Machine Protection and Collimation

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CAS Accelerator School
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- Beam losses
- Continuous beam losses and Collimation
- Accidental beam losses and Machine Protection

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- Beam losses
- Continuous beam losses and Collimation
- Accidental beam losses and Machine Protection
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Protection from Energy and Power

- Risks come from Energy stored in a system (Joule), and Power when operating a system (Watt)
  - “very powerful accelerator” … the power flow needs to be controlled
- An uncontrolled release of the energy, or an uncontrolled power flow can lead to unwanted consequences
  - Loss of time for operation or damage of equipment
- This is true for all systems, in particular for complex systems such as accelerators
  - For the RF system, power converters, magnet system …
  - For the beams
- The 2008 accident during LHC operation happened during test runs without beam

Damage of LHC during the 2008 accident

Accidental release of an energy of 600 MJoule stored in the magnet system - No Beam

Machine Protection protection related to beams

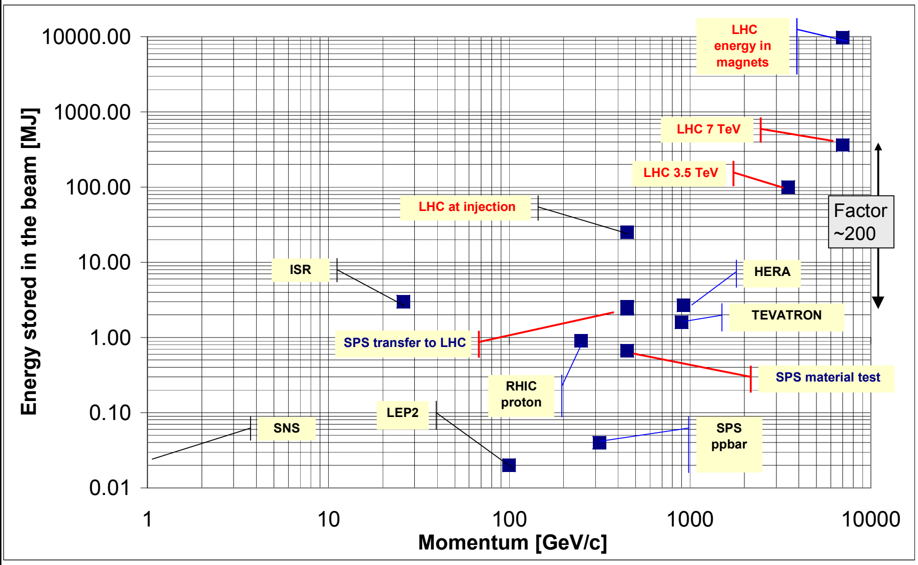
Many accelerators operate with high beam intensity and/or energy

- For synchrotrons and storage rings, the energy stored in the beam is increasing with time (from ISR to LHC)
- For linear accelerators and fast cycling machines, the beam power increases

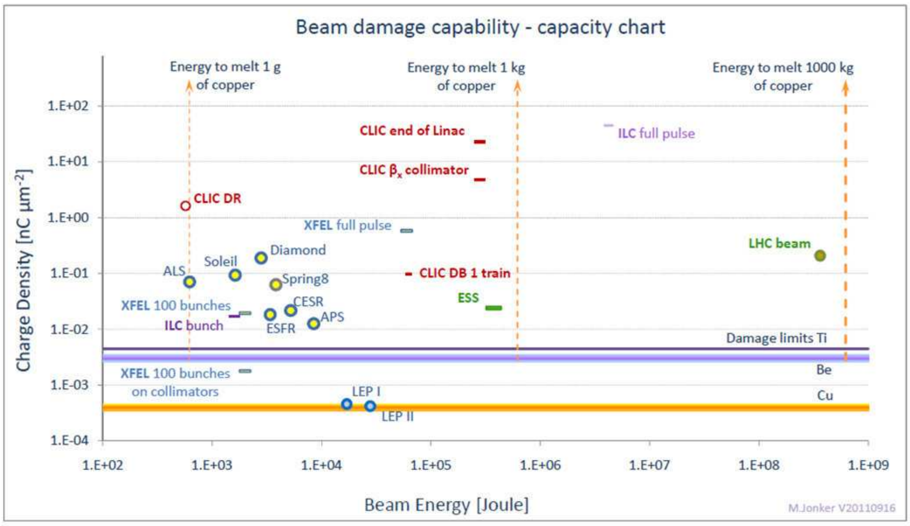
The emittance becomes smaller (down to a beam size of nanometer)

- This is becoming increasingly important for future projects, with increased beam power / energy density (W/mm^2 or J/mm^2) and increasingly complex machines (such as ILC and CLIC, but also at XFEL)

Livingston type plot: Energy stored magnets and beam



Beam damage capabilities



M.Jonker

Beam losses

In accelerators, particles are lost due to a variety of reasons: beam gas interaction, losses from collisions, losses of the beam halo, …

- Continuous beam losses are inherent during the operation of accelerators
  - Taken into account during the design of the accelerator
- Accidental beam losses are due to a multitude of failures mechanisms
- The number of possible failures leading to accidental beam losses is (nearly) infinite

Beam losses, machine protection and collimation

Continuous beam losses: **Collimation** prevents too high beam losses around the accelerator (beam cleaning)

A collimation system is a (very complex) system installed in an accelerator to capture these particles

Such system is also called (beam) Cleaning System

Accidental beam losses: **"Machine Protection"** protects equipment from damage, activation and downtime

Machine protection includes a large variety of systems

Regular and irregular operation

Regular operation	**Failures during operation**
Many accelerator systems	Beam losses due to failures, timescale from nanoseconds to seconds
Continuous beam losses	Machine protection systems
Collimators for beam cleaning	Collimators
Collimators for halo scraping	Beam absorbers

Beam losses and consequences

- Particle losses lead to particle cascades in materials that deposit energy in the material
  - the maximum energy deposition can be deep in the material at the maximum of the hadron / electromagnetic shower
- The energy deposition leads to a temperature increase
  - material can vaporise, melt, deform or lose its mechanical properties
  - risk to damage sensitive equipment for some 10 kJ, risk for damage of any structure for some MJoule (depends on beam size)
  - superconducting magnets could quench (beam loss of ~mJ to J)
- Equipment becomes activated due to beam losses (acceptable is ~1 W/m, but must be "As Low As Reasonably Achievable – ALARA")

Energy deposition and temperature increase

- There is no straightforward expression for the energy deposition
- The energy deposition is a function of the particle type, its momentum, and the parameters of the material (atomic number, density, specific heat)
- Programs such as FLUKA, MARS, GEANT and others are being used for the calculation of energy deposition and activation
- Other programs are used to calculate the response of the material (deformation, melting, …) to beam impact (mechanical codes such as ANSYS, hydrodynamic codes such as BIG2 and others)

Question: what is dangerous (stored beam energy, beam power)?

SPS experiment: Beam damage with 450 GeV proton beam

Controlled SPS experiment

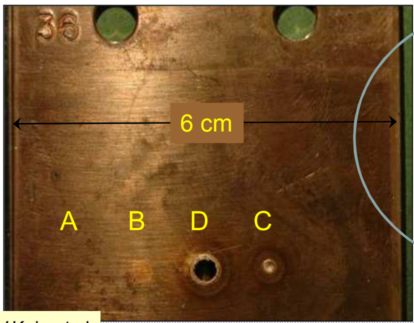
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

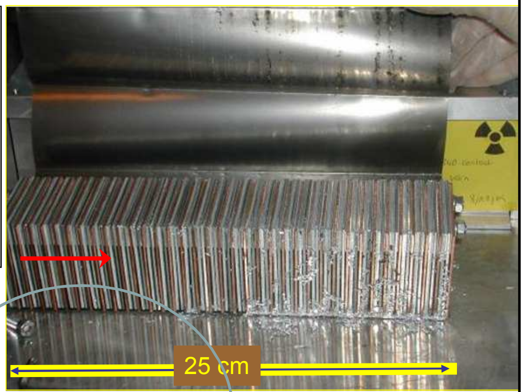
above damage limit for copper

stainless steel no damage

- $2 \cdot 10^{12}$ protons

below damage limit for copper





- 0.1 % of the full LHC 7 TeV beams
- factor of three below the energy in a bunch train injected into LHC
- Damage limit ~200 kJoule

V.Kain et al

Damage of a pencil 7 TeV proton beam (LHC)

copper

Maximum energy deposition in the proton cascade (one proton) $E_{max\_Cu} := 1.5 \cdot 10^{-5} \frac{J}{kg}$

Specific heat of copper is $c_{Cu\_spec} = 384.5600 \frac{1}{kg} \frac{J}{K}$

To heat 1 kg copper by, say, by $\Delta T := 500K$, one needs: $c_{Cu\_spec} \cdot \Delta T \cdot 1kg = 1.92 \times 10^{5} J$

Number of protons to deposit this energy is: $\frac{c_{Cu\_spec} \cdot \Delta T}{E_{max\_Cu}} = 1.28 \times 10^{10}$ Copper

graphite

Maximum energy deposition in the proton cascade (one proton) $E_{max\_C} := 2.0 \cdot 10^{-6} \frac{J}{kg}$

Specific heat of graphite is $c_{C\_spec} = 710.6000 \frac{1}{kg} \frac{J}{K}$

To heat 1 kggraphite by, say, by $\Delta T := 1500K$, one needs: $c_{C\_spec} \cdot \Delta T \cdot 1kg = 1.07 \times 10^{6} J$

Number of protons to deposit this energy is: $\frac{c_{C\_spec} \cdot \Delta T}{E_{max\_C}} = 5.33 \times 10^{11}$ graphite

What parameters are relevant?

