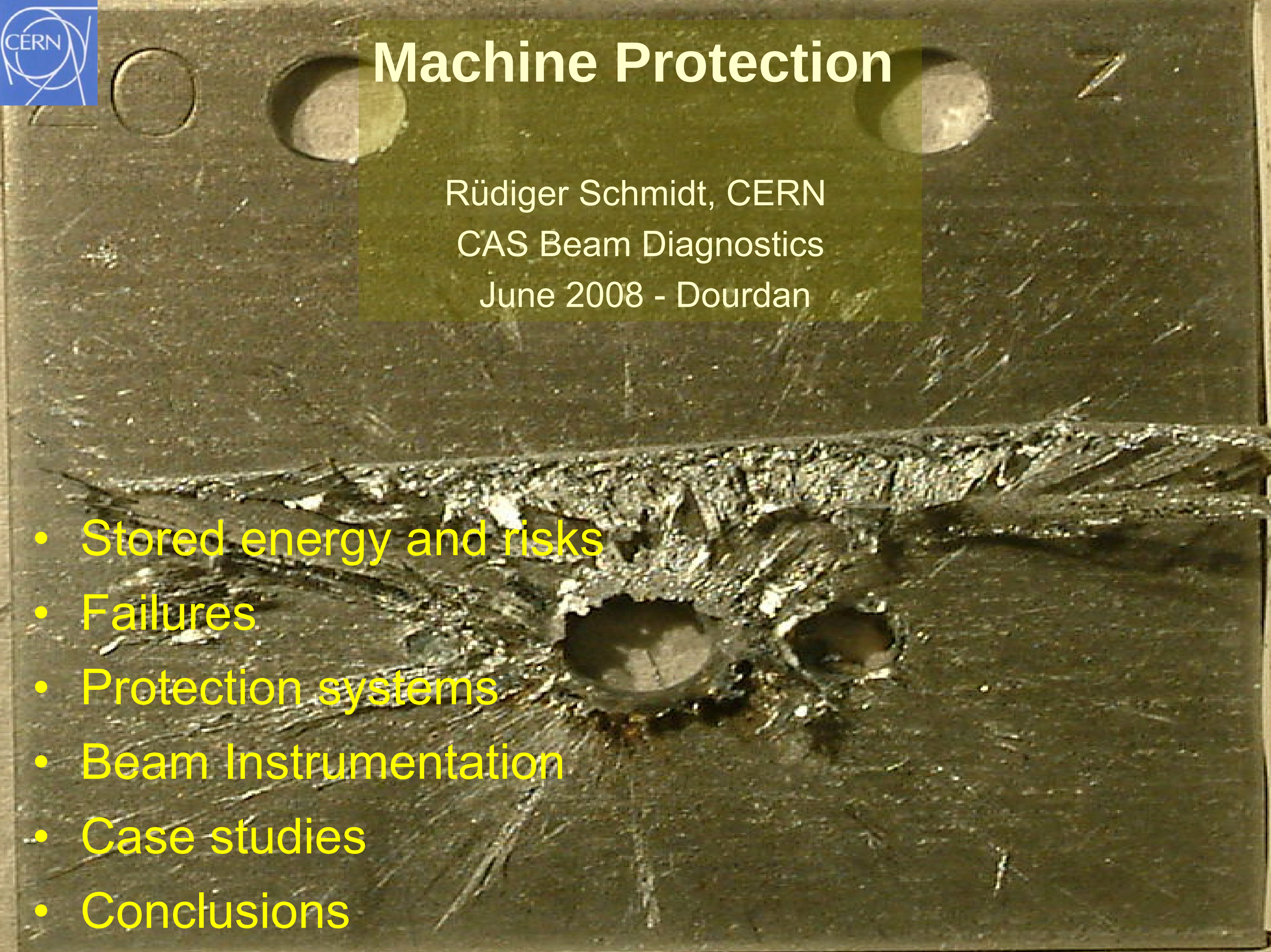


Machine Protection

Rüdiger Schmidt, CERN

CAS Beam Diagnostics

June 2008 - Dourdan

- Stored energy and risks
- Failures
- Protection systems
- Beam Instrumentation
- 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, other high power equipment, power cables, normal conducting magnets, RF systems, etc.)
  - **In this presentation "Machine Protection": protect equipment from damage or unacceptable activation caused by the beam**

Risks and protection

- Protection is required since there is some risk
- Risk = probability of an accident (in number of accident per year)
  - • consequences (in Euro, downtime, radiation dose to people)
- Probability of an uncontrolled 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 failure modes?
- Consequences of an uncontrolled 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

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
  - some limited risk to damage sensitive equipment for some 10 kJ, large risk for some MJoule
  - equipment becomes activated due to beam losses (acceptable is ~1 W/m and As Low As Reasonably Achievable - ALARA)
  - superconducting magnets could quench
- 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

What parameters are relevant?

- Momentum of the particle
- Particle type
  - Activation is mainly an issue for hadron accelerators
- 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)
- Time structure of beam

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)
- Linear colliders / accelerators with very high beam power densities due to small beam size
  - SLAC Linac, ILC, CLIC, NLC and FLASH (average power of 50 kW)
  - 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

Accelerators that require protection systems II

- 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
- 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, …)

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

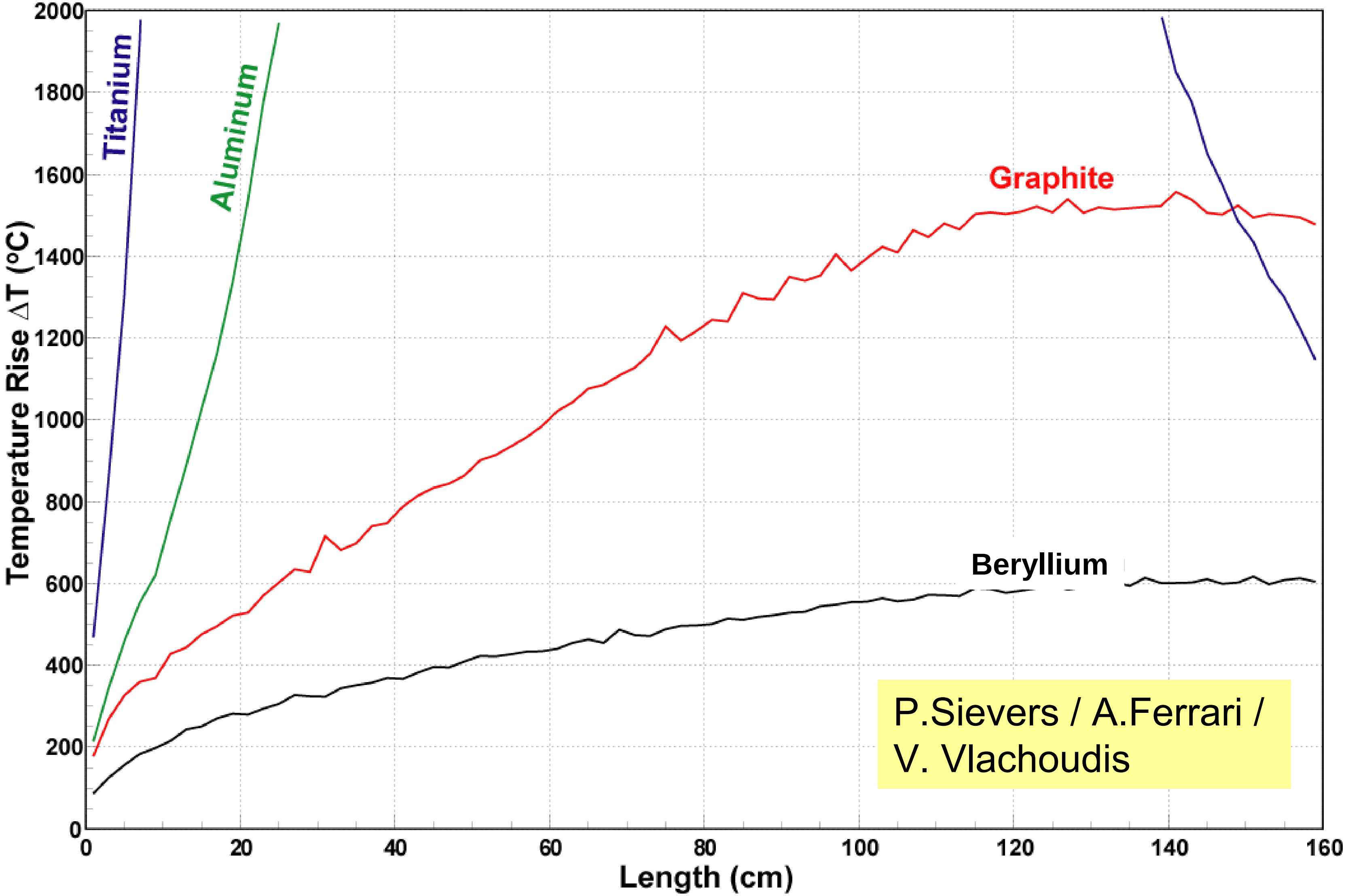
Specific heat of graphite is $c_{C\_spec} = 710.6000 \frac{1}{kg} \frac{J}{K}$

