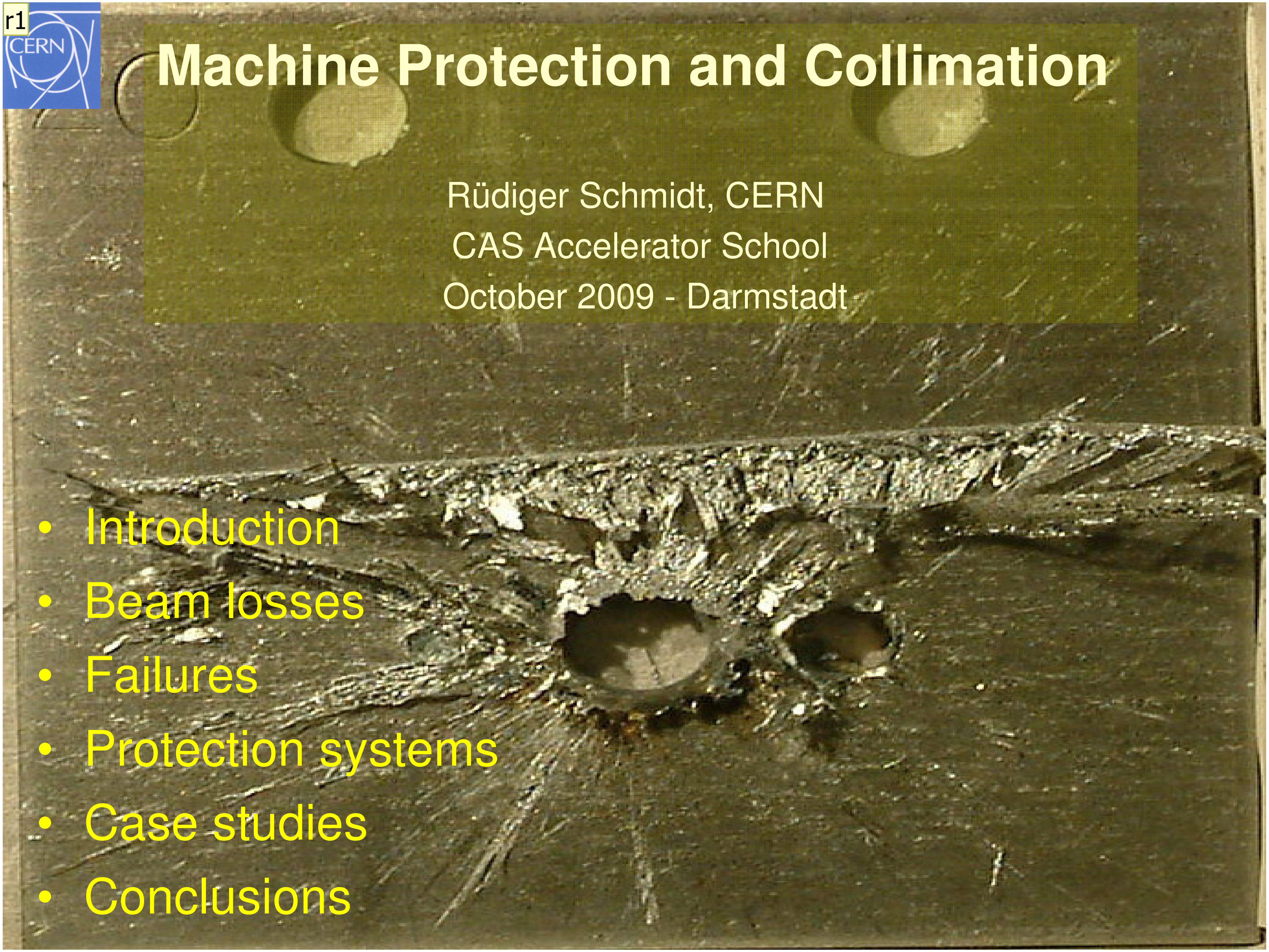
# Machine Protection and Collimation

Rüdiger Schmidt, CERN
CAS Accelerator School
October 2009 - Darmstadt

- Introduction
- Beam losses
- Failures
- Protection systems
- Case studies
- Conclusions



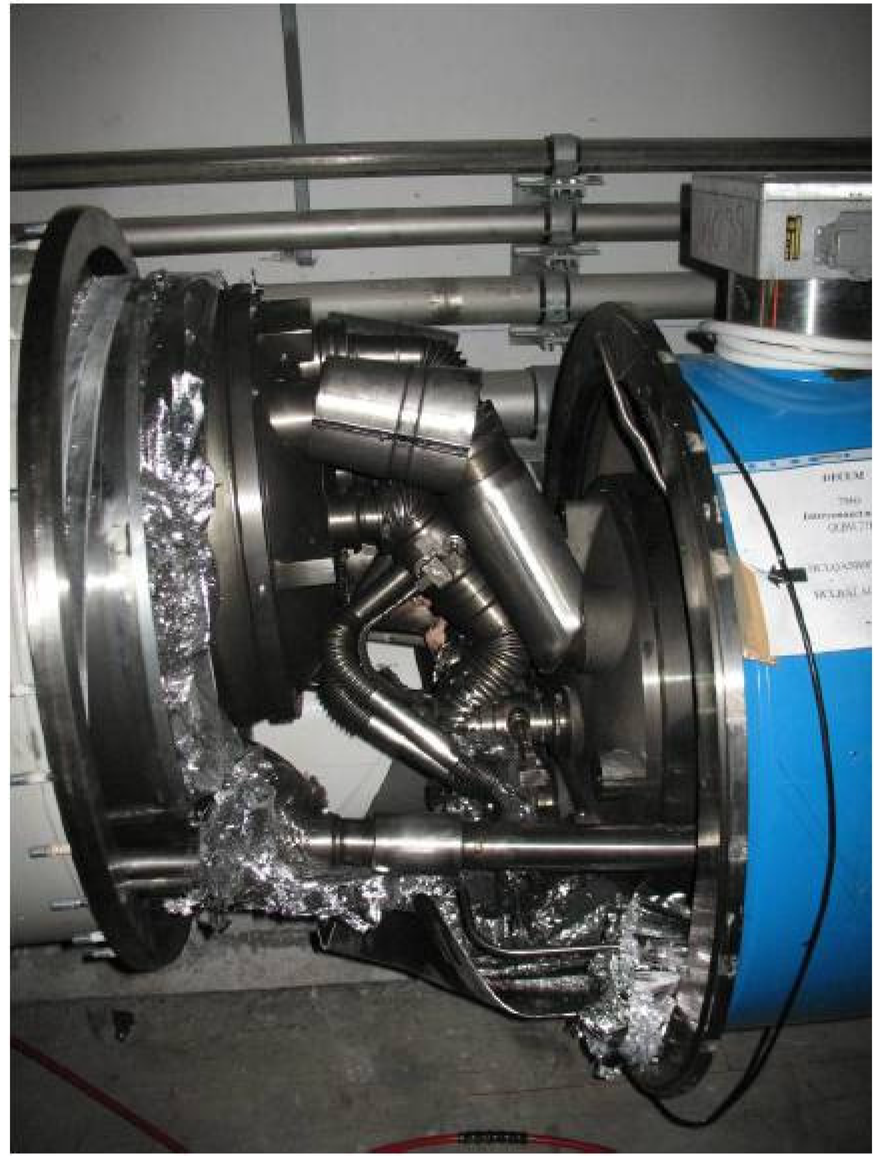
# Safety and protection for accelerators

Accelerators, as all other technical systems, must respect some general principles with respect to safety

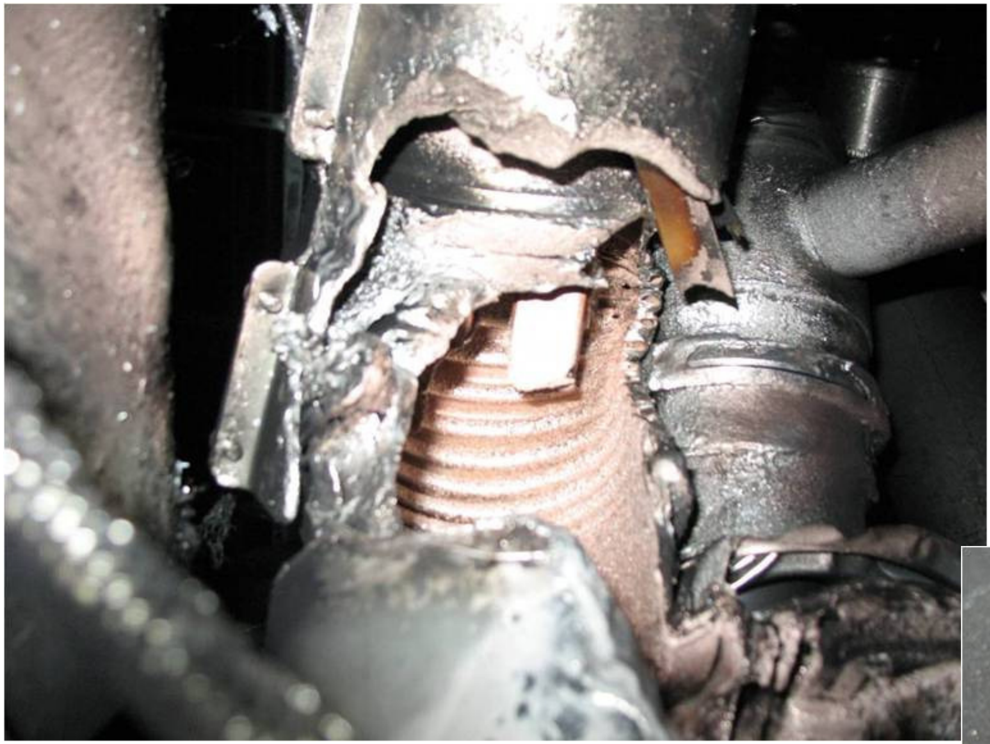
- Protect the people (e.g. follows legal requirements)
- Protect the environment (e.g. follows legal requirements)
- Protect the equipment

Independent of beam (superconducting magnets, normal conducting magnets, power cables, other high power equipment, RF, etc.)

# Accidental release of 600 MJoule stored in the LHC dipole magnets (one out of eight sectors, interconnect)



# Accidental release of 600 MJoule stored in the LHC dipole magnets (tubes inside vacuum vessel)



# Beam losses

Regular beam losses: Collimation system for beam cleaning (...another lecture)

Accidental beam losses: Machine Protection and Collimation systems

"Machine Protection": **protect equipment** from damage, activation, downtime and background to experiments **caused by beam** – by accidental beam losses

# 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

# Regular beam losses: Collimation

Example: Continuous beam with a power of 1 MW

- a loss of 1% corresponds to 10 kW – not to be lost along the beam line to avoid activation of material, heating, quenching, …

Example: 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 to order of 1 W

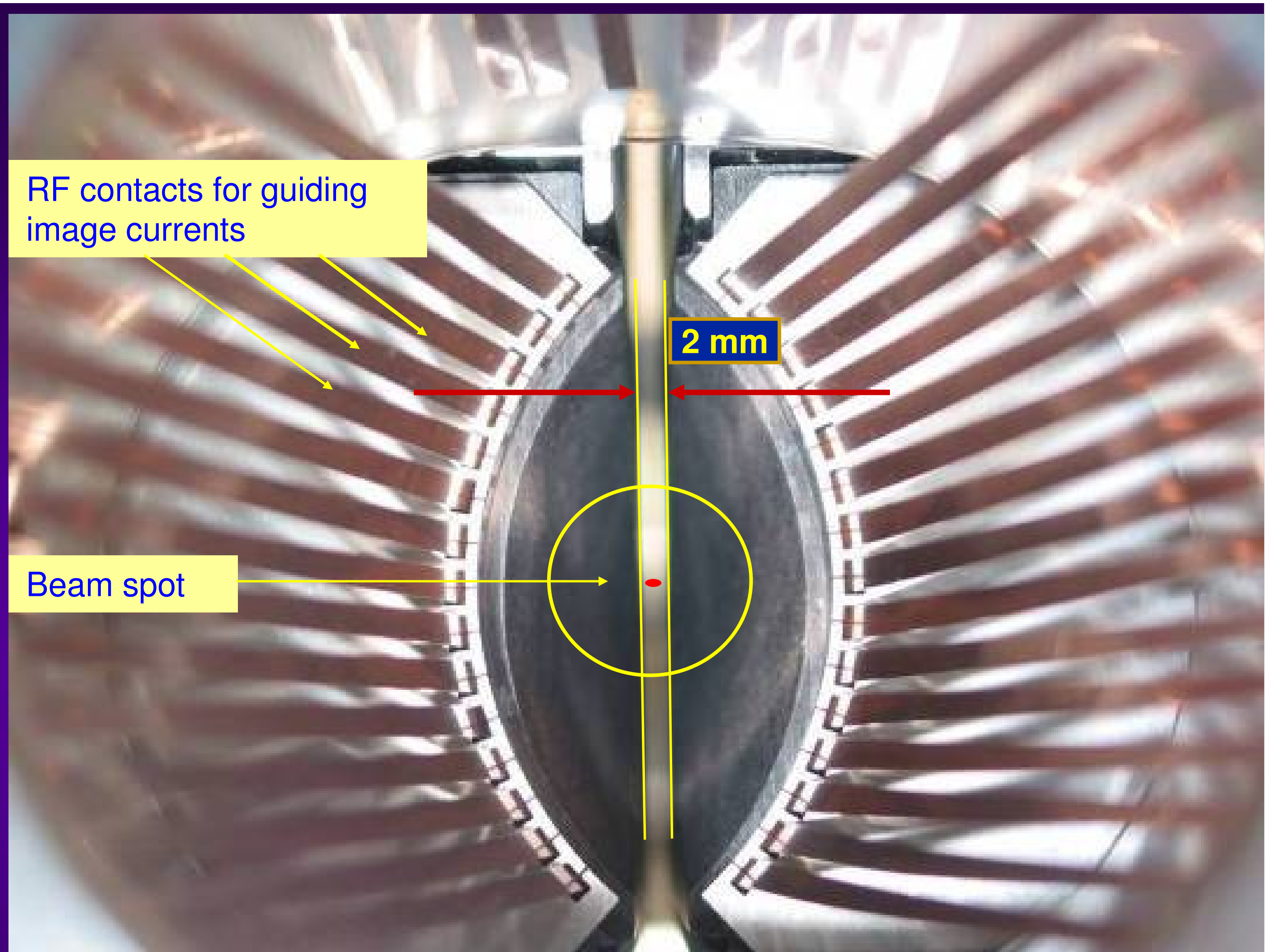
Limitation of beam losses is in order of 1 W/m to avoid activation and still allow hands-on maintenance