- Momentum of the particle
- Particle type
  - Activation is mainly an issue for hadron accelerators
- Time structure of beam
- Energy stored in the beam
  - one MJoule can heat and melt 1.5 kg of copper
  - one MJoule corresponds to the energy stored in 0.25 kg of TNT
- Beam power
  - one MWatt during one second corresponds to a MJoule
- Beam size
- Beam power / energy density (MJoule/mm^2, MWatt/mm^2)

The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

Machine protection to be considered for an energy stored in the beam >> 1 kJ
Very important if beam > 1MJ

Range of high energy protons in matter

Continuous beam losses: Collimation

Continuous beam with a power of 1 MW (SNS, JPARC, ESS)

- a loss of 1% corresponds to 10 kW – not to be lost along the beam line to avoid activation of material, heating, quenching, …
- assume a length of 200 m: 50 W/m, not acceptable
- Ideas for accelerators of 5 MW, 10 MW and more

Limitation of beam losses is in order of 1 W/m to avoid activation and still allow hands-on maintenance

- avoid beam losses – as far as possible
- define the aperture by collimators
- capture continuous particle losses with collimators at specific locations

LHC stored beam with an energy of 360 MJ

- Assume lifetime of 10 minutes corresponds to beam loss of 500 kW, not to be lost in superconducting magnets
- Reduce losses by four orders of magnitude

….but also: capture fast accidental beam losses

Accidental beam losses: Machine Protection

Single-passage beam loss in the accelerator complex (ns - μs)

- transfer lines between accelerators or from an accelerator to a target station (target for secondary particle production, beam dump block)
- failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
- failures in linear accelerators
- too small beam size at a target station

Very fast beam loss (ms)

- multi turn beam losses in circular accelerators
- due to a large number of possible failures, mostly in the magnet powering system, with a typical time constant of ~1 ms to many seconds

Fast beam loss (some 10 ms to seconds)

Slow beam loss (many seconds)

Classification of failures

- Type of the failure
  - hardware failure (power converter trip, magnet quench, AC distribution failure such as thunderstorm, object in vacuum chamber, vacuum leak, RF trip, kicker magnet misfires, ….)
  - controls failure (wrong data, wrong magnet current function, trigger problem, timing system, feedback failure, ..)
  - operational failure (chromaticity / tune / orbit wrong values, …)
  - beam instability (due to too high beam / bunch current / e-clouds)
- Parameters for the failure
  - time constant for beam loss
  - probability for the failure } defined as risk
  - damage potential }
- Machine state when failure occurs
  - beam transfer, injection and extraction (single pass)
  - acceleration
  - stored beam

Example for Active Protection - Traffic

- A monitor detects a dangerous situation


- An action is triggered

- The energy stored in the system is safely dissipated


Example for Passive Protection

- The monitor fails to detect a dangerous situation
- The reaction time is too short
- Active protection not possible – passive protection by bumper, air bag, safety belts

Strategy for protection and related systems

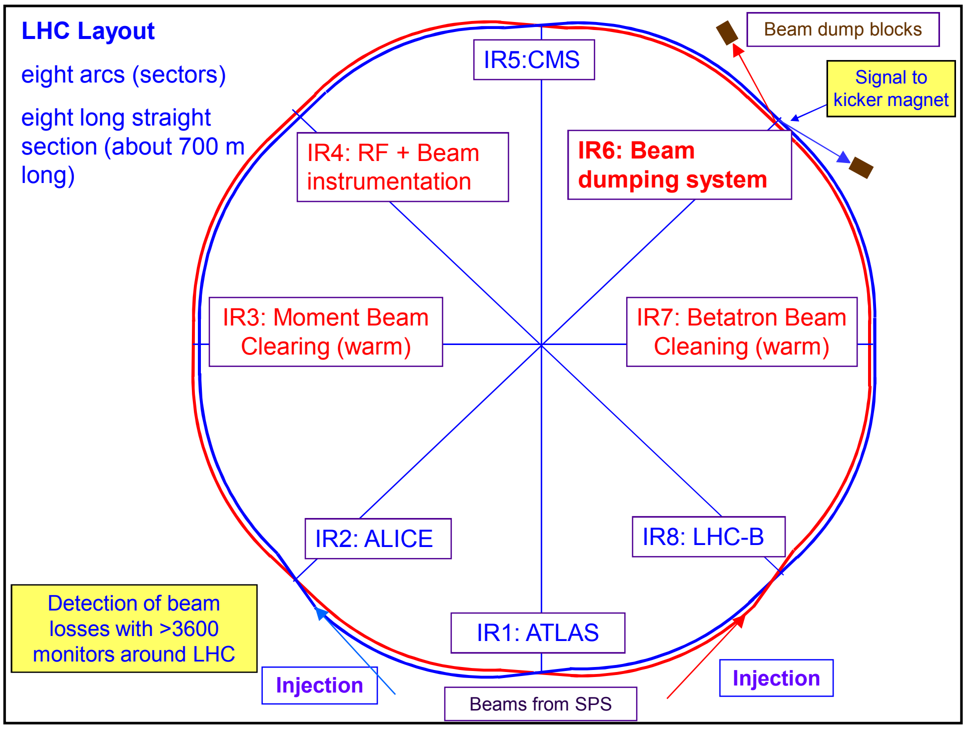
- Avoid that a specific failure can happen
- Detect failure at hardware level and stop beam operation
- Detect initial consequences of failure with beam instrumentation ….before it is too late…
- Stop beam operation
  - stop injection
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - hardware monitoring and beam monitoring
  - beam dump (fast kicker magnet and absorber block)
  - collimators and beam absorbers
  - beam interlock systems linking different systems

Example for LHC

Collimation and Machine Protection during operation

Assume that two 100 MJoule beams (=25 kg TNT) are circulating with the speed of light through the 56 mm diameter vacuum chamber and 2 mm wide collimators

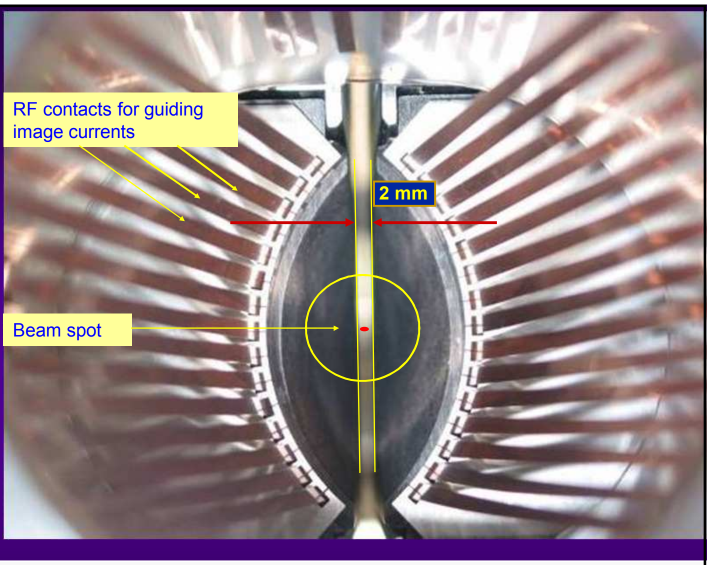
1. Suddenly the AC distribution for CERN fails – no power!
2. An object falls into the beam
3. The betatron tune is driven right onto a 1/3 order resonance

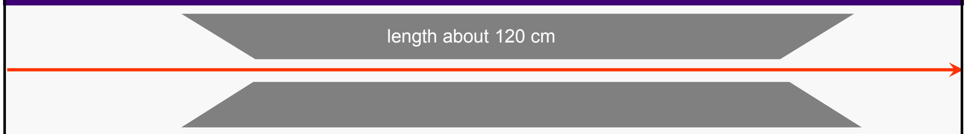


View of a two sided collimator

for LHC

about 100 collimators are installed

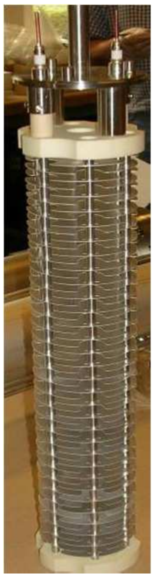




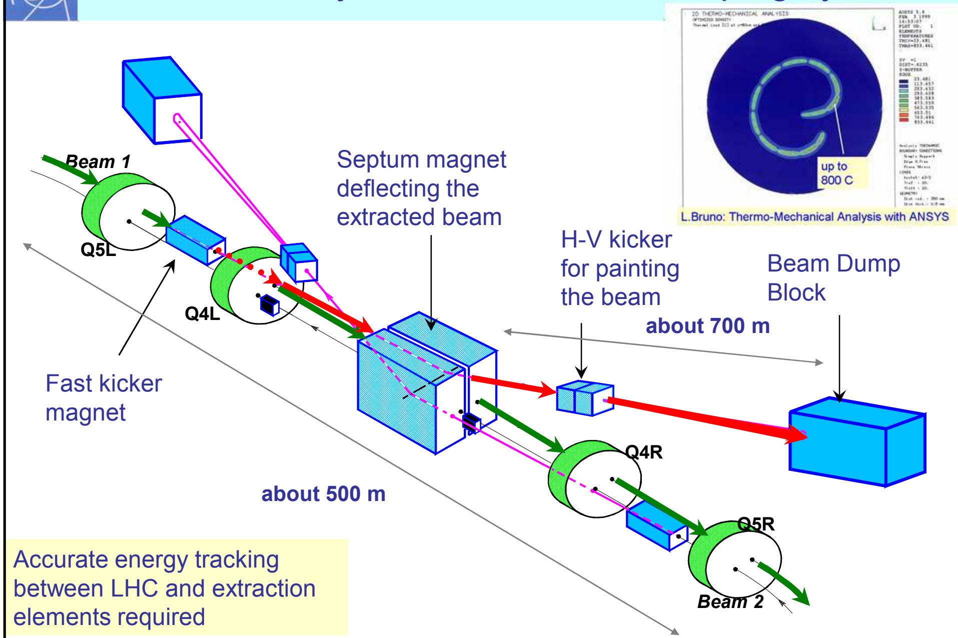
Ralph Assmann, CERN

Beam Loss Monitors

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are ~3600 chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !