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

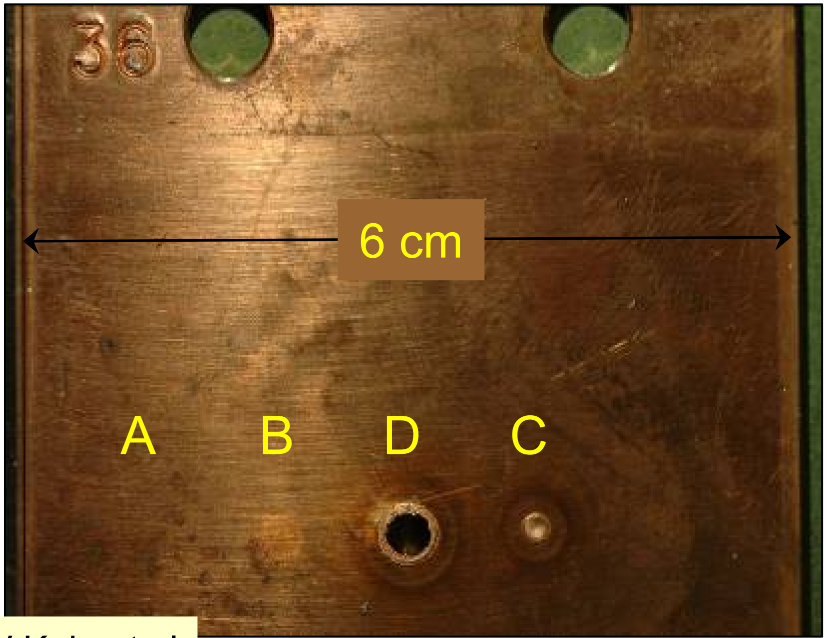
- $8 \cdot 10^{12}$ protons clear damage
- beam size $\sigma_{x/y}$ = 1.1mm/0.6mm

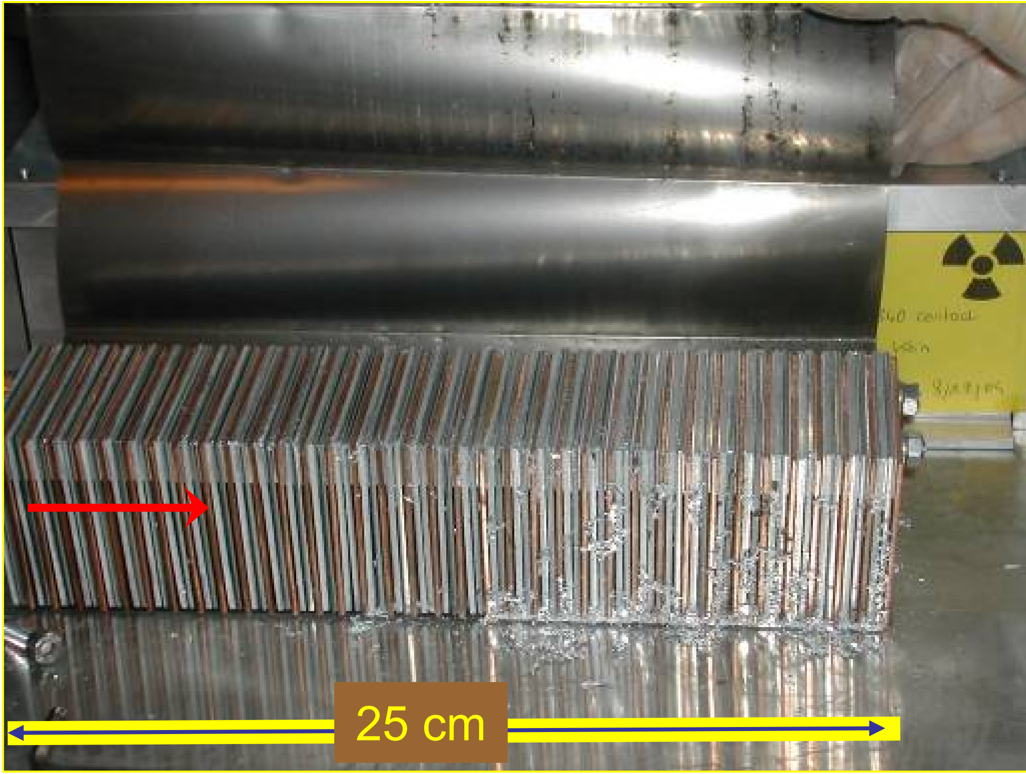
above damage limit for copper

stainless steel no damage

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

below damage limit for copper



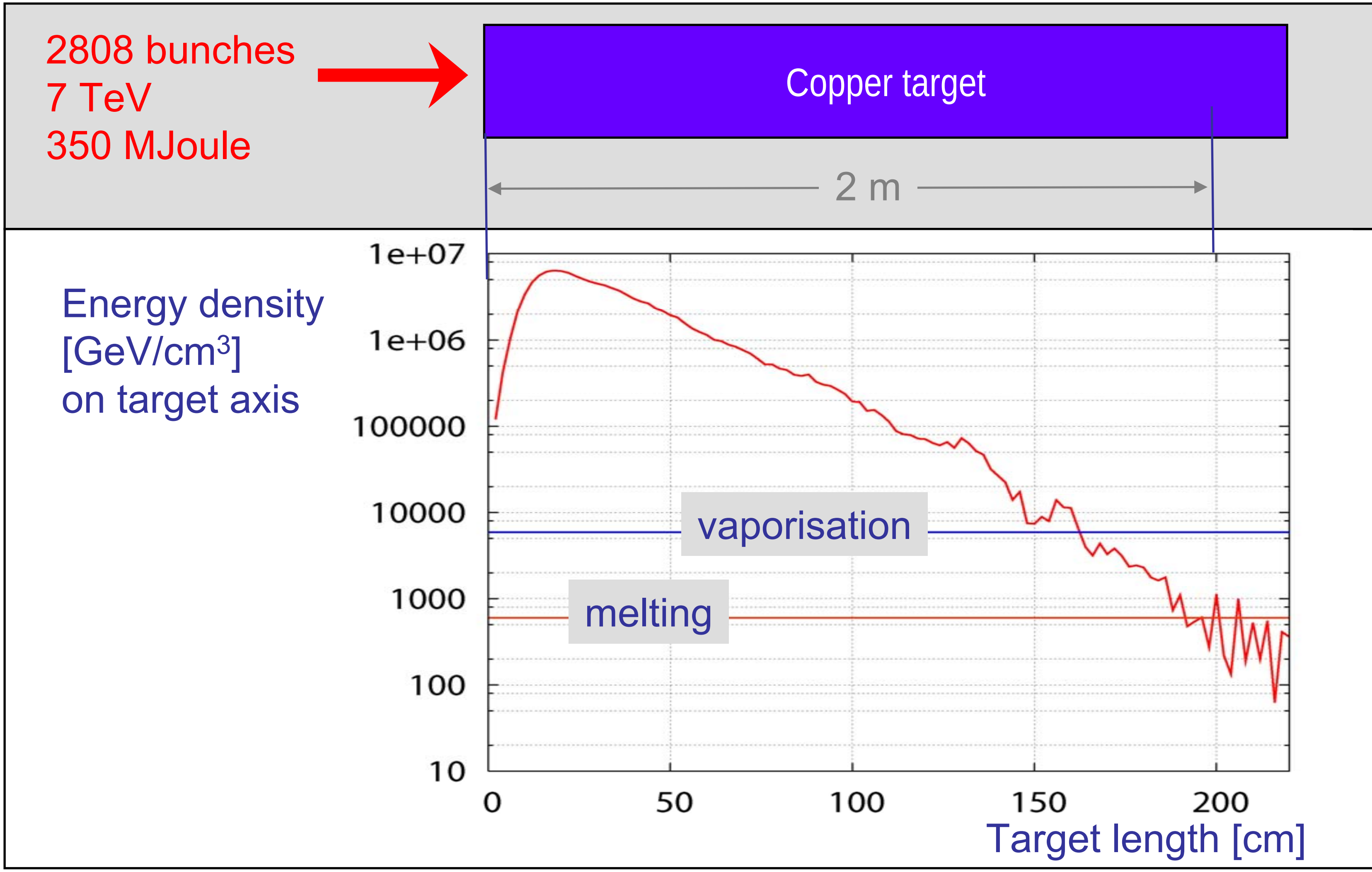


0.1 % of the full LHC 7 TeV beams

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.

