LHC Machine Protection

Acknowledgments to my colleagues of the MPWG
for input and material. J.Wenninger B.Todd R.Schmidt B. Puccio

Rossano Giachino
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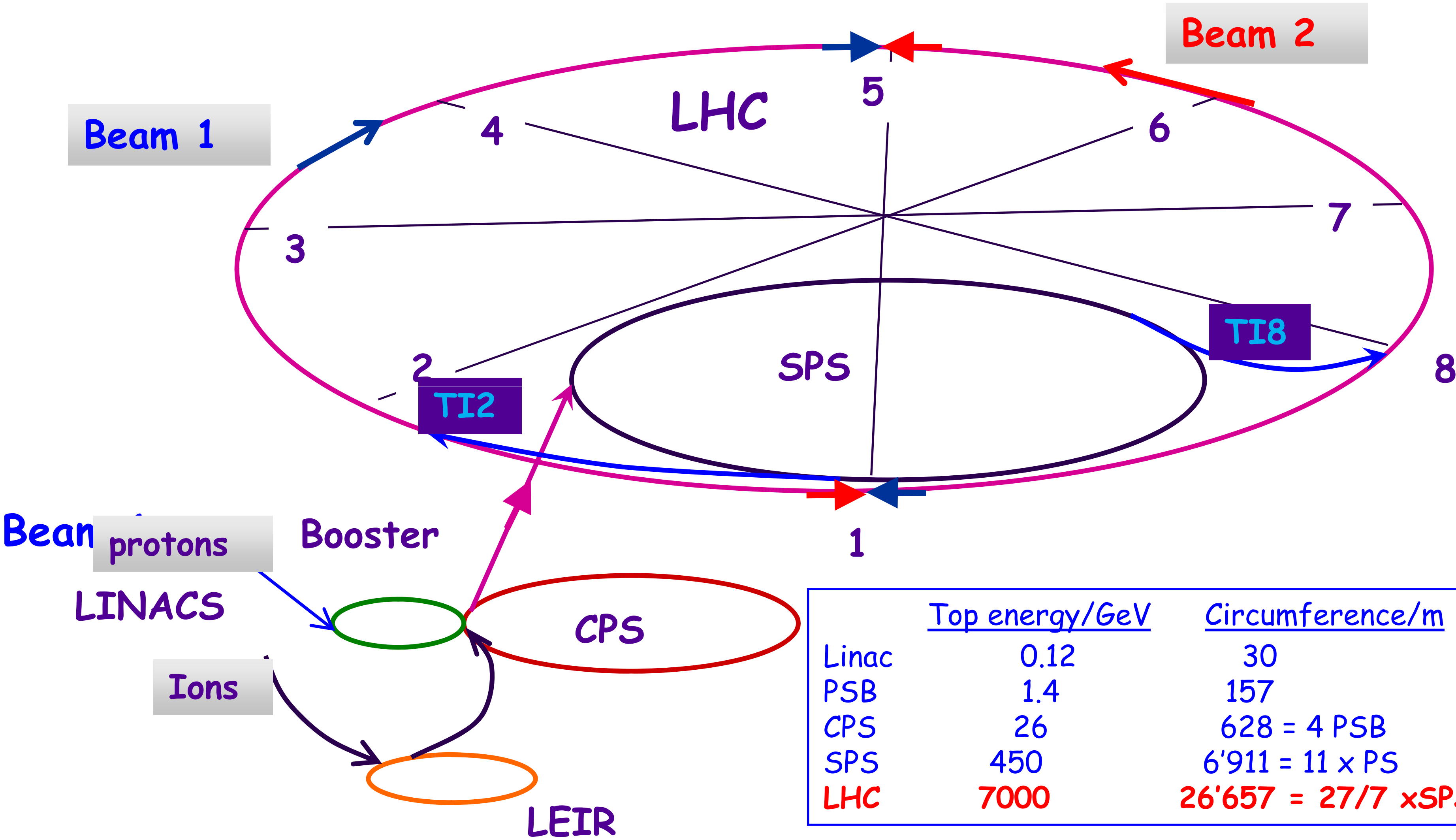
Outline

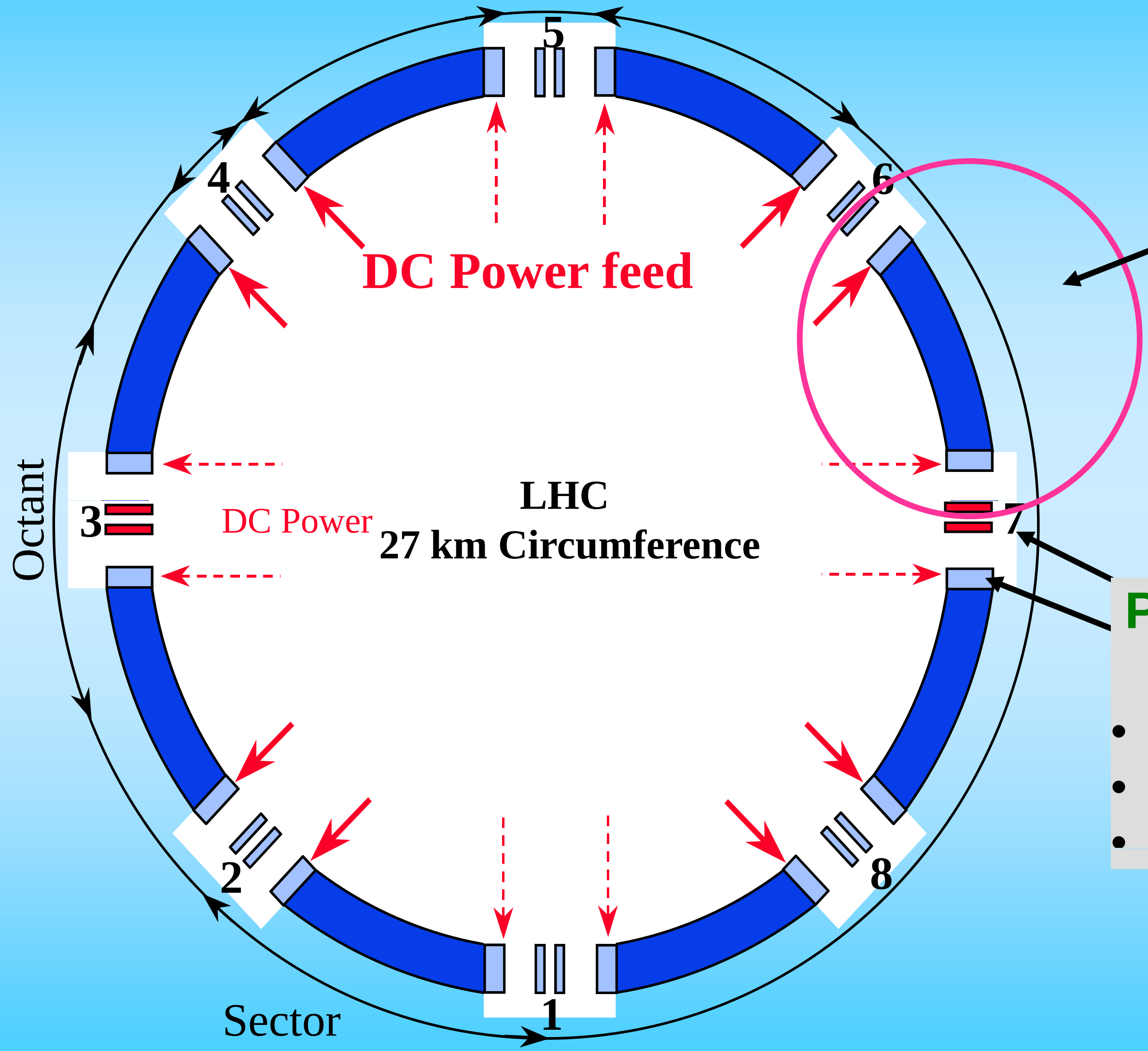
- Energy stored in the LHC magnets
  - **LHC Dipole Magnets**
  - **Power Interlock Controllers**
  - **Quench Protection System**
- Energy stored in the LHC beams
  - **LHC Beam Energy**
  - **Beam Losses and Damage Potential**
  - **Beam Absorbers, Beam Dump and Collimators**
  - **Beam Interlock System**
- Conclusion



	Top energy/GeV	Circumference/m
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 xSPS

Note the energy gain/machine of 10 to 20 – and not more !
The gain is typical for the useful range of magnets !!!