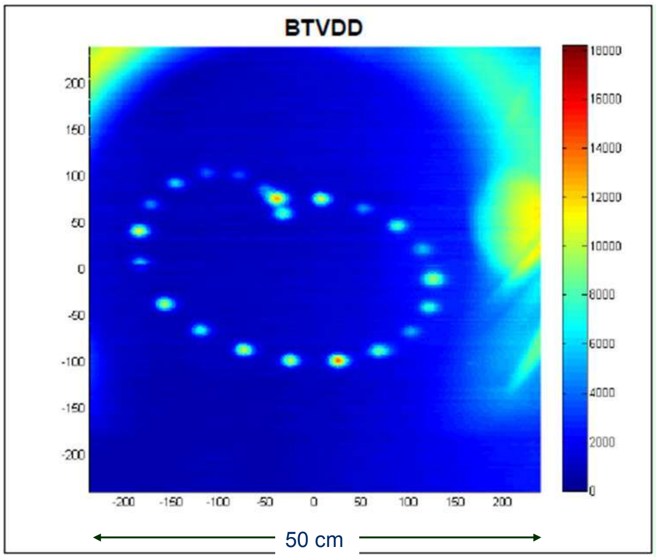
Schematic layout of LHC beam dumping system



Accurate energy tracking between LHC and extraction elements required

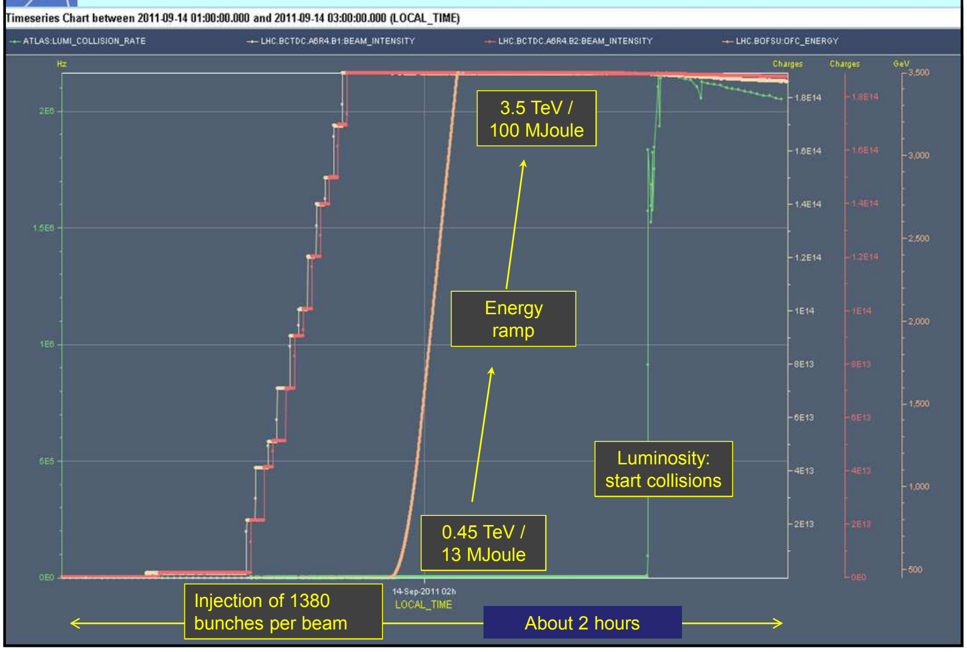
The LHC dump block during the construction phase

Beam dump

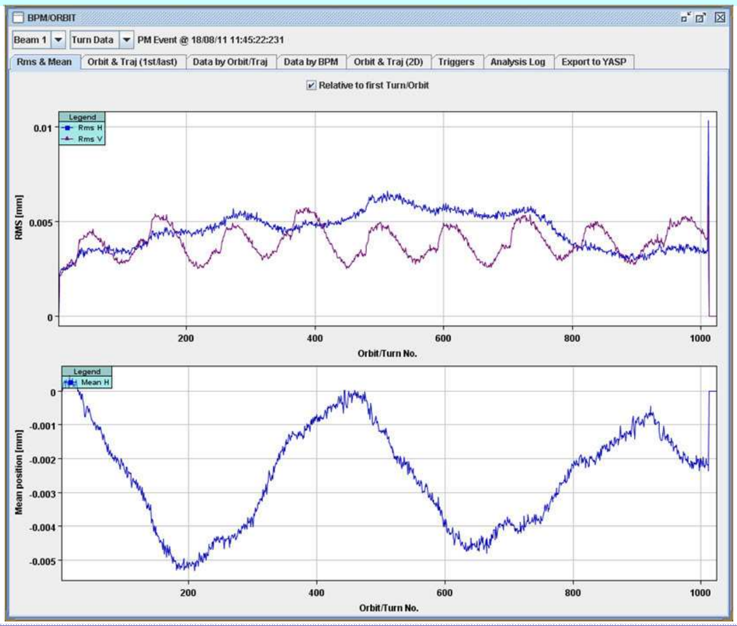


- Screen in front of the beam dump block
- Each light dot shows the passage of one proton bunch traversing the screen
- Each proton bunch has a different trajectory, to better distribute the energy across a large volume

LHC from injection to collisions



Orbit for last 1000 turns before power cut



Continuous beam losses

Example for power radiated during particle collisions for LHC

Rate of collision: $f[Hz] = L[cm^{-2} \cdot s^{-1}] \cdot \sigma\ [cm^2]$

Power in collision products: $P[W] = f[Hz] \cdot E[eV]$

Assume LHC operating at 7 TeV with a luminosity of:

$$L = 10^{34} \cdot [cm^{-2} \cdot s^{-1}]$$

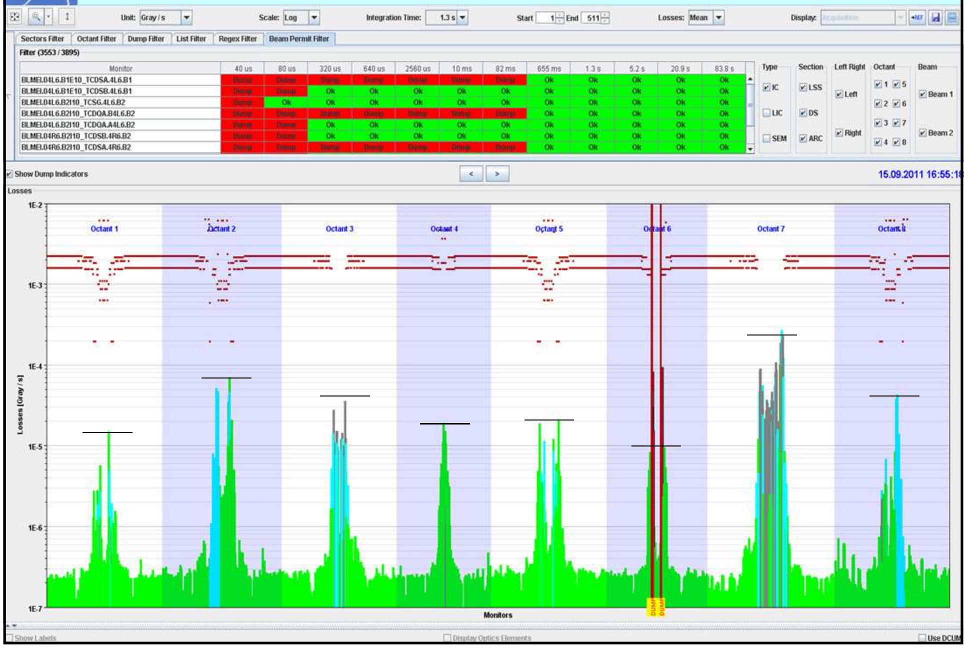
Total cross section for pp collision of 110 mBarn:

$$P[W] = 10^{34} \cdot [cm^{-2} \cdot s^{-1}] \cdot 10^{-25}\ [cm^2] \cdot 7[TeV]$$

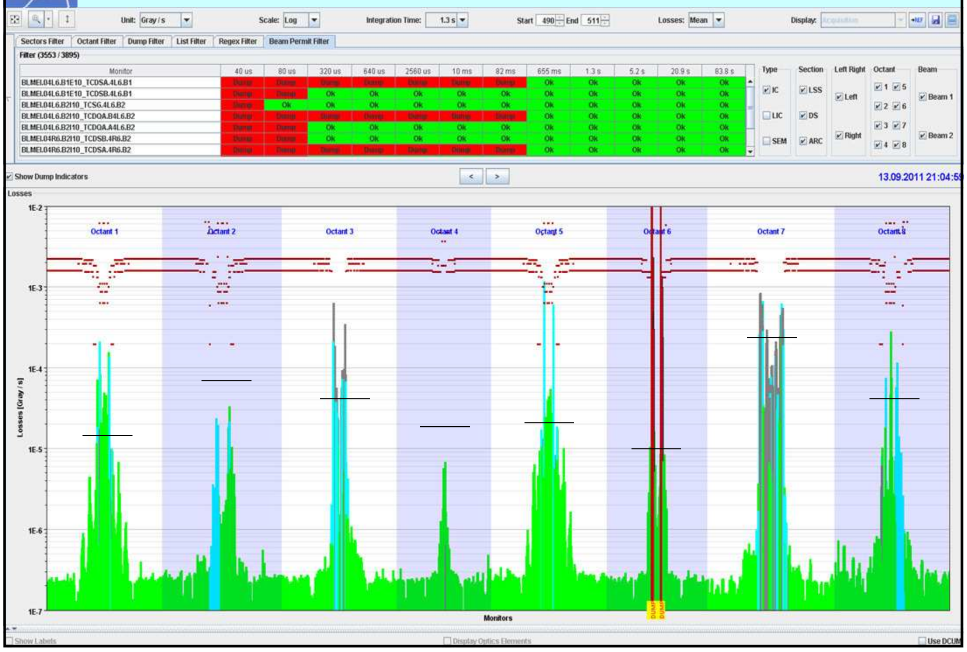
Power in collision products per experiment: $P[W] = 1100[W]$

- Some fraction of the protons are deflected by a small angle and remain in the vacuum chamber
- Some fraction hits close-by equipment

