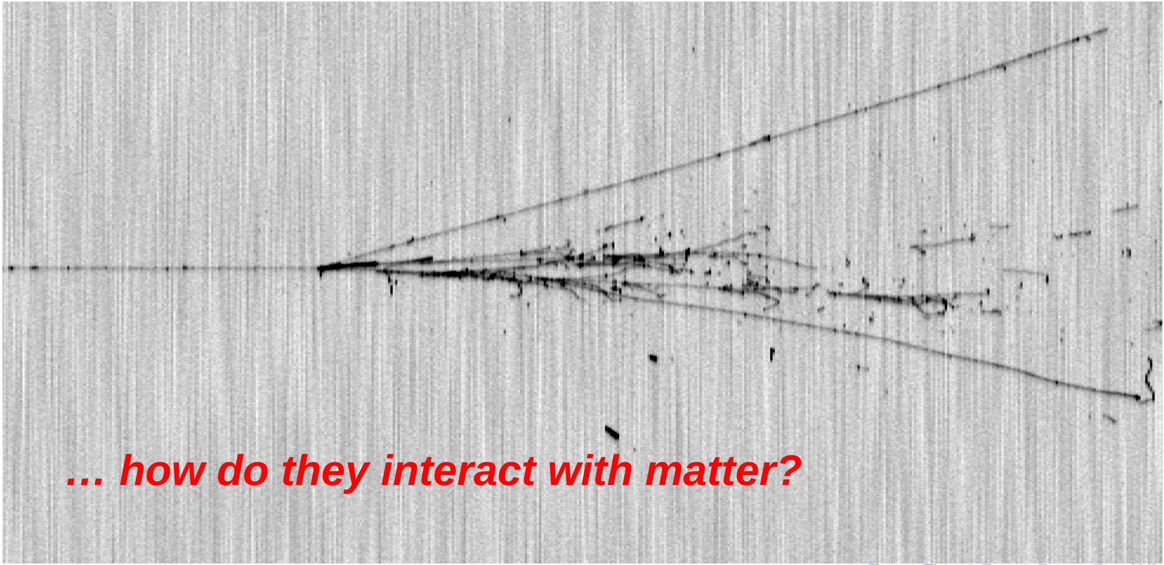


Fast beam instabilities



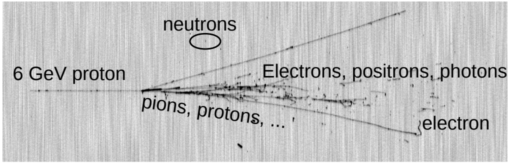
Reduce likelihood (if possible), otherwise monitor and take action if necessary (beam extraction);
For some scenarios (mis-steering of beam), passive protection needed (protection absorbers)

But when high-energy hadrons are lost in a collider ...



... how do they interact with matter?

The main actors (in a hadron machine)

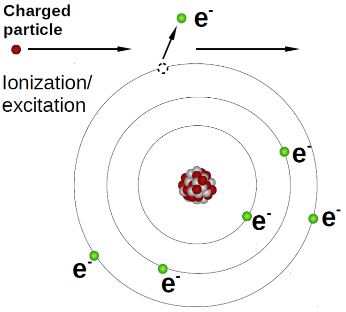


Some properties:

- **Hadrons:**
  - **Proton (p)** 938 MeV/c² stable
  - **Neutron (n)** 940 MeV/c² τ=880 s
  - **Charged pions (π^+, π^-)** 140 MeV/c² τ=2.6×10^{-8} s ($c\tau$=780 cm) [mainly $\pi^+ \rightarrow \mu^+\nu_\mu, \pi^- \rightarrow \mu^-\overline{\nu}_\mu$]
  - **Neutral pions (π^0)** 135 MeV/c² τ=8.5×10^{-17} s ($c\tau$=25 nm) [mainly $\pi \rightarrow \gamma\gamma$]
  - **Charged and neutral kaons, (anti)hyperons, antiprotons, antineutrons ...**
- **Photons (γ)**, stable, m=0
- **Leptons:**
  - **Electron, positron (e^-, e^+)** 511 keV/c² stable
  - **Muons (μ^-, μ^+)** 106 MeV/c² τ=2.2×10^{-6} s ($c\tau$=687 m) [mainly $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu, \mu^- \rightarrow e^-\overline{\nu}_e\nu_\mu$]

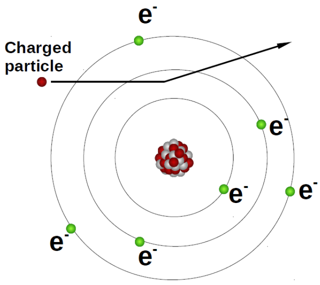
Electromagnetic interactions of charged particles

Coulomb interactions with electrons



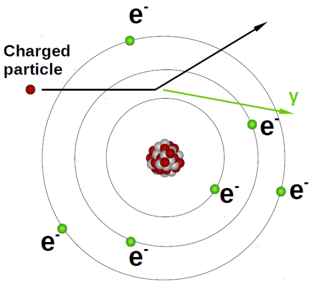
Projectile loses energy, but angular deflection rather small

Coulomb interactions with nucleus (elastic)



Projectile changes direction, but energy loss rather small (exception: low-energy heavy projectiles like ions)

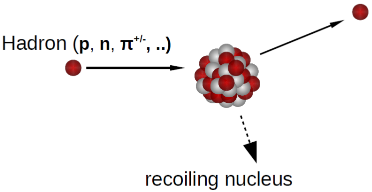
Coulomb interactions with nucleus (radiative)



Energy loss under emission of Bremsstrahlung photon (relevant for e-/e+ above few 10 MeV, for other particles only at very high energies)

