Beam Loss and Machine Protection

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GSI Seminar 24/5/2018

DANGER

DO NOT OPERATE THIS MACHINE WITHOUT PROPER PROTECTION

Protection is required if there are risks

What can go wrong?
What are the consequences?
How to prevent accidents?
How to control and operate a particle accelerators in presence of risks?

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 / accident**.
- **Consequences** and **Probability** of a hazard interact together to create **RISK**, can be quantified:

RISK = Consequences · Probability

Related to accelerators

- Consequences of a failure in a hardware systems or uncontrolled beam loss (in €, downtime, radiation dose to people, reputation)
- Probability of such event
- The higher the **RISK**, the more **Protection** needs to be considered

Risk 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
  - Damage of equipment and loss of time for operation
  - For particle beams, activation of equipment
- In particular relevant for complex particle accelerators
  - For equipment, such as **RF system**, **power converters**, **magnet system** …
  - For **particle beams**
- Particle accelerators use large amount of power (few MW to many MW)

Where does the energy go in case of failure?

Risks in many areas of an accelerator complex

- Risks for personnel
  - Electrical, cryogenics, radiation, fire, transport and handling, …
- Risks for the environment
  - Radiation, release of (toxic) gases, fluids (e.g. oil spill), …
- Typical risks as for many technical installations, some examples:
  - Normal conducting magnets (overheating, electrical risks)
  - Power converter (overheating, electrical risks)
  - RF (power flow not as desired)
  - Transport of magnets (several ten tons)

These risks are not discussed here

- see Joint International Accelerator School on "Beam Loss and Accelerator Protection“ http://uspas.fnal.gov/programs/JAS/JAS14.shtml

Here: **Risks when operating with particle beams** (some comments on risks related to superconducting magnets)

Hazards related to particle beams

- **Regular beam losses** during operation
  - To be considered since losses lead to activation of equipment and possibly quenches of superconducting magnets
  - Radiation induced effects in electronics (Single Event Effects)
- **Accidental beam losses** due to failures: understand hazards, e.g. mechanisms for accidental beam losses
  - Hazards becomes accidents due to a failure, machine protection systems mitigate the consequences
- Understand interaction of particle beams with the environment
  - Heating, activation, mechanical damage,…
- Understand mechanisms for damage of components
- Understand effects from electromagnetic fields and synchrotron radiation that potentially lead to damage of equipment

Not new: Machine Protection 50 years ago

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, JUNE 1967

THE SLAC LONG ION CHAMBER SYSTEM FOR MACHINE PROTECTION*

Max Fishman and Daryl Reagan
Stanford Linear Accelerator Center, Stanford University, Stanford, California

Introduction

If missteered at high power, the SLAC electron beam can cause local melting of accelerator components in a fraction of a second. Even relatively low level irradiation of the accelerator waveguide will cause harm, gradually changing critical dimensions by altering the crystal structure of the copper. To protect the accelerator, a system has been installed which is based upon a single long ion chamber[1] that runs the whole 3 km length of the accelerator housing. The signal from the ion chamber operates equipment that turns off the beam when any local radiation level becomes too high.

Energy and Power for particle beams

Many accelerators operate with high beam intensity and/or high particle energy

Energy in beam: $E_{beam} = N \cdot E_{particle}$

Beam power: $P_{beam} = \frac{N \cdot E_{particle}}{\Delta T}$

- For **synchrotrons and storage rings**, the energy stored in the beam increased over the years (at GSI, from SIS18 to SIS100)
- For **linear accelerators and fast cycling machines**, the beam power increased
- For **some accelerators**, the emittance becomes smaller (down to nm for ILC), very high power / energy density (W/mm^2 or J/mm^2)
- Even **small amount of energy** can lead to **some (limited) damage** - can be an issue for sensitive equipment (e.g. physics experiments and particle detectors)

Energy in the LHC collider

Nominal energy per proton is 7 TeV

Very high luminosity

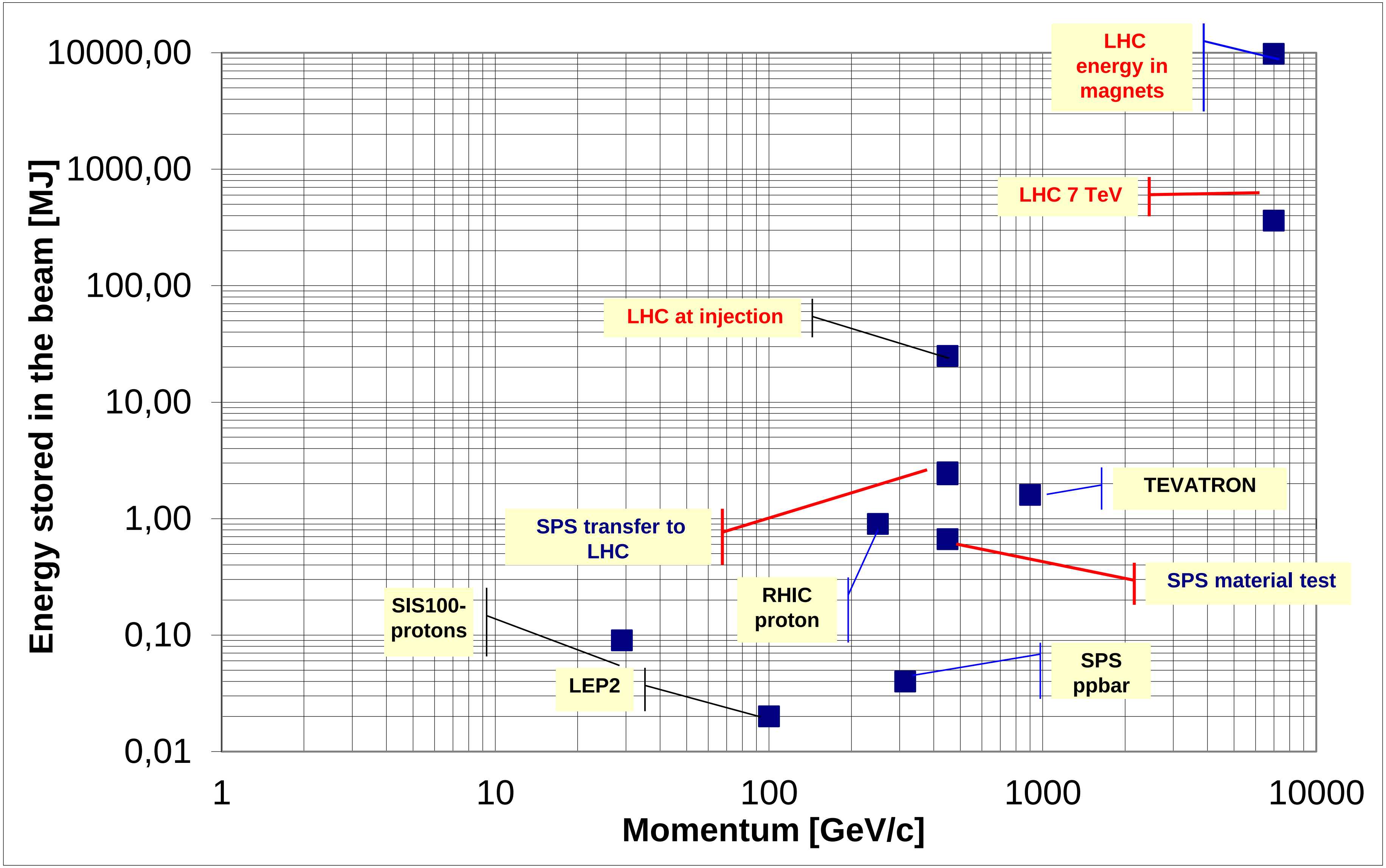
Many many many many protons (about $3 \cdot 10^{14}$ in each beam)

Energy in beam = Number of protons · Proton energy

Superconducting magnets

Energy in magnets $\simeq \boldsymbol{B^2 \cdot V}$

Energy stored in beam and magnets



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

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

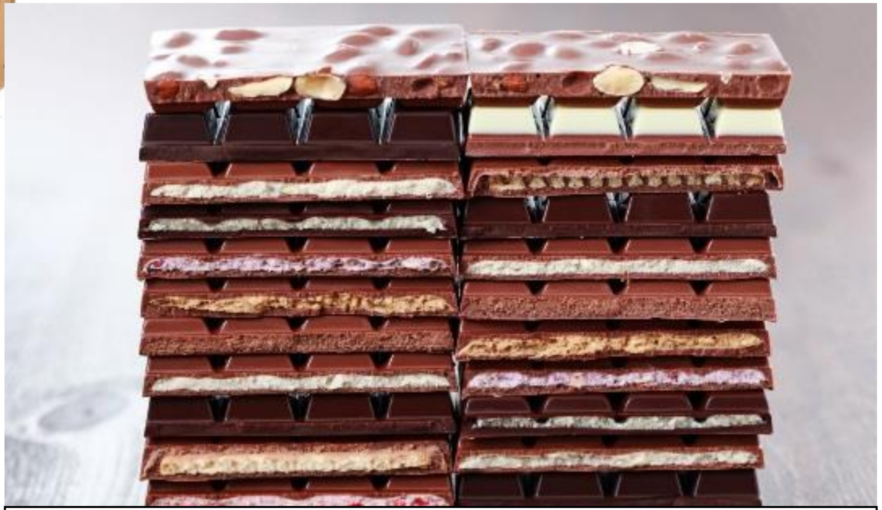
- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

It matters most how easy and fast the energy is released !!

……the LHC magnets

The energy stored in the LHC dipole magnets of 9 GJ corresponds to the energy of 2000 kg TNT

Airbus A330 at 700 km/h



450 kg of chocolate

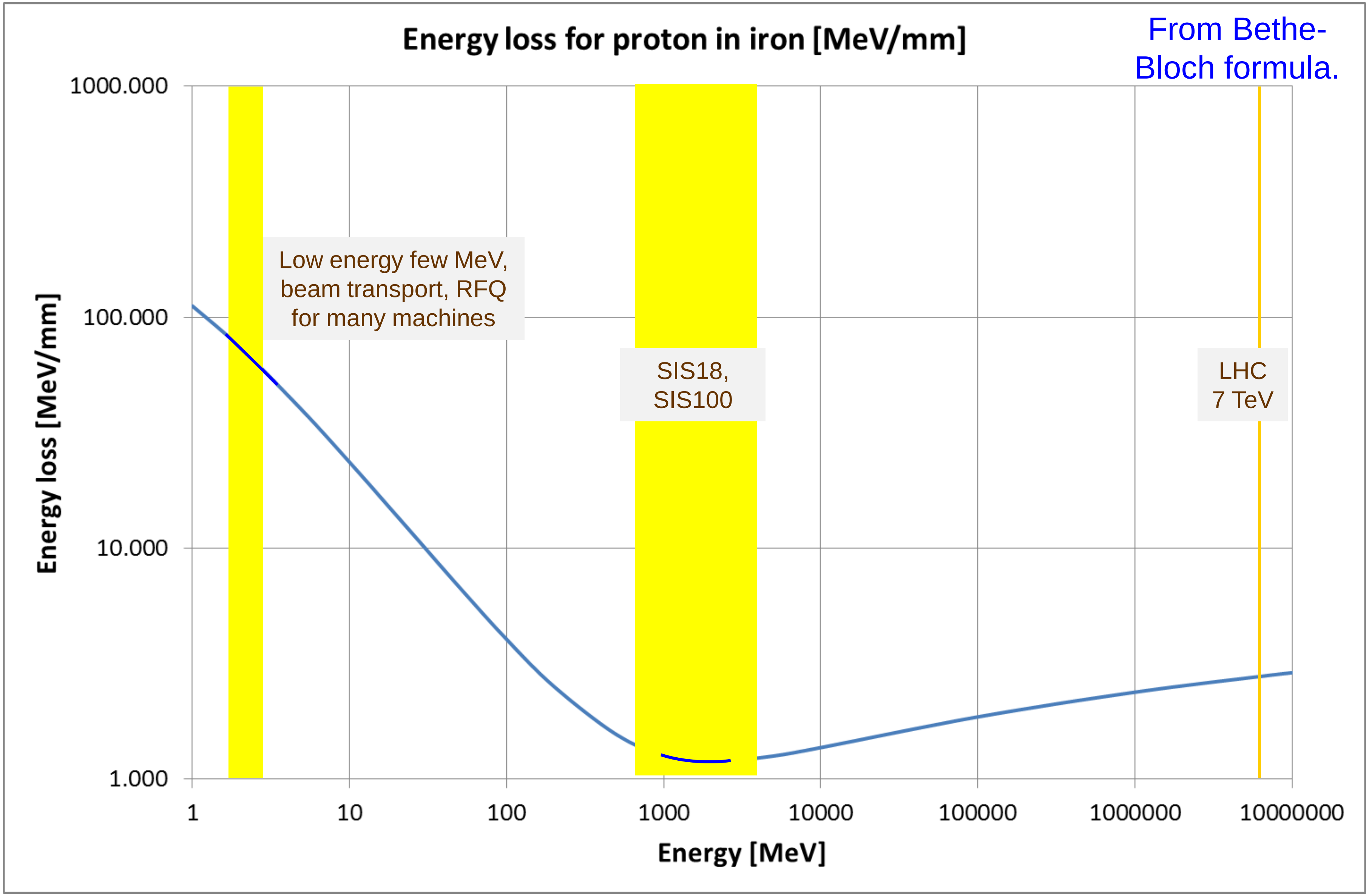
(Accidental) beam loss and consequences

Beam losses and consequences

- Charged particles moving through matter: interaction with electrons of atoms in the material, exciting or ionizing the atoms => **energy loss** is described by **Bethe-Bloch formula**.
- If the particle energy is high enough, particle collisions lead to **particle cascades**, 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 less than one kJ, risk for damage of any structure for some MJ (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

Ionisation energy loss for one proton in iron

(stainless steel, copper very similar)

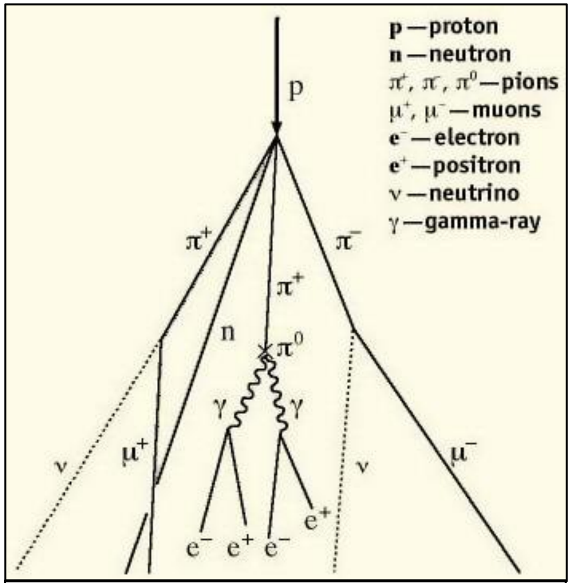


Heating of material with high energy protons

Nuclear inelastic interactions (hadronic shower)

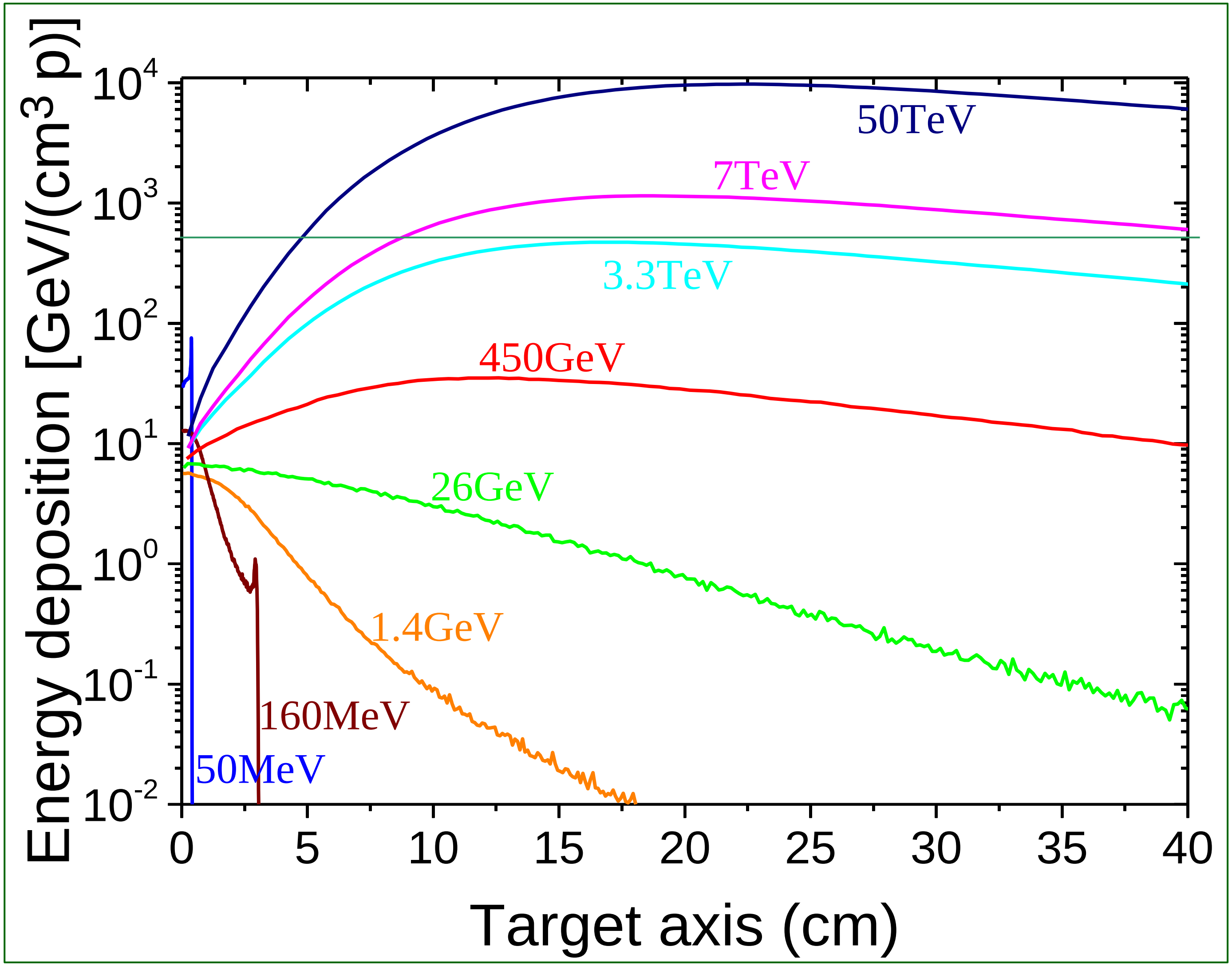
- Creation of pions when going through matter
- Causes electromagnetic shower through decays of pions
- Exponential increase in number of created particles
- Final energy deposition to large fraction done by large number of electromagnetic particles
- Scales roughly with total energy of incident particle
- 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 simulation codes, such as FLUKA, GEANT or MARS



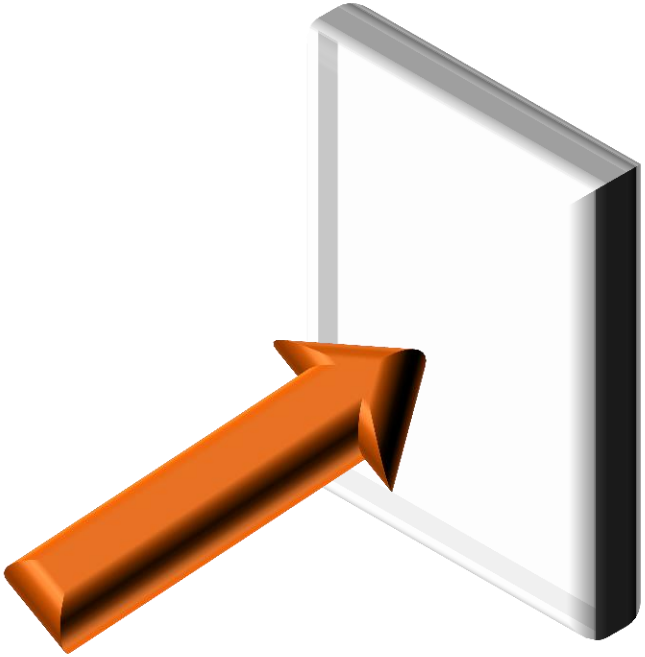
http://williamson-labs.com/ltoc/cbr-tech.htm

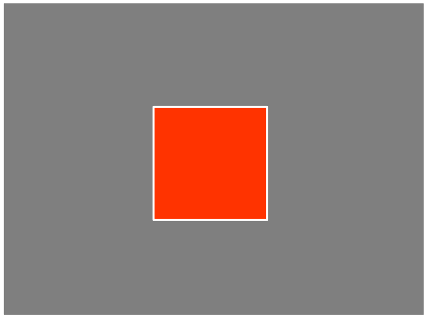
Energy loss of a proton shower in copper



Y.Nie (CERN), V.Chetvertkova (GSI) et al. published in PRAB

Beam losses in a thin window





- 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

Beam losses and consequences at 7 TeV

Maximum energy deposition for one proton in copper: $E_{maxCu} = 1.5 \cdot 10^{-5}\, J/kg$

Specific heat of copper: $c_{Cu\_spec} = 384.6 \frac{J}{kg \cdot K}$

Energy to heat 1 kg of copper by $\Delta T = 500\ {}^{0}K$

$$c_{Cu\_spec} \cdot \Delta T \cdot 1\, kg = 1.92 \cdot 10^{5}\, Joule$$

Number of protons required to deposit this energy in copper:

$$(c_{Cu\_spec} \cdot \Delta T)/E_{maxCu} = 1.28 \cdot 10^{10}$$

For graphite: $E_{maxC} = 2.0 \cdot 10^{-6}\, J/kg$ $\quad c_{C\_spec} = 710.6 \frac{J}{kg \cdot K}$

Number of protons required to deposit this energy in carbon:

$$(c_{C\_spec} \cdot \Delta T)/E_{maxC} = 5.33 \cdot 10^{11}$$

Heating of material with low energy protons
(Iron 3 MeV, thin window)

Temperature increase in the material: $dT = (N_p \cdot dEdx)/(c_p \cdot F_{beam} \cdot \rho)$

Assume beam size with $\sigma_h = 1mm$ and $\sigma_v = 1mm$

Assume iron with the specific heat of $c_p = 440 \frac{J}{kg \cdot K}$

Assume iron with the specific weight of $\rho = 7860\ kg/m^3$

Energy loss per proton and mm: $dEdx = 59.7\ \frac{MeV}{mm}$

Number of protons : $1.16 \cdot 10^{12}$

Energy of protons : $3\ MeV$

Temperature increase: $dT = 763\ K$

Example for FRIB at MSU for uranium beams

Proceedings of SRF2011, Chicago, IL USA

ANALYSIS OF BEAM DAMAGE TO FRIB DRIVER LINAC*

Y. Zhang#, D. Stout, J. Wei, Facility for Rare Isotope Beams (FRIB),
Michigan State University, East Lansing, MI 48824, USA

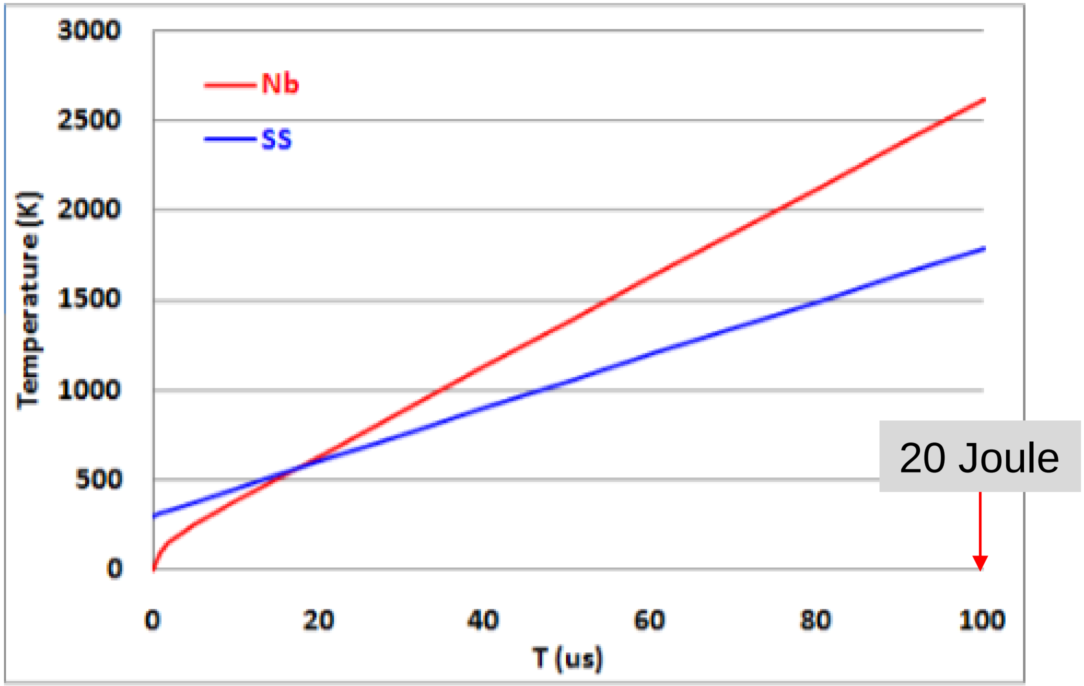


Fig. 1: Temperature vs. time of stainless steel (SS) from 300K, and niobium (Nb) from 2K, after hit by a uranium beam, 100 MeV/u, 200 kW, and beam rms radius 1 mm.

1 us = 0.2 Joule

Beam losses and consequences

- Calculate material response (deformation, melting, …) with mechanical codes (ANSYS, hydrodynamic codes such as BIG2..)
- Beams at very low energy have limited power/energy…. however, the energy deposition per particle 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
- Energy deposition of ion beams can be very large
- Beams at very high energy can have a tremendous damage potential
  - for LHC, damage of metals for ~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, possibly damage beyond repair

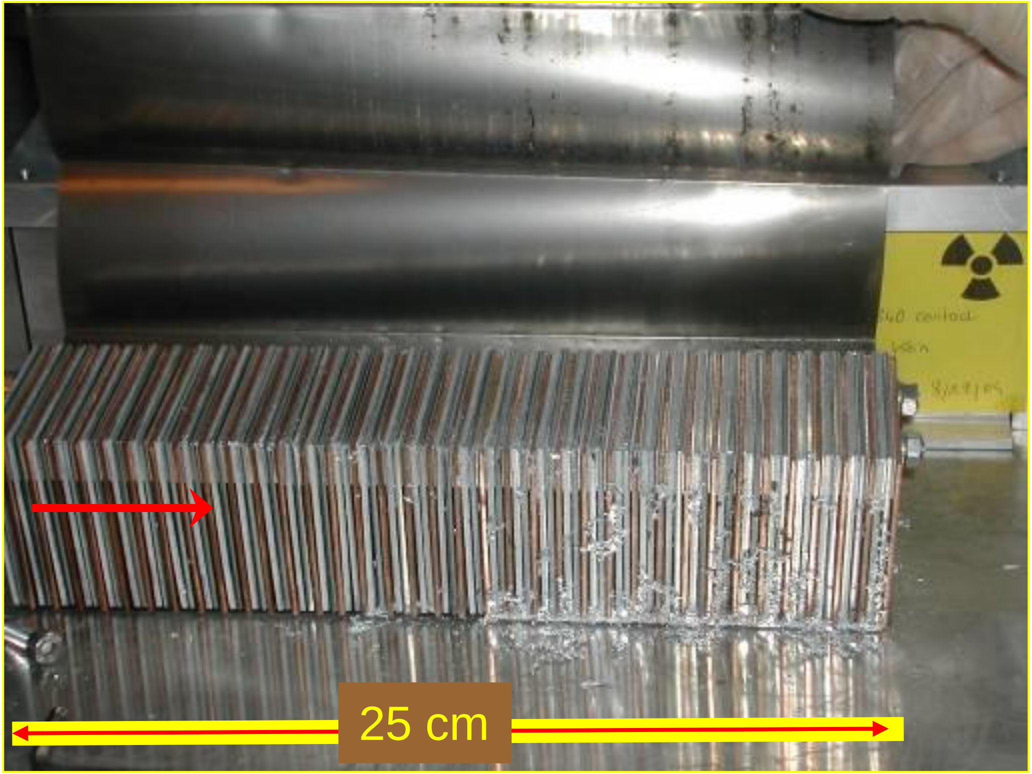
SPS experiment: Beam damage with 450 GeV protons

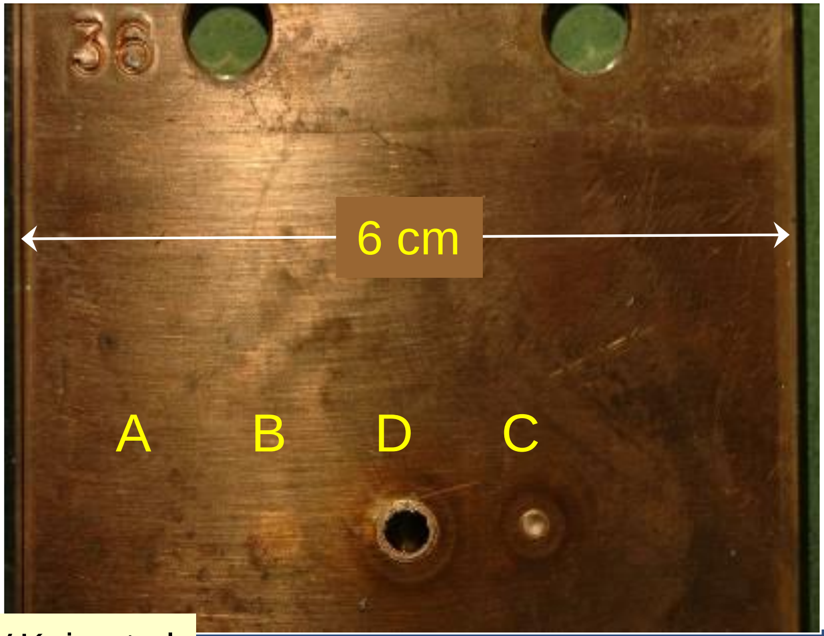
Controlled SPS experiment

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

stainless steel no damage

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

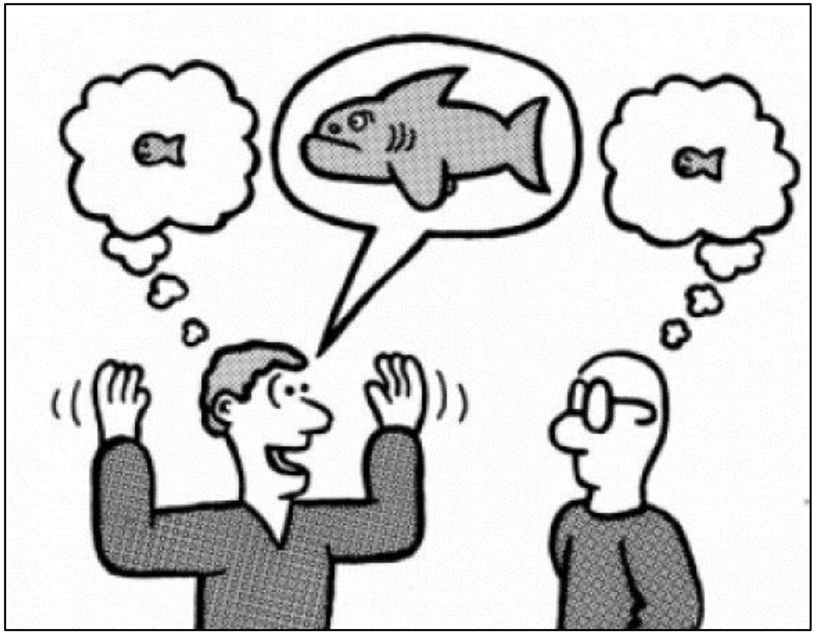




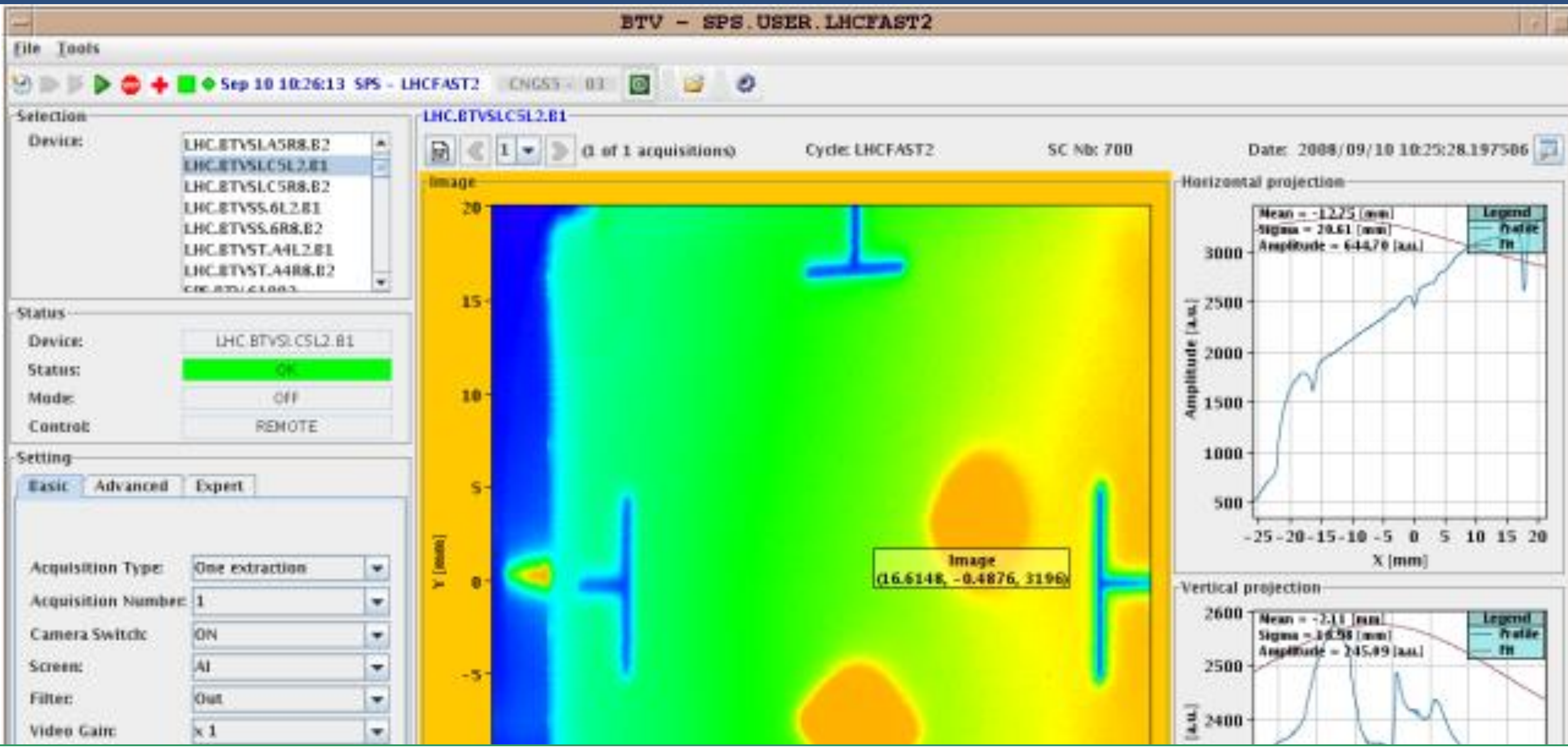
- 0.1 % of the full LHC 7 TeV beams
- factor of three below the energy in a bunch train injected into LHC
- damage (melting) limit ~200 kJoule

V.Kain et al

"…..do not exaggerate -
large accelerators are operating since many years without accidents……."



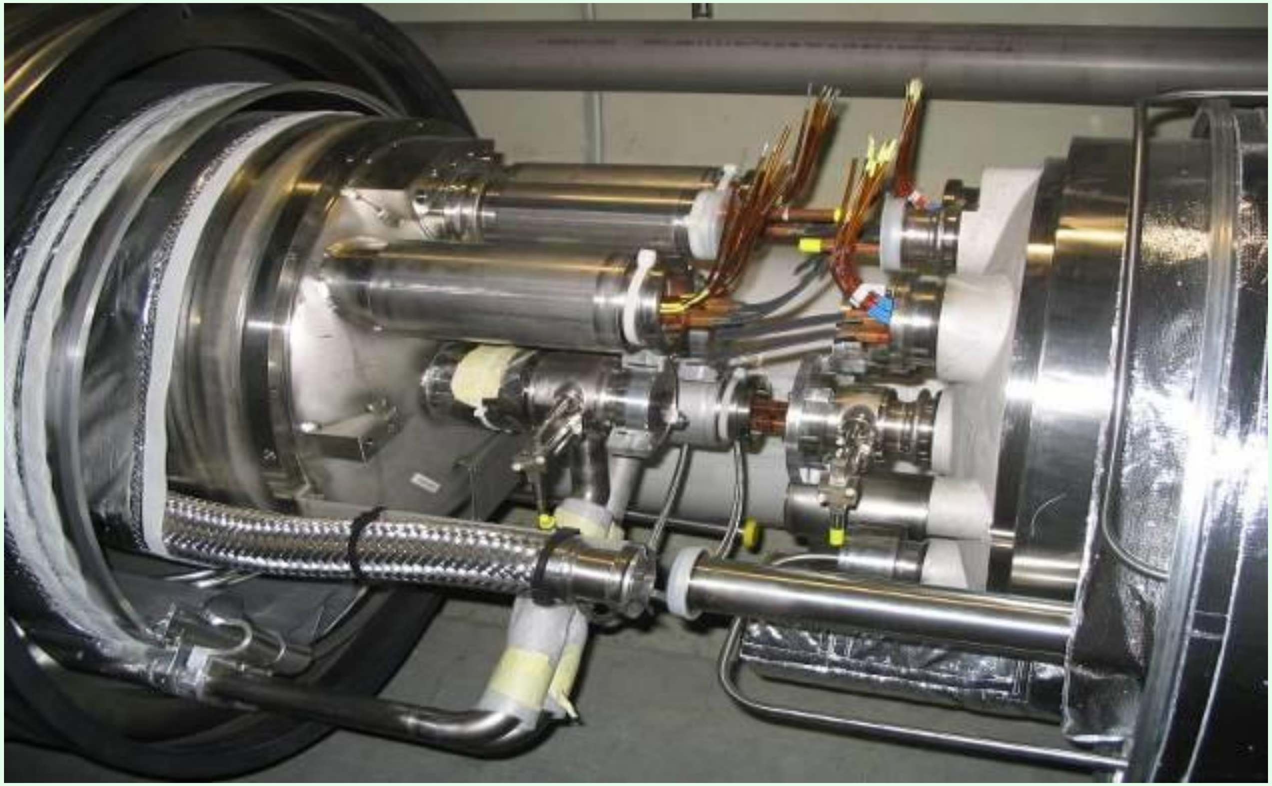
LHC on 10 September 2008: Success!



