Protection of the LHC
Overview

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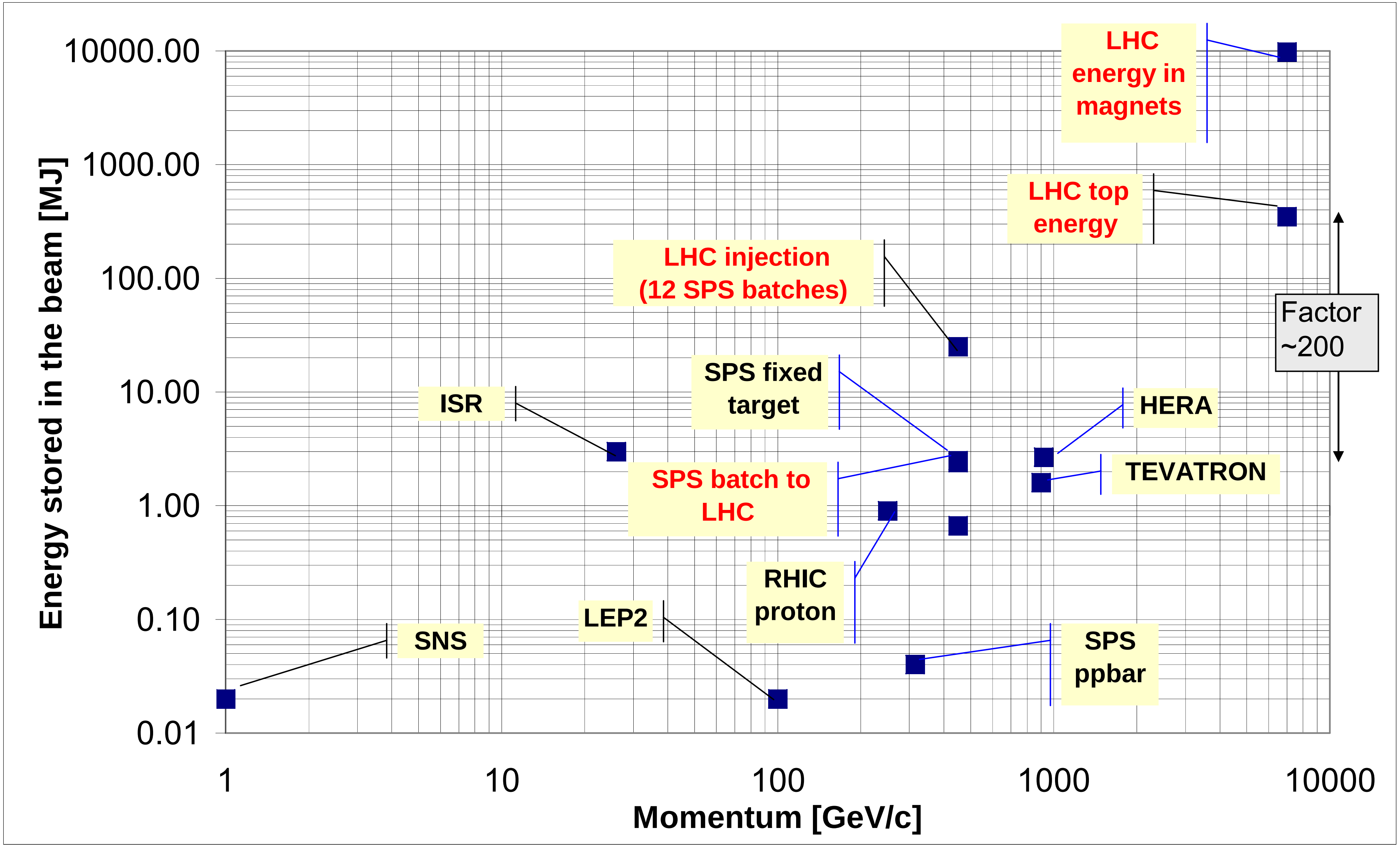
Review on Machine Protection and Interlocks April 2005

- Risks when operating LHC with beam
- Failures and beam losses
- Protection systems
- Strategy
- Organisation
- Conclusions

Livingston type plot: Energy stored in the beam



based on graph from R.Assmann

Relevant LHC parameters for 7 TeV (protons)

Momentum at collision	7	TeV/c
Luminosity	10^{34}	$cm^{-2}s^{-1}$
Dipole field at 7 TeV	8.33	Tesla
Typical beam size	200-300	μm

- Energy stored in the magnet system: 10 GJoule
- Energy stored in one (of 8) dipole circuit: 1.1 GJoule
- Energy stored in one beam: 362 MJoule
- Average beam power, both beams: some 10 kWatt
- Instantaneous beam power for one beam: 3.9 TWatt

  …..during 89 μs

- Energy to heat and melt one kg of copper: 700 kJ

Bunch intensities, quench and damage level

Nominal bunch intensity	$1.1 \cdot 10^{11}$
Intensity one "pilot" bunch	$5 \cdot 10^{9}$
Batch from SPS (216/288 bunches at 450 GeV)	$3 \cdot 10^{13}$ ←
Nominal beam intensity with 2808 bunches	$3 \cdot 10^{14}$ ←
Damage level for fast losses at 450 GeV	$1\text{-}2 \cdot 10^{12}$ ←
Damage level for fast losses at 7 TeV	$1\text{-}2 \cdot 10^{10}$
Quench level for fast losses at 450 GeV	$2\text{-}3 \cdot 10^{9}$
Quench level for fast losses at 7 TeV	$1\text{-}2 \cdot 10^{6}$ ←

- Damage assessment at 450 GeV supported by a dedicated experiment in the SPS, by observations and calculations
- Damage assessment at 7 TeV approximate, from calculations that have been benchmarked with the 450 GeV data
- If damage: depends on detailed geometry, material, etc.