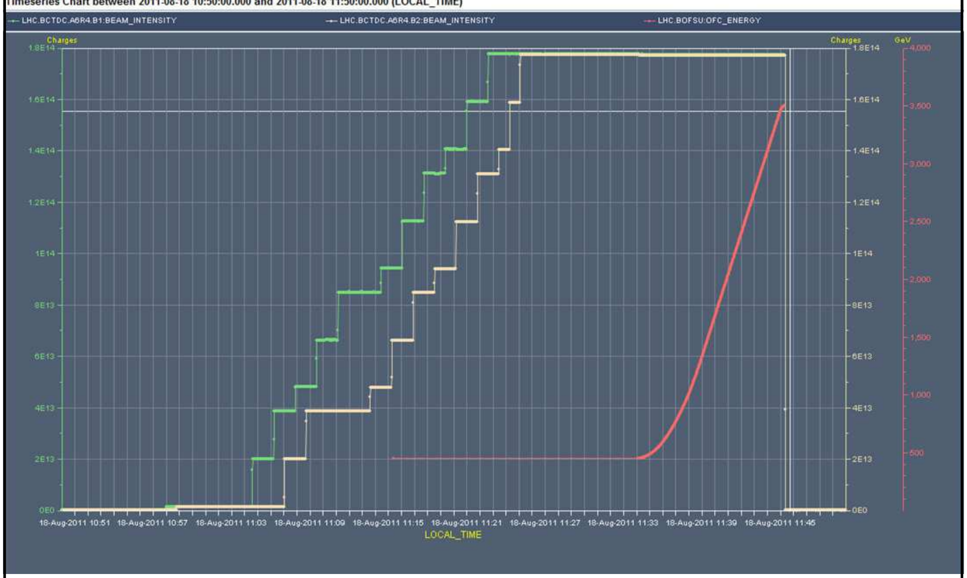
Beam losses before collisions



Continuous beam losses during collisions



Total power cut atLHC - 18 August 2011, 11:45



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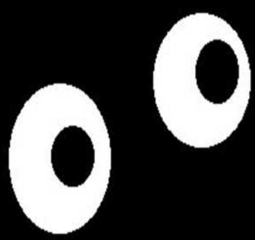
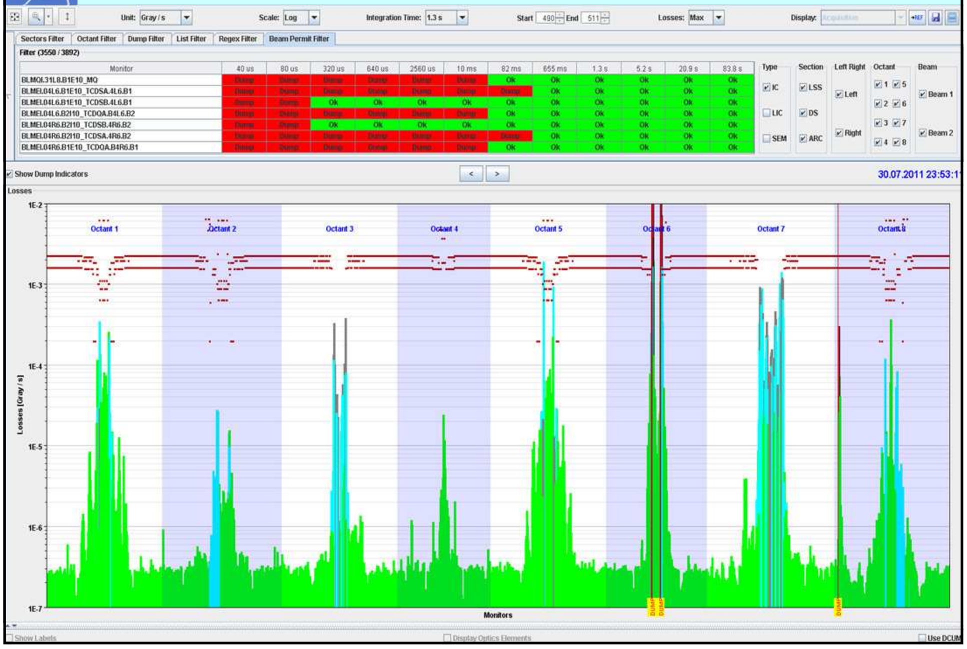


1. Suddenly the AC distribution for CERN fails – no power for LHC!

Accidental beam losses during collisions



Beam losses during collisions

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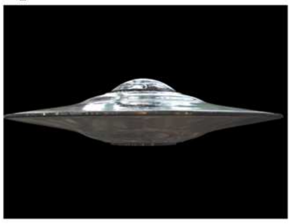
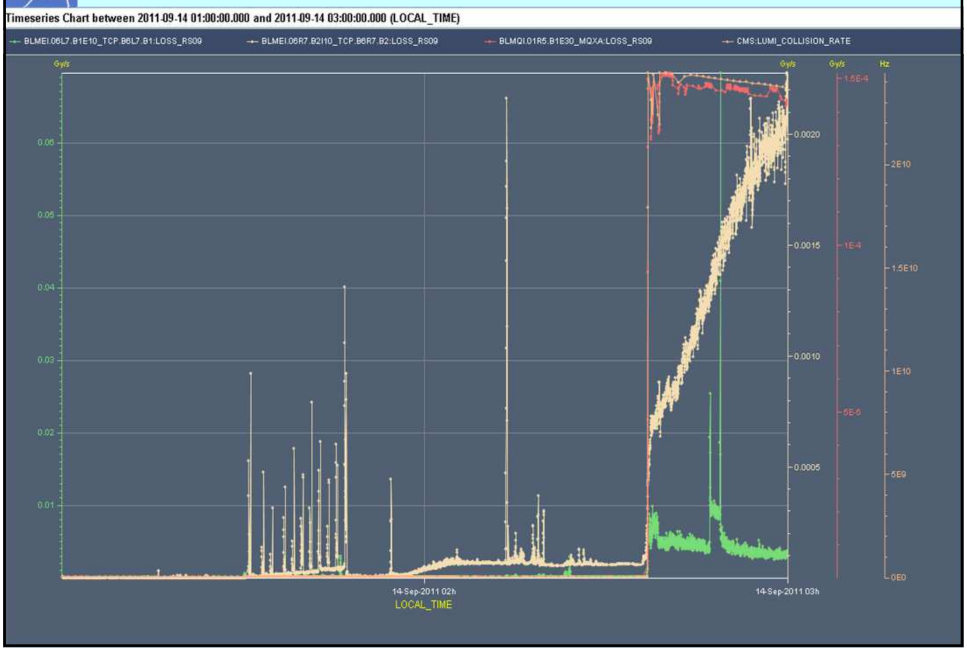
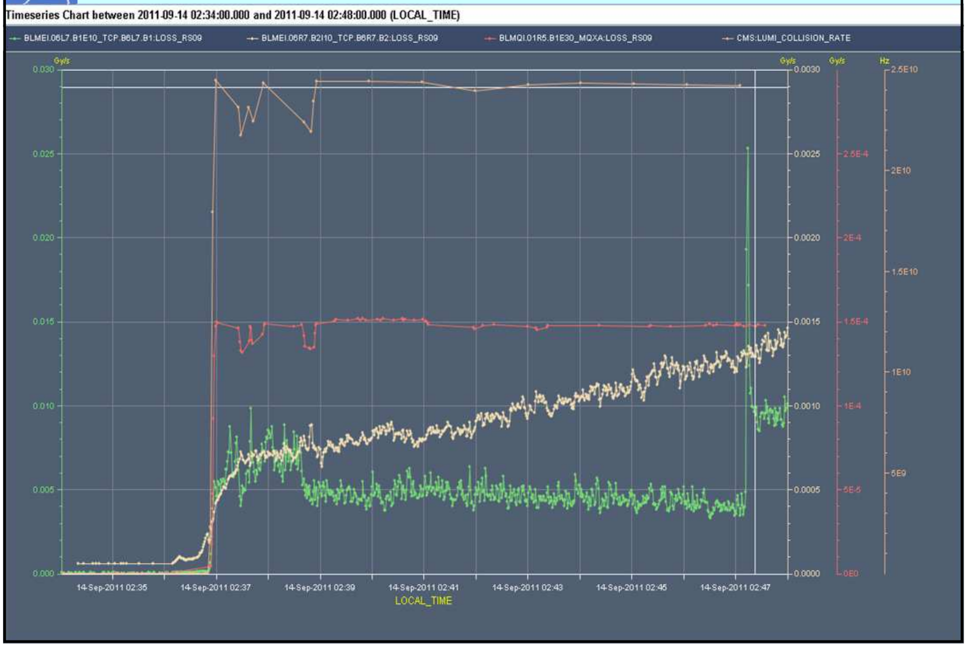
UFO at LHC



LHC from injection to collisions: beam loss



…zoom - going into collisions



Beam cleaning system captures beam losses

- In case protons are lost because of low lifetime
- In case of protons are lose when colliding beams, and scattering of protons during the collisions that would be lost around the LHC
- In case of protons outside the RF bucket – losing slowly energy – are captured by collimators in the Momentum Cleaning Insertion

Questions

- How to stop high energy protons?
- Why so many collimators?
- Why carbon composite or graphite used for most collimators?

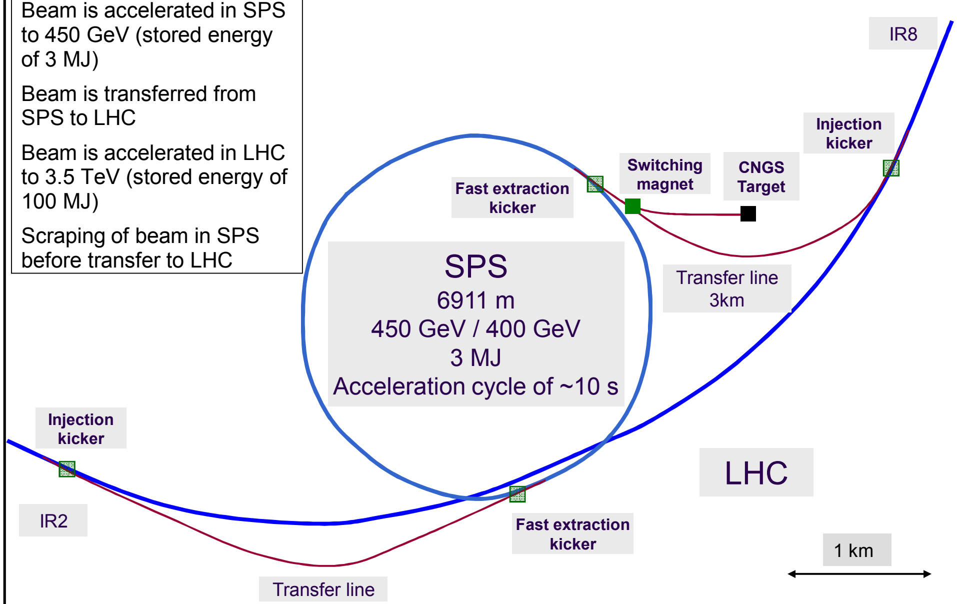
SPS, transfer line and LHC

Beam is accelerated in SPS to 450 GeV (stored energy of 3 MJ)