Hadronic interactions

Elastic nuclear interactions

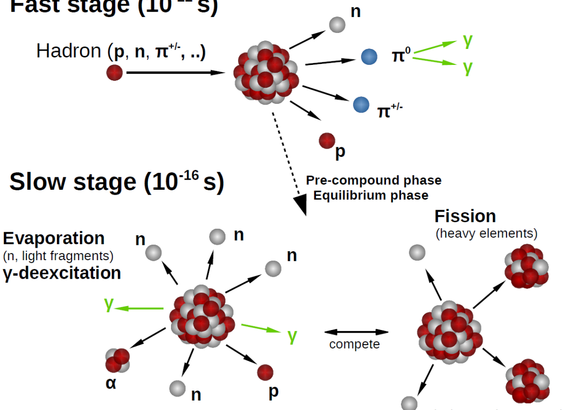


→ no new particles produced
→ no change of internal structure of projectile and target nucleus

Inelastic nuclear interactions

Fast stage (10^{-22} s)

Slow stage (10^{-16} s)

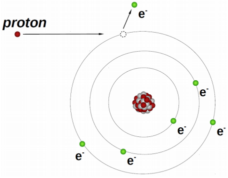


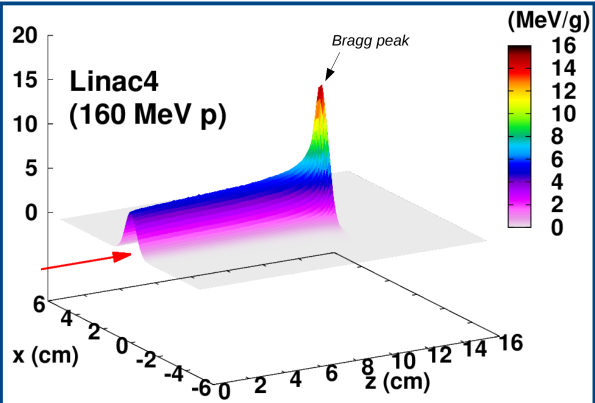
Fission products can also undergo evaporation

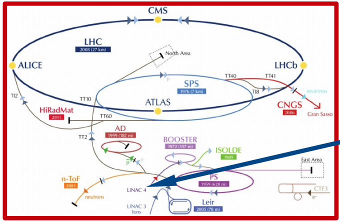
Beam-matter interactions: a matter of beam energy (1/2)

Let's assume a proton beam impacts on a block of Graphite

Most protons range out (ionizing energy loss)



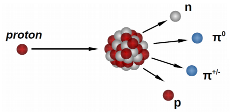


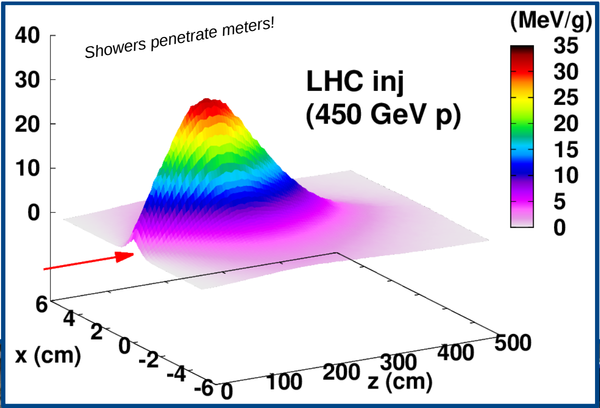


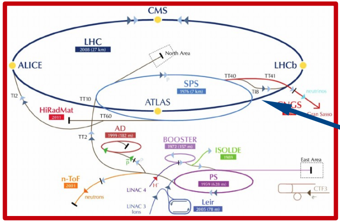
Beam-matter interactions: a matter of beam energy (2/2)

Let's assume a proton beam impacts on a block of Graphite

Nuclear interactions,
particle cascades (showers)!

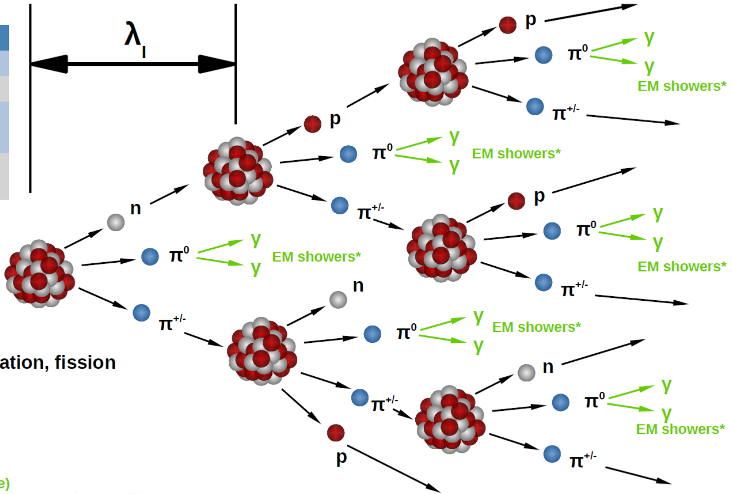






Hadronic showers: basics

Particle	**Mean life**	**Main decay mode**
Protons (p)	stable	-
Neutrons (n)	880 s	$n \to pe^-\overline{\nu}_e$-
Charged pions (π^+,π^-)	2.6×10^{-8} s	$\pi^+ \to \mu^+\nu_\mu$ $\pi^- \to \mu^-\overline{\nu}_\mu$
Neutral pions (π^0)	8.5×10^{-17} s	$\pi^0 \to \gamma\gamma$