- Avoid beam losses – as far as possible
- Define the aperture by collimators
- Capture continuous particle losses with collimators at specific locations

….but also: capture fast accidental beam losses

# View of a two sided collimator

# **for LHC**




# Beam losses and consequences

- Particle losses lead to particle cascades in materials
  - 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 and As Low As Reasonably Achievable - ALARA)
- Energy deposition and temperature increase
  - there is no straightforward expression for the energy deposition
  - function of the particle type, its momentum, and the parameters of the material (atomic number, density, specific heat)
  - programs such as FLUKA, MARS or GEANT are being used for the calculation of energy deposition and activation

# 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) $E_{max\_C} := 2.0 \cdot 10^{-6} \frac{J}{kg}$

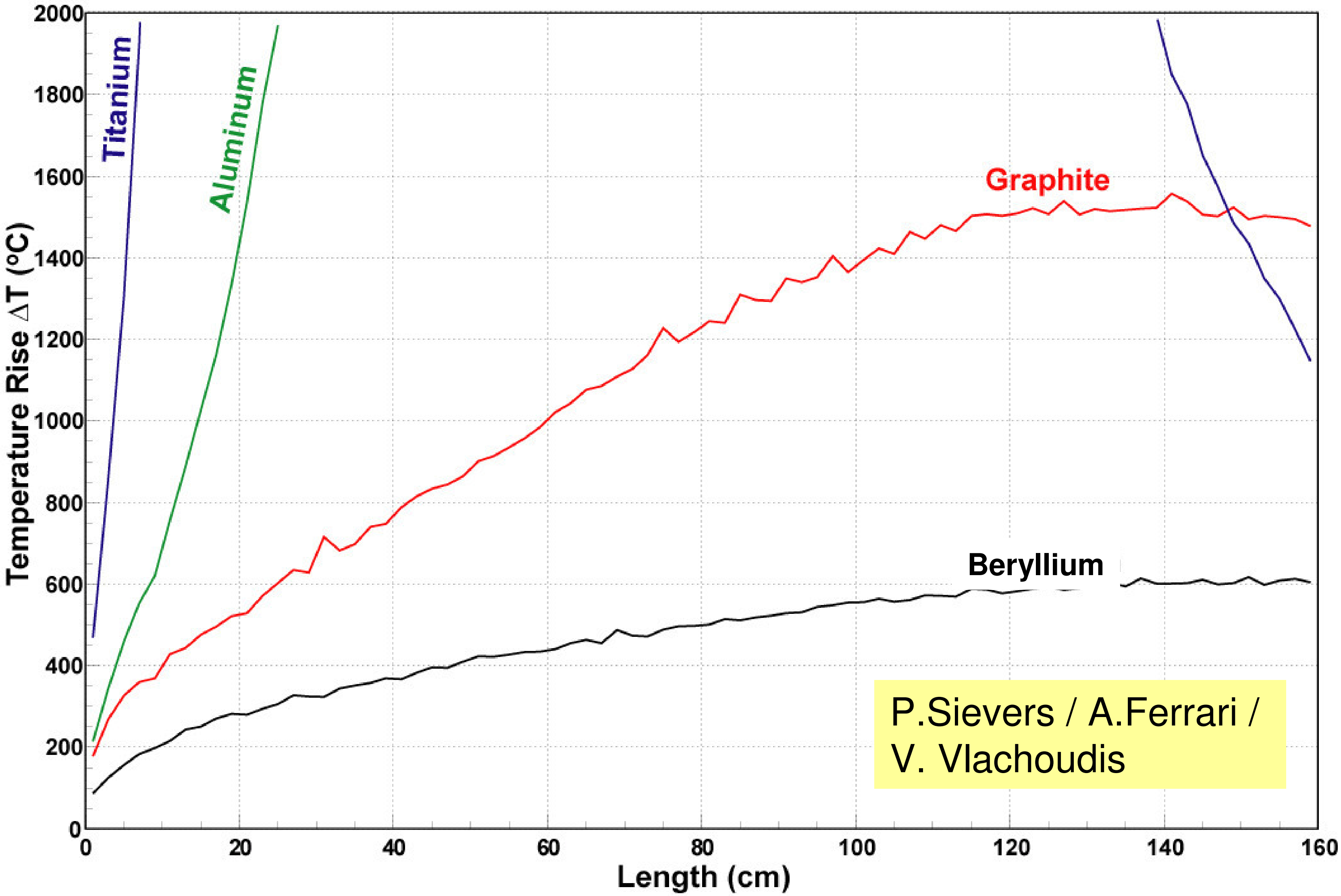
Specific heat of graphite is $c_{C\_spec} = 710.6000 \frac{1}{kg} \frac{J}{K}$

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

# Accidental kick by the beam dump kicker at 7 TeV

part of beam touches collimators (about $2{\cdot}10^{12}$ from $3{\cdot}10^{14}$)



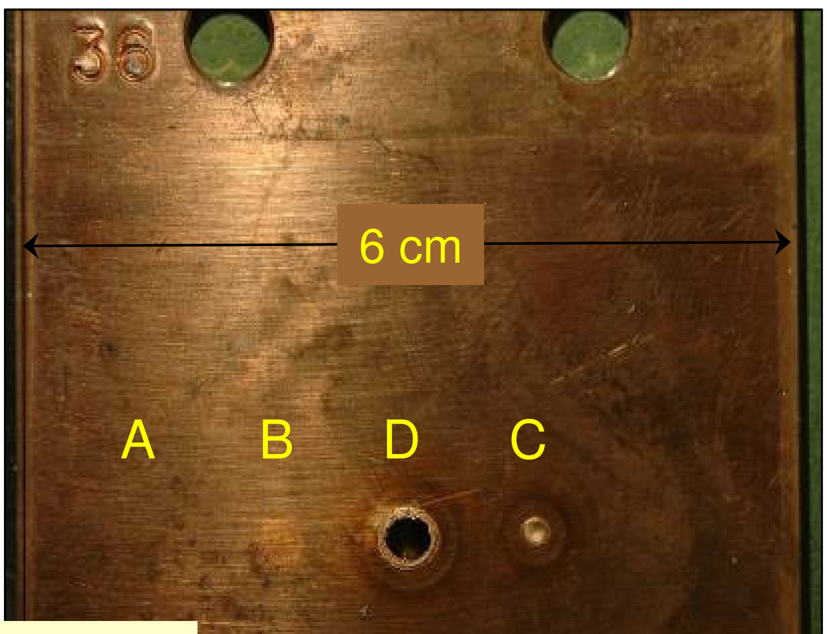
# SPS experiment: Beam damage with 450 GeV proton beam

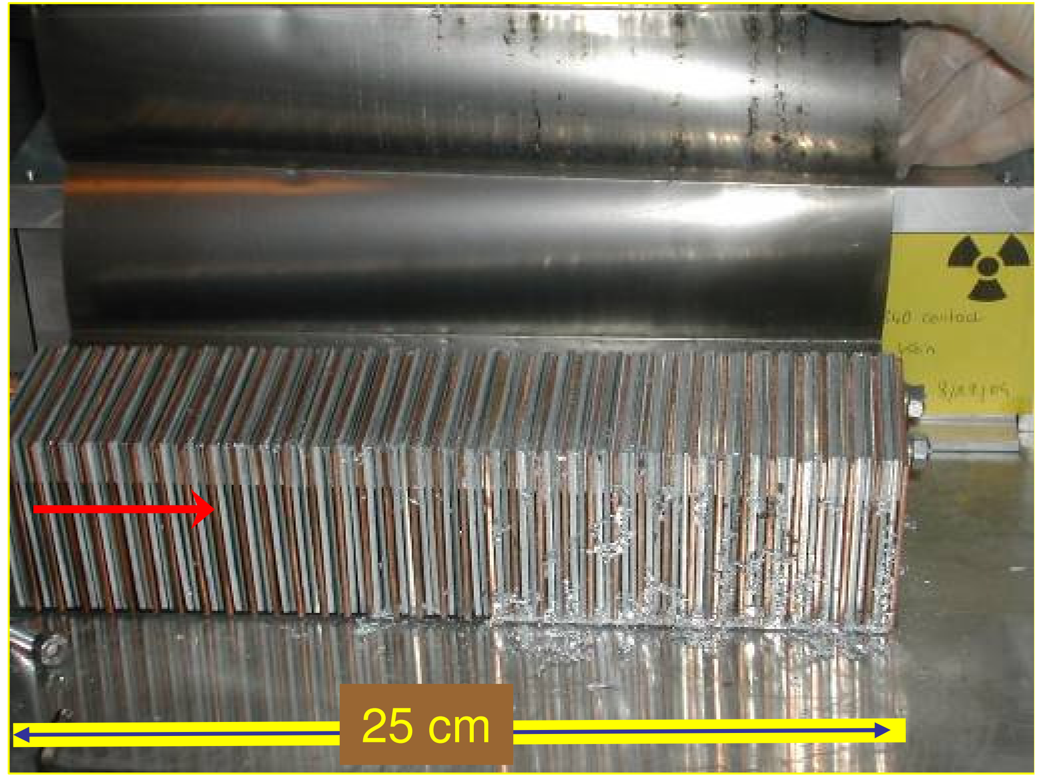
Controlled SPS experiment
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

above damage limit for copper

stainless steel no damage
- $2 \cdot 10^{12}$ protons

below damage limit for copper



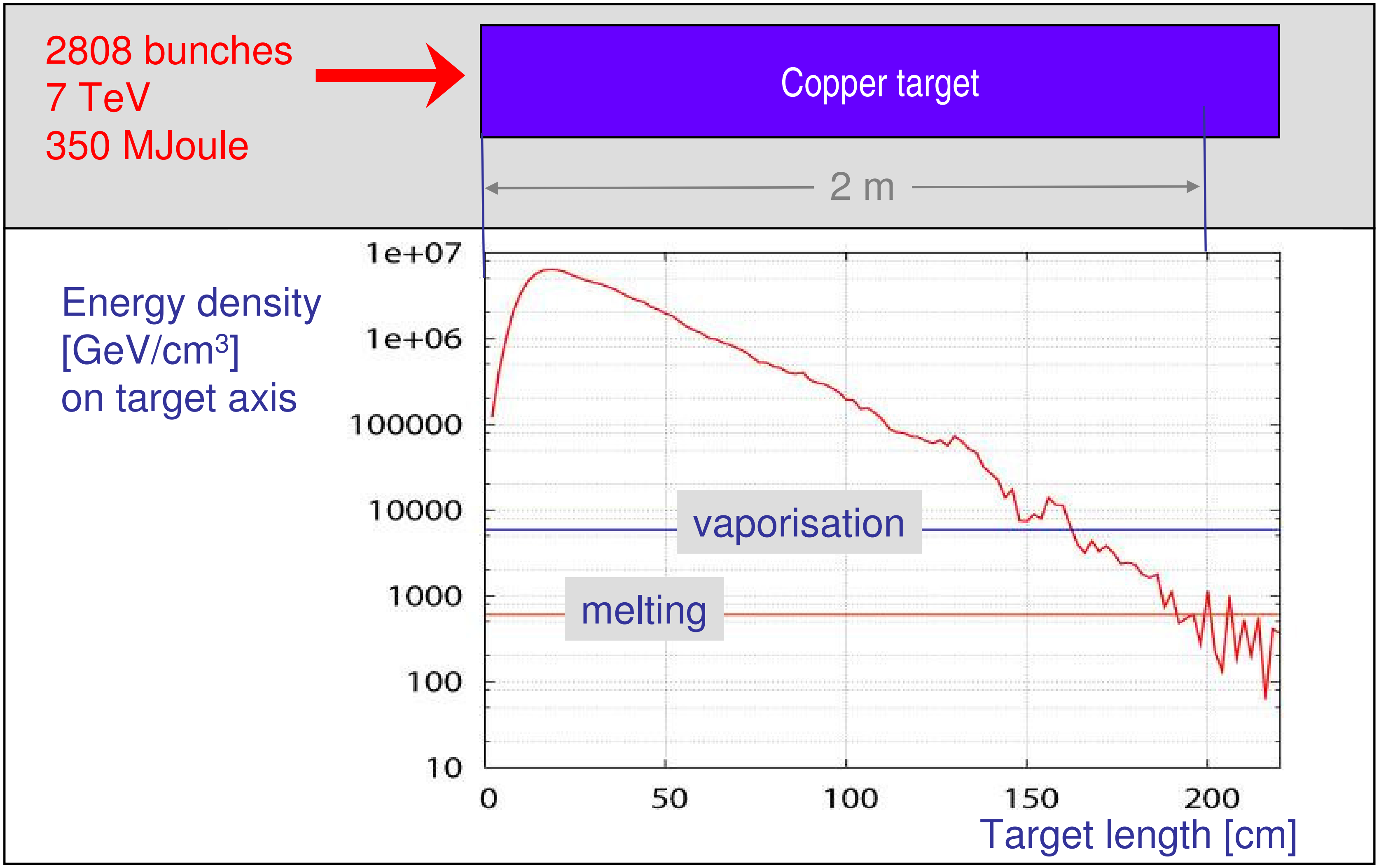




0.1 % of the full LHC 7 TeV beams

factor of three below the energy stored in the bunch train injected into LHC

V.Kain et al

# Full LHC beam deflected into copper target




N.Tahir (GSI) et al.