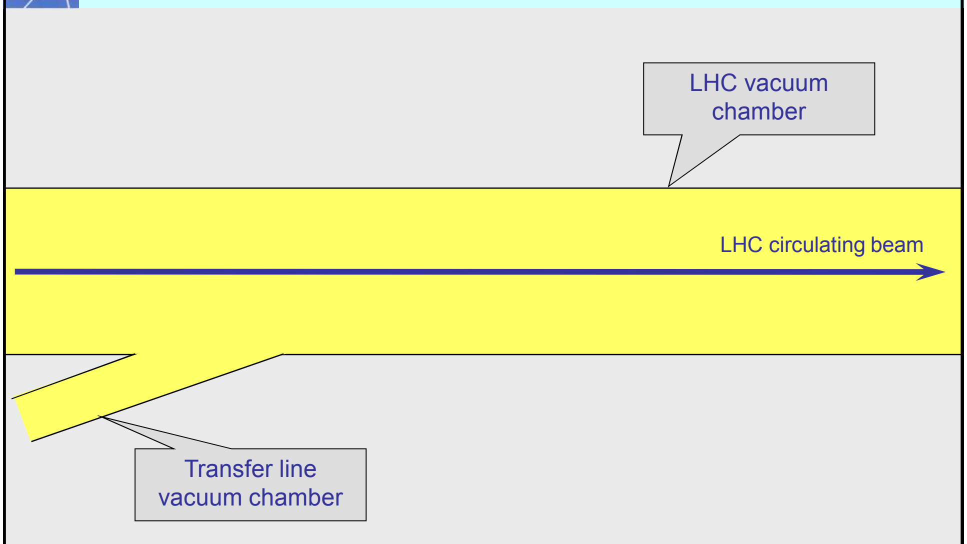
Beam is transferred from SPS to LHC

Beam is accelerated in LHC to 3.5 TeV (stored energy of 100 MJ)

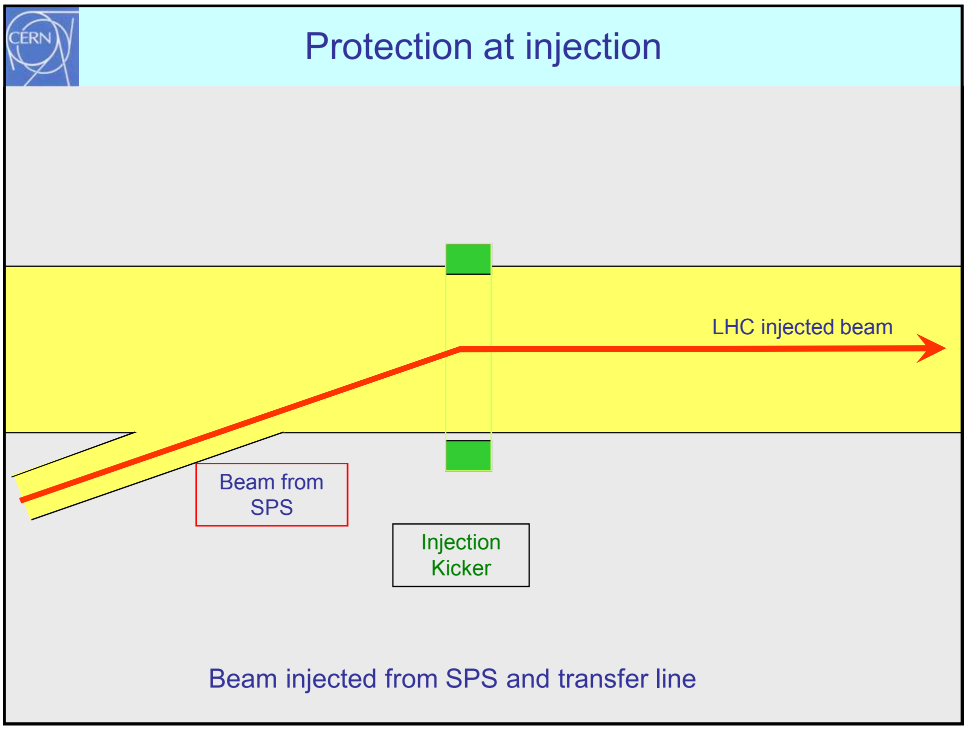
Scraping of beam in SPS before transfer to LHC

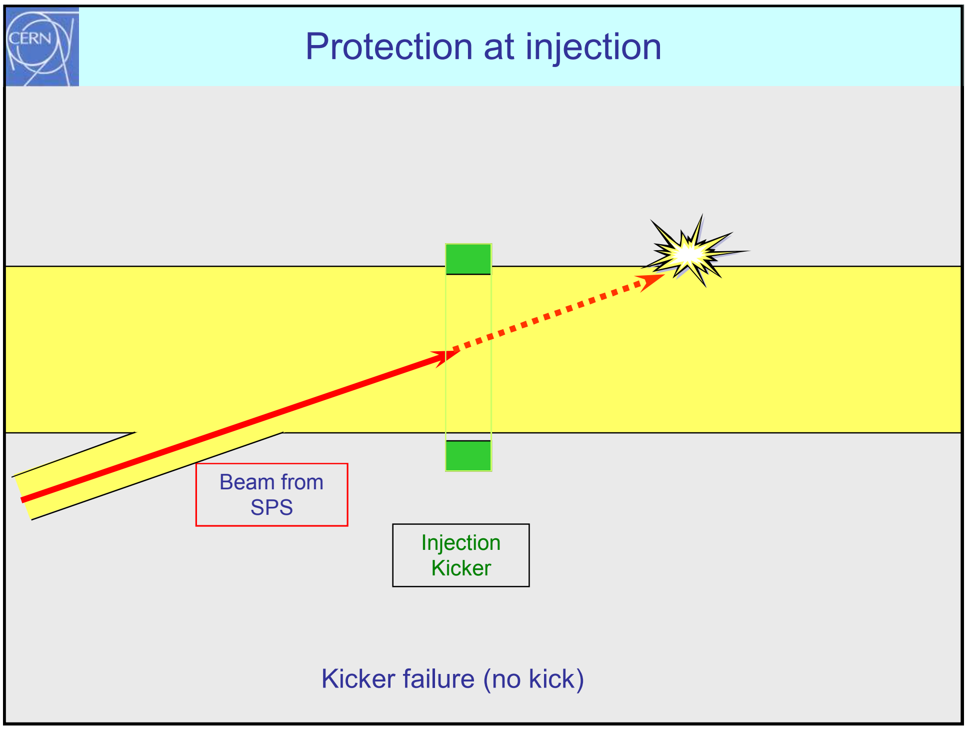


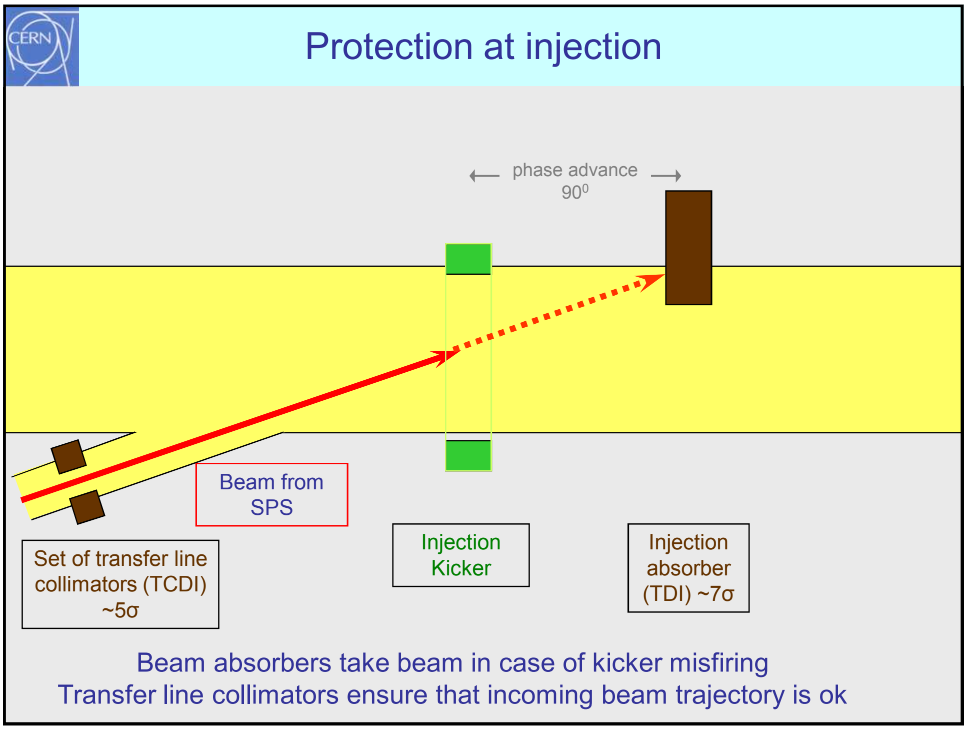
Protection at injection

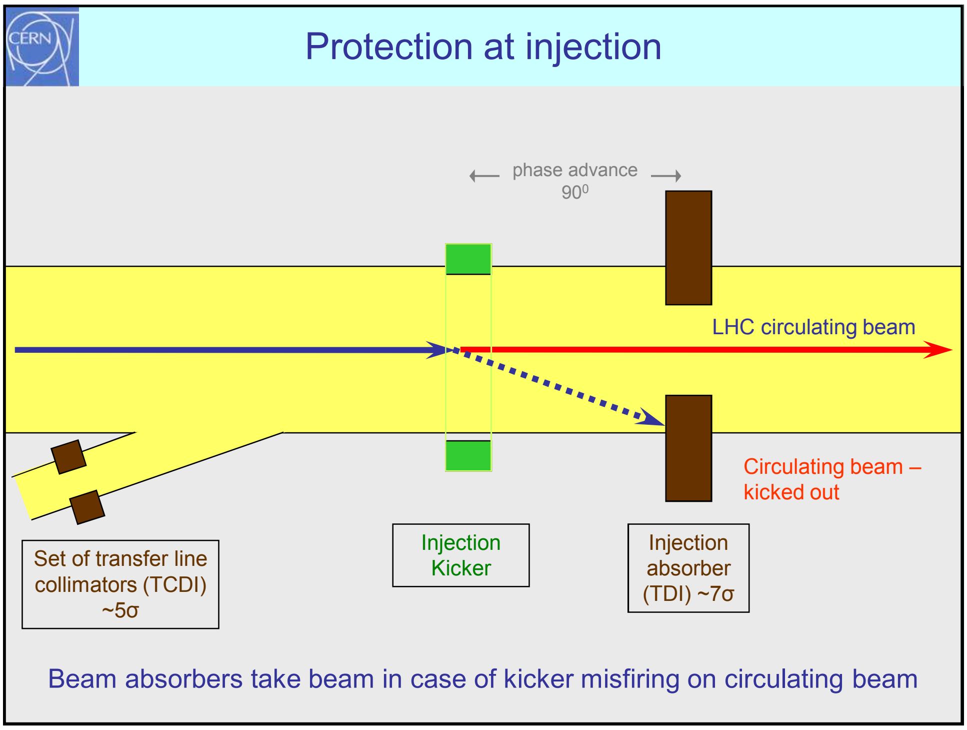


Circulating beam in LHC


Protection at injection
LHC injected beam
Beam from SPS
Injection Kicker
Beam injected from SPS and transfer line