+Evaporation, gamma-deexcitation, fission

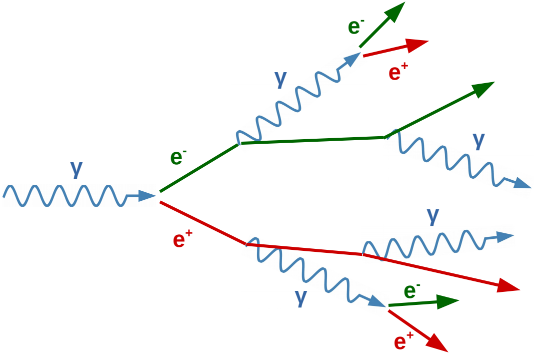
Non-negligible fraction of initial energy can go into binding energy + recoils

*EM showers:
- → concentrated along the shower core (shorter/less wide)
- → ~ do not give rise to hadronic showers (photo-nuclear cross section small)
- → not only π^0 but also other particles like η

roughly continues until particle energy falls below pion production threshold

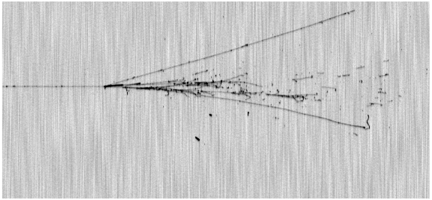
Electromagnetic showers: basics

- **Relevant processes:**
  - **High-energy e^-/e^+ lose energy mainly through bremsstrahlung**
  - **For photons at such energies, dominant interaction is pair production**
- **Cascade development:**
  - **At high energy ($\gtrsim$ GeV), these processes lead to particle multiplication**

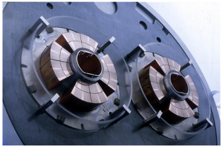


EM showers: ~do not give rise to hadronic showers (photo-nuclear cross section is small)

Beam-matter interactions: effects



__Quench__ due to heating (ionizing energy loss)



Degradation of material properties
due to radiation damage (ionization and non-ionizing energy loss) and gas production (nuclear collisions)

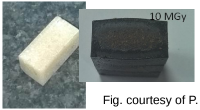


Fig. courtesy of P. Fessia

Quasi-instantaneous damage
due to shock-heating (ionizing energy loss)

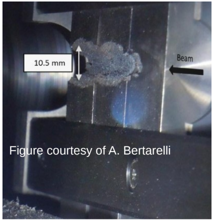
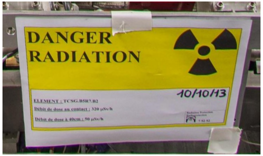


Figure courtesy of A. Bertarelli

__Activation__ due to production of radionuclides (nuclear collisions)



Single event effects in electronics
due to current pulse (ionizing energy loss)

Cumulative damage in electronics
(ionizing energy loss and non-ionizing energy loss)

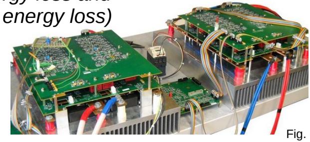
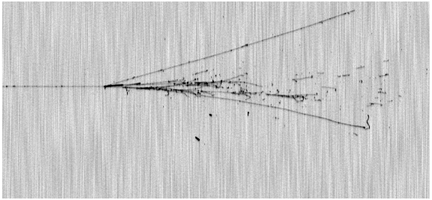


Fig. courtesy of TE/EPC

List not exhaustive!

Beam-matter interactions: effects

Quench *due to heating (ionizing energy loss)*



Degradation of material properties *due to radiation damage (ionization and non-ionizing energy loss) and gas production (nuclear collisions)*

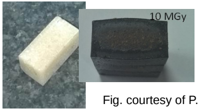


Fig. courtesy of P. Fessia

Quasi-instantaneous damage *due to shock-heating (ionizing energy loss)*

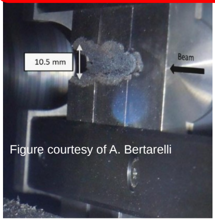
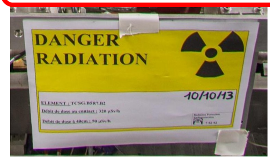


Figure courtesy of A. Bertarelli

Activation *due to production of radionuclides (nuclear collisions)*



Cumulative damage in electronics *(ionizing energy loss and non-ionizing energy loss)*

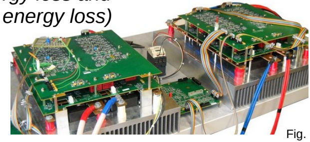
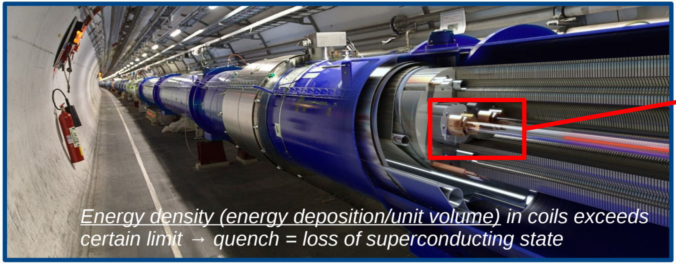


Fig. courtesy of TE/EPC

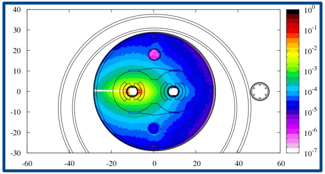
Single event effects in electronics *due to current pulse (ionizing energy loss)*

List not exhaustive!