Unfortunately, nine days later...

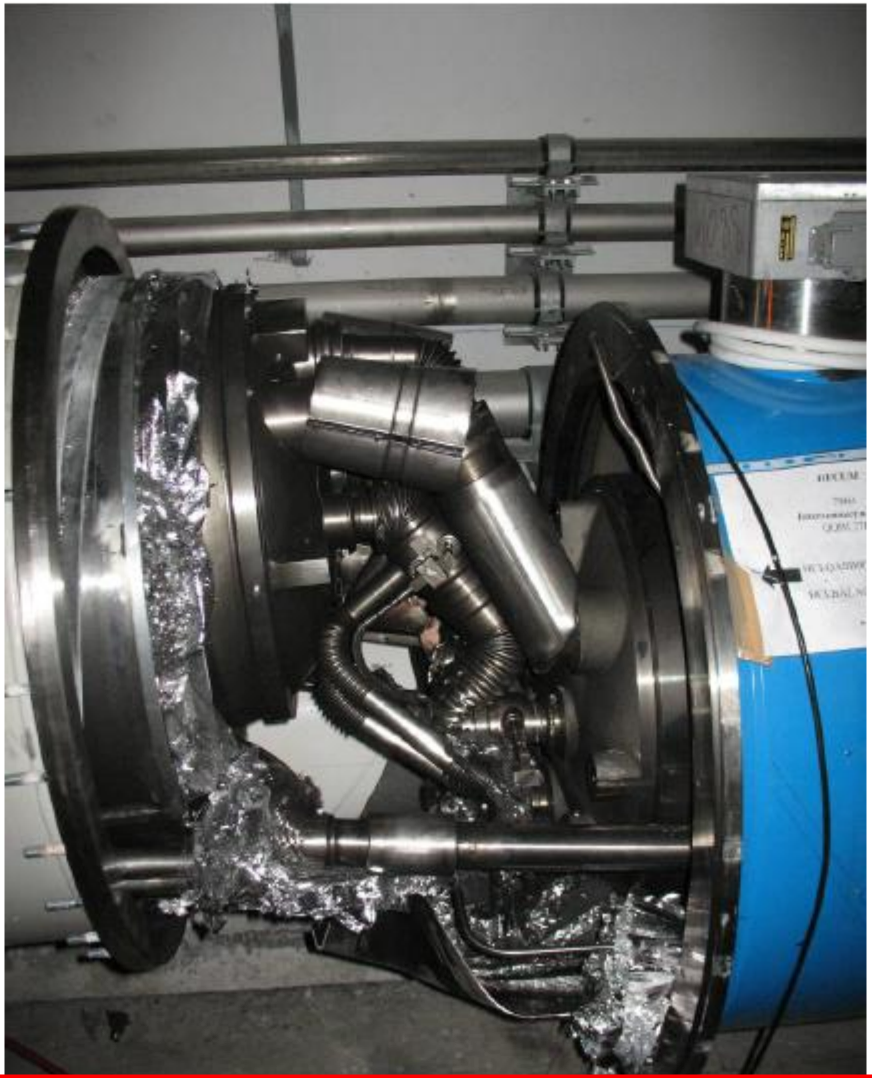
The incident of 19 September 2008

- **10000** high current superconducting **cable joints** – all soldered in situ in the tunnel and **one** of these connections was **defective**



One joint ruptured, with 600 MJ stored in the magnets – 70% of this energy was dissipated in the tunnel, electric arcs, vaporizing material, and moving magnets around

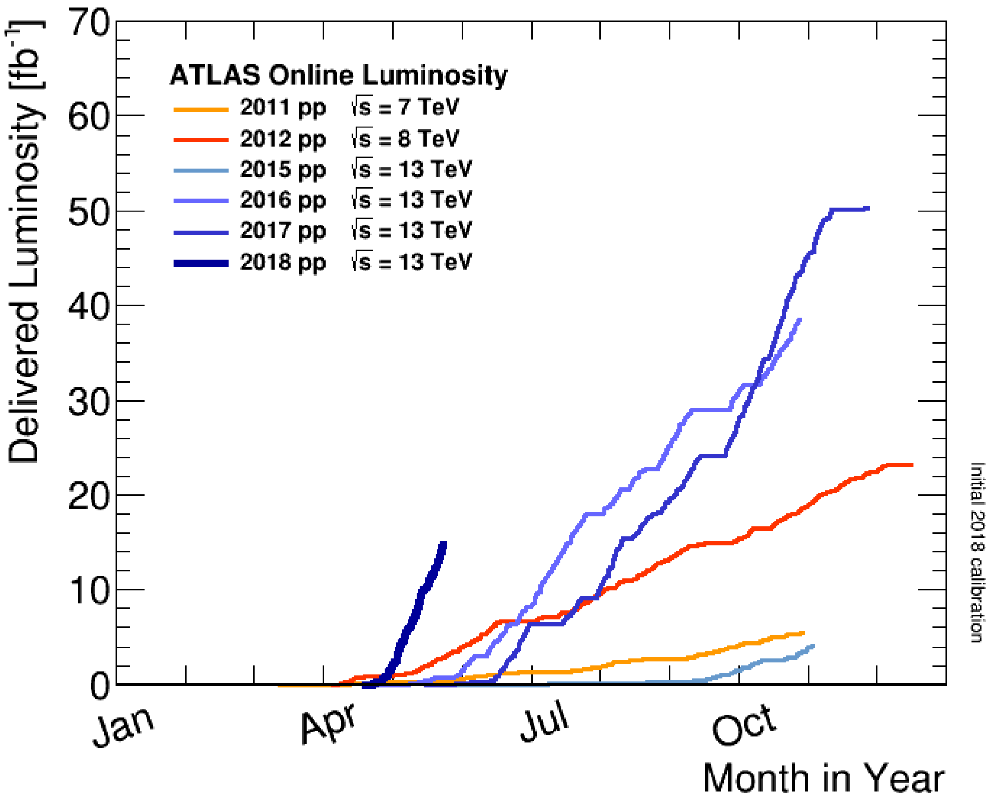
Remark: do not need beam to cause damage…
…..LHC after the 2008 accident



Accidental release of an energy of 600 MJoule stored in the magnet system - no beam – watch out!

Recovery from the accident

- Damage has a large impact on the availability of an accelerator
- For the LHC, it took a long time (about one year) to repair the magnets
- A new protection layer for superconducting magnets and bus-bars was installed
- Energy was limited to 3.5 TeV
- Re-start about 1 year later
- During a two years shut-down 2013-2014 the interconnects were repaired
- Now operating at 6.5 TeV

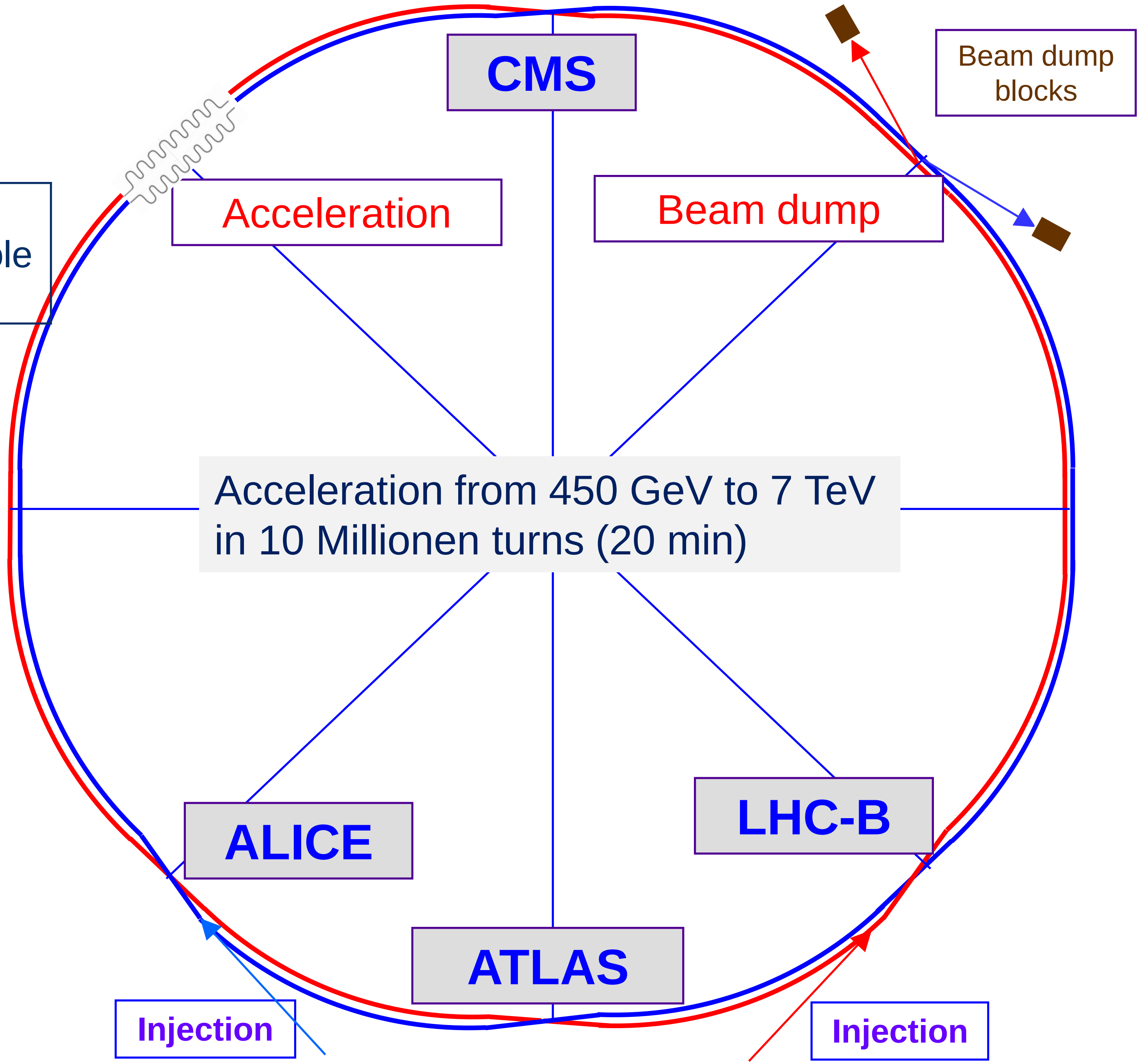


Performance is excellent

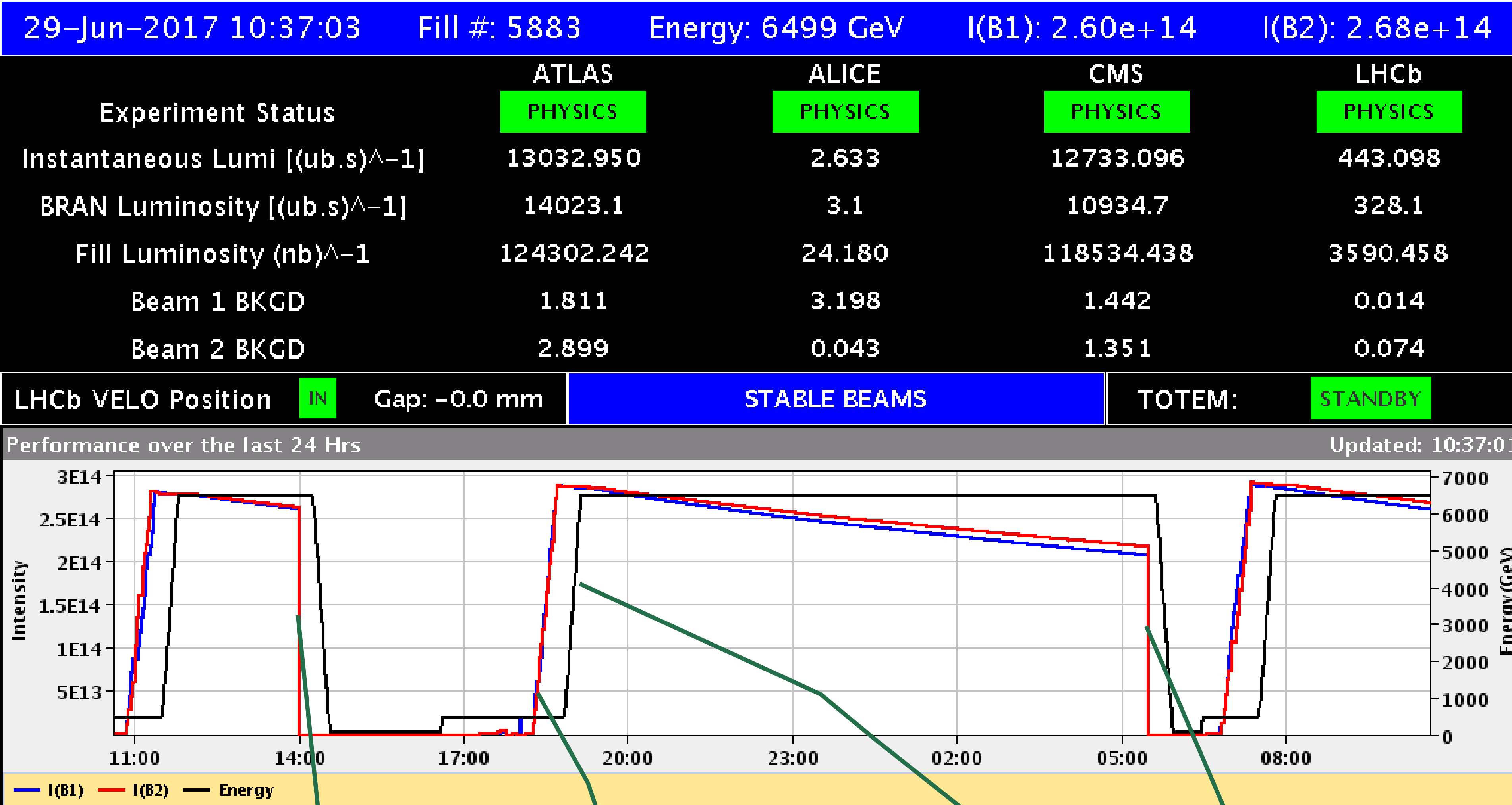
Machine Protection in a Synchrotron

LHC

In the arcs:
1232 deflecting dipole magnets



- 27 km
- 2 beams
- 11246 turns/ second
- 8 arcs
- 8 straight sections



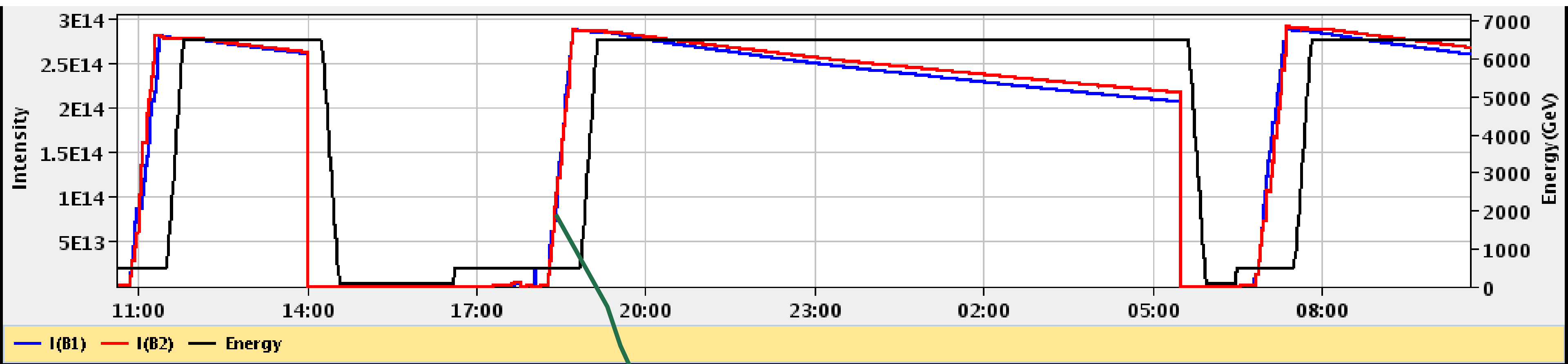
Failure: what to do with 290 MJ ?

Injection of 9 * 288 bunches = 9 *2.5 MJ

Ramp from 450 GeV to 6.5 TeV => total energy for each beam is 290 MJ

End of the fill: what to do with the beams?

Machine Protection at Injection



Injection of 9 * 288 bunches = 9 *2.5 MJ

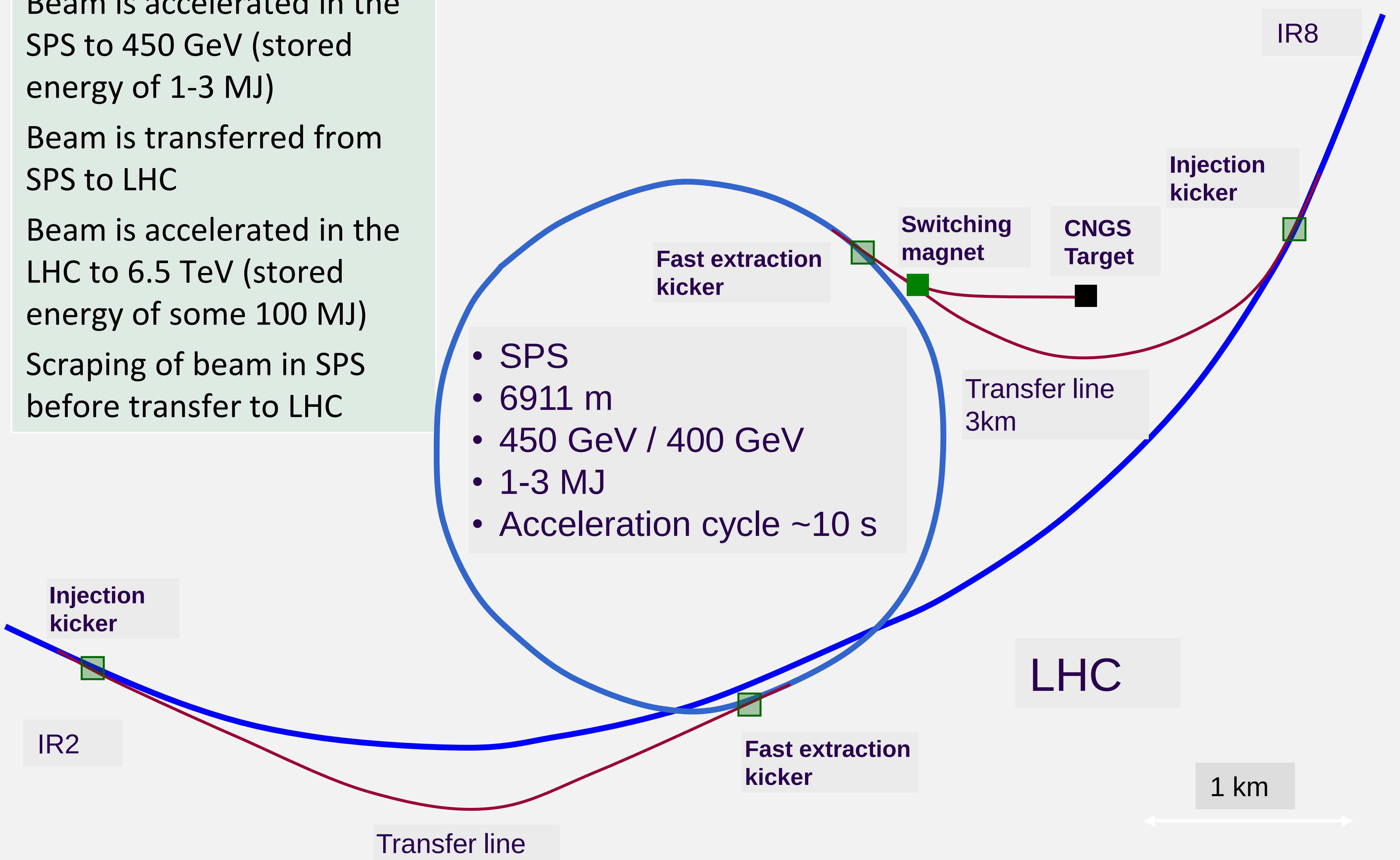
SPS, transfer line and LHC

Beam is accelerated in the SPS to 450 GeV (stored energy of 1-3 MJ)

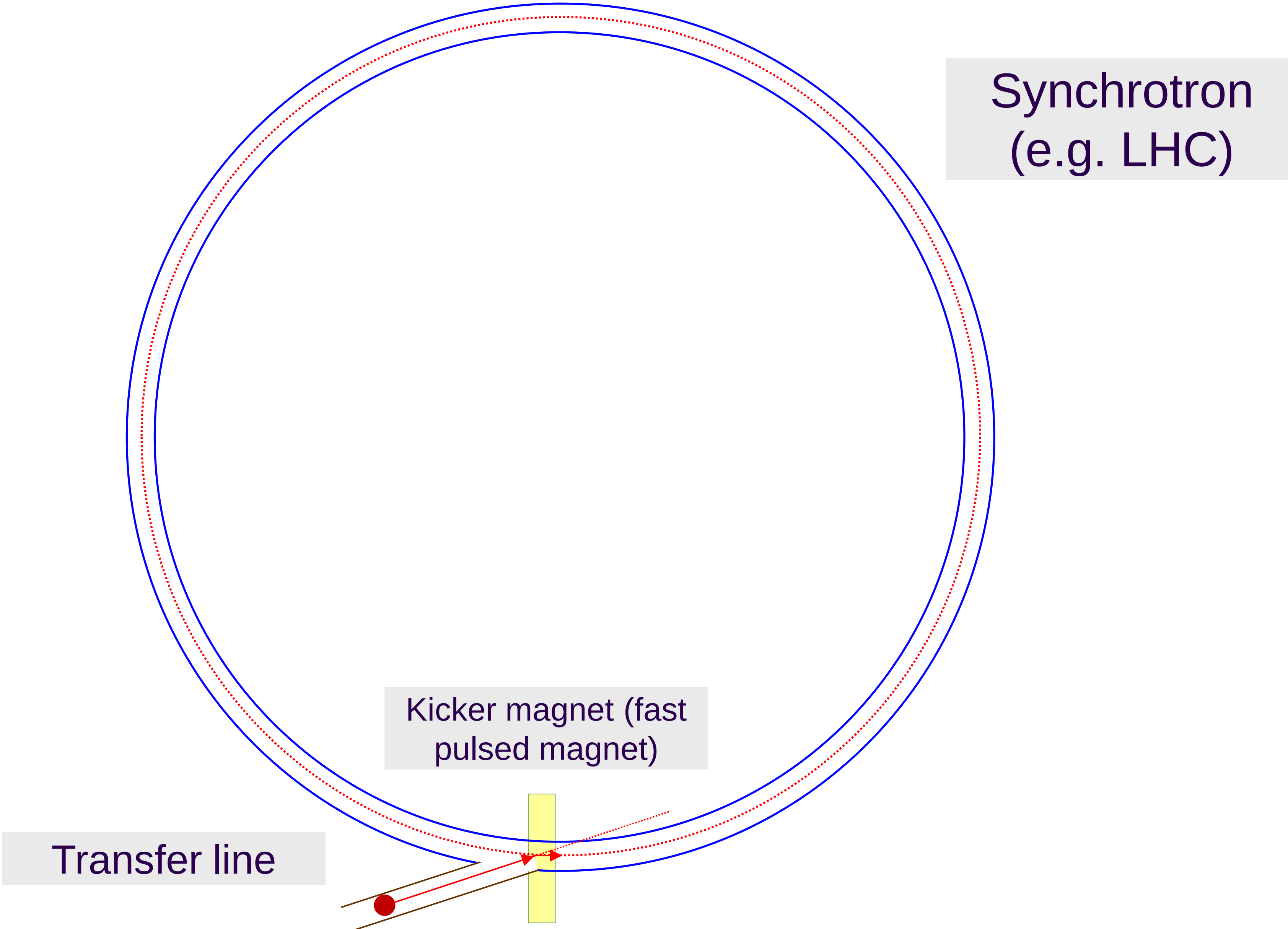
Beam is transferred from SPS to LHC

Beam is accelerated in the LHC to 6.5 TeV (stored energy of some 100 MJ)

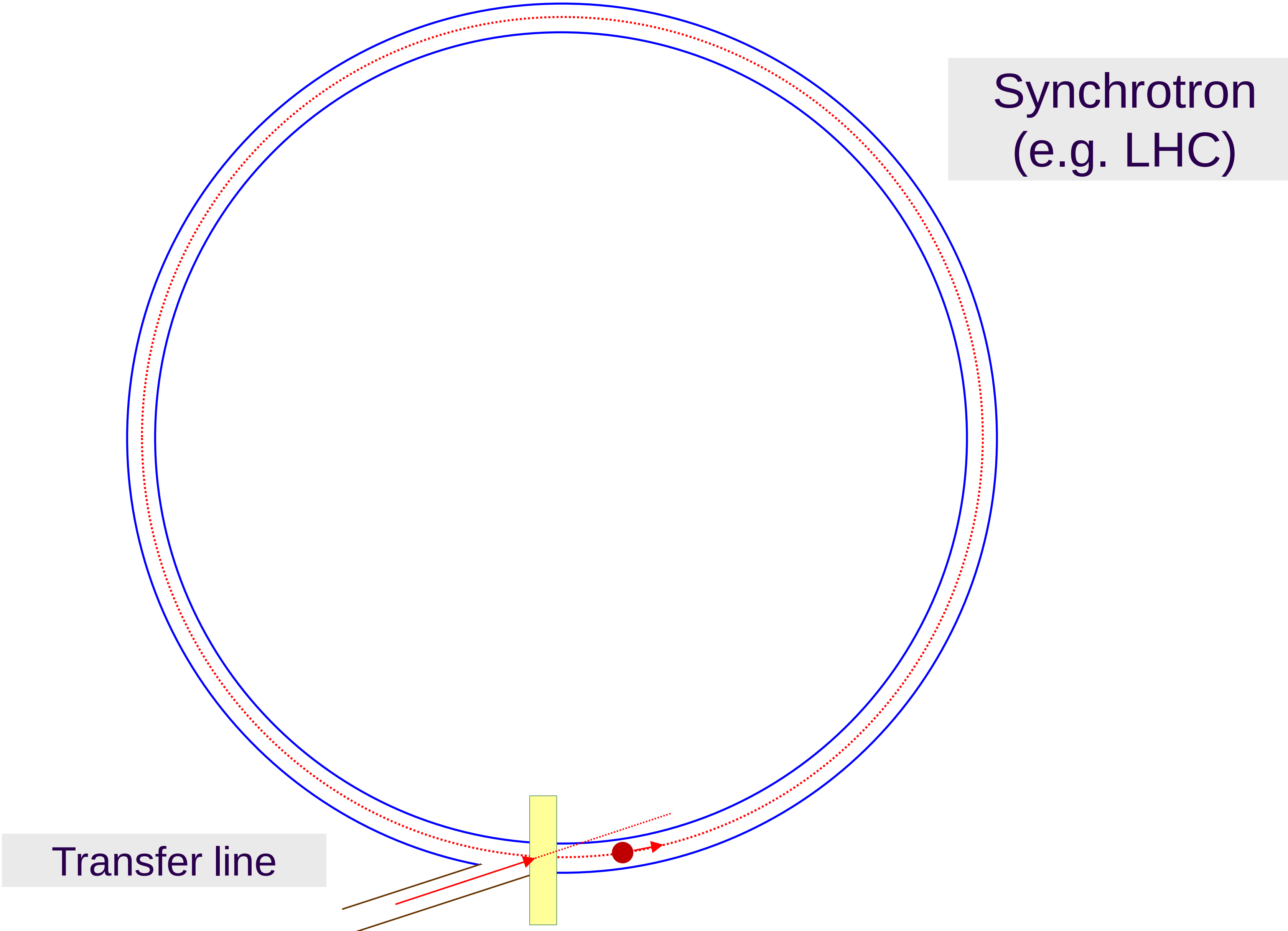
Scraping of beam in SPS before transfer to LHC



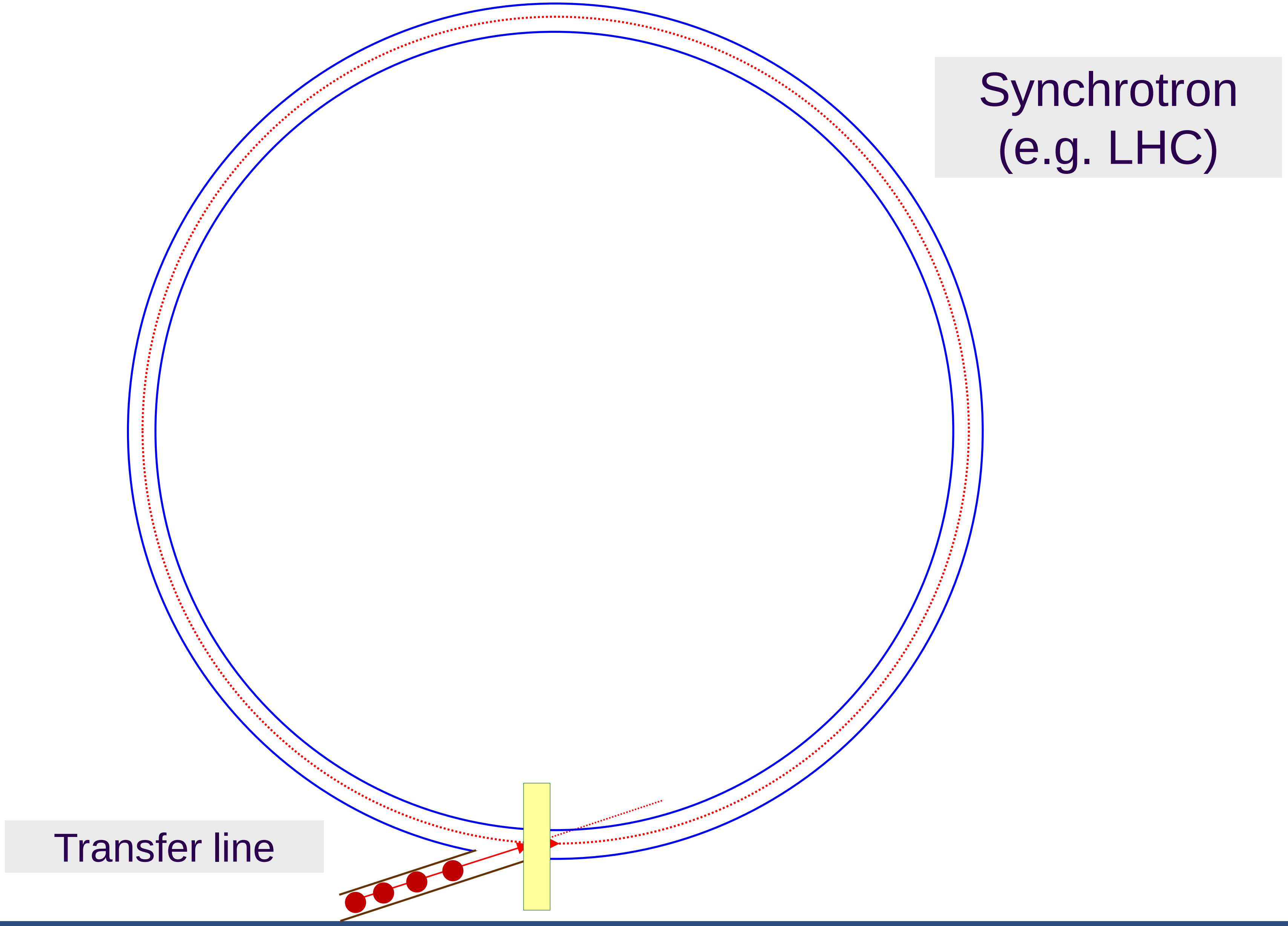
Before injection of one bunch into LHC



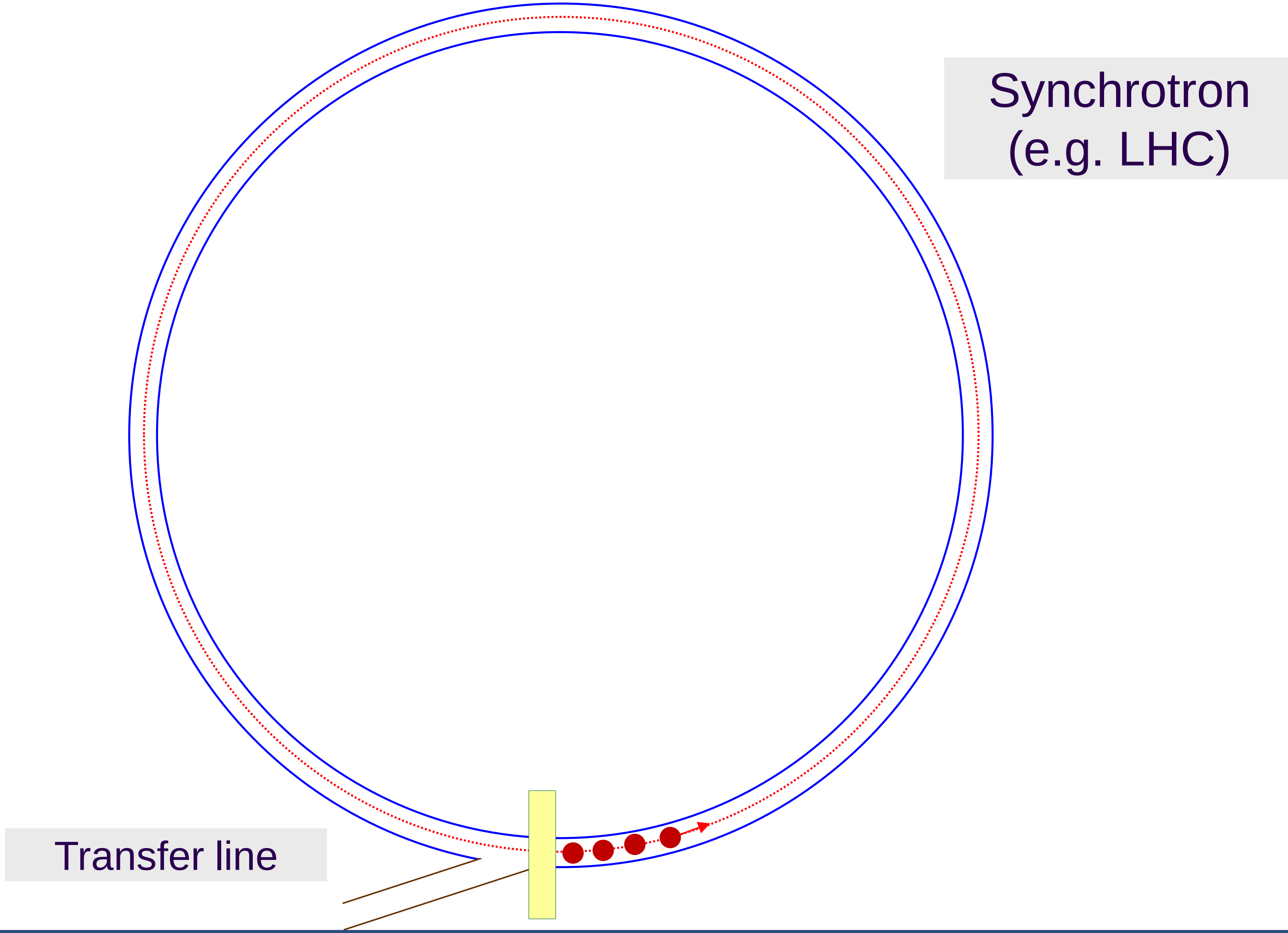
After injection of one bunch into LHC



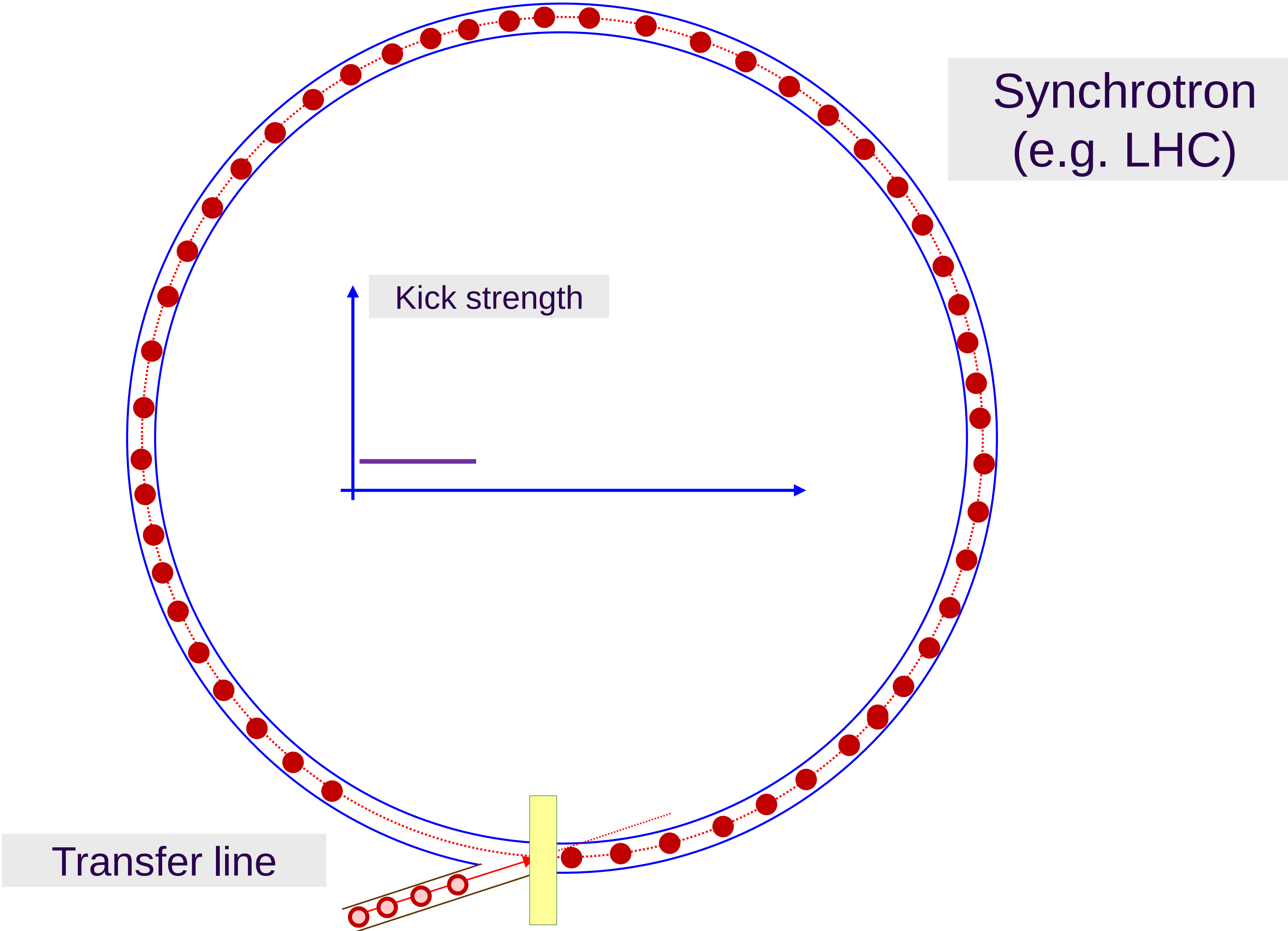
Before injection of a bunch train into LHC