LHC Powering in 8 Sectors



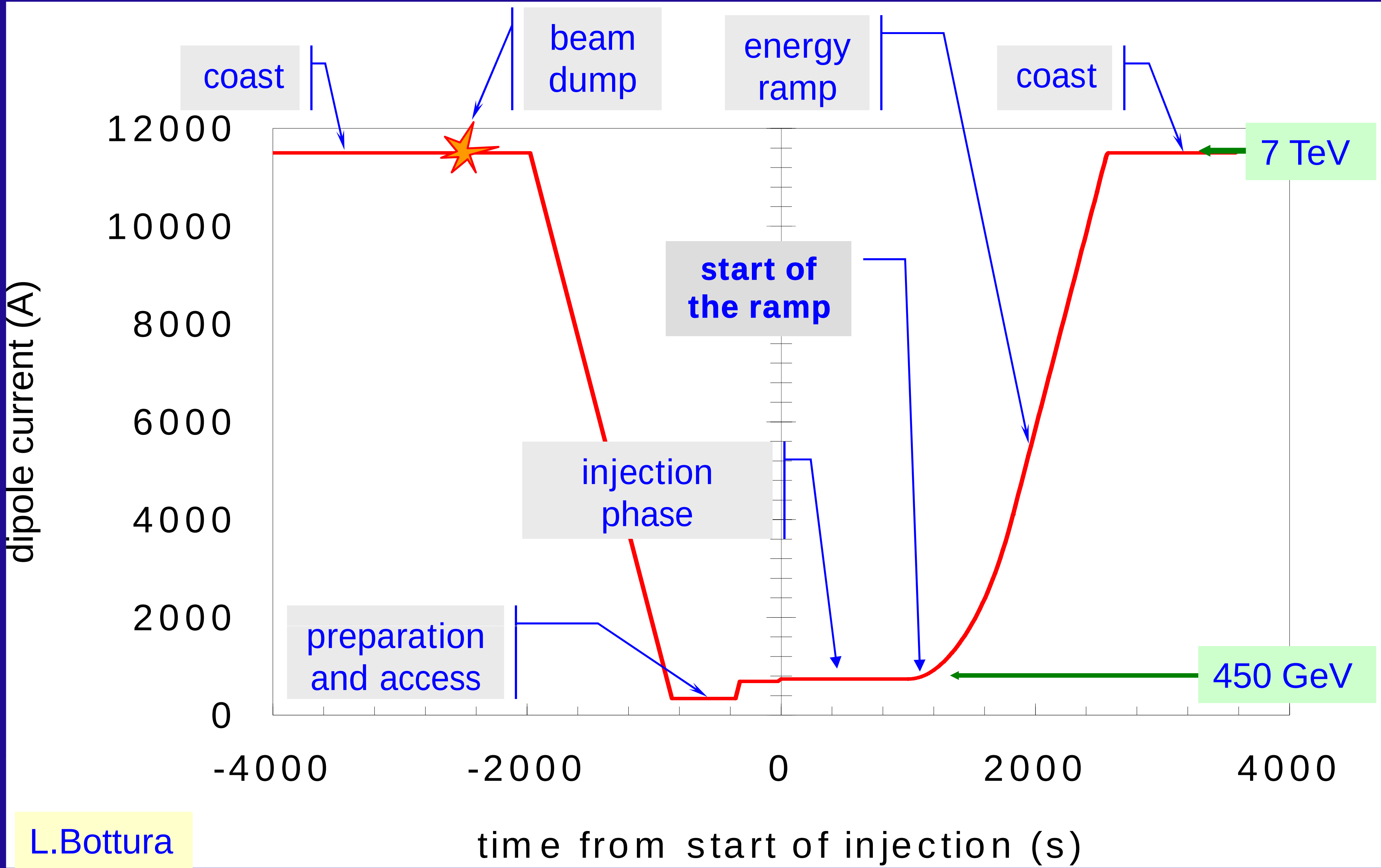
Powering Sector:

154 dipole magnets & about 50 quadrupoles total length of 2.9 km

Powering Subsectors:

- long arc cryostats
- triplet cryostats
- cryostats in matching section

LHC cycle: charging the magnetic energy



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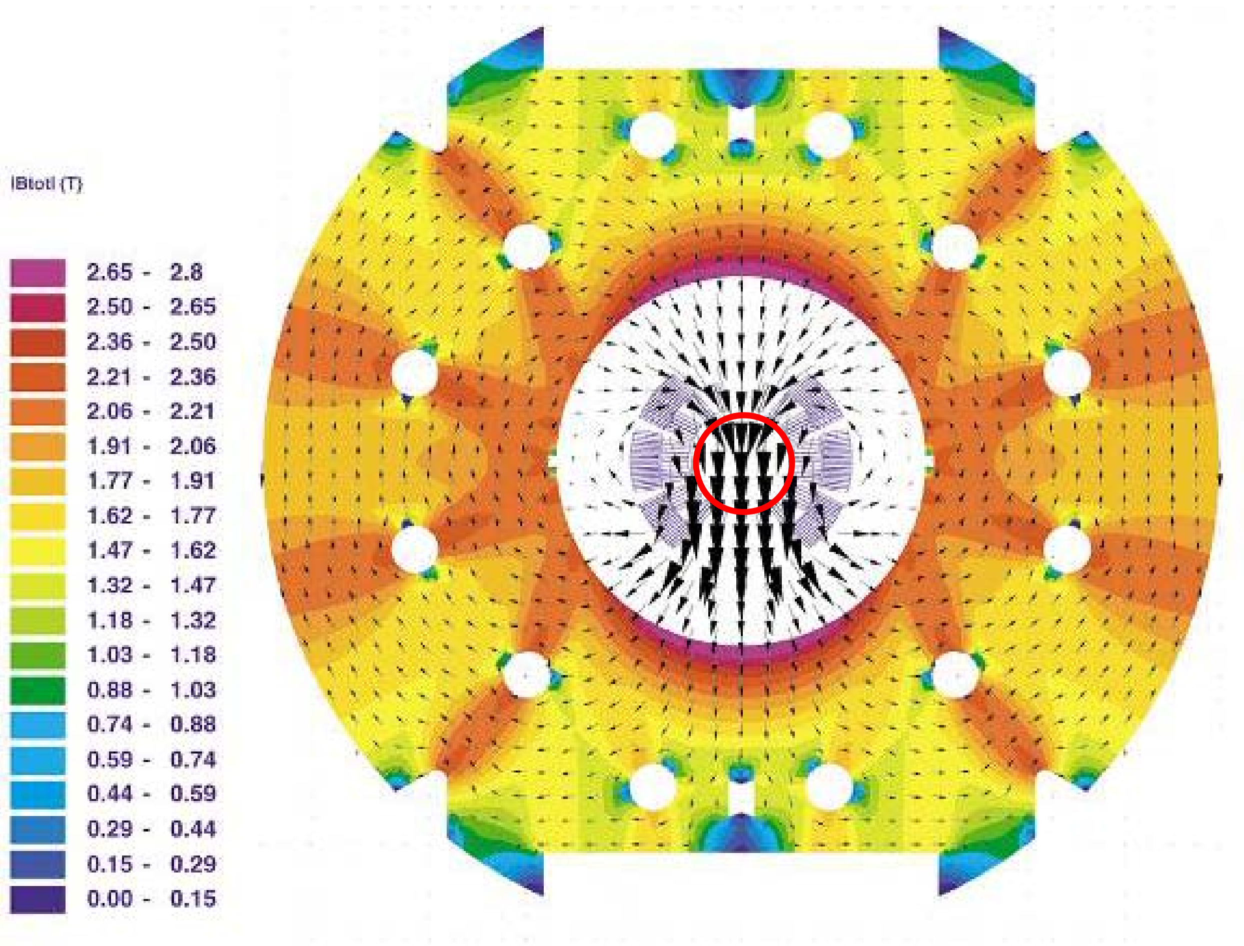
Energy stored in LHC magnets : where