Quenches of superconducting magnets



Energy density (energy deposition/unit volume) in coils exceeds certain limit → quench = loss of superconducting state



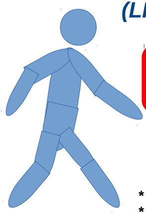
LHC@7TeV → Quench ~ $O(\mathrm{mJ/cm}^3)$

Energy of the stored LHC beam (2018) ≈

S. Terfloth, Wikipedia, CC BY-SA 3.0

Kinetic energy of a 400 t train traveling at a speed of 140 km/h

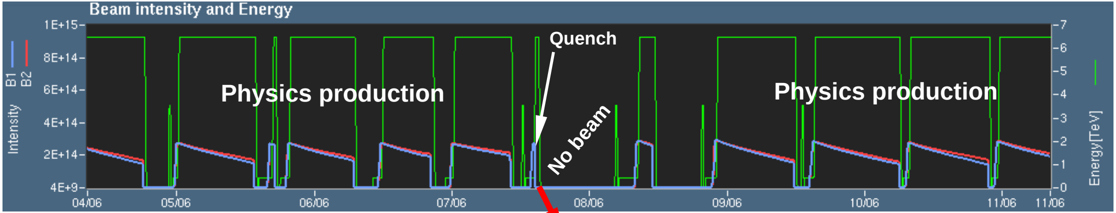
Beam loss energy to induce a quench (LHC@7TeV, msec loss duration) ≈

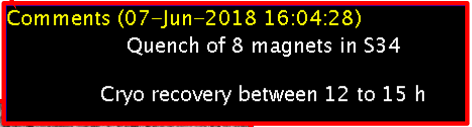


Kinetic energy of a pedestrian (70 kg*) walking at 5 km/h**

**** 70 kg= average weight of a European (Wikipedia)***
**** 5 km/h= preferred walking speed of humans (Wikipedia)***

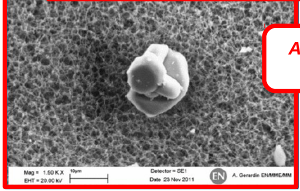
Quenches of superconducting magnets - quench recovery




Comments (07-Jun-2018 16:04:28)

Quench of 8 magnets in S34

Cryo recovery between 12 to 15 h



A dust particle fell into the beam...

Quench in the LHC:

→ *beam safely extracted on dump block before magnetic field degrades*

(i.e. quench is not a catastrophic event)

But: quench recovery can be lengthy

→ *too many quenches = performance limitation*

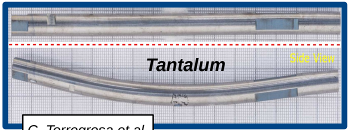
→ *quench prevention important! (still some quenches not avoidable)*

Damage due to shock-heating

Fast beam losses → instantaneous damage if stress waves strong enough

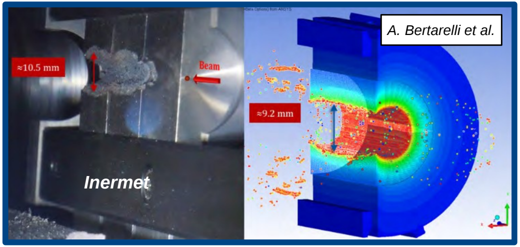
Energy densities ~ O(100J/cm^3-kJ/cm^3)*

****Onset of damage depends on many parameters (loss duration, material properties, spatial energy density distribution, etc.)***



C. Torregrosa et al.

Beam impact tests in HiRadMat facility (SPS, 440 GeV/c)



A. Bertarelli et al.

Energy of the stored LHC beam (2018) ≈

S. Terfloth, Wikipedia, CC BY-SA 3.0

Kinetic energy of a 400 t train traveling at a speed of 140 km/h

Beam loss energy to induce damage in copper ≈*

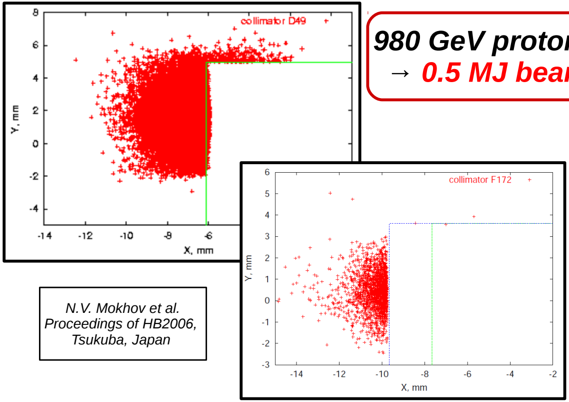
Kinetic energy of a 1 t car driving at a speed of 70 km/h

**V. Kain et al., "Material damage test with 450 GeV LHC-type beam", PAC 2005.*

Damage due to shock-heating - example from Tevatron (Fermilab)

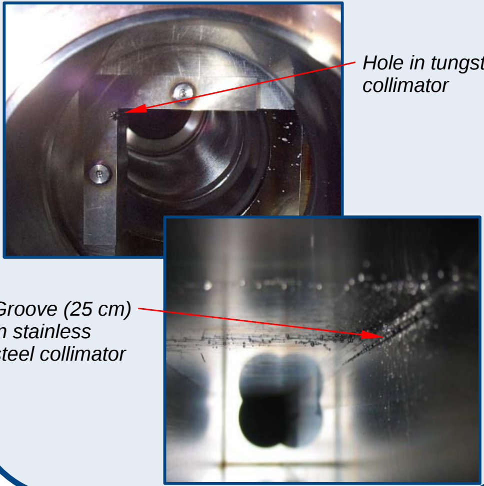
Tevatron quench incident 2003

Beam line detector (Roman Pot) accidentally inserted itself into the beam → showers quenched magnets → beam orbit drift (5μm/turn) → ***impact on collimators***



