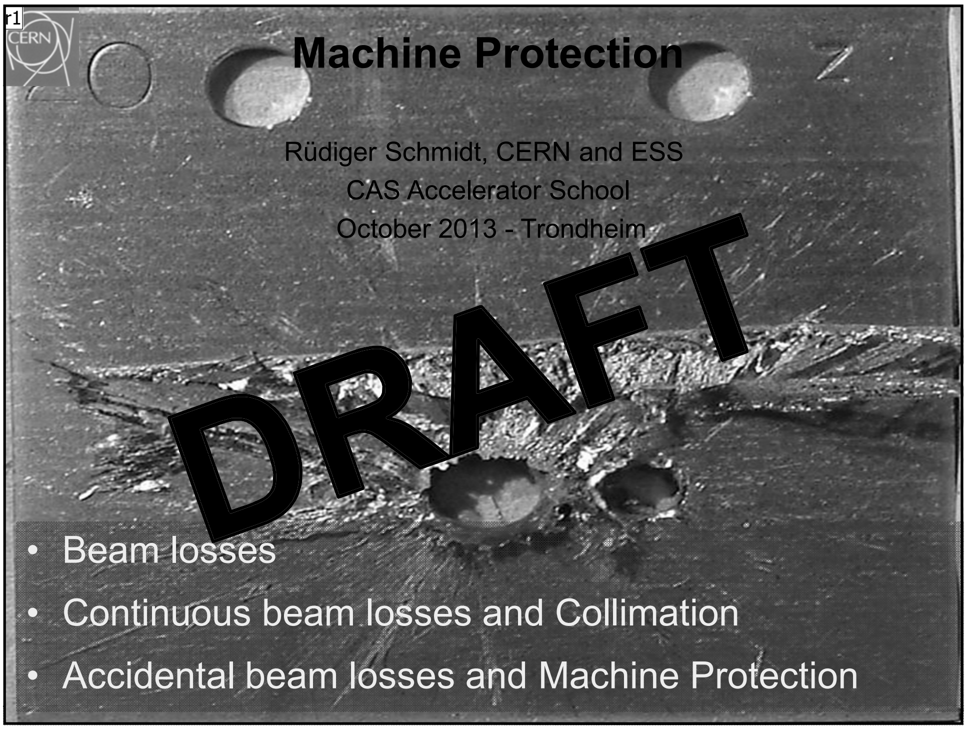


Machine Protection

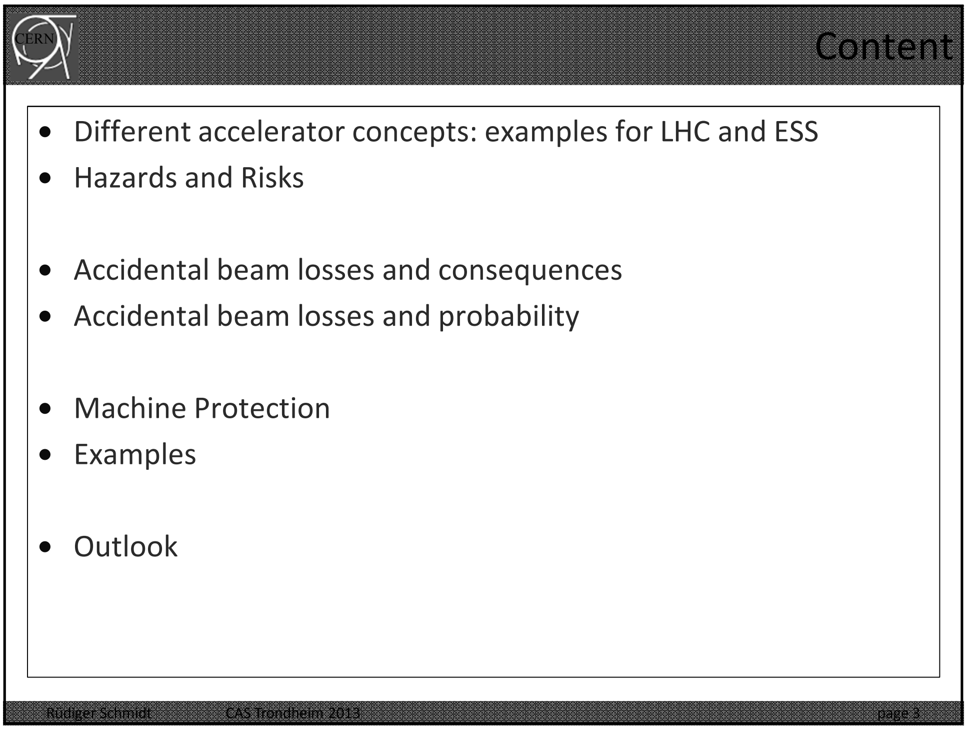
Rüdiger Schmidt, CERN and ESS
CAS Accelerator School
October 2013 - Trondheim

- Beam losses
- Continuous beam losses and Collimation
- Accidental beam losses and Machine Protection

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
  - For particle beams, activation 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 particle beams

Lecture on Machine Protection for preventing damage caused by particle beams



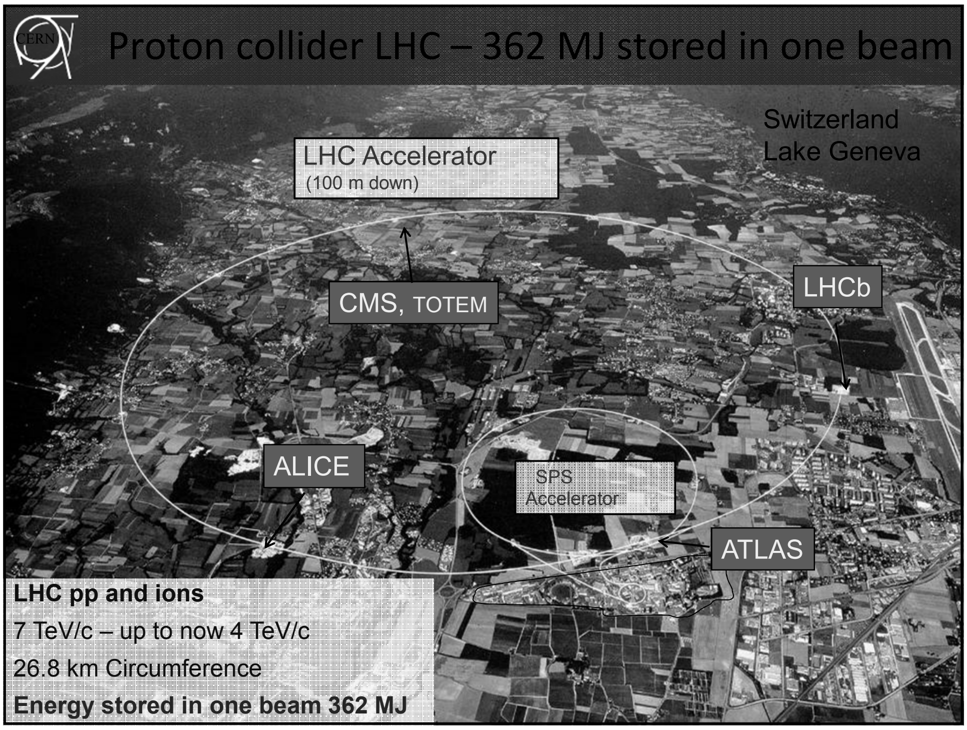
Content

- Different accelerator concepts: examples for LHC and ESS
- Hazards and Risks

- Accidental beam losses and consequences
- Accidental beam losses and probability

- Machine Protection
- Examples

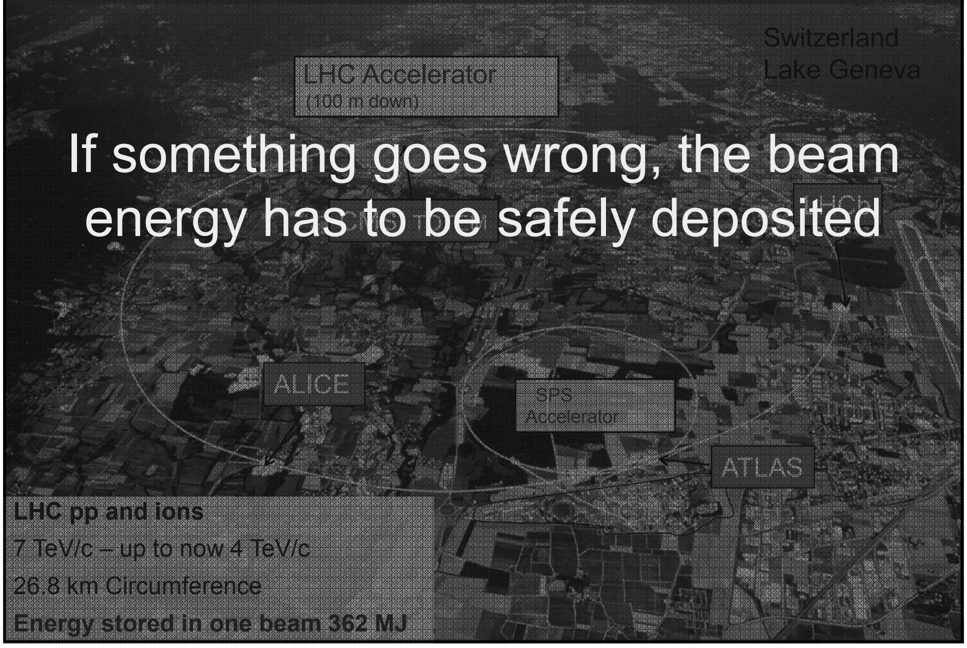
- Outlook



Proton collider LHC – 362 MJ stored in one beam

LHC pp and ions
7 TeV/c – up to now 4 TeV/c
26.8 km Circumference
Energy stored in one beam 362 MJ

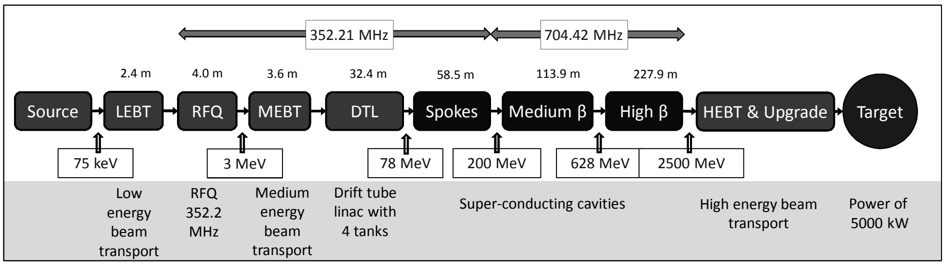
Proton collider LHC – 362 MJ stored in one beam



If something goes wrong, the beam energy has to be safely deposited

LHC pp and ions
7 TeV/c – up to now 4 TeV/c
26.8 km Circumference
Energy stored in one beam 362 MJ

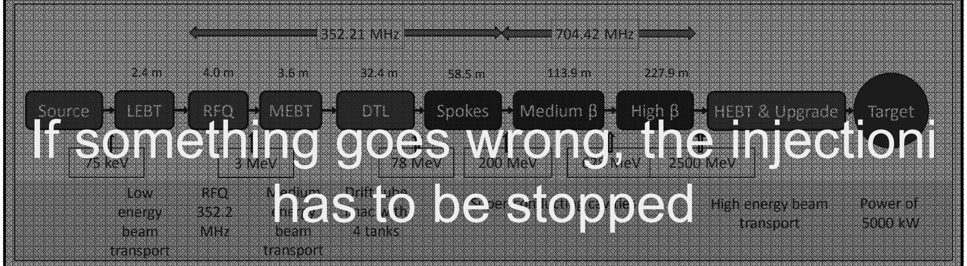
ESS Lund / Sweden – 5 MW beam power



- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average power of 5 MW**
- Peak power of 125 MW

As an example for a high intensity linear accelerator (similar to SNS and J-PARC)