PPP principle for machine protection

- Protect the machine
  - highest priority is to avoid damage of the accelerator
- Protect the beam
  - complex protection systems will always reduce the availability of the machine
  - in the design of protection systems: minimise number of “false” interlocks stopping operation
  - trade-off between protection and operation
- Provide the evidence
  - if the protection systems stop operation (e.g. dump the beam or inhibit injection), clear diagnostics should be provided
  - if something goes wrong (damage, but also near miss), it should be possible to understand the reason why
  - synchronised transient recording of all relevant systems

Active and passive protection

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

Active protection

- Detect failure
- Turn off the beam as soon as possible (e.g. the source, the RF, …)
- Prohibit beam from being injected into the next part of the accelerator complex
- Abort the beam from a storage ring / accumulator ring

Passive protection

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

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)
- 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 (applies to: Very fast, Fast and Slow beam loss)

Strategy for protection and related systems

- Avoid that a specific failure can happen (e.g. no fast valve)
- Detect failure at hardware level and stop beam operation
  - monitoring of the hardware
- 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

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 is vital 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, …

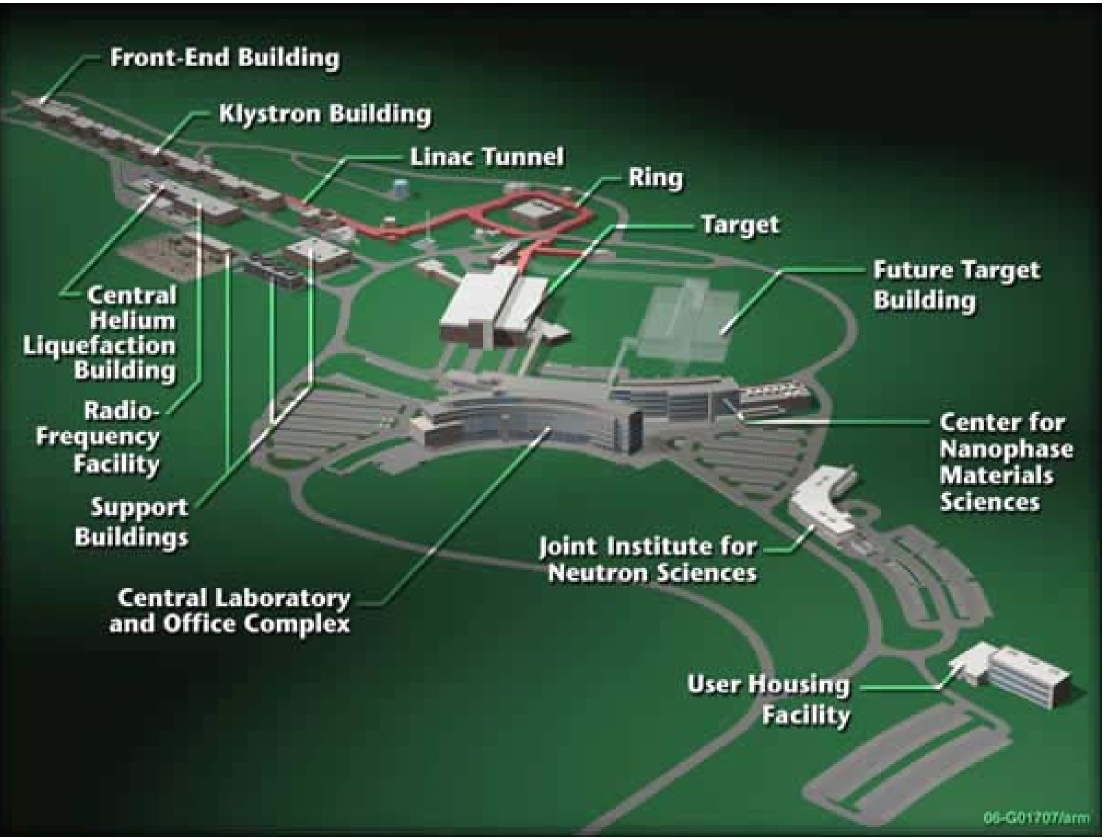
Beam instrumentation failures

- Beam Loss Monitors
  - no or too low reading not providing a beam stop trigger
  - threshold incorrect (too high could be dangerous)
- Beam Position Monitors
  - constant offset independent of the beam position
  - closed-orbit feedback tries to correct the suspected bump
  - closed-orbit bump develops and beam touches aperture
  - even if the beam is dumped, e.g. due to beam losses, part of the beam might hit the aperture
- Beam Current Transformers
  - no reading or too low reading in presence of high intensity beam: risk of extraction of high intensity beam into external beam line / target / …
  - too high reading in case of comparing beam intensity in beam line: risk to continue operation in presence of high losses

Case studies

The principles of machine protection are illustrated with examples from SNS and LHC

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

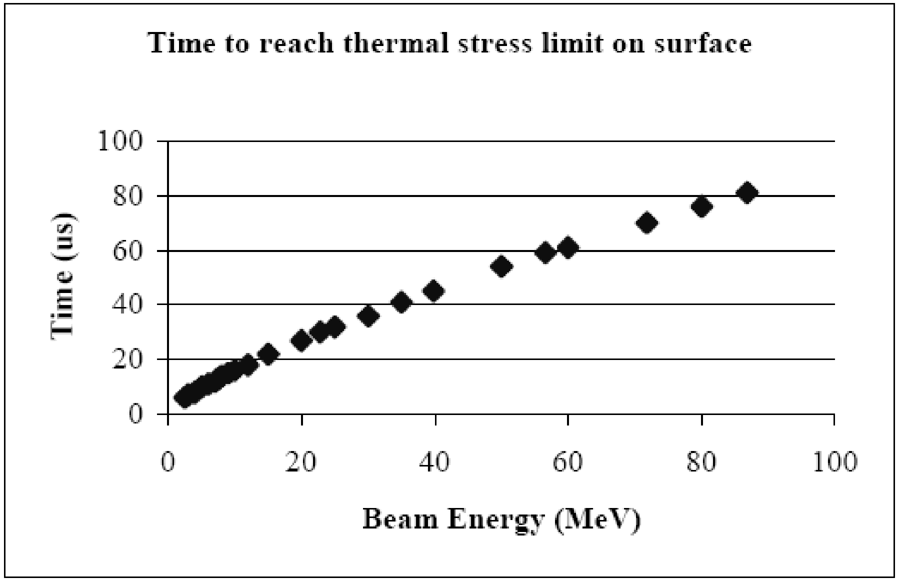
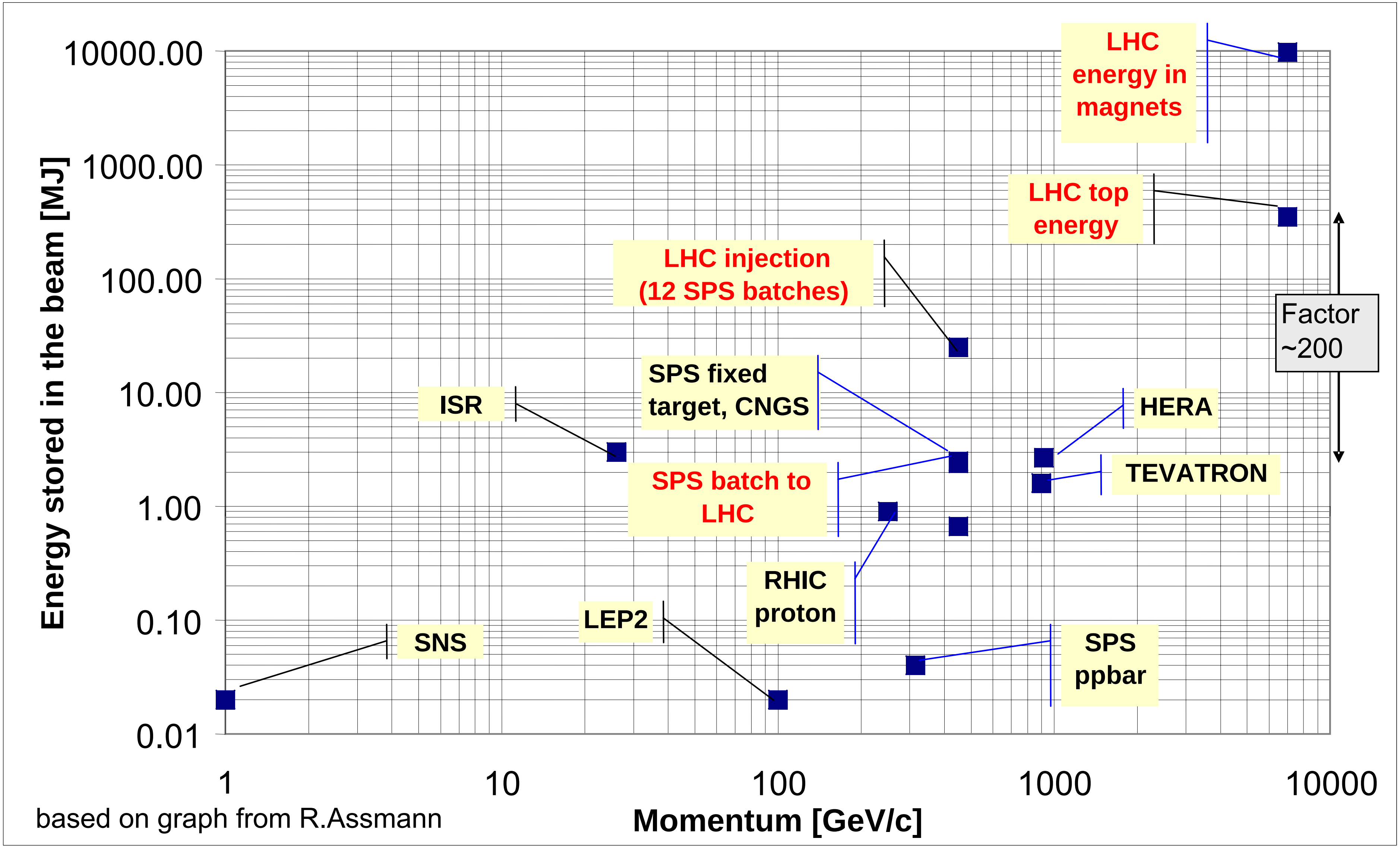


Figure 2. Time to reach the thermal stress limit in copper verses beam energy.