980 GeV protons
→ 0.5 MJ beam

N.V. Mokhov et al.
Proceedings of HB2006,
Tsukuba, Japan



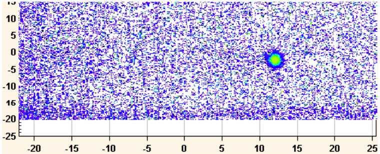
Hole in tungsten collimator

Groove (25 cm) in stainless steel collimator

Damage due to shock-heating - example from SPS (CERN)

CERN SPS extraction incident 2004

*Beam extraction for material testing → fault on extraction septum magnet → wrong trajectory → **impact on vacuum chamber***

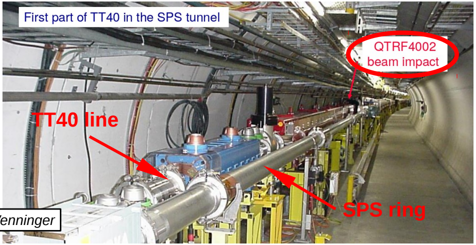


450 GeV

$3.4\text{x}10^{13}$ protons

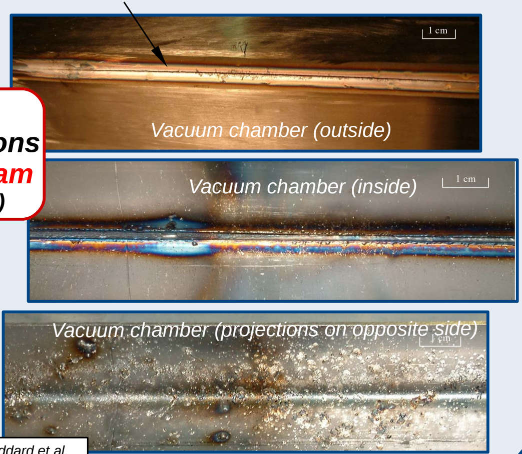
→ 2.5 MJ beam

(0.7 x 0.7 mm)



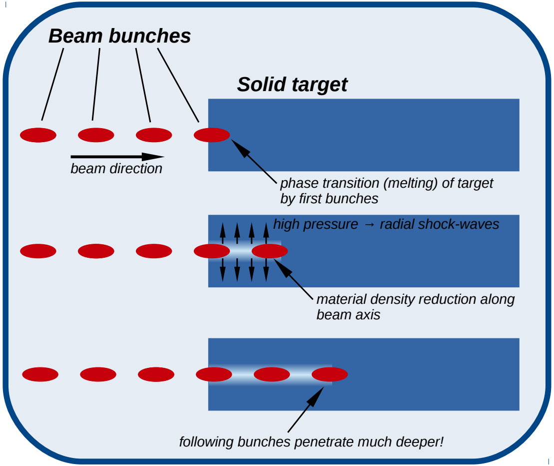
J. Wenninger

Vacuum chamber ripped open over 25 cm



B. Goddard et al.
AB-Note-2005-014 BT

Damage due to shock-heating - hydrodynamic tunneling



Beam bunches

Solid target

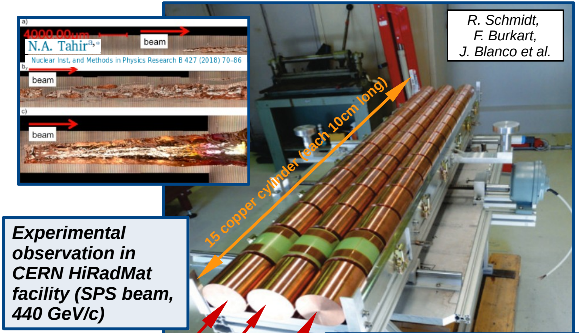
beam direction

phase transition (melting) of target by first bunches

high pressure → radial shock-waves

material density reduction along beam axis

following bunches penetrate much deeper!



N.A. Tahir[a,*]

Nuclear Inst, and Methods in Physics Research B 427 (2018) 70-86

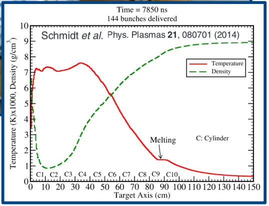
R. Schmidt,
F. Burkart,
J. Blanco et al.

Experimental observation in CERN HiRadMat facility (SPS beam, 440 GeV/c)

Shot 3:
144b
σ=0.2mm

Shot 2:
108b
σ=0.2mm

Shot 1:
144b
σ=2mm



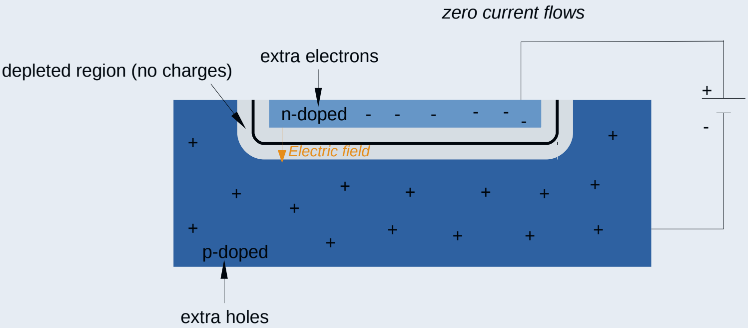
Schmidt *et al.* Phys. Plasmas **21**, 080701 (2014)

→ **High-energy proton machines: loss of full beam on single spot must be avoided!**

Single event effects in electronics - basic mechanism

Passage of ***ionizing particle*** *→ charge collected on sensitive node > critical charge → electrical disturbance*