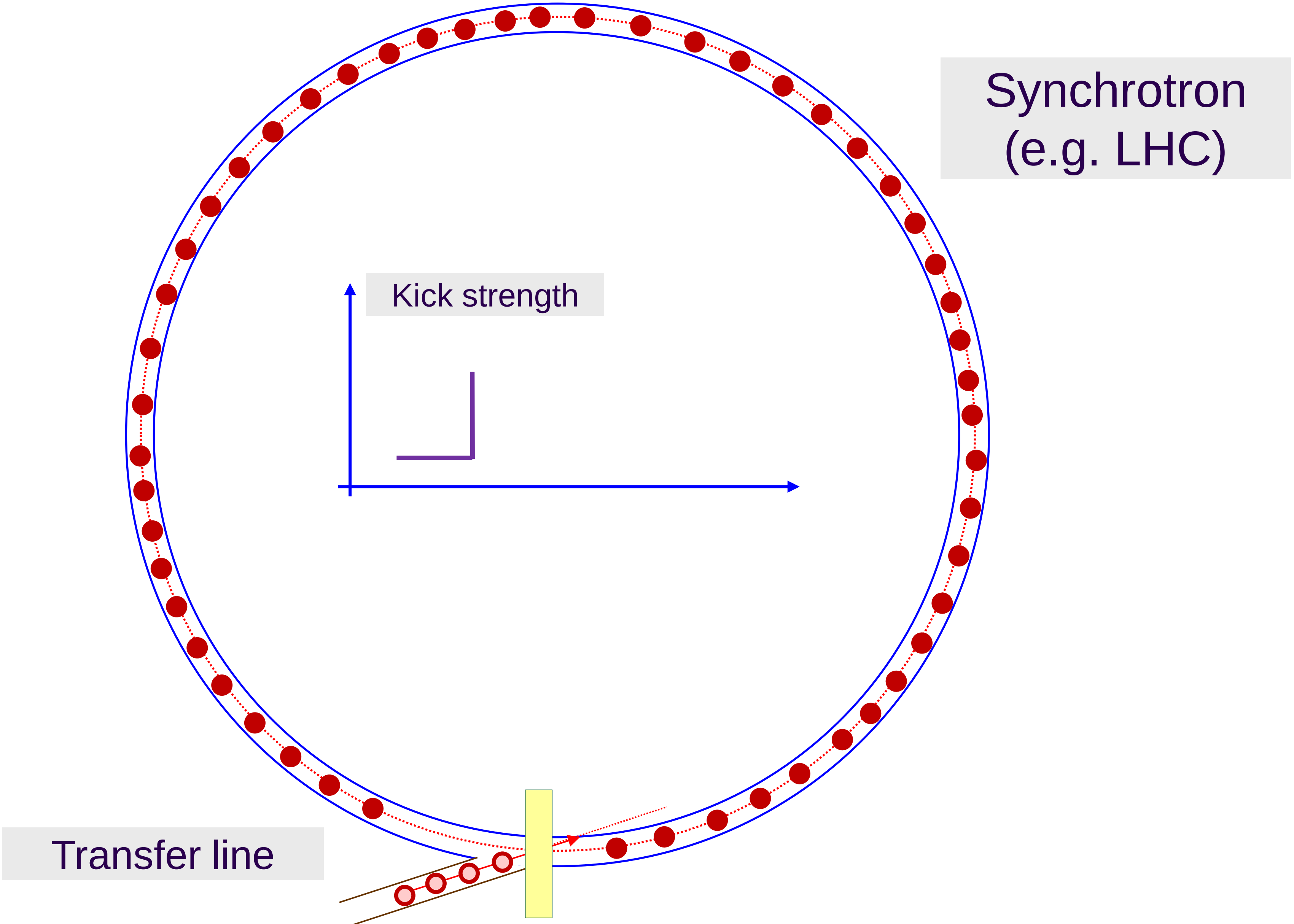
After injection of a bunch train into LHC



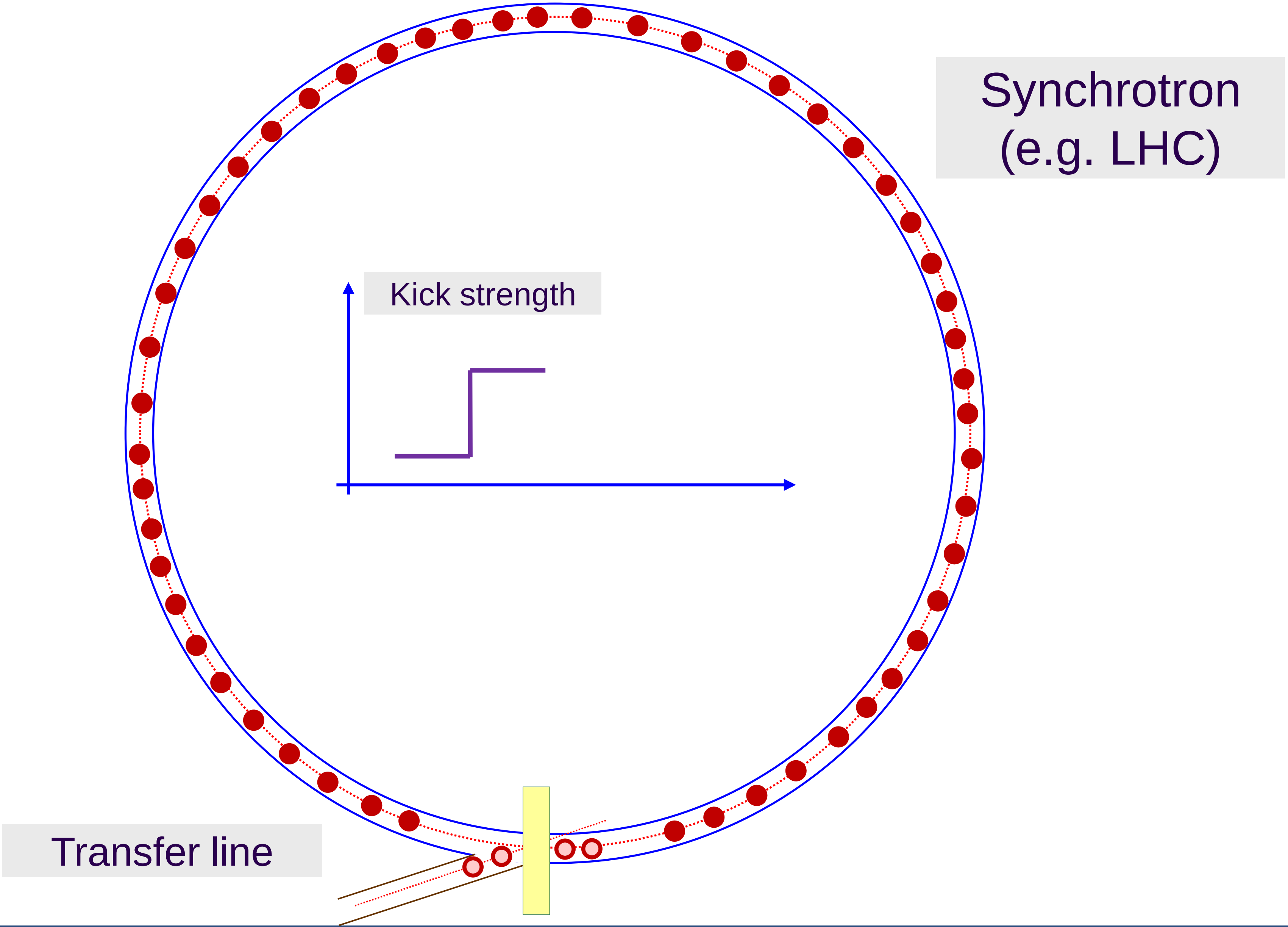
Before injection of a bunch train, LHC already filled



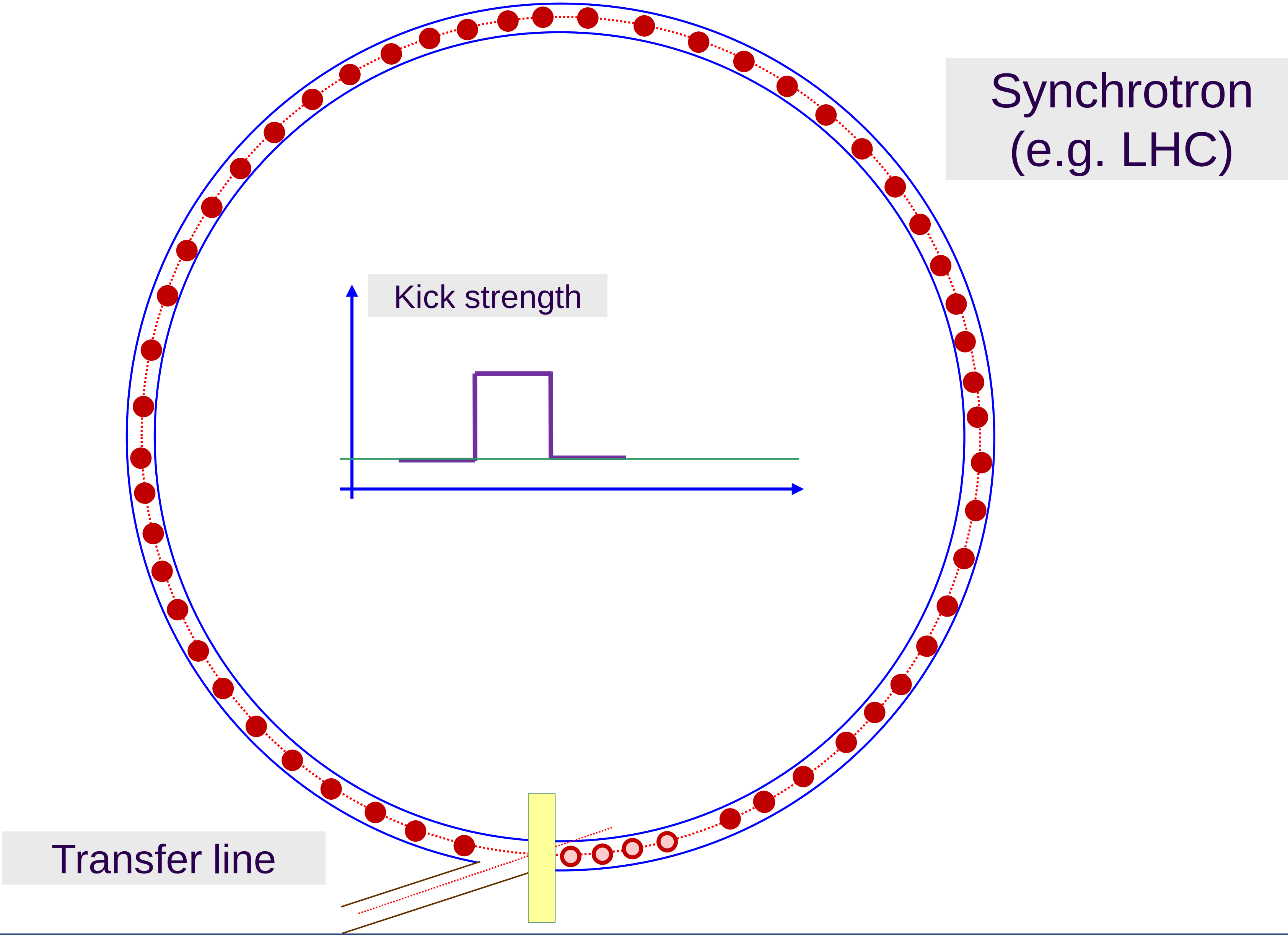
Before injection of a bunch train, LHC already filled



During injection of a bunch train, LHC already filled



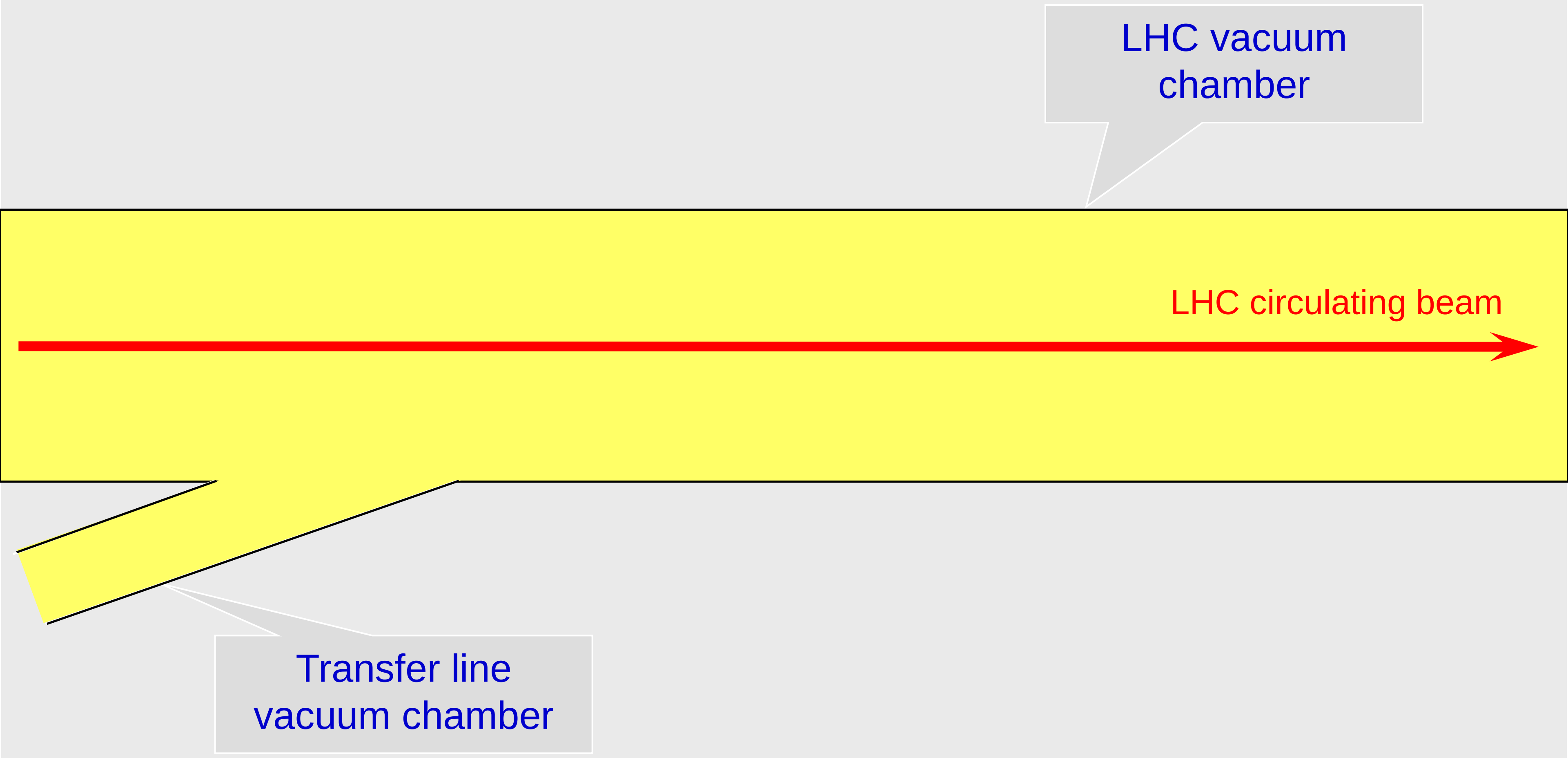
After injection of a bunch train, LHC already filled



Question

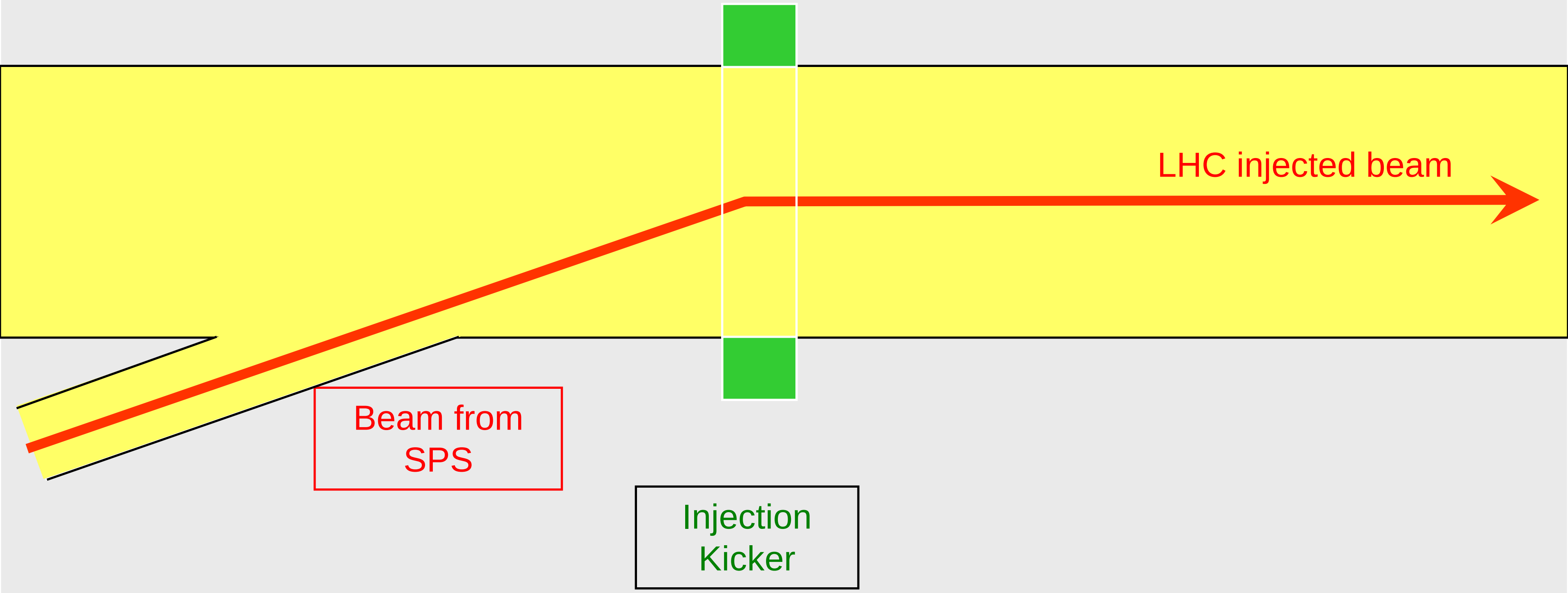
What can go wrong during injection ?

Protection at injection

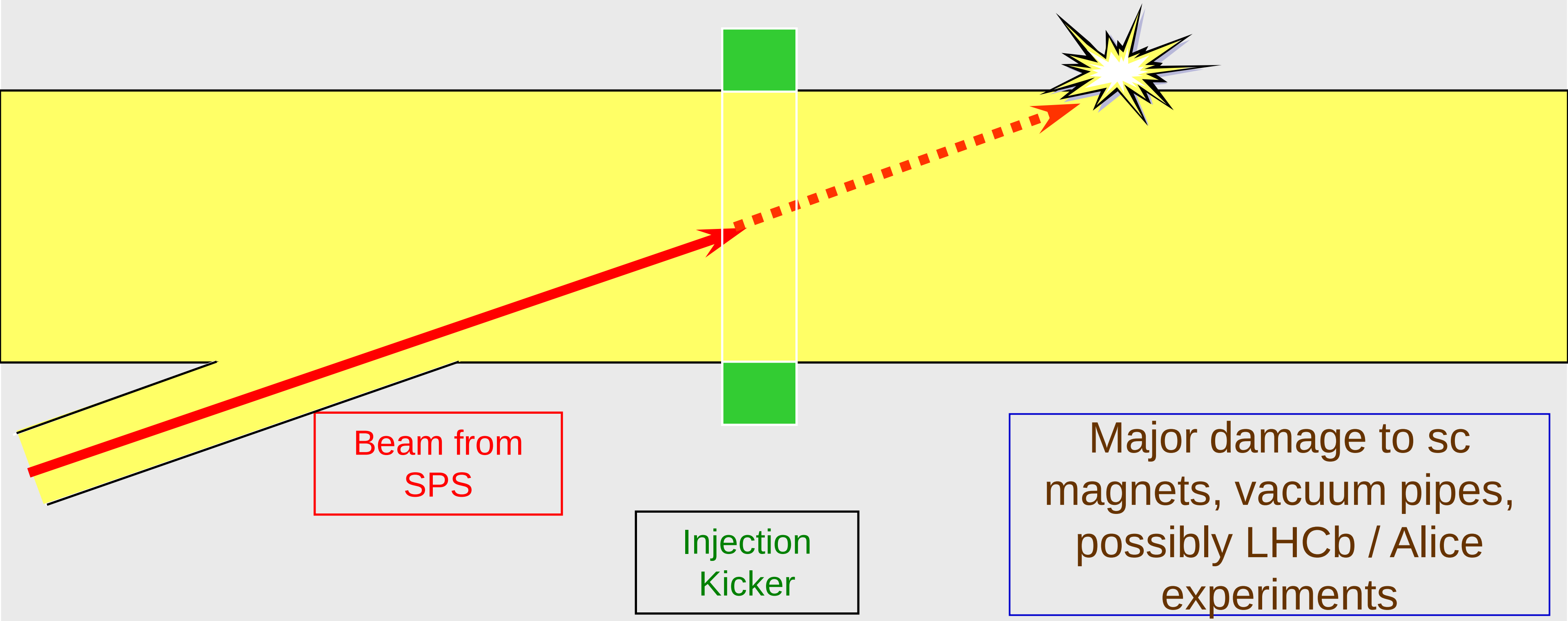


Circulating beam in LHC

Protection at injection

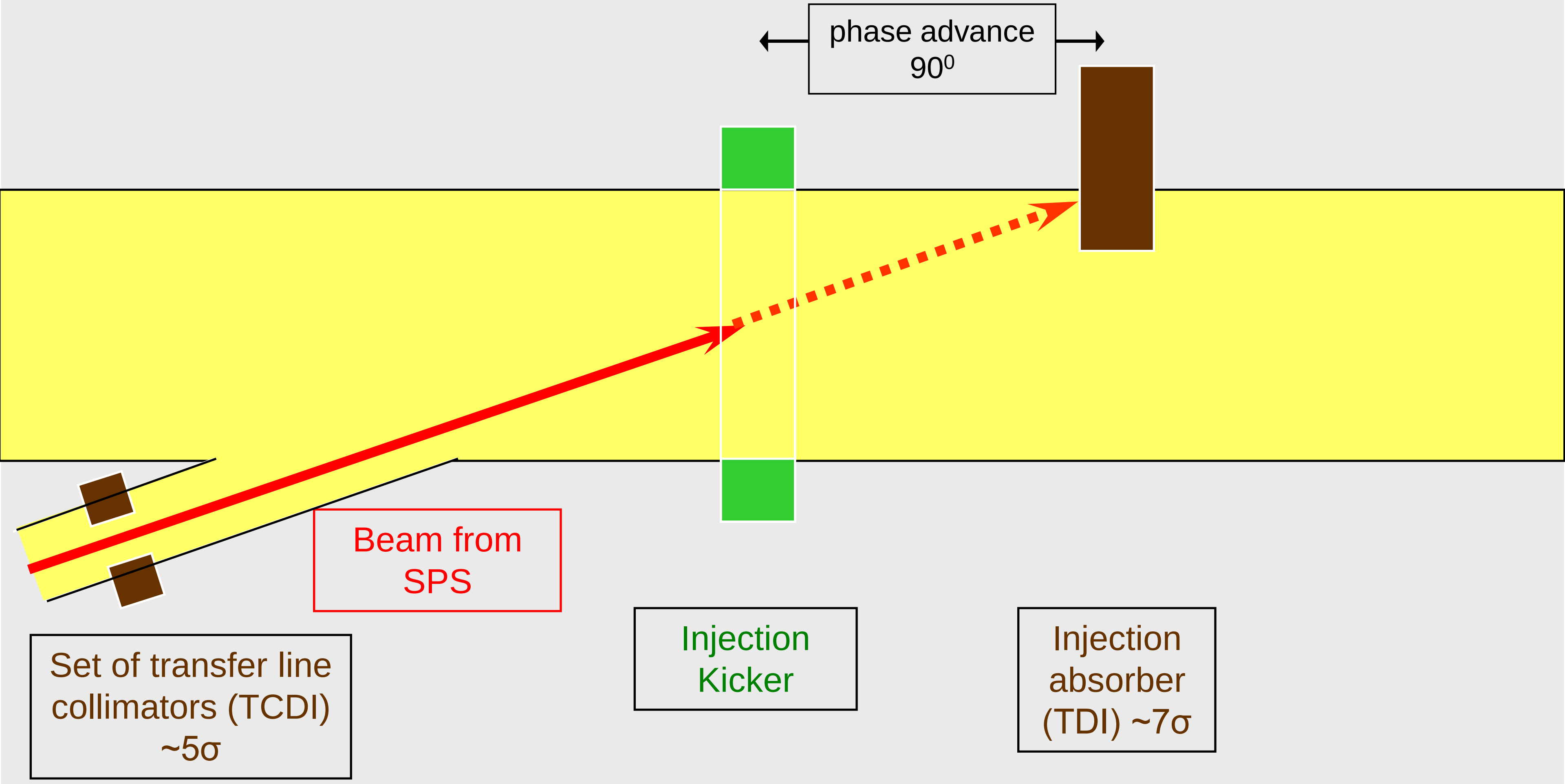


Beam injected from SPS and transfer line



Kicker failure (no kick)

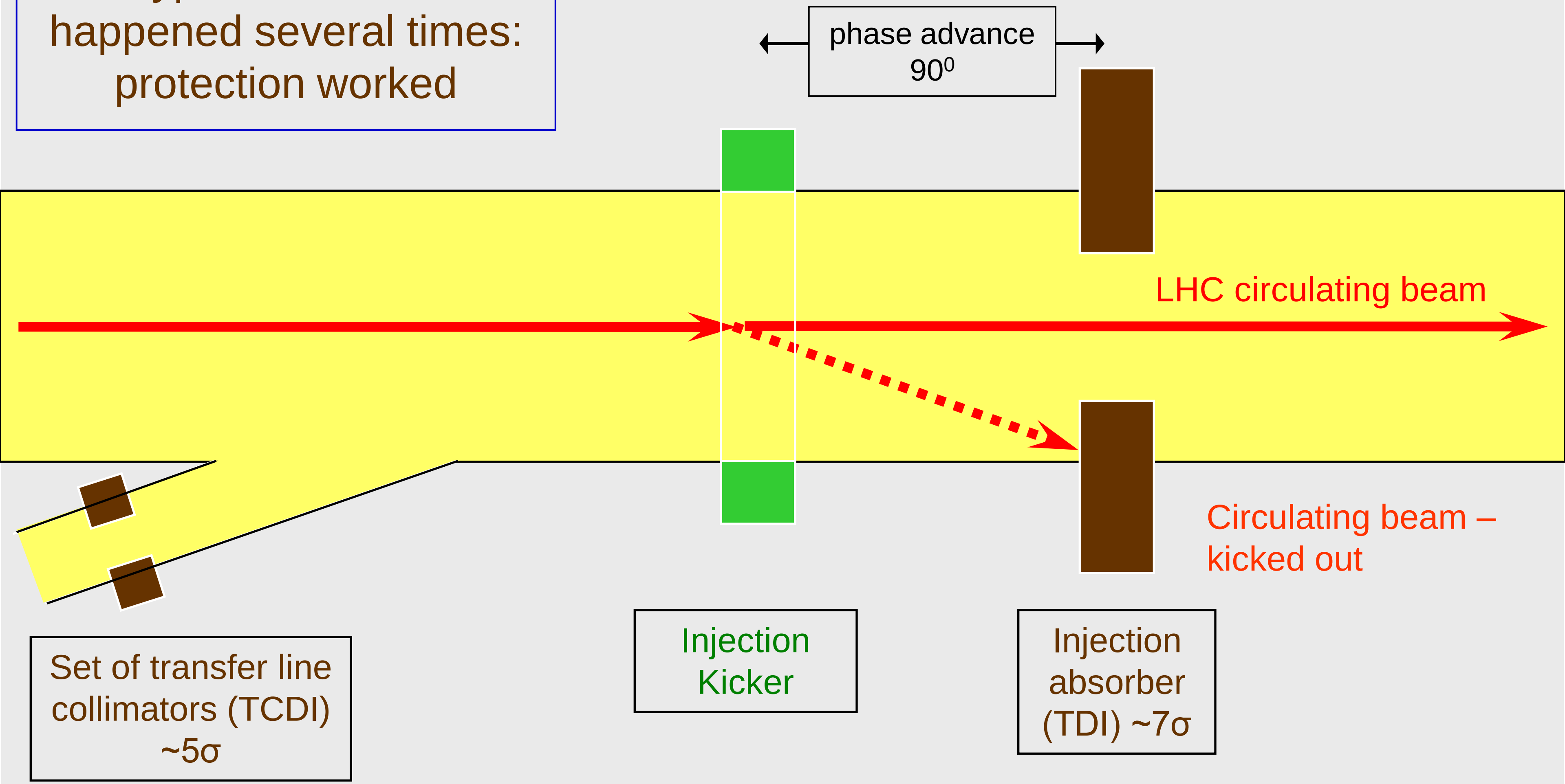
Protection at injection



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

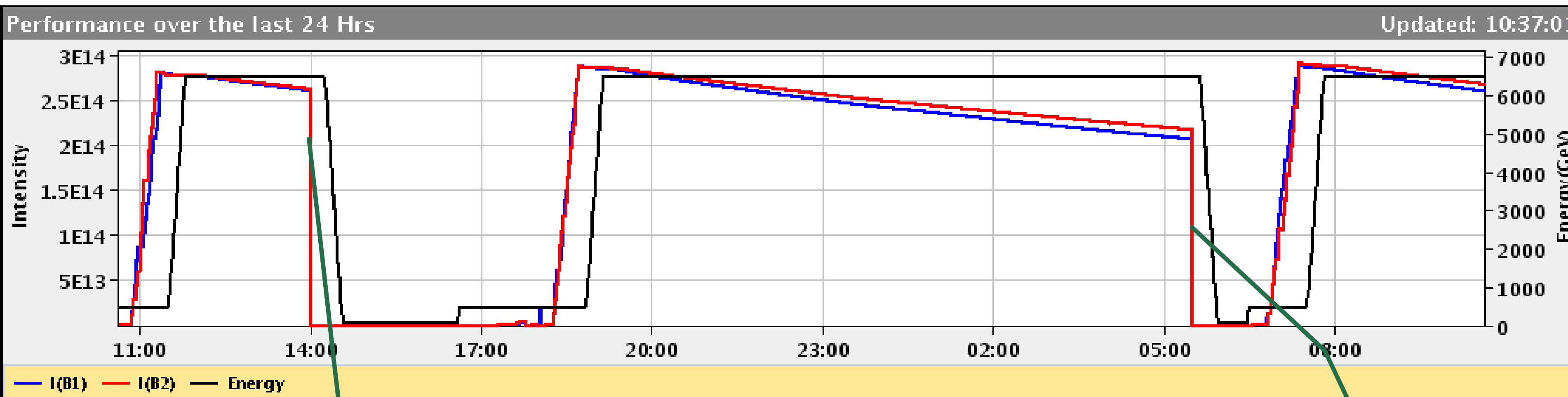
Protection at injection

This type of kicker failure happened several times: protection worked



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

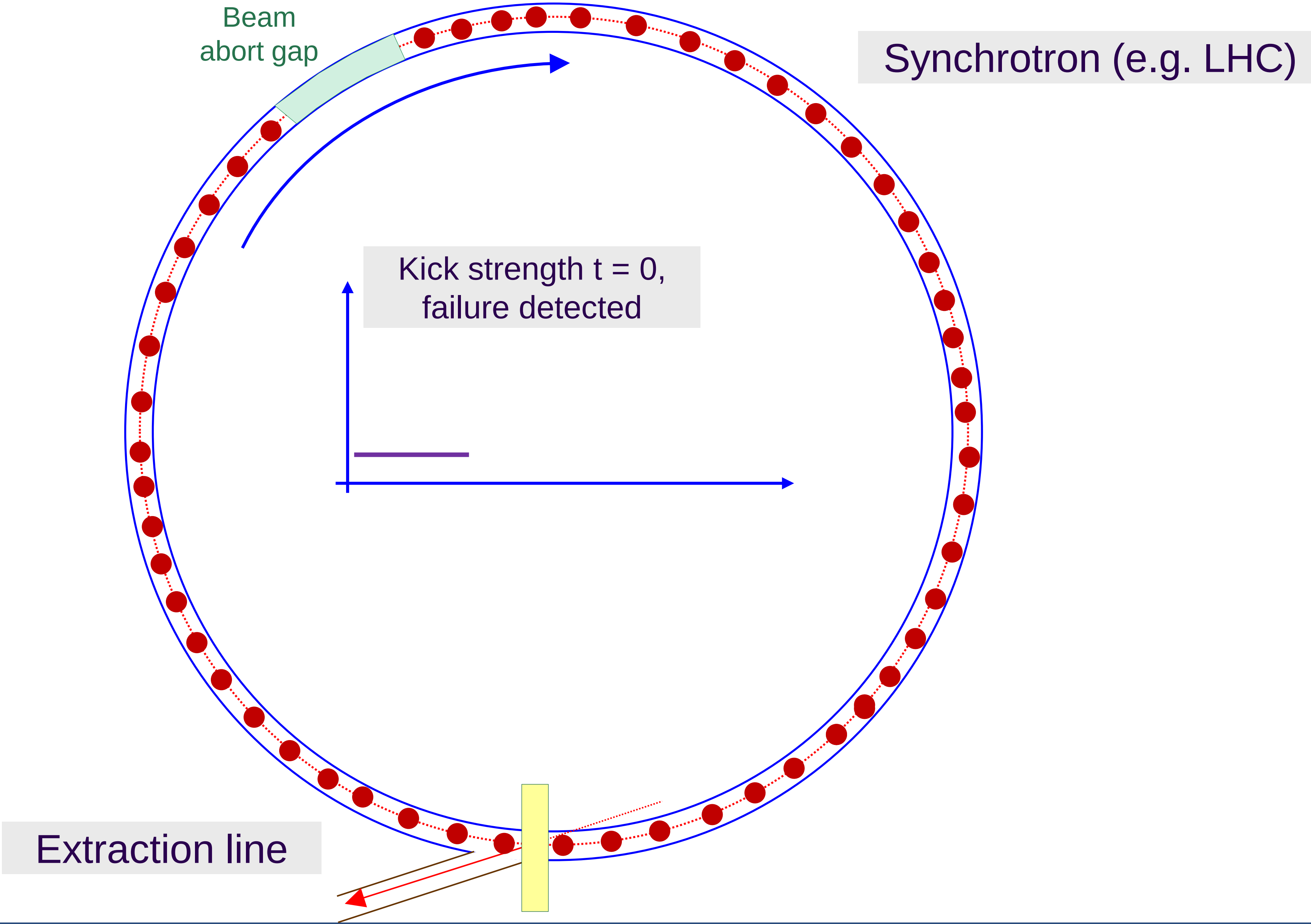
Getting rid of the beams – the beam dumping system



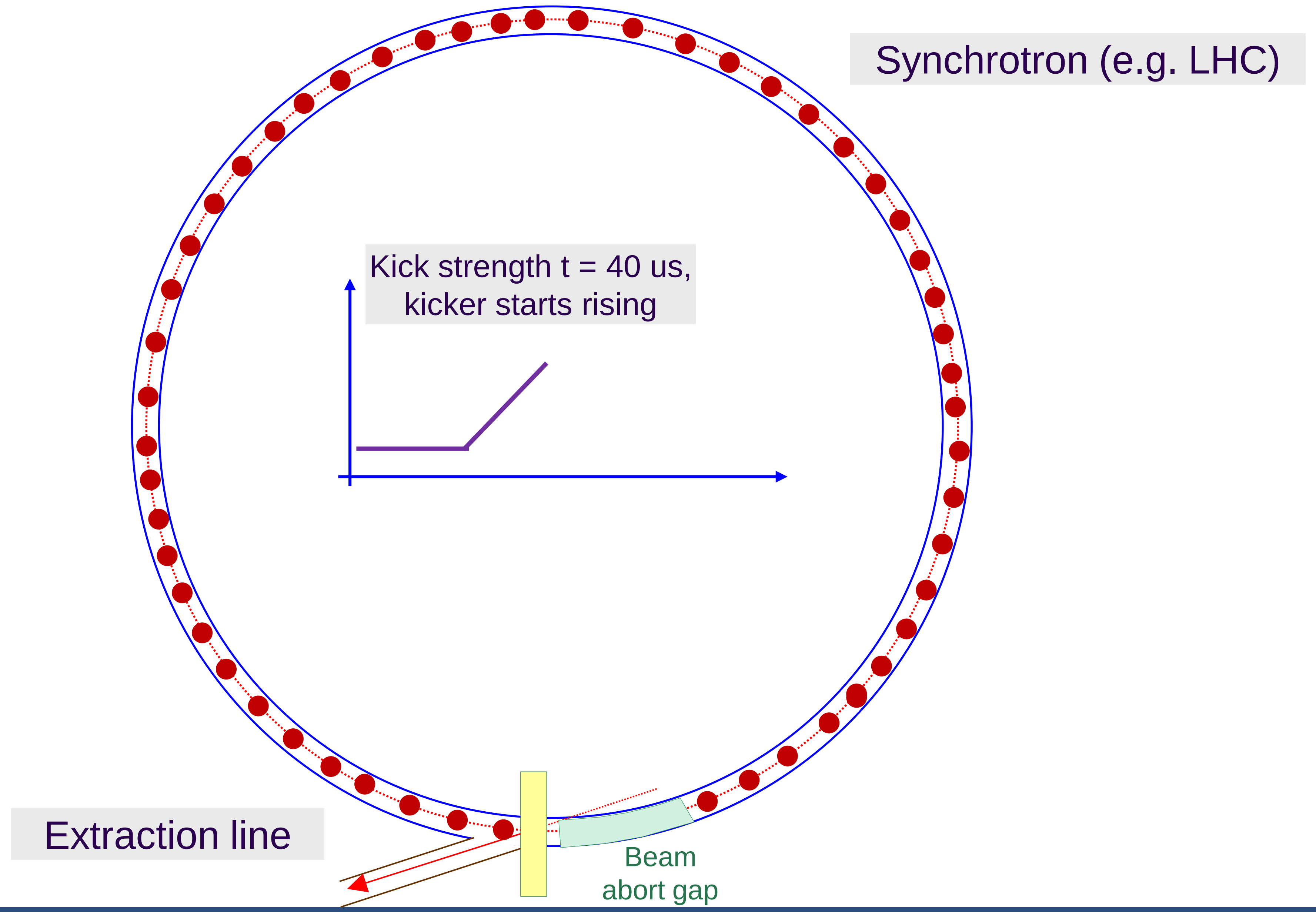
Failure: what to do with 290 MJ ?