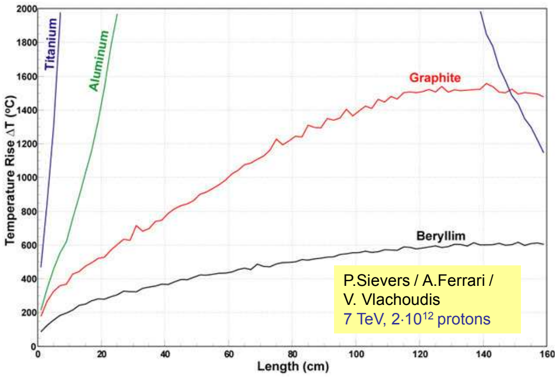

Protection at injection
Beam from SPS
Injection Kicker
Kicker failure (no kick)


Protection at injection
phase advance
90⁰
Beam from
SPS
Set of transfer line
collimators (TCDI)
~5σ
Injection
Kicker
Injection
absorber
(TDI) ~7σ
Beam absorbers take beam in case of kicker misfiring
Transfer line collimators ensure that incoming beam trajectory is ok


Protection at injection
phase advance
90⁰
LHC circulating beam
Circulating beam –
kicked out
Set of transfer line
collimators (TCDI)
~5σ
Injection
Kicker
Injection
absorber
(TDI) ~7σ
Beam absorbers take beam in case of kicker misfiring on circulating beam

Collimator material

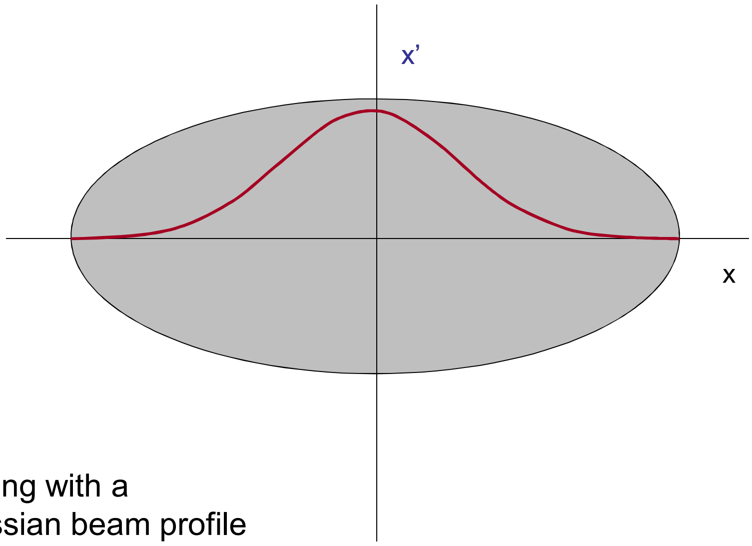
- Metal absorbers would be destroyed
- Other materials for injection absorber preferred, graphite or boron nitride for the injection absorber
- In case of a partial kick (can happen), the beam would travel further to the next collimators in the cleaning insertions
- For collimators close to the beam, metal absorbers would be destroyed
- Other materials for collimators close to the beam are preferred (carbon – carbon)



Collimation

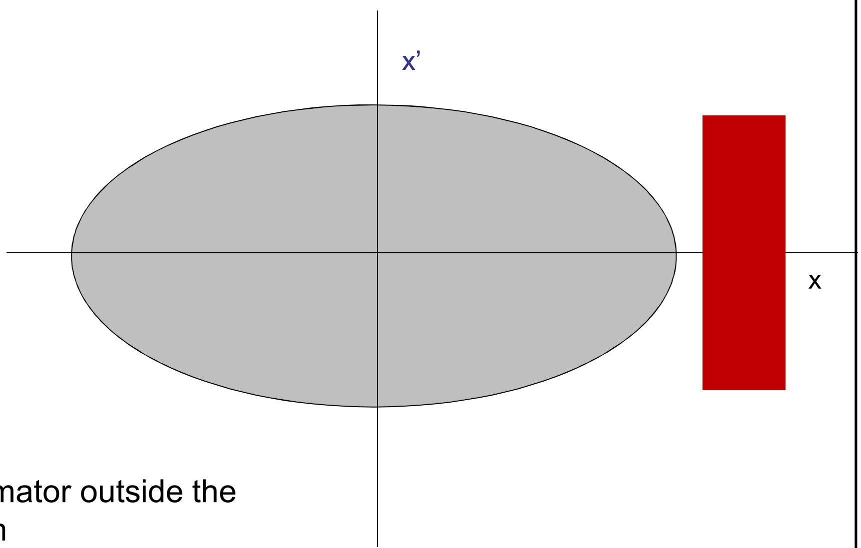
- For a circular accelerator, the transverse distribution of beams is in general Gaussian, or close to Gaussian (beams can have non-Gaussian tails)
- In general, particles in these tails cause problems when they might touch the aperture
  - Background
  - Quenches in magnets (for accelerators with sc magnets)
  - For high intensity machines, possible damage of components
- Nearly all particles that are in the centre go first through the tails before getting lost (except those that do a inelastic collision with gas molecules)
- Tails are scraped away using collimators

Phase space and collimation



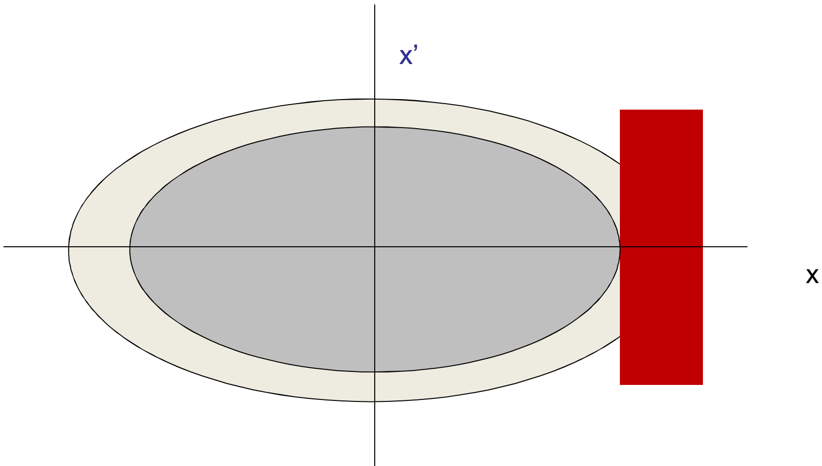
Starting with a
Gaussian beam profile

Phase space and collimation



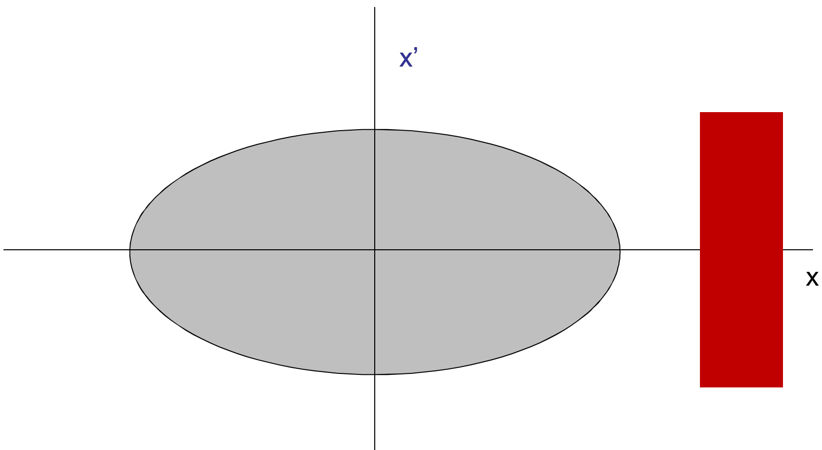
Collimator outside the
beam

Phase space and collimation: multi turn



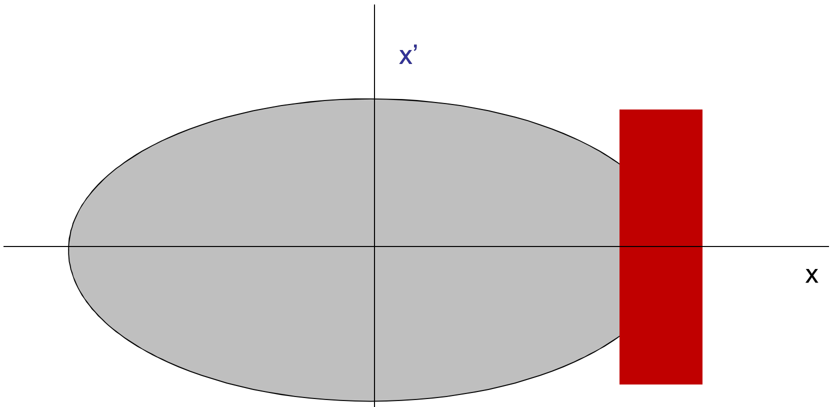
Collimator driven into the beam tail: loss of particles

