Machine Protection for the LHC and the Fast Magnet Current change Monitors

Rüdiger Schmidt
Markus Zerlauth
CERN

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Machine Protection – a novel challenge in accelerator physics and technology

Status of LHC

LHC Machine Protection

Fast Magnet Current change Monitors for Machine Protection

Machine Protection – a novel challenge in accelerator physics and technology

The protection of accelerators with **high beam power** and **high stored energy** has become a topic of intense research in recent years

- Accelerators with MW beam power (PSI, SNS, other future projects)
- Very high brightness beams (Future linear colliders, XFELs, SLsources)
- Storage rings with very high stored beam and magnet energy (HERA, TEVATRON, SPS and LHC)
- The performance of some proton accelerators is limited by beam losses and subsequent activation of materials

There are several **general requirements** for the protection systems

- Protect accelerator equipment: first priority is to **protect equipment** from damage
- Protect the beam: **unnecessary downtime should be avoided** to maximise availability
- Provide the evidence: complete and coherent **diagnostics data should be provided** to accurately understand what caused the failure and if the protection systems functioned correctly

LHC: Main Parameters and Challenges

The LHC Accelerator

LEP: e+e- 104 GeV/c (1989-2000)

Circumference 26.8 km

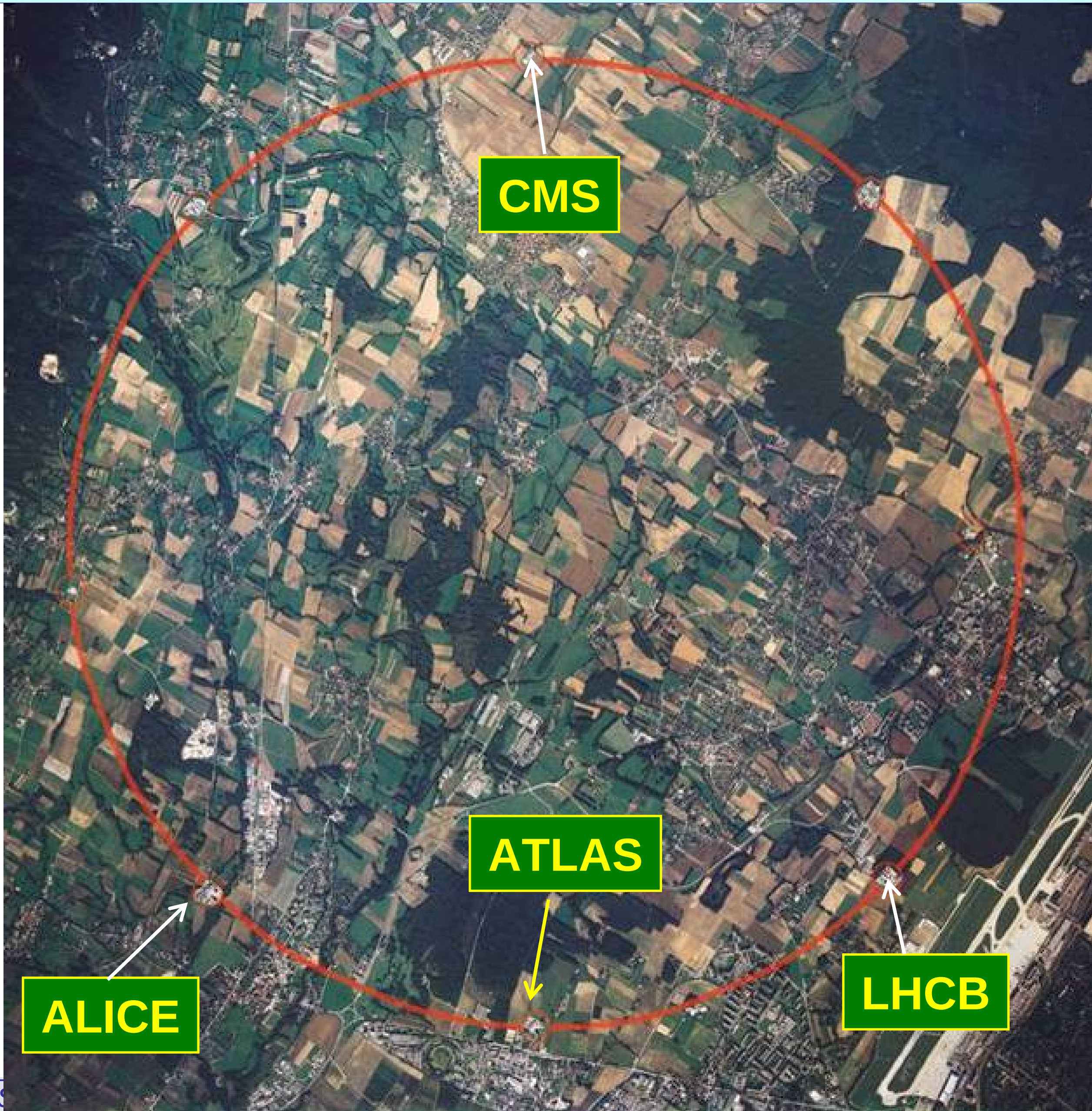
Superconducting LHC
p-p (+ion) Collider
7 TeV/c in LEP tunnel
2 rings