End of the fill: what to do with the beams?

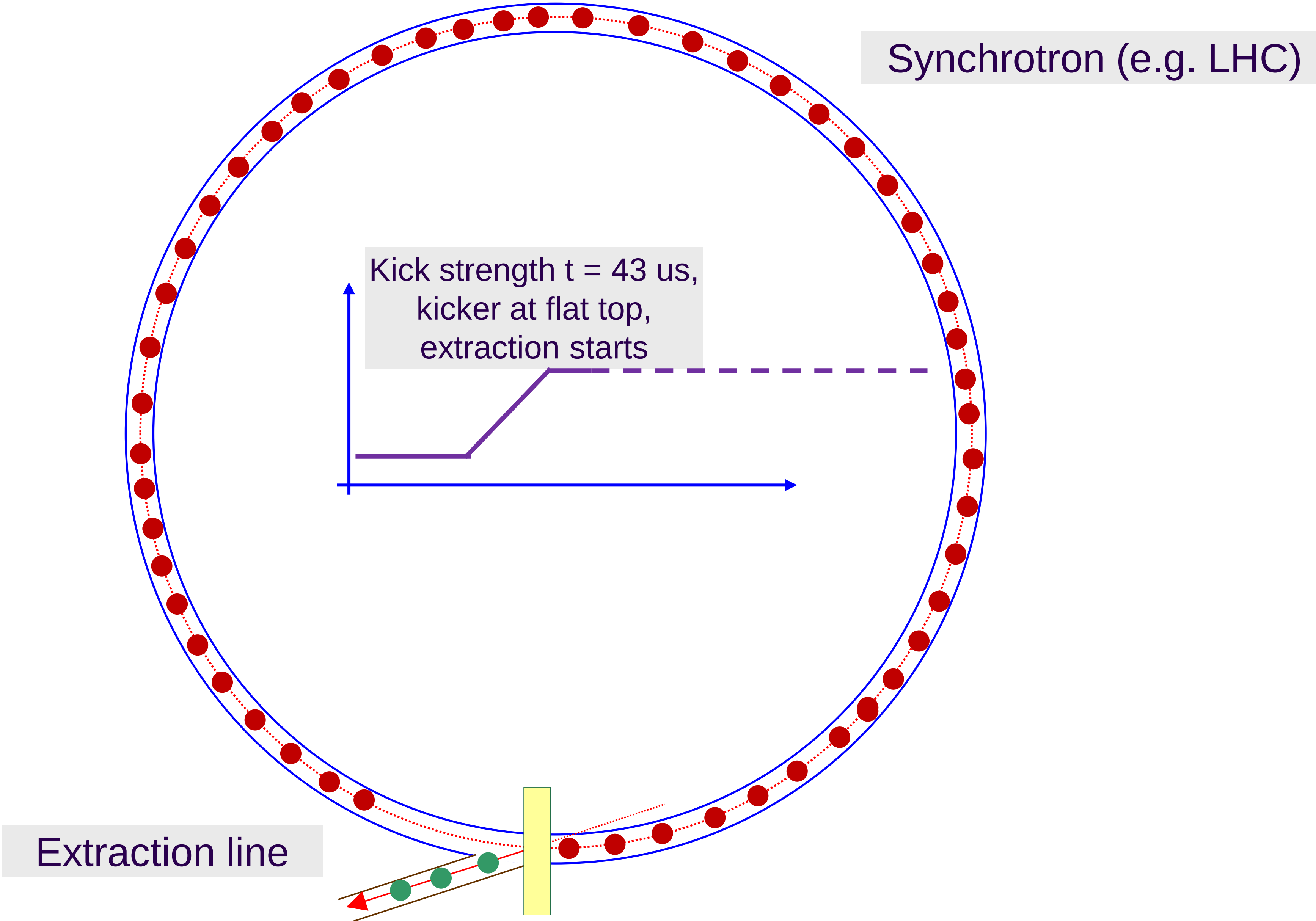
Detecting a failure



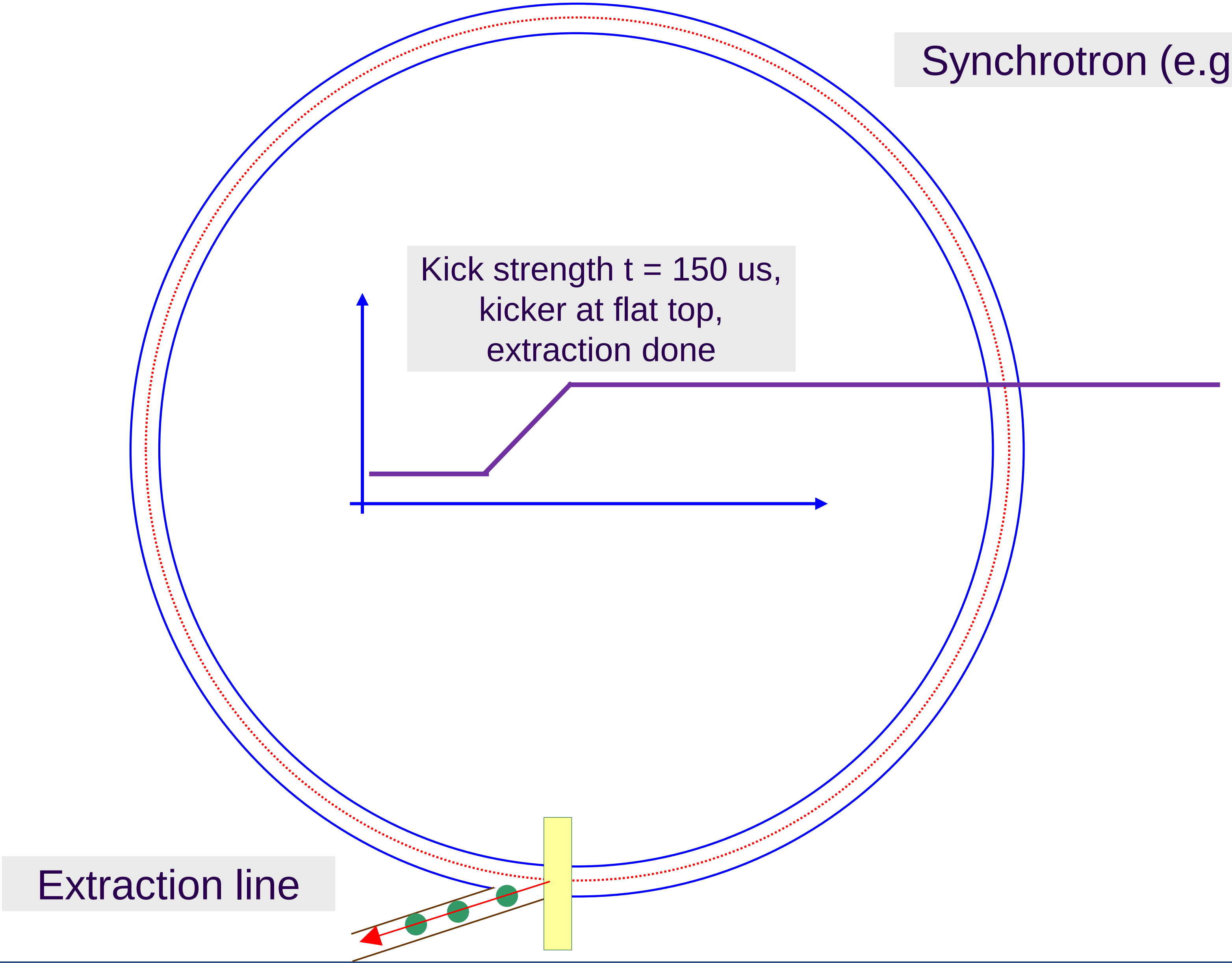
Before extraction of the beam



Before extraction of the beam



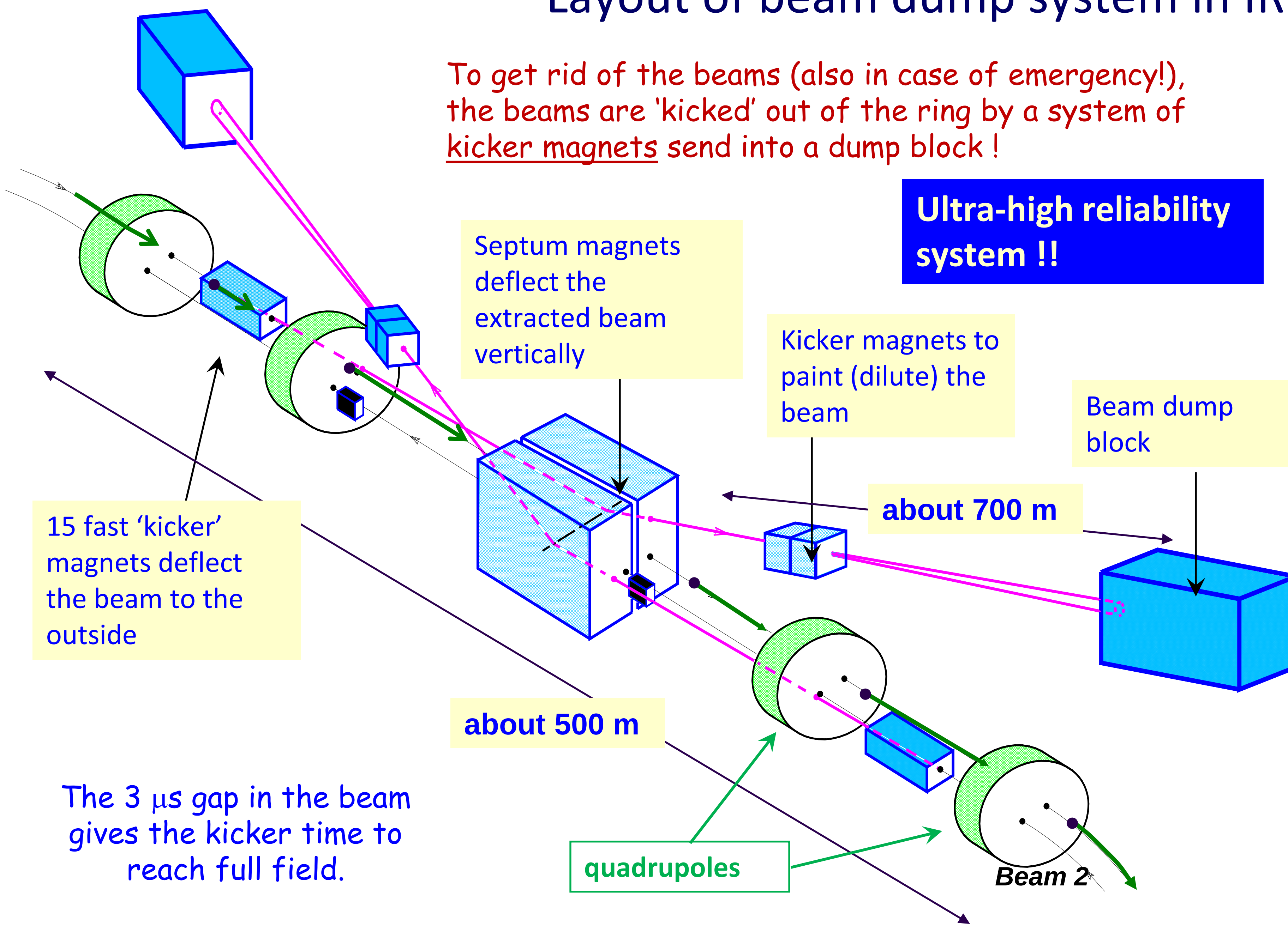
After injection of a bunch train into LHC



Layout of beam dump system in IR6

To get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets send into a dump block !

Ultra-high reliability system !!

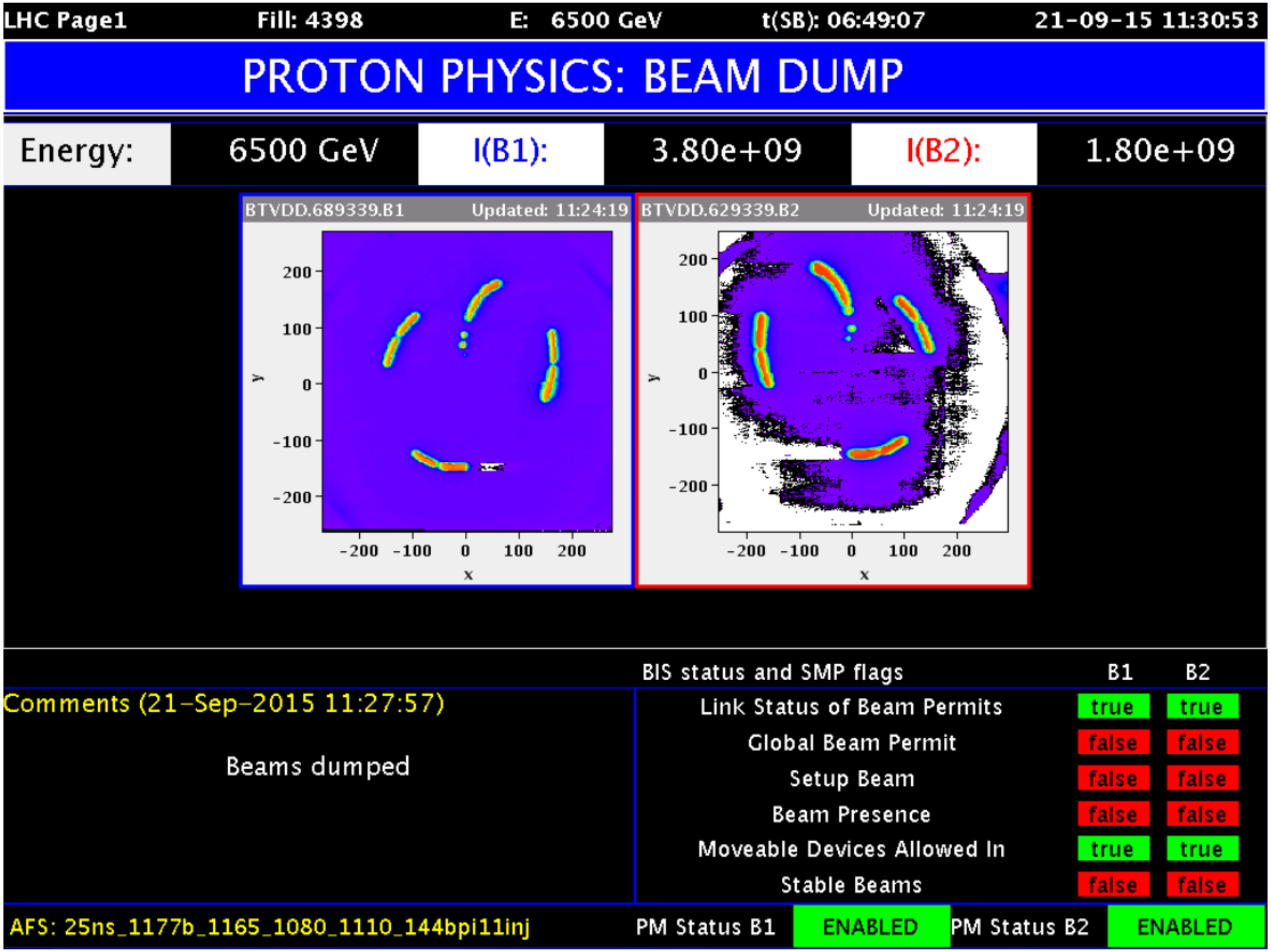


The 3 μs gap in the beam gives the kicker time to reach full field.

Beam dump line

700 m long tunnel to beam dump block- beam size increases

Beam dump with 1380 bunches



Beam spot at the end of the beam dumping line, just in front of the beam dump block

Worst case accidents

Proton collider

Hydrodynamic tunnelling

- The beam impacts on a target, e.g. due to a failure of the injection of extraction kicker
- For LHC, bunches arrive every 25 or 50 ns
- The time structure of the beam plays an essential role
- The first bunches arrive, deposit their energy, and lead to a reduction of the target material density
- Bunches arriving later travel further into the target since the material density is reduced (predicted for SSC, N.Mokhov et al.)
- LHC: **tunnelling of the beam through about 30 m** is expected

Copper or carbon target

N.Tahir et al., simulation tool validated by experiments

Machine Protection Strategy

Time scale for accidental beam losses

Active protection

Passive protection

Accidental beam losses

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)
- beam sent to wrong destination (e.g. high intensity beam send to equipment designed for low intensity)
- failures of kicker magnets (injection, extraction, special kicker magnets, for example for diagnostics)
- 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)

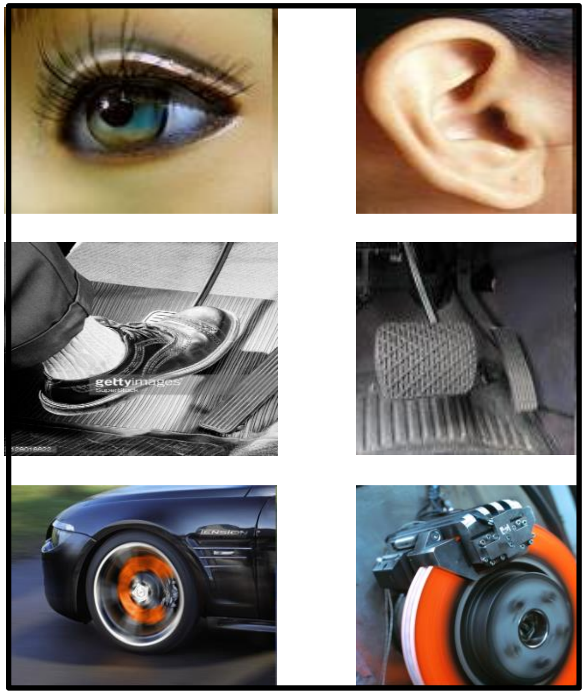
Slow beam loss (many seconds)

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 (too high beam current / bunch current / e-clouds)
- The number of possible failures for accidental beam losses is (nearly) infinite
- Parameters for the failure
  - Probability for the failure
  - Damage potential
  - **Time constant for beam loss**

$\left.\begin{array}{l}\text{Probability for the failure}\\ \text{Damage potential}\end{array}\right\}$ Risk = Probability * Consequences

Active and Passive Protection



Active protection

- A sensor detects a dangerous situation
- An action is triggered by an actuator
- The energy stored in the system is safely dissipated

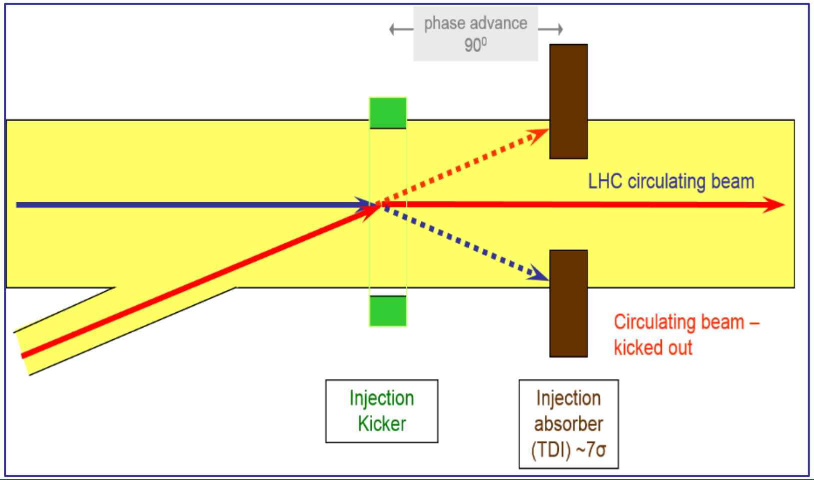
Passive protection

- Preferred if possible to operate without active protection
- Active protection not possible, e.g. the reaction time is too short
- Monitors fail to detect a dangerous situation (redundancy)

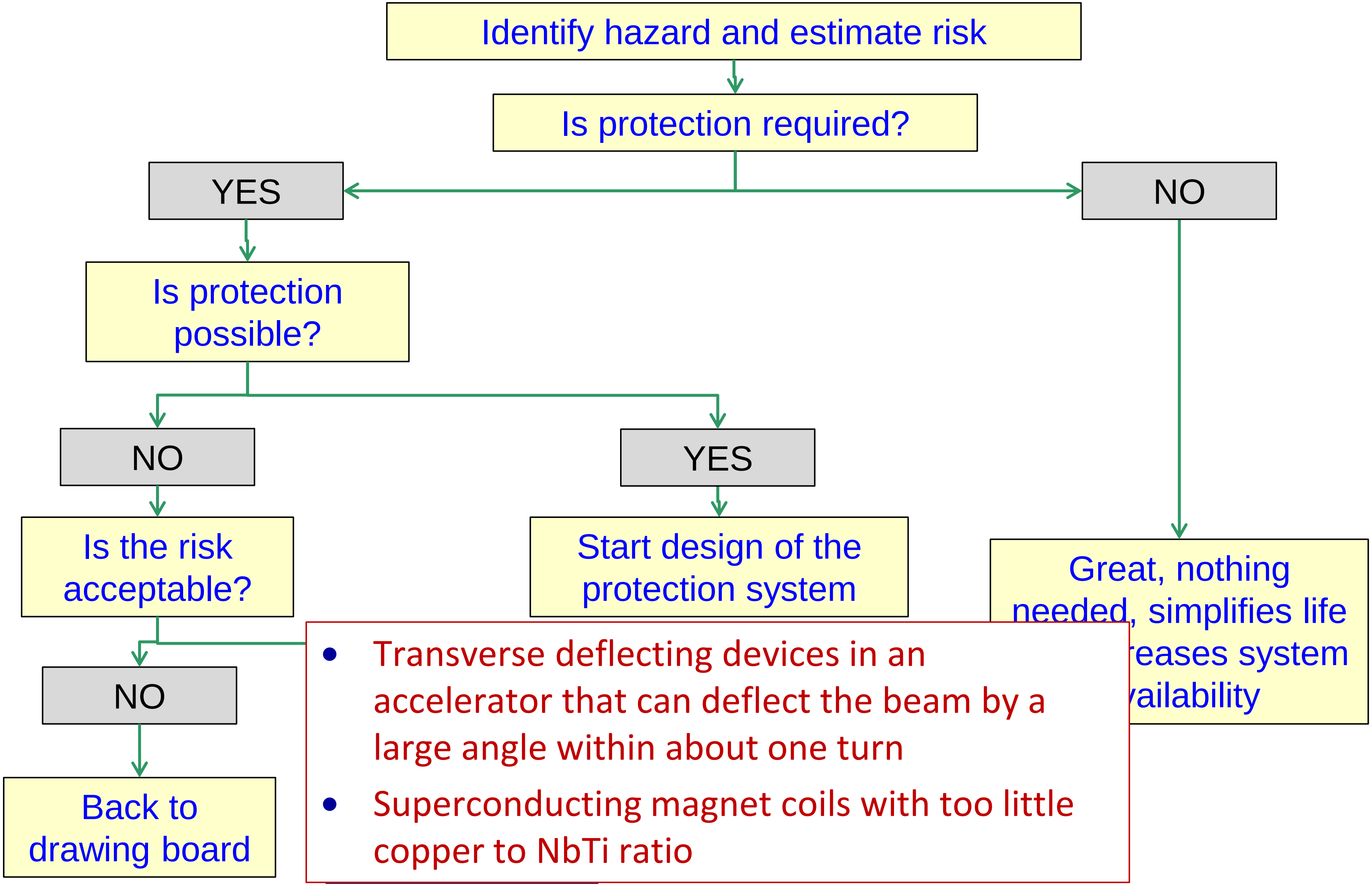
Active protection

- A system is monitored, the monitor delivers some values (e.g. beam loss monitors measuring beam losses)
- The acceptable range of values is predefined (e.g. maximum beam losses within a time interval)
- If a value is out of the predefined range (e.g. after an equipment failure): take action (dump circulating beam, stop injection, ….)
- The information has to travel from the monitor to the activator (extraction system, injection inhibit, …) => interlock system
- There is some **reaction time required for the response** (depending on the system this can range between some ns and many seconds)

- Necessary when the time required for the response is too short
- Might simplify the protection system
- Example: **fast extraction / injection of a high intensity beam**
  - Extraction is performed with a fast kicker magnet
  - A kicker failure leading to a wrong deflection angle cannot be excluded
  - The range of plausible failures (=deflection angles) needs to be defined
  - If the beam could damage hardware, protection absorbers are required
  - Movable absorbers: need to be at the correct position
  - Ensure that the elements in the transfer line have the correct settings



Analysing need for machine protection

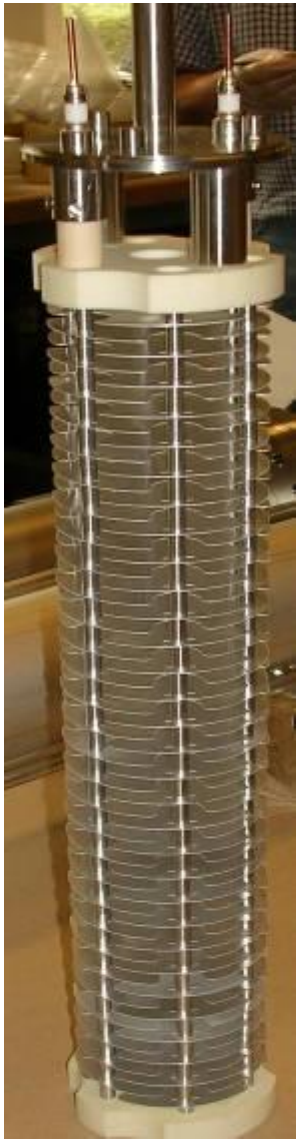


- Transverse deflecting devices in an accelerator that can deflect the beam by a large angle within about one turn
- Superconducting magnet coils with too little copper to NbTi ratio

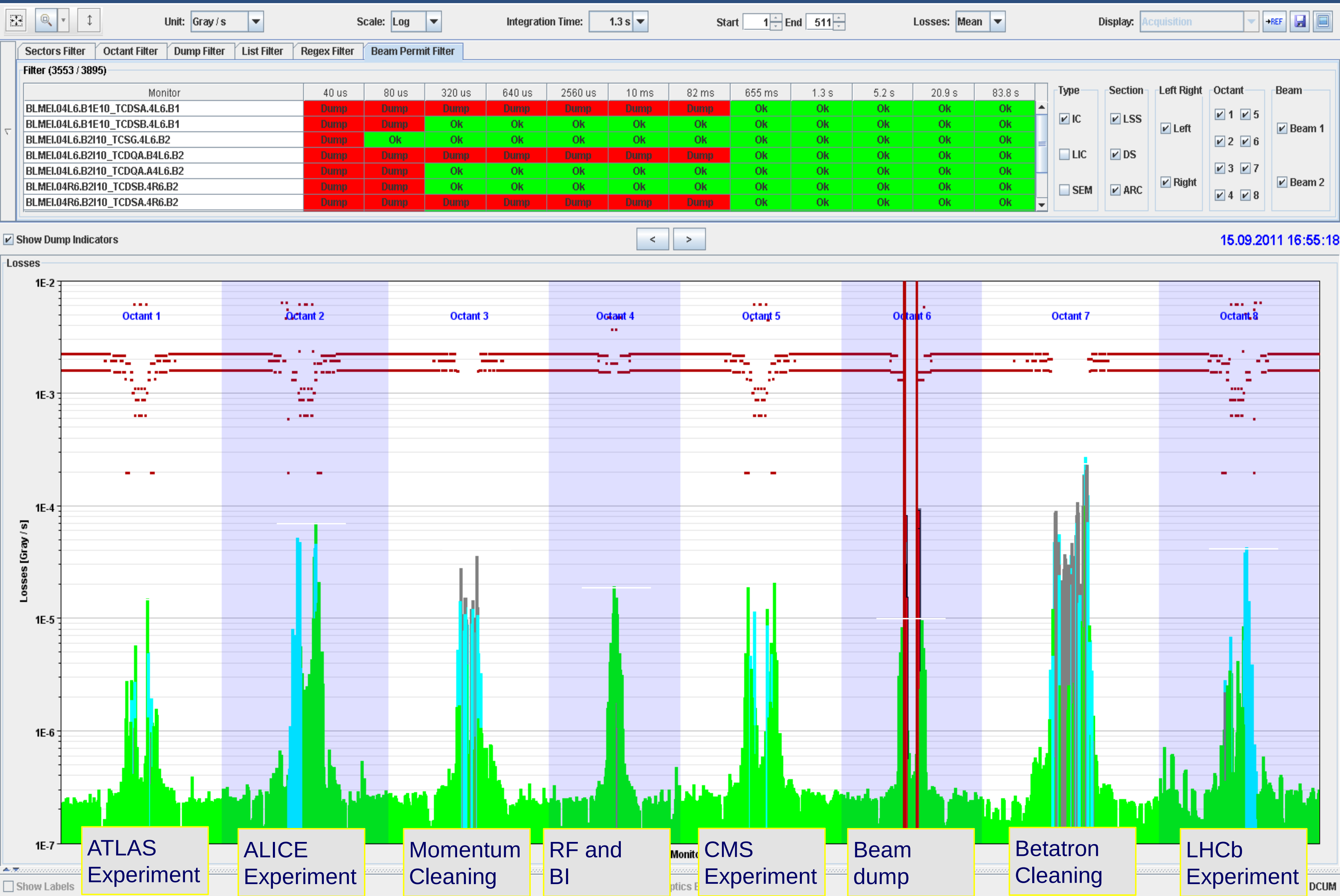
LHC strategy for machine protection

• Definition of aperture by collimators.	**Beam Cleaning System**
• Passive protection by beam absorbers and collimators for specific failure cases.	**Collimator and Beam Absorbers**
• Early detection of equipment failures generates dump request, possibly before 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 extracting beams onto the external dump blocks.	**Beam Dumping System** **Stop beam at source**
• 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**

- 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 !
- Very important beam instrumentation!