# Is protection required?

# 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

# Accelerators that require protection systems I

- 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)
- Hadron colliders with large stored energies in the beams – discharge of large stored energy is challenging
  - Colliders using protons / antiprotons (TEVATRON, HERA, LHC)
  - Synchrotrons accelerating beams for fixed target experiments (SPS)
- 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, …)

# 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)
- Parameters for the failure
  - damage potential
  - probability for the failure
  - time constant for beam loss

  (damage potential and probability for the failure: defined as risk)
- Machine state when failure occurs
  - beam transfer, injection and extraction (single pass)
  - acceleration
  - stored beam

# Time constant for beam losses

## Single turn (single-passage) beam loss in accelerators (ns - μs)

- failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
- trip of crab cavity (to be better understood)
- transfer lines between accelerators and from an accelerator to a target station (target for secondary particle production, beam dump block)
- 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 some 10 turns to many seconds

## Fast beam loss (some 10 ms to seconds)

## Slow beam loss (many seconds)

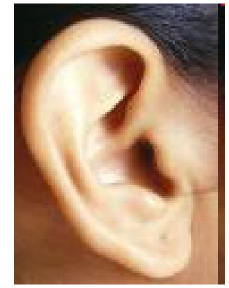
**Active protection**

# Strategy for protection and related systems

- Avoid that a specific failure can happen (e.g. no fast vacuum valve if not absolutely required)
- Detect failure at hardware level and stop beam operation
- Detect initial consequence 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 with the logics and linking different systems

# 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

# Active and passive protection

Start operation with low intensity beam ("pilot beam")

Active protection

- Detect failure
- Turn off the beam as fast as possible (e.g. source, RF, …)
- Only permit beam injection into the next part of the accelerator complex in case of positive confirmation that all parameters are within predefined limits
- Abort the beam from a storage ring / accumulator ring

Passive protection

- Install collimators and beam absorbers, in particular if active protection is not possible

# Active protection

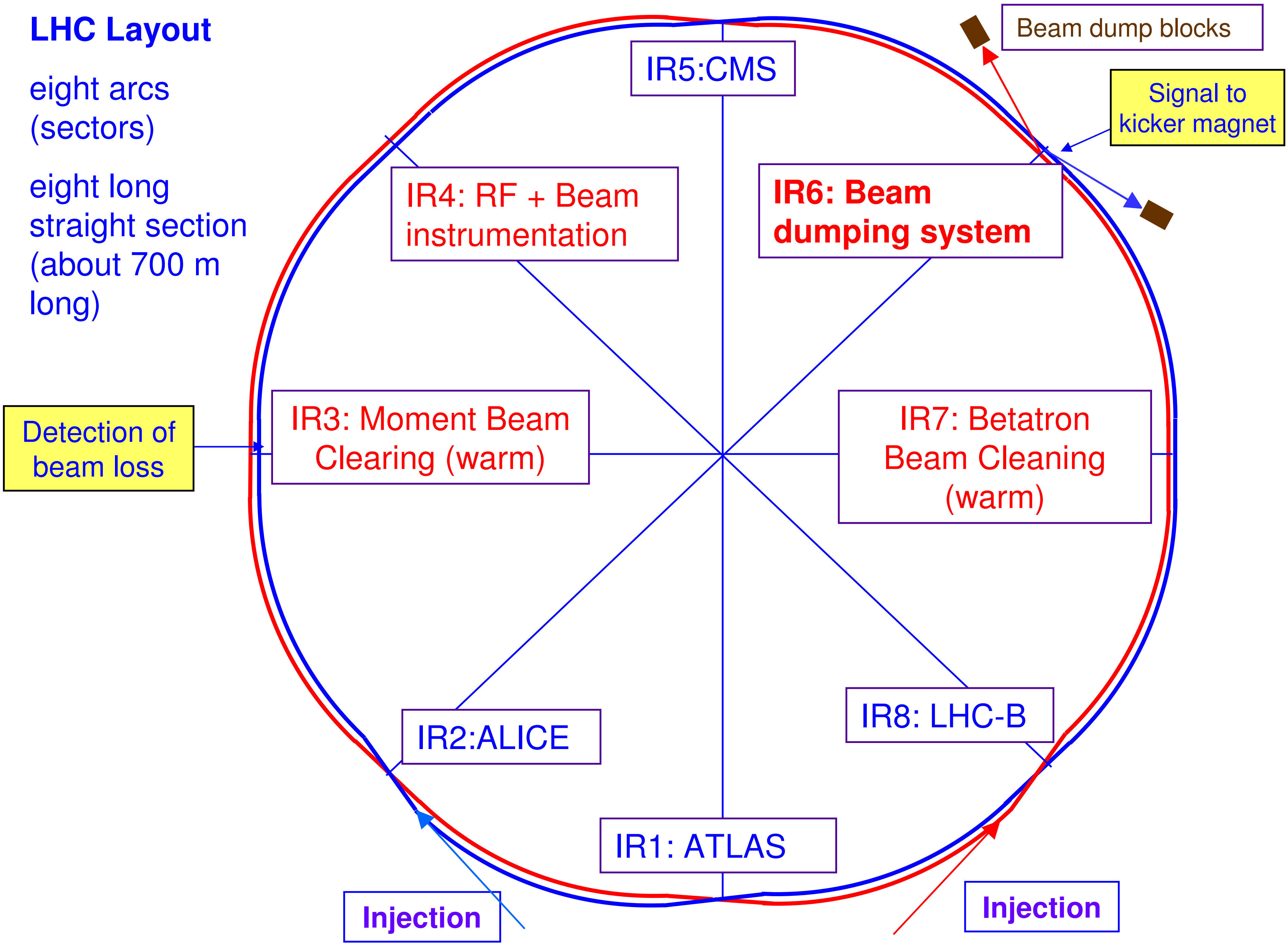
Monitoring of the beam detects a failure and allows to switch off the beam before damage

- Stored beam in a circular accelerator
  - multi turn beam losses
  - monitor beam losses, and dump the beam if losses exceed threshold
- “Continuous” beam in linacs of other accelerators
  - continuous: if the time constant for a failure is such that the source can be switched off in time
- There is a large number of possible failures, mostly in the magnet powering system, with a typical time constant of ms to many seconds

## LHC Layout

eight arcs (sectors)

eight long straight section (about 700 m long)

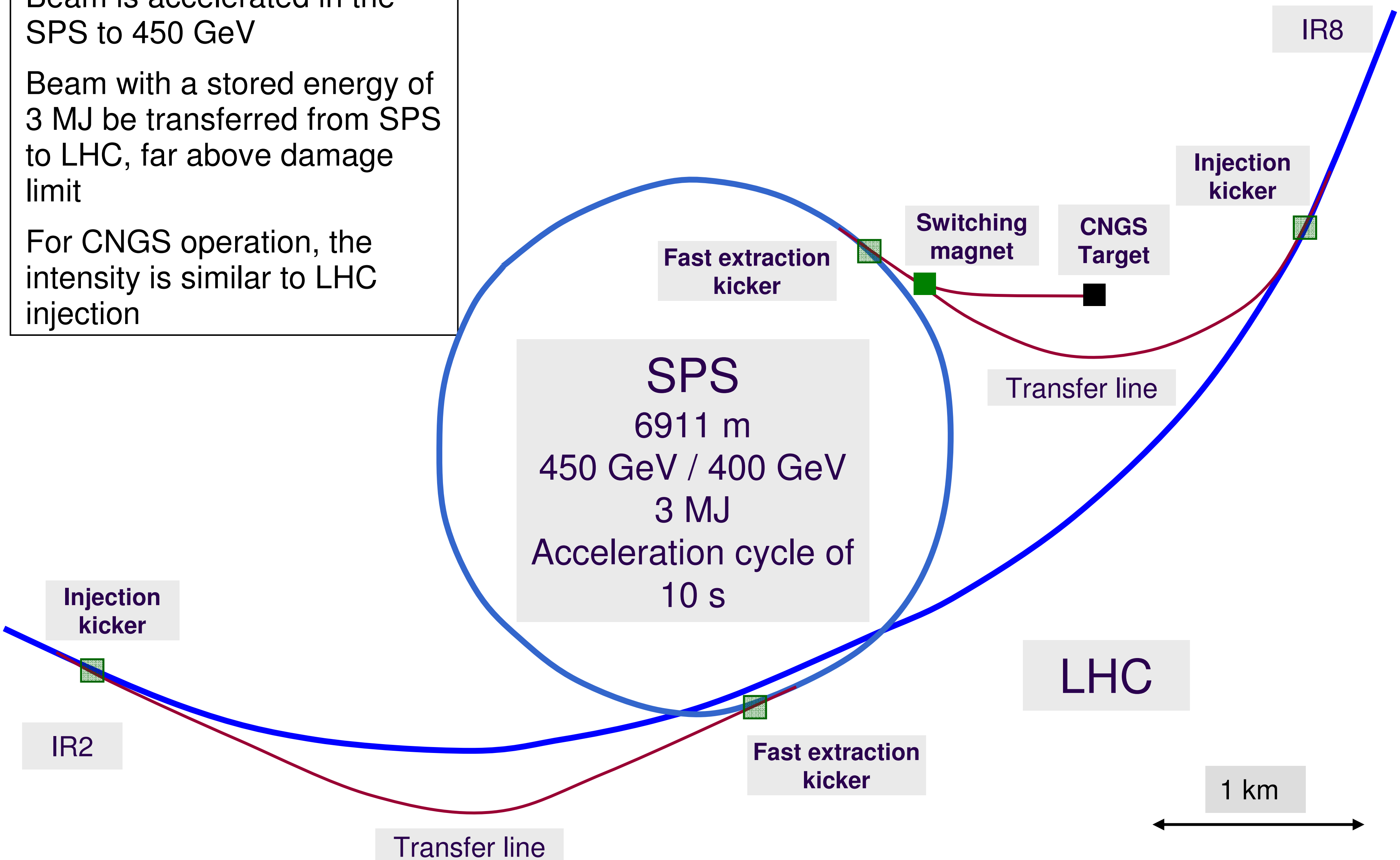


# SPS, transfer line, LHC injection and CNGS

Beam is accelerated in the SPS to 450 GeV

Beam with a stored energy of 3 MJ be transferred from SPS to LHC, far above damage limit

For CNGS operation, the intensity is similar to LHC injection



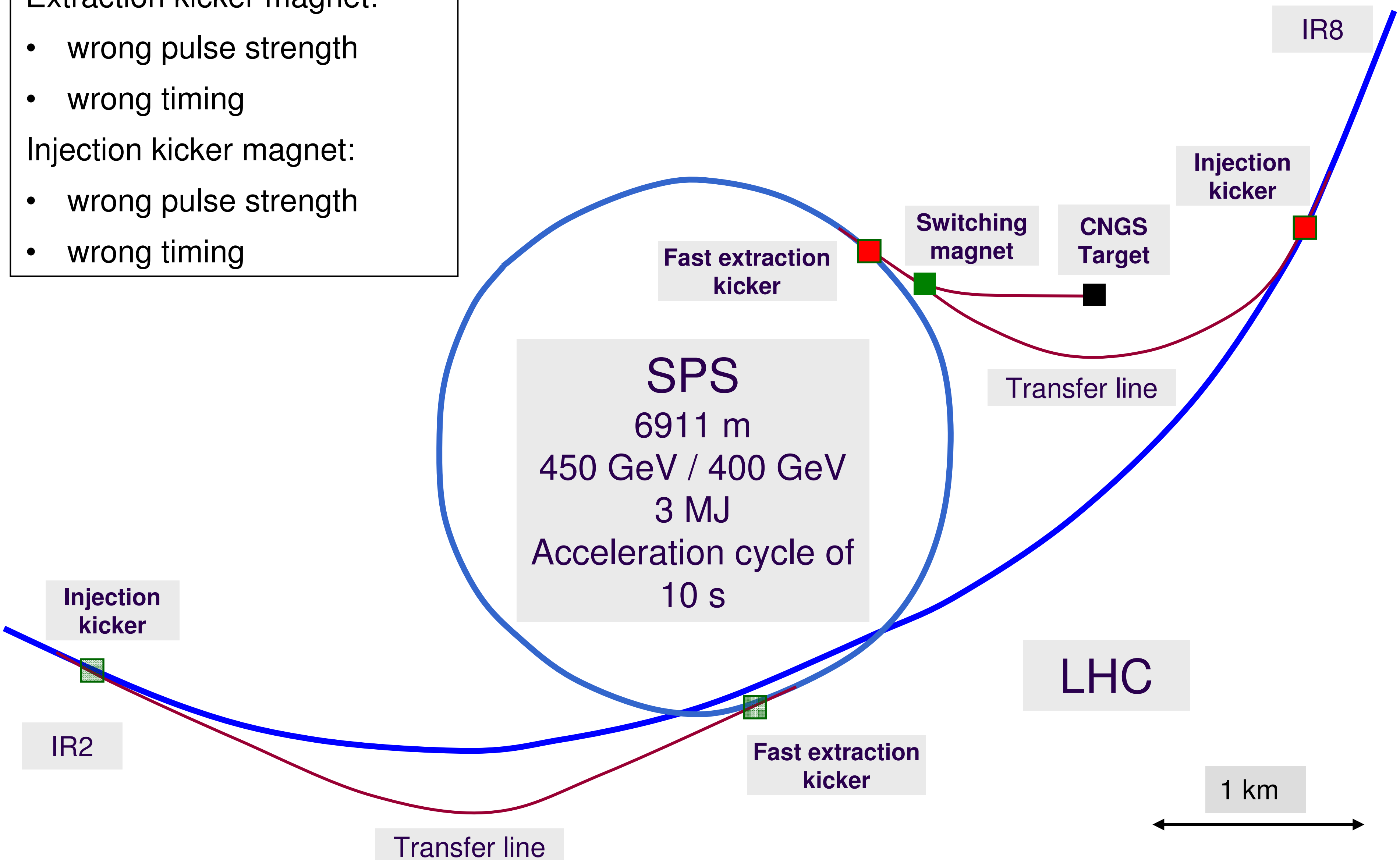
# Failure of a kicker magnet

Extraction kicker magnet:

- wrong pulse strength
- wrong timing

Injection kicker magnet:

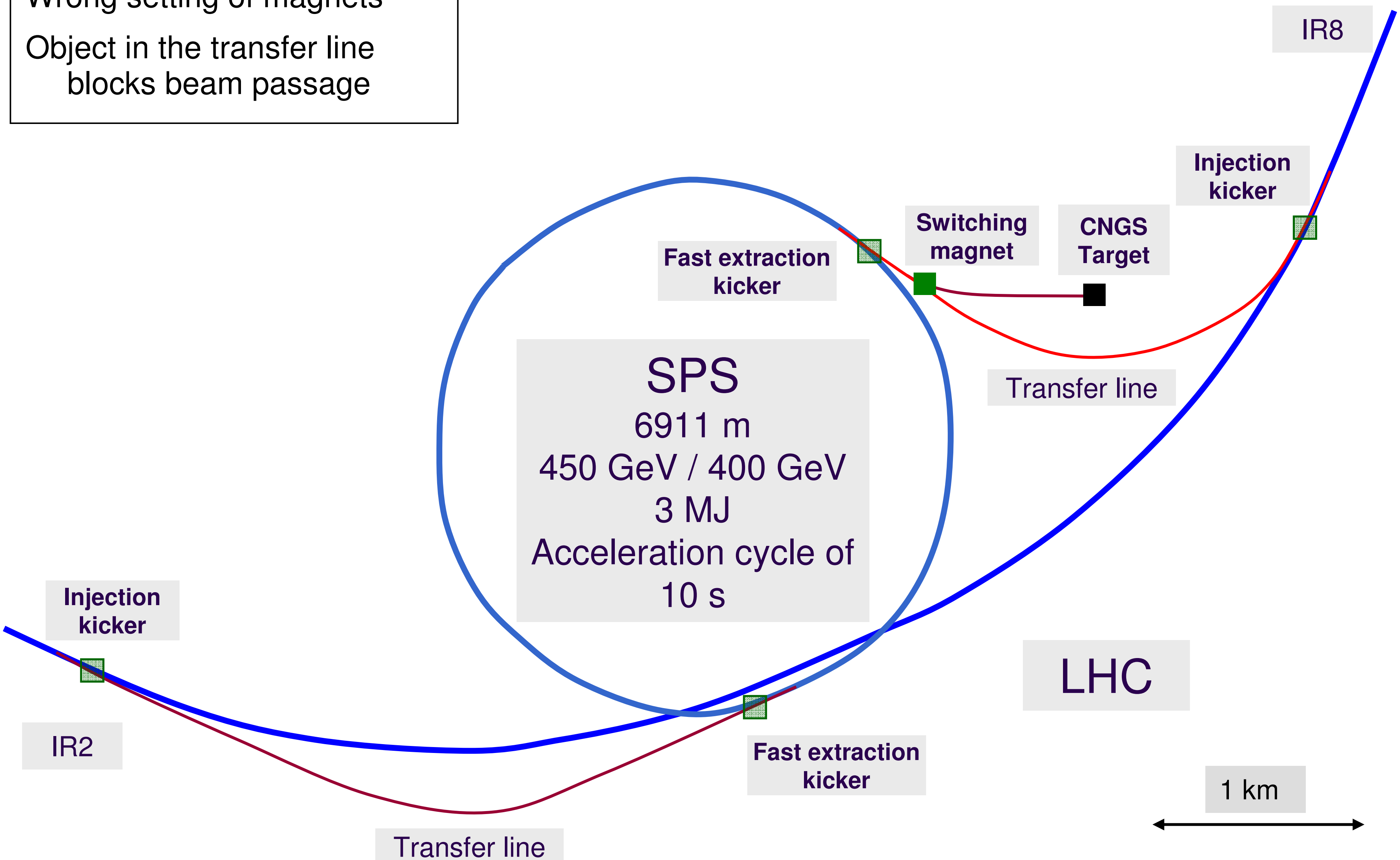
- wrong pulse strength
- wrong timing



# Failure in the transfer line (magnet, other element)

Wrong setting of magnets

Object in the transfer line blocks beam passage



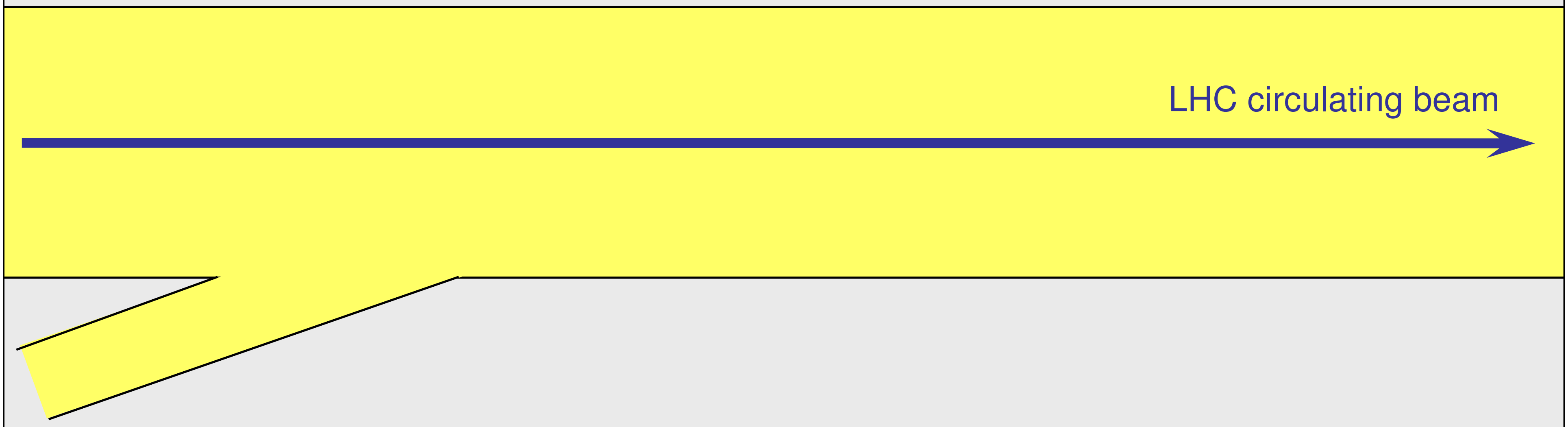
# Protection for beam transfer from SPS to LHC

- After extraction the trajectory is determined by the magnet fields: safe beam transfer and injection relies on correct settings
  - orbit bump around extraction point in SPS during extraction with tight tolerances verified with BPMs
  - correct magnet currents (slow pulsing magnets, fast pulsing magnets)
  - position of vacuum valves, beam screens,… must all be OUT
  - energy of SPS, transfer line and LHC must match
  - LHC must be ready to accept beam
- Verifying correct settings just before extraction and injection

A signal "**extraction permit**" is **required to extract beam from SPS** and another signal "**injection permit**" to **inject beam into LHC**

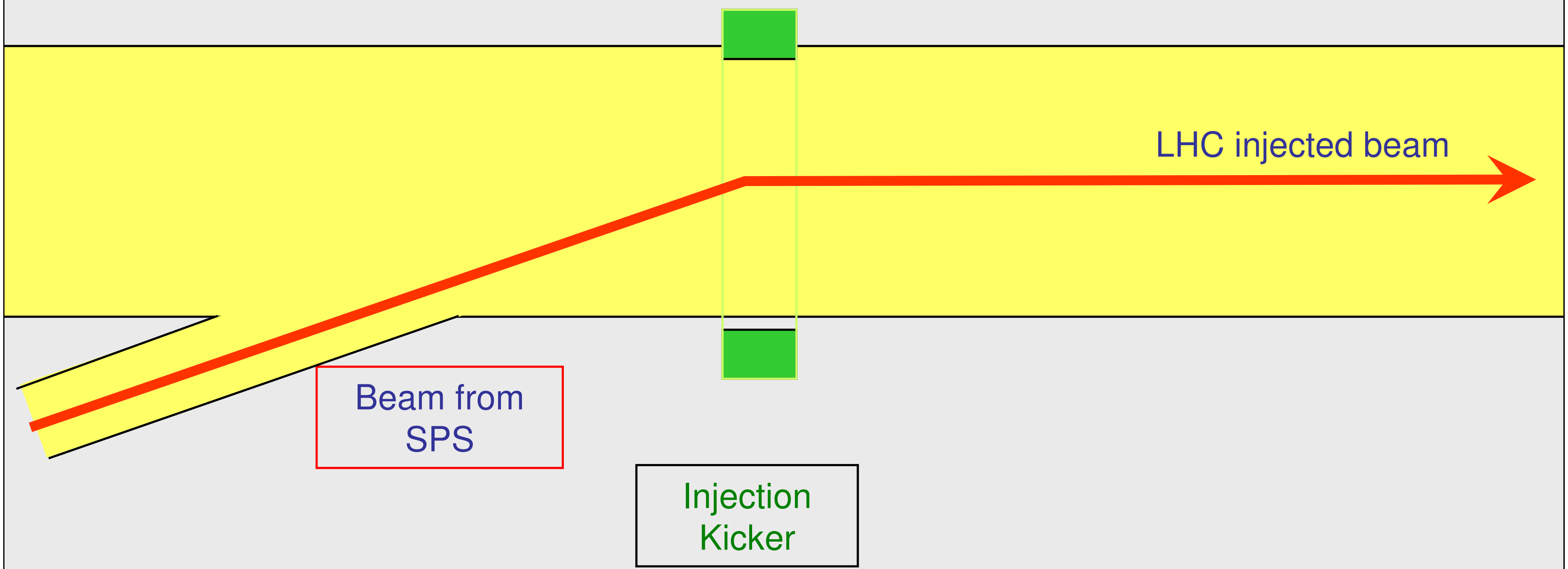
- The kicker must fire at the correct time with the correct strength
- Position of collimators and beam absorbers in SPS, transfer line and LHC injection region to protect from misfiring