- 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.

Livingston type plot: Energy stored magnets and beam



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

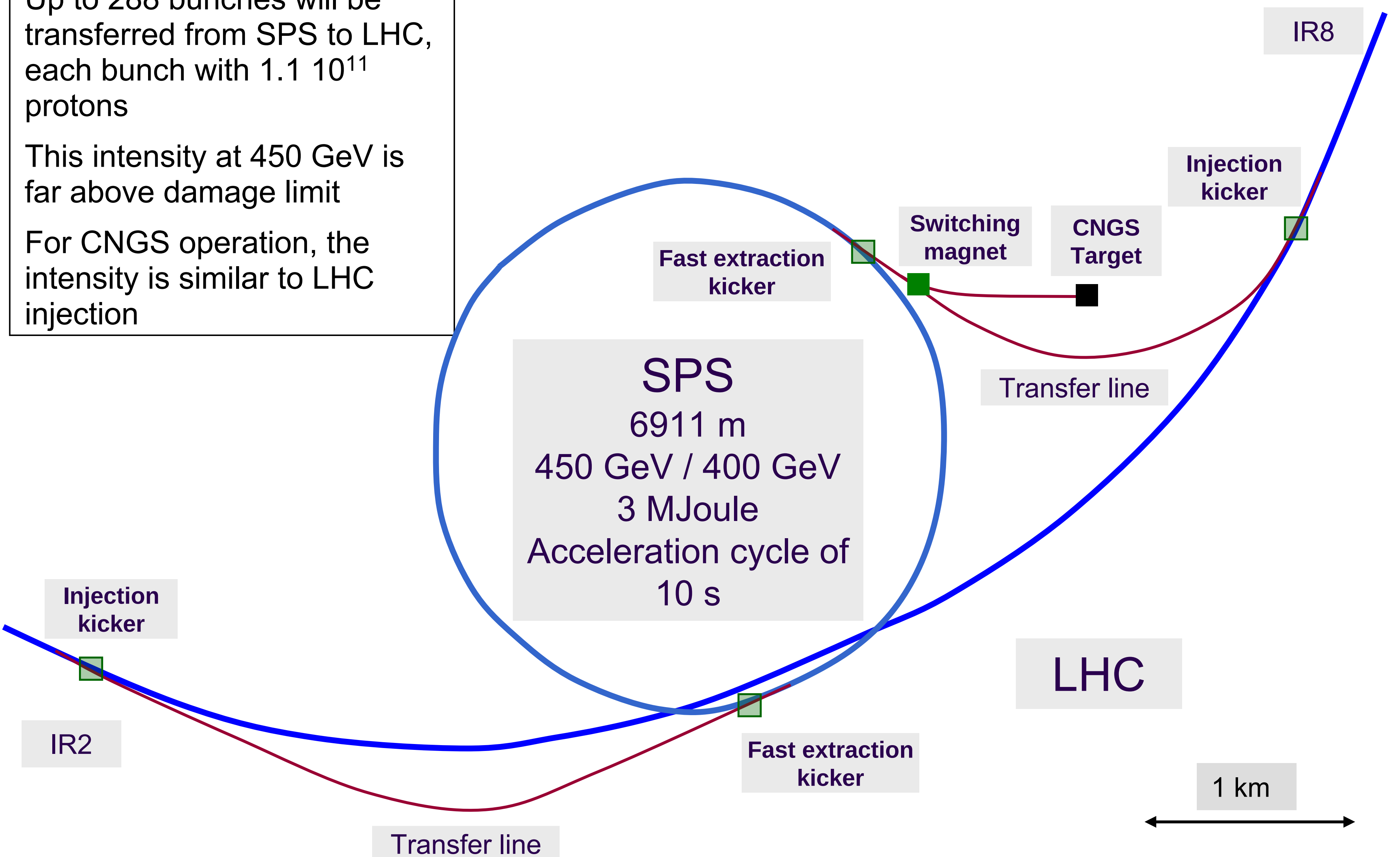
• Definition of aperture by collimators.	**Beam Cleaning System**
• Early detection of failures for equipment acting on beams generates dump request, possibly before the beam is affected.	**Powering Interlocks** **Fast Magnet Current change Monitor**
• Active monitoring of the beams detects abnormal 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.	**Beam Absorbers**

SPS, transfer line, LHC injection and CNGS

Up to 288 bunches will be transferred from SPS to LHC, each bunch with 1.1 10^{11} protons

This intensity at 450 GeV is far above damage limit

For CNGS operation, the intensity is similar to LHC injection



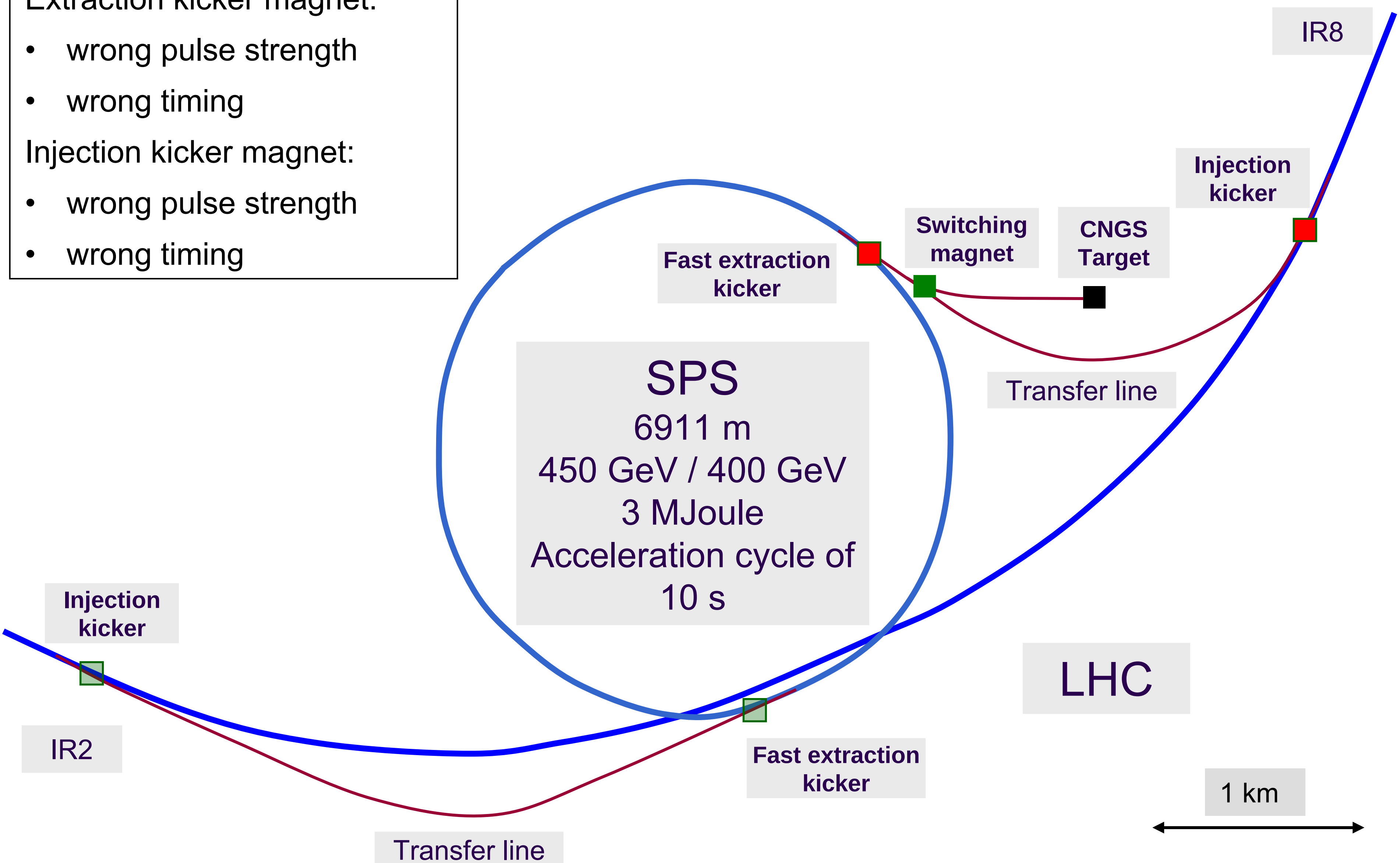
Failure of a kicker magnet

Extraction kicker magnet:

- wrong pulse strength
- wrong timing

Injection kicker magnet:

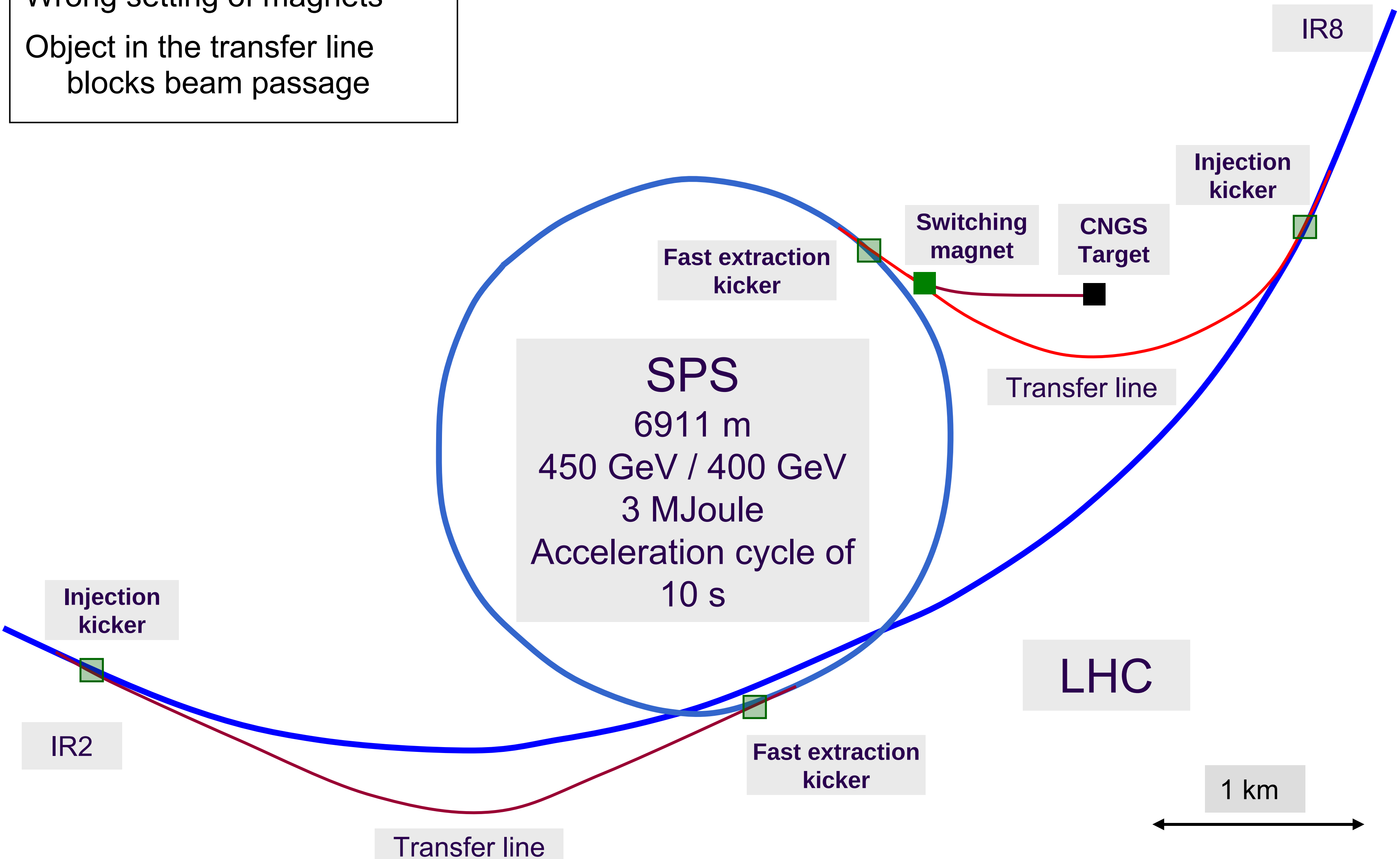
- wrong pulse strength
- wrong timing



Failure in the transfer line (magnet, other element)

Wrong setting of magnets

Object in the transfer line
blocks beam passage



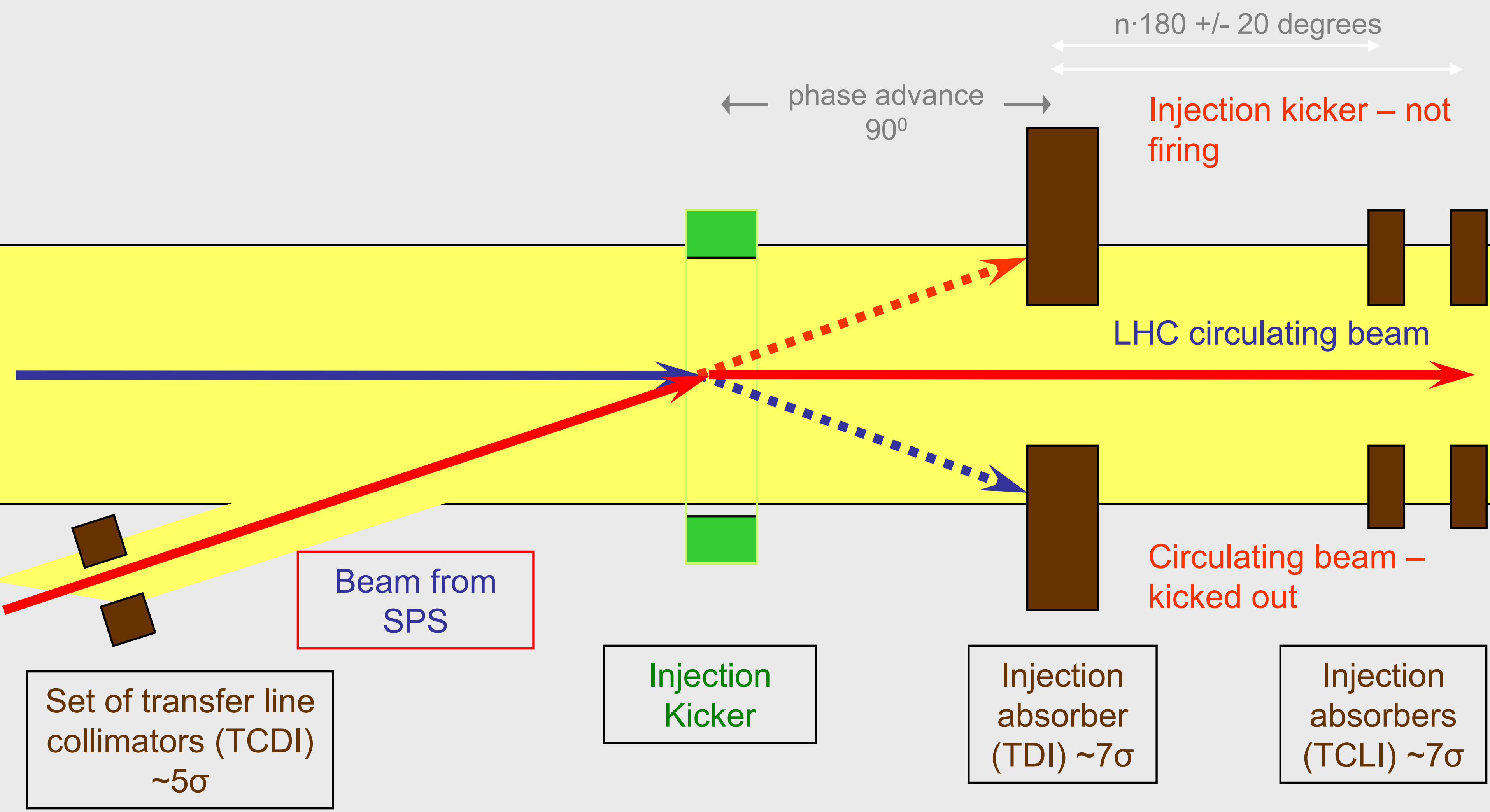
Protection for beam transfer from SPS to LHC