Example: *reverse-biased* ***p-n junction*** *(most sensitive)*



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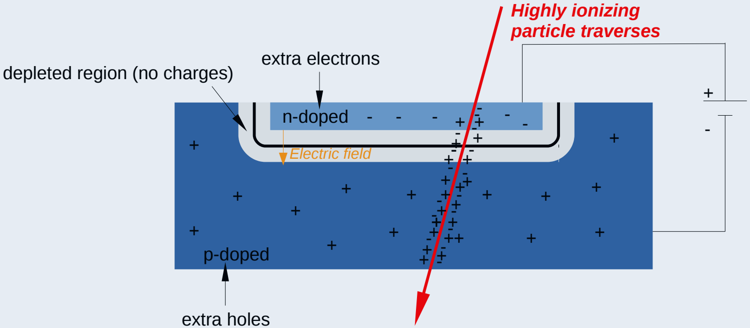

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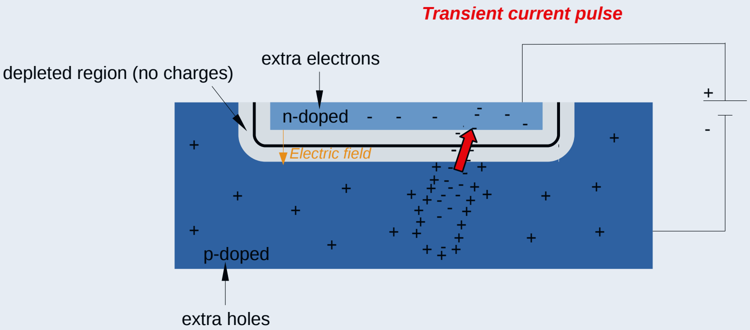

- *fast collection (funneling → distortion of potential)*
- *slow collection (diffusion)*

Single event effects in electronics - basic mechanism

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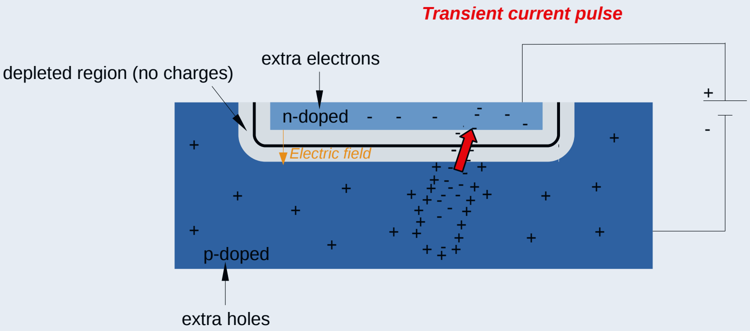


- fast collection (funneling → distortion of potential)

- slow collection (diffusion)

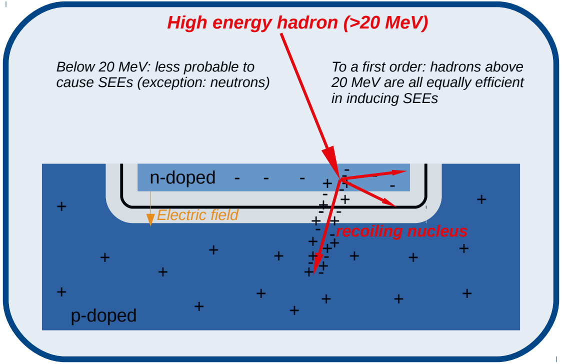
A variety of phenomena:
- ***Soft errors*** *(recoverable): Single Event Upset (SEU), Multiple Bit Upset (MBU), Single Event Transient (SET), ...*
- ***Hard errors*** *(not recoverable): Single Event Latch-up (SEL), Single Event Burnout (SEB), ...*

Single event effects in electronics - which particles?

Essentially only ions create sufficient charge densities

<u>But:</u>

Hadron accelerators → ***indirect ionization by secondary hadrons!***

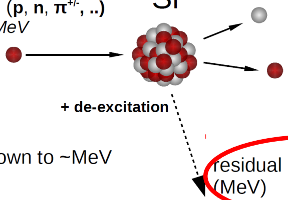

High energy hadron (>20 MeV)

Below 20 MeV: less probable to cause SEEs (exception: neutrons)

To a first order: hadrons above 20 MeV are all equally efficient in inducing SEEs

Inelastic nuclear collisions of hadrons:

Hadron (**p**, **n**, **$\pi^{+/-}$**, **..**)
E > 20 MeV



+ de-excitation

+ (n, α) down to ~MeV

residual nucleus recoils (MeV)

Also: capture of thermal neutrons in ^{10}B

Can cause Single Event Effects!

Single event effects in electronics - an early example at CERN

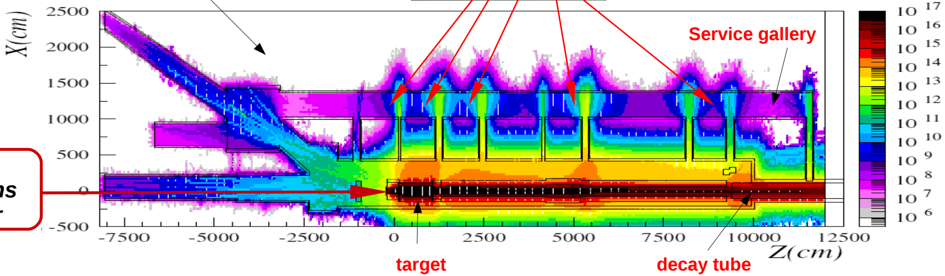
CNGS (CERN Neutrinos to Gran Sasso) radiation issues 2007

*Single Event Effects in micro-controllers → successive failures of ventilation system → 2007 run stopped ahead of schedule → **relocation of electronics + improvement of shielding (53m^3 of concrete, 6m thick)***