ESS Lund / Sweden – 5 MW beam power

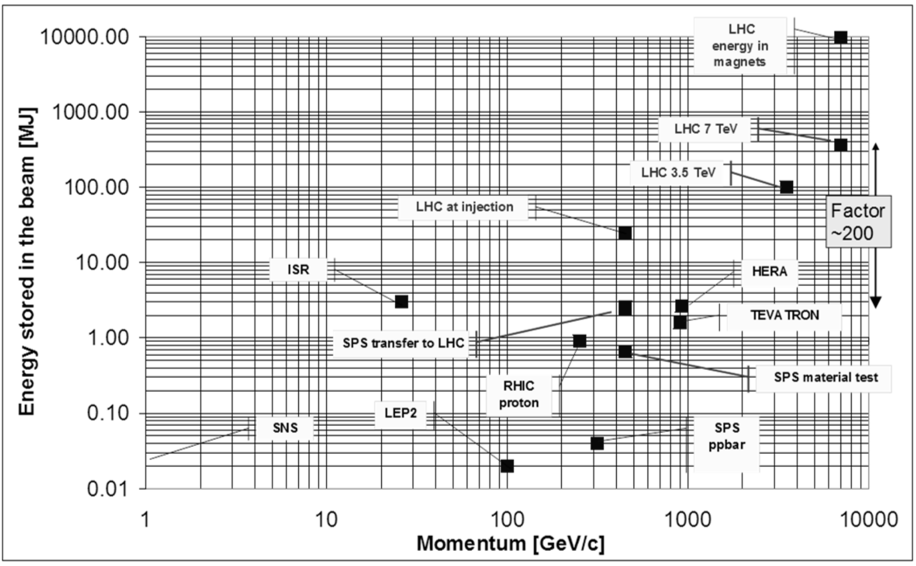


If something goes wrong, the injectioni has to be stopped

- Operating with protons
- Operation with beam pulses at a frequency of 14 Hz
- Pulse length of 2.86 ms
- **Average power of 5 MW**
- Peak power of 125 MW

As an example for a high intensity linear accelerator (similar to SNS and J-PARC)

Energy stored in beam and magnet system

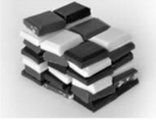


What does it mean ……… MJoule ?

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.

360 MJoule: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

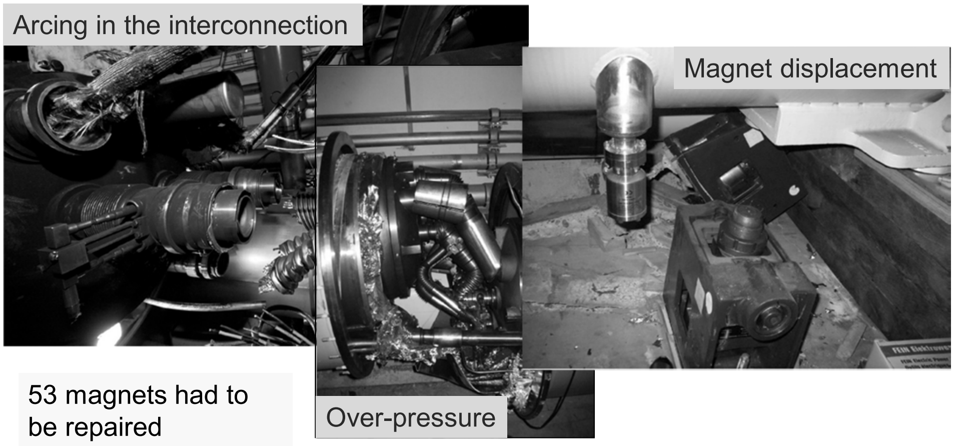


It's how ease the energy is released that matters most !!

Consequences of a release of 600 MJ at LHC

The 2008 LHC accident happened during test runs without beam.

An interconnect was not ok and opened. An electrical arc provoked a He pressure wave damaging ~700 m of LHC, polluting the beam vacuum over more than 2 km.



53 magnets had to be repaired

Machine 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 increased 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 important today, and even more relevant for future projects, with increased beam power / energy density (W/mm^2 or J/mm^2) and increasingly complex machines

Hazards and Risks

Hazard and Risk for accelerators

- **Hazard:** a situation that poses a level of threat to the accelerator. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes "active“: **incident**. **Hazard** and **possibility** interact together to create **RISK**, can be quantified:

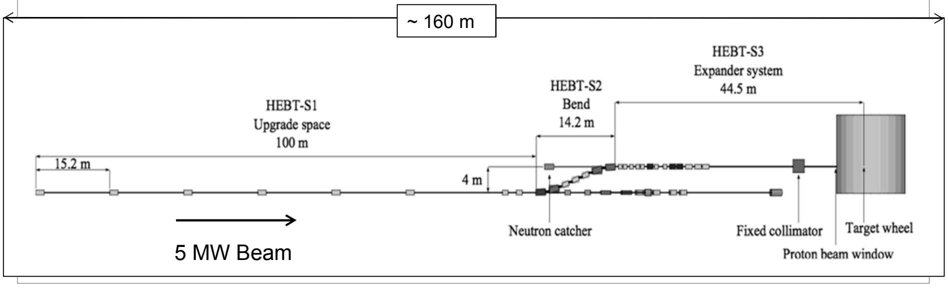
RISK = Consequences · Probability

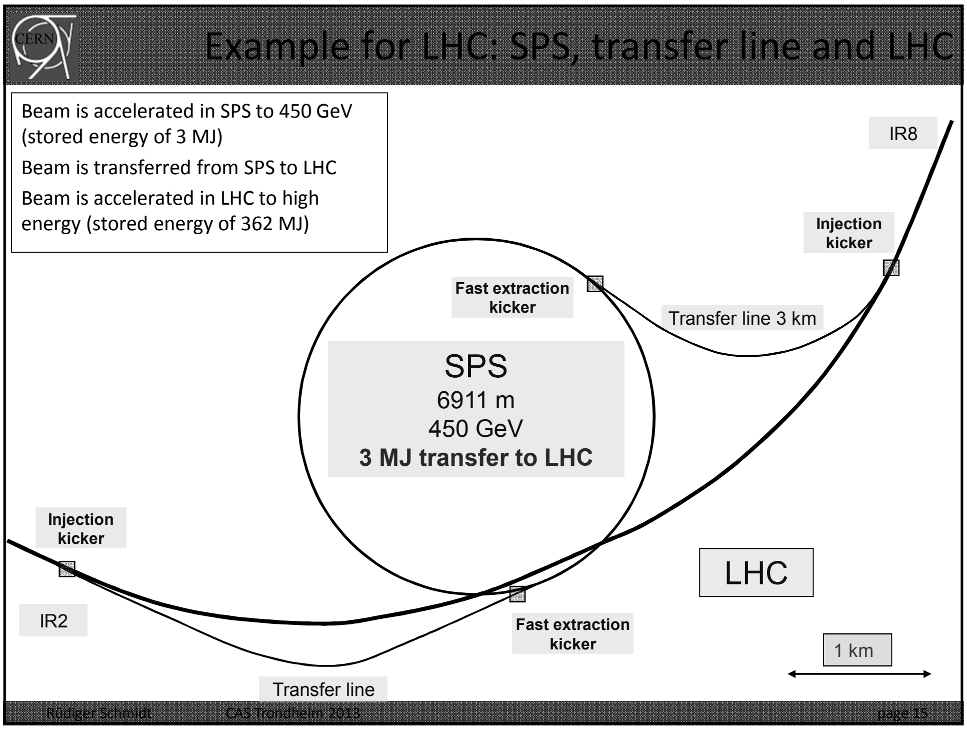
Related to accelerators

- Consequences of an uncontrolled beam loss
- Probability of an uncontrolled beam loss
- The higher the **RISK**, the more **Protection** is required

Example for ESS

- Bending magnet in an accelerator deflecting the beam
- Assume that the power supply fails and the magnets stops deflecting the beam
  - Probability: good MTBF for power supply is 100000 hours = 15 years
- The beam is not deflected and hits the vacuum chamber
  - Consequences: what is expected to happen?



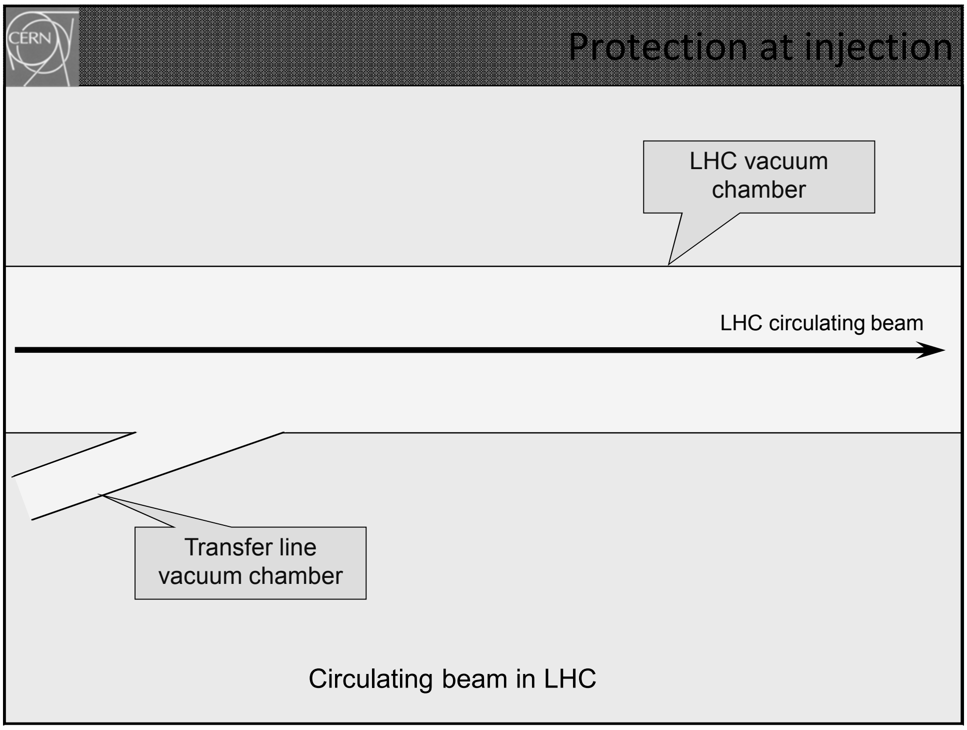


Example for LHC: SPS, transfer line and LHC

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

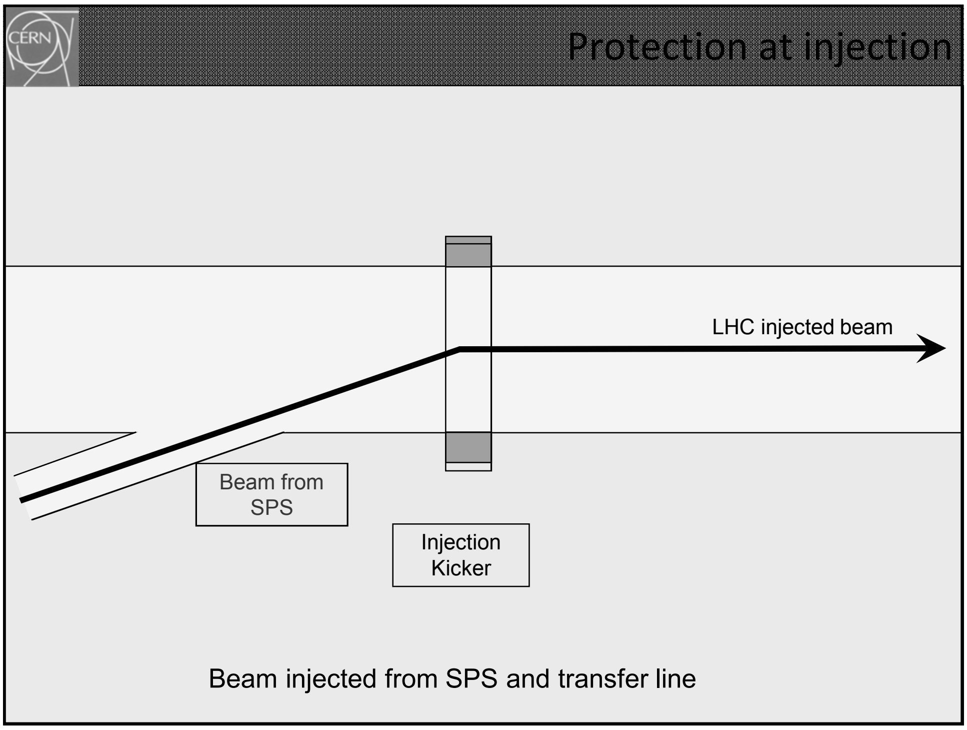
Beam is transferred from SPS to LHC

Beam is accelerated in LHC to high energy (stored energy of 362 MJ)