Most energy is stored in the magnetic field of the dipoles



B = 8.33 Tesla   I = 11800 A   L = 0.108 H

Energy stored in LHC magnets

Energy is proportional to volume inside magnet aperture and to the square of the magnet field

$E_{dipole} = 0.5 \bullet L_{dipole} \bullet I^{2}_{dipole}$

Energy stored in one dipole is 7.6 MJoule

For all 1232 dipoles in the LHC: 9.4 GJ

The energy stored in the magnets corresponds to ..

an aircraft carrier at battle-speed of 55 km/h

The energy stored in the magnets corresponds to ..

10 GJoule corresponds to…

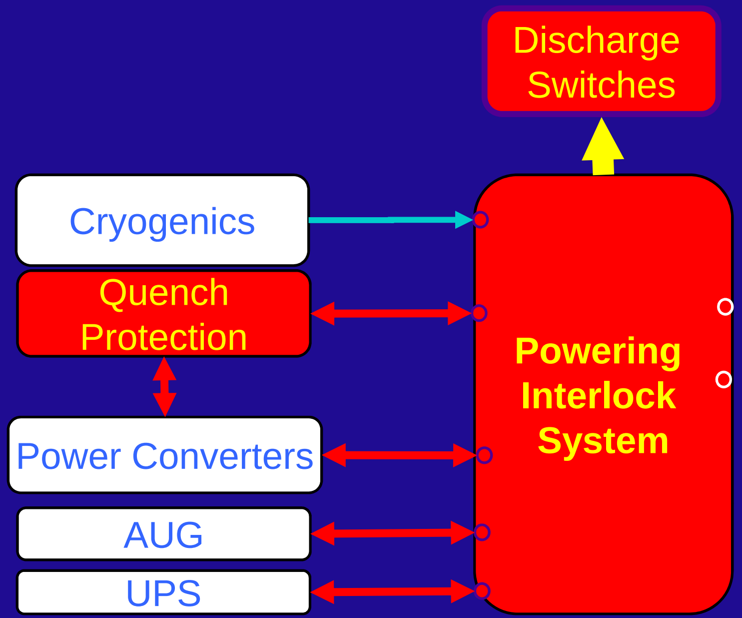
the energy of 1900 kg TNT
the energy of 400 kg Chocolate

An important point to determine :

How fast can this energy be released?

Powering Interlock Controller

- PLC-based Powering Interlock Controllers (PIC) are used to manage the interlock signal between the power converters and the quench protection system.
- The PIC also interfaces to the Beam Interlock System and will request a beam dump if the electrical circuit that fails is considered to be critical for beam operation.



Quench

A Quench is the phase transition of a super-conducting to a normal conducting state.

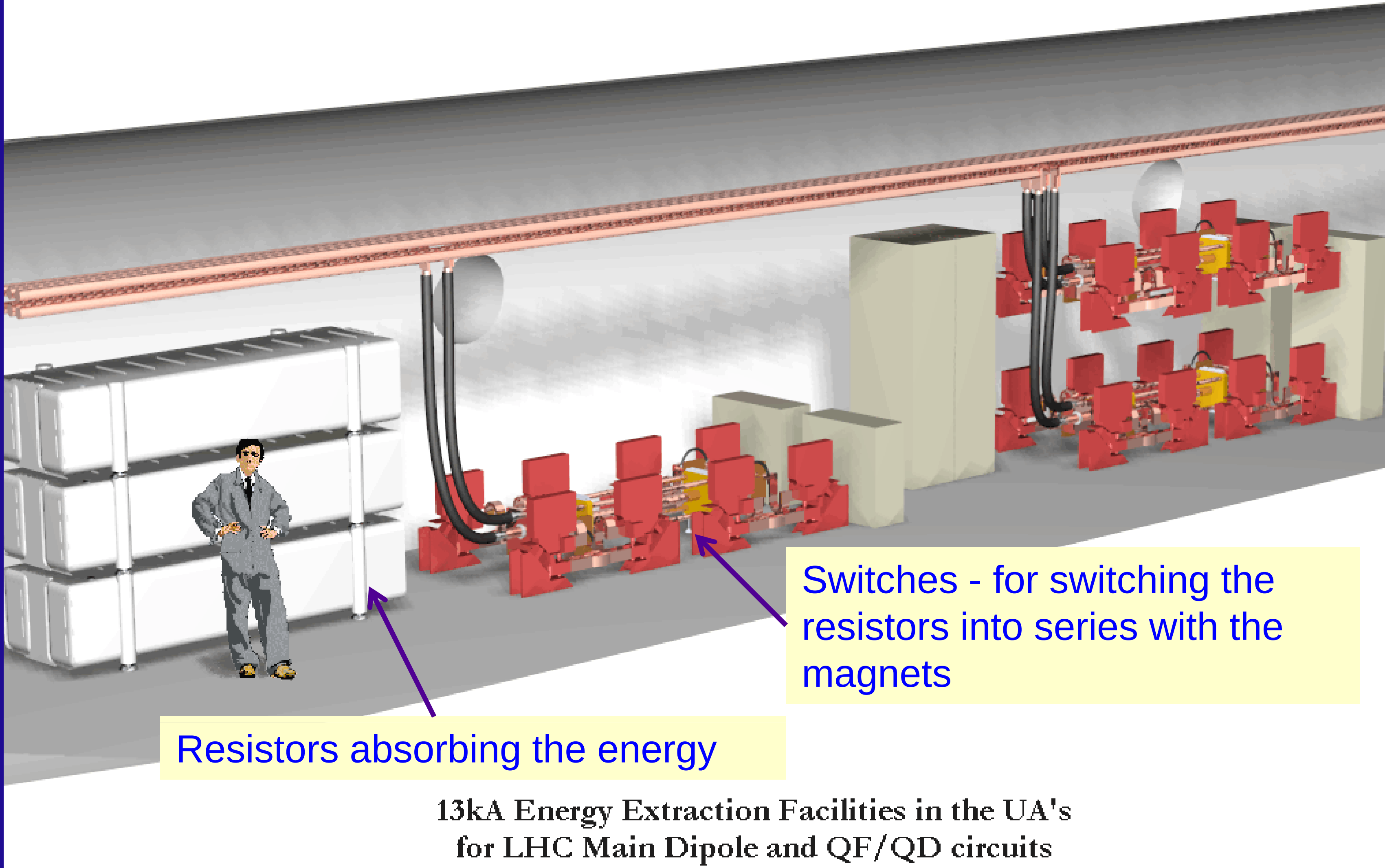
Quenches are initiated by an energy in the order of mJ