Beam damage potential at 450 GeV

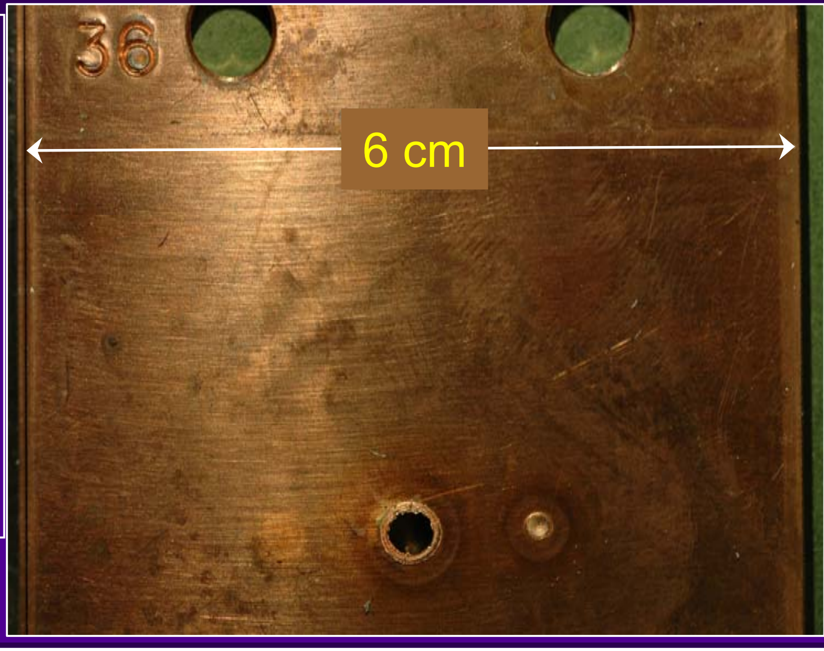
Controlled experiment at the SPS

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

above damage limit

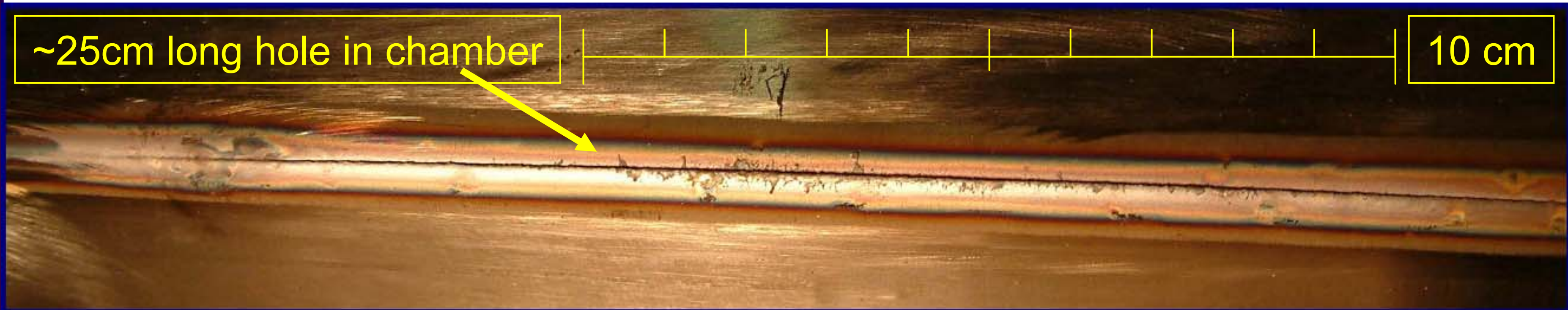
- $2 \cdot 10^{12}$ protons

below damage limit

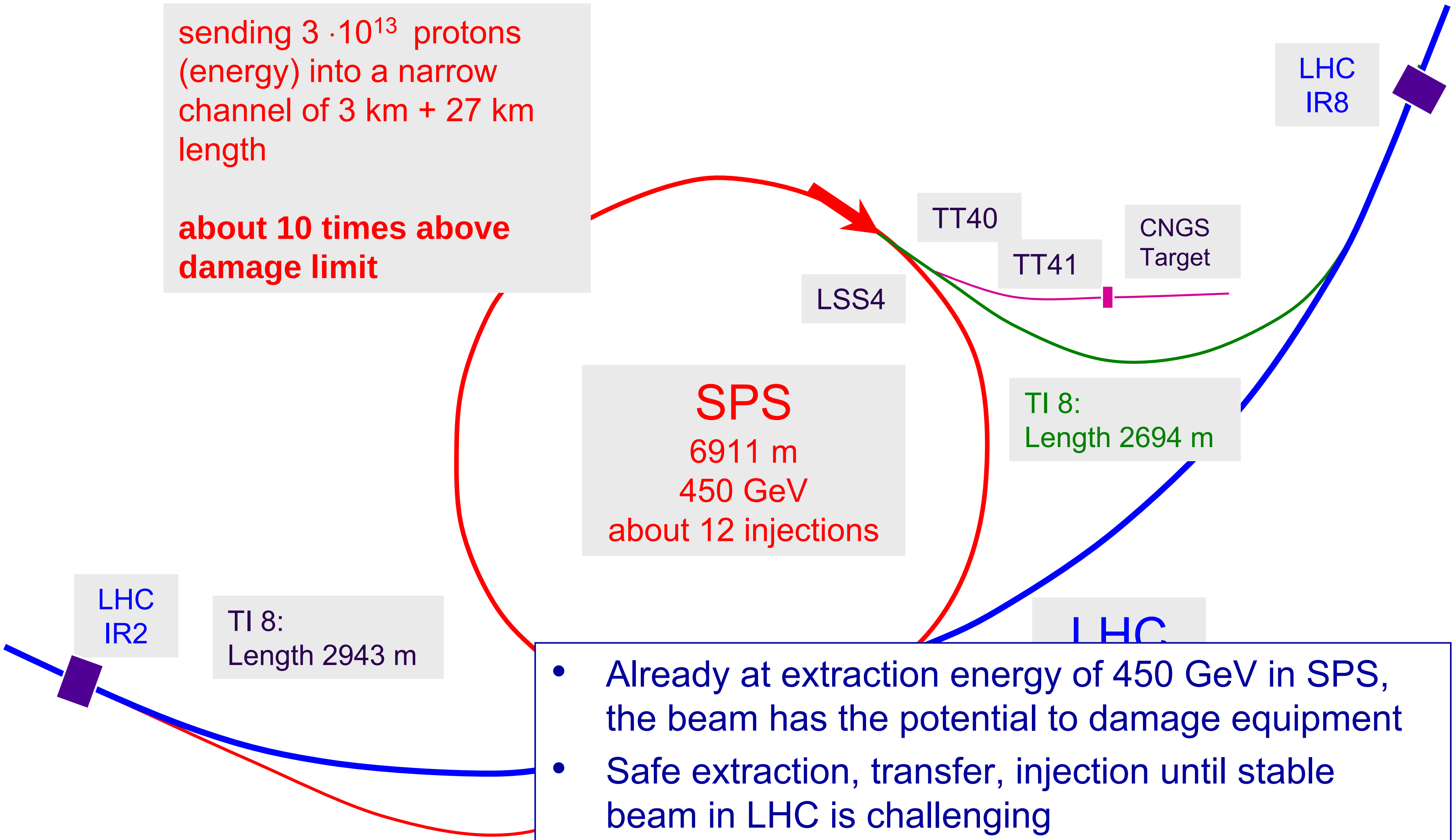


1 full nominal batch $3 \cdot 10^{13}$ above damage limit (gazing incidence)

25th of October: MSE trip during high intensity extraction. Damage of QTRF pipe and magnet.

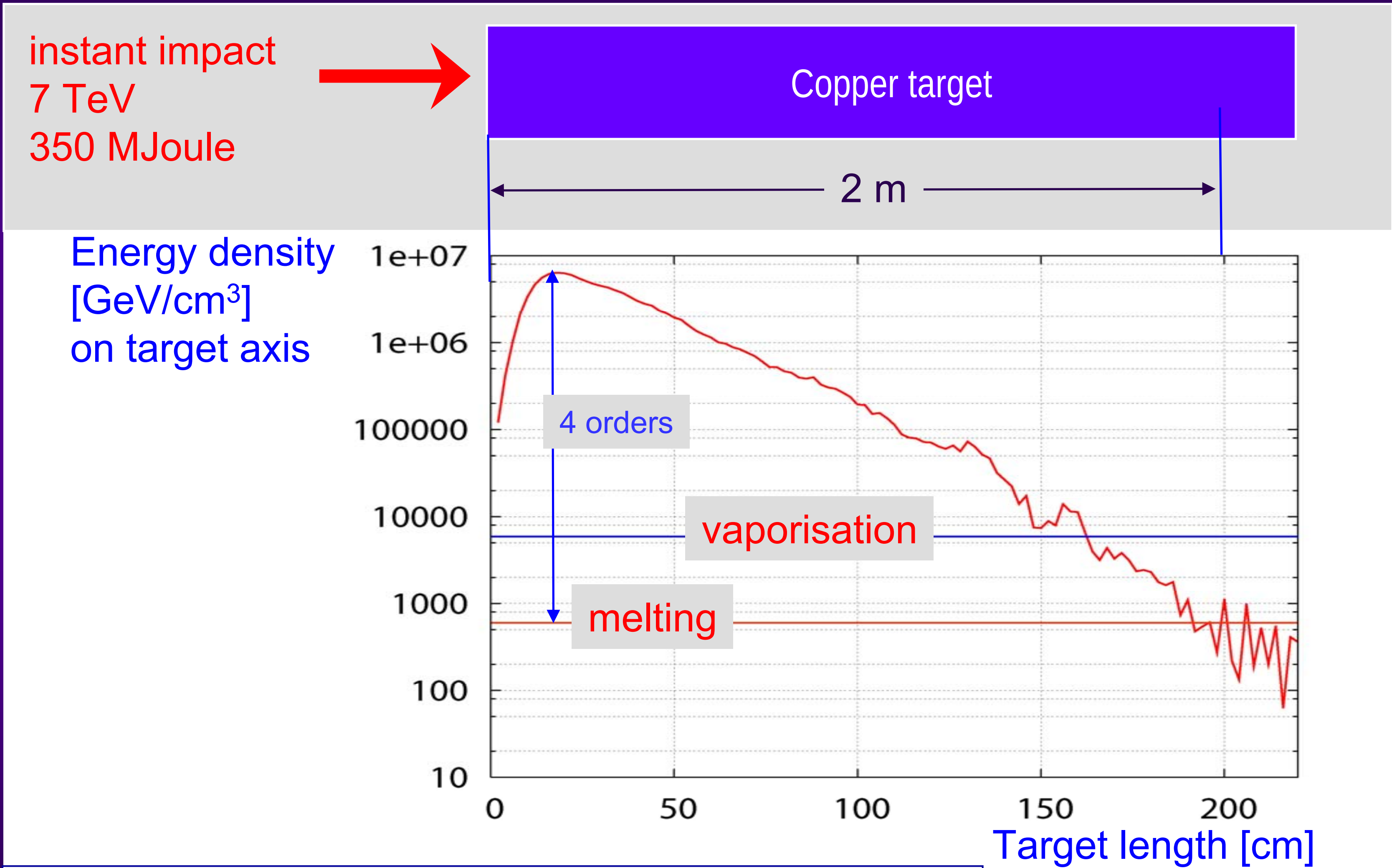


Transfer and injection: SPS and transfer lines to LHC



- Already at extraction energy of 450 GeV in SPS, the beam has the potential to damage equipment
- Safe extraction, transfer, injection until stable beam in LHC is challenging