Protection at injection

Circulating beam in LHC



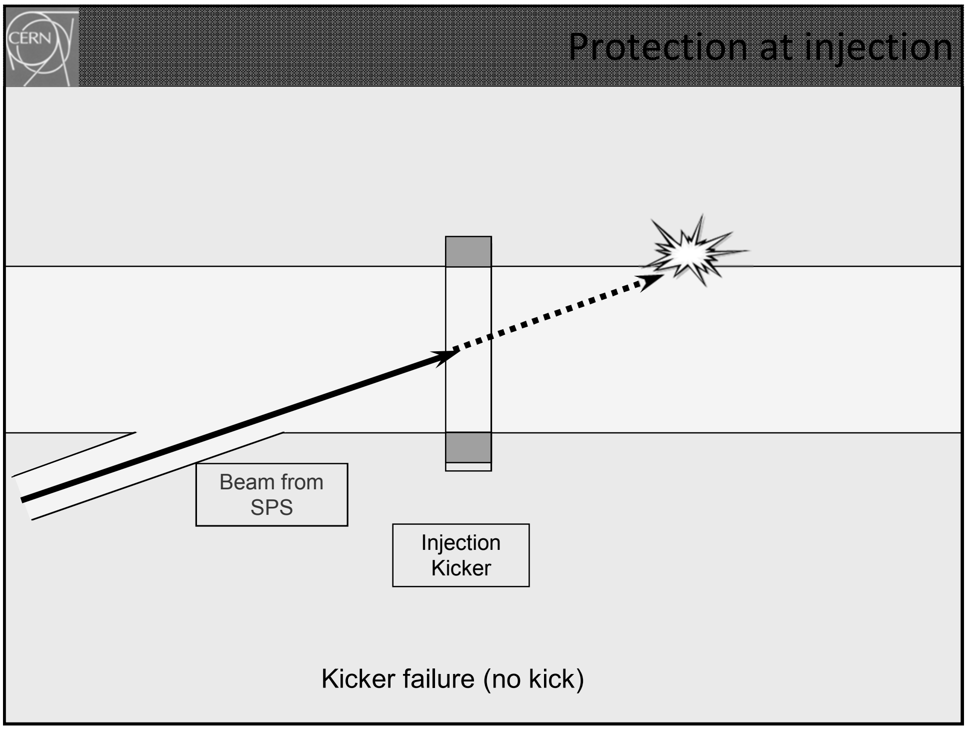
Protection at injection

LHC injected beam

Beam from SPS

Injection Kicker

Beam injected from SPS and transfer line

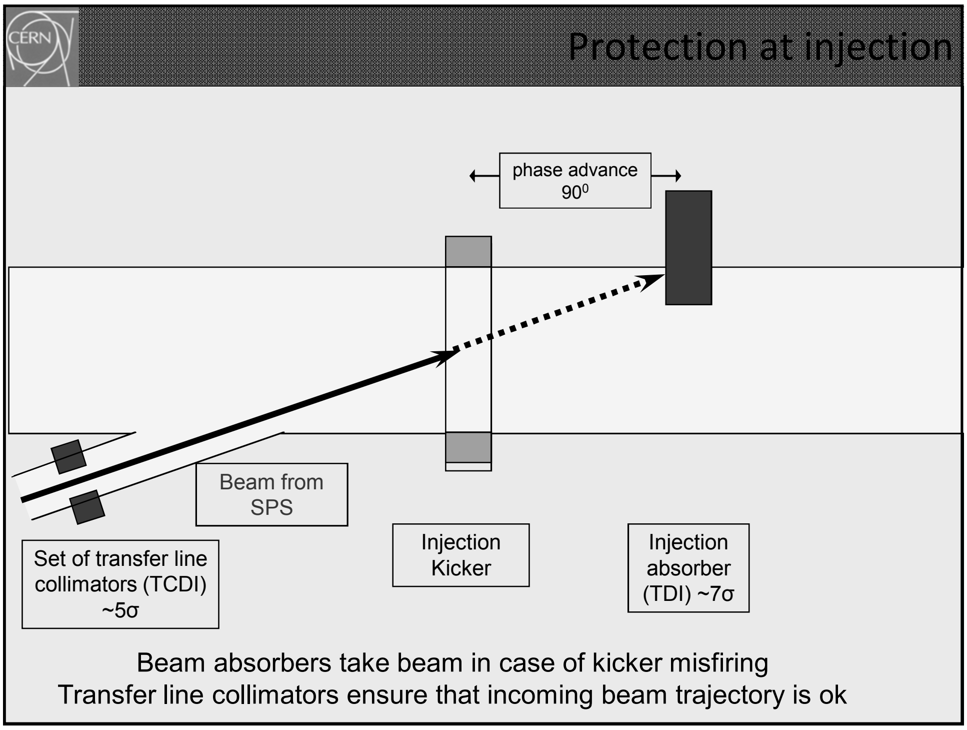


Protection at injection

Beam from SPS

Injection Kicker

Kicker failure (no kick)



Protection at injection

phase advance 90^0

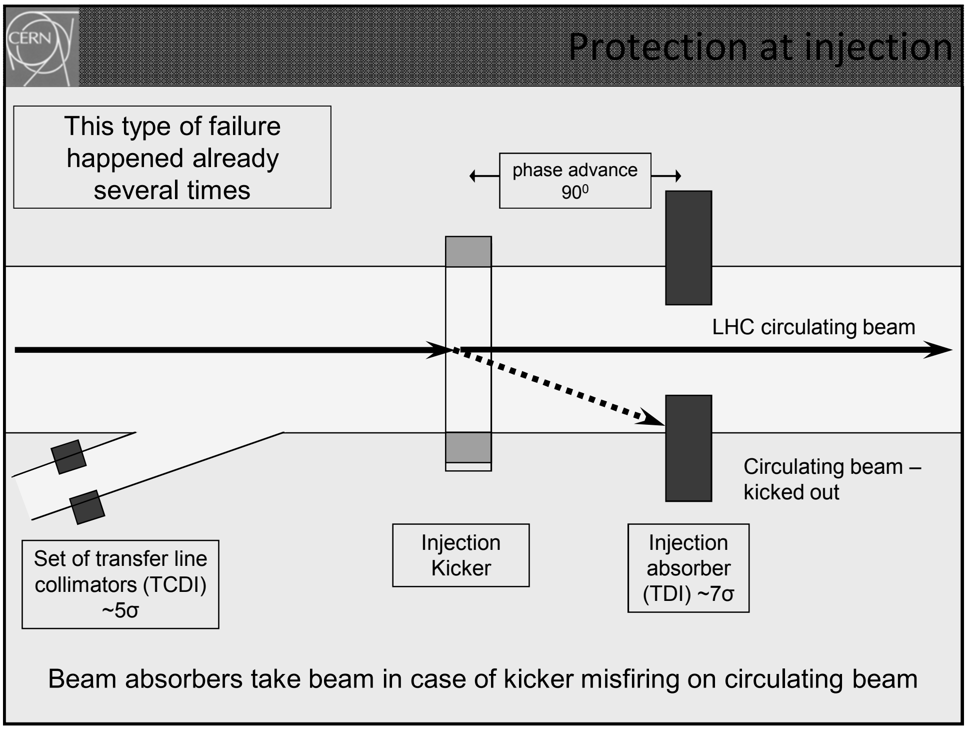
Beam from SPS

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

This type of failure happened already several times

phase advance 90^0

LHC circulating beam

Circulating beam – kicked out

Set of transfer line collimators (TCDI) ~5σ

Injection Kicker

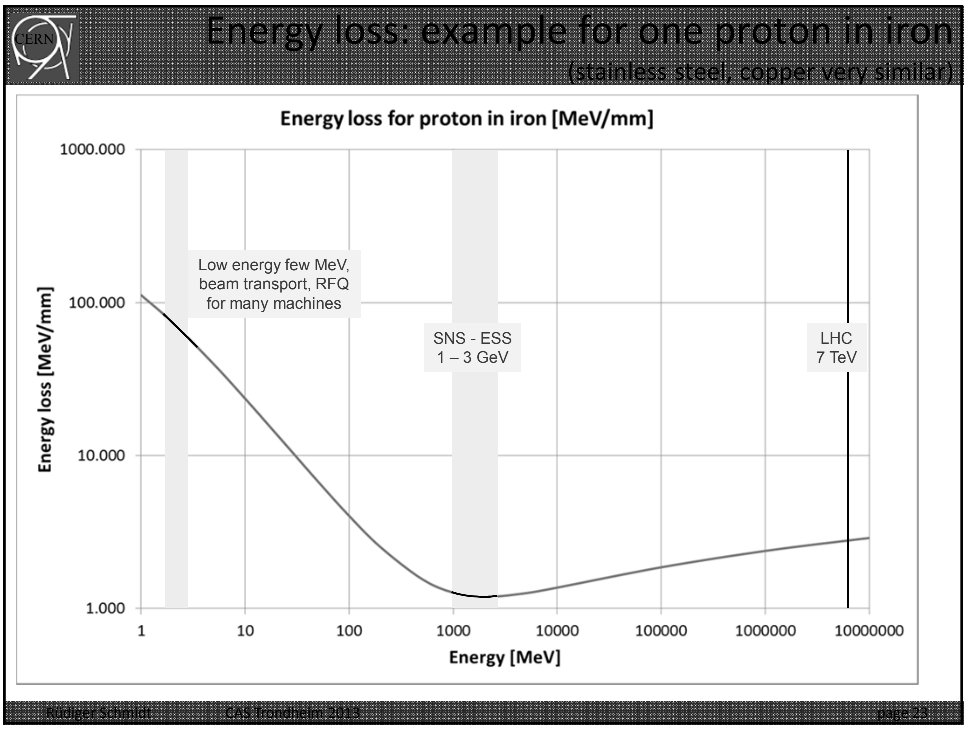
Injection absorber (TDI) ~7σ

Beam absorbers take beam in case of kicker misfiring on circulating beam

Consequences of (accidental) beam loss

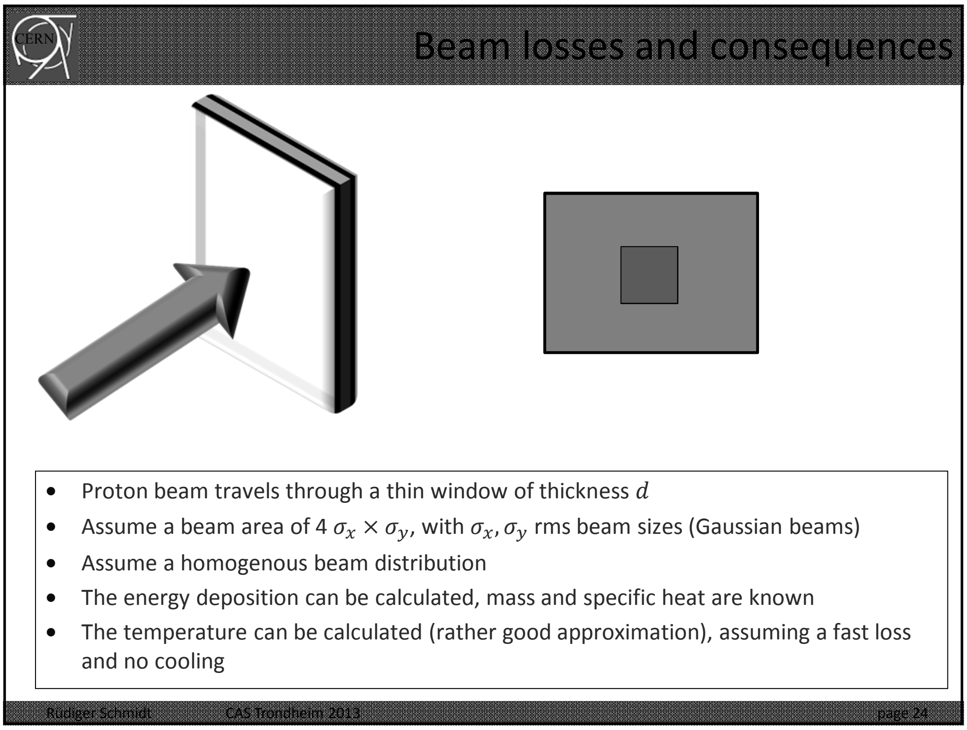
Beam losses and consequences

- Charged particles moving through matter interact with the electrons of atoms in the material, exciting or ionizing the atoms => energy loss of traveling particle described by **Bethe-Bloch formula**.
- If the particle energy is high enough, particle losses lead to particle cascades in materials, increasing the deposited energy
  - 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)
  - superconducting cavities performance degradation by some 10 J
  - activation of material, risk for hand-on-maintenance