- Movement of the superconductor by several μm (friction and heat dissipation)
- Beam losses
- Failure in cooling

To limit the temperature increase after a quench

- The quench has to be detected
- The energy is distributed in the magnet by force-quenching the coils using quench heaters
- The magnet current has to be switched off within « 1 second

Energy extraction system in LHC tunnel



If it does not work…

During magnet testing the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

P.Pugnat

Challenges for quench protection

- Detection of quench for all main magnets
  - 1600 magnets in 24 electrical circuits
  - ~800 others
- Detection of quench across all HTS current leads
  - 2000 Current Leads
- Firing heater power supplies, about
  - 6000 heater units

Failure in protection system

False quench detection: downtime of some hours
Missed quench detection: damage of magnet, downtime 30 days

Systems must be very reliable

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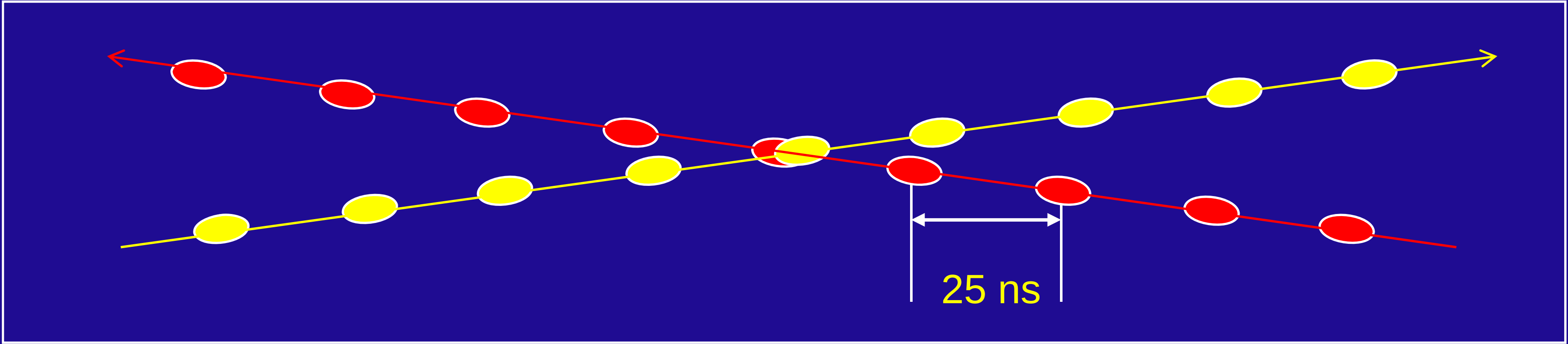
Energy stored in the beams



Stored beam energy: Proton Energy • Number of Bunches • Number of protons per bunch

Proton Energy: 7 TeV

In order to achieve very high luminosity:

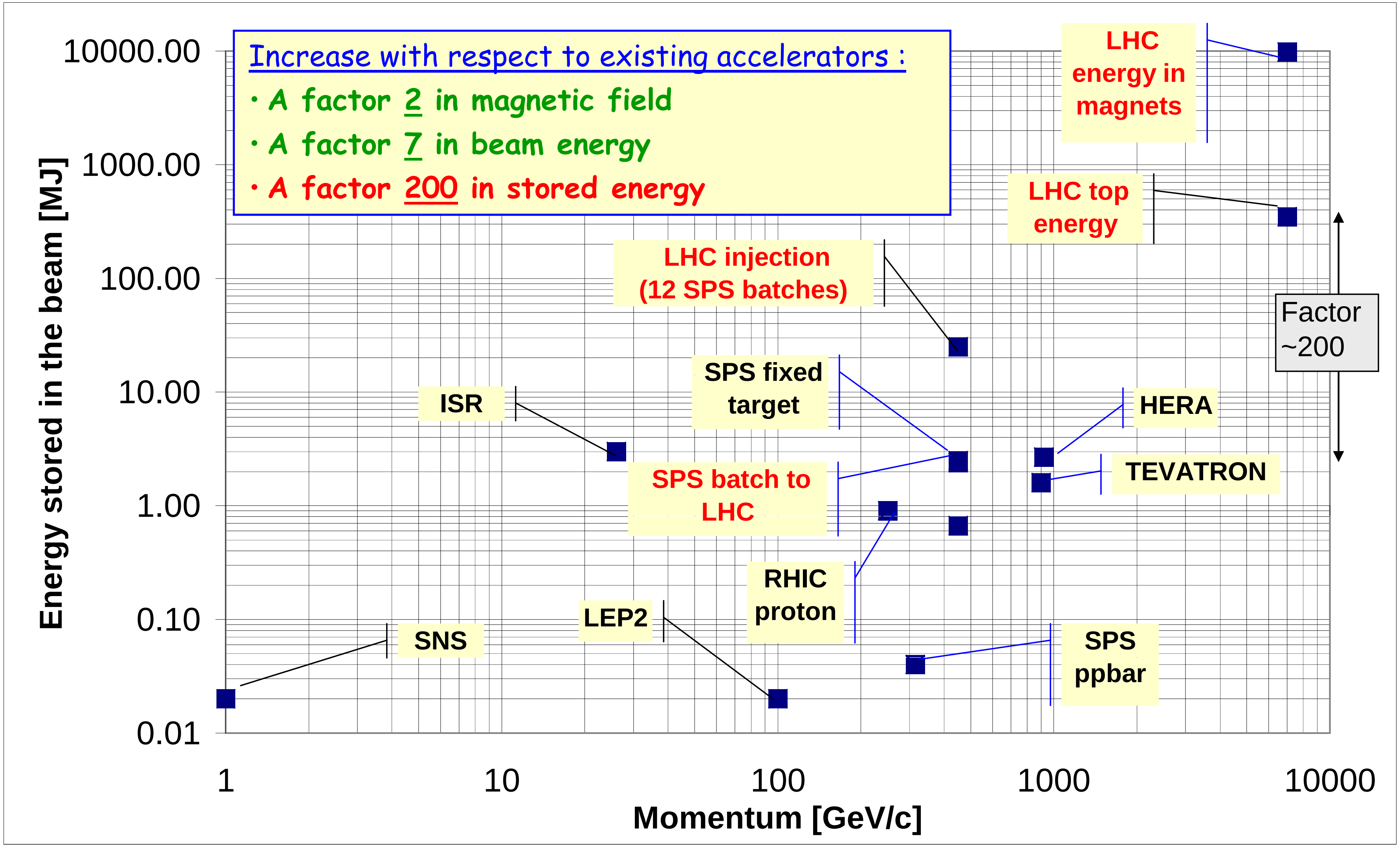
Number of bunches per beam: 2808

Number of protons per bunch: 1.05×10^{11}

} 3×10^{14} protons / beam

Stored energy per beam: 362 MJoule

Stored energy comparison



A proton injected into the LHC will end its life…

- In a collision with an opposing beam proton
  - **The goal of the LHC !**
- On the LHC beam dump
  - **At the end of a fill, be it scheduled or not.**
- On a collimator or on a protection device/absorber
  - **The collimators must absorb protons that wander off to large amplitudes to avoid quenches.**