Full 7 TeV LHC beam deflected into copper target



The full 7 TeV LHC beam (2808 bunches) deflected into a copper target could penetrate between 10 m and 40 m into such target

N.Tahir (GSI) et al.

Beam cleaning and machine protection

Beam cleaning

- Assuming a beam lifetime of 0.2 hours: > 10^{11} p/sec are lost, quench level 10^6 - 10^7 protons
- Beam cleaning with **many collimators**, limiting the aperture and catching particles around the accelerator
- Cleaning must be **extremely efficient** to avoid quenches**:** tiny beam loss (at the 10^{-8} level) risks to quench magnets

Machine Protection

- The beam dump blocks are the **ONLY** elements to **absorb the full LHC beam** without damage.
- **Beam extraction** into beam dump blocks for unsafe situations, detected by **beam instruments** and **hardware surveillance**

Collimators and protection

- In general, any **particles lost** should **impact on collimators** first
- Beam absorbers / collimators for different kind of failures and for protecting against quenches

Failure leading to beam losses within one turn or less

From extraction from SPS, via transfer and injection until LHC circulating beams

- Kicker failures – at extraction from SPS and at injection into LHC
- Magnetic elements having wrong settings
- Object in beam pipe (e.g. vacuum valve, screen, …)

For circulating beams in LHC

- Failure of kickers, for injection, tune measurements (small kicks) and aperture exploration (large kicks)
- Failure when extracting the beams

Circulating beams: failures leading to beam losses for many turns that require immediate beam dump

- Failures in the magnet and powering system

- Wrong operational parameter (tune, chromaticity, orbit, …)
- Beam instability
- Object moves into beam
- Transverse damper has wrong phase
- Vacuum problem
- RF trip

Beam losses and time constant

time

min ... hours

ms ... sec

µs

accidental beam losses

Very slow beam losses (lifetime 0.2 hours or more)

Cleaning system to limit beam losses around the ring: see presentations on cleaning system and collimators

Very fast beam losses (some turns to some milliseconds)

Fast beam losses (5 ms – several seconds)

Slow beam losses (several seconds – 0.2 hours)

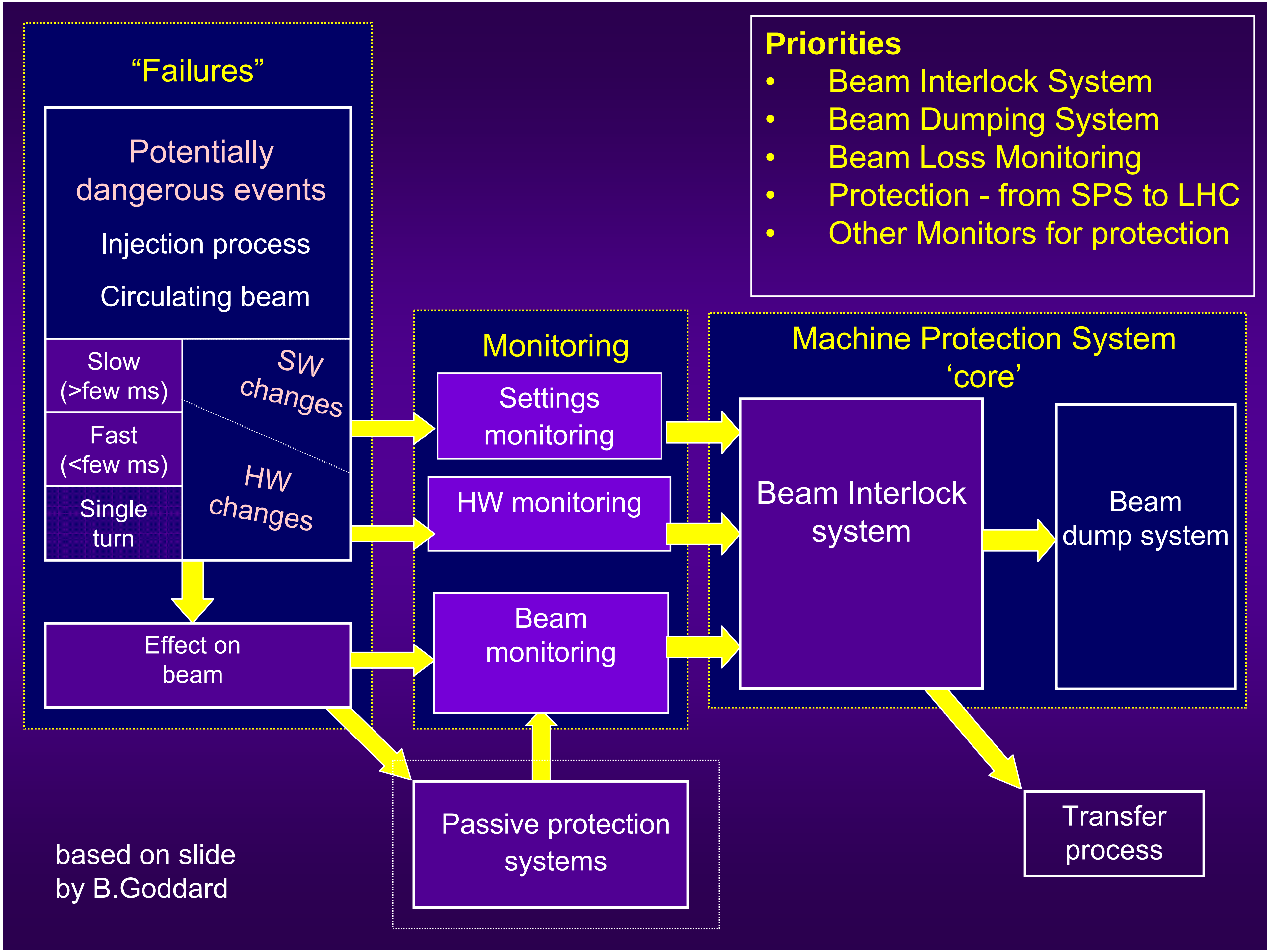
At all times collimators limit the aperture – particles lost on collimators

Hardware surveillance and beam monitoring, detecting failure and extracting the beams into beam dump block

Ultra fast beam losses

- **Single turn failures at injection**
- **Single turn failures at extraction**
- **Single turn failures with stored beams**

Hardware surveillance and passive protection with beam absorbers


“Failures”
Potentially dangerous events
Injection process
Circulating beam
Slow (>few ms)
Fast (<few ms)
Single turn
SW changes
HW changes
Effect on beam
Monitoring
Settings monitoring
HW monitoring
Beam monitoring
Passive protection systems
Machine Protection System ‘core’
Beam Interlock system
Beam dump system
Transfer process
Priorities
• Beam Interlock System
• Beam Dumping System
• Beam Loss Monitoring
• Protection - from SPS to LHC
• Other Monitors for protection
based on slide by B.Goddard

Tasks of the protection systems

Protect the machine

- **First priority:** Protect (sensitive) LHC equipment and transfer line equipment from damage
- **Second priority:** Prevent superconducting magnets from quenching by dumping the beam BEFORE particle losses become too large. Downtime after a quench is in the range of 1 hour – 8 hours