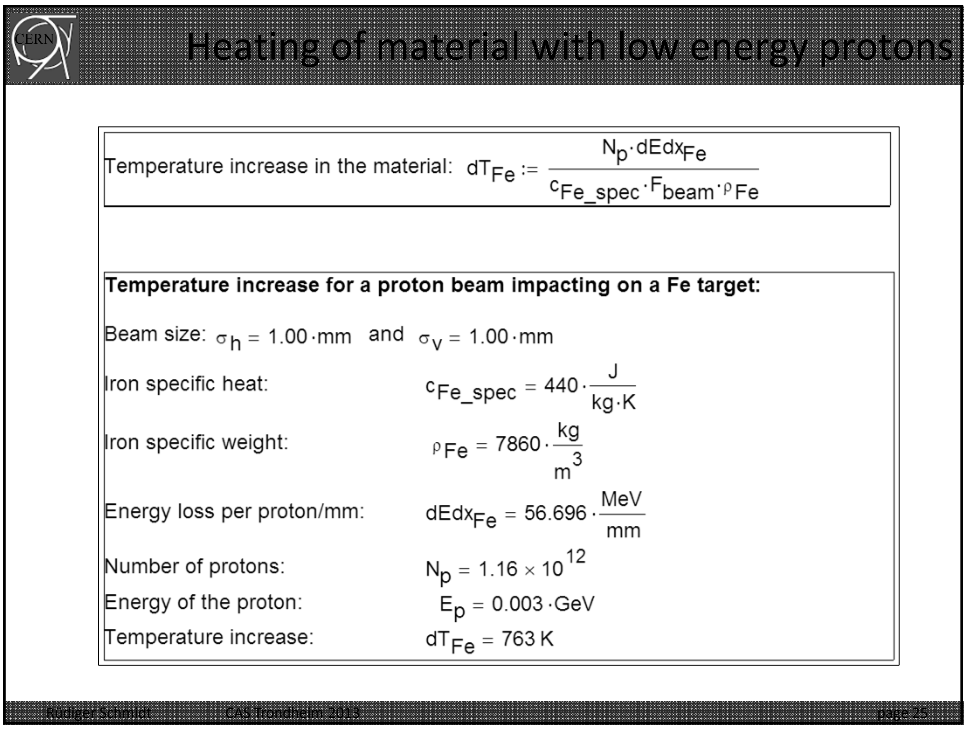
Energy loss: example for one proton in iron

(stainless steel, copper very similar)



Beam losses and consequences

- Proton beam travels through a thin window of thickness d
- Assume a beam area of 4 $\sigma_x \times \sigma_y$, with σ_x, σ_y rms beam sizes (Gaussian beams)
- Assume a homogenous beam distribution
- The energy deposition can be calculated, mass and specific heat are known
- The temperature can be calculated (rather good approximation), assuming a fast loss and no cooling



Heating of material with low energy protons

Temperature increase in the material: $dT_{Fe} := \frac{N_p \cdot dEdx_{Fe}}{c_{Fe\_spec} \cdot F_{beam} \cdot \rho_{Fe}}$

Temperature increase for a proton beam impacting on a Fe target:

Beam size: $\sigma_h = 1.00 \cdot mm$ and $\sigma_v = 1.00 \cdot mm$

Iron specific heat: $c_{Fe\_spec} = 440 \cdot \frac{J}{kg \cdot K}$

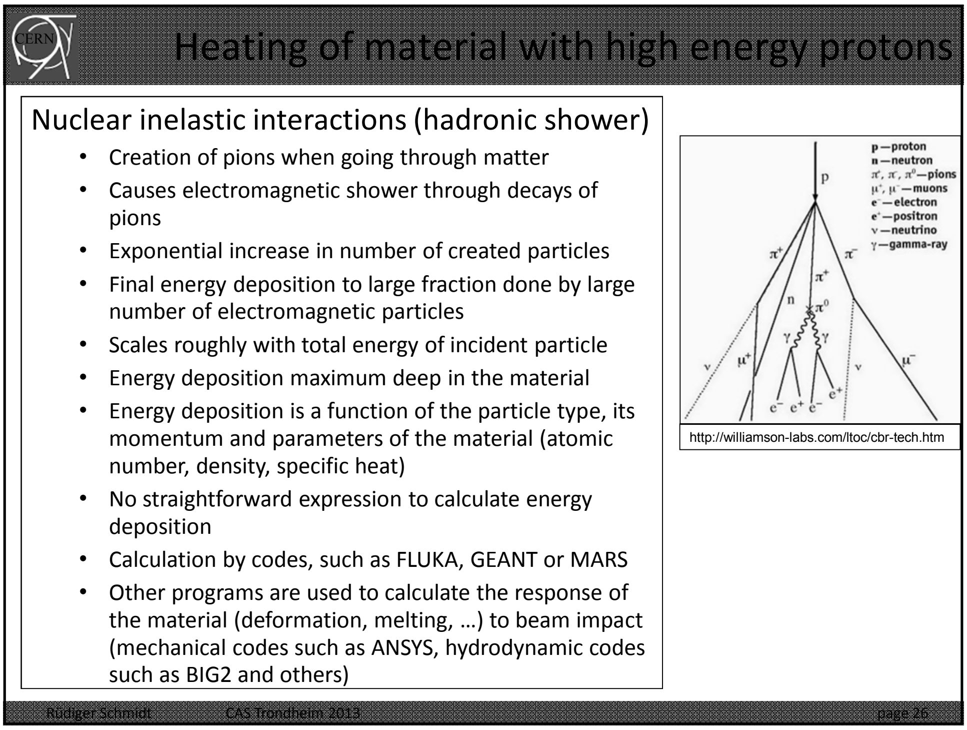
Iron specific weight: $\rho_{Fe} = 7860 \cdot \frac{kg}{m^3}$

Energy loss per proton/mm: $dEdx_{Fe} = 56.696 \cdot \frac{MeV}{mm}$

Number of protons: $N_p = 1.16 \times 10^{12}$

Energy of the proton: $E_p = 0.003 \cdot GeV$

Temperature increase: $dT_{Fe} = 763\,K$



Heating of material with high energy protons

Nuclear inelastic interactions (hadronic shower)

- Creation of pions when going through matter
- Causes electromagnetic shower through decays of pions
- Exponential increase in number of created particles
- Final energy deposition to large fraction done by large number of electromagnetic particles
- Scales roughly with total energy of incident particle
- Energy deposition maximum deep in the material
- Energy deposition is a function of the particle type, its momentum and parameters of the material (atomic number, density, specific heat)
- No straightforward expression to calculate energy deposition
- Calculation by codes, such as FLUKA, GEANT or MARS
- 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)

http://williamson-labs.com/ltoc/cbr-tech.htm

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: $\frac{c_{Cu\_spec} \cdot \Delta T}{E_{max\_Cu}} = \boxed{1.28 \times 10^{10}}$ Copper

graphite

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

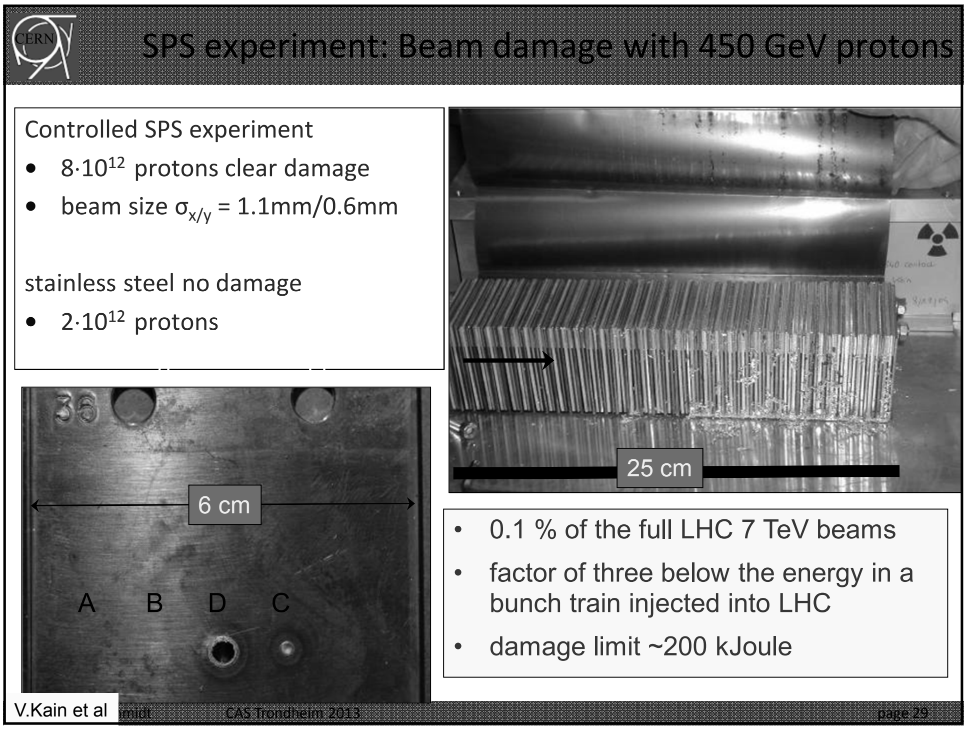
Specific heat of graphite is $c_{C\_spec} = 710.6000 \frac{1}{kg} \frac{J}{K}$

To heat 1 kg graphite 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: $\frac{c_{C\_spec} \cdot \Delta T}{E_{max\_C}} = \boxed{5.33 \times 10^{11}}$ graphite

Beam losses and consequences

- Beams at very low energy have less power…. however, the energy deposition is very high, and can lead to (limited) damage in case of beam impact
  - issue at the initial stage of an accelerator, after the source, low energy beam transport and RFQ
  - limited impact (e.g. damaging the RFQ) might lead to long downtime, depending on spare situation
- Beams at very high energy can have a tremendous damage potential
  - for LHC, damage of metals with beam loss in the order of a few 10^{10} protons
  - one LHC bunch has about $1.5 \cdot 10^{11}$ protons, in total up to 2808 bunches
  - in case of catastrophic beam loss, damage beyond repair