# Protection at injection



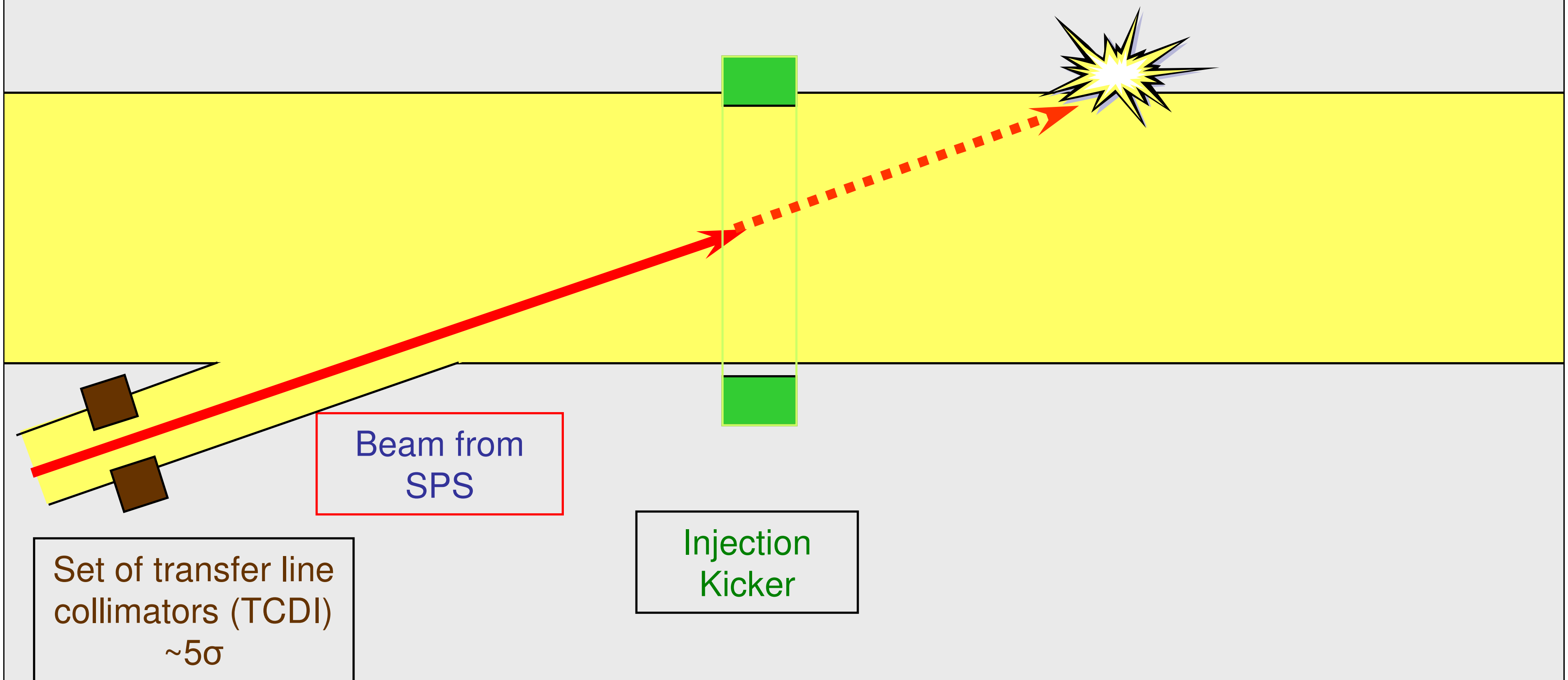

Circulating beam in LHC

# Protection at injection



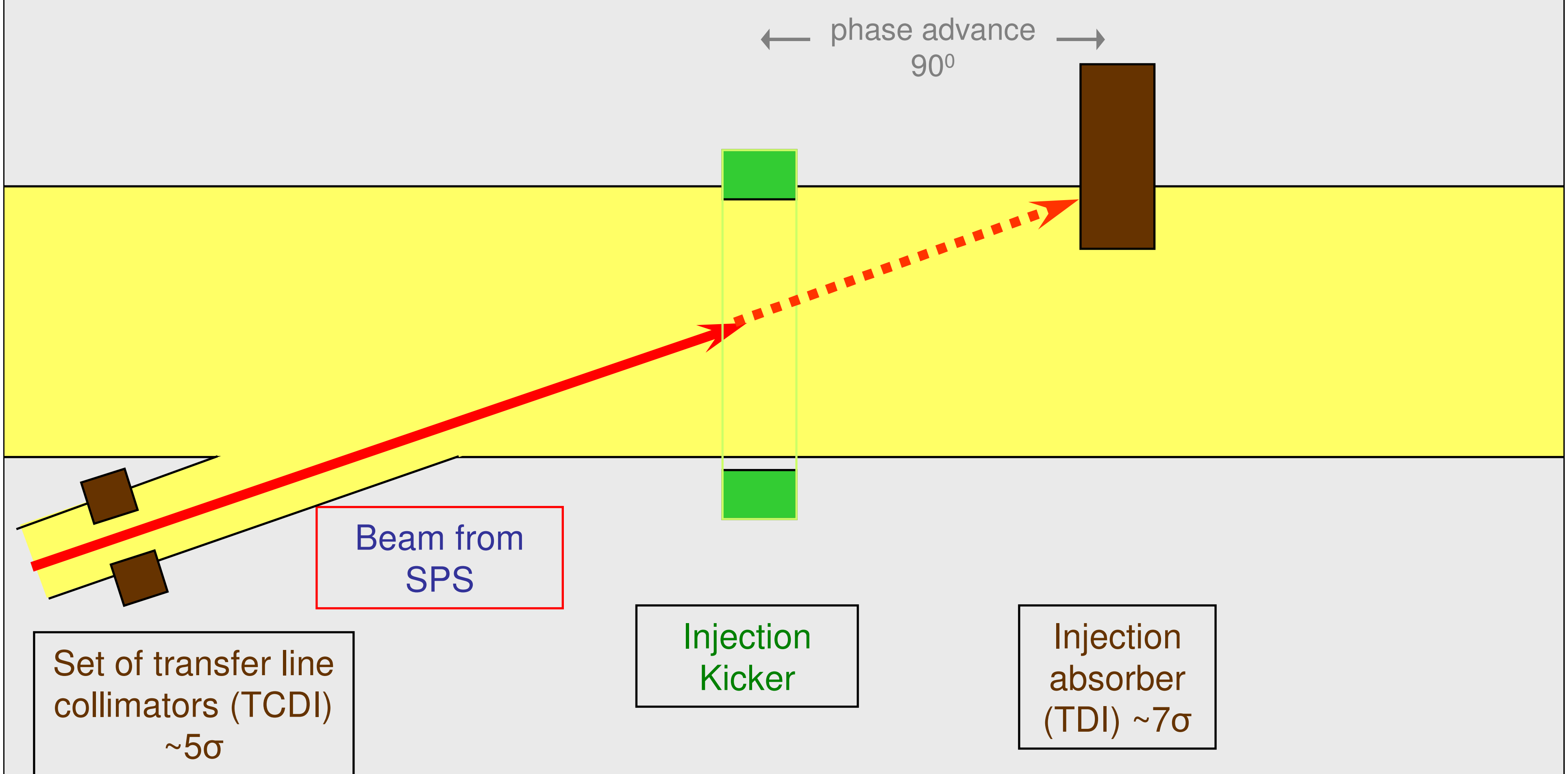

Beam injected from SPS and transfer line

# Protection at injection



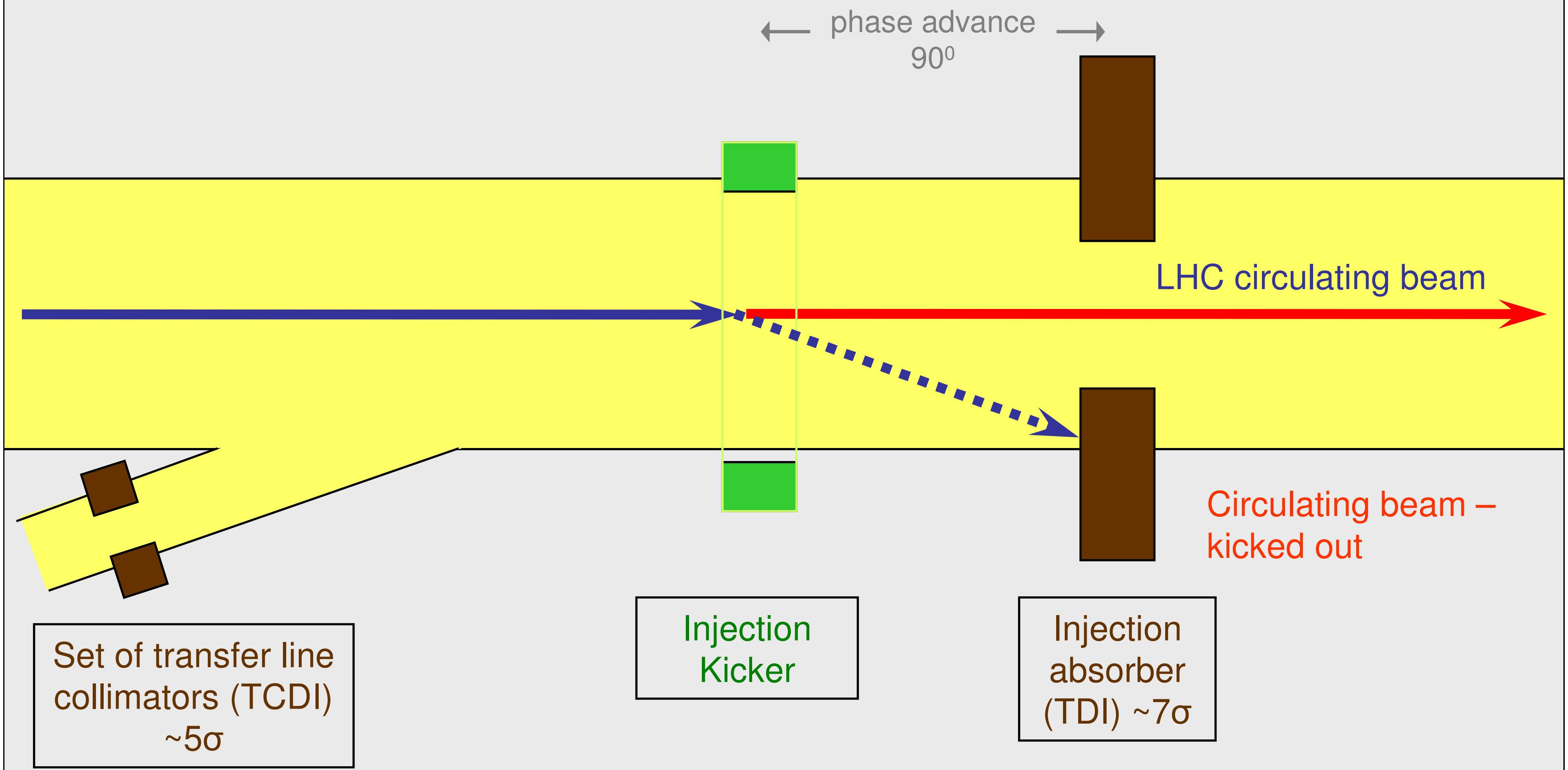

Kicker misfiring (no kick)

# Protection at injection



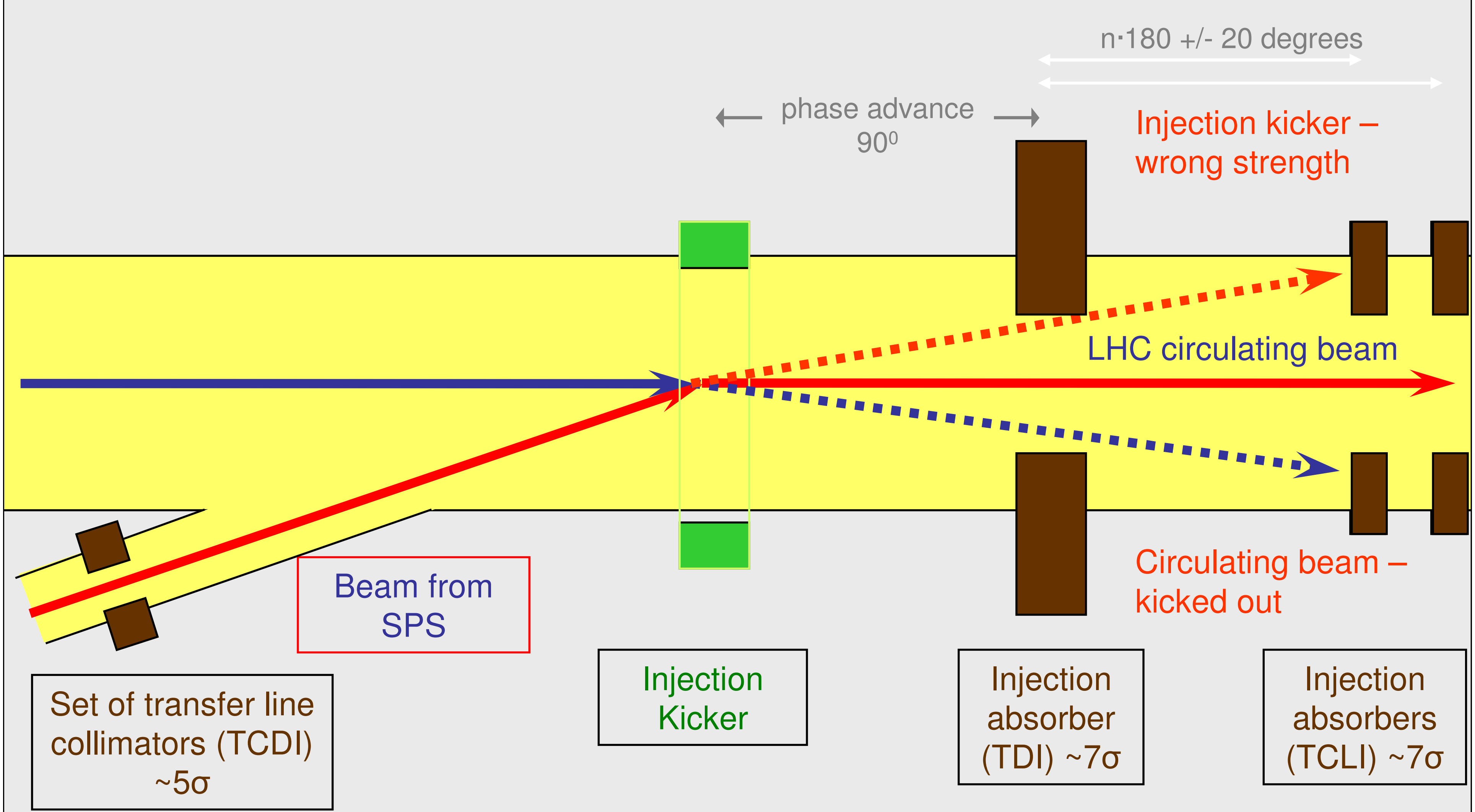

Beam absorbers take beam in case of kicker misfiring
Transfer line collimators ensure that incoming beam trajectory is ok