Protect the beam

- The protection systems should only dump the beam when necessary. False beam dumps to be avoided

Provide the evidence

- In case of failure, complete and correct diagnostic messages should be provided (post mortem recording)

Protection against failures for single turn beam losses

Programmed actions: injection, regular beam dump, when using aperture kickers, …

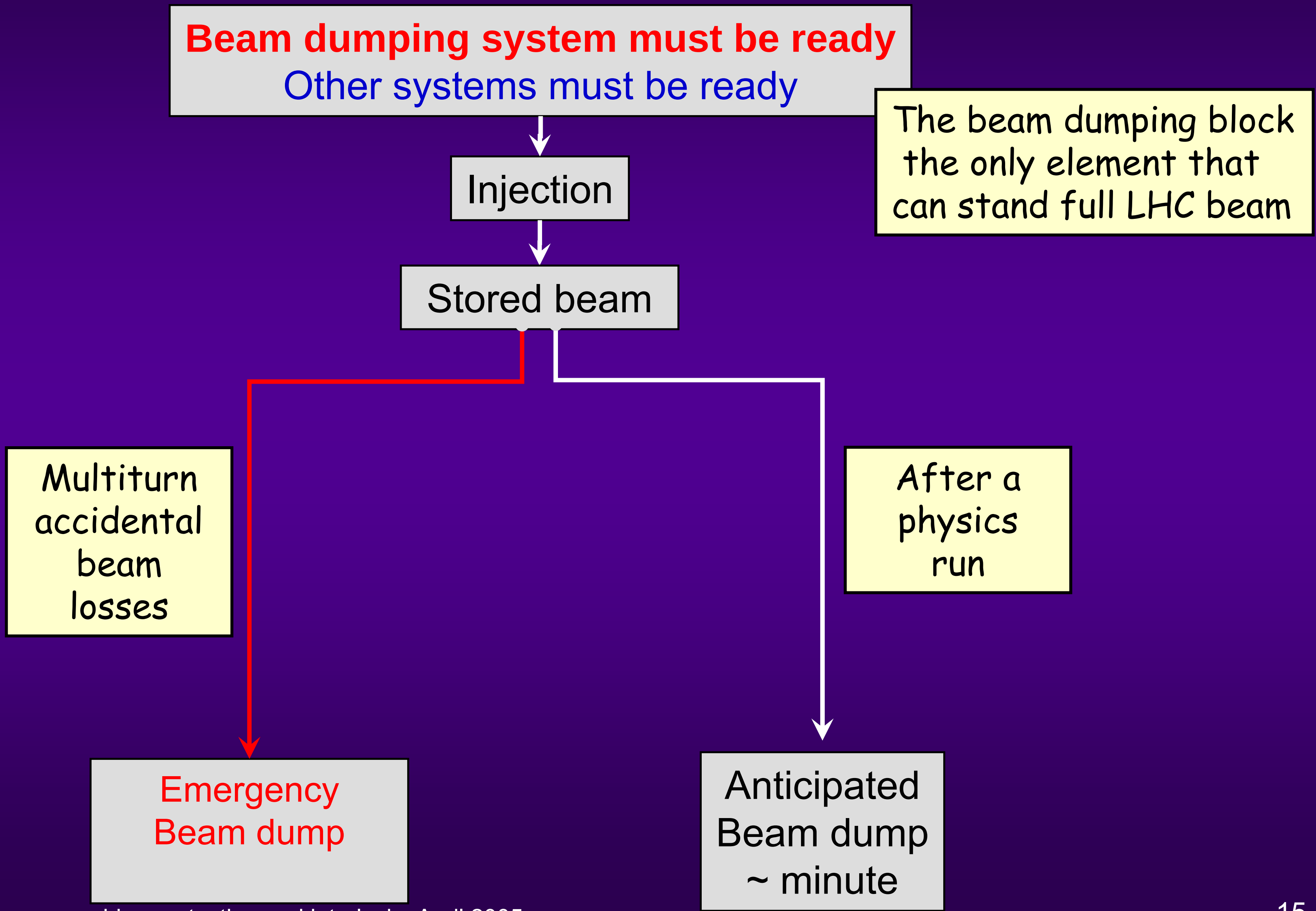
- Checking equipment status and beam status: if OK, go ahead
- Not possible for emergency beam dumps

Failures: machine protection to avoid damage

- Equipment surveillance
- Ensure that collimators and beam absorber are in correct position
- **Passive protection** with beam absorbers

see presentations on beam dumping systems, interlocking, performance of injection protection systems and position of collimators

Protection against failures for multiturn beam losses



Protection against failures for multiturn beam losses

Beam dumping system must be ready

Other systems must be ready

Injection

Stored beam

Failure

Beam Interlock System

signal to Beam Dump

Emergency Beam dump

< 270 μs

Anticipated Beam dump ~ minute

Magnets and kickers in the beam dumping system must track the energy

The systems involved in the active protection are based on failsafe hardware, and do not rely on computers with operating systems

Protection in the presence of circulating beams

A signal is required to trigger the beam dumping system **(no signal – no beam dump)**

Extraction of beam towards beam dump block must be done correctly

No single turn failures permitted (no fast kicks)

- Injection kicker should NEVER fire accidentally when not operating at 450 GeV
- Other kickers (aperture kickers) should never fire when LHC operates with high intensity beam

Strategy for protection: example for injection

If potentially dangerous actions are planned: injection (similar for starting the ramp, starting beta squeeze, beam dump at end of fill)

1) Automatic sequencing of actions by software

- check if all elements are in the correct state
- allow for injection only if all OK

2) Avoid dangerous situations by applying procedures

- inject into empty LHC only with low intensity beam
- only if beam is circulating, inject high intensity beam

3) Hardware surveillance can stop action

- surveillance of equipment to detect last moment change of relevant parameter (e.g. power converter trip just before injection or extraction from SPS)

4) Protect in case of failure

- beam absorbers for single turn failures

Strategy for protection: redundant systems to detect unsafe situation (circulating beam)

Beam dump requests from hardware monitoring

- Hardware surveillance (for many systems)
- Quench detected by Quench Protection System
- Fast magnet current change monitors

Beam dump requests from beam monitoring

- Beam loss monitors at collimators and other aperture limitations
- Beam loss monitors in the arcs
- Beam position (change) monitors
- Fast beam current decay ("lifetime") monitors

Design principles for machine protection

No single failure should lead to equipment damage

- Redundant systems
- At least two channels should capture a failure (for example, by equipment monitoring and by beam monitoring)
- Failsafe systems: "Failsafe" leads to a beam dump in case of a failure in the protection systems – downtime of the accelerator but no damage

No erroneous manipulation on protection systems should compromise the accelerator safety (e.g. swapping two cables)

Quantification of risks coherent across systems – using standards (Safety Integrity Level - SIL)

Quantifying safety and reliability: SIL Levels

Safety Integrity Levels (SIL) - suggested by norm IEC 61508

If **(risk • frequency)** are high => high SIL level

SIL levels 4: Probability of a dangerous failure per hour 10^{-9} … 10^{-8}

1 dangerous failure between 10000 and 100000 years (aircrafts and nuclear power plants)

SIL levels 3: Probability of a dangerous failure per hour 10^{-8} … 10^{-7}

1 dangerous failure between 1000 and 10000 years

SIL levels 2: Probability of a dangerous failure per hour 10^{-7} … 10^{-6}

1 dangerous failure between 100 and 1000 years

SIL levels 1: Probability of a dangerous failure per hour 10^{-6} … 10^{-5}

1 dangerous failure between 10 and 100 years

SIL levels 3 or 4: Beam dumping system and Beam interlocks

LHC Machine Protection includes many systems

What are systems for machine protection? Those systems that would not be required without high stored energy in magnets and beams

- Beam Dumping System
- Beam and Powering Interlocks
- Beam Loss Monitor System
- Collimation System
- Quench Protection / Energy Extraction Systems

Systems that are not machine protection with hardware interfaces to the machine interlocks

- Beam instruments (BPM, BCT, screens, …)
- Vacuum
- Power converters
- RF and Transverse damper
- Access
- LHC experiments
- Kickers (injection, Q-kickers, aperture kickers)