SPS experiment: Beam damage with 450 GeV protons

Controlled SPS experiment

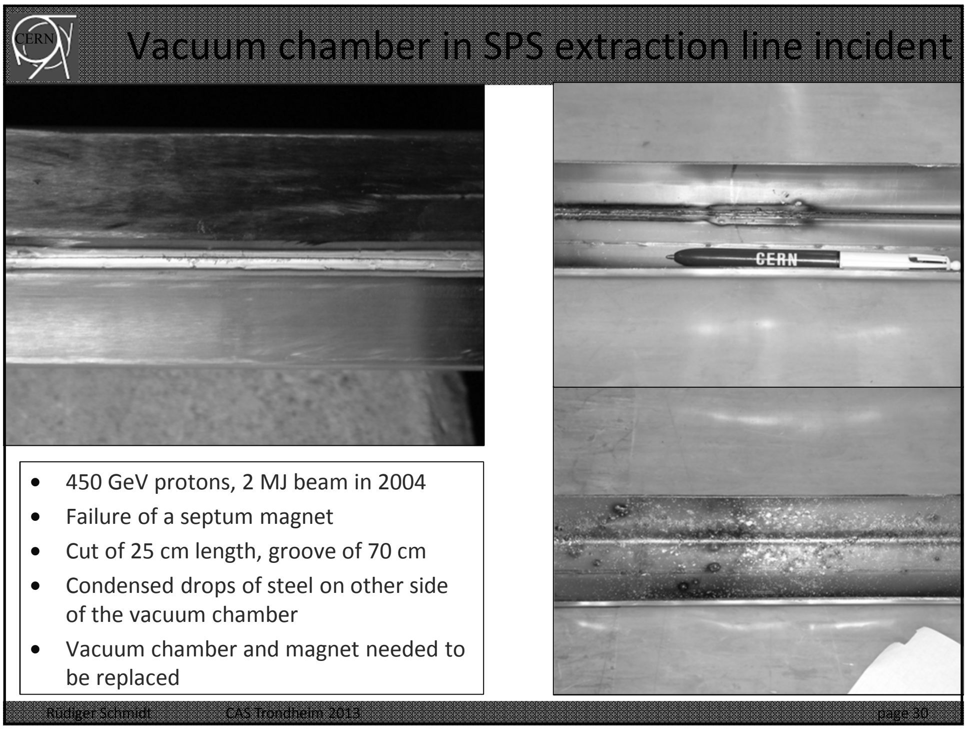
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

stainless steel no damage

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

- 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



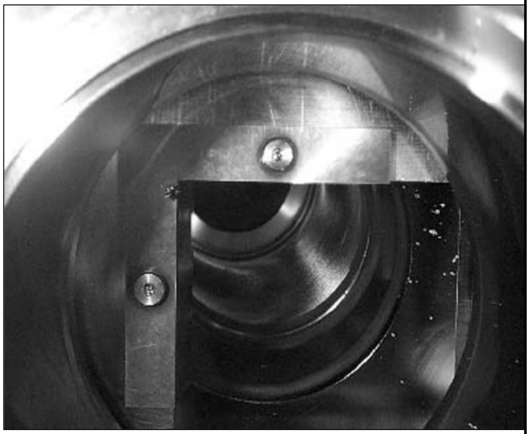
Vacuum chamber in SPS extraction line incident

- 450 GeV protons, 2 MJ beam in 2004
- Failure of a septum magnet
- Cut of 25 cm length, groove of 70 cm
- Condensed drops of steel on other side of the vacuum chamber
- Vacuum chamber and magnet needed to be replaced

Collimator in Tevatron after an incident in 2003

- A Roman pot (movable device) moved into the beam
- Particle showers from the Roman pot quenched superconducting magnets
- The beam moved by 0.005 mm/turn, and touched a collimator jaw surface after about 300 turns
- The entire beam was lost, mostly on the collimator

Observation of HERA tungsten collimators: grooves on the surface when opening the vacuum chamber were observed. No impact on operation.

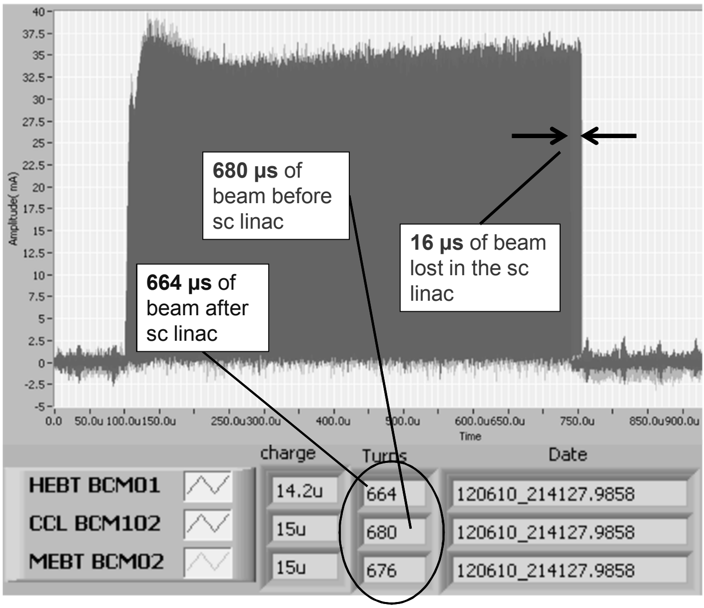


Beam losses in SNS linac

Beam Current Monitors (BCM) measure current pulse at different locations along the linac.

About 16 µsec of beam lost in the superconducting part of linac

Beam energy in 16 µs
End of DTL = 30 J
End of CCL = 66 J
End of SCL = 350 J



680 µs of beam before sc linac

664 µs of beam after sc linac

16 µs of beam lost in the sc linac

	charge	Turns	Date
HEBT BCM01	14.2u	664	120610_214127.9858
CCL BCM102	15u	680	120610_214127.9858
MEBT BCM02	15u	676	120610_214127.9858

Beam loss with low energy deposition

- Beam might hit surface of HV system (RFQ, kicker magnets, cavities)
- Surfaces with HV, after beam loss performance degradation might appear (not possible to operate at the same voltage, increased probability of arcing, …)
- SNS: errant beam losses led to a degradation of the performance of superconducting cavity
  - Bam losses likely to be caused by problems in ion source, low energy beam transfer and normal conducting linac
  - Cavity gradient needs to be lowered, conditioning after warm-up helps in most cases
  - Energy of beam losses is about 100 J
  - Damage mechanisms not fully understood, it is assumed that some beam hitting the cavity desorbs gas or particulates (=small particles) creating an environment for arcing

Accidental beam loss and probability

Beam losses mechanisms

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 with (massive) material blocks installed in an accelerator to capture halo 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, including collimators (or beam absorbers) to capture mis-steered beam

Regular and irregular operation

Regular operation

Many accelerator systems

Continuous beam losses

Collimators for beam cleaning

Collimators for halo scraping

Collimators to prevent ion-induced desorption

Failures during operation

Beam losses due to failures, timescale from nanoseconds to seconds

Machine protection systems

Collimators

Beam absorbers

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

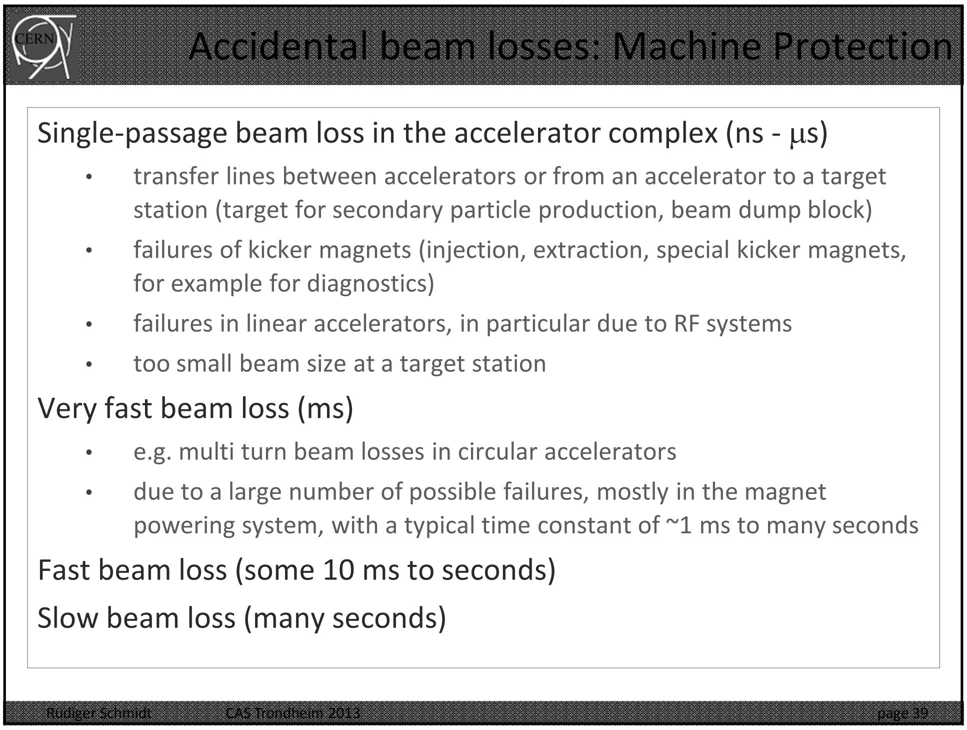
Limitation of beam losses is in order of 1 W/m to avoid activation and still allow hands-on maintenance

- 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)

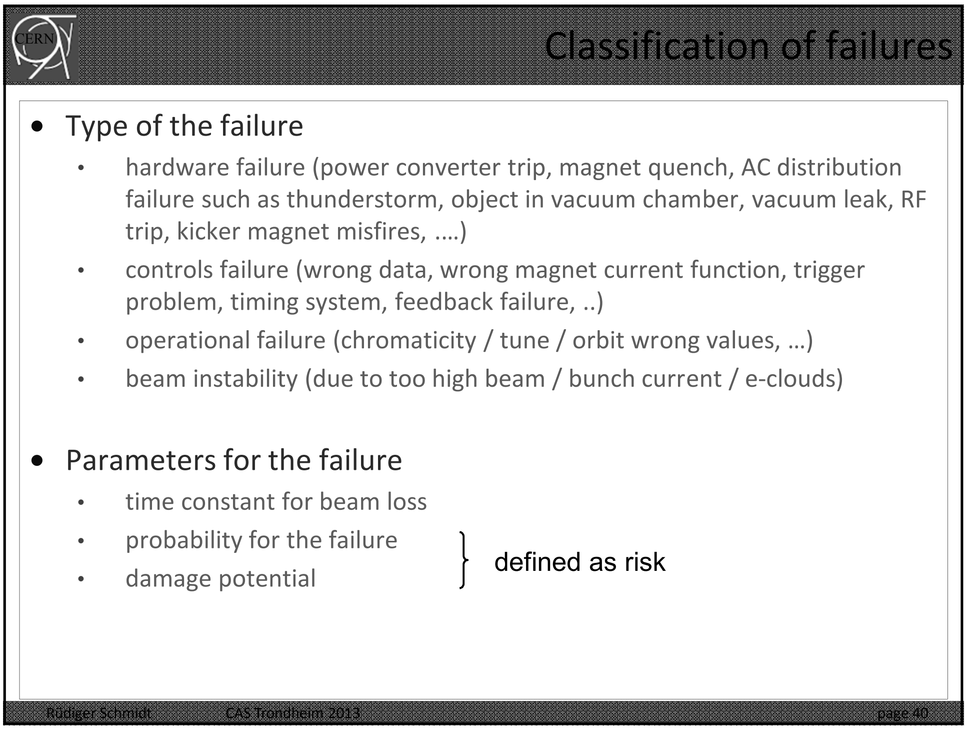
- transfer lines between accelerators or from an accelerator to a target station (target for secondary particle production, beam dump block)
- failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
- failures in linear accelerators, in particular due to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

Very fast beam loss (ms)

- e.g. 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
  - damage potential

} defined as risk

Probability of a failure leading to beam loss

- Experience from LHC (the most complex accelerator)
  - When the beam are colliding, the optimum length of a store is in the order of 10-15 hours, then ended by operation
  - Most fills (~70 %) are ended by failures, the machine protection systems dump the beams
  - **MTBF of about 6 h**
- Other large accelerators (SNS, plans for ESS, synchrotron light sources)
  - **MTBF between 20 h and up to several 100 h**