Beam induced damage test

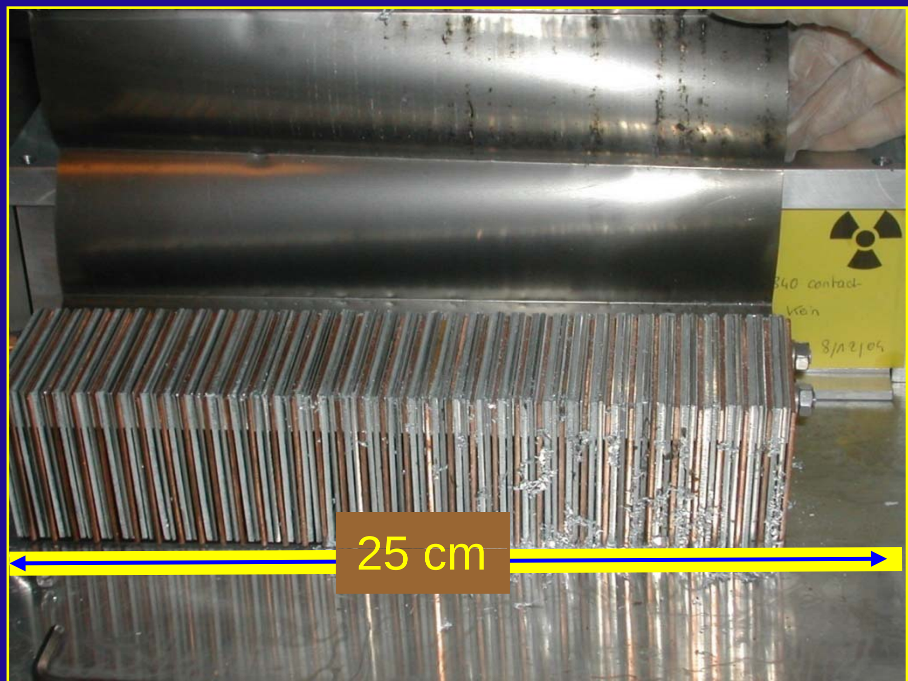
The effect of a high intensity beam impacting on equipment is not so easy to evaluate, in particular when you are looking for damage :

heating, melting, vaporization …

→ Controlled experiment:

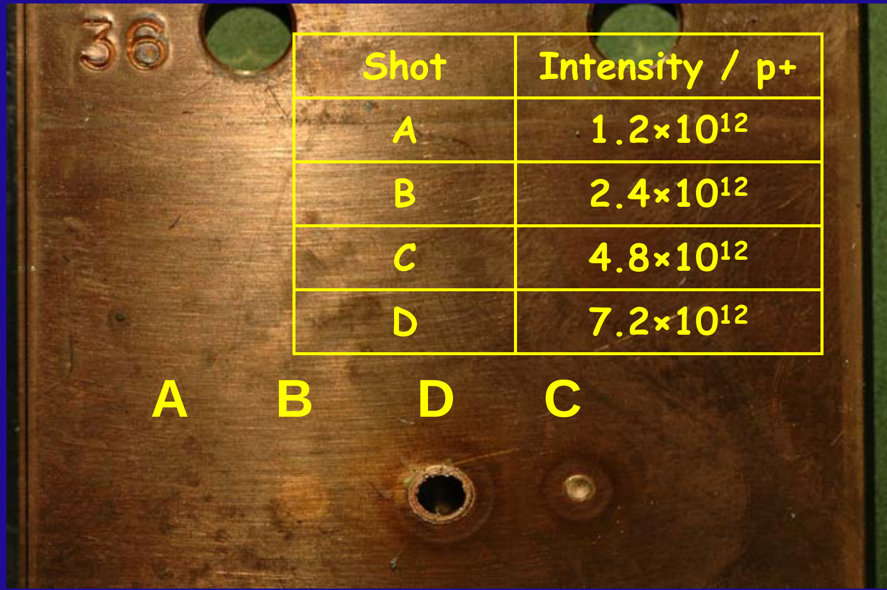
- **Special target (sandwich of Tin, Steel, Copper plates) installed in an SPS transfer line.**
- **Impact of 450 GeV LHC beam (beam size $\sigma_{x/y}$ ~ 1 mm)**

Beam →



Results….

- Melting point of Copper is reached for an impact of ≈ 2.5×10^{12} p.
- Stainless steel is not damaged, even with 7×10^{12} p.
- Results agree with simulation



Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

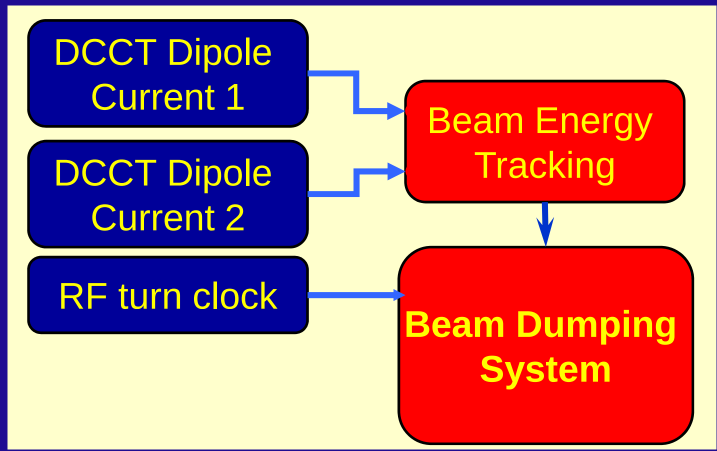
Based on those results the MPWG has adopted for the LHC a limit for safe beams with nominal emittance @ **450 GeV** of:

10^{12} protons ~ 0.3% of the total intensity

Scaling the results yields a limit @ **7 TeV** of:

10^{10} protons ~ 0.003% of the total intensity

Beam absorber

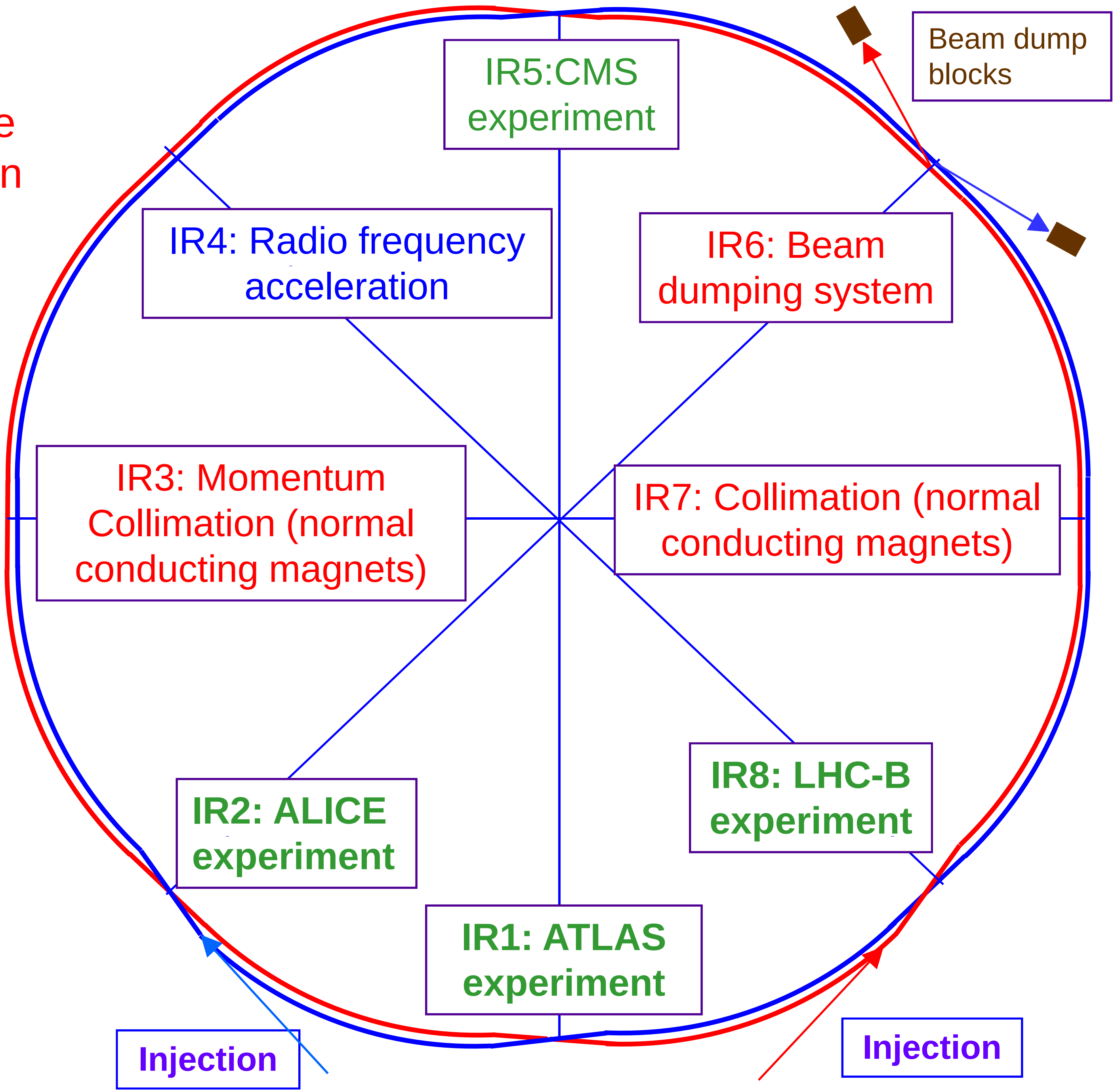


- **The beam dump block is the ONLY element of the LHC that can safely absorb all the beam!**

- *All other absorbers in the LHC (collimators and protection devices) can only stand partial losses* – typically up to a full injected beam, i.e. equivalent to the energy stored in the SPS at 450 GeV.

LHC Layout

IR3, IR6 and IR7 are devoted to protection and collimation !



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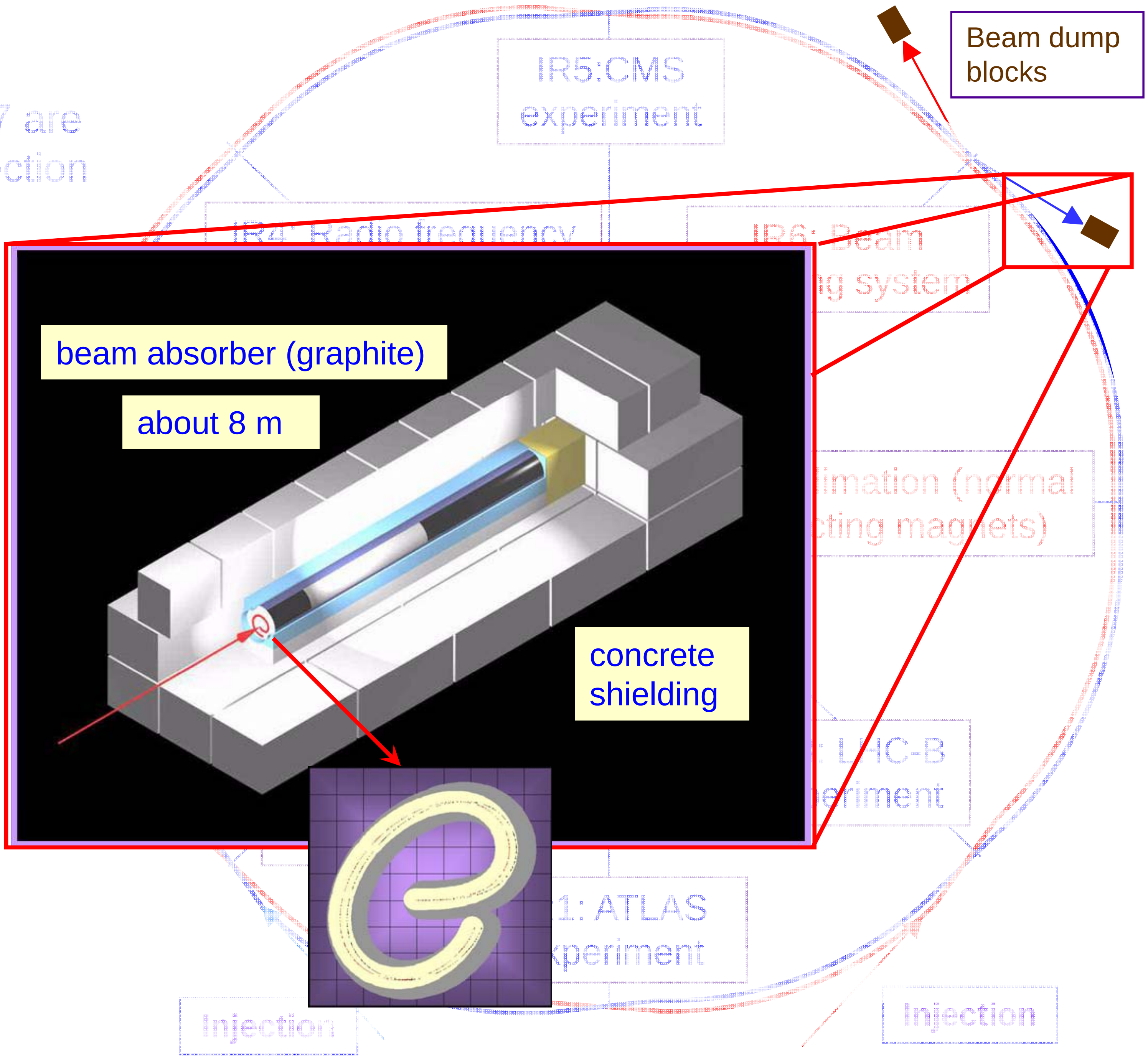
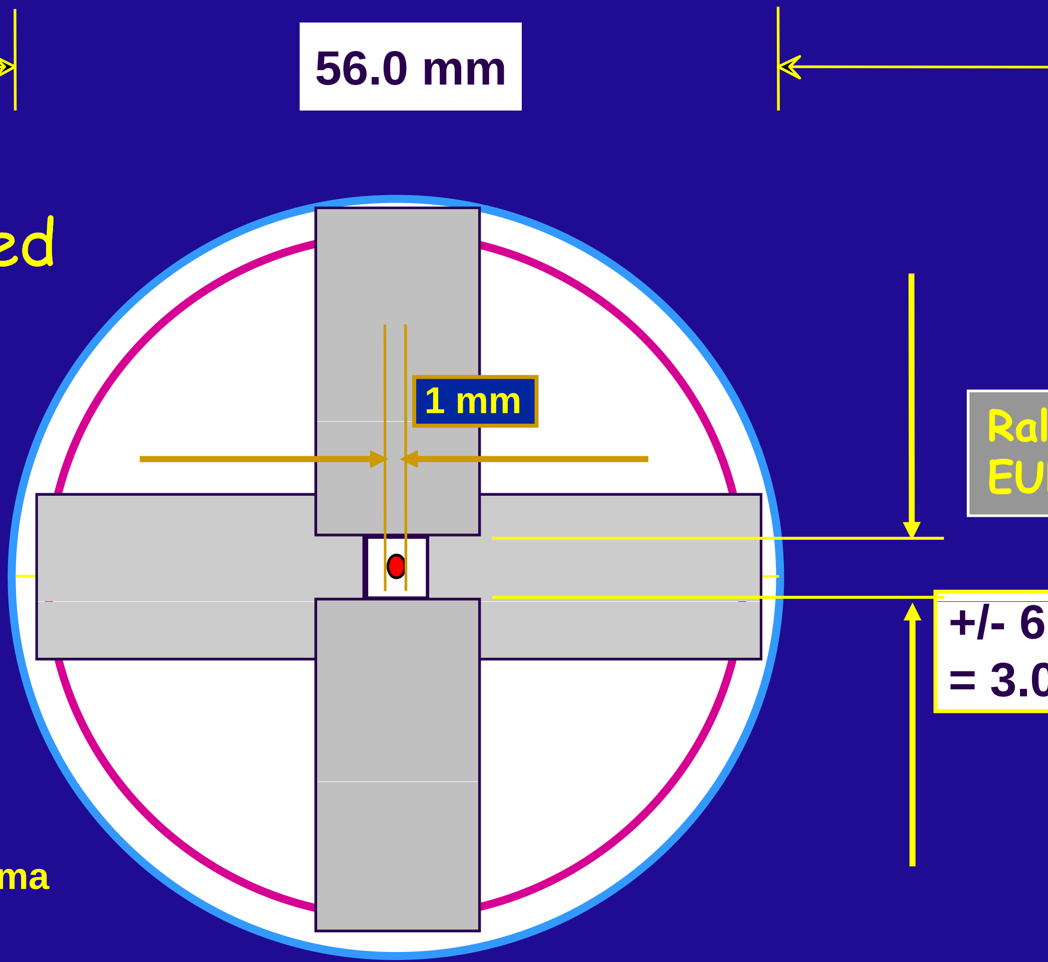