LHC Machine Protection is across several projects and working groups

Projects

- LHC Beam Dump (B.Goddard)
- LHC Collimation (R.Assmann)
- LHC Transfer Lines and Injection (V.Mertens)
- Beam Loss Monitors (B.Dehning)
- Quench Protection and Energy Extraction (R.Denz / K.Dahlerup-Petersen)
- Beam and Powering Interlocks (R.Schmidt)

Protection issues are discussed in several working groups

- Machine Protection WG (R.Schmidt / J.Wenninger)
- Injection WG (V.Mertens)
- Collimation WG (R.Assmann)
- Electrical Engineering WG (K.H.Mess)
- LEADE (Interface machine ⇔ experiments) (E.Tsesmelis)

The challenge of LHC Machine Protection and collimation was addressed progressively

In the initial design (< 1995)

- Beam Dumping system
- (Initial) Beam Cleaning system
- Quench Protection system
- LHC Transfer Lines and Injection
- Beam Loss Monitors

Much later (~2001-2003)

- Beam Interlocks and Powering Interlocks
- Additional collimators to protect against various types of failures

Recently (~2003-2004)

- Monitor to detect fast magnet current changes
- Safe LHC Parameter distribution
- Beam position monitors for protection
- BCT for protection

Just starting: software / controls and machine protection

Status of some systems

Systems for machine protection are in different phases of development / construction

Some examples

- The quench protection system has been constructed, and will be commissioned soon
- Most components of the beam dumping system are under construction
- Beam interlock system: first generations are working in the SPS
- The use of BCTs to detect fast beam current decay is under study
- A system to detect fast magnet current changes is under development (collaboration with HERA / DESY)

Reviews addressed some of the systems

- Quench Protection system
- Beam Cleaning System

LHC Experiments and machine protection

- When the machine is protected, in general the experiments are also protected (larger relative aperture in experiments)
- Some failure cases have been studied specifically addressing risks to experiments

Interfaces between LHC experiments and Interlocks

- Some experiments can move their detectors close to the beam, similar to other devices moving towards the beam => similar interlocking strategy
- Radiation monitors in experiments – similar to beam loss monitors for the accelerator => same interlocking procedures
- Experimental magnets that deflect the beam – similar to other accelerator magnets => similar interlocking procedures

No details during this review

(Lead) ions and machine protection

- Stored energy in ion beams two orders of magnitude lower than for protons
- Fewer types of failures, since only 592 bunches in one beam (fewer single turn failures modes)
- Ion beams have a very different energy deposition characteristics than protons
  - penetration into material is much less
  - local energy deposition for the same stored beam energy larger
  - FLUKA program improved to calculate energy deposition
- Switchover from protons ⇔ ions is an issue
  - protection parameters must change (e.g. BLM thresholds)
- Ions and the needs for protection to be addressed this year

Outline of the review

Introduction to protection: first two presentations

Two session on core of machine protection systems (no other redundant systems)

- Dumping the beam
- Beam interlocking

Session on events leading to beam losses

Session on equipment surveillance and beam monitoring

- BLMs can also be considered as a core protection system (some redundancy)

Machine protection and operation

For specific issues coming up during the review

- Free slot: interactive session (closed)

Executive session (closed session)

Open summary session

Conclusions

The LHC Machine Protection is a very complex topic

- It is not possible to cover all aspects during the review
- It is not possible to cover aspects in depth

Priority is given to the core of the machine protection systems

1. Beam dumping system
2. Beam interlocks
3. Beam loss monitoring

- and systems connected to the beam interlocks

Work is ongoing, and not all issues have been covered

Input from the review committee will help us to better focus future activities

Acknowledgements

The presentation is based on the work that was performed in many groups in several CERN Departments, as well as collaborators from other labs (DESY, Fermilab, GSI, Protvino, Triumf, ….)

Contributions of **many colleagues** are acknowledged, in particular for the discussions in the Machine Protection WG, Collimation WG and Injection WG

Particular thanks for **J. Wenninger as co-organiser**

And thanks to my colleagues that prepared the programme: R.Assmann, R.Bailey O.Bruning, H. Burkhardt, B.Dehning, B.Goddard, V.Kain, M.Lamont, B.Puccio and J.Uythoven

Safe operation AND availability of LHC

Safety increases using two channels in parallel, each channel could dump the beam

- This increases the number of false beam dumps

Reducing number of false beam dumps by voting strategy (**2 Out Of 3** or **2 Out Of 4) –** done for quench protection

- Not always possible (for example, for beam dumping system)
- Keep cost under control

Introduce flexibility by making the system "rigid but flexible"

- Safe Beam Flag: relaxing protection when operating with "safe beam" = beam below damage threshold
- Configurable system driven by information in a centralised database for coherency

Bootstrapping of the LHC

- Masking protection channels possible due to Safe Beam Flag

This review

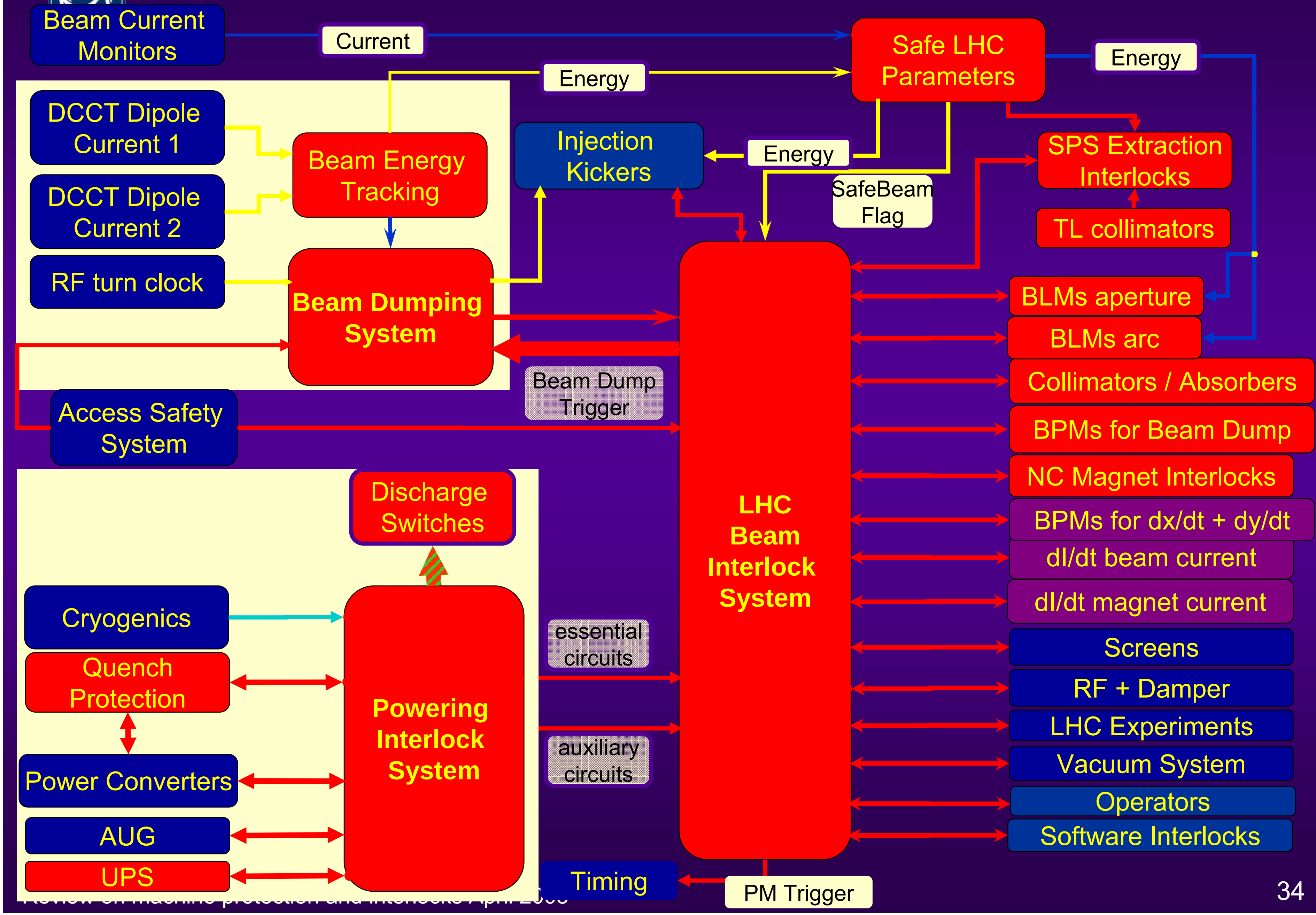
The overall strategy of the LHC machine protection is discussed.