(…. more accurate numbers are appreciated)

- At high power accelerators, most failures would lead to damage if not mitigated = > the machine protection system is an essential part of the accelerator

---

Machine Protection

Example for Active Protection - Traffic

- A monitor detects a dangerous situation
- An action is triggered
- The energy stored in the system is safely dissipated



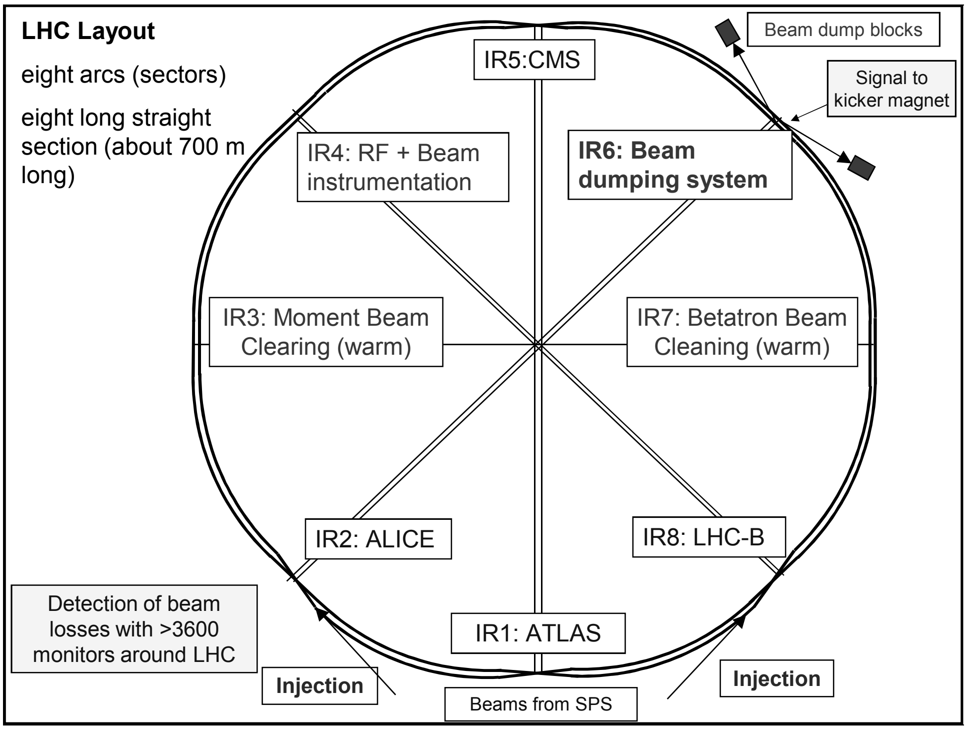


Example for Passive Protection

- 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
  - inhibit injection
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - equipment monitoring and beam monitoring
  - beam dump (fast kicker magnet and absorber block)
  - chopper to stop the beam in the low energy part
  - collimators and beam absorbers
  - beam interlock systems linking different systems



LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)

IR5:CMS

IR6: Beam dumping system

IR4: RF + Beam instrumentation

IR3: Moment Beam Clearing (warm)

IR7: Betatron Beam Cleaning (warm)

IR2: ALICE

IR8: LHC-B

IR1: ATLAS

Beam dump blocks

Signal to kicker magnet

Detection of beam losses with >3600 monitors around LHC

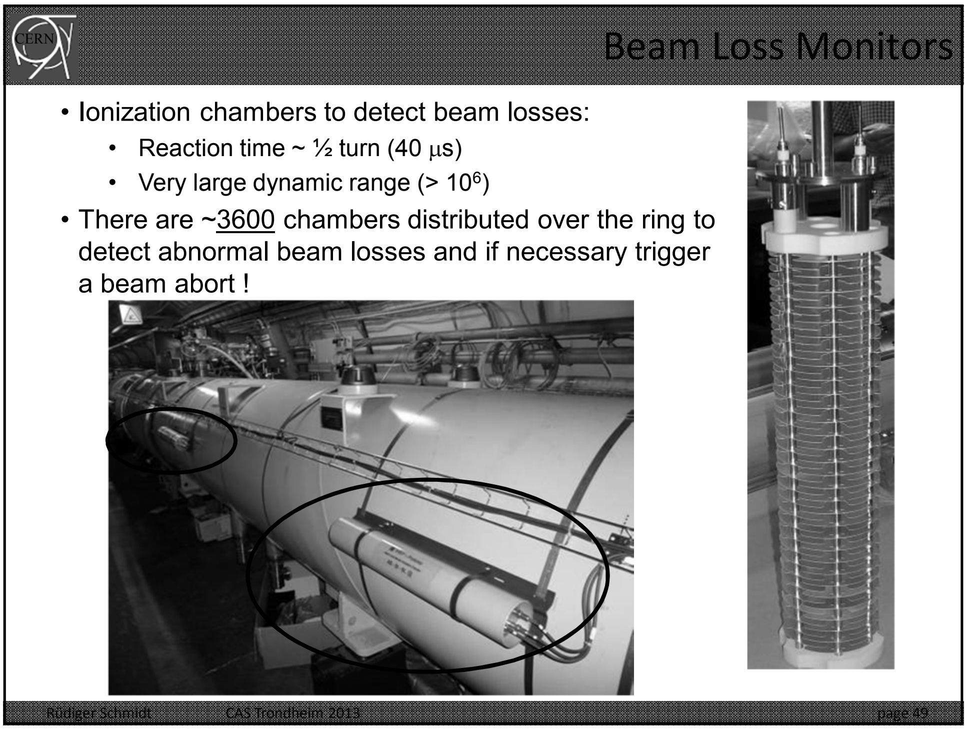
Injection

Injection

Beams from SPS

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, …



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 !

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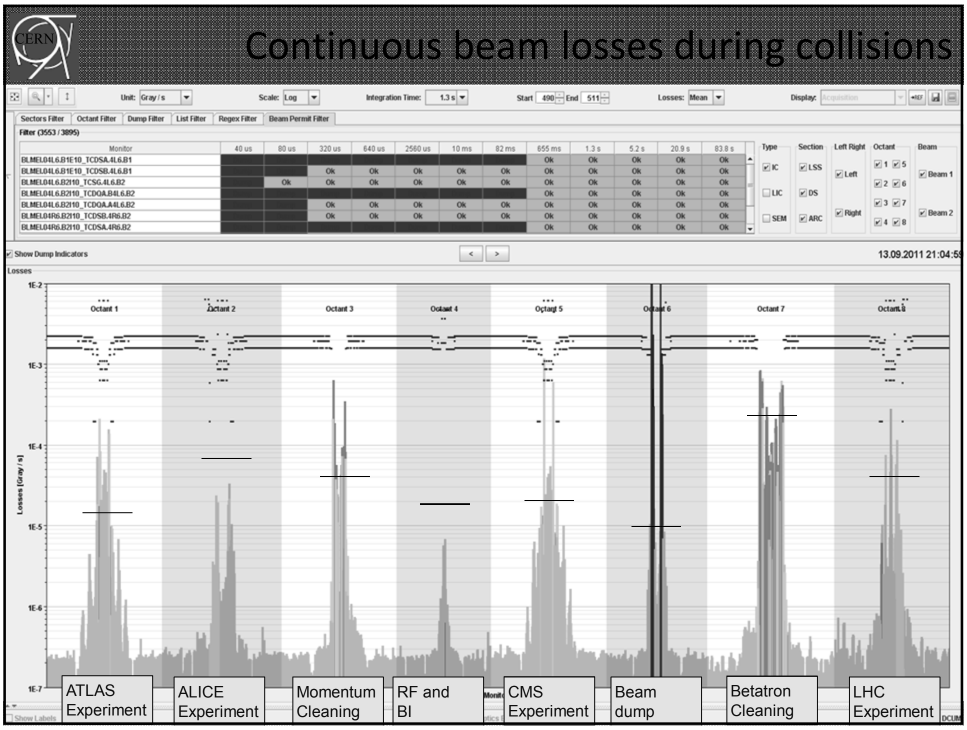


Continuous beam losses during collisions

Unit: Gray / s Scale: Log Integration Time: 1.3 s Start 490 End 511 Losses: Mean Display: Acquisition

Filter (3553 / 3895)

Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMEL04L6.B1E10_TCDSA.4L6.B1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Ok	Ok	Ok	Ok	Ok
BLMEL04L6.B1E10_TCDSB.4L6.B1	[illegible]	[illegible]	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEL04L6.B2I10_TCSG.4L6.B2	[illegible]	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEL04L6.B2I10_TCDQA.B4L6.B2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Ok	Ok	Ok	Ok	Ok
BLMEL04L6.B2I10_TCDQA.A4L6.B2	[illegible]	[illegible]	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEL04R6.B2I10_TCDSB.4R6.B2	[illegible]	[illegible]	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEL04R6.B2I10_TCDSA.4R6.B2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Ok	Ok	Ok	Ok	Ok

Type: ☑ IC ☐ LIC ☐ SEM

Section: ☑ LSS ☑ DS ☑ ARC

Left Right: ☑ Left ☑ Right

Octant: ☑ 1 ☑ 5 ☑ 2 ☑ 6 ☑ 3 ☑ 7 ☑ 4 ☑ 8

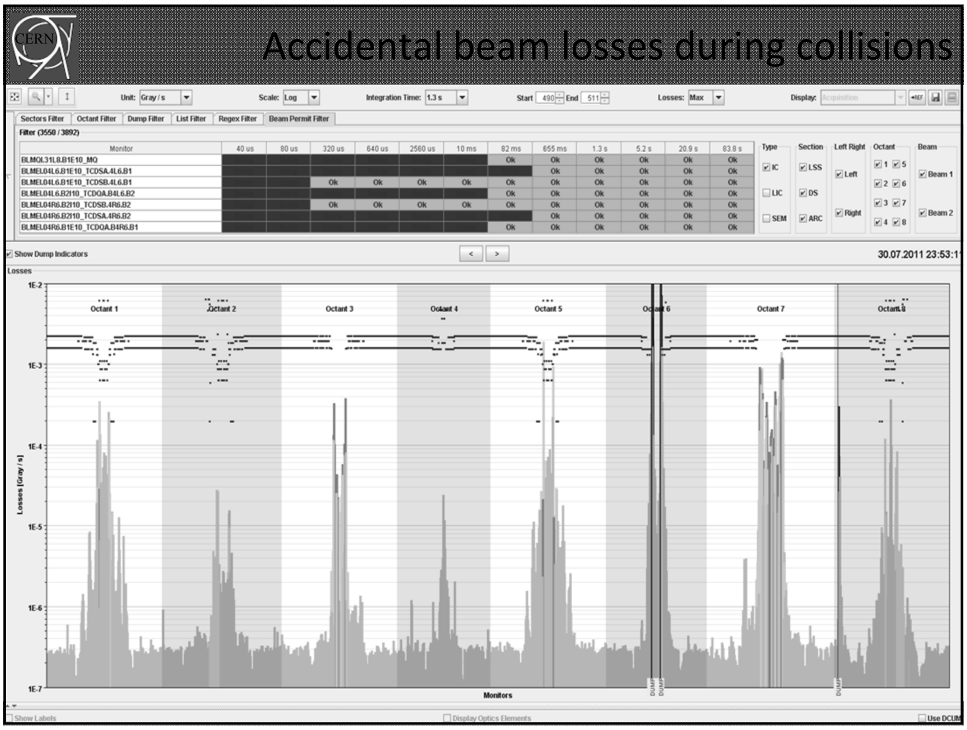
Beam: ☑ Beam 1 ☑ Beam 2

☑ Show Dump Indicators

13.09.2011 21:04:5

ATLAS Experiment | ALICE Experiment | Momentum Cleaning | RF and BI | CMS Experiment | Beam dump | Betatron Cleaning | LHC Experiment

Accidental beam losses during collisions



Unit: Gray / s　Scale: Log　Integration Time: 1.3 s　Start 490 End 511　Losses: Max　Display: Acquisition

Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3550 / 3892)