- 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**

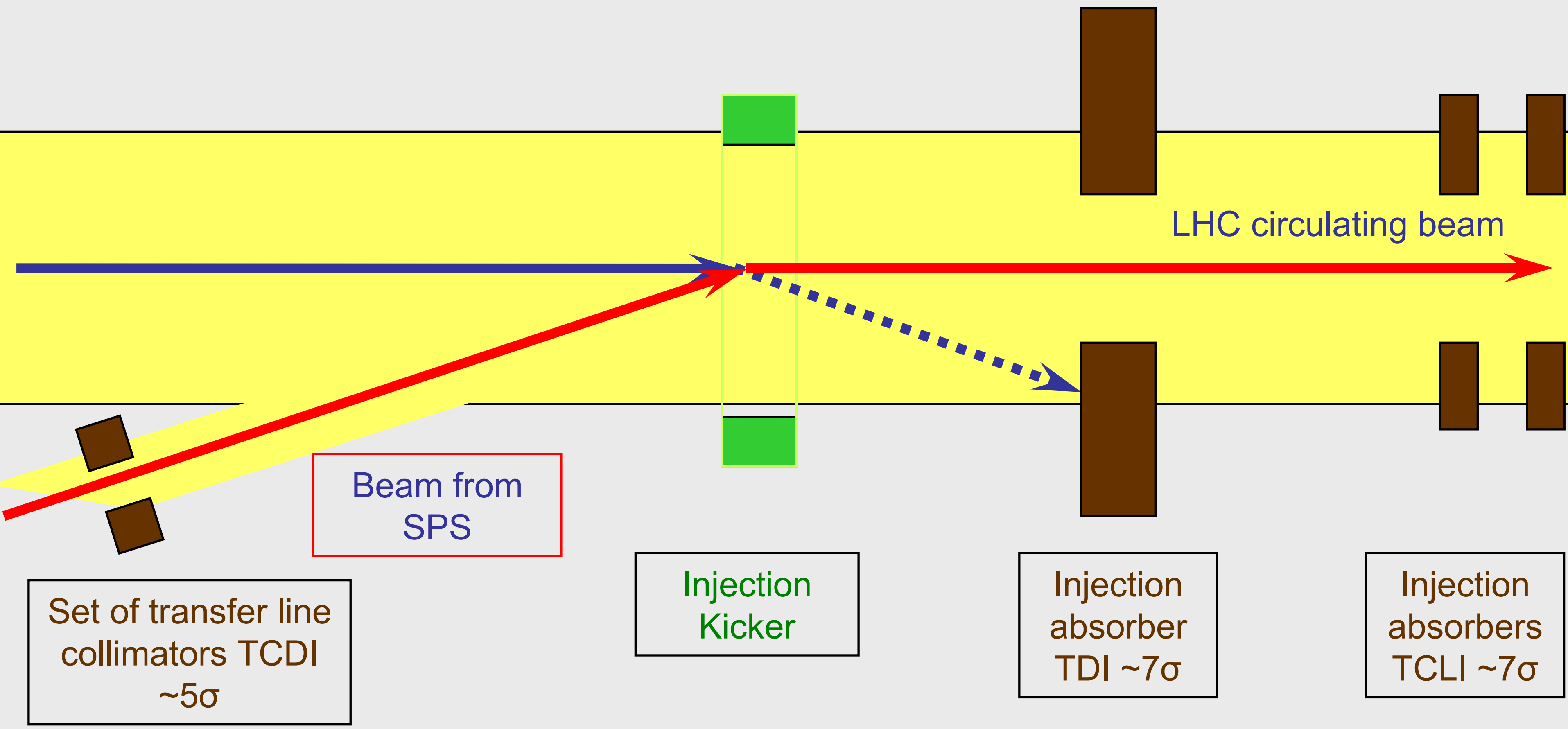
- The kicker must fire at the correct time with the correct strength
- Position of collimators and beam absorbers in SPS, transfer line and LHC injection region to protect from misfiring

Protection in case of kicker misfiring



Beam absorbers take beam in case of kicker misfiring

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

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

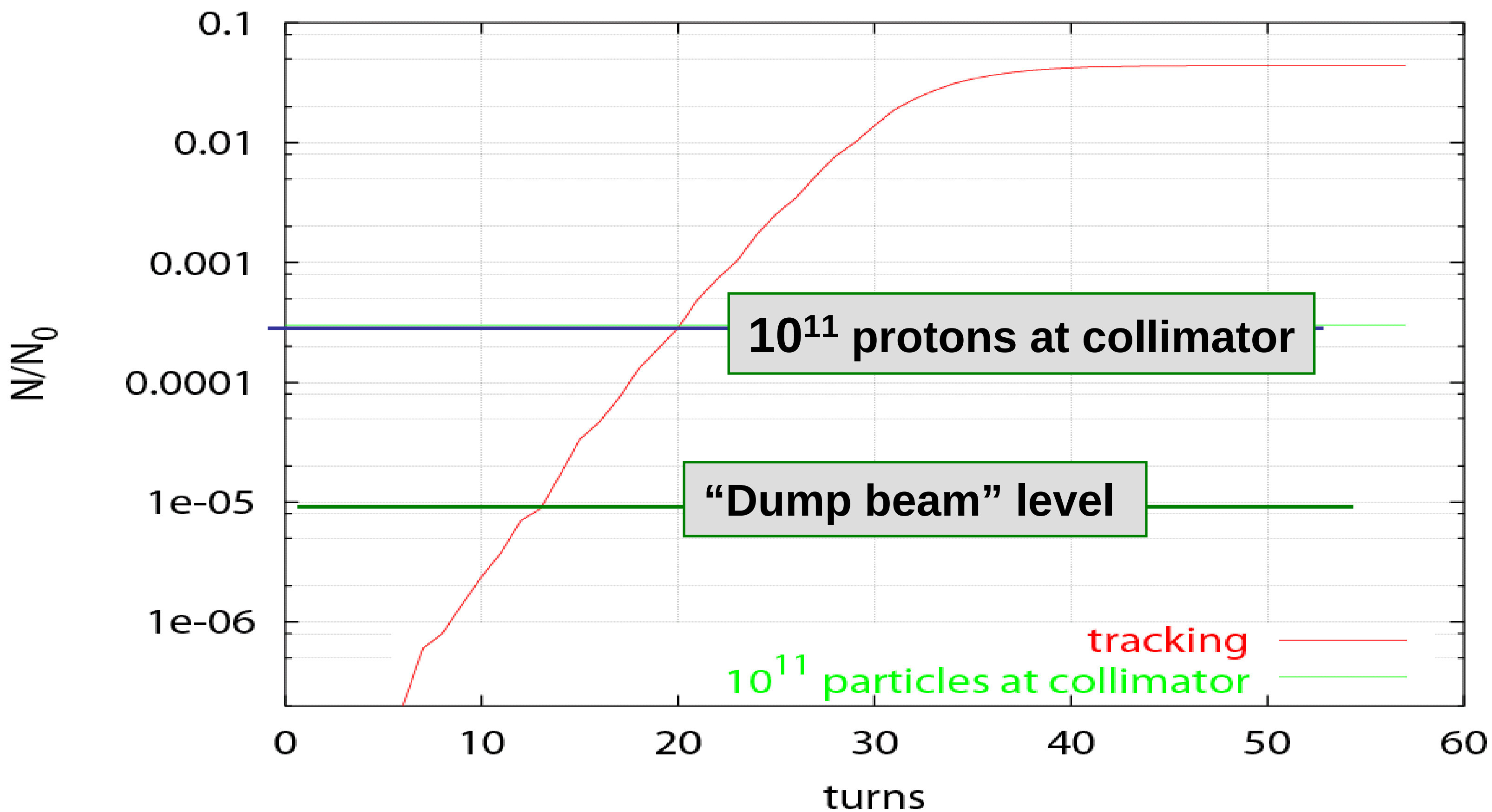
Local orbit bump

- 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

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 !