The functionality of the systems with respect to machine protection is presented.

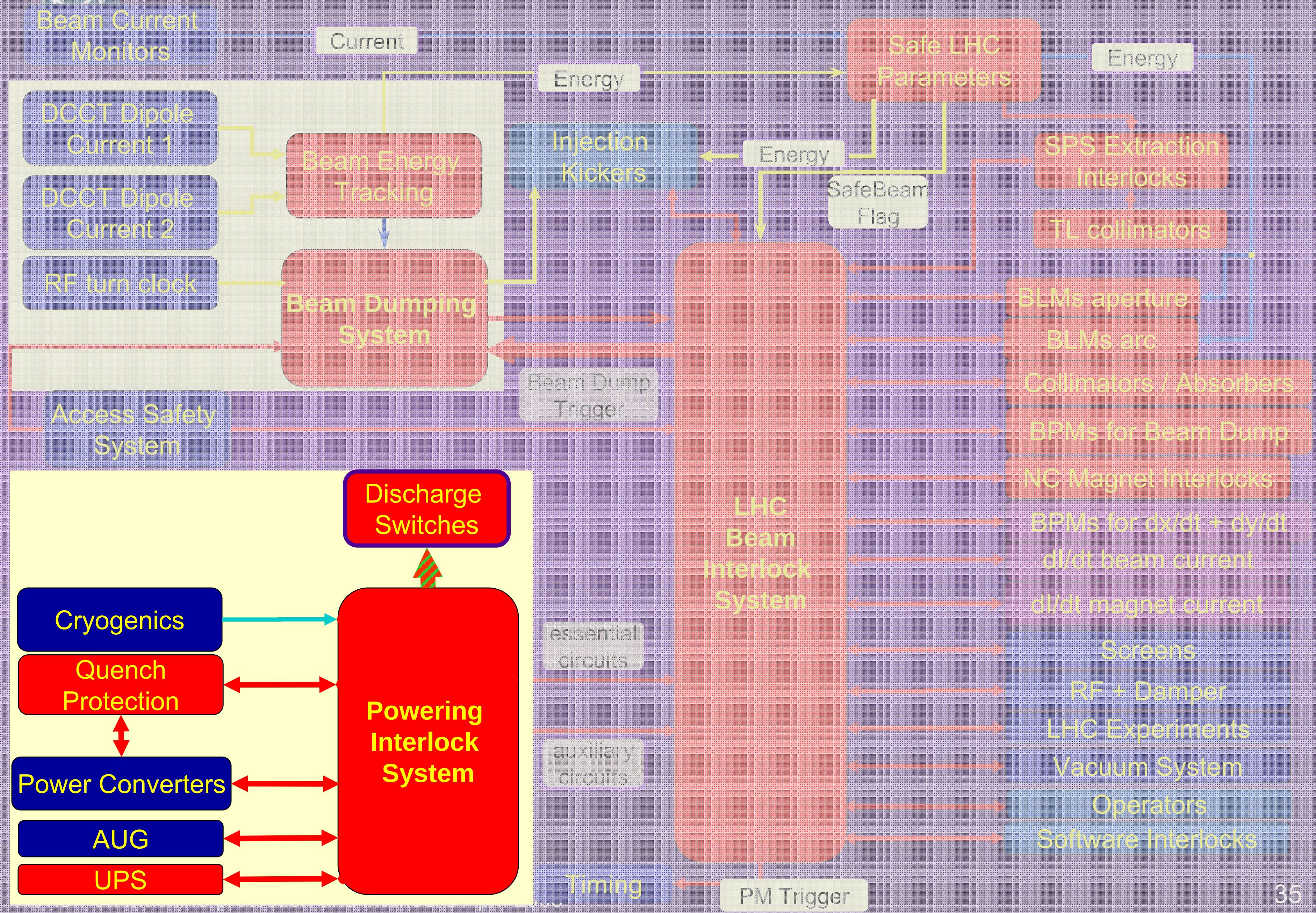
Main emphasis of the review is on the interfaces between these systems during beam operation.

Abort gap monitoring

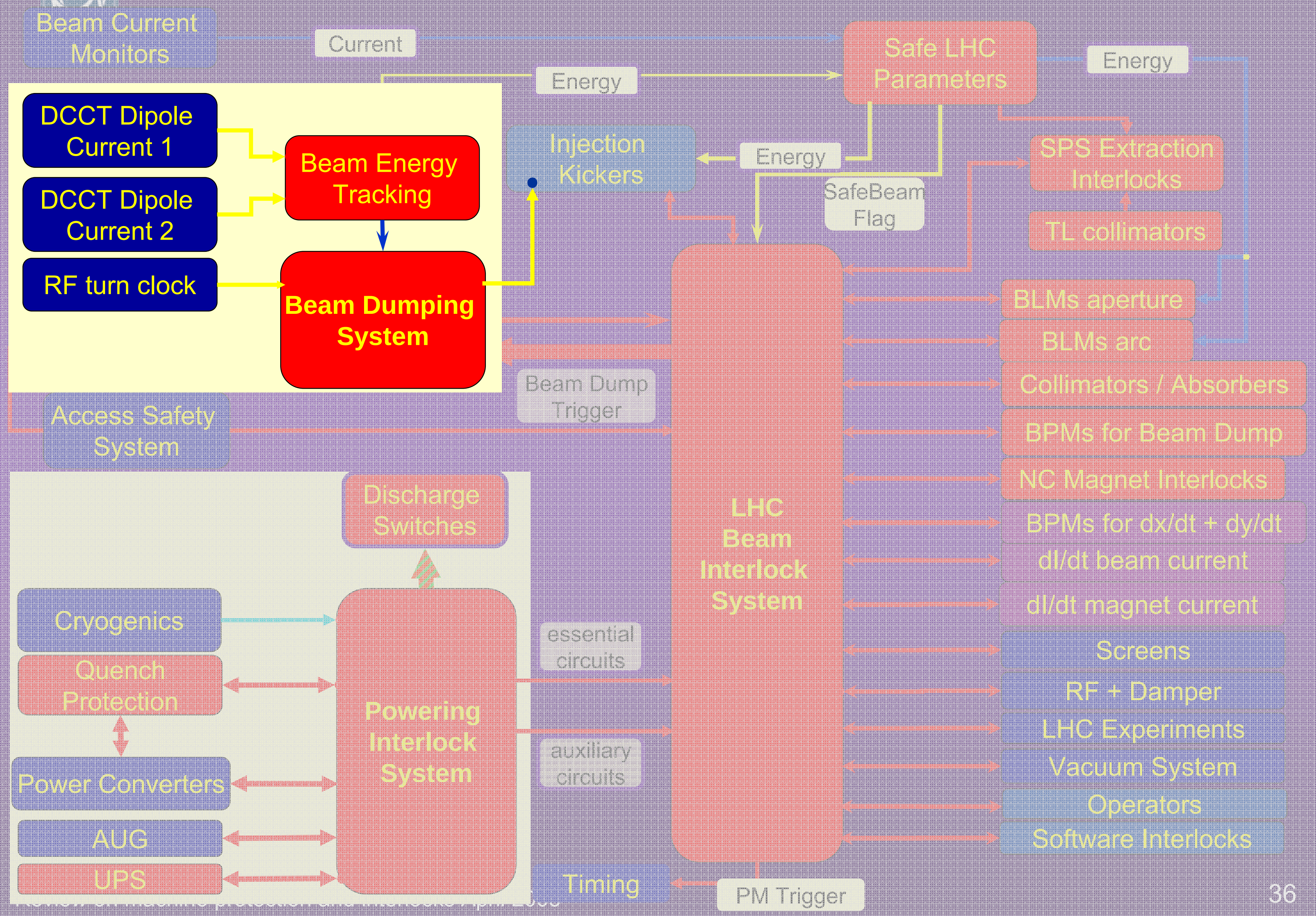
Machine Protection Systems and (HW) Interfaces