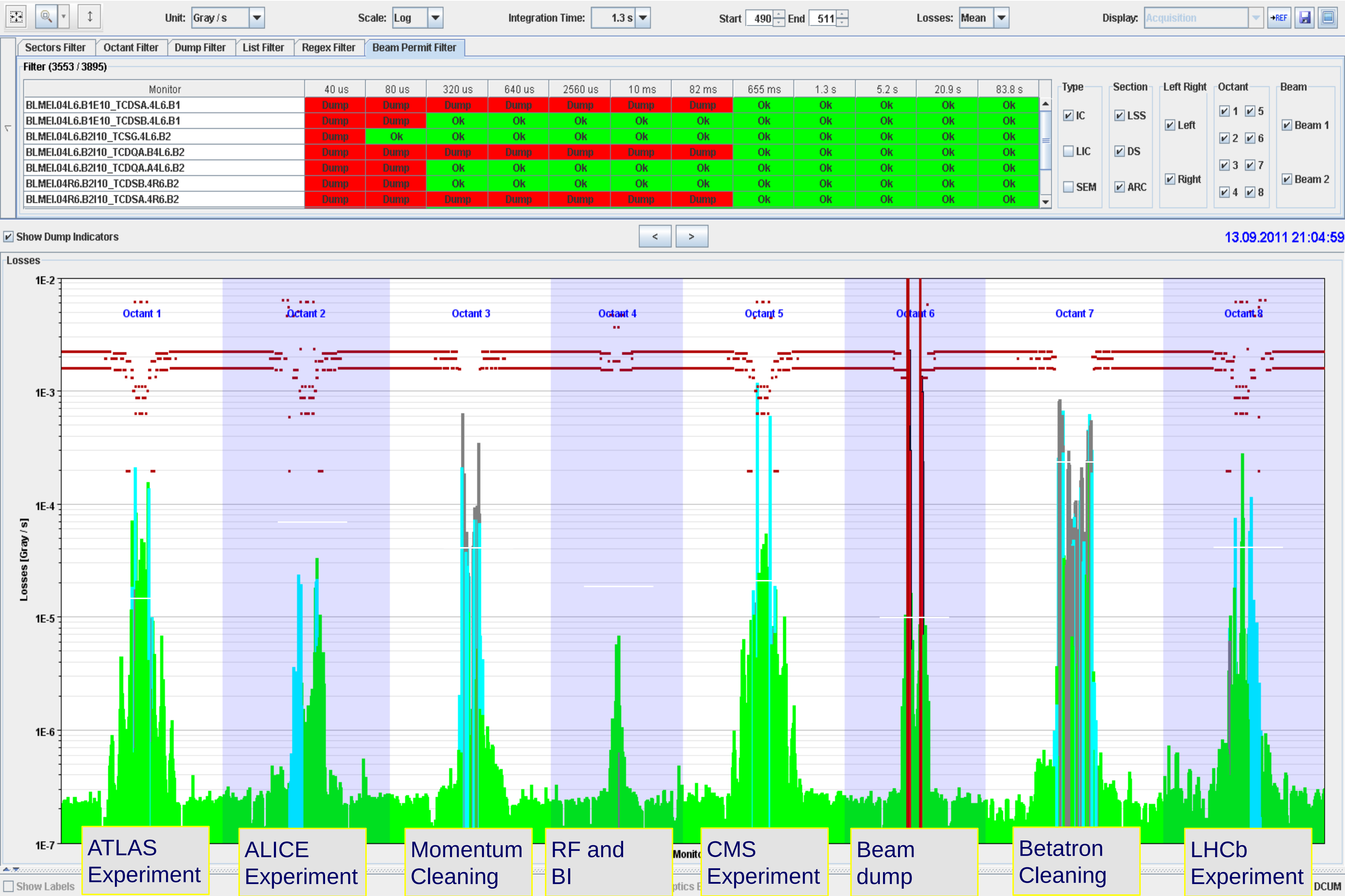


BLM system: beam losses before collisions

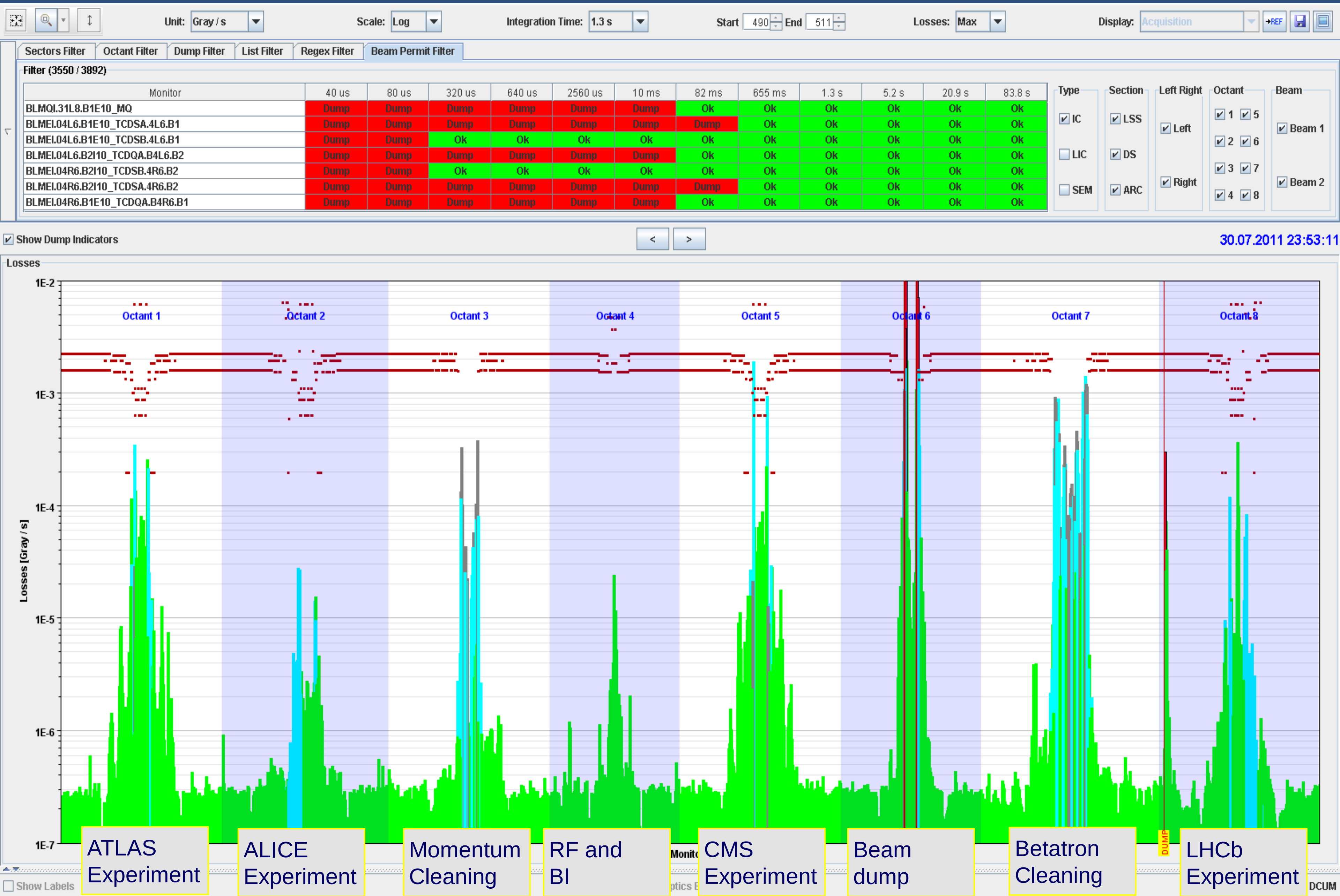


Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B2I10_TCDQA.A4L6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok

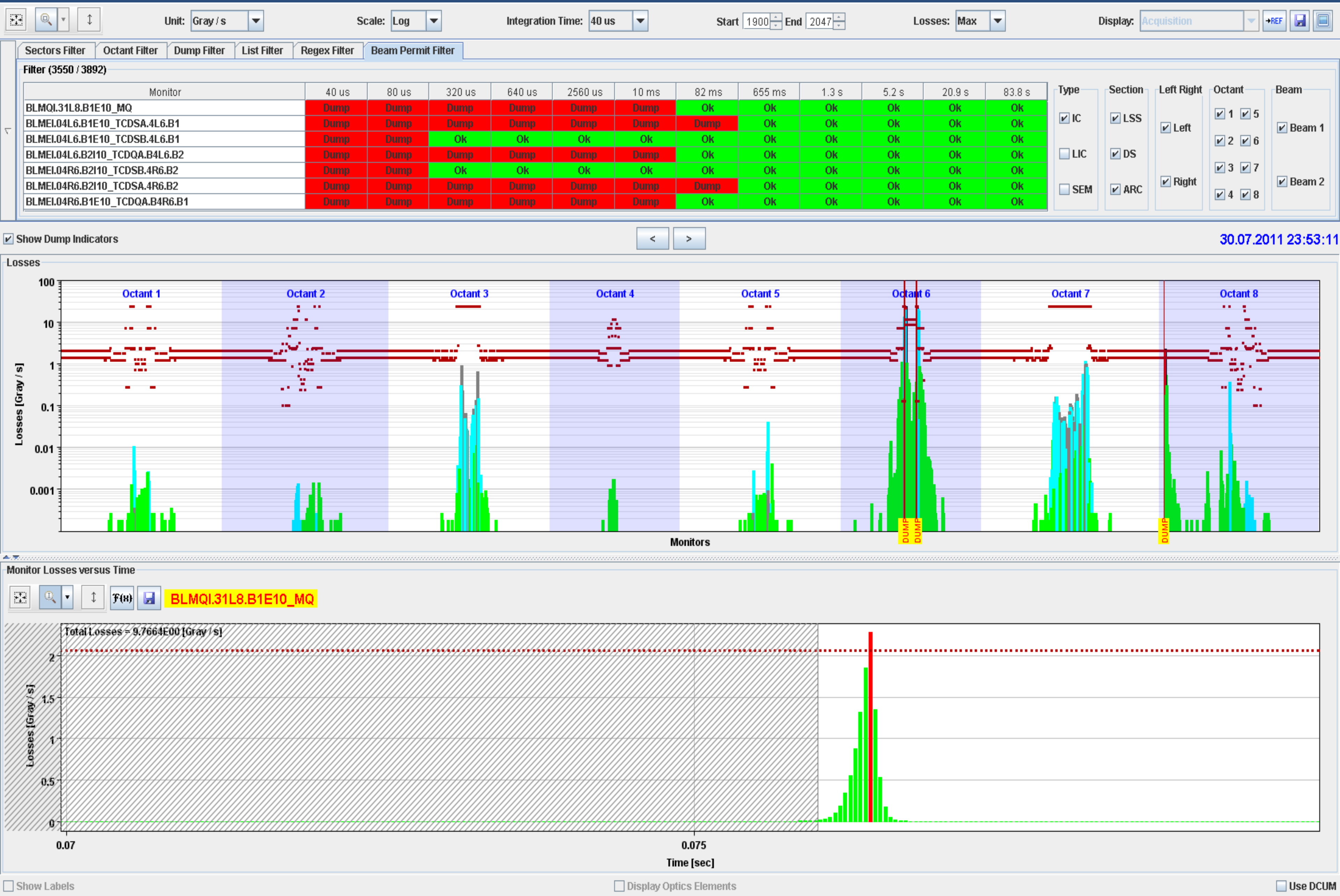
Continuous beam losses during collisions



Accidental beam losses during collisions



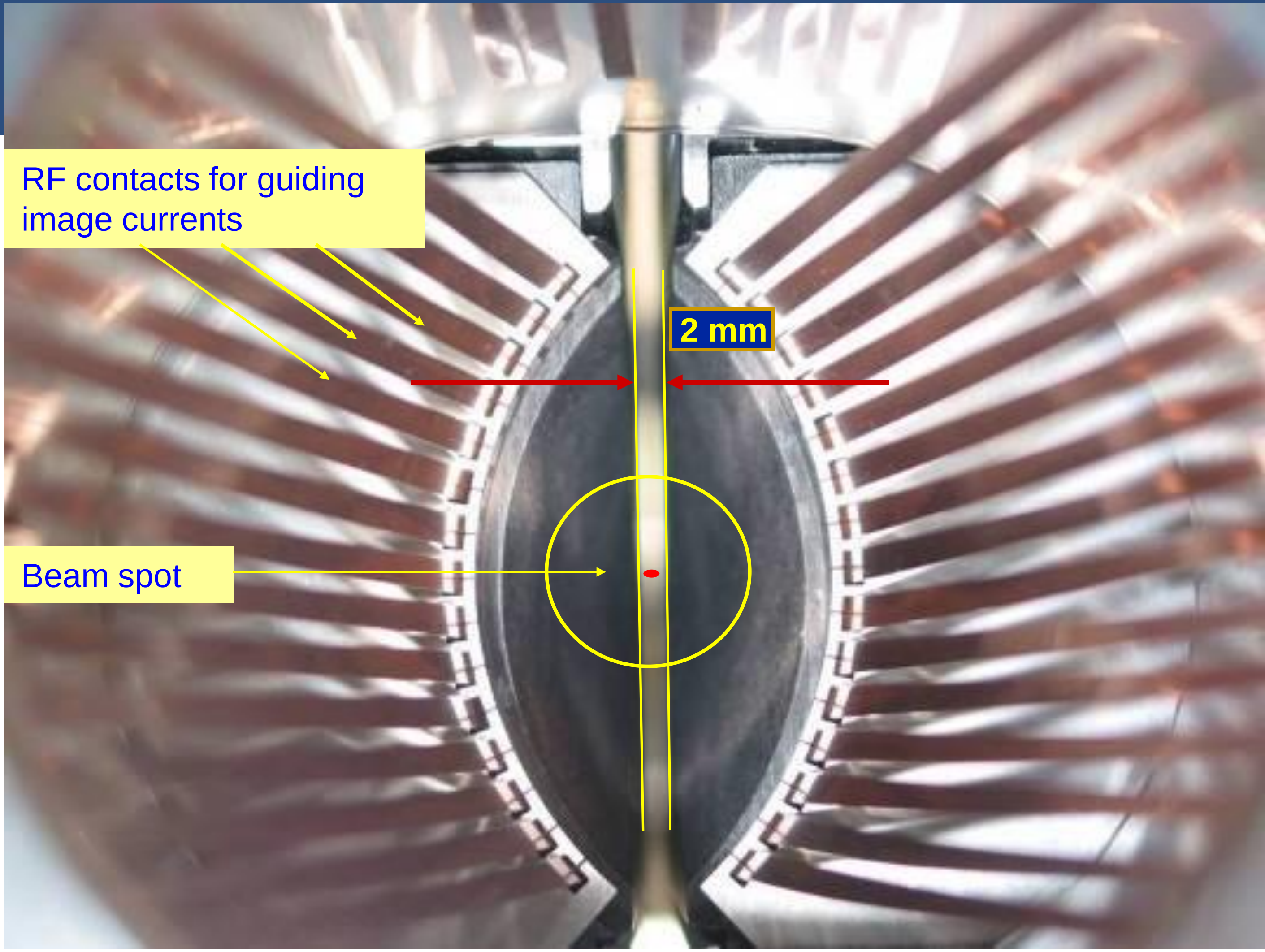
Accidental beam losses during collisions

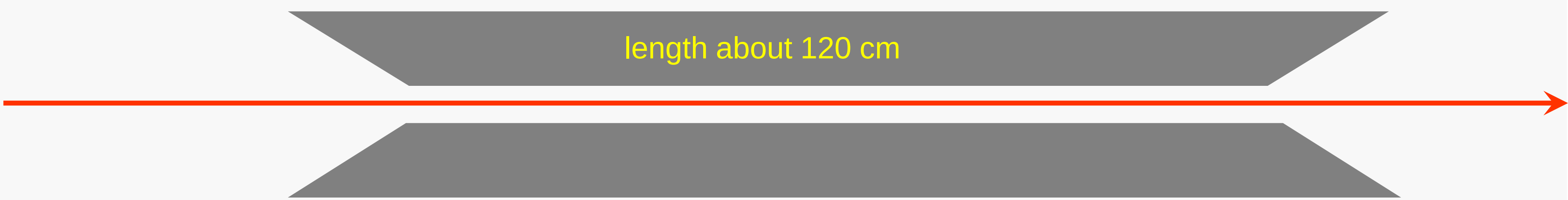


Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok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

View of a two sided collimator

about 100 collimators are installed in LHC





Three Principles for Machine Protection

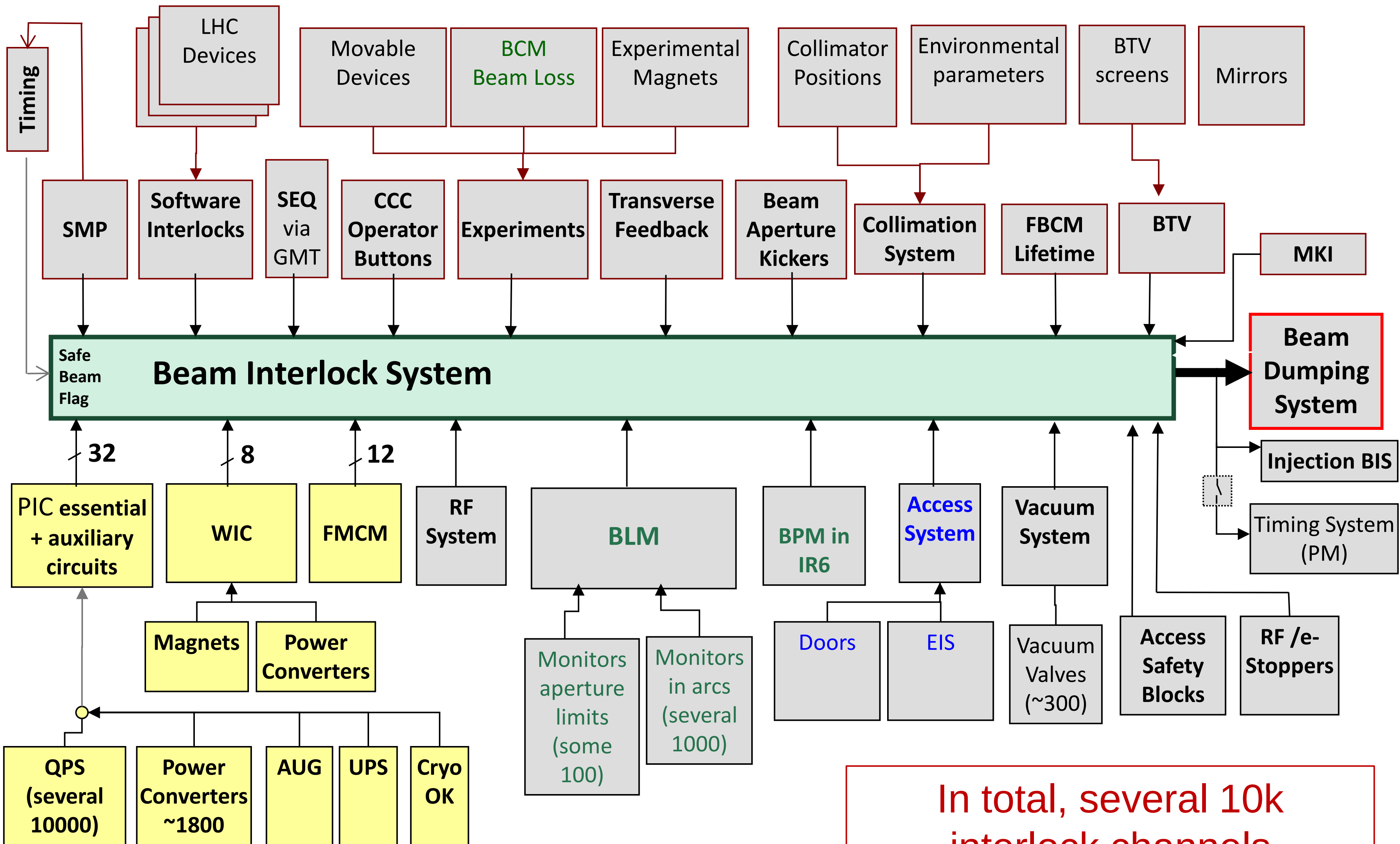
1. **Protect the equipment** (machine protection systems + interlock systems)

2. **Protect the process** (high availability systems)
   - Machine protection systems will always contribute to downtime
   - Protection action ONLY if a hazard becomes active (e.g. something went wrong threatening to damage equipment)

3. **Provide the evidence** (post mortem, logging of data)
   - Provide post mortem buffers in equipment (record data, and stop after protection action kicks in) – many of LHC luminosity fills dumped prematurely
   - Synchronisation of different systems is ultra – critical, to understand what happened
   - Post operational checks by the controls system

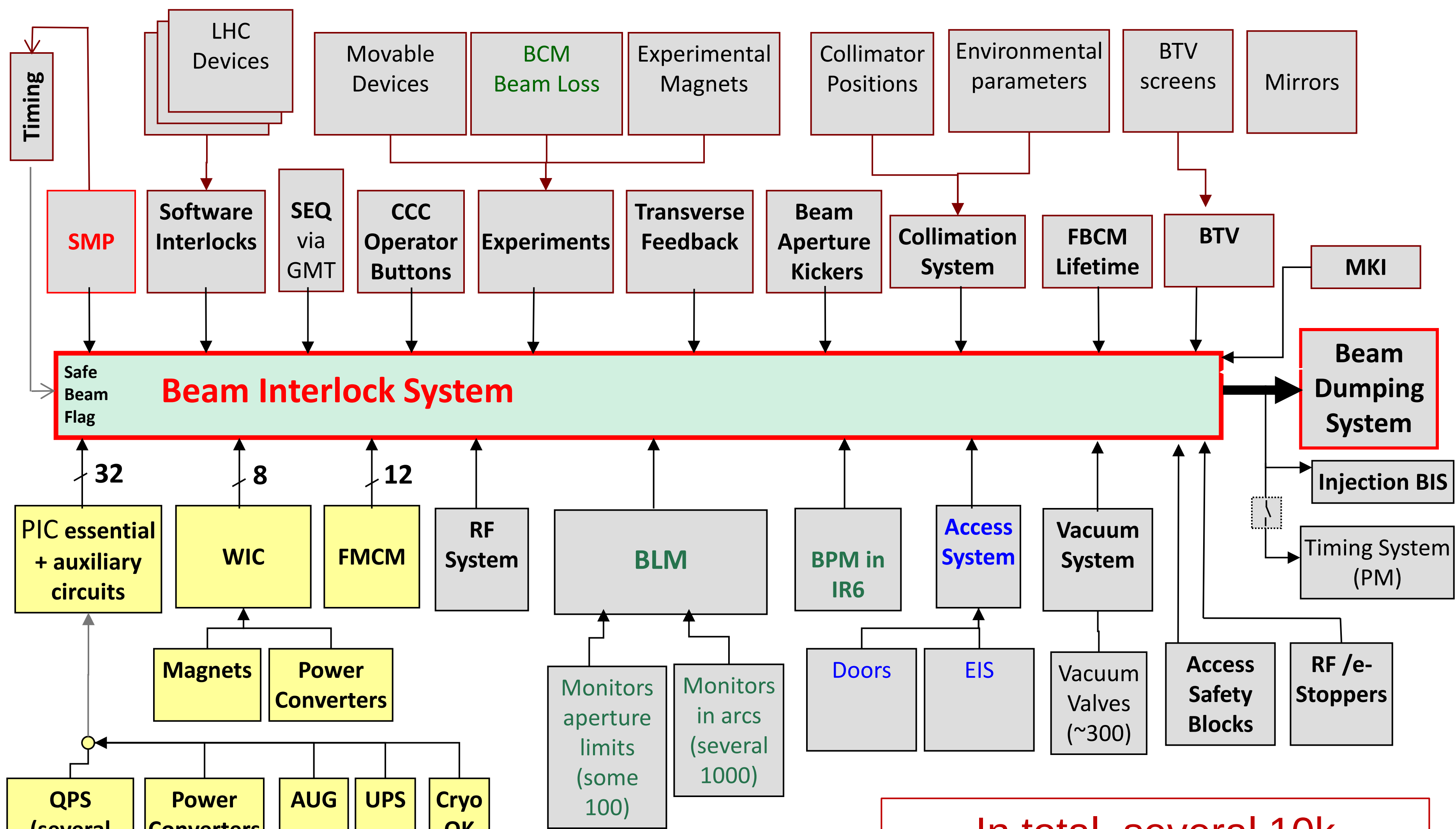
Interlock Systems

LHC Interlock Systems and inputs



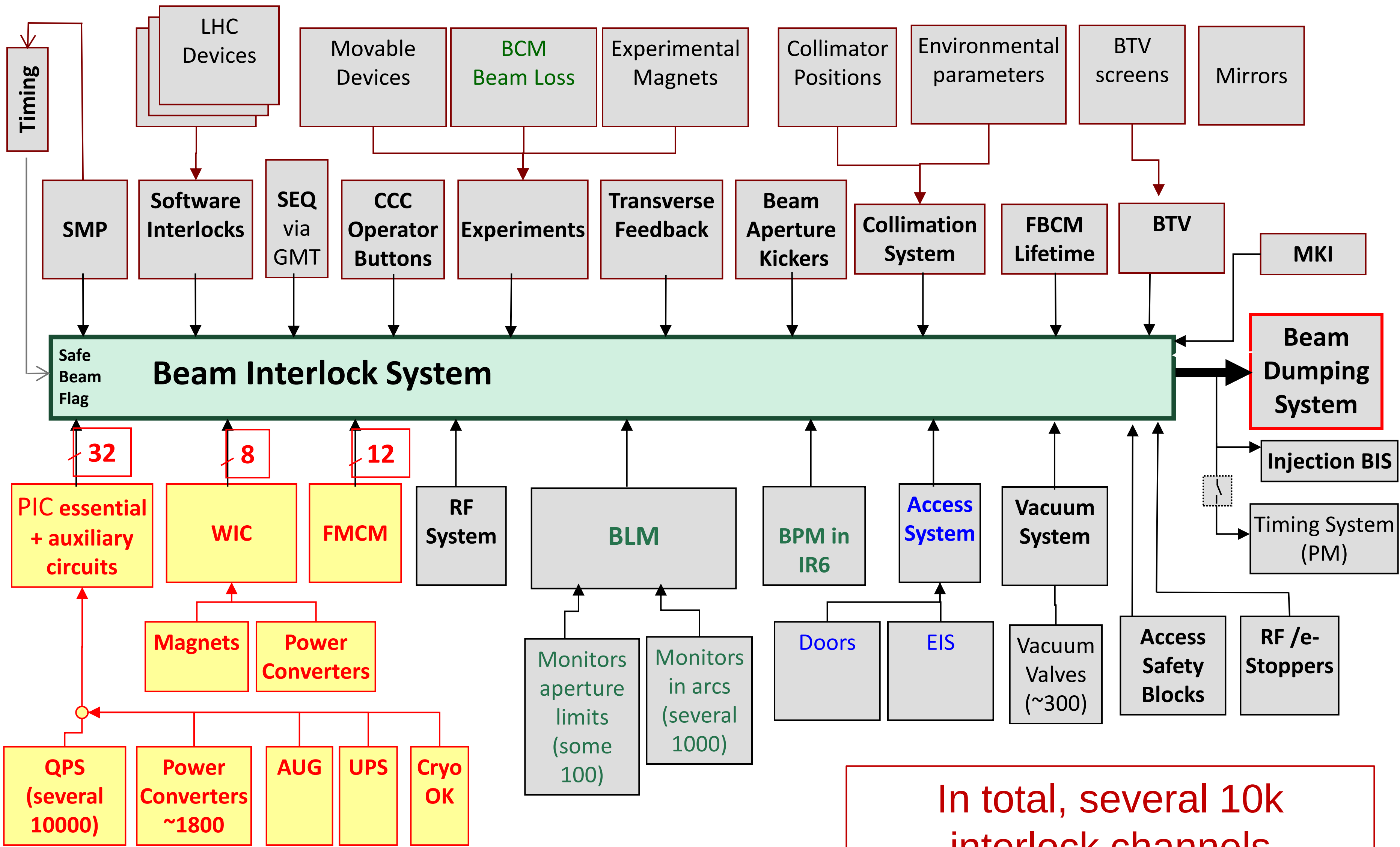
In total, several 10k interlock channels

Beam Interlock Systems



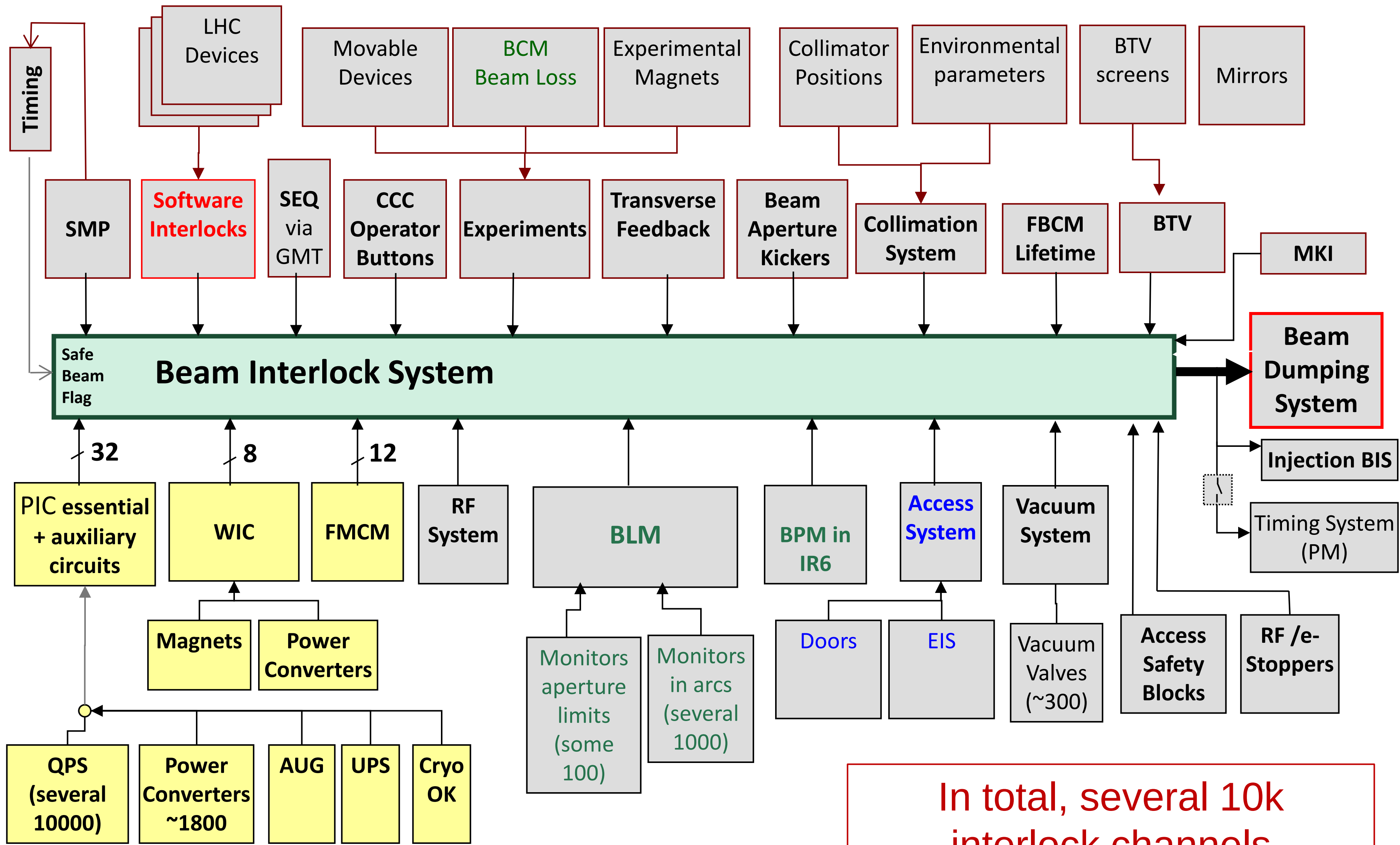
In total, several 10k interlock channels

Powering Interlock Systems



In total, several 10k interlock channels

Software Interlock Systems



In total, several 10k interlock channels

Will the machine ever work with so many interlocks ?

YES: LHC works!   but…..

1. Commissioning: it does not automatically work from day 1
   - Wildly bypassing interlocks …. there is lot of experience with such approach….
   - Plan for disabling interlocks in the machine protection design

2. Set-up beam flag
   - For low beam intensity / energy, it is possible to IGNORE interlock conditions
   - If parameter for set-up beams are violated – interlock becomes active
3. Design machine protection systems with availability in mind
   - Using redundancy
   - Demonstrating availability
   - 3600 BLMs rarely trigger a beam dump

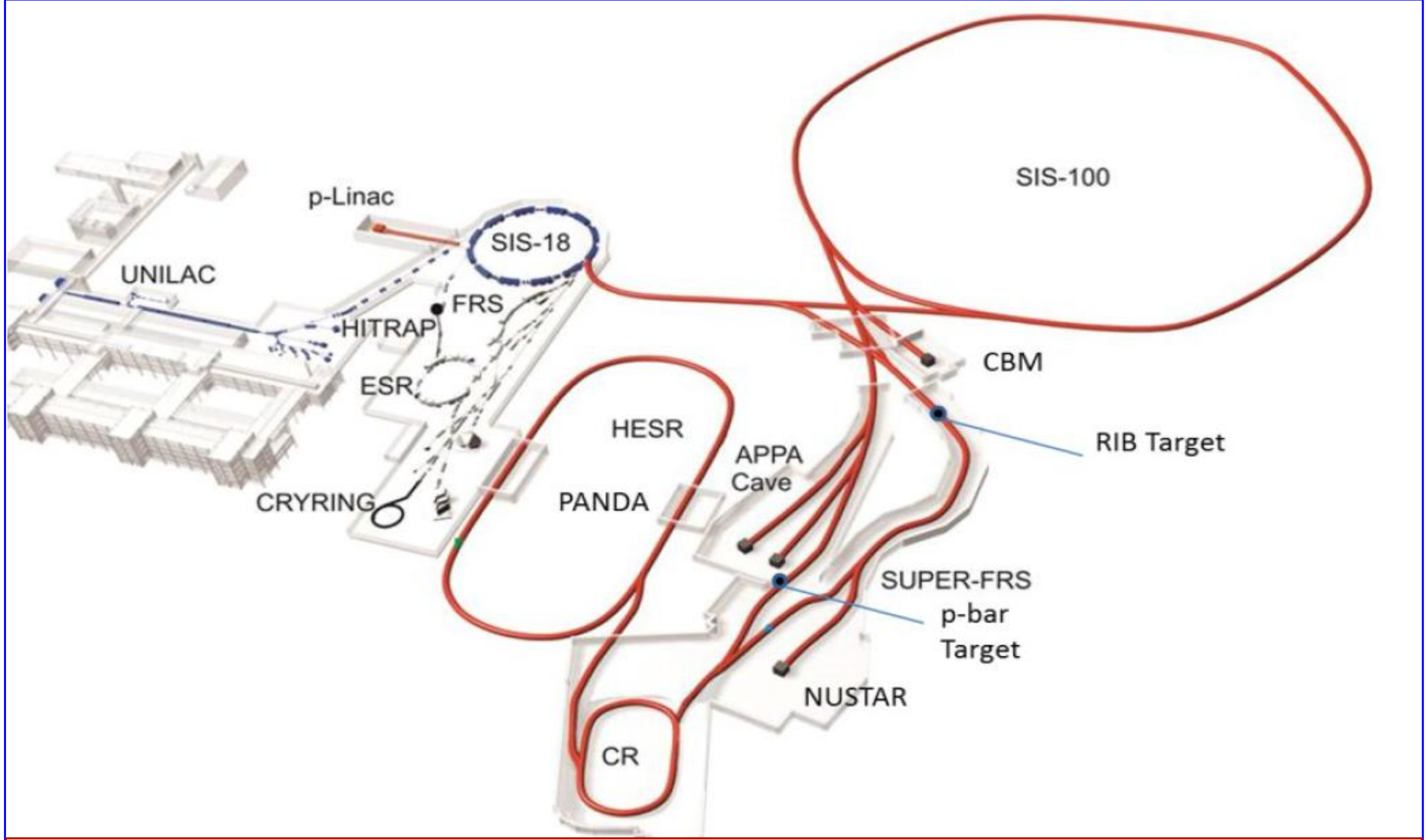
MP systems: design recommendations

- **Avoid** (unnecessary) **complexity** for protection systems
- **Failsafe** design
  - Detect internal faults and remote testing, for example between two runs
- Critical equipment should be **redundant** (possibly diverse)
- Critical processes not by software and operating system
- No remote changes of most critical parameters
- **Calculate safety / availability / reliability**
  - Use methods to analyse critical systems and predict failure rate
- **Managing interlocks**
  - See “setup beams”
- **Time stamping** for all system with adequate **synchronisation**
- **Keep safety** (protection of people) and **machine protection strictly separate**

MPS strategy (e.g. LHC, LINAC4, CLIC, …)

1. A strategy to limit the rate with which magnetic fields and device positions can change.
2. A post cycle beam and equipment quality assessment system to inhibit the next cycle when performance parameters are outside predefined limits. A beam restart system: i.e. an intensity ramp sequence provides an appropriate protection depending on the machine mode and state.
3. A version control and parameter change authorization system.
4. A fault recording, analysis and playback system (Logging, Post Mortem).
5. Written procedures to introduce changes in the parameters that control the machine protection system.
6. A set of test procedures to thoroughly test the components of the machine protection system after each change in the system.
7. A spares policy to reduce the loss of operational availability caused by unavoidable beam damage to equipment.
8. A different culture in the Lab – "Safety Culture"

FAIR Machine Protection



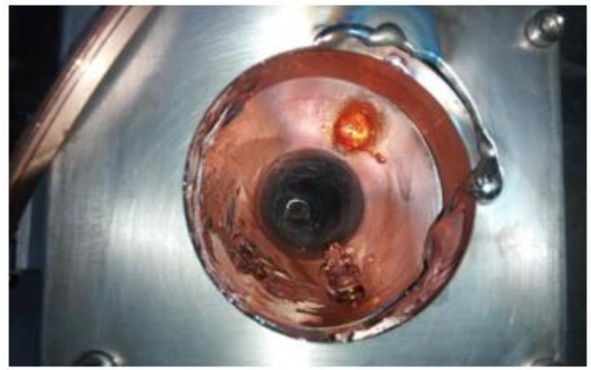
- For proton beams, SIS100 has about 30 times more energy stored compared to SIS18
- Challenge is not the extremely large energy or power, but the flexibility, operating with low and high beam current and different particle species
- Damage is already possible for little energy

Machine protection…….

- is not equal to interlocks
- 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
- for LHC, the Machine Protection Working Group was created in 2001 and is still active

Chinese ADX CW SRF Linac Demo

Farady cup and valve damage



Farady cup damage and cryo module degradation

Valve damage

The broken fast valve

Energy released in the order of a few to several 10 kJ

After 3 beam accidents within 2 years at the Chinese ADX CW SRF Linac Demo

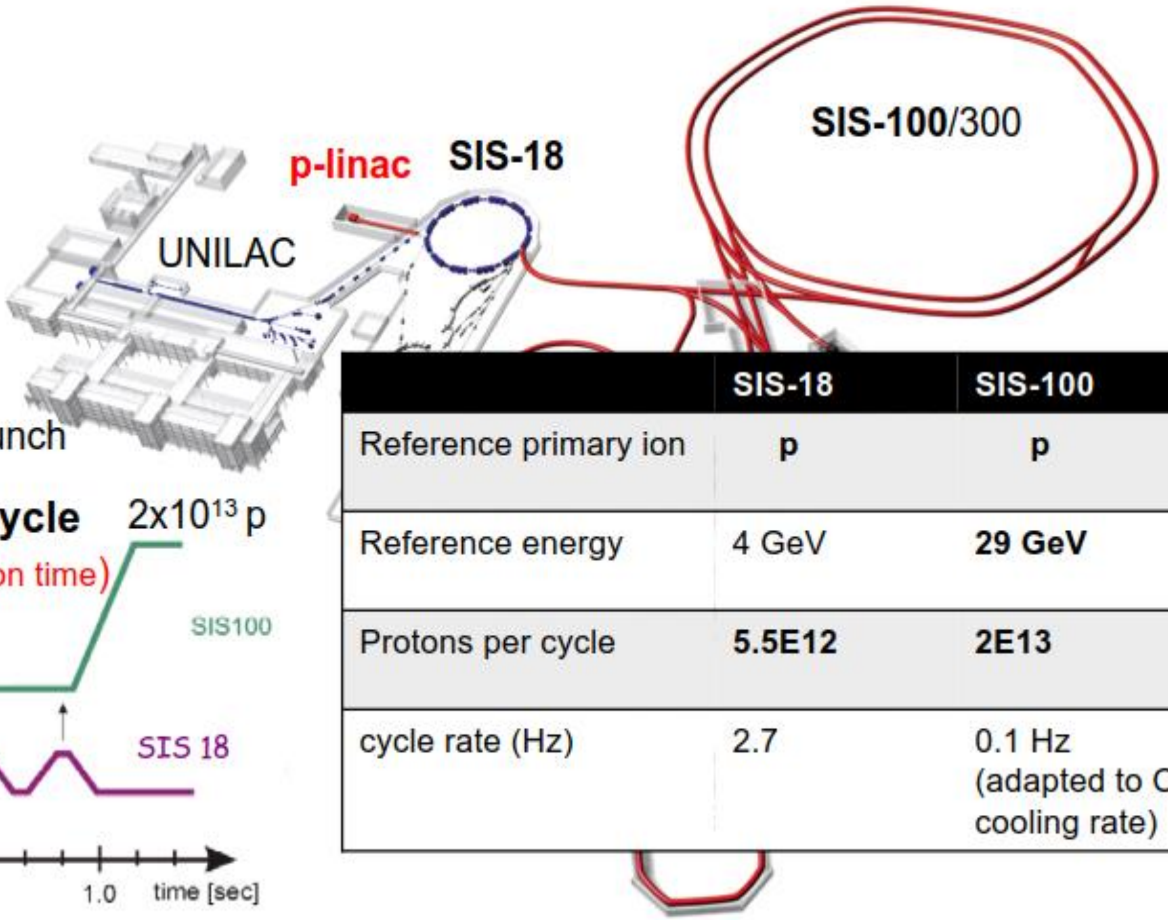
lessons and experiences

Lessons

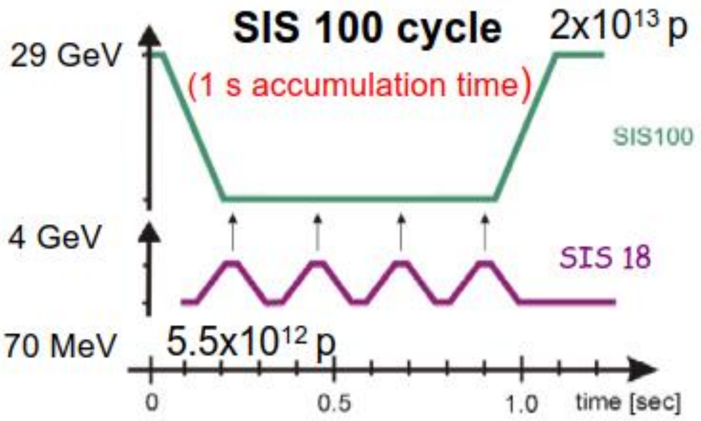
- MPS, MPS, MPS …….
    1. Self-check function of MPS is important. To make sure every action is in order in advance.
    2. All trigger levels of detector in MPS should be defined carefully, and be free of noise, such as vacuum gauges, BPMs
    3. The executive component MUST be reliable.
    4. Do not bypass any MPS signal until it is well understood.
- The protection logic
    1. Interlock system itself should not recover beam until be reset manually, such as chopper.
    2. Action sequences of inserting devices should be clearly defined to minimize the damage of machine.
- Some other lessons
    1. Operation regulations
    2. Direction signal of beam on the FC/DUMP/target is important, for example, an optical camera system is very important at beginning stage.
    3. Double check lattice during beam power ramping up.
    4. Stop high power beam to analyze any abnormal or strange phenomena.
    5. ……

Reserve

FAIR primary beam chain: Protons



SIS-100 extraction:
Single, short (50 ns) bunch



	SIS-18	SIS-100
Reference primary ion	p	p
Reference energy	4 GeV	**29 GeV**
Protons per cycle	**5.5E12**	**2E13**
cycle rate (Hz)	2.7	0.1 Hz (adapted to CR cooling rate)

Optional: 8 injections and up to 4E13 protons ('space charge limit').