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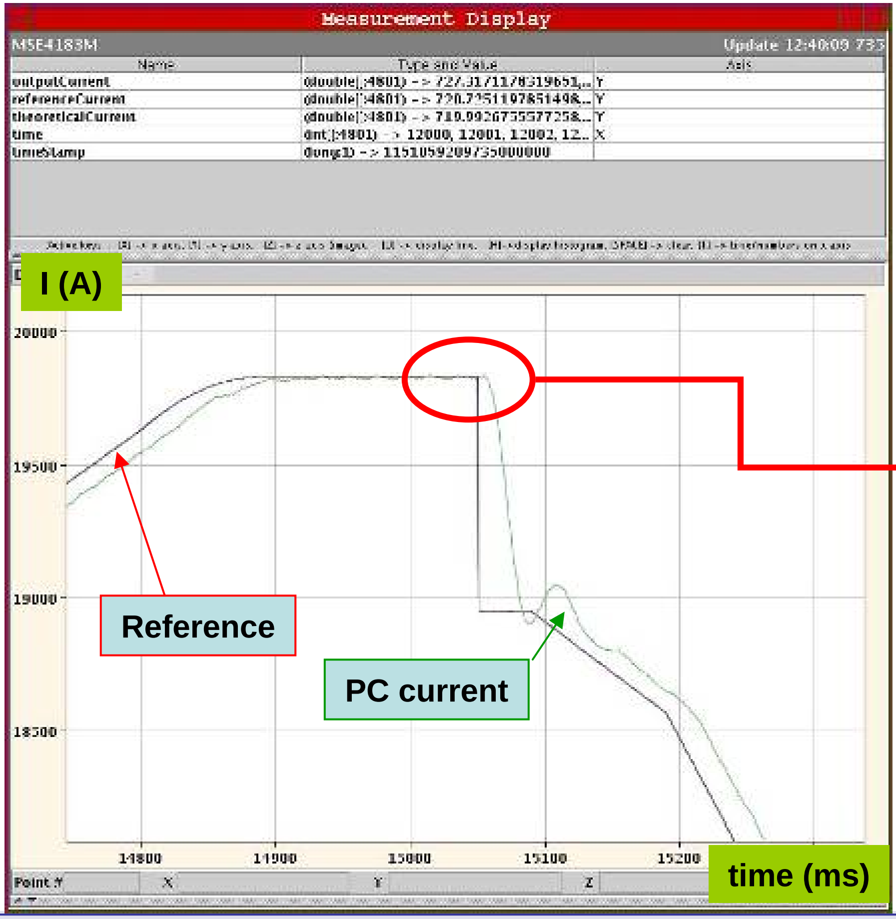
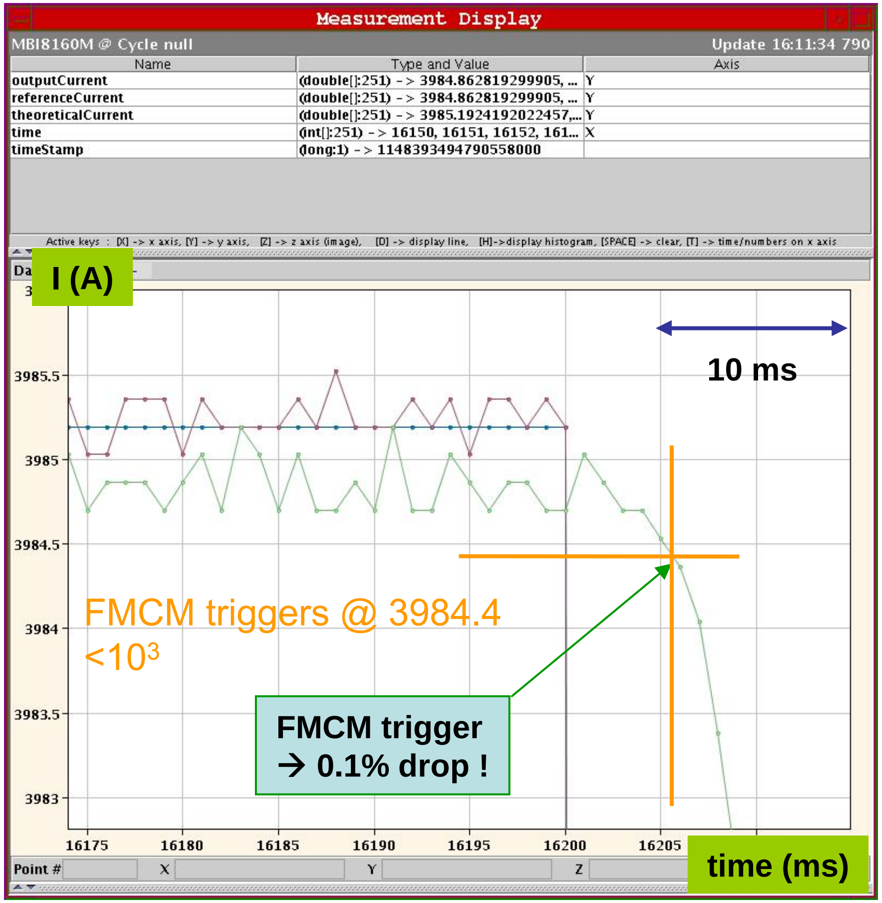
Fast Magnet Current change Monitors

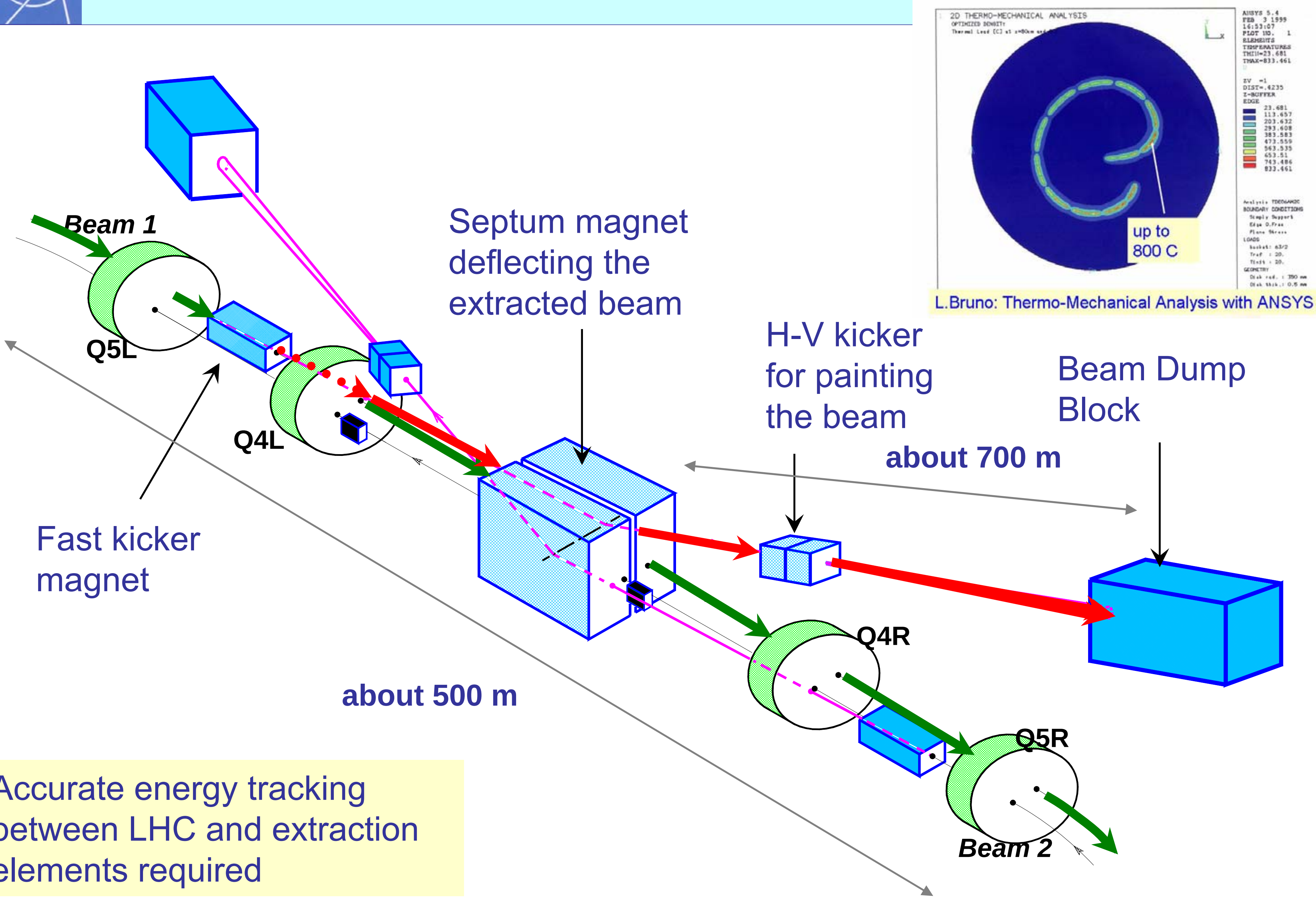
(initial development for HERA, upgrade for LHC in collaboration with DESY)