Collimators at 7 TeV, squeezed optics



Ralphs Assmanns EURO

Beam +/- 3 sigma

Example: Setting of collimators at 7 TeV - with luminosity optics

Very tight settings → orbit feedback !!

Beam Interlock System and Inputs

- Protection for the entire machine against beam incidents.
- Interface to all parties involved in protection, including powering interlock systems and injectors (SPS).
- Microsecond reaction times.

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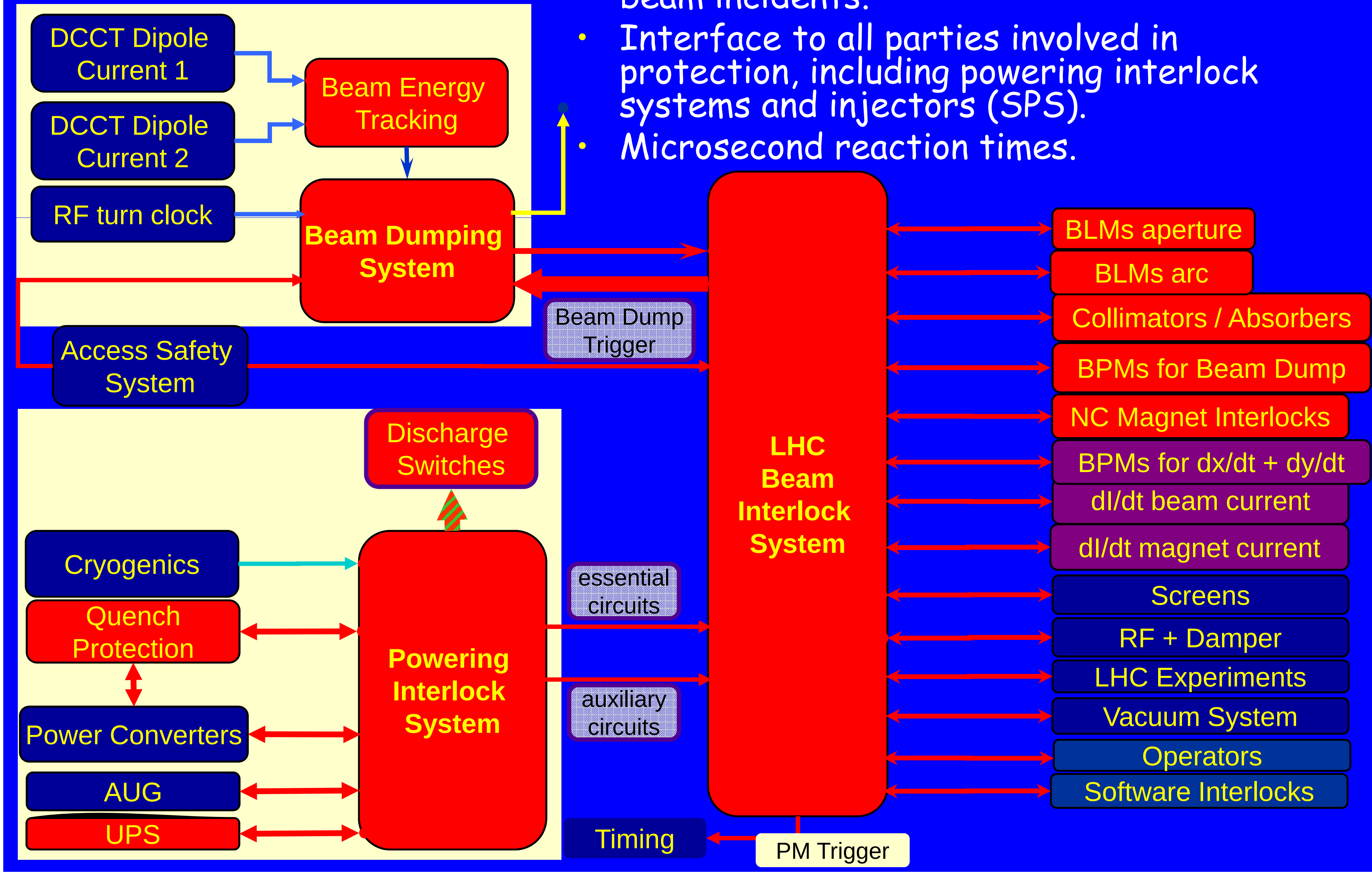
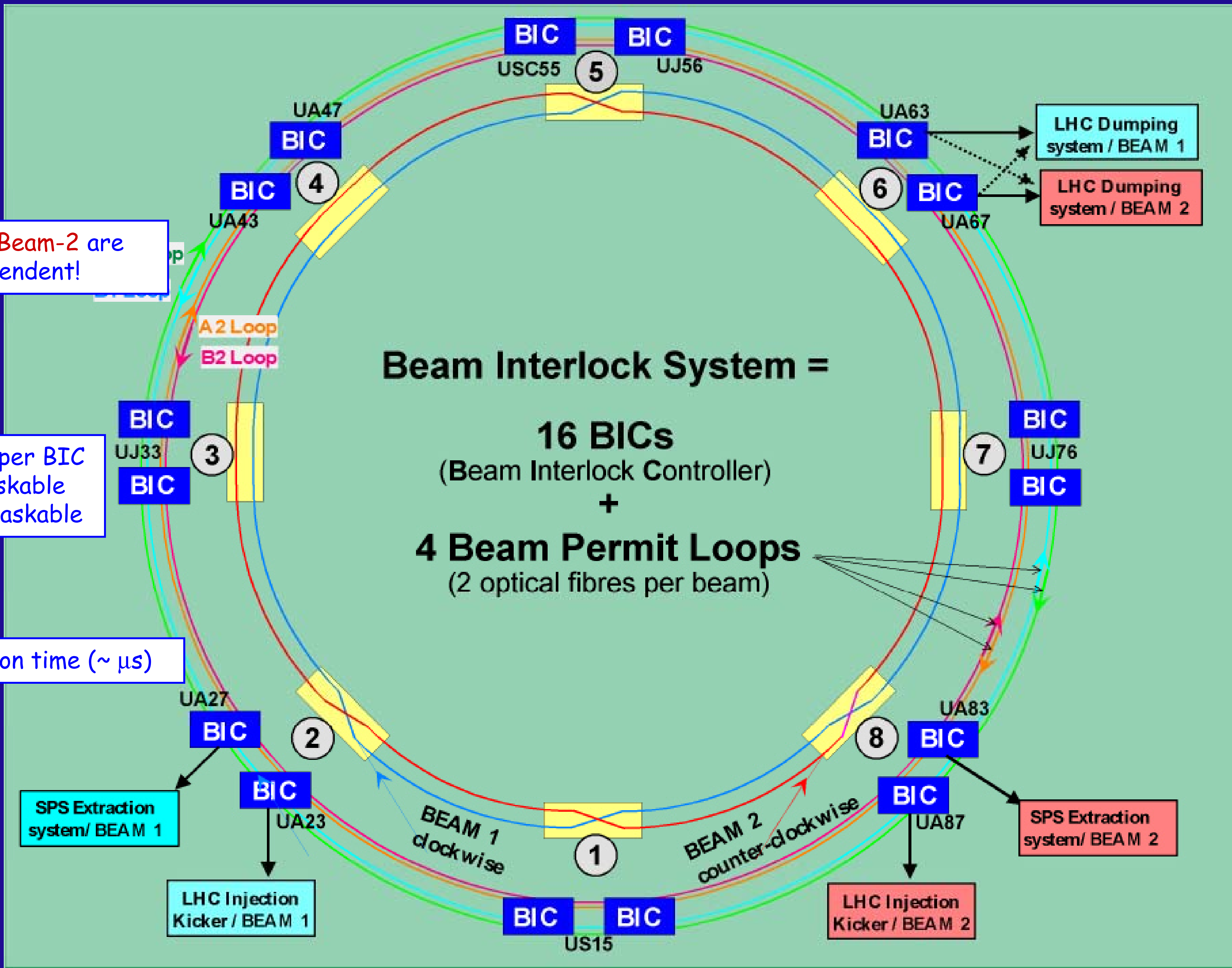