# Protection at injection



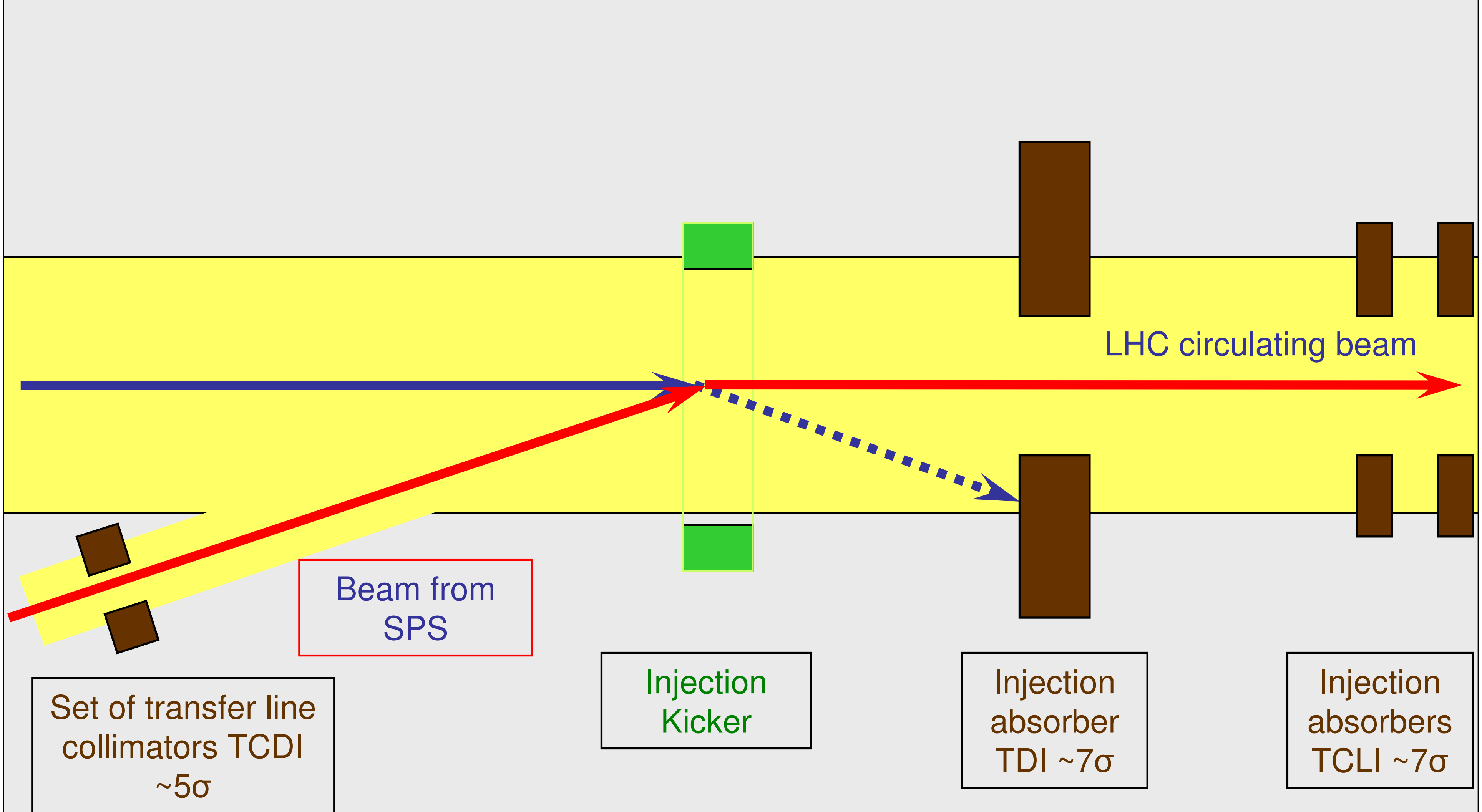

Beam absorbers take beam in case of kicker misfiring on circulating beam

# Protection at injection




Beam absorbers take beam in case of kicker wrong strength

# Probe Beam: Replacing low intensity beam by a full batch from SPS




Only when beam is circulating in the LHC, injection of high intensity beam is permitted – verification of LHC magnet settings

# 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

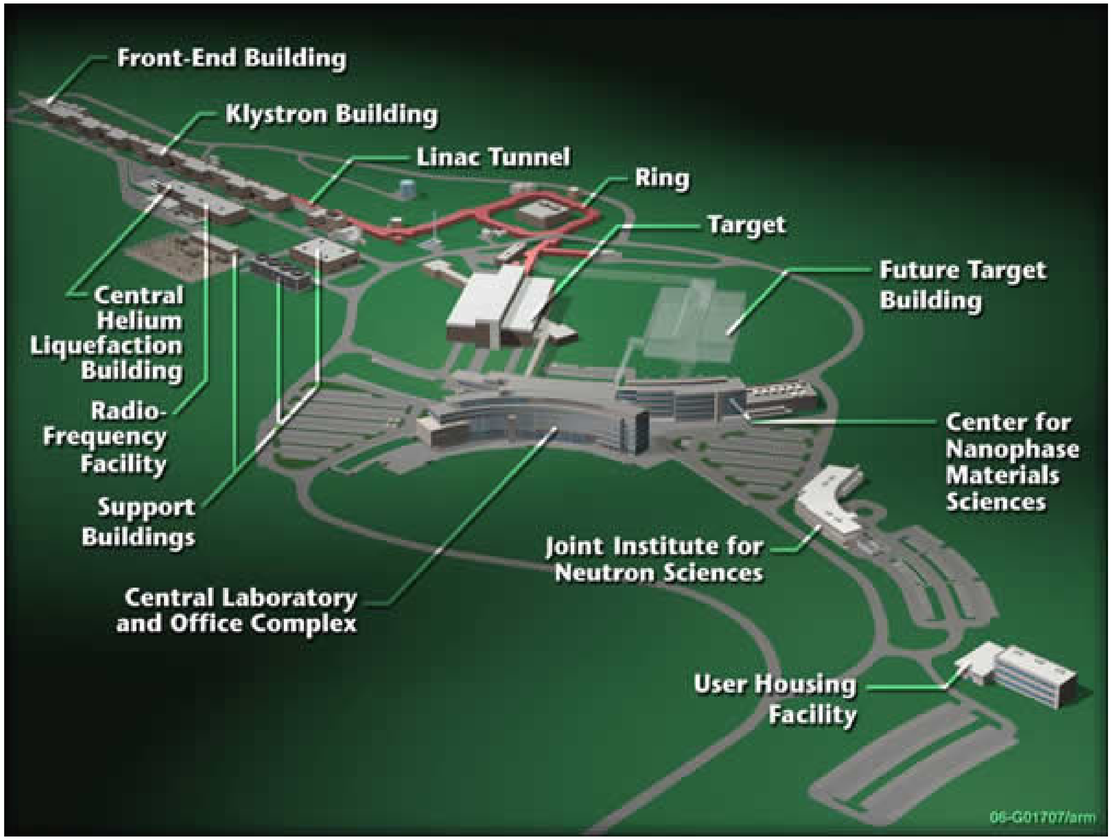
# Beam instrumentation for machine protection

- 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, …

# Case studies

The principles of machine protection are illustrated with examples from different accelerators

# Example: SNS




- normal conducting linac
- superconducting linac
- accumulator ring
- transfer lines
- target station
- beam power on target 1.4 MW
- beam pulse length 1 ms
- repetition rate 60 Hz

- (more or less) continuous beam to above 1 MW
  - the deposited energy is proportional to the time of exposure
  - the risk (possible damage) increases with time
- Protection by detecting the failure and stopping injection and acceleration

# SNS damage limits

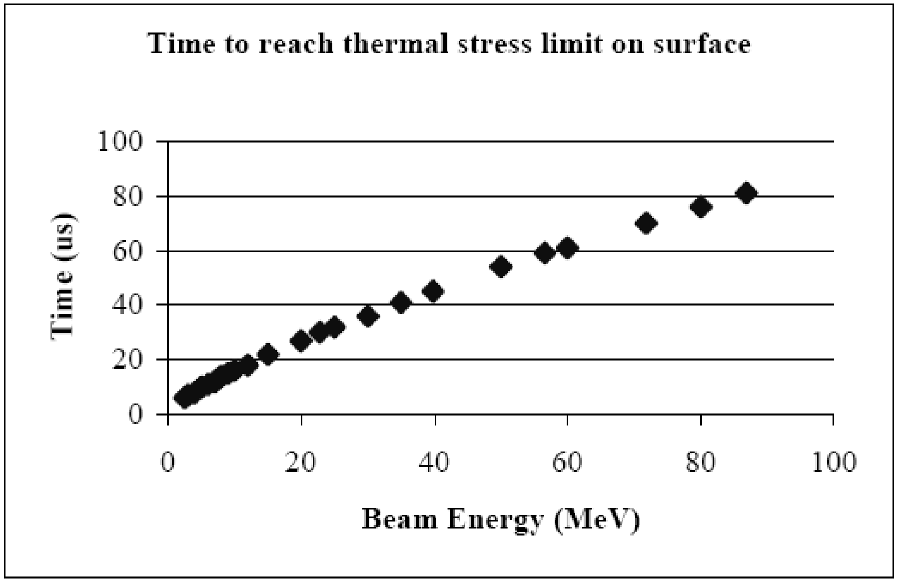
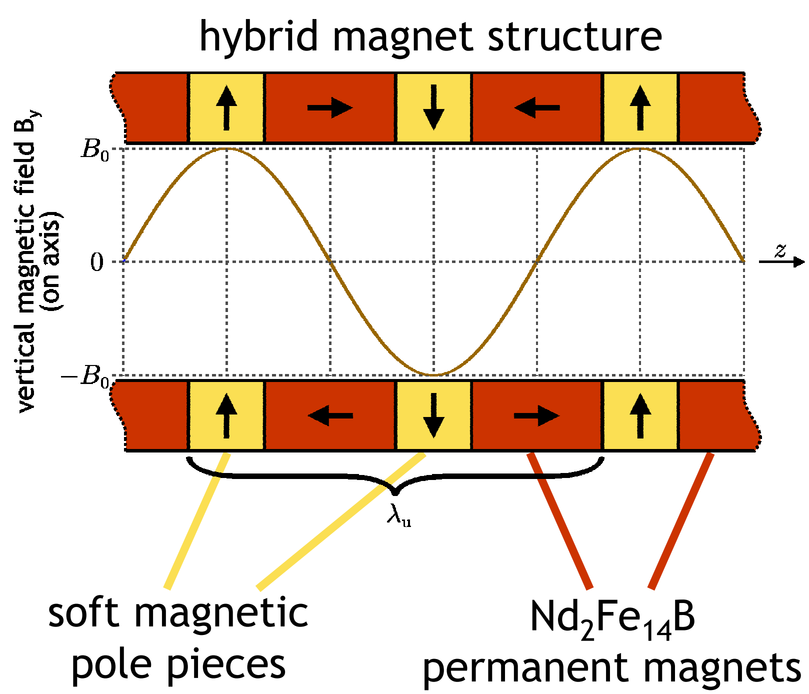



Figure 2. Time to reach the thermal stress limit in copper verses beam energy.

- Damage of a copper cavity: Time to reach the thermal stress limit for copper assuming a beam size of 2 mm, a current of 36 mA and an energy density of 62 J/gm as maximum permitted energy deposition (from C.Sibley, PAC 2003)
- The SNS MP system uses inputs from BLMs, beam current monitors, RF, power supplies, vacuum system, kickers, etc.

# Radiation Damage to Undulator Magnets

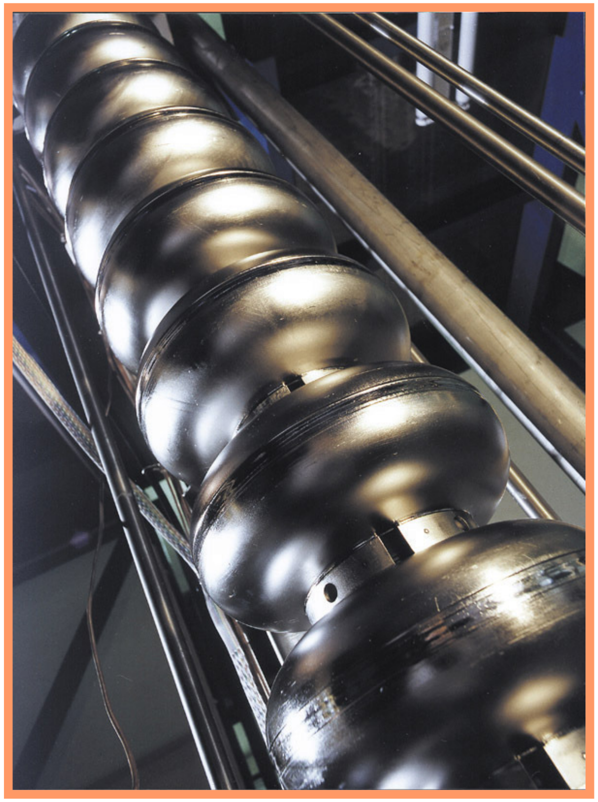



- $Nd_2Fe_{14}B$ magnets lose magnetization when irradiated
- literature: relative demagnetization rate $10^{-8}$/Gy (gammas) – $10^{-4}$/Gy (fast neutrons)