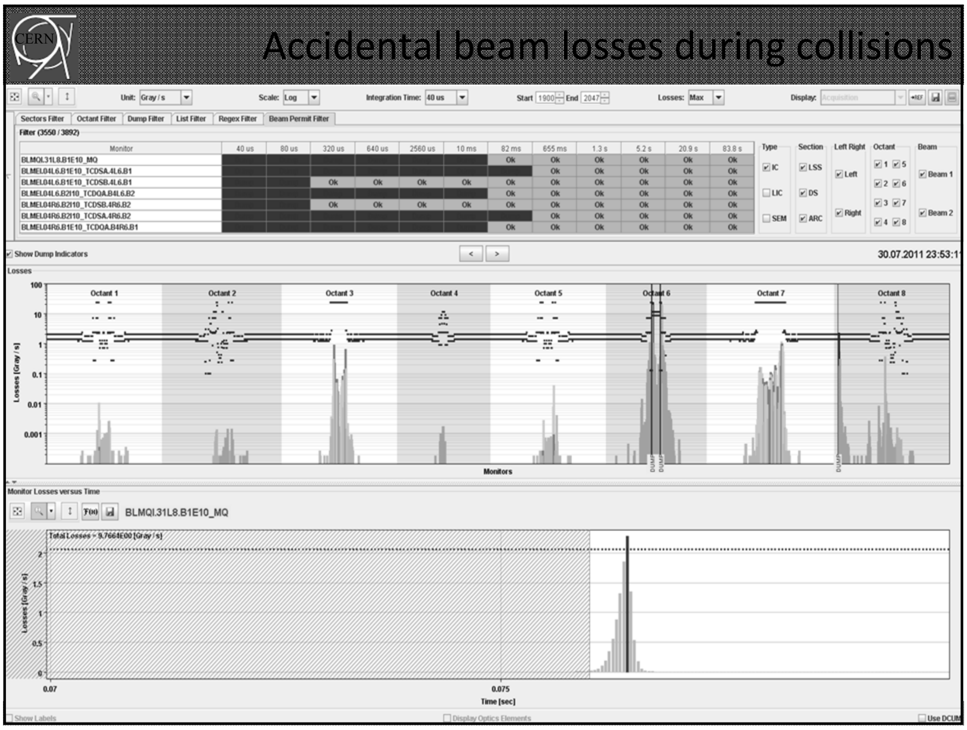
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ							Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1								Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1			Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2							Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2			Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2								Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1							Ok	Ok	Ok	Ok	Ok	Ok

Type: ☑ IC ☐ LIC ☐ SEM　Section: ☑ LSS ☑ DS ☑ ARC　Left Right: ☑ Left ☑ Right　Octant: ☑ 1 ☑ 5 ☑ 2 ☑ 6 ☑ 3 ☑ 7 ☑ 4 ☑ 8　Beam: ☑ Beam 1 ☑ Beam 2

☑ Show Dump Indicators　30.07.2011 23:53:1

☐ Show Labels　☐ Display Optics Elements　☐ Use DCUM

Accidental beam losses during collisions



Unit: Gray / s　Scale: Log　Integration Time: 40 us　Start 1900 End 2047　Losses: Max　Display: Acquisition

Sectors Filter | Octant Filter | Dump Filter | List Filter | Regex Filter | Beam Permit Filter

Filter (3550 / 3892)

Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ							Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1								Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1			Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2							Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2			Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2								Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B1E10_TCDQA.B4R6.B1							Ok	Ok	Ok	Ok	Ok	Ok

Type: ☑ IC ☐ LIC ☐ SEM　Section: ☑ LSS ☑ DS ☑ ARC　Left Right: ☑ Left ☑ Right　Octant: ☑ 1 ☑ 5 ☑ 2 ☑ 6 ☑ 3 ☑ 7 ☑ 4 ☑ 8　Beam: ☑ Beam 1 ☑ Beam 2

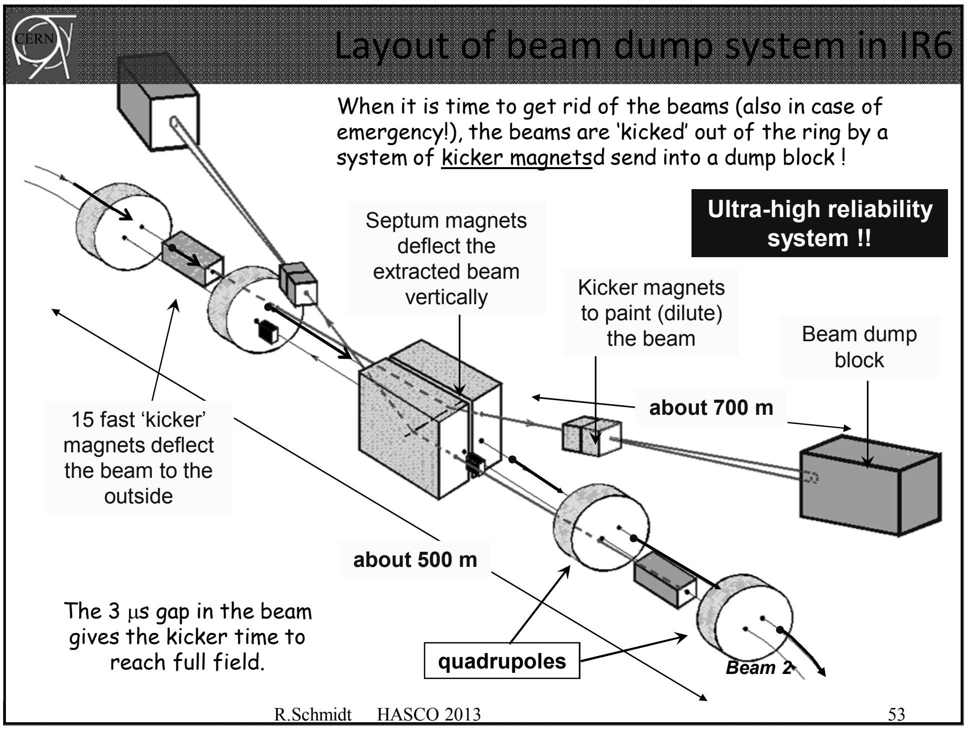
☑ Show Dump Indicators　30.07.2011 23:53:1

Monitor Losses versus Time

BLMQI.31L8.B1E10_MQ

Total Losses = 9.7664E00 [Gray / s]

☐ Show Labels　☐ Display Optics Elements　☐ Use DCUM



Layout of beam dump system in IR6

When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of <u>kicker magnets</u>d send into a dump block !

Ultra-high reliability system !!

Septum magnets deflect the extracted beam vertically

Kicker magnets to paint (dilute) the beam

Beam dump block

about 700 m

15 fast 'kicker' magnets deflect the beam to the outside

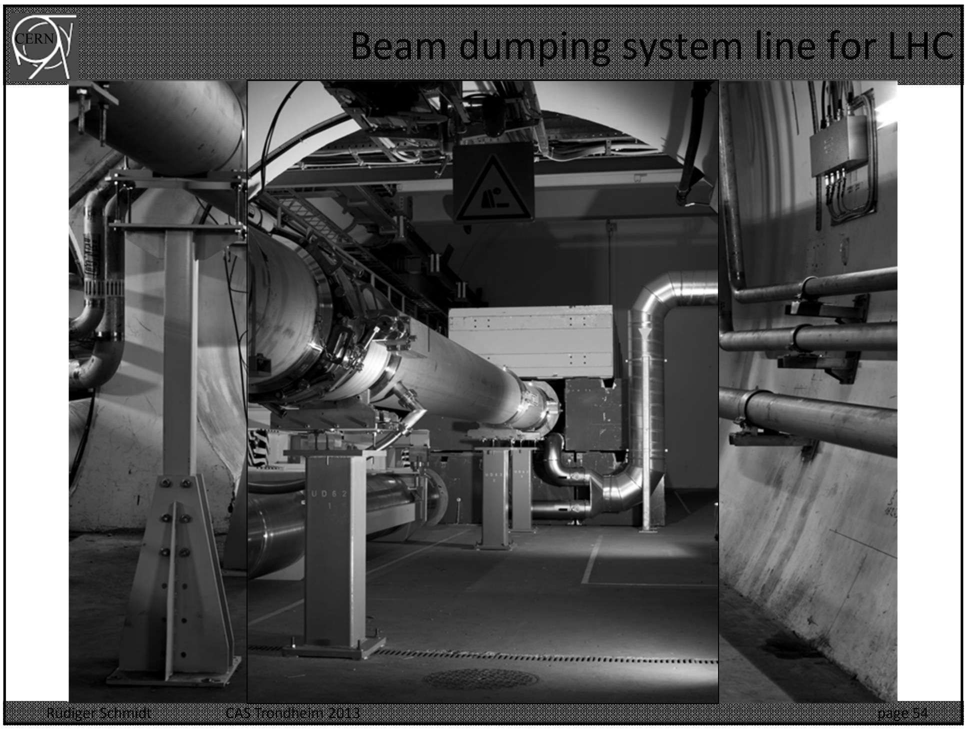
about 500 m

The 3 μs gap in the beam gives the kicker time to reach full field.

quadrupoles

Beam 2

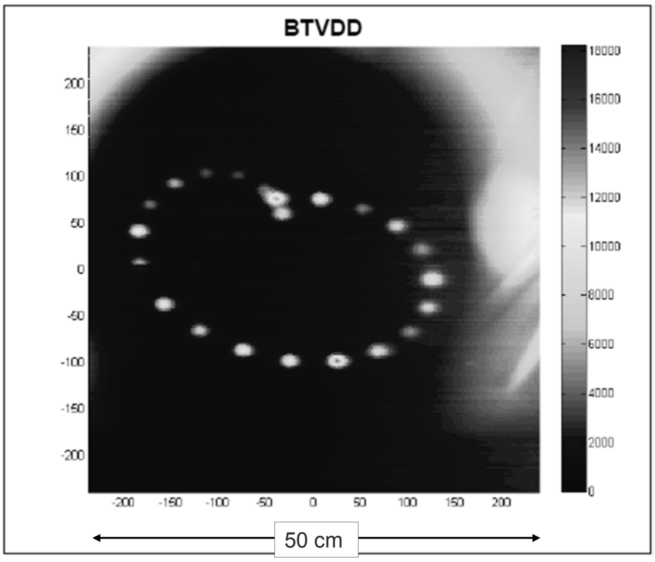
R.Schmidt HASCO 2013 53



Beam dumping system line for LHC

Rüdiger Schmidt CAS Trondheim 2013 page 54

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

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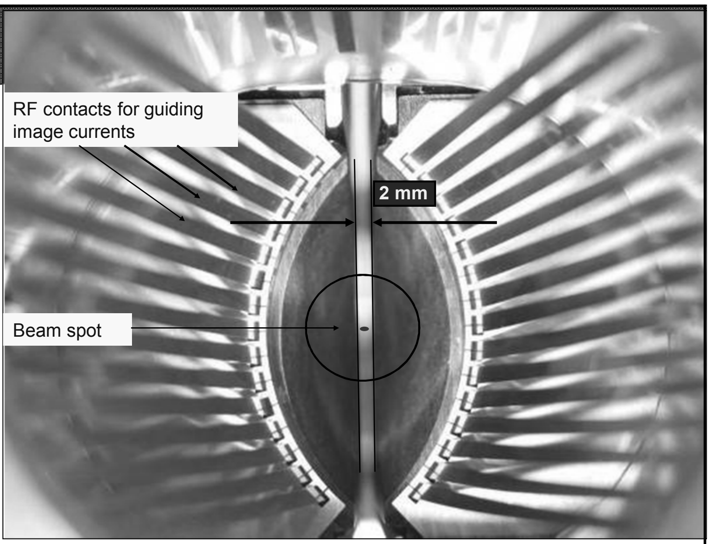
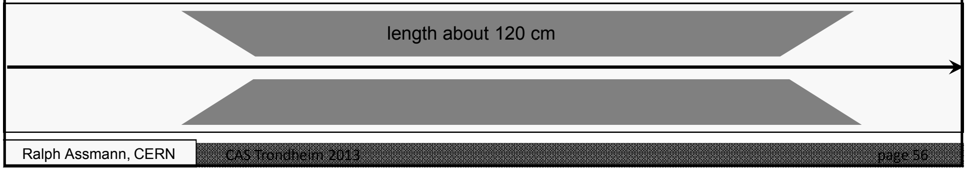
View of a two sided collimator **for LHC**

about 100 collimators are installed in LHC





Ralph Assmann, CERN

High power accelerators …

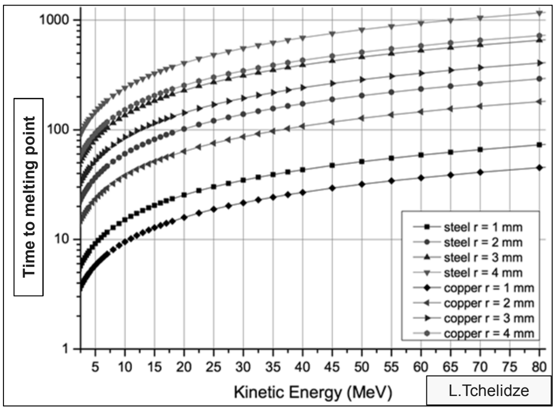
- Operate with beam power of 1 MW and more
- SNS – 1 MW, PSI cyclotron – 1.3 MW, ESS – planned for 5 MW, FRIB (ions) – planned for 0.4 MW
- ESS (4 % duty cycle): in case of an uncontrolled beam loss during 1 ms, the deposited energy is up to 130 kJ, for 1 s it is up to 5 MJ
- It is required to inhibit the beam after detecting uncontrolled beam loss – how fast?
- The delay between detection and "beam off" to be considered