Architecture of the BEAM INTERLOCK SYSTEM

Beam-1 / Beam-2 are Independent!

20 Users per BIC
Half maskable
Half un-maskable

- fast reaction time (~ μs)



Safe LHC parameters

Safe Beam Flags required by

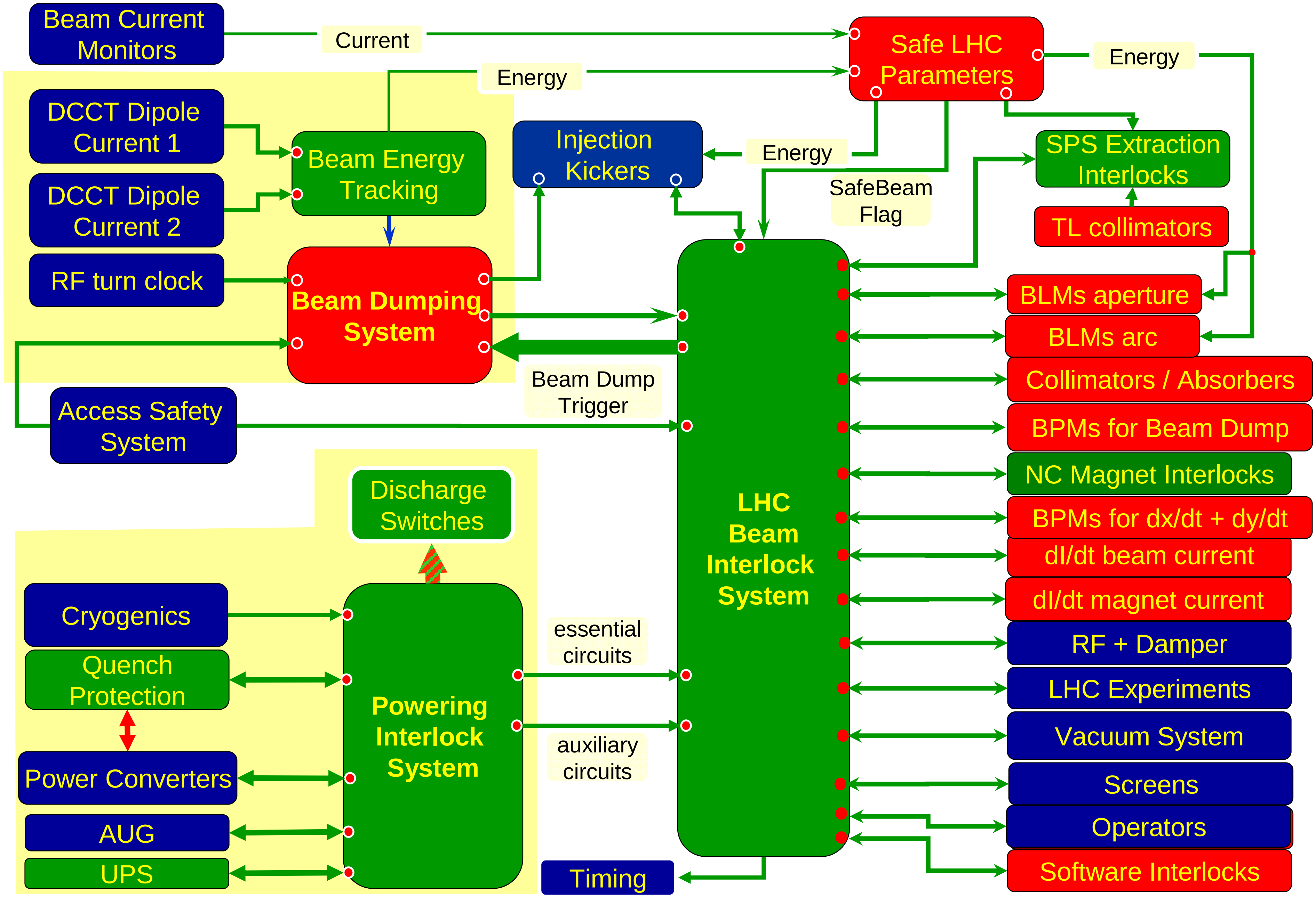
- **Beam Interlock Controllers, to permit masking of selected interlock channels, in particular during commissioning**
- **Aperture kickers, to disable kickers when there is no "safe" beam**

Beam Presence Flags required by

- **SPS extraction, to permit extraction of high intensity beam only when there is circulating beam in the LHC**

Machine protection systems

Green : *ready* before first beam



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Conclusions

There is **no single "Machine Protection System"**: LHC Machine Protection relies on **several systems working reliably together**

Safe operation of the LHC **start at the SPS**, via extraction into TT40/TI8 and TI2, via the transfer lines, via LHC injection etc.

Safe operation of the LHC **requires a culture**:

- as soon as the magnets are powered, there is the risk of damage due to the stored magnet energy
- as soon as the beam intensity is above a certain value (…that is much less than 0.1% of the full 7 TeV beam), there is the risk of beam induced damage
- safe operation of the LHC relies **not only on the various hardware systems**, but also on **operational procedures** and on the **controls system ("software interlocks")**

Machine protection at the LHC

- Machine protection activities of the LHC are coordinated by the LHC Machine Protection Working Group (MPWG),

  co-chaired by R. Schmidt & J. Wenninger.

  http://lhc-mpwg.web.cern.ch/lhc-mpwg/

- Since 2004 the MPWG is also coordinating machine protection at the SPS (ring & transfer lines).