1982 : First studies

2003 : Start of LHC installation

2005 : Start of hardware commissioning

2007 : Commissioning with beam planned

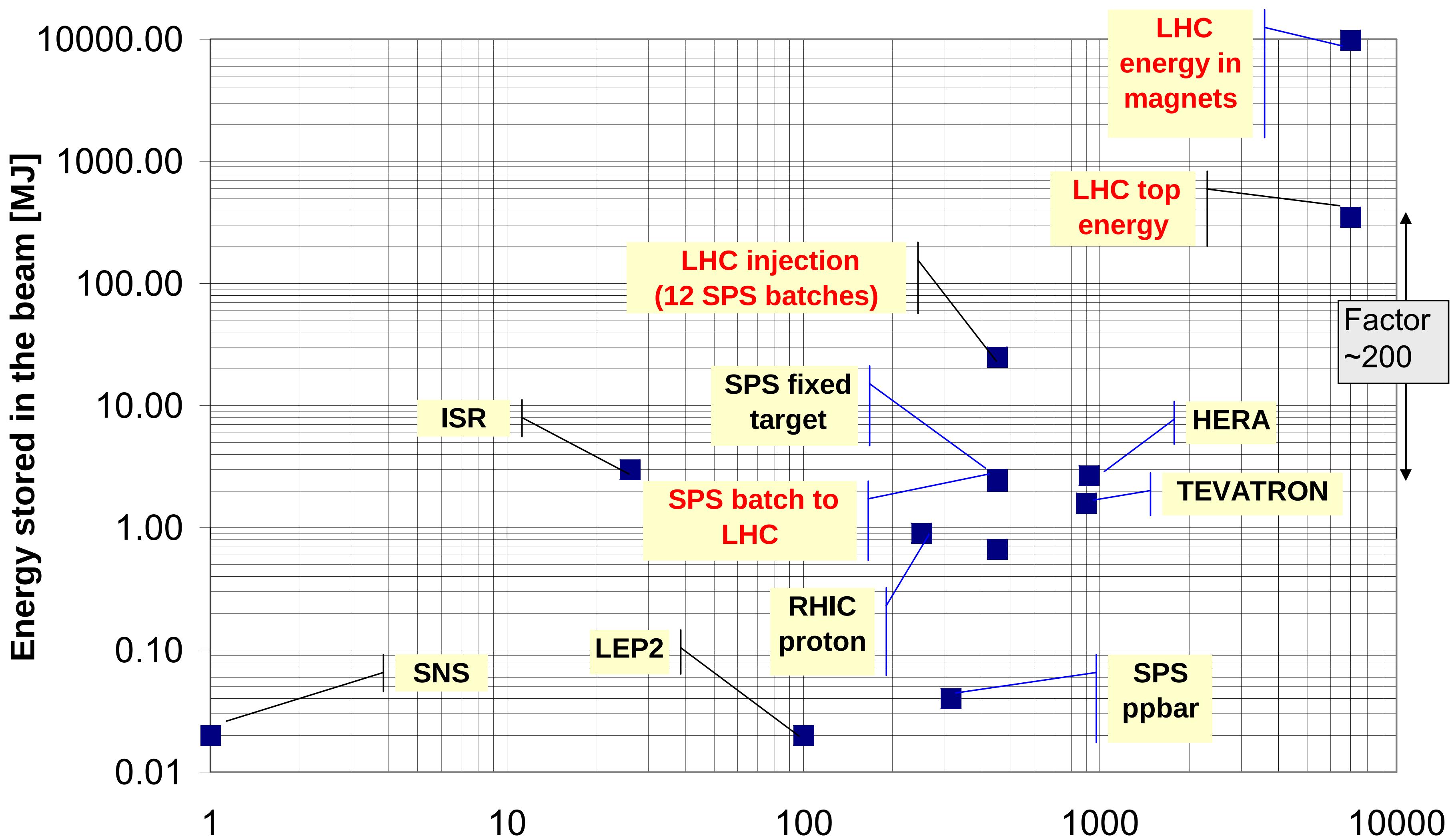


Relevant LHC parameters for 7 TeV (protons)

Momentum at collision	7	TeV/c
Luminosity	10^{34}	$cm^{-2}s^{-1}$
Dipole field at 7 TeV	8.33	Tesla
Number of bunches	2808	
Protons per bunch	$1.15 \cdot 10^{11}$	
Typical beam size	200-300	μm
Beam size at IP	16	μm