Observations at various accelerators

Some observations

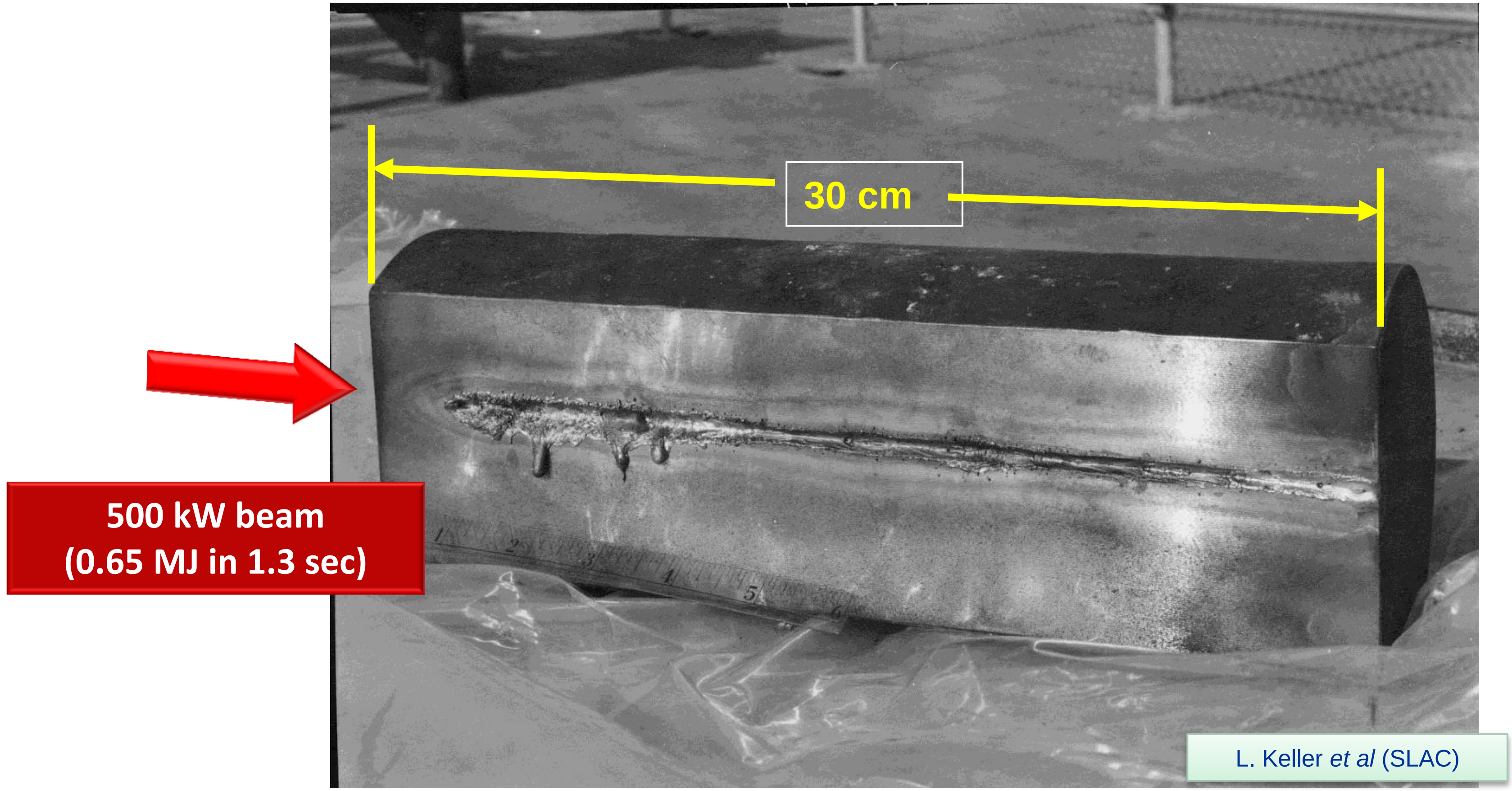
- Several accidents happened during injection and extraction of beams (SPS-proton-antiproton collider, SPS fixed target-TT40, J-PARC)
- An accident happened when operating with circulating beams (Tevatron)
- An accident happened during beam commissioning at very low energy (CERN-Linac4)
- A very serious accident happened at LHC during superconducting magnet commissioning (no beam operation)
- Several accidents happened at the ADS CW SRF Linac Demo in China (beam power few kW, design few MW)
- On several occasions it was observed that accelerator components were heating up and deforming due to the interaction of high intensity beam with the environment (beam instruments, bellows, …)

Accidents at accelerators in the past

Accident: **An unfortunate incident** that happens unexpectedly and unintentionally, typically **resulting in damage** or injury.

- SLAC: Damage Test 1971
- SPS proton antiproton collider 1986: Damage of UA2
- Tevatron proton antiproton collider 2003: Damage of collimator
- SPS synchrotron 2004: Damage of transfer line TT40
- SPS – TT40 Damage Test 2004
- LHC magnet powering: Severe damage of magnet system
- LINAC 4 (2013) at very low energy: Beam hit a bellow and a vacuum leak developed
- JPARC 2013: Damage of target – release of radioactive material

- Damage test of a 30 cm long **Copper** Block (SLAC – **1971**)
- A ~2-mm 500 kW Beam enters a few mm from the edge.
- It took about 1.3 sec to melt through the block (slow accident).



CERN-SPS Proton Antiproton Collider

- Build as proton synchrotron to accelerate protons to 450 GeV and direct beam on a target for Fixed Target Experiments starting in 1978
  - Normal conducting magnets, no ultrahigh vacuum required
- Transformed the SPS accelerator from a Fixed Target Synchrotron into a Proton Antiproton collider in 1980 … 1982
- Operating as Proton Antiproton Collider until 1990
- Once, injected beam went for 10 min into the UA2 experiment … not appreciated: do not forget the **protection of the experiments**
- **Antiprotons are very rare**, takes a **long time** to produce them
- Sometime the beams were lost …….. many hours to produce a new stack of antiprotons
- **Lessons** from SPS Proton Antiproton Collider:
  - **Protect the experiments**
  - **Protect the beam**

CRN-SPS Proton Synchrotron

- Very different parameters from Proton Antiproton Collider
  - Cycle time in the order of some seconds to some ten seconds, high intensity beams
  - Used for fixed target physics, neutrino production and as injector for LHC
  - Requirements for the vacuum system are moderate
- If the beam is lost … no big issue, wait for next cycle

  …. however, beam losses should not lead to damage
- Beam current constantly being increased over the years
- Operating in different modes with different extraction lines
- Several (minor) accidents during the history of the SPS by beam induced damage
  - Damage, e.g. replacing a magnet, can be fixed in a short time (< one day)
- **Lesson from SPS Proton Synchrotron: Protect the machine from uncontrolled beam losses**

Damage to silicon detector in UA2 at SPS

- Damage to the silicon detector in the UA2 experiment at the Proton Antiproton Collider
- The beam was injected for about 10 minutes
- The electrostatic separators, normally used to create an orbit bump at the experiment, were still set to high energy
- The bump directed the beam directly into UA2

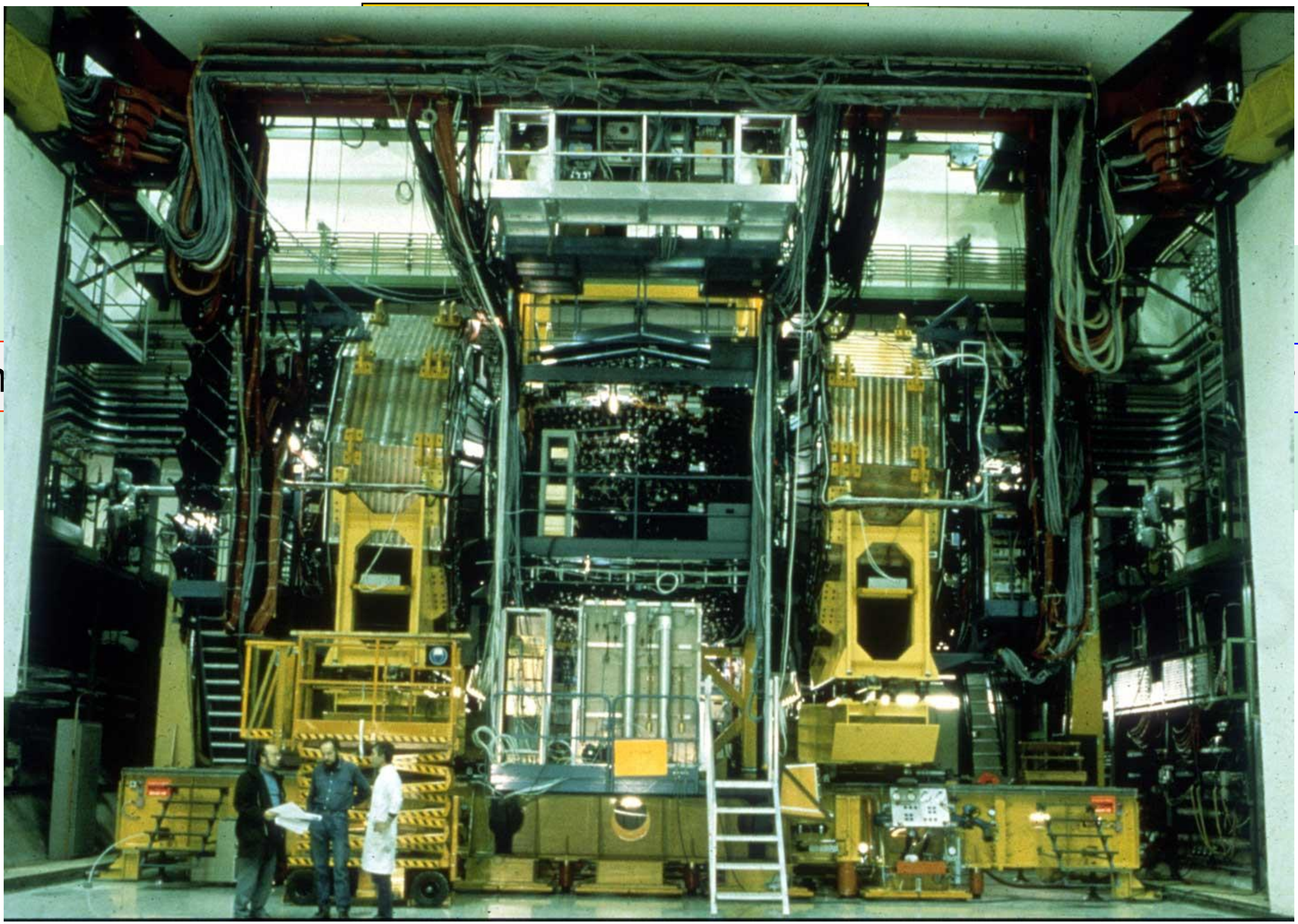
5. SILICON PAD DETECTORS IN THE UA2 SPS COLLIDER EXPERIMENT

5.1 Outer Si array during 1987 and 1988

The 1 m^2 area Si detector array [6] built at Ø 30 cm around the UA2 interaction region suffered a major degradation on 10 December 1987, as seen from the pedestal width measurements illustrated in fig. 6. For ~ 10 min. a severe beam loss occurred during a machine development session. At the end of 1987 run the integrated dose of ionizing radiation was found to be 30 Gy (3 krad) and the neutron flux (3–25 MeV) had been 2.8×10^9 cm^{-2}. The degradation of reverse currents for the pads on one board is shown graphically in fig. 7. The distribution of the current increase ΔI_l for about

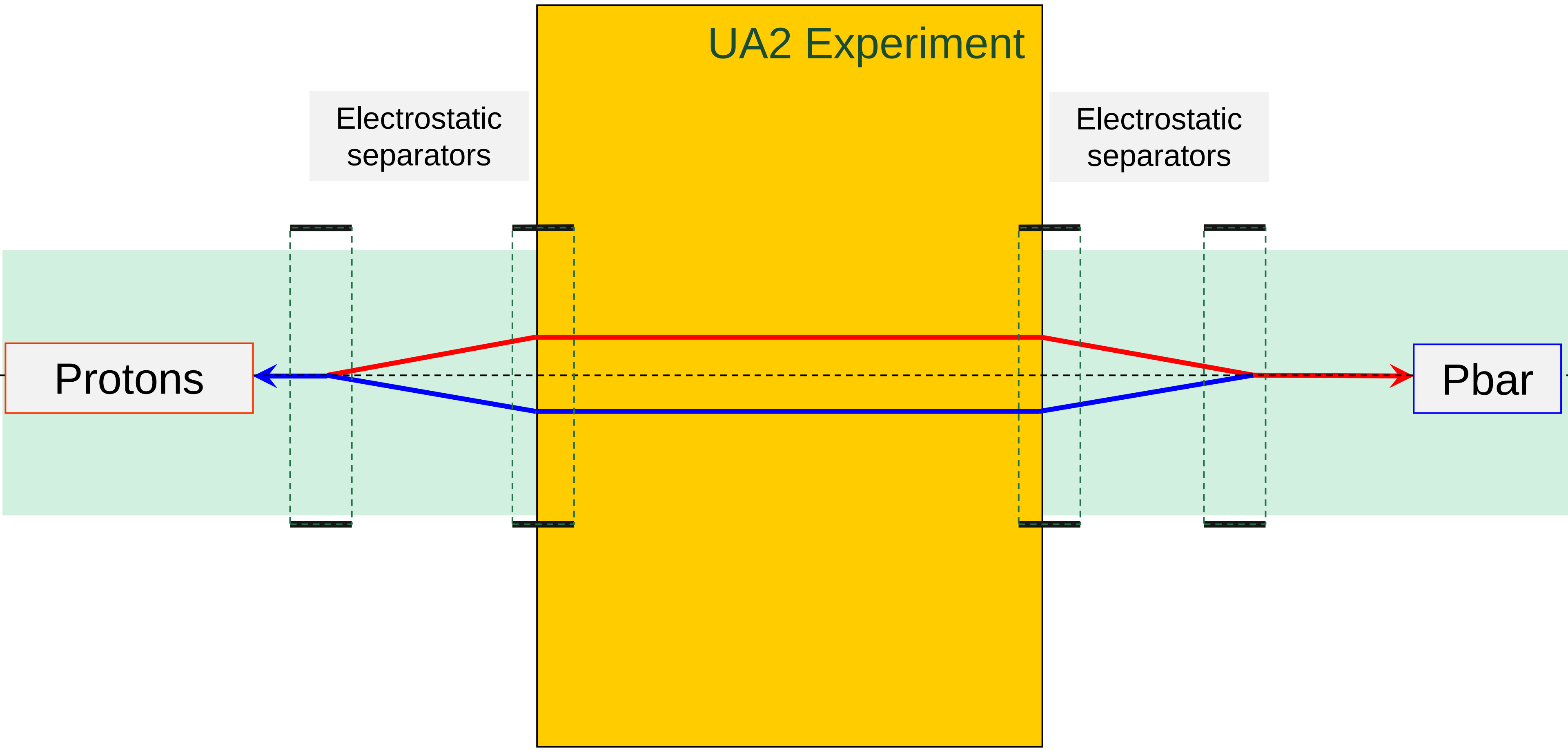
Colliding beams in UA2

Proton



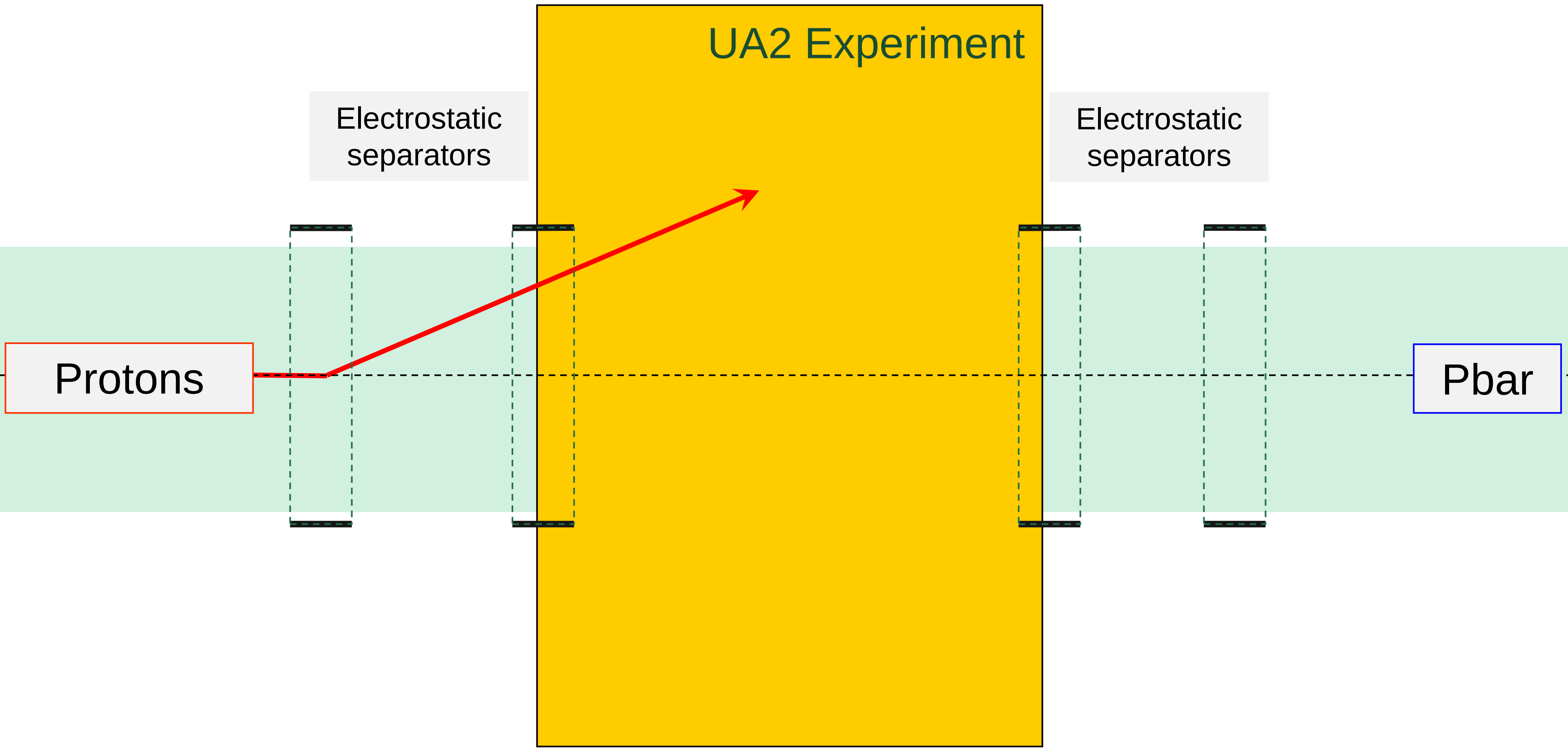
bar

Separation bump



- The beam needed to be **separated at injection energy of 26 GeV and during the energy ramp to 315 GeV**
- This was done with electrostatic separators that were also ramped

….try to inject beam

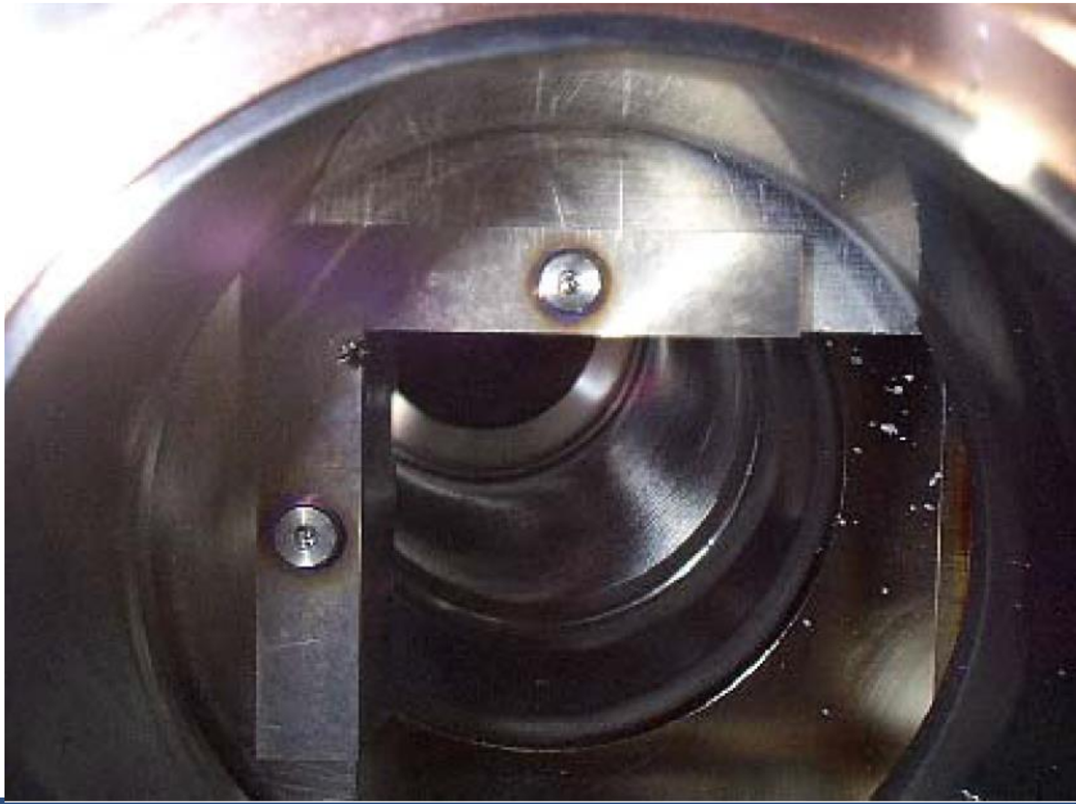


- One day, for injection at 26 GeV, the separators were left at the setting for 315 GeV – much too large angle, and operation was surprised to see not circulating beam - **using UA2 as a beam dump**

Tevatron accident

December 5, 2003, 16 house quench during the end of a proton-antiproton colliding beam store followed by the damage of two collimators used for halo reduction at the CDF and DØ interaction points. A cryogenic spool piece that houses correction elements was also damaged as a result of helium evaporation and pressure rise during the quench, requiring 10 days of Tevatron downtime for repairs.

- 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
- BLMs switched off during ramp

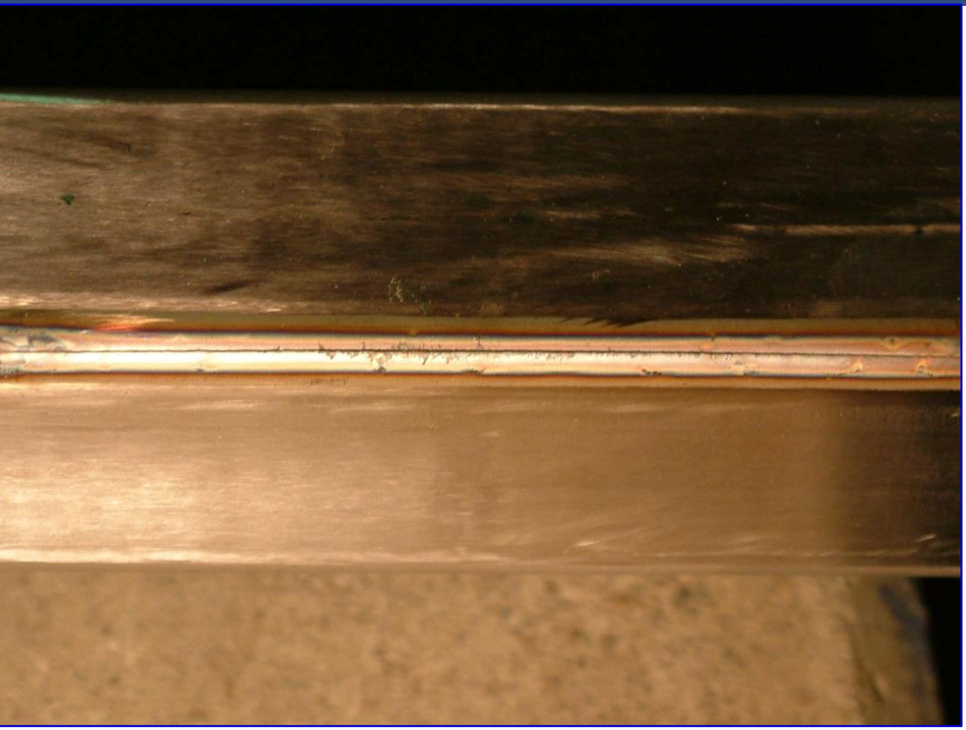


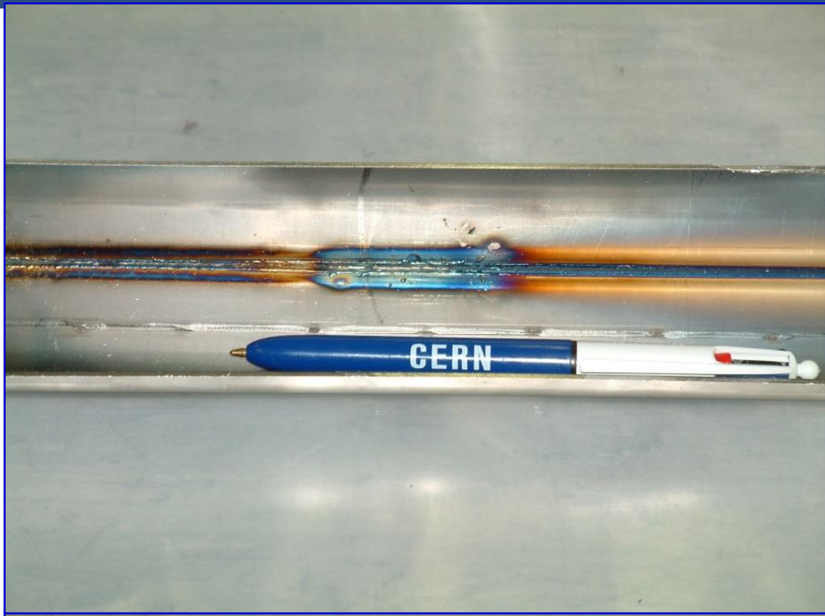
HERA proton collimator in 2003

- HERA collimators – 5 mm grove, never noticed during operation, only when machine was opened

https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/talks/bjh_6_06_talk.pdf

Vacuum chamber in SPS extraction line incident





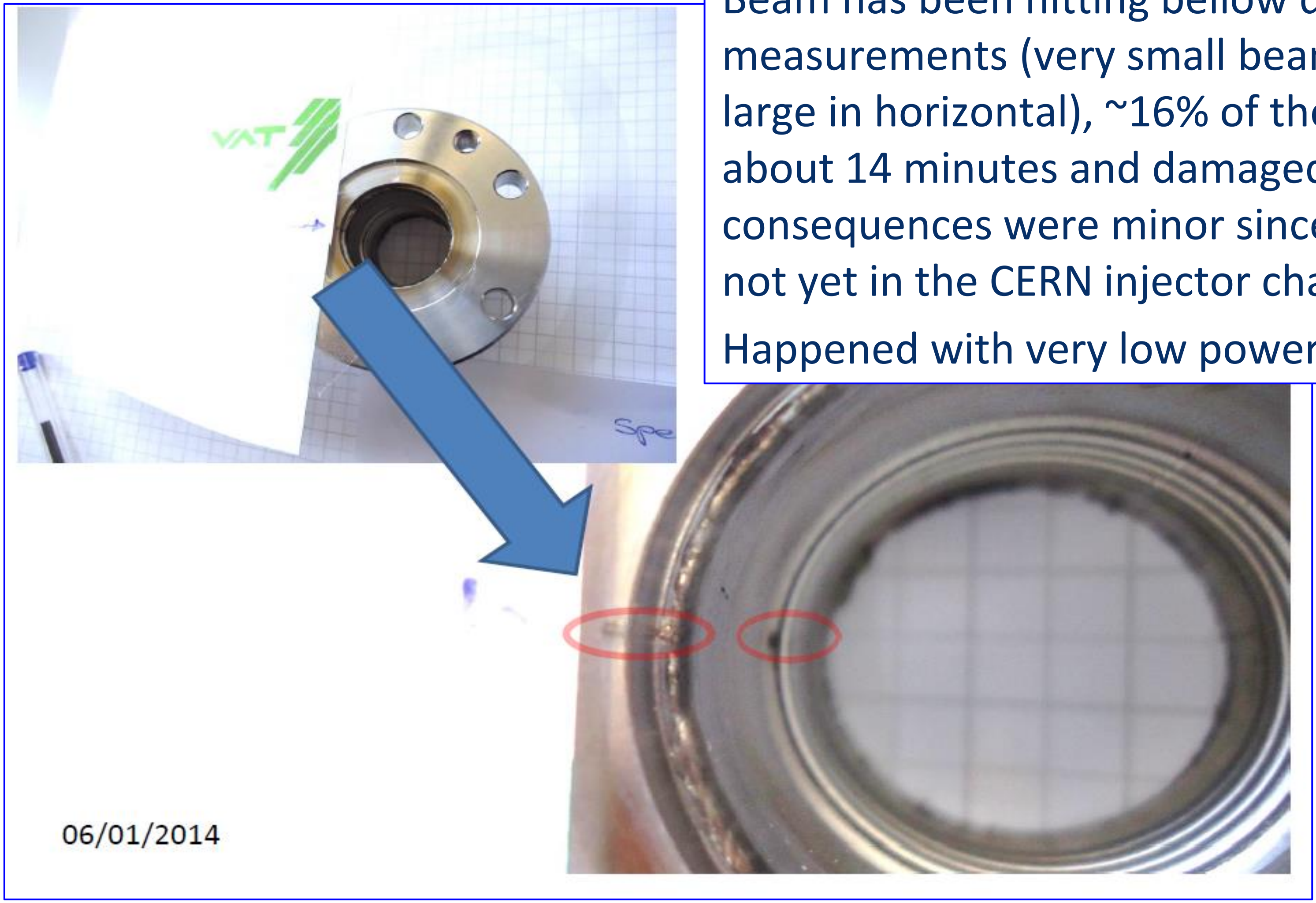
- 450 GeV protons, 2 MJ beam in 2004
- Failure of a septum magnet
- Cut of 25 cm length, groove of 70 cm
- Condensed drops of steel on other side of the vacuum chamber
- Vacuum chamber and magnet replaced

CERN-LINAC 4 during commissioning at 3 MeV

On 12 December 2013 a vacuum leak on a below developed in the MEBT line.

Beam has been hitting bellow during special measurements (very small beams in vertical, large in horizontal), ~16% of the beam lost for about 14 minutes and damaged the bellow. The consequences were minor since LINAC4 was not yet in the CERN injector chain.

Happened with very low power beam (few W).

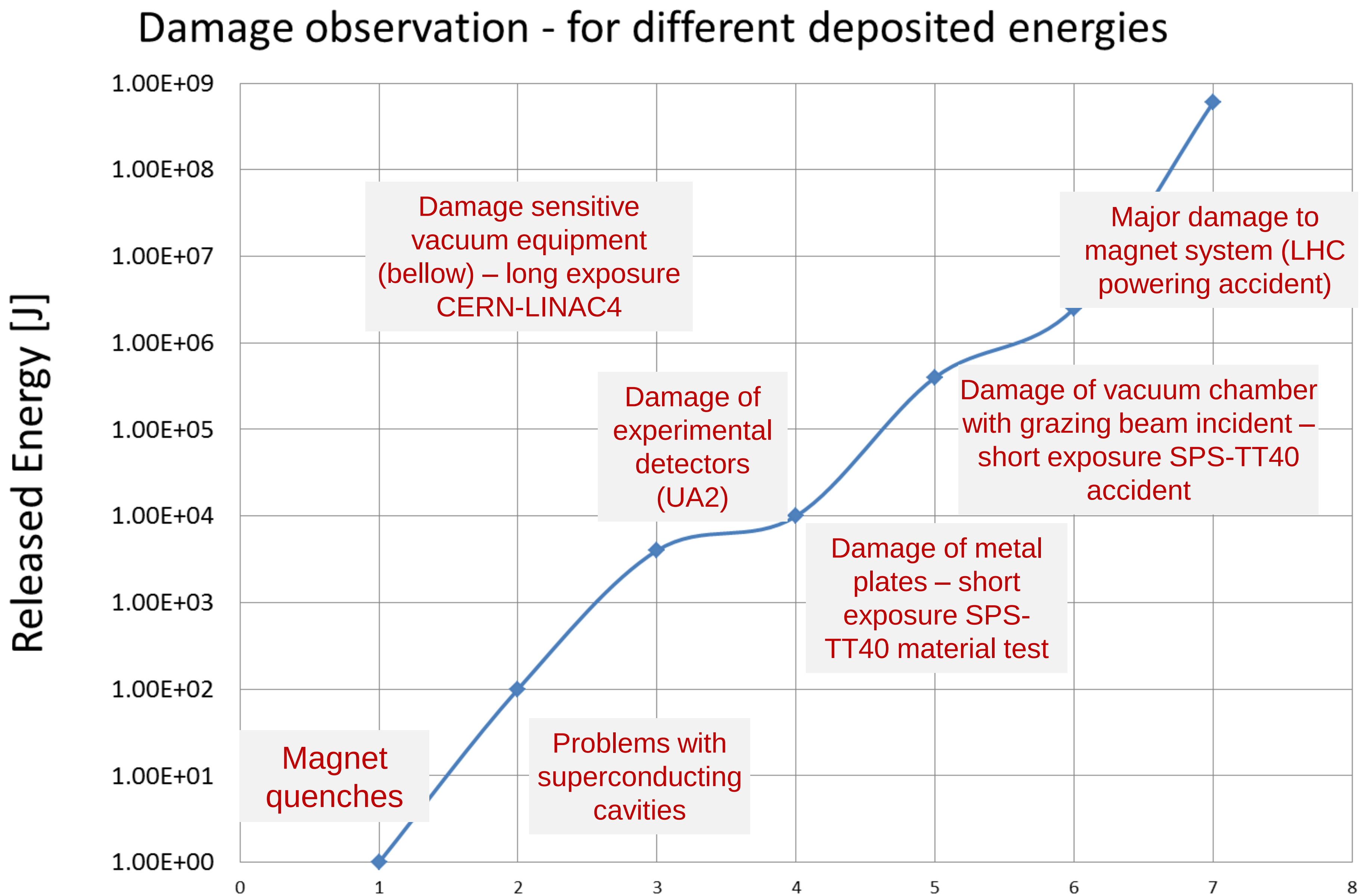


A.Lombardi

J-PARC radioactive material leak accident

- A radioactive material leak accident occurred at the Hadron Experimental Facility on May 23, 2013.
- The accident was triggered by a **malfunction of the slow extraction system** of the Main Ring synchrotron (MR). May 2013, one of the spill feedback quadrupole magnets, Extraction Quadrupole (EQ), malfunctioned.
- A beam consisting of $2x10^{13}$ protons was extracted within a very short time of 5 ms and delivered to the gold target in the HD facility, normally a total of $3x10^{13}$ protons were extracted for 2 s. **The gold target was instantaneously heated up to an extraordinarily high temperature** and partially damaged. The **radioactive material dispersed from the gold target** and **leaked into the primary beam-line room**, because the target container was not hermetically sealed.
- After **seven-month long shutdown** due to the accident, beam operation of the linac was restarted in December 2013.