Example for ESS

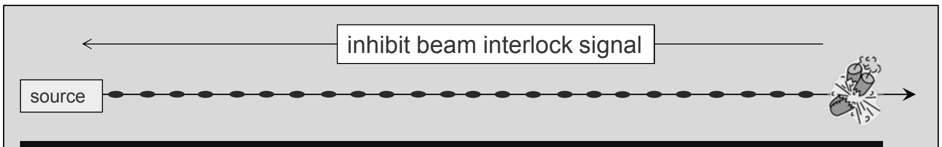
Example:

After the DTL normal conducting linac, the proton energy is 78 MeV. In case of a beam size of 2 mm radius, melting would start after about 200 μs.

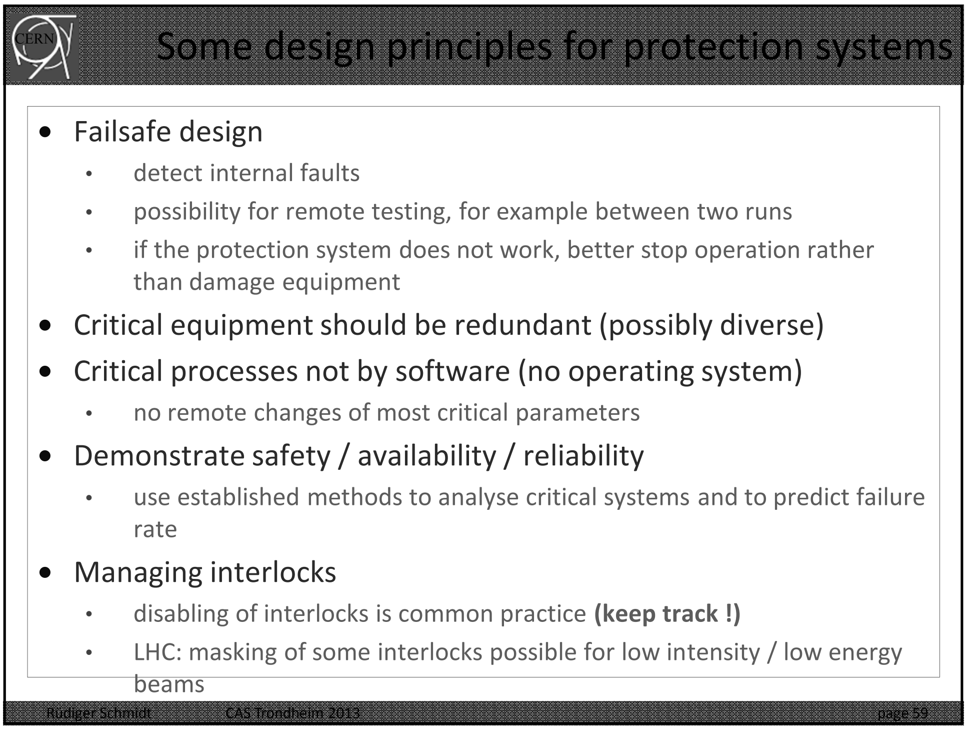
Inhibiting beam should be in about 10% of this time.



L.Tchelidze

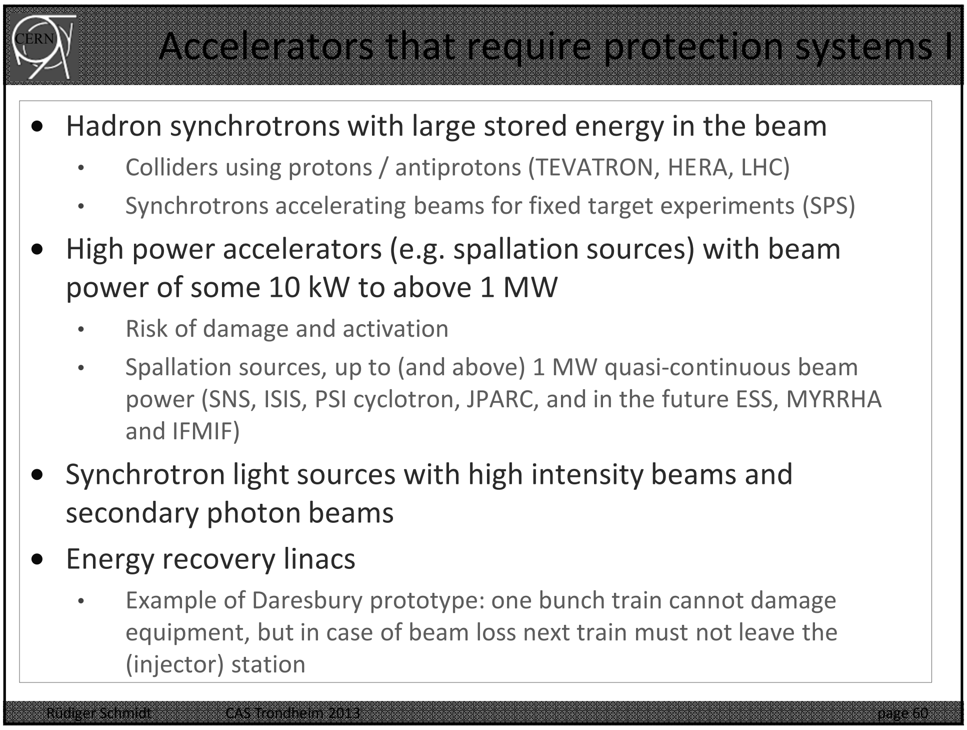


dT = dT_detect failure + dT_transmit signal + dT_inhibit source + dT_beam off



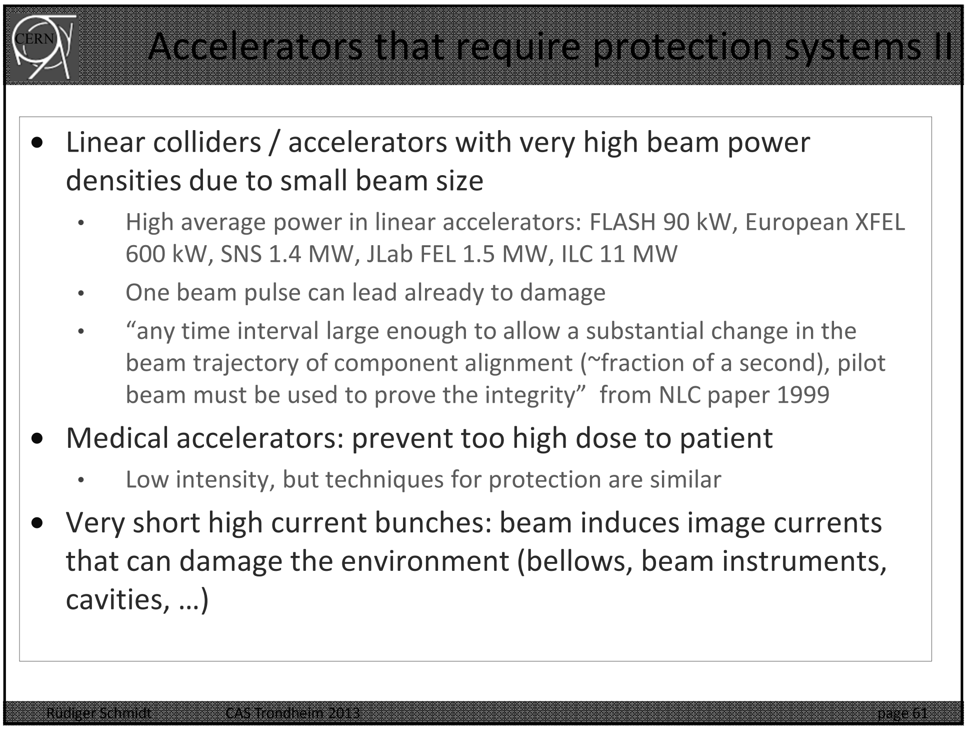
Some design principles for protection systems

- 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



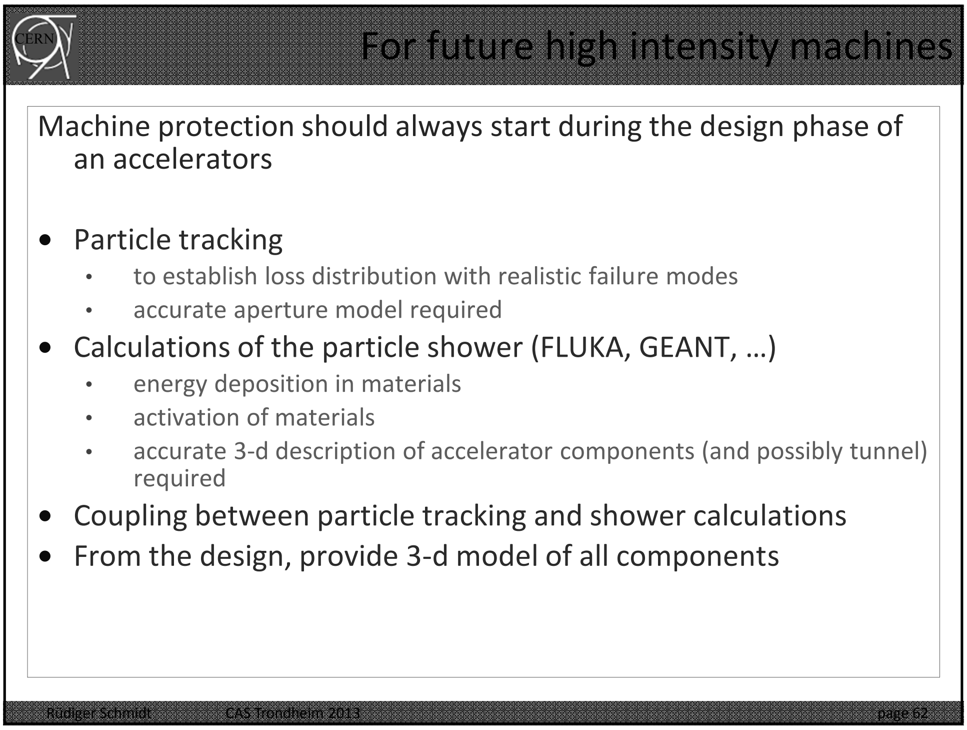
Accelerators that require protection systems I

- 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, …)



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