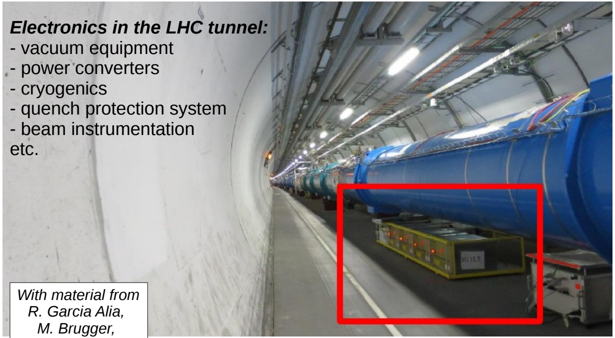
With material from:
E. Gschwendtner,
I. Efthymipoulos, M. Brugger,
A. Ferrari, L. Sarchiapone

High-energy hadron (>20 MeV) fluence for a nominal year

400 GeV
4.5x10^{19} protons
on target/year



Single event effects in electronics - LHC



Electronics in the LHC tunnel:
- vacuum equipment
- power converters
- cryogenics
- quench protection system
- beam instrumentation

etc.

With material from
R. Garcia Alia,
M. Brugger,
R. Secondo

Radiation monitoring

Shielding requirements

Shower simulations

Test facilities

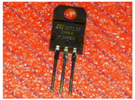
Component testing

Development

Many accelerator systems are based on **COTS*** components
→ **readily available, performance, costs (many components)**

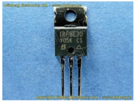
***COTS = Commercial-Off-The-Shelf**

Response to radiation can strongly vary!!



STP3NV80
(N-channel, 800V)

22 destructive events before LS1

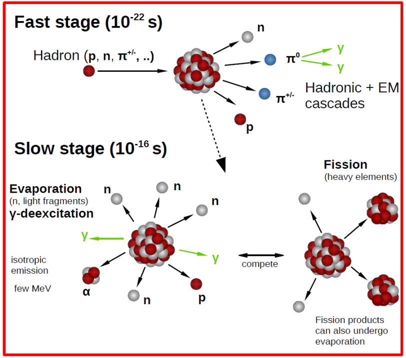


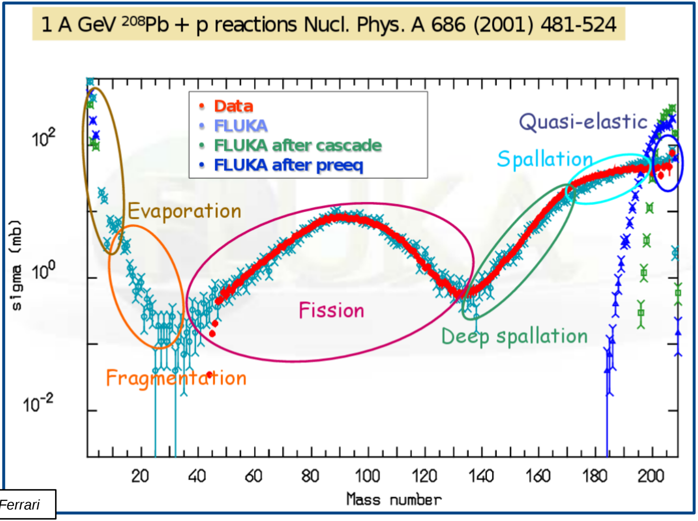
IRFBE30
(N-channel, 800V)

One destructive event before LS1

Example: MOSFET with similar specs but different sensitivity!

Activation - production of radioactive nuclides in hadron accelerators




1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524

A. Ferrari

- **Many residuals are unstable (radioactive)**

Activation - radioactive decay modes

Chart of stable and unstable nuclides

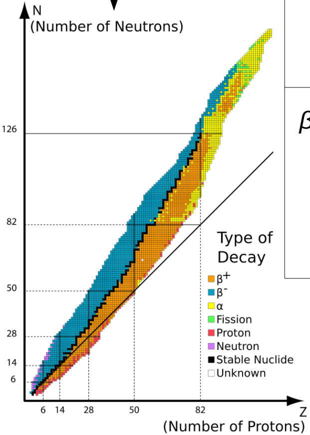
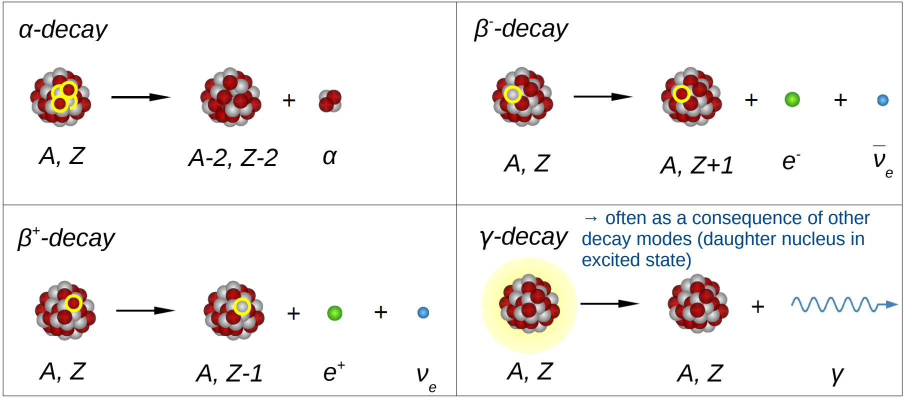


Chart: Wikipedia, Napy1kenobi, Sjlegg



→ often as a consequence of other decay modes (daughter nucleus in excited state)

+ electron capture, spontaneous fission, proton emission, neutron emission, internal conversion etc.