Observed damage for deposited energy

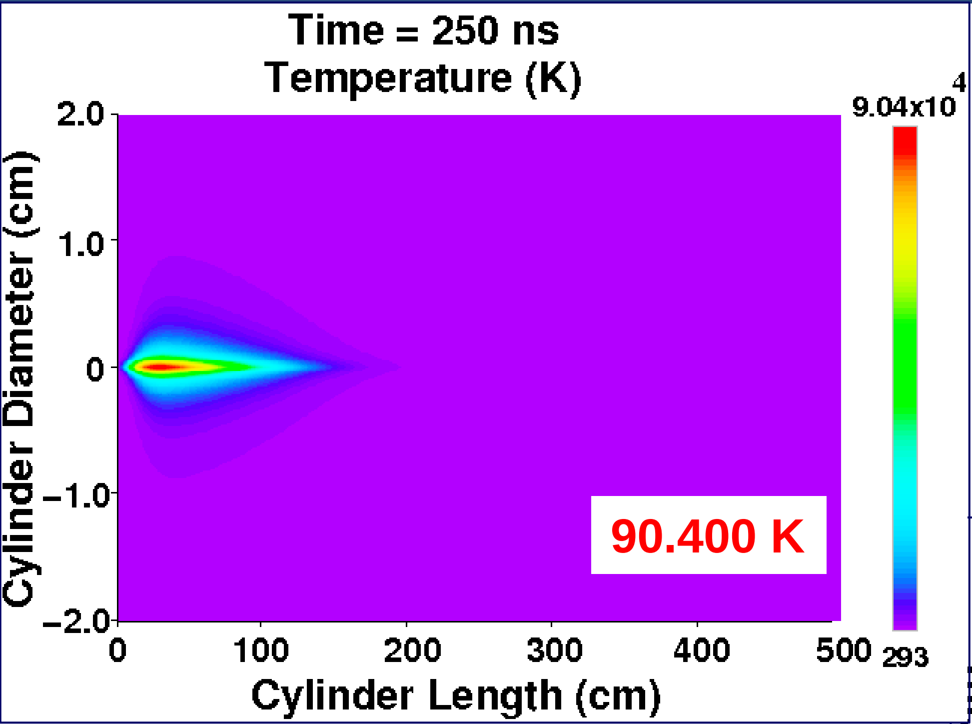


Hydrodynamic tunneling

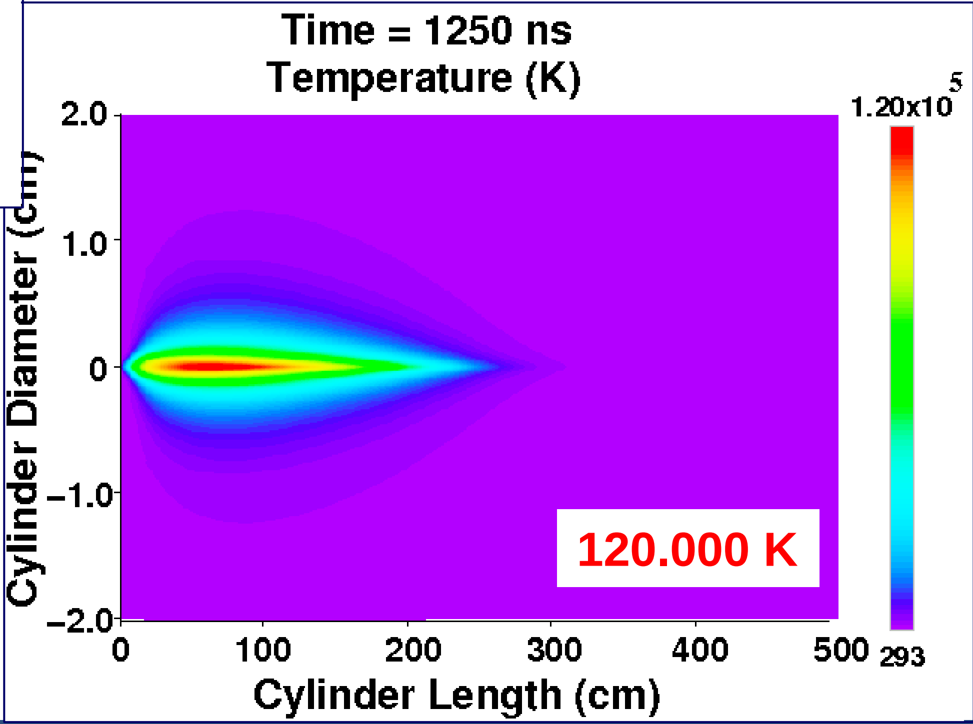
How to perform calculations?

- Assume **LHC Beam impacts** on **Solid Cylindrical Target**
  - 2808 bunches with 1.1×10^{11}protons, $\sigma = 0.5\ \mathrm{mm}$, 25 ns bunch distance, target length of 6 m, Radius = 5 cm, Density = 2.3 g/cm3
- The energy deposition for few bunches is calculated with FLUKA
- The hydrodynamic code BIG2 uses the 3d energy deposition to calculate temperature, pressure and density of the target
- The programs are run iteratively
  - FLUKA 3d energy loss data is used as input to BIG2
  - BIG2 3d density data is used as input for FLUKA
- The modified density distribution is used in FLUKA to calculate the energy loss corresponding to this new density distribution
- The new energy loss distribution is used in BIG2 which is run for time step
- LHC: **tunnelling of the beam through about 30 m** is expected

FCC: Temperature profile

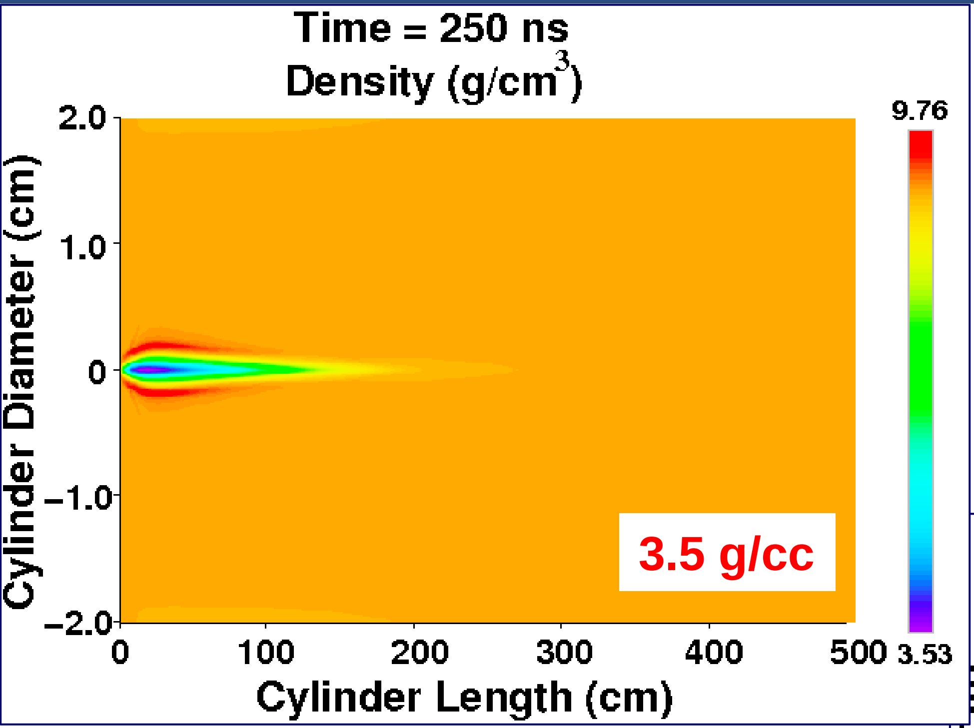


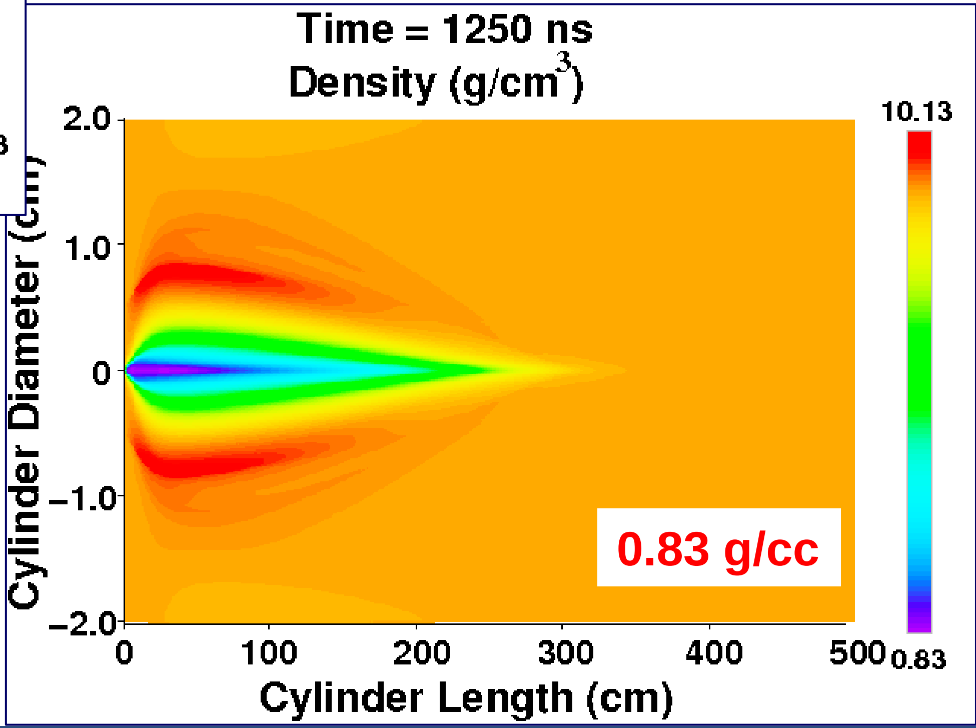
- FCC 100 km long accelerator.
- Particle energy of 40 TeV.
- Copper, Length = 5 m, Radius = 2 cm.
- The simulation took about 15 months.



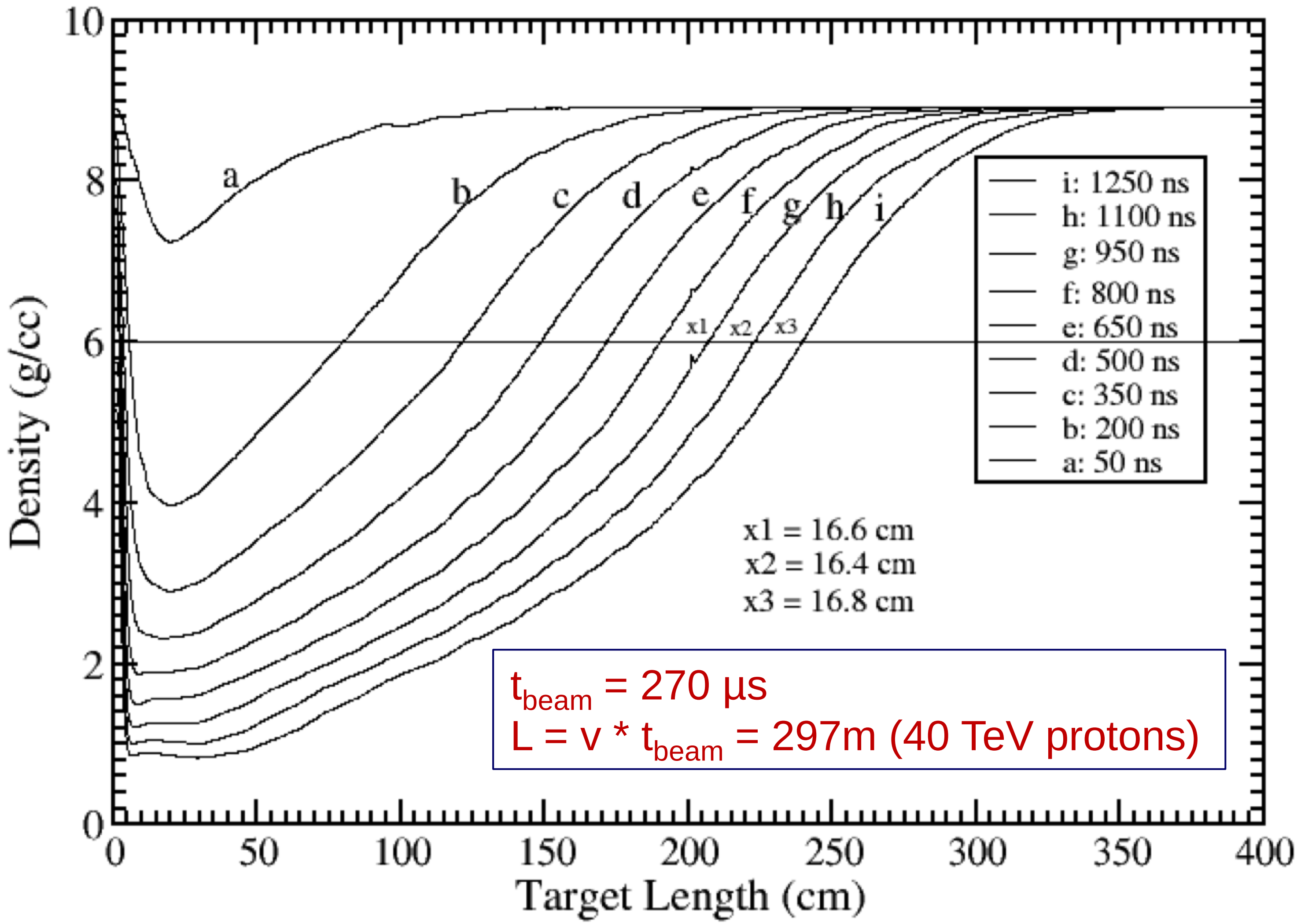
Naeem Tahir, Florian Burkart

Density profile





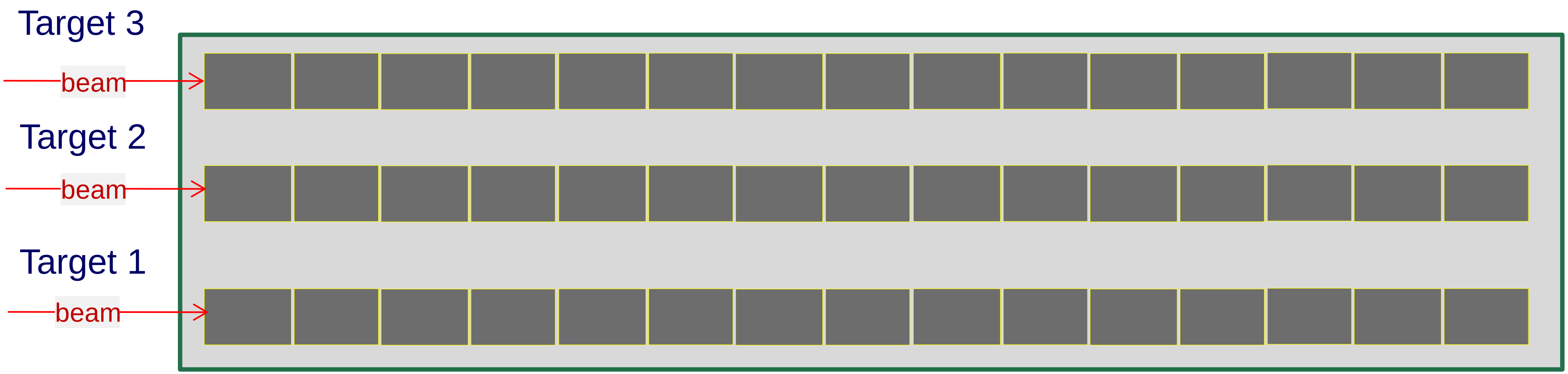
Density profile on axis



t_{beam} = 270 µs

L = v * t_{beam} = 297m (40 TeV protons)

Principle of the code validation experiment
using a copper target



Copper Target length of about 2 m

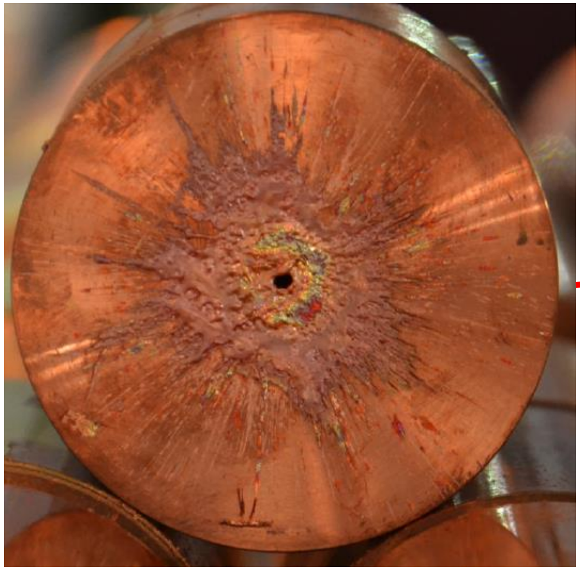
Target 1: 144 bunches ~1.9E11@50ns, 2.0mm σ -> no tunnelling expected

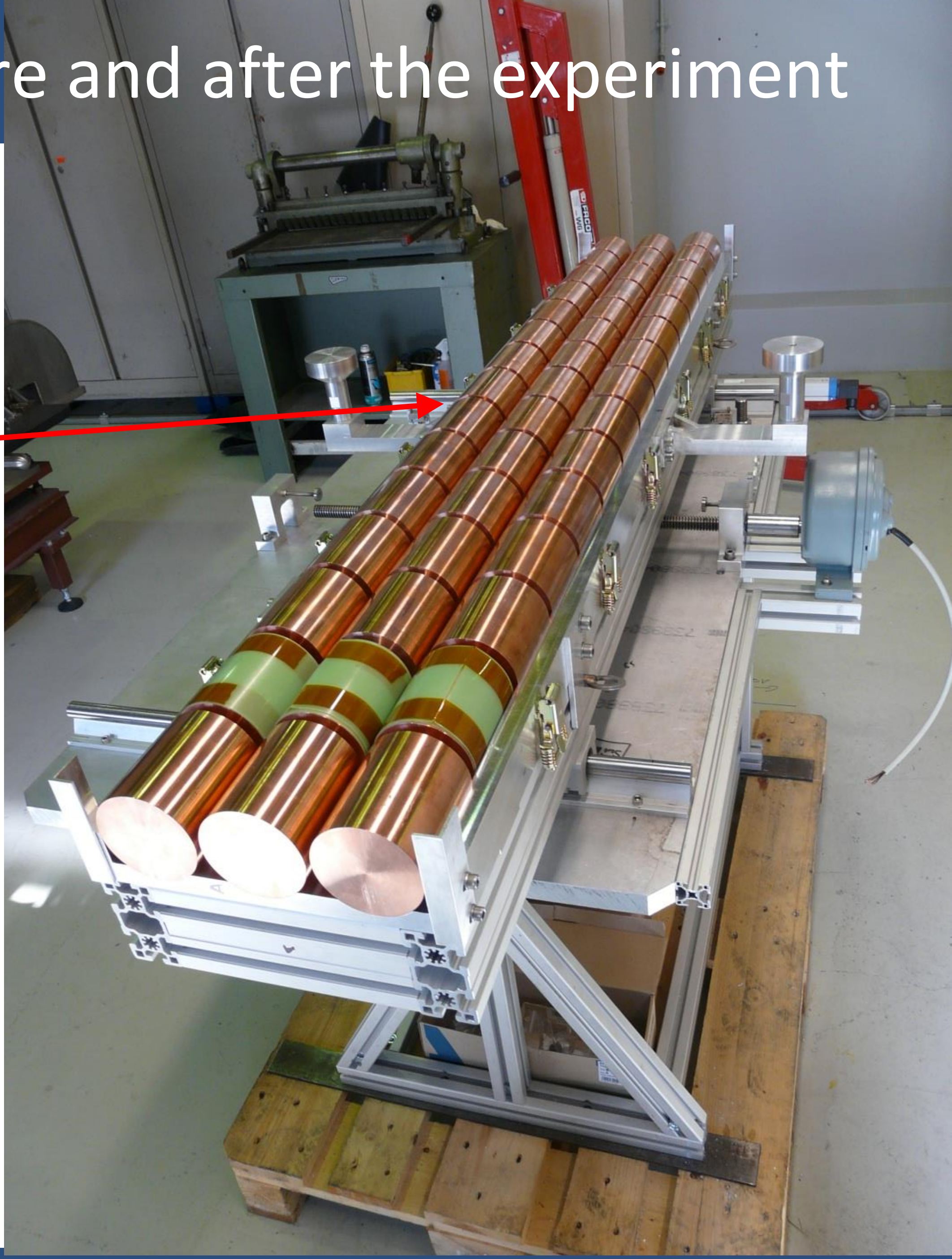
Target 2: 108 bunches ~1.9E11@50ns, 0.2mm σ -> tunnelling expected

Target 3: 144 bunches ~1.9E11@50ns, 0.2mm σ -> tunnelling expected

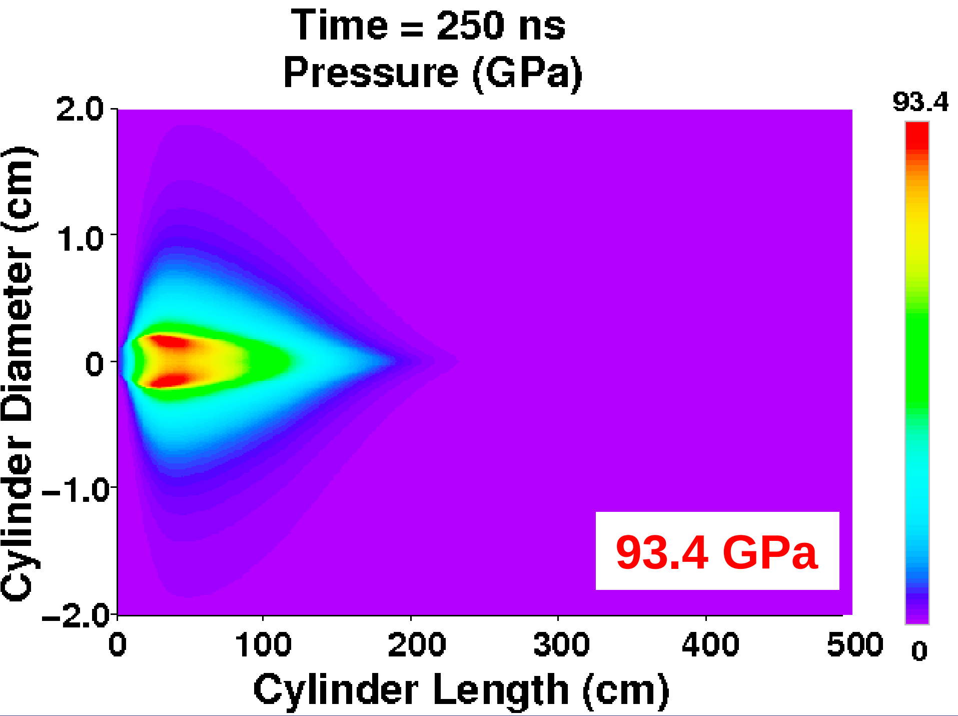
Juan Blanco, Florian Burkart, et al.

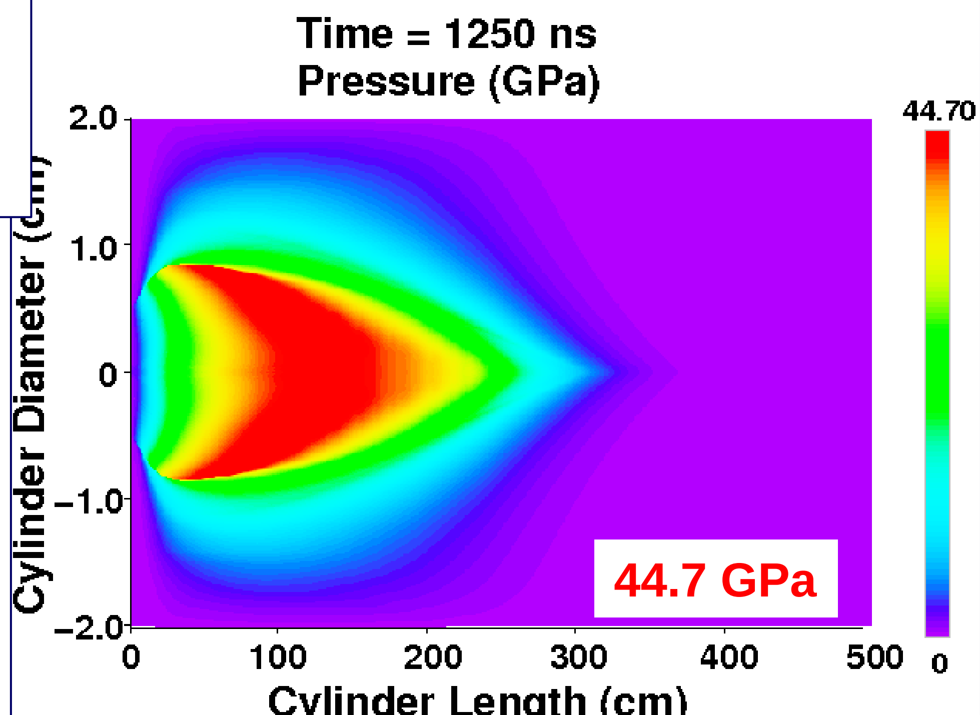
Copper target before and after the experiment

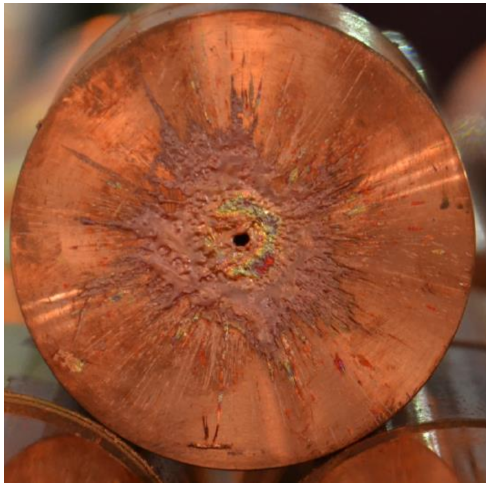




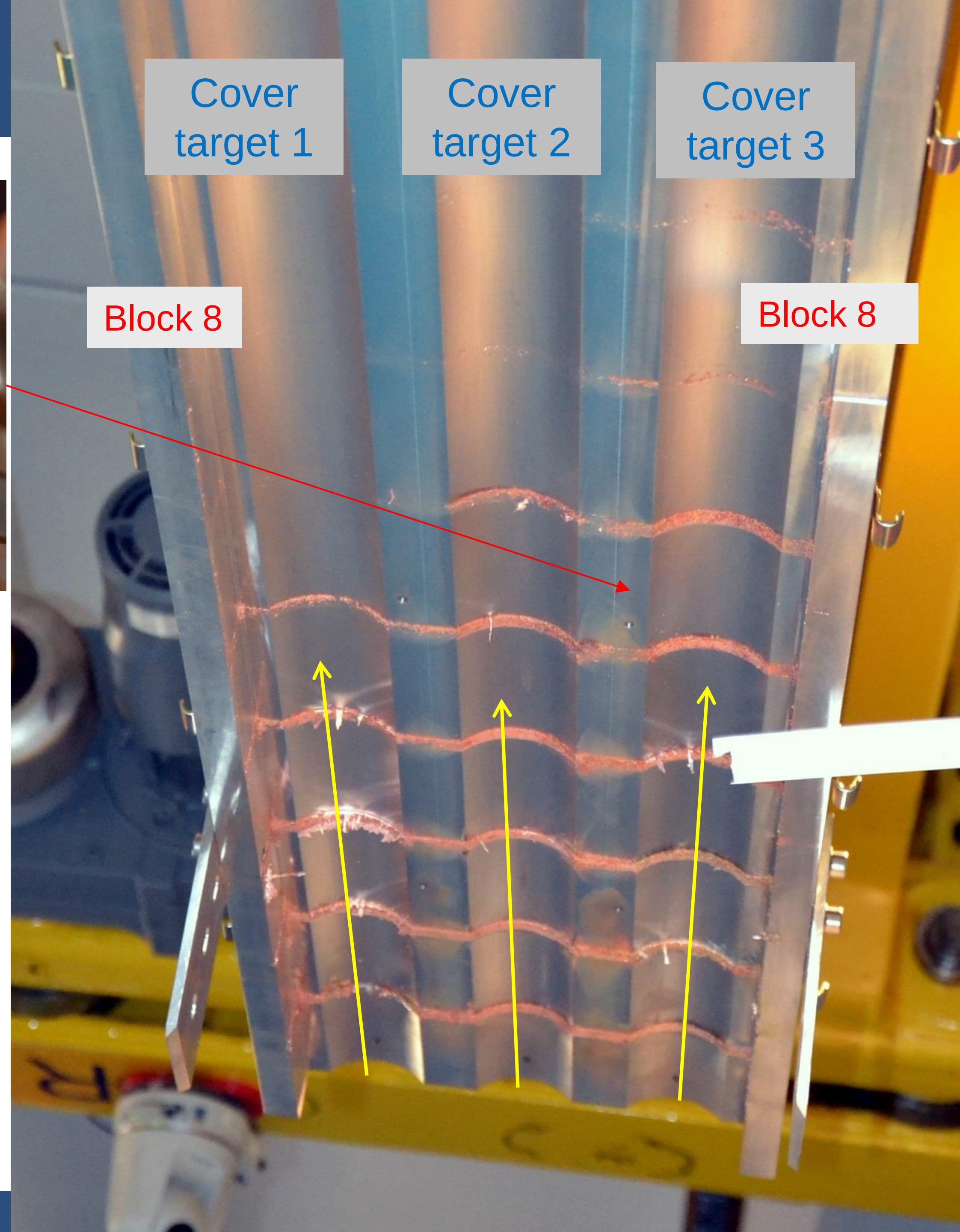
- The range of the beam in target 3 is larger than in target 1 and 2
- Clear indication for tunnelling


Time = 250 ns
Pressure (GPa)
93.4
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Diameter (cm)
Cylinder Length (cm)
93.4 GPa


Time = 1250 ns
Pressure (GPa)
44.70
2.0
1.0
0
−1.0
−2.0
0
100
200
300
400
500
Cylinder Diameter (cm)
Cylinder Length (cm)
44.7 GPa



- Cover of the targets: the molten copper escapes between the targets and leaves clear traces on the cover
- The range of the beam in target 3 is larger than in target 1 and 2
- Clear indication for tunnelling



Machine Protection and Collimation

Continuous beam losses: Collimation

Limitation of beam losses is in order of 1 W/m (high energy protons) avoids activation and allows 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 for 7 TeV operation

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

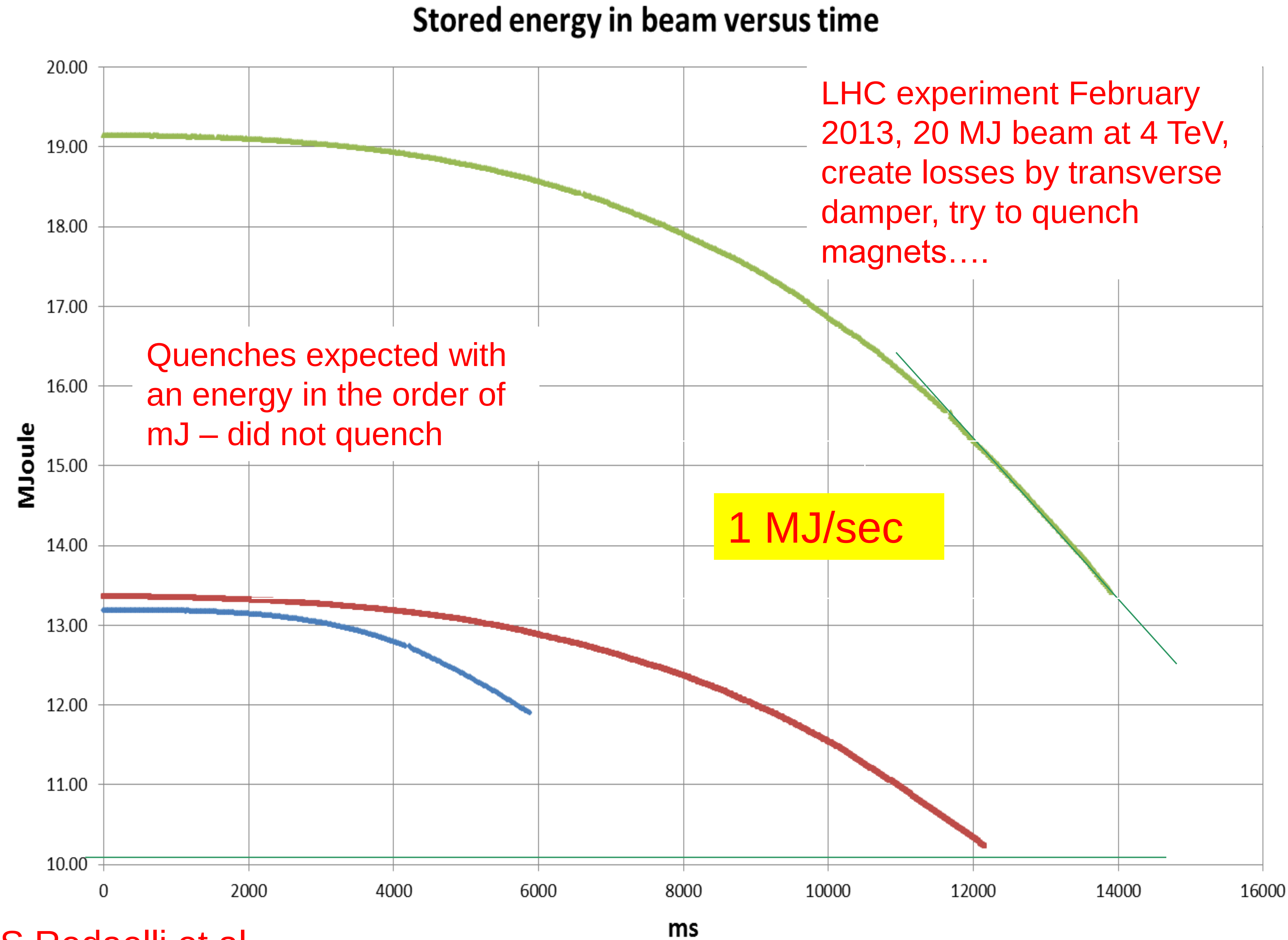
Continuous beam with a power of 5 MW (e.g. ESS)

- a loss of 0.1% corresponds to 5 kW – not to be lost along the beam line to avoid activation of material, heating, quenching, …
- assume a length of 500 m: 10 W/m, not acceptable
- ~0.01% of beam loss is the limit

….but also: capture fast accidental beam losses

Strategy for protection: Protection Systems

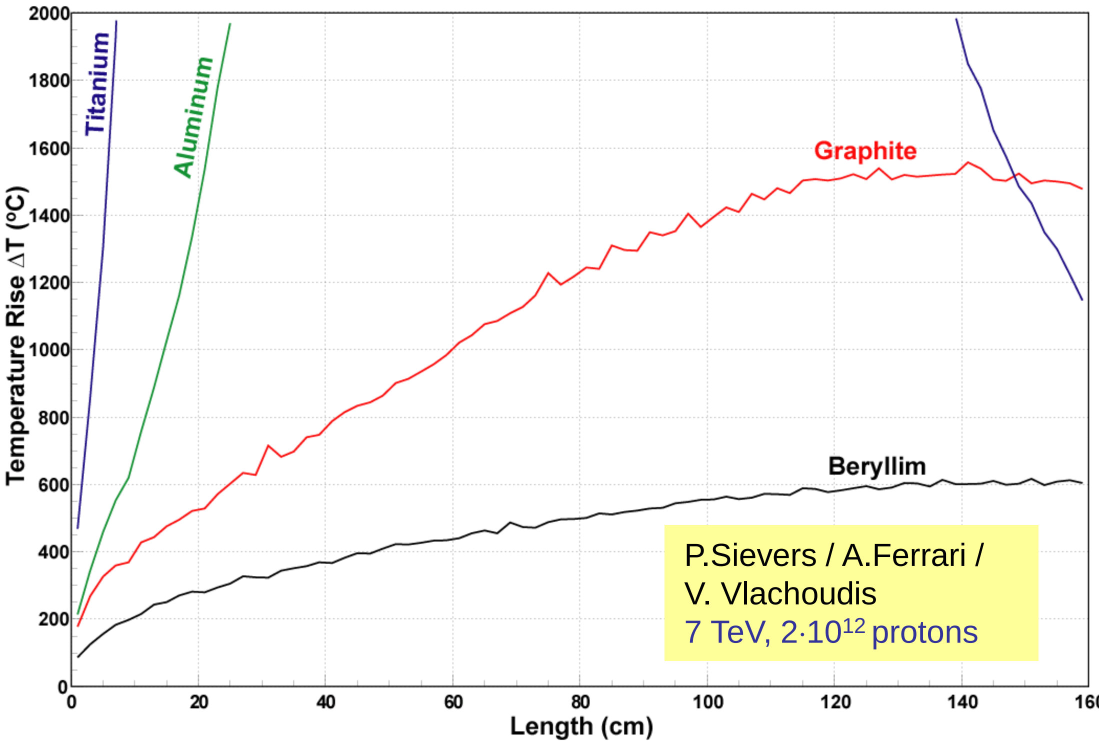
- Avoid that a specific failure can happen
  - time constants for element, such as magnet
- Detect failure at hardware level and stop beam operation
- Detect initial consequences of failure with beam instrumentation ….before it is too late…
- Stop beam operation
  - stop injection or at low energy (chopper)
  - extract beam into beam dump block
  - stop beam by beam absorber / collimator
- Elements in the protection systems
  - hardware monitoring and beam monitoring (beam loss monitors)
  - beam dump (fast kicker magnet and absorber block), chopper, RF
  - collimators and beam absorbers
  - beam interlock systems linking different systems



S.Redaelli et al.