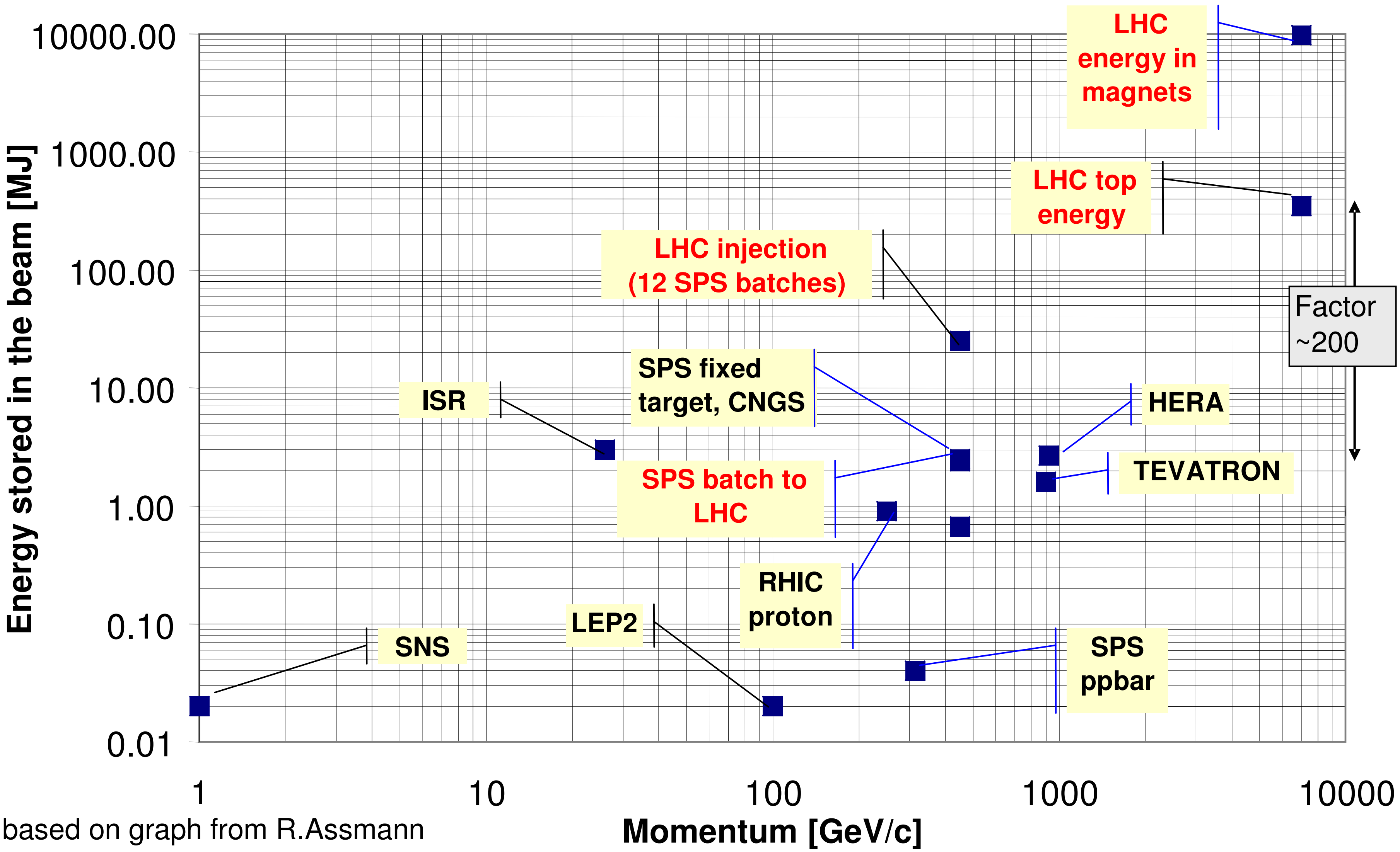
# Conclusion

- Superconducting linacs can transport dangerously powerful beams
- Permanent magnet undulators are among the most vulnerable components
- Beam losses must be controlled tightly (FLASH design: $3 \cdot 10^{-8}$)
- Dark current can be problematic
- Good passive & active protection is required

- FLASH machine protection system is fully functional & reliable
- XFEL machine protection system will be more complex, but concepts & first prototypes are ready



# **Livingston type plot:** Energy stored magnets and beam




based on graph from R.Assmann

# Machine Protection during all phases of operation

- The LHC is the first accelerator with the intensity of the injected beam already far above threshold for damage, protection during the injection process is mandatory
- At 7 TeV, fast beam loss with an intensity of about 5% of one single “nominal bunch” could damage equipment (e.g. superconducting coils)
- The only component that can stand a loss of the full beam is the beam dump block - all other components would be damaged
- The LHC beams must ALWAYS be extracted into the beam dump blocks
  - at the end of a fill
  - in case of failure
- During powering, about 10 GJ is stored in the superconducting magnets, quench protection and powering interlocks must be operational long before starting beam operation

# 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**<br>**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**<br>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** |

# Multiturn beam losses

## Consequence of a magnet powering failure

- Closed orbit grows and moves everywhere the ring or downstream the linac (follows free betatron oscillation with one kick)
- Beam size explodes
- Can happen very fast (for example, if a normal conducting magnet trips or after a magnet quench)
- Can be detected around the entire accelerator

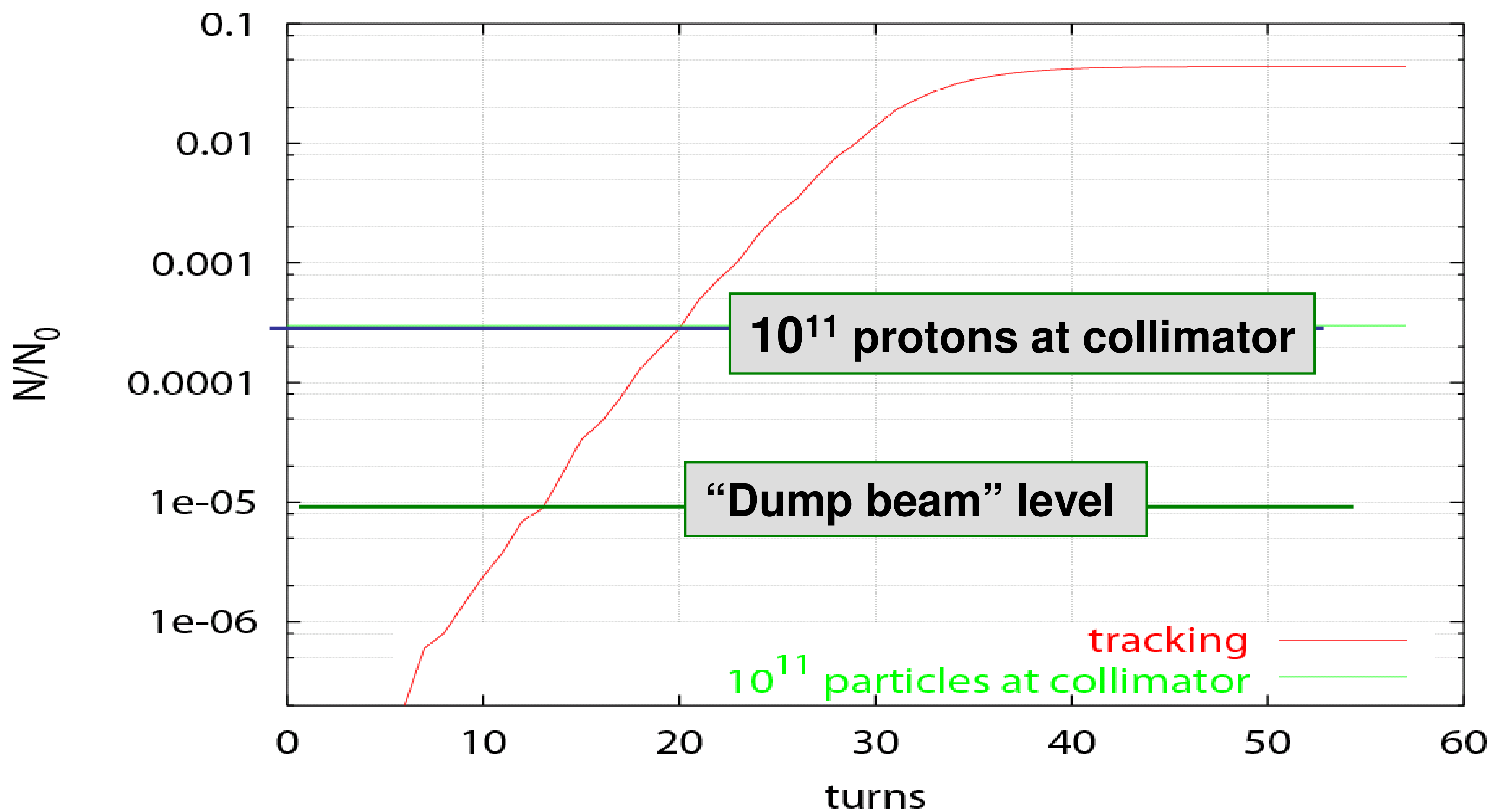
## Local orbit bump

- Can be generated due to BPM offset
- Needs several magnets to fail and cannot happen very fast
- Might be detected only locally

- Protection: Detect failure and dump beam
- Detection by equipment monitoring and beam monitoring

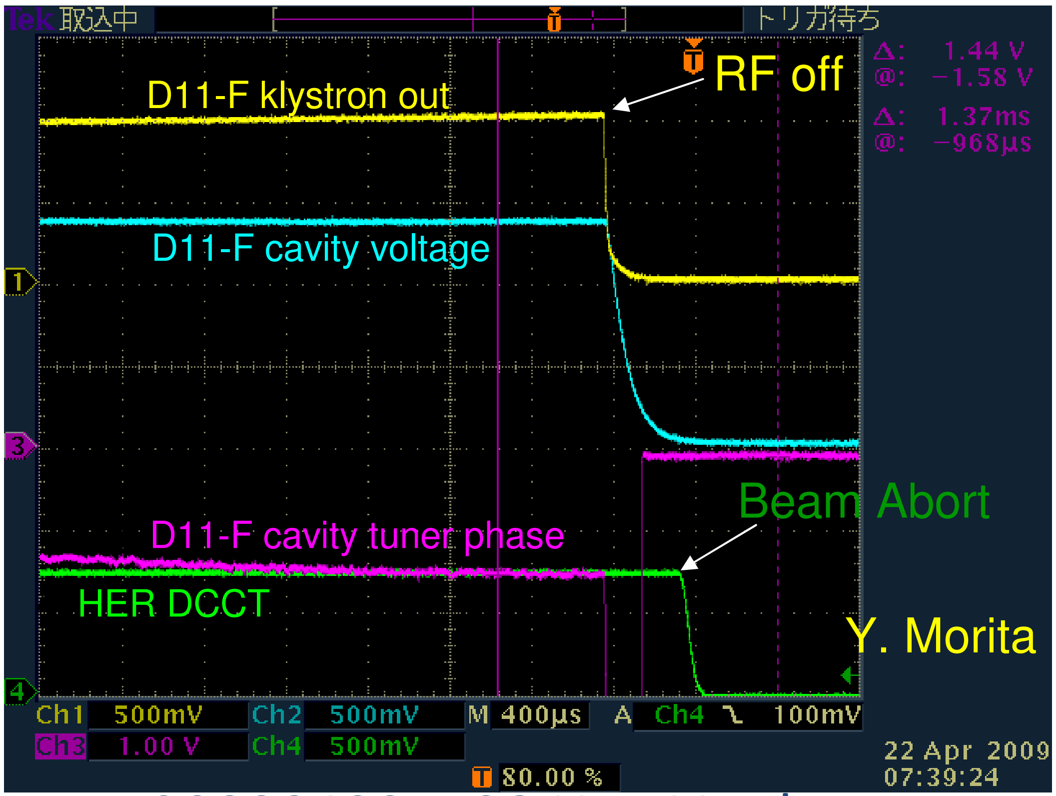
# Failure of normal conducting magnets

After about 13 turns $3 \cdot 10^9$ protons touch collimator, about 6 turns later $10^{11}$ protons touch collimator



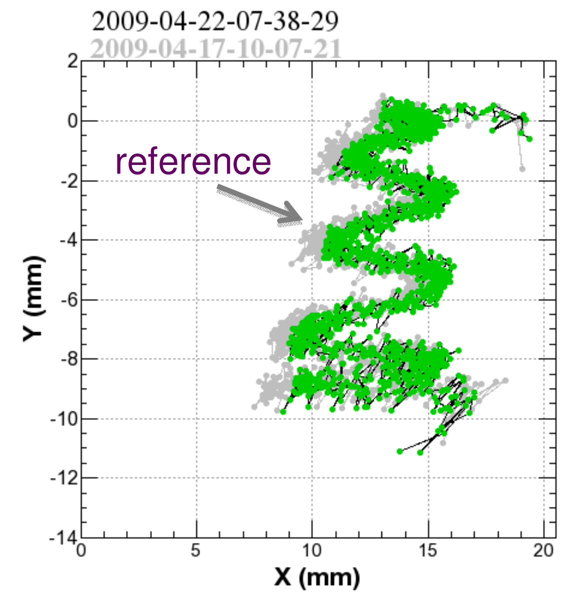

V.Kain / O.Bruning

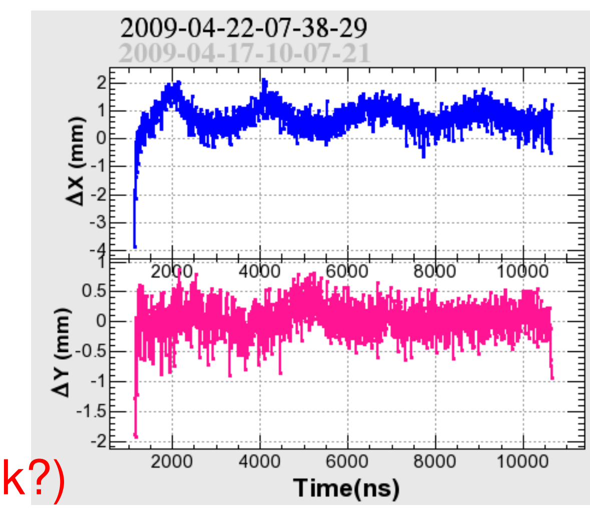
# What happens in case of crab rf trip?




20090422 7:38 HER Vc abort

Beam positions of aborted beam




Typical example when HER Crab RF trips.

HER beam current: 750 mA

We abort the beam in case of crab rf trip.

In some case, the beam is kicked more largely by the crab after rf trip and before rf off (-> Nakanishi's talk?)