Phase space and collimation: multi turn



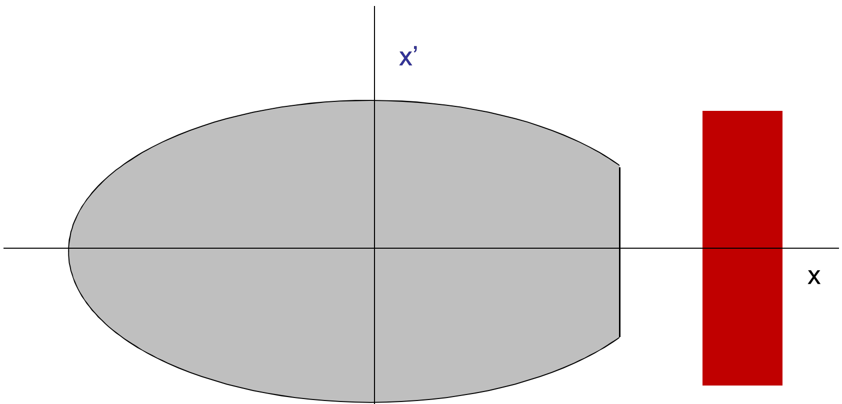
Collimator again outside the beam – beam size reduction (for proton synchrotrons)

Phase space and collimation: single turn



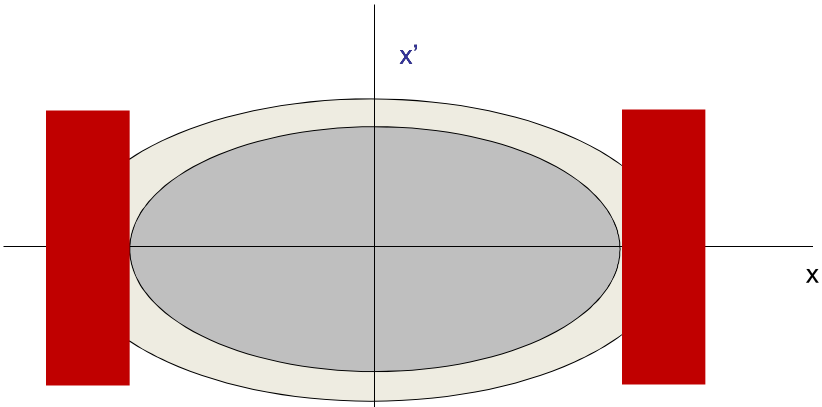
Collimator in a transfer line or linac: cuts only part of the beam

Phase space and collimation: single turn



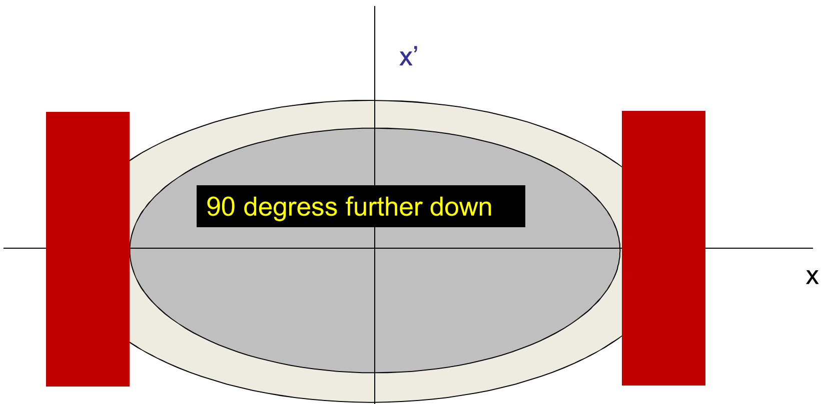
Collimator in a transfer line or linac: cuts only part of the beam

Phase space and collimation: single turn



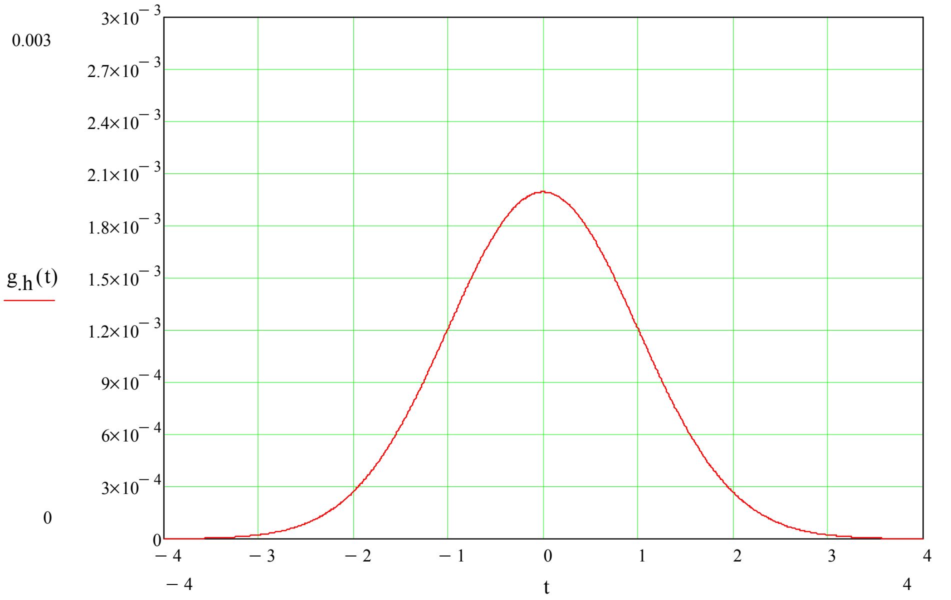
Collimator in a transfer line or linac: several collimators are required

Phase space and collimation: single turn

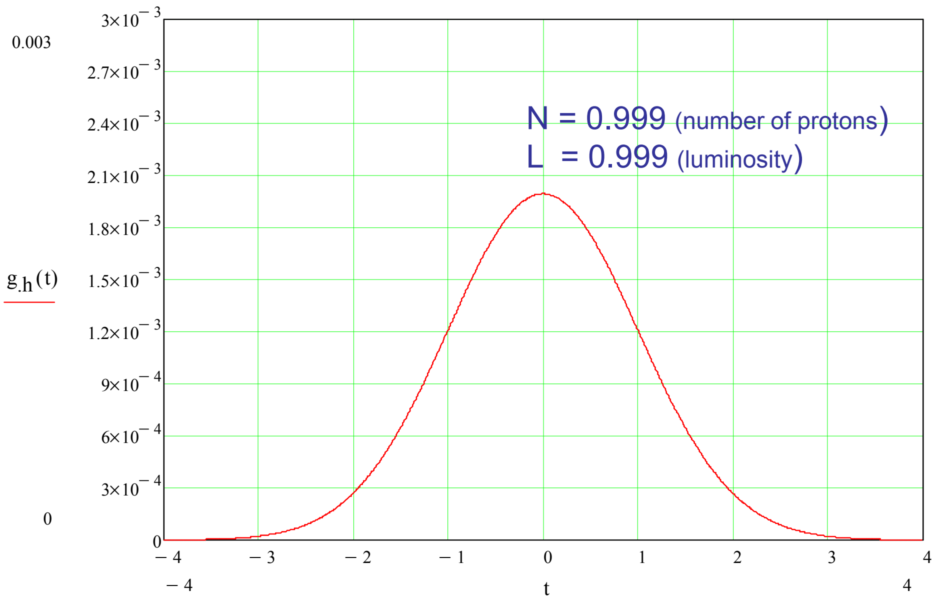


Collimator in a transfer line or linac: several collimators are required …. at different betatron phases

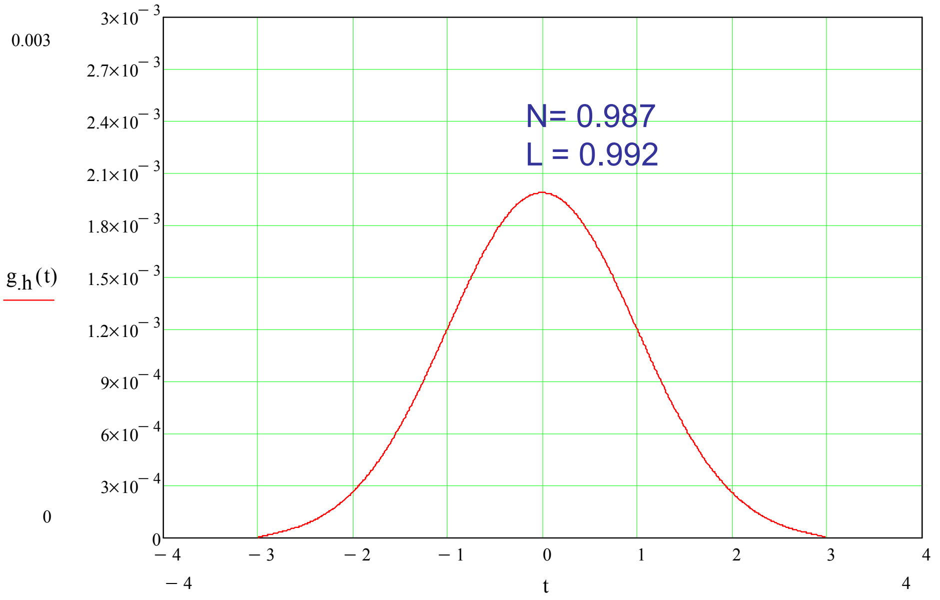
Gaussian beam not collimated



Gaussian beam collimated at 4 sigma



Gaussian beam collimated at 3 sigma



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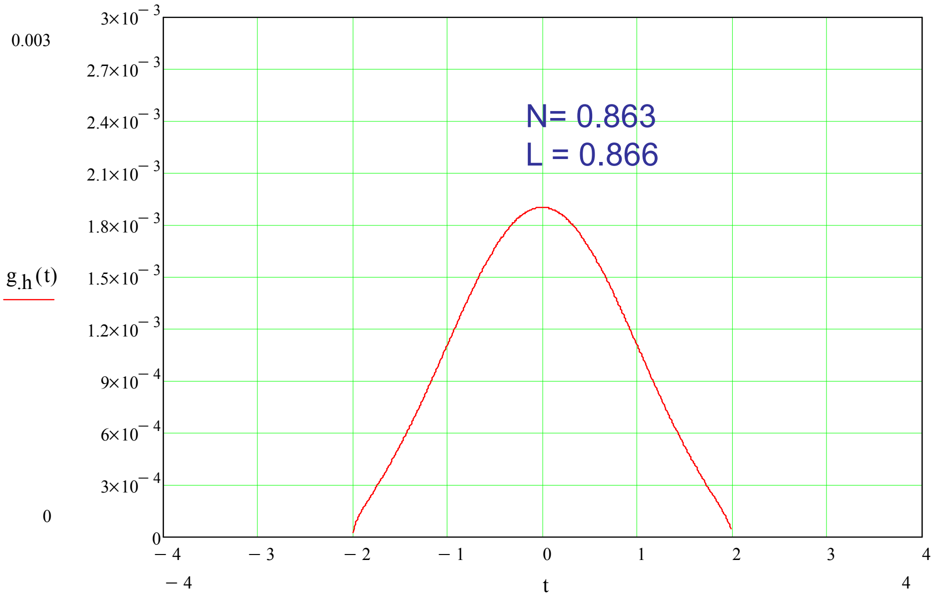
Gaussian beam collimated at 2 sigma



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Collimation: why so many?