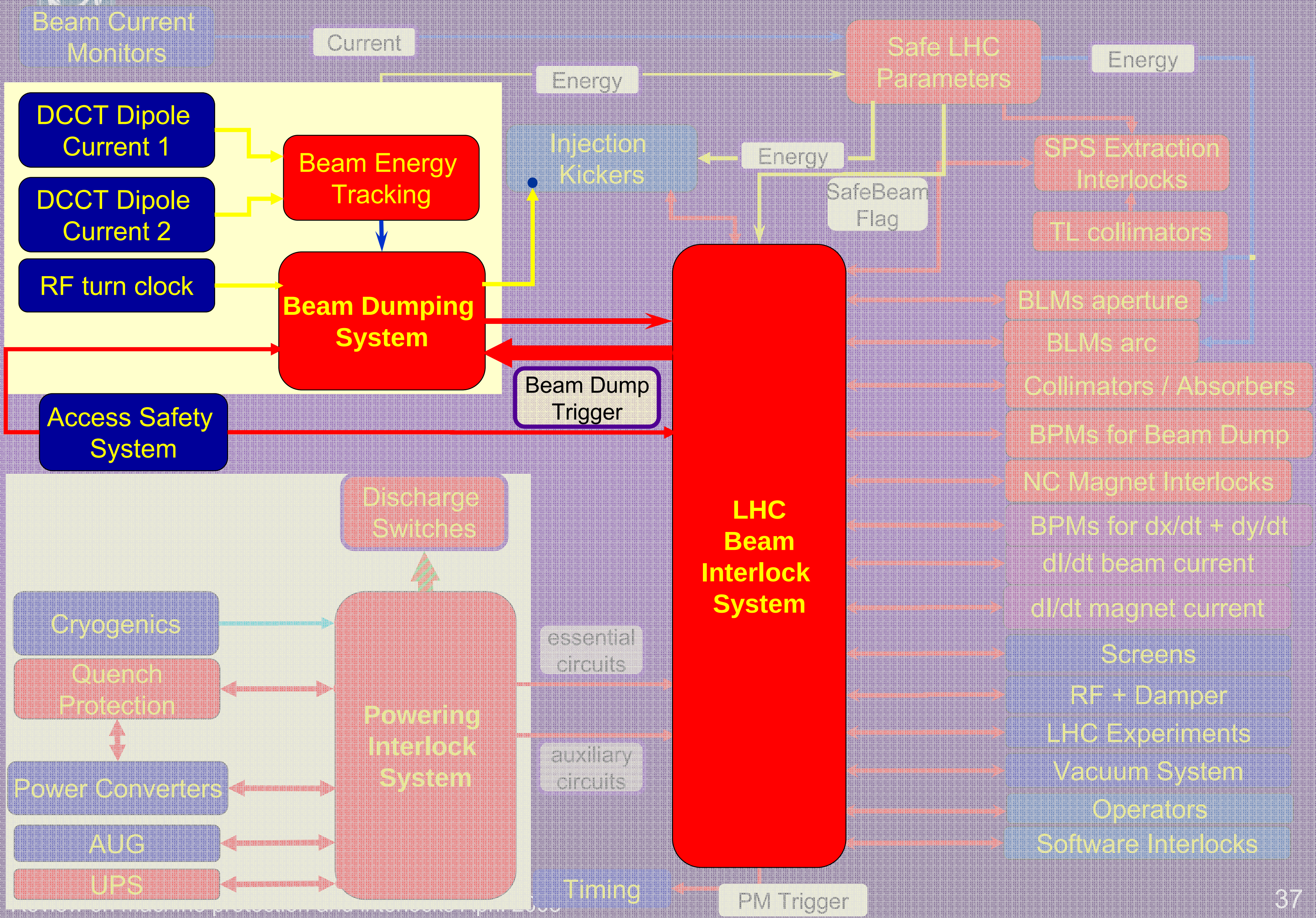
Protection and Magnet Powering



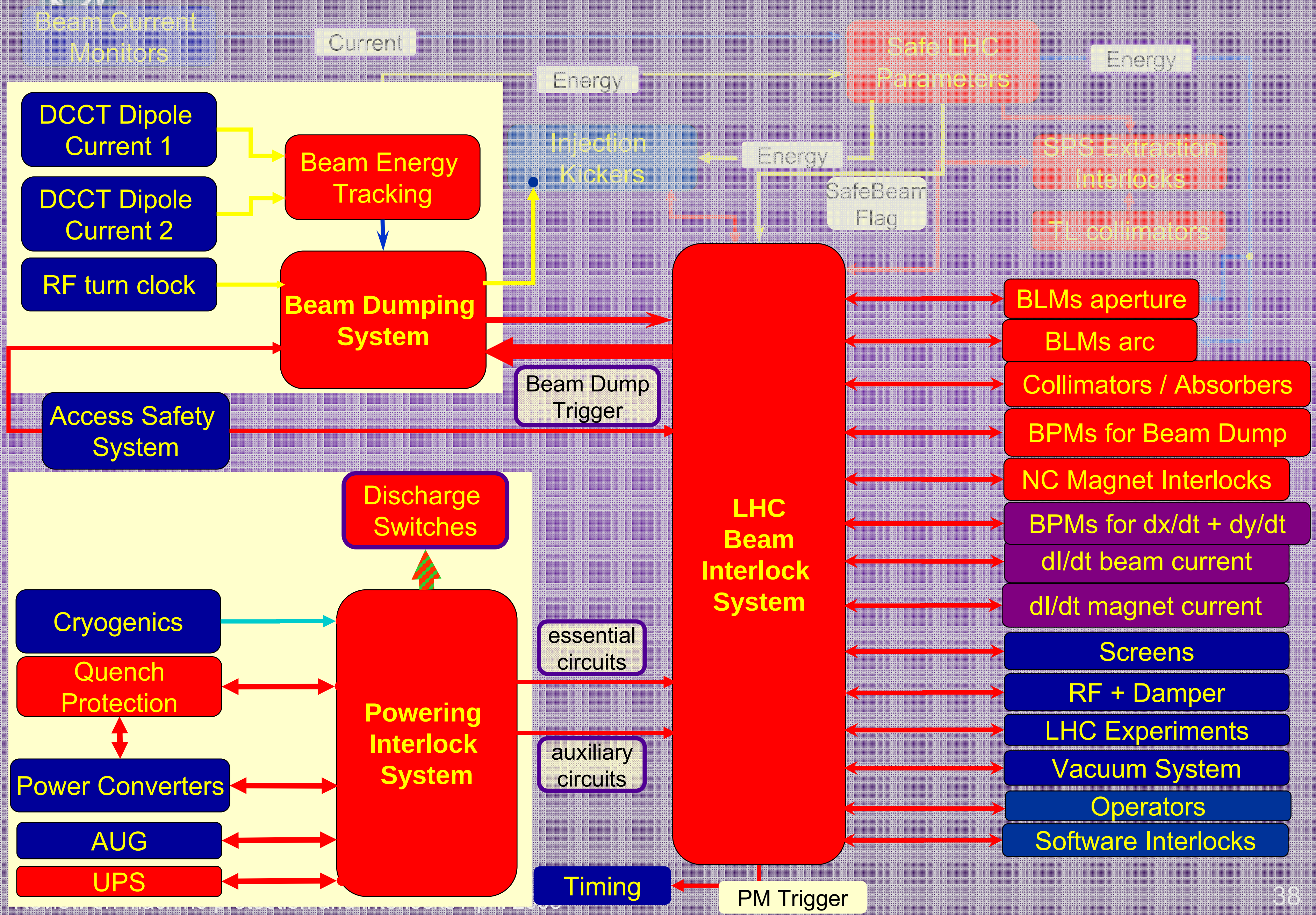
Beam Dumping System



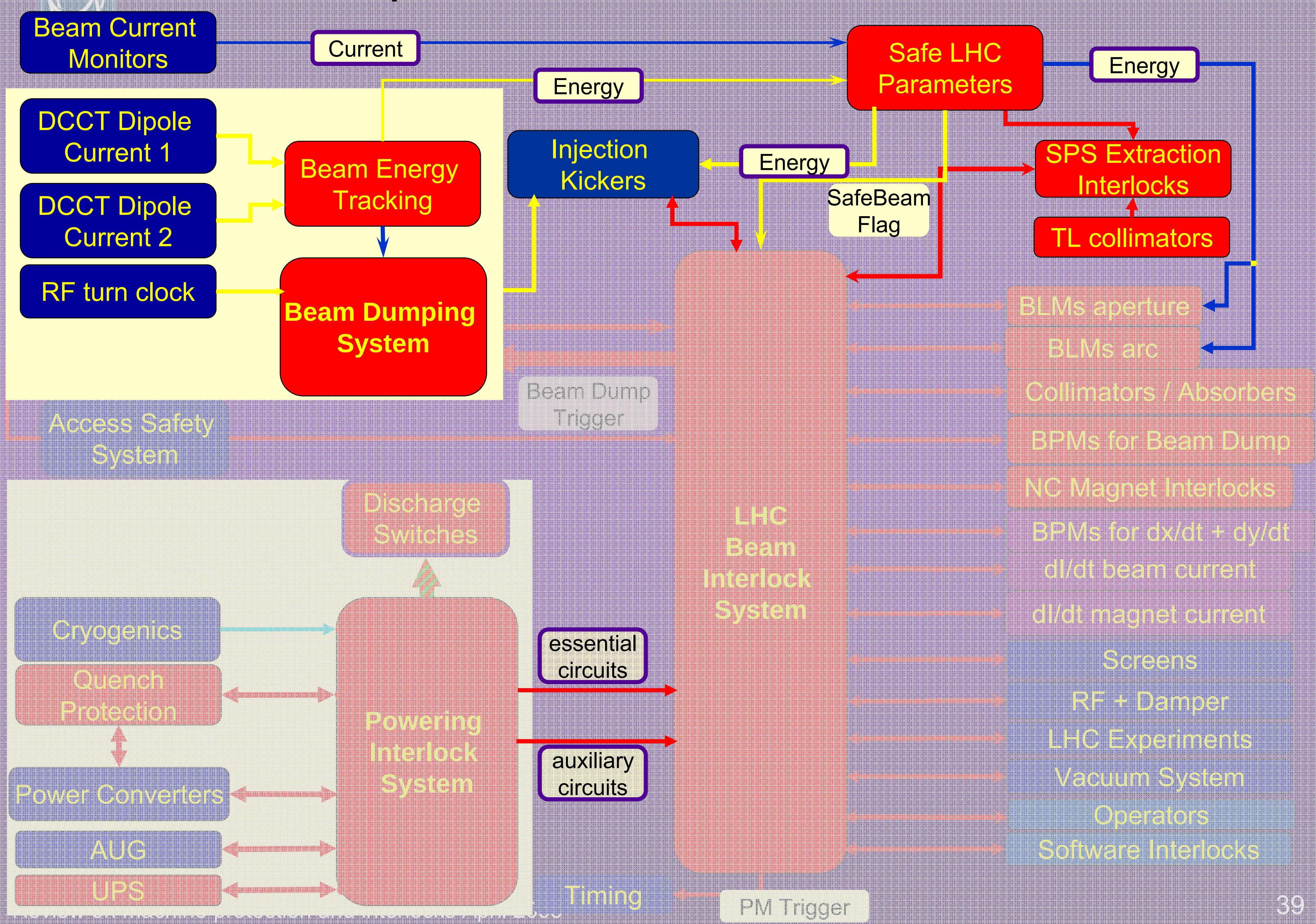
Beam Dumping System and Triggers



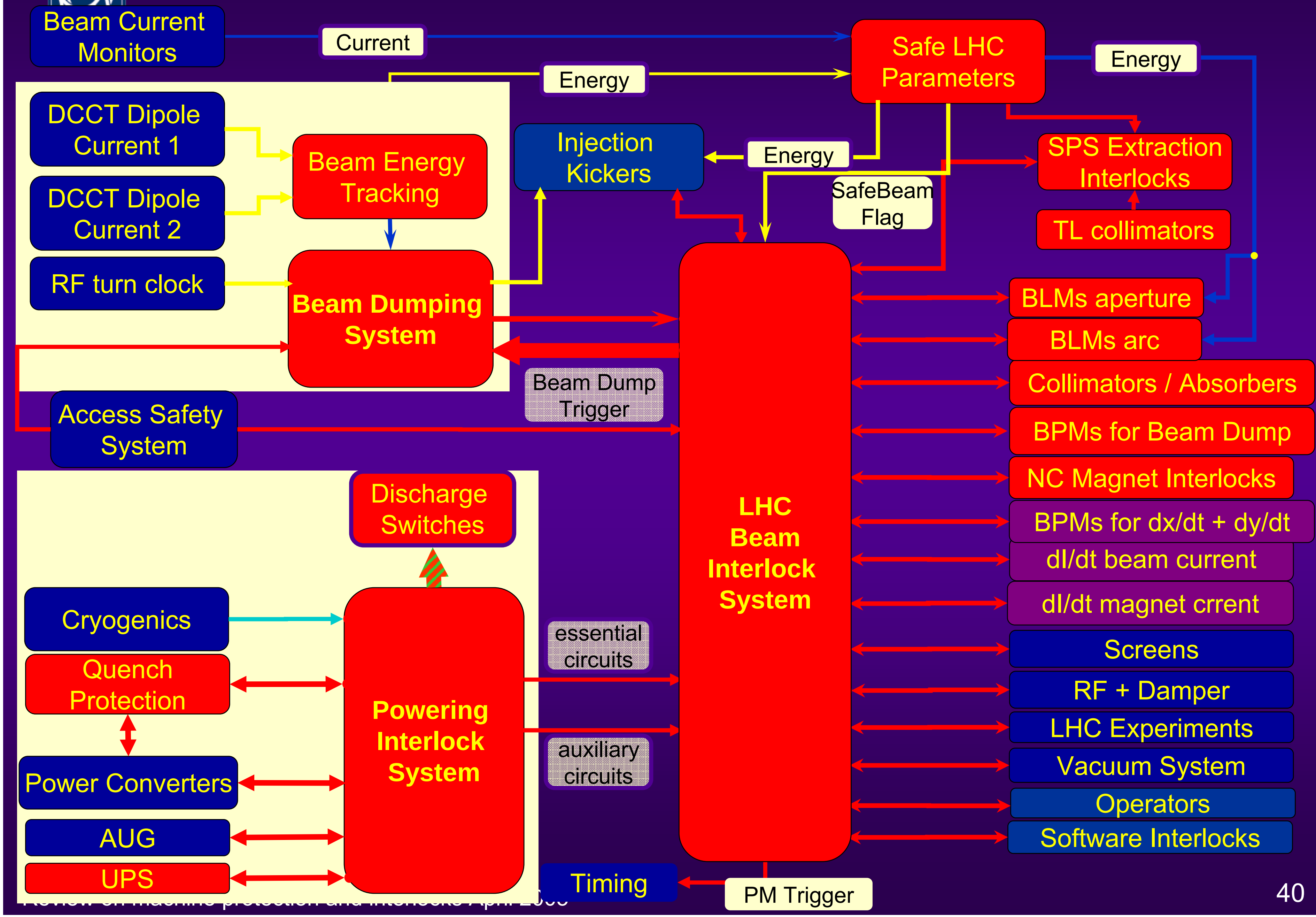
Beam Interlock System and Inputs



Safe LHC parameters



All systems and hardware links



Failures increasing risks

Such failures would not cause beam losses

- could lead to damage in combination with other failure(s)
- **require corrective action**

- Collimators / Beam absorber / other objects not in correct position with respect to beam
  - could lead to damage, e.g. in case of single turn failure
- RF: too many particles leave buckets
- Closed orbit outside tolerance
  - would be detected by orbit monitoring
  - might lead to insufficient cleaning efficiency (if another aperture becomes primary or secondary collimator)
- Beta beating outside tolerance