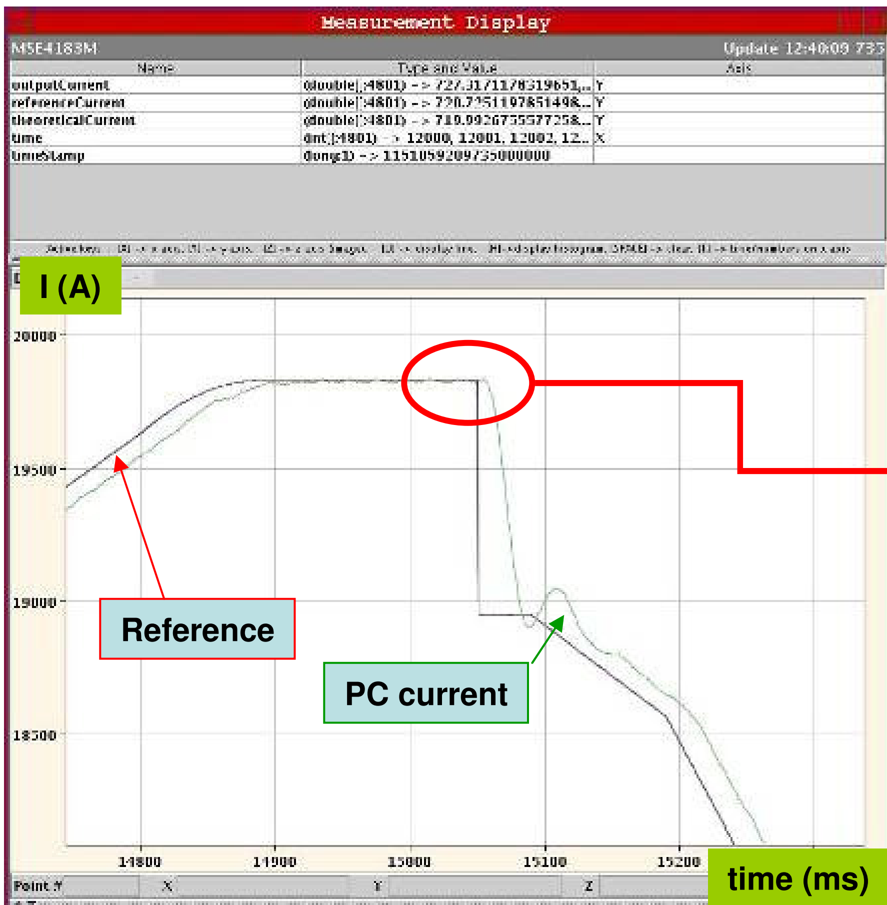
# Beam Loss Monitors

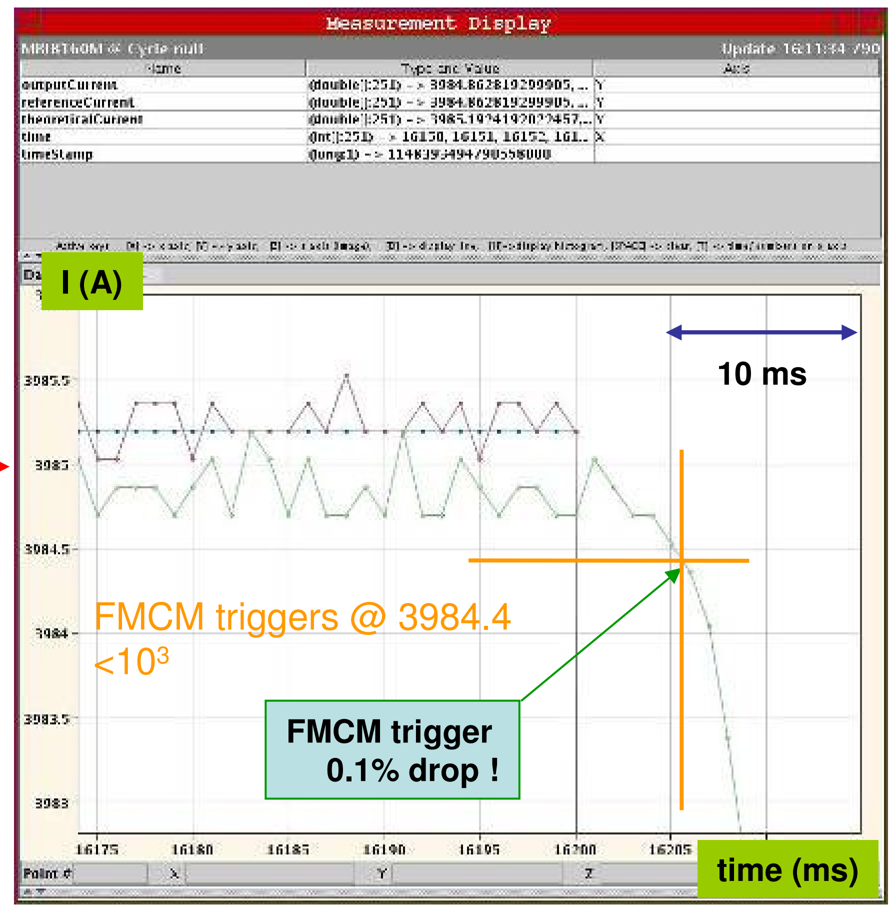
- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> $10^6$)
- There are ~3600 chambers and 400 other monitors distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !

# Fast Magnet Current change Monitors

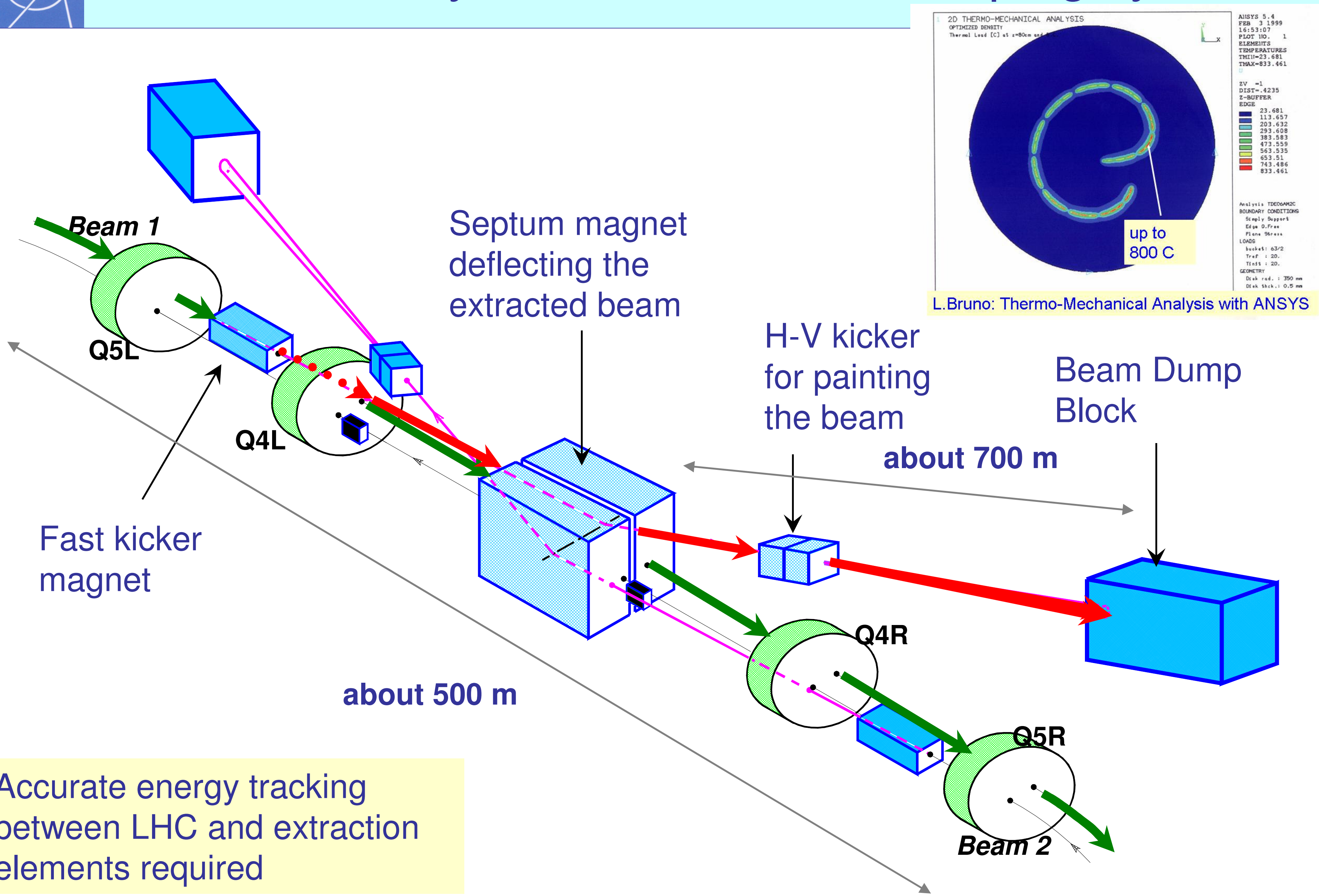
## (initial development for HERA, upgrade for LHC in collaboration with DESY)

- Several FMCMs are installed on critical magnets
- Tested using steep reference changes to trigger FMCM. The trigger threshold and the magnet current (resolution one ms)
- Beam tests confirmed these results



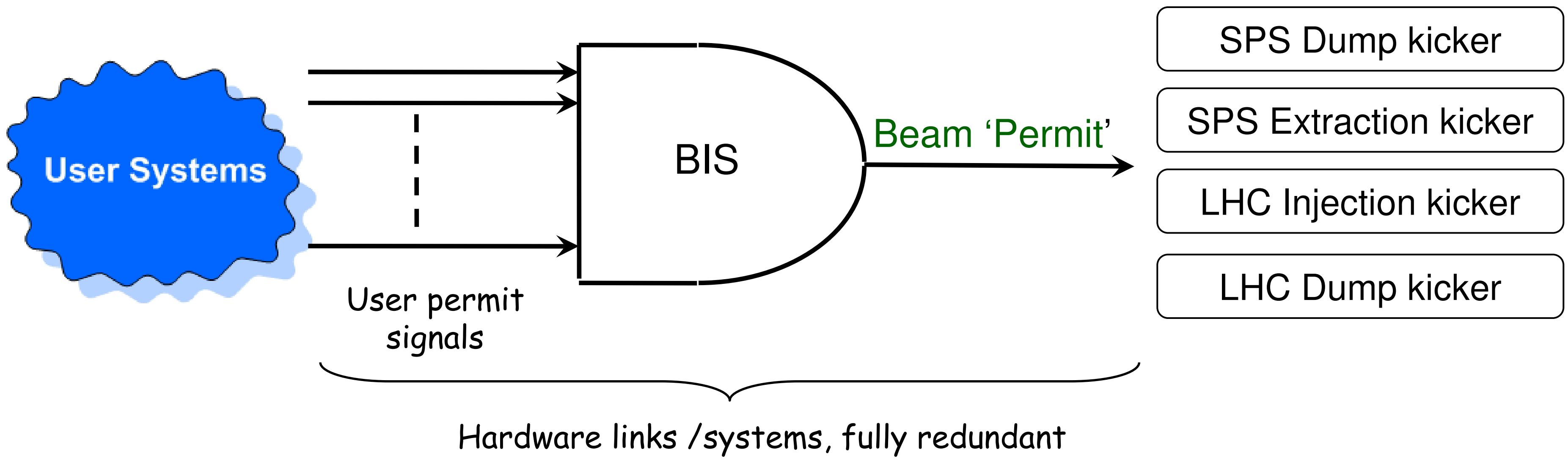
# Schematic layout of LHC beam dumping system



L.Bruno: Thermo-Mechanical Analysis with ANSYS

Accurate energy tracking between LHC and extraction elements required

# Principle of LHC / SPS Beam Interlock Systems




- '**User systems**' survey equipment or beam parameters, detect failures and send a hardwired signal to the beam interlock system **(user permit)**
- The BIS combines **user permits** and produces **beam permit**
- The **beam permit** is a hardwired signal to injection / extraction kickers :
-
- LHC ring: absence of beam permit dump triggered !
- LHC injection: absence of beam permit no injection !
- SPS: absence of beam permit no extraction !

# Machine Protection and Controls

- **Software Interlock Systems (SIS)** provides additional protection for complex but also less critical conditions
  - Surveillance of magnet currents to avoid certain failures (local bumps) that would reduce the aperture
  - The reaction time of those systems will be at the level of a few seconds
  - The systems rely entirely on the computer network, databases, etc – clearly not as safe as HW systems!
- **Sequencer:** program to execute defined procedures
  - To execute defined well-tested procedures for beam operation
- **Logging and PM systems**: recording of data – continuous logging and for transients (beam dump, quench, …)
  - Very important to understand what happened

# 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 fairly comprehensive understanding of all aspects of the accelerator (accelerator physics, operation, equipment, instrumentation)
- 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

# Acknowledgements to many colleagues from CERN and to the authors of the listed papers


- R.F.Koontz, Multiple Beam Pulse of the SLAC Injector, IEEE 1967
- R.Bacher et al., The HERA Quench Protection System, a Status Report, 1996
- C.Adolphsen et al., The Next Linear Collider Machine Protection System, PAC 1999
- M.C.Ross et al., Single Pulse Damage in Copper, LINAC 2000
- C.Sibley, Machine Protection Strategies for High Power Accelerators, PAC 2003
- C.Sibley, The SNS Machine Protection System: Early Commissioning Results and Future Plans, PAC 2005
- S.R.Buckley and R.J.Smith, Monitoring and Machine Protection Designs for the Daresbury Laboratory Energy Recovery Linac Prototype, EPAC 2006
- L.Fröhlich et al., First Operation of the FLASH Machine Protection System with long Bunch Trains, LINAC 2006
- L.Fröhlich et al., First Experience with the Machine Protection System of FLASH, FEL 2006
- L.Froehlich, Machine Protection for FLASH and the European XFEL, DESY PhD Thesis 2009
- N.V.Mokhov et al., Beam Induced Damage to the TEVATRON Components and what has been done about it, HB2006
- M.Werner and K.Wittenburg, Very fast Beam Losses at HERA, and what has been done about it, HB2006
- S.Henderson, Status of the Spallation Neutron Source: Machine and Experiments, PAC 2007
- A.C.Mezger, Control of a 1 MW Beam, to be completed
- H.Yoshikawa et al., Current Status of the Control System for J-PARC Accelerator Complex, ICALEPCS 2007