LHC collimator material

- Metal absorbers would be destroyed
- Other materials for injection absorber preferred, graphite or boron nitride for the injection absorber, novel materials are being investigated
- In case of a partial kick (can happen), the beam travels further to the next collimators in th



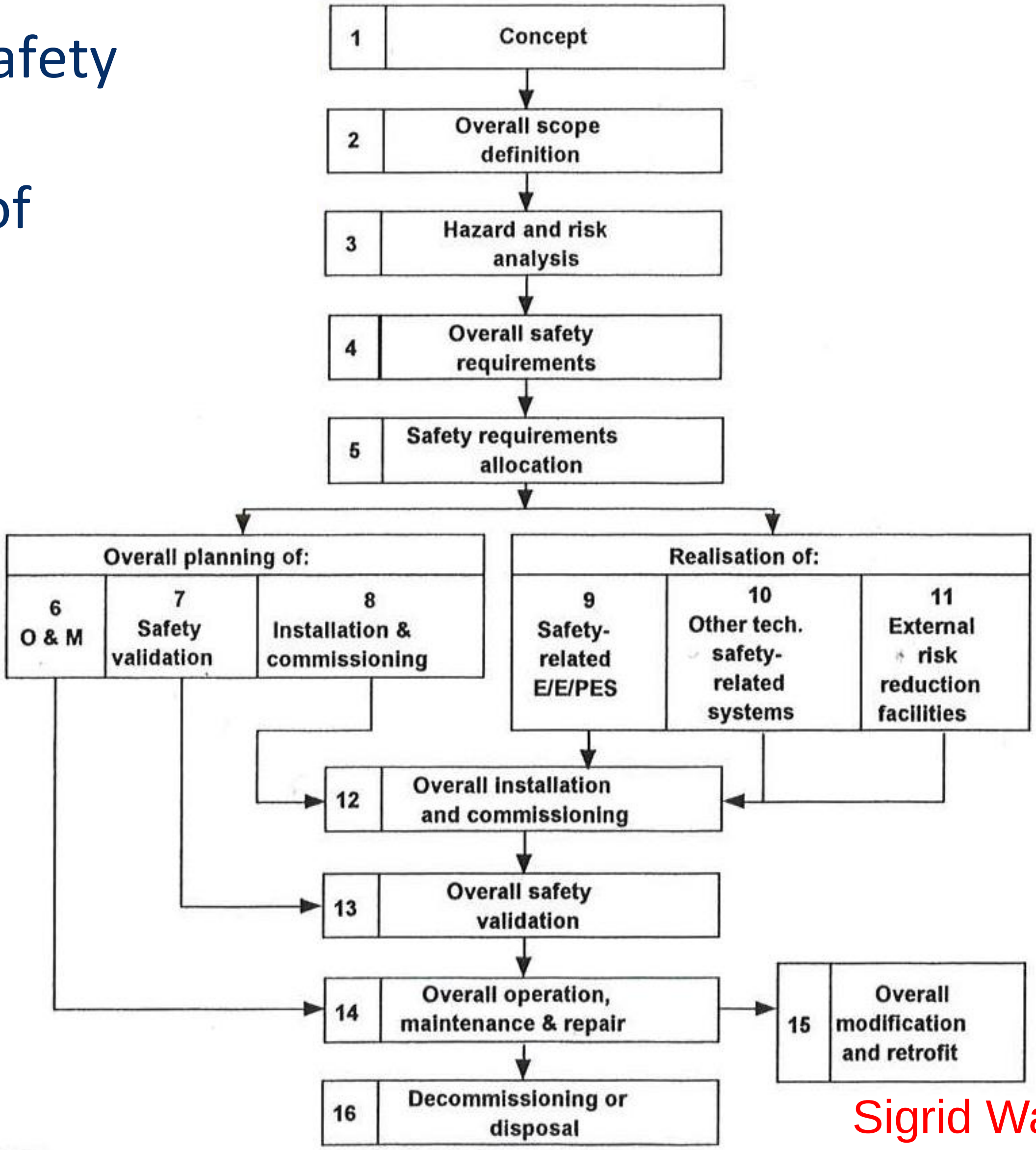
Safety principles

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

IEC 61508 Safety Lifecycle

‘A model for structuring safety management activities throughout the life cycle of safety- related systems’



Handout Principles of System Safety Engineering and Management,

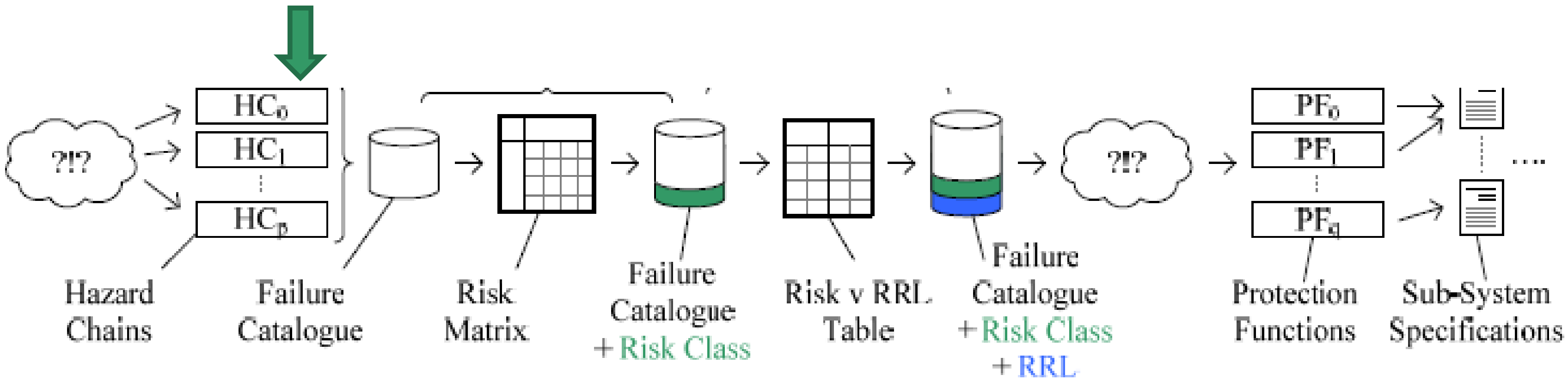
Workshop, CERN 2011, Redmill Consultancy, London

Sigrid Wagner

Safety case

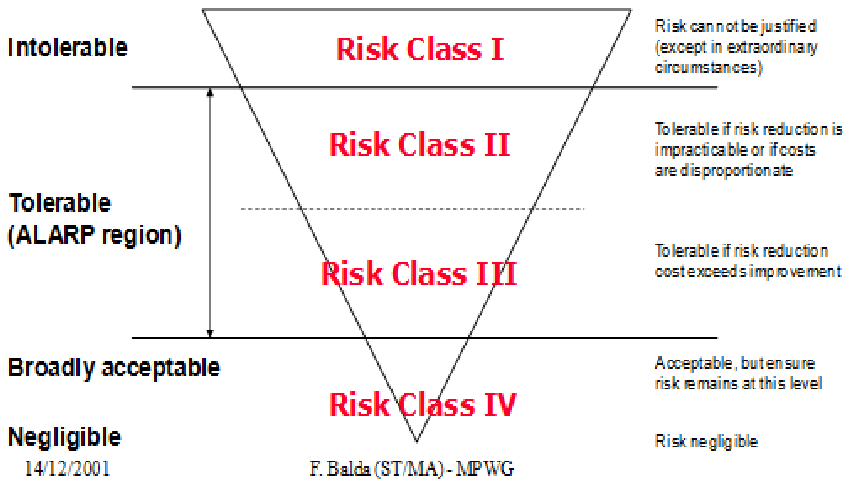
- The MPS was designed considering a large number of possible failures of LHC equipment
- The knowledge of these failures and of the machine protection functions implemented to cover these failures is distributed over the different teams involved in the design and operation of the LHC
- A recent project (Sigrid Wagner) aims at bringing together this knowledge in **a common failure catalogue.**
- The objective is to create a “safety case”
  - documentation ‘ to go to court with’
  - including, claim, argument, evidence
- Details can be discussed if of interest

Hazard and Risk Analysis and Protection requirements



Proceeding in lifecycle from hazard chains to definition of protection functions

Frequency	Consequence			
	Catastrophic	Major	Severe	Minor
Frequent	I	I	I	II
Probable	I	I	II	III
Occasional	I	II	III	III
Remote	II	II	III	IV
Improbable	II	III	IV	IV
Negligible / Not Credible	III	IV	IV	IV



Sigrid Wagner

Comment to LHC Machine Protection

- Some protection systems were considered early in the project (beam dumping system, magnet protection, beam loss monitors)
- Consideration for coherent approach on machine protection started in 2000 – done by the team working in interlocks that links all systems
- Lot of work since then (e.g. 10-20 PhD theses on machine protection)
- Stated to use "formal methods" since ~2004 (calculation of reliability, availability etc.)
- Together with design and construction of systems considerations for documentation, commissioning etc.
- Very important: diagnostics for protection (what stopped the beam?)

‘Standard’ design of safety systems

- In the world of industry different standards exist to guide engineers in the design of safety systems (elevators, cars, ….)
  - IEC61508, …
- Accelerators are very special machines
- Safety must be ensured for
  1. Personnel
  2. Environment
  3. **Machine**
  4. **“Beam”**
- Common standards are applied to personnel and environmental protection systems
- Machine related protection can follow a relatively free approach for the design (still inspired by standards…)
  - Watch out for coupling between protection of machine and people

From Safety to Protection

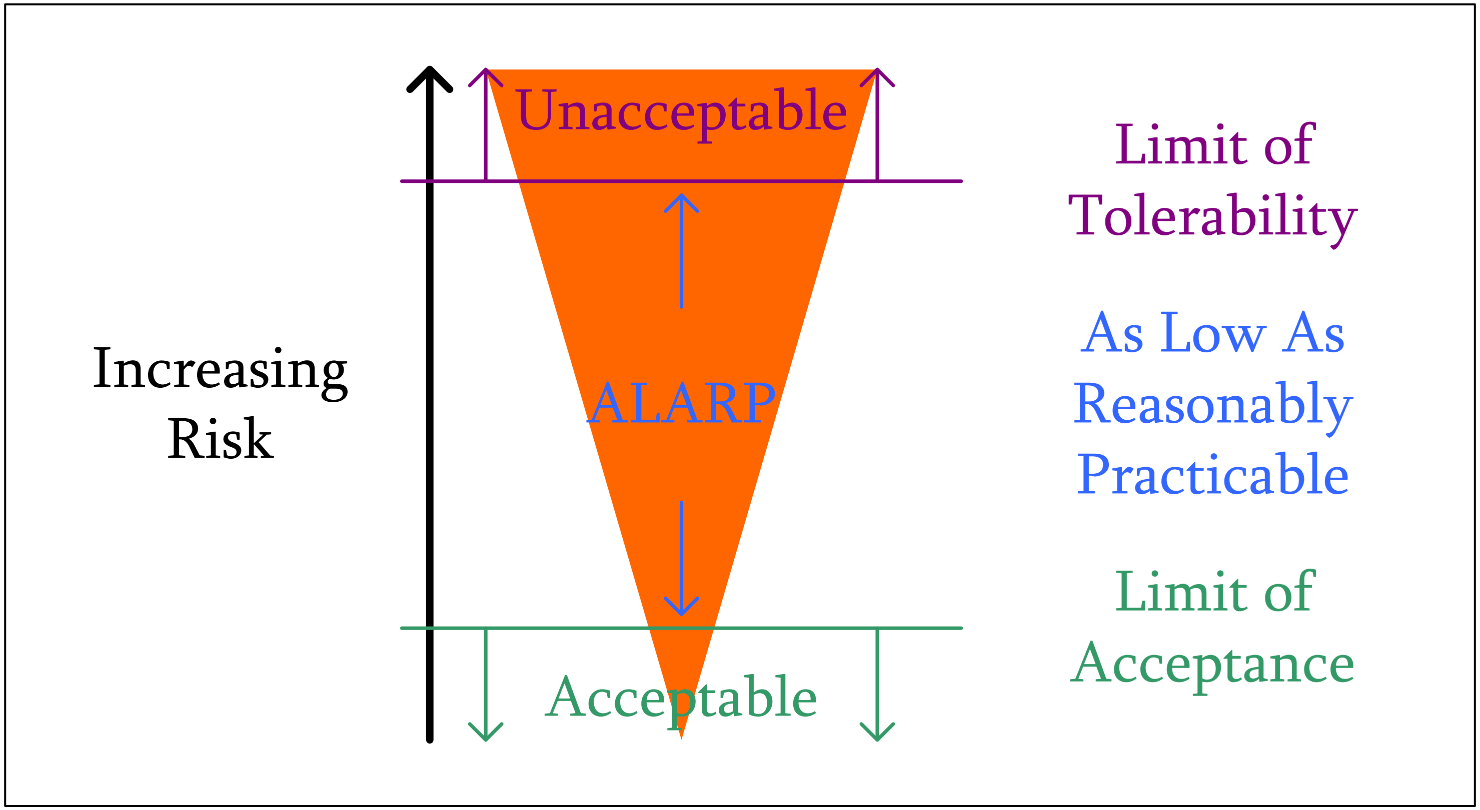
- IEC 61508 is an international standard of rules applied in industry, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems (E/E/PE, or E/E/PES))
- Safety standards have been developed over many years for system with risks to humans

- **Avoid mixing systems in accelerator to protect equipment with systems to protect people**

- Ideas from Safety Integrity Level (SIL) concept of the IEC 61508 were applied => **PIL** = **P**rotection **I**ntegrity **L**evel

M.Kwiatkowski, Methods for the application of programmable logic devices in electronic protection systems for high energy particle accelerators, CERN-THESIS-2014-048

Unacceptable and acceptable risk



- Acceptable’ or ‘Unacceptable’ risk depends on the context!
- Different for user-oriented facilities, medical accelerators, fundamental research, …

Classification of unacceptable / acceptable risk

	Per year	Catastrophic	Major	Moderate	Low	Negligible
Cost [MCHF]		> 10	5-50	0.5-5	0.05-0.5	0-0.05
Downtime [days]		> 300	30-300	3-30	0.3-3	0-0.3
Frequent	1					
Probable	0.1					
Occasional	0.01					
Remote	0.001					
Not credible	0.0001					

Example of D1 failure

	Per year	Catastrophic	Major	Moderate	Low	Negligible
Cost [MCHF]		> 10	5-50	0.5-5	0.05-0.5	0-0.05
Downtime [days]		> 300	30-300	3-30	0.3-3	0-0.3
Frequent	1					
Probable	0.1		D1 failure			
Occasional	0.01					
Remote	0.001					
Not credible	0.0001					

Risk for D1 Hazard far above acceptable level
=> Protection required

Risk reduction by protection system

	Per year	Catastrophic	Major	Moderate	Low	Negligible
Cost [MCHF]		> 10	5-50	0.5-5	0.05-0.5	0-0.05
Downtime [days]		> 300	30-300	3-30	0.3-3	0-0.3
Frequent	1					
Probable	0.1					
Occasional	0.01					
Remote	0.001					
Not credible	0.0001					

D1 failure

Risk reduction for D1 Hazard to acceptable level

Protection Integrity Level

	Per year	Catastrophic	Major	Moderate	Low	Negligible
Cost [MCHF]		> 10	5-50	0.5-5	0.05-0.5	0-0.05
Downtime [days]		> 300	30-300	3-30	0.3-3	0-0.3
Frequent	1	4	3	2	1	0
Probable	0.1	3	[illegible]	1	0	0
Occasional	0.01	2	1	0	0	0
Remote	0.001	1	0	0	0	0
Not credible	0.0001	0	0	0	0	0

D1 failure

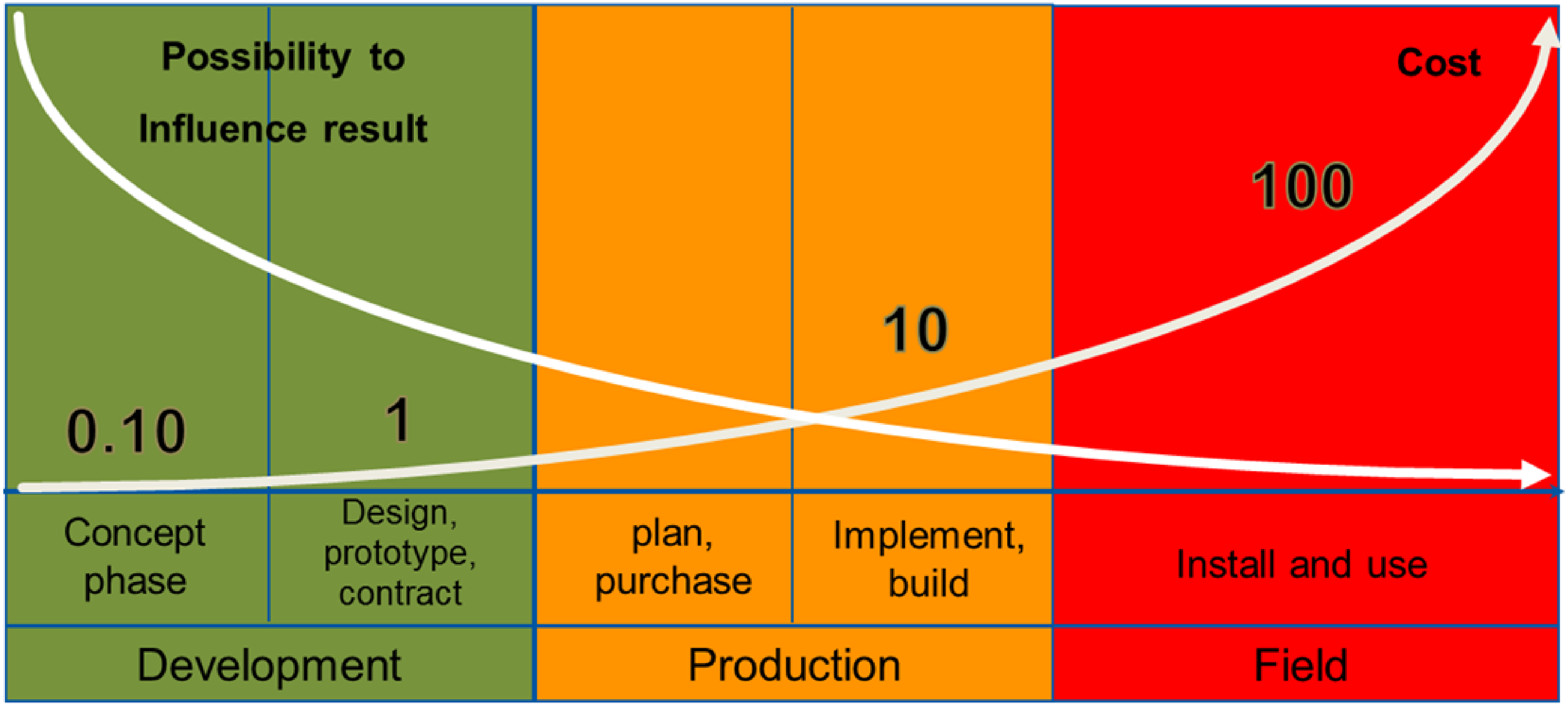
Protection integrity level

Steps for building a protection system….

1. Understand hazards (example: failure of D1)
2. Estimation of risk and required Protection Integrity Level for the system
3. (From other lectures) Definition of the concept of the protection system(s) (Fast current monitor, beam loss monitors, beam interlock system, beam dumping system)
4. Development of the protection systems
5. Fabrication of the system
6. Extensive tests
7. Commissioning
8. Monitoring during operation

Reliability analysis / monitoring
Demonstrate reliability

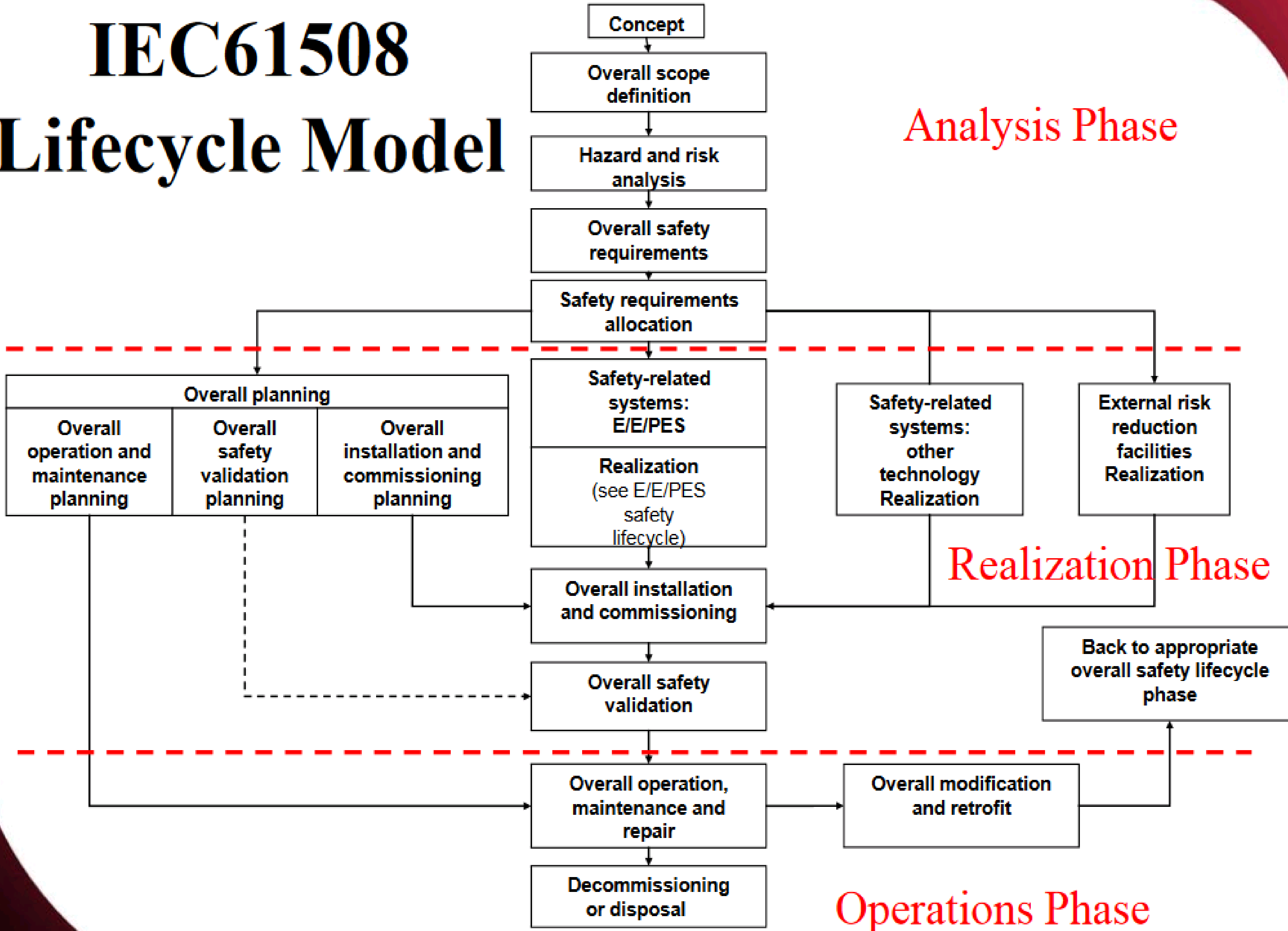
Importance of Reliability Analyses

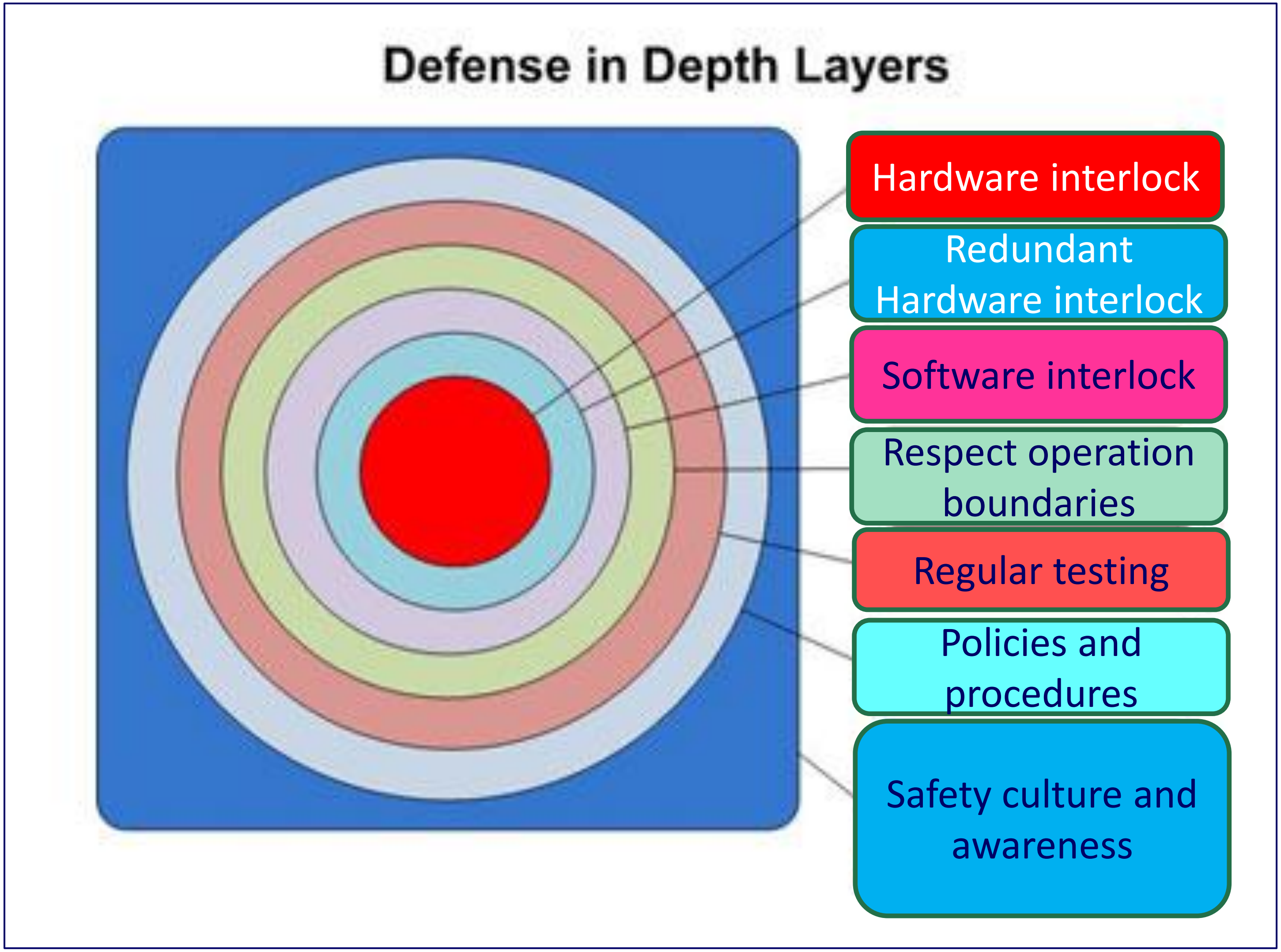


- The earlier reliability constraints are included in the design, the more effective the resulting measures will be

Prof. Dr. B. Bertsche, Dr. P. Zeiler, T. Herzig, IMA, Universität Stuttgart, CERN Reliability Training, 2016

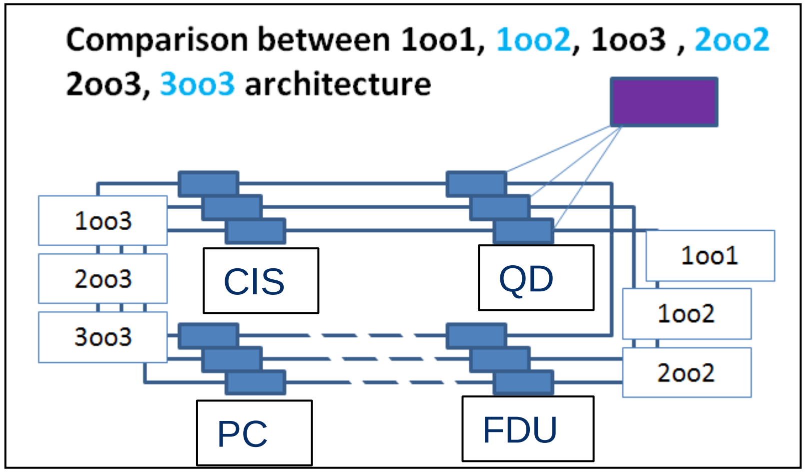
IEC61508 Lifecycle Model



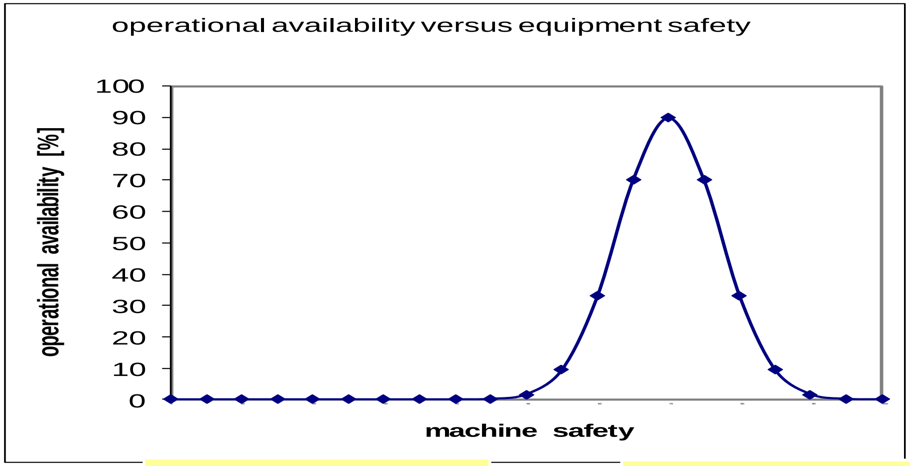

Defense in Depth Layers
Hardware interlock
Redundant Hardware interlock
Software interlock
Respect operation boundaries
Regular testing
Policies and procedures
Safety culture and awareness

Machine Protection and Availability

- If the only objective is to maximising safety, this risks to reduce the overall availability – find a reasonable compromise
- For protection system: majority voting to be considered to increase failure tolerance
- Optimum has been found with 2oo3 voting systems
- Prototype powering interlock system developed for ITER



S. Wagner



Downtime for repairs due to insufficient protection systems

Downtime dominated by too complex Protection Systems

Design guidelines for protection systems

- Having a vision to the operational phase of the system helps….
- Test benches for electronic systems should be part of the system development
    - Careful testing in conditions similar to real operation
- Reliable protection does not end with the development phase. Documentation for installation, maintenance and operation of the MPS
- The accurate execution of each protection function must be explicitly tested during commissioning
- Requirements are established for the test interval of each function
- Most failure are due to power supplies, mechanical parts and connectors

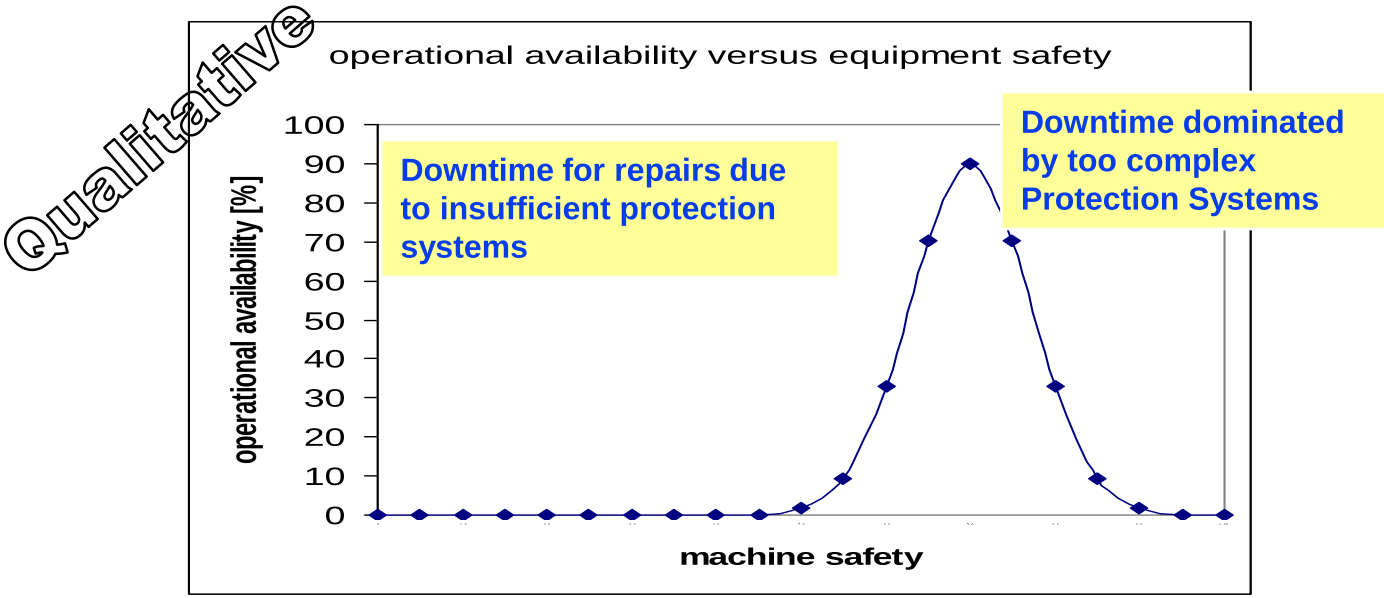
The LHC machine need protection systems, but….

Machine Protection is not an objective in itself, it is to

maximise operational availability by minimising down-time (quench, repairs)

avoid expensive repair of equipment and irreparable damage

Operations workshop
R.Schmidt - Villars
30/01/2001



Side effects from LHC Machine Protection System compromising operational efficiency must be minimised

Approach to designing a protection system

1. **Identify hazards**: what failures can have a direct impact on beam parameters and cause loss of particles (….hitting the aperture)
2. **Classify** the **failures** in different categories
3. **Estimate** the **risk** for each failure (or for categories of failures)
4. Work out the **worst case failures**
5. Identify **how to prevent** the **failures** or **mitigate** the **consequences**
6. **Design** systems for **machine protection**

……then **back to square 1**

….starting in the early design phase, continuous effort, not only once….

Risks related to accelerator systems

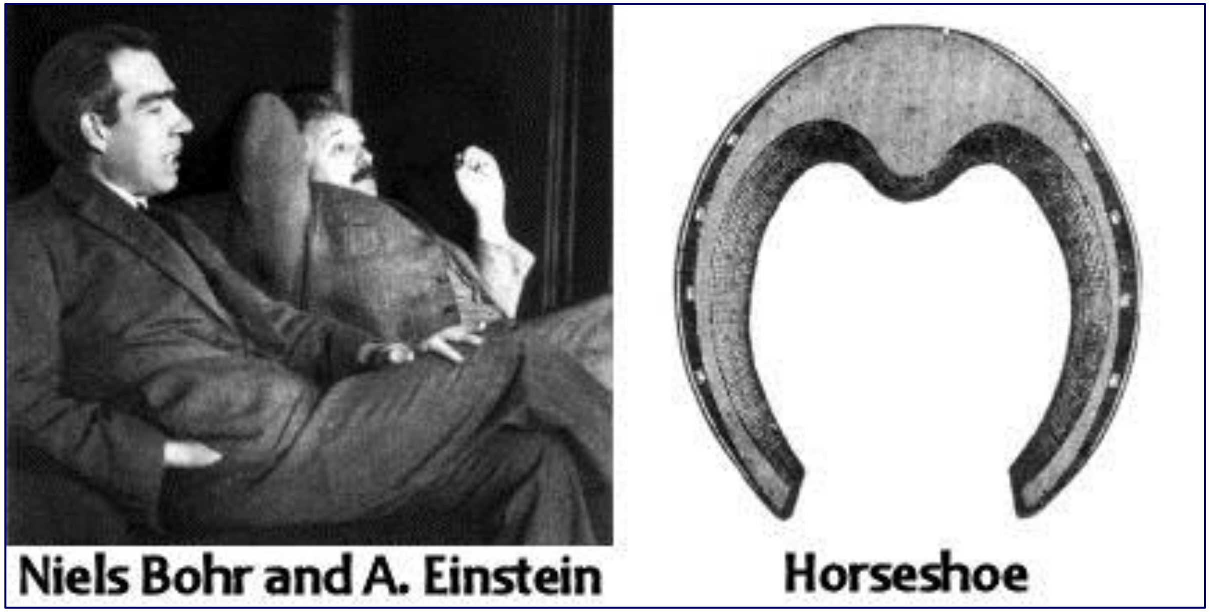
- Normal conducting magnets
  - (Water) cooling required, and interlocks to monitor if it works correctly
- RF systems (modulator, klystrons, waveguides, cavities): high voltages, arcs can damage the structure
  - Requires complex and fast interlock systems
  - For high beam intensity: in case of transition from **beam on => beam off**, RF system has to cope with such transients
- High Voltage systems (e.g. kicker magnets) - risk of arcing
- Powering systems (power converters, power distribution, electrical network)

These risks are not discussed here

- see Joint International Accelerator School on "Beam Loss and Accelerator Protection“ http://uspas.fnal.gov/programs/JAS/JAS14.shtml


Joint International Accelerator School
http://uspas.fnal.gov/programs/JAS/JAS14.shtml
Beam Loss
and
Accelerator Protection
November 5-14, 2014
Newport Beach, California, USA
This school is intended for physicists and engineers who are or may be engaged in the design, construction, and/or operation of accelerators with high power photon or particle beams and/or accelerator sub-systems with large stored energy.
The USPAS will offer a limited number of scholarships. Both U.S. and international participants are welcome to request a scholarship on their Application Form

If you are working on protection…..



- Einstein was visiting the home of Nobel Prize winner Niels Bohr, the famous atom scientist.
- As they were talking, Einstein kept glancing at a horseshoe hanging over the door. Finally, unable to contain his curiosity any longer, he demanded: “Niels, it can’t possibly be that you, a brilliant scientist, believe that foolish horseshoe superstition! ? !”
- “Of course not,” replied the scientist. “But I understand it’s lucky whether you believe in it or not.”

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