- 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



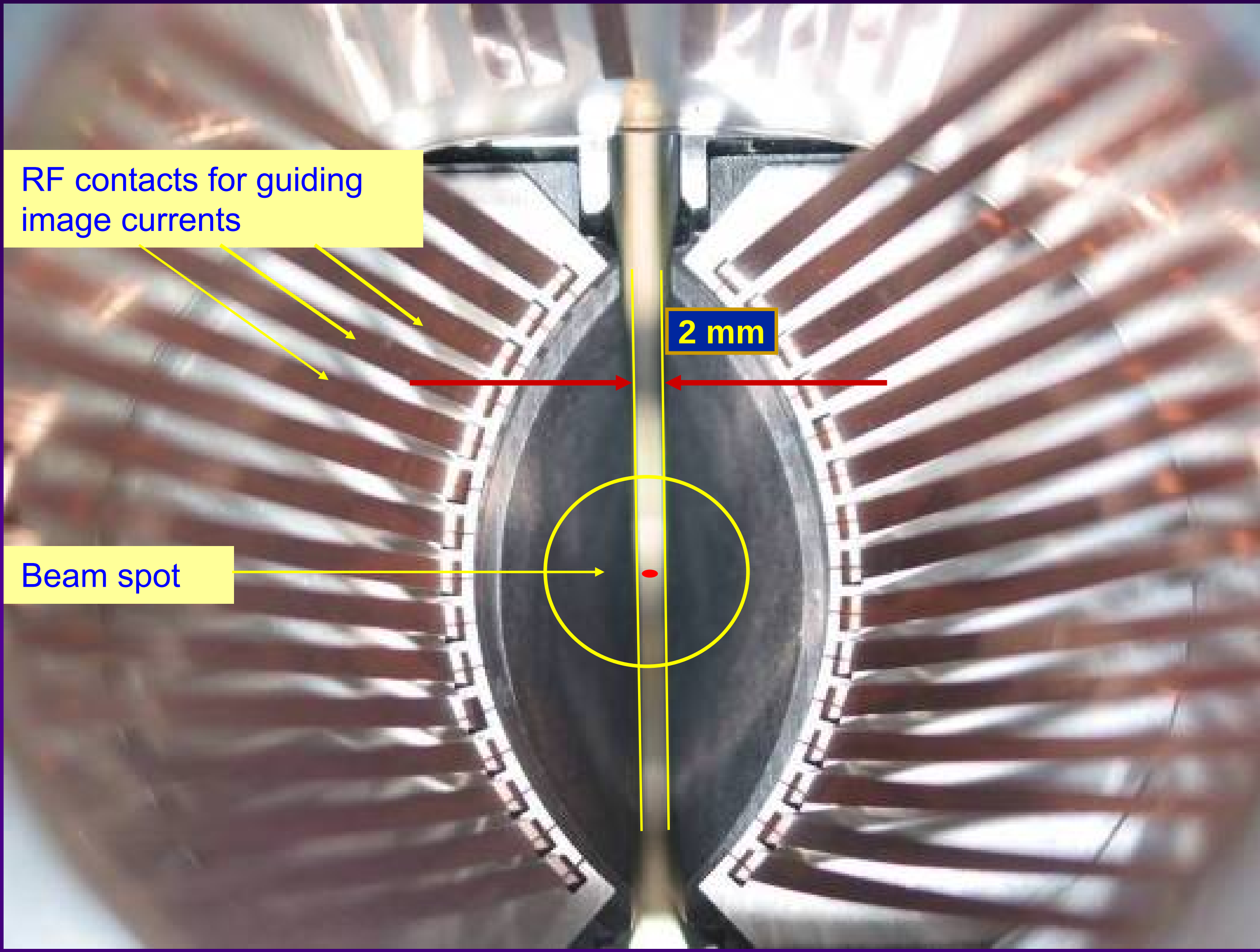


Schematic layout of LHC beam dumping system

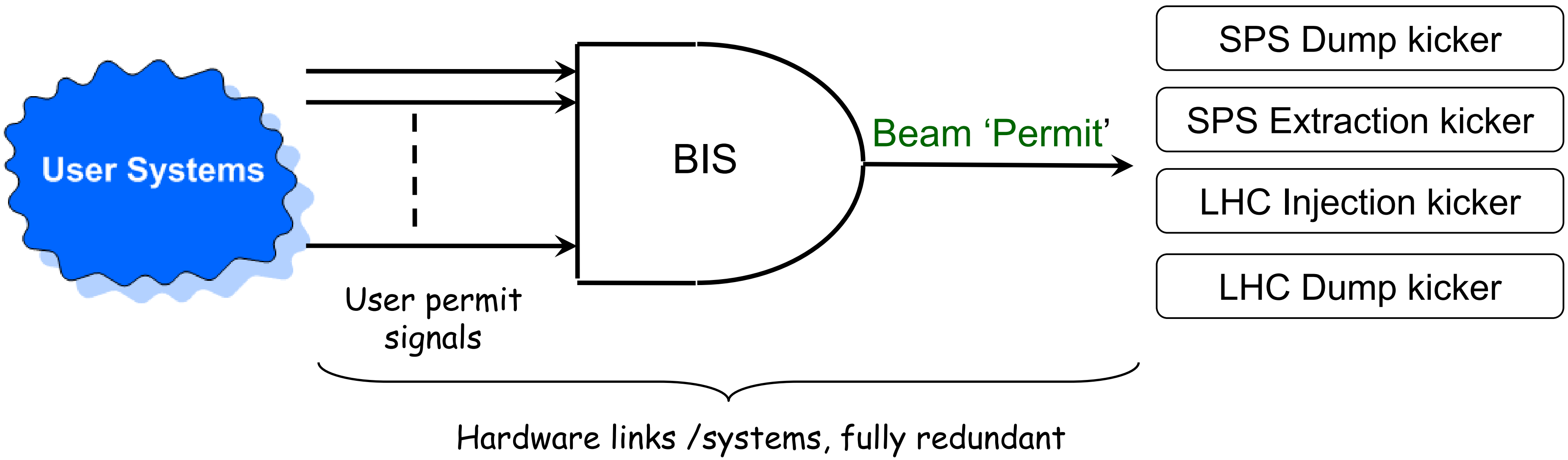


Accurate energy tracking between LHC and extraction elements required

View of a two sided collimator



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 !

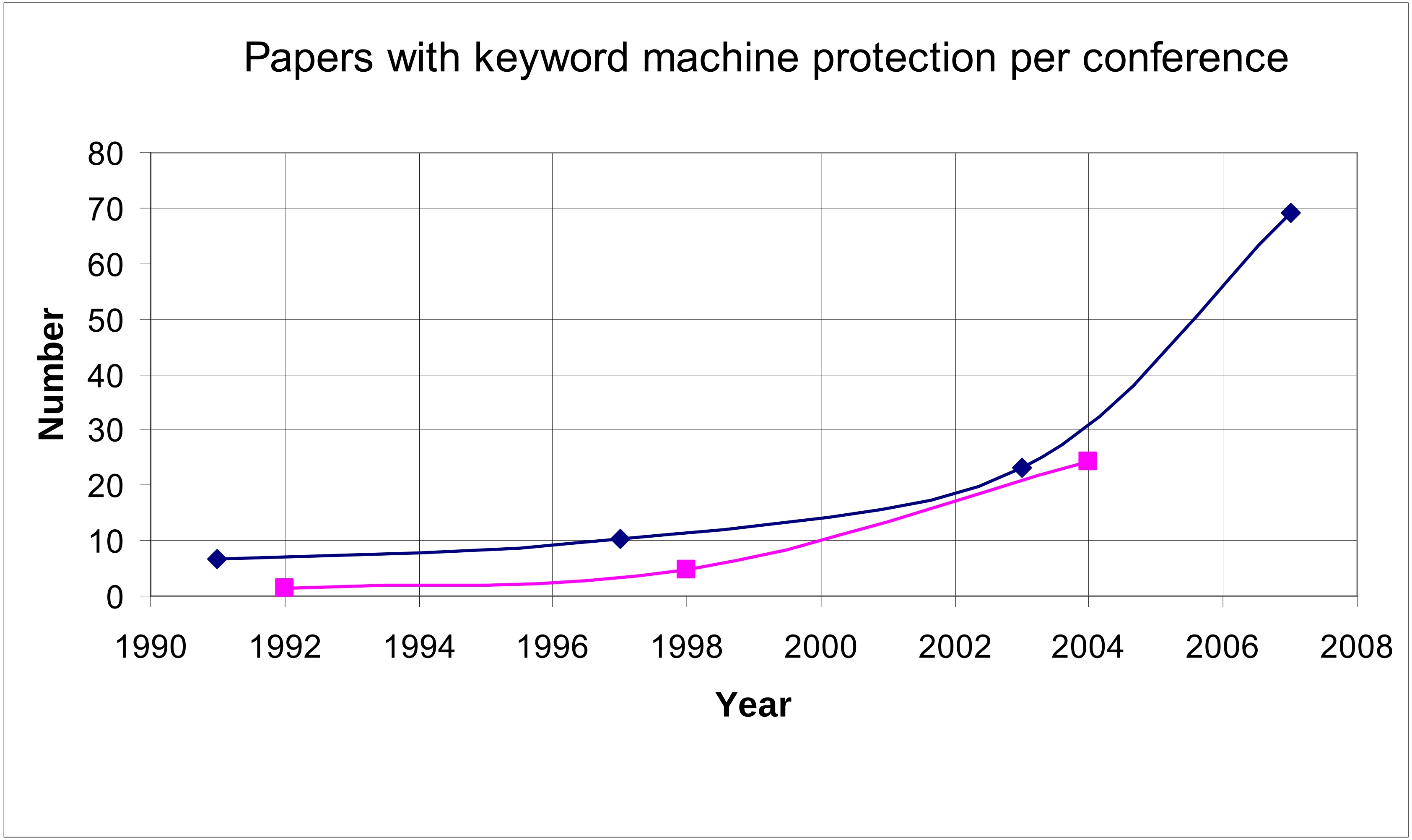
Machine Protection and Controls

- **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

Beam instrumentation wish list

- Very reliable and robust instrumentation (use design principles from design of protection systems, redundancy, fail-safe, quantify reliability)
  - objective is an availability of 99.99% for future projects (required for some projects, e.g. energy amplifier)
  - in particular for Beam Position Monitors, Beam Current Transformers, Beam Loss Monitors
  - in some cases compromises between performance and robustness should be considered
- Very fast beam current change monitor
  - detecting changes of the beam current accurately in a very short time
  - example: 10^{10} protons within one or a few turns for LHC would efficiently protect the accelerator from damage (….and be redundant to 4000 BLMs for protection from damage)

Conference papers on Machine Protection



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

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