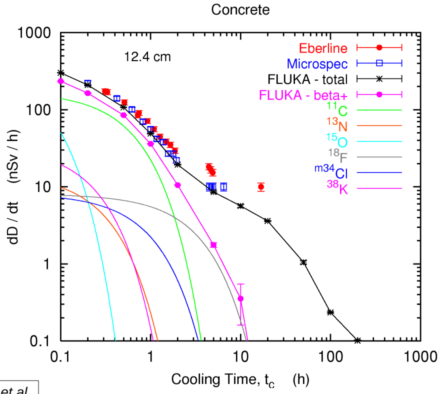
→ *Nuclides can have competing decay modes*

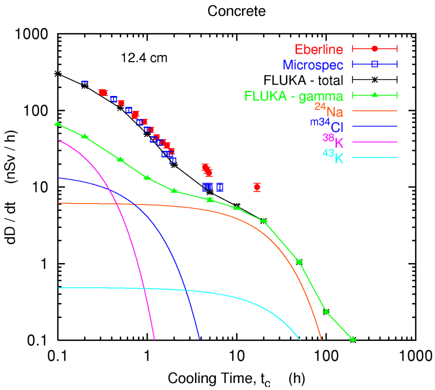
→ *Daughter nuclides can be unstable as well (decay chains)*

Activation - nuclide contribution to residual dose versus cooling time

Cooling time = time after beam OFF

Example: sample of ***concrete****, activated in stray radiation field of a copper target (mixed hadron beam, 120 GeV/c)*





M.Brugger et al.

Activation - radiation area classification at CERN

Personal dosimeter

\+ limits for airborne radioactivity and surface contamination (not shown in table)

Classification of radiation areas at CERN

Effective dose a person can receive in 1 year in this area

Operational quantity (external exposure):

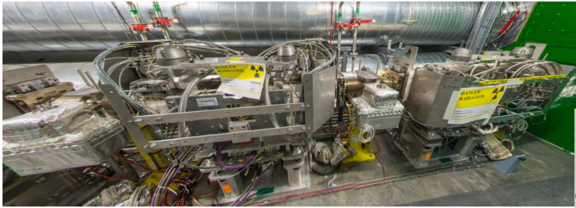
	Area	Dose limit [year]	Ambient dose equivalent rate		Sign	
			Work place	Low occupancy	RADIATION ZONE SURVEILLÉE RADIATION ZONE CONTRÔLÉE CONTROLLED AREA	
	Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h		
Radiation Area	Supervised	6 mSv	3 μSv/h	15 μSv/h	Dosimeter obligatory Dosimètre obligatoire Radiation Protection Radioprotection ☎	
	Simple	20 mSv	10 μSv/h	50 μSv/h	Dosimeter obligatory Dosimètre obligatoire Radiation Protection Radioprotection ☎	Controlled Area
	Limited Stay	20 mSv		2 mSv/h	LIMITED STAY SÉJOUR LIMITÉ Dosimeters obligatory Dosimètres obligatoires Radiation Protection Radioprotection ☎	
	High Radiation	20 mSv		100 mSv/h	HIGH RADIATION HAUTE RADIATION Dosimeters obligatory Dosimètres obligatoires Radiation Protection Radioprotection ☎	
	Prohibited	20 mSv		> 100 mSv/h	PROHIBITED AREA ZONE INTERDITE No Entry Défense d'entrer Radiation Protection Radioprotection ☎	

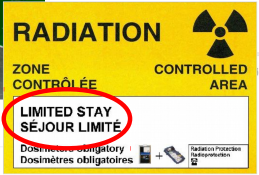
RP group

Activation - access for technical interventions (example LHC)

Interventions in radiation areas
→ need to be optimized

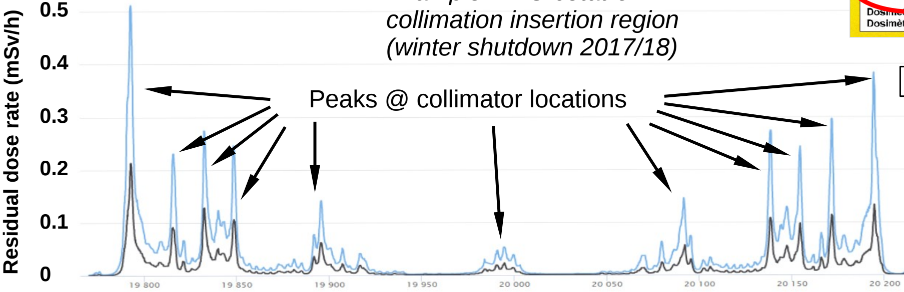
ALARA = As low as reasonably achievable





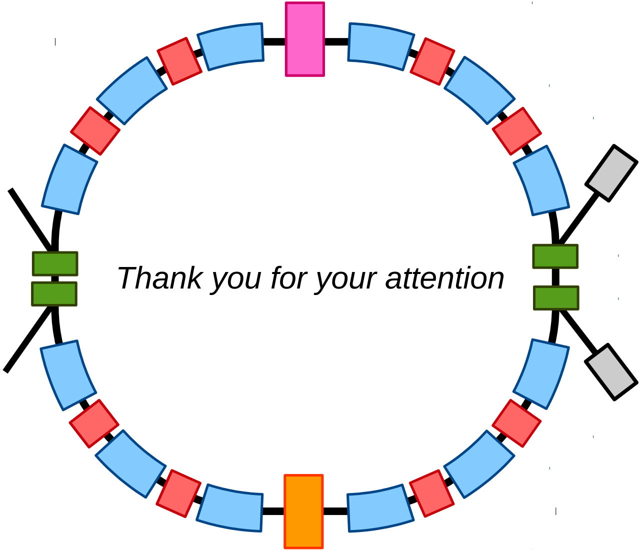
Radiation mapping before access:

Example: LHC betatron collimation insertion region (winter shutdown 2017/18)



C. Adorisio

Blue = at start of shutdown **Black line = after 6 weeks of cooldown**



Thank you for your attention