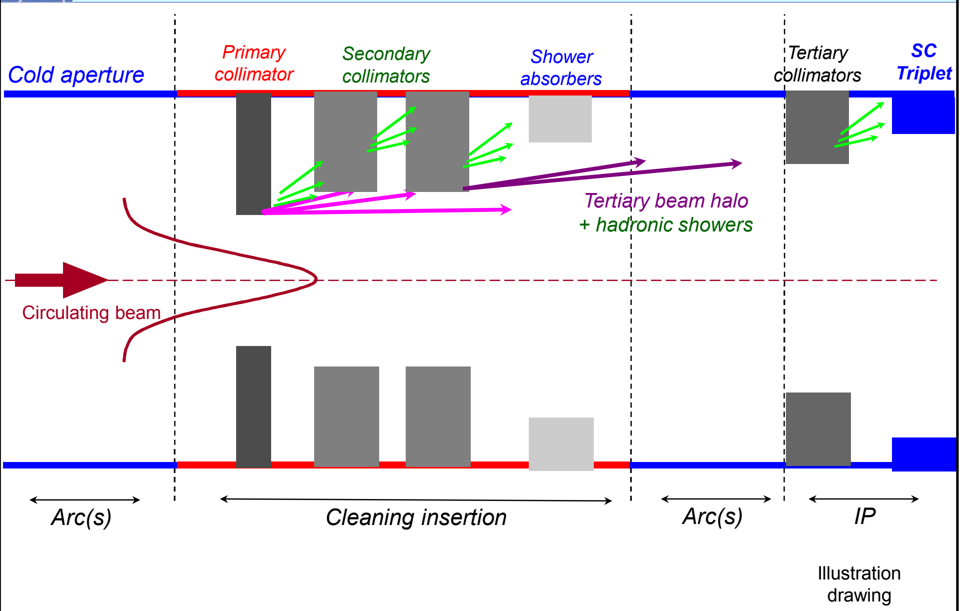
Answer A:

- For a transfer line or a linear accelerator, many collimators are required to take out particles at all phases

Answer B:

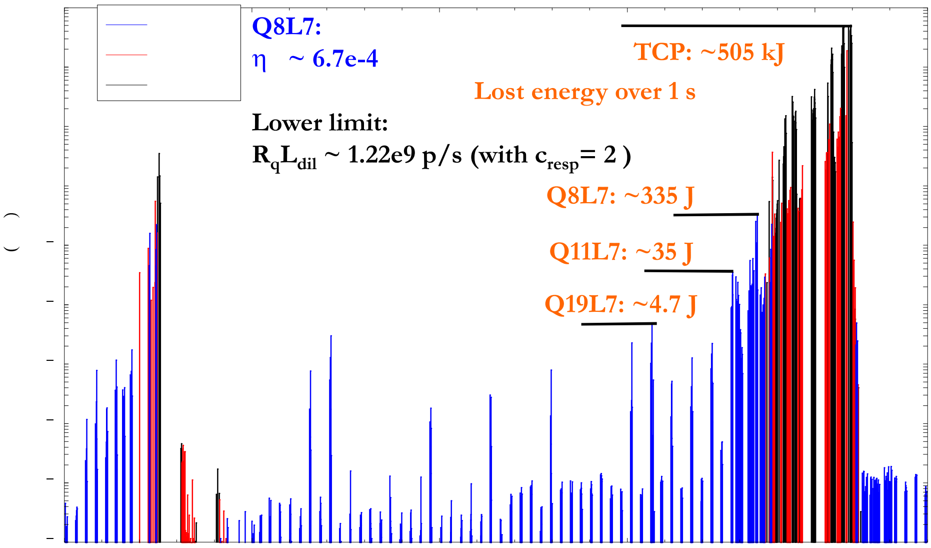
- Cite: "It is not possible to stop a high energy proton, it is only possible to make them mad"
- Collimators cannot stop a high energy proton
- The particle impact on a collimator jaw is very small, in the order of microns or even less
- Particles scatter….. depends on particle type, energy and impact on collimator jaw
- Staged collimation system in a ring and in a transfer line

Betatron beam cleaning



Measurement: 500kJ losses at primary collimators (loss rate: 9.1e11 p/s) – IR7

LHC Collimation Project
CERN



Film from Alessandro

LHC: Strategy for machine protection

• Definition of aperture by collimators.	**Beam Cleaning System**
• Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.	**Powering Interlocks** **Fast Magnet Current change Monitor**
• Active monitoring of the beams detects abnormal beam conditions and generates beam dump requests down to a single machine turn.	**Beam Loss Monitors** Other Beam Monitors
• Reliable operation of beam dumping system for dump requests or internal faults, safely extract the beams onto the external dump blocks.	**Beam Dumping System**
• Reliable transmission of beam dump requests to beam dumping system. Active signal required for operation, absence of signal is considered as beam dump request and injection inhibit.	**Beam Interlock System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Collimator and Beam Absorbers**

Accidental beam losses: Risks and protection

- Protection is required since there is some risk
- Risk = probability of an accident (in number of accidents per year)
  • consequences (in Euro, downtime, radiation dose to people)
- Probability of an accidental beam loss
  - What are the failure modes the lead to beam loss into equipment (there is an practical infinite number of mechanisms to lose the beam)?
  - What is the probability for the most likely failures?
- Consequences of an accidental beam loss
  - Damage to equipment
  - Downtime of the accelerator for repair (spare parts available?)
  - Activation of material, might lead to downtime since access to equipment is delayed
- The higher the risk, the more protection becomes important

Some design principles for protection systems

- Failsafe design
  - detect internal faults
  - possibility for remote testing, for example between two runs
  - if the protection system does not work, better stop operation rather than damage equipment
- Critical equipment should be redundant (possibly diverse)
- Critical processes not by software (no operating system)
  - no remote changes of most critical parameters
- Demonstrate safety / availability / reliability
  - use established methods to analyse critical systems and to predict failure rate
- Managing interlocks
  - disabling of interlocks is common practice **(keep track !)**
  - LHC: masking of some interlocks possible for low intensity / low energy beams

Accelerators that require protection systems I

- Hadron synchrotrons with large stored energy in the beam
  - Colliders using protons / antiprotons (TEVATRON, HERA, LHC)
  - Synchrotrons accelerating beams for fixed target experiments (SPS)
- High power accelerators (e.g. spallation sources) with beam power of some 10 kW to above 1 MW
  - Risk of damage and activation
  - Spallation sources, up to (and above) 1 MW quasi-continuous beam power (SNS, ISIS, PSI cyclotron, JPARC, and in the future ESS, MYRRHA and IFMIF)
- Synchrotron light sources with high intensity beams and secondary photon beams
- Energy recovery linacs
  - Example of Daresbury prototype: one bunch train cannot damage equipment, but in case of beam loss next train must not leave the (injector) station

Accelerators that require protection systems II

- Linear colliders / accelerators with very high beam power densities due to small beam size
  - High average power in linear accelerators: FLASH 90 kW, European XFEL 600 kW, SNS 1.4 MW, JLab FEL 1.5 MW, ILC 11 MW
  - One beam pulse can lead already to damage
  - "any time interval large enough to allow a substantial change in the beam trajectory of component alignment (~fraction of a second), pilot beam must be used to prove the integrity" from NLC paper 1999
- Medical accelerators: prevent too high dose to patient
  - Low intensity, but techniques for protection are similar
- Very short high current bunches: beam induces image currents that can damage the environment (bellows, beam instruments, cavities, …)

Beam instrumentation for machine protection

- Beam Loss Monitors
  - stop beam operation in case of too high beam losses
  - monitor beam losses around the accelerator (full coverage?)
  - could be fast and/or slow (LHC down to 40 μs)
- Beam Position Monitors
  - ensuring that the beam has the correct position
  - in general, the beam should be centred in the aperture
  - for extraction: monitor extraction bump using BPMs (redundant to magnet current)
- Beam Current Transformers
  - if the transmission between two locations of the accelerator is too low (=beam lost somewhere): stop beam operation
  - if the beam lifetime is too short: dump beam
- Beam Size Monitors
  - if beam size is too small could be dangerous for windows, targets, …

For future high intensity machines

Machine protection should always start during the design phase of an accelerators

- Particle tracking
  - to establish loss distribution with realistic failure modes
  - accurate aperture model required
- Calculations of the particle shower (FLUKA, GEANT, …)
  - energy deposition in materials
  - activation of materials
  - accurate 3-d description of accelerator components (and possibly tunnel) required
- Coupling between particle tracking and shower calculations
- From the design, provide 3-d model of all components

Summary

Machine protection

- is not equal to equipment protection
- requires the understanding of many different type of failures that could lead to beam loss
- requires comprehensive understanding of all aspects of the accelerator (accelerator physics, operation, equipment, instrumentation, functional safety)
- touches many aspects of accelerator construction and operation
- includes many systems
- is becoming increasingly important for future projects, with increased beam power / energy density (W/mm^2 or J/mm^2) and increasingly complex machines

Thank you very much for your attention