- Energy stored in one beam: **362 MJoule**
- Energy stored in the magnet system: **10 GJoule**
- Energy stored in one (of 8) dipole circuit: 1.1 GJoule
- Energy to heat and melt one kg of copper: ~600 kJoule

Livingston type plot: Energy stored in magnets and beam



based on graph from R.Assmann

Protection and Beam Energy

A small fraction of beam loss is sufficient for damage ($\sim10^{-4}$)

Very efficient protection systems throughout the operational cycle are required

A tiny fraction of beam loss is sufficient to quench a magnet ($\sim10^{-8}$)

Very efficient beam cleaning is required

- Sophisticated beam cleaning with about 50 collimators, each with two jaws, in total about 90 collimators and beam absorbers
- Collimators are close to the beam (full gap as small as 2.2 mm, for 7 TeV with fully squeezed beams), particles will always touch collimators first !

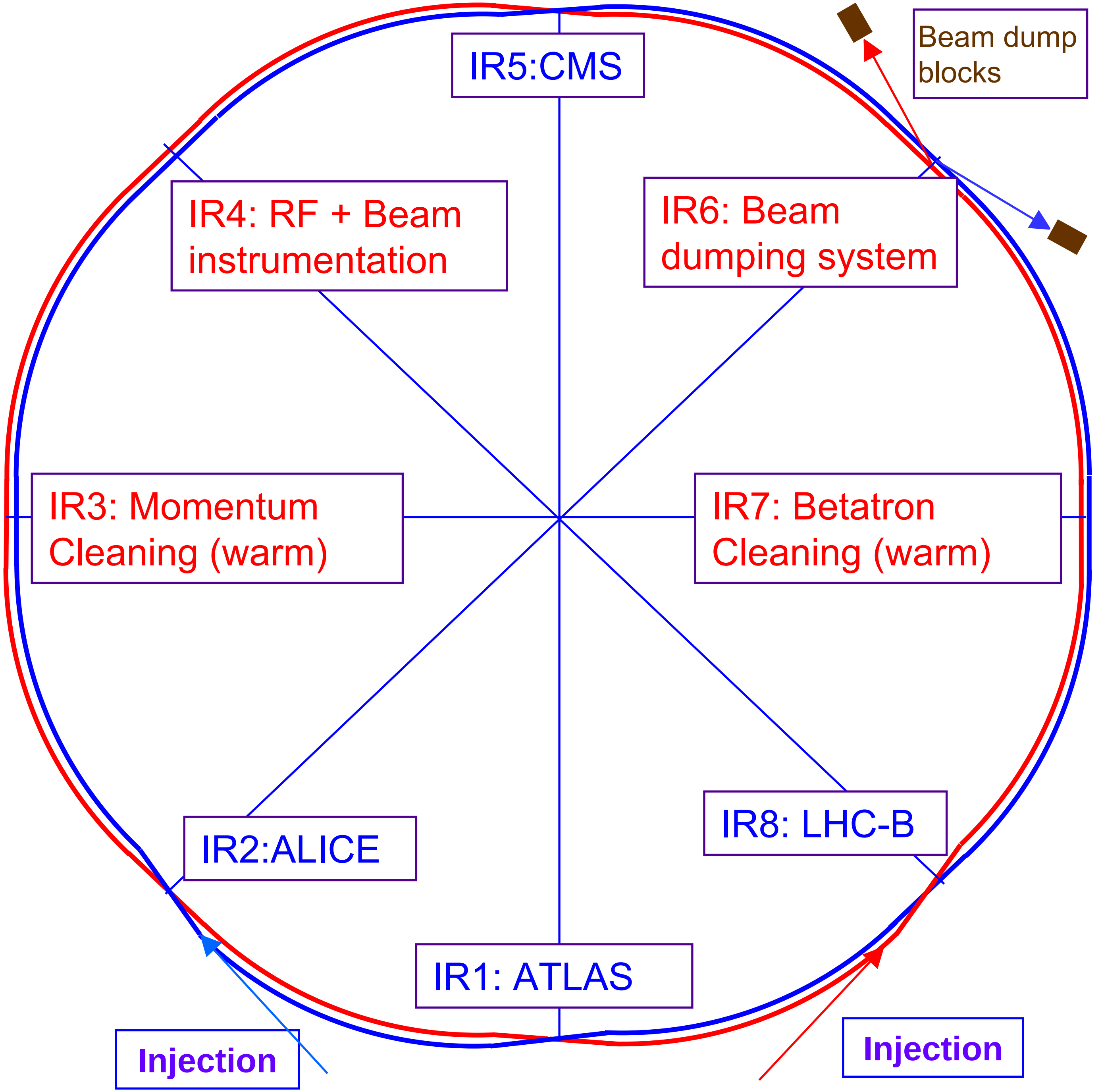
The LHC accelerator complex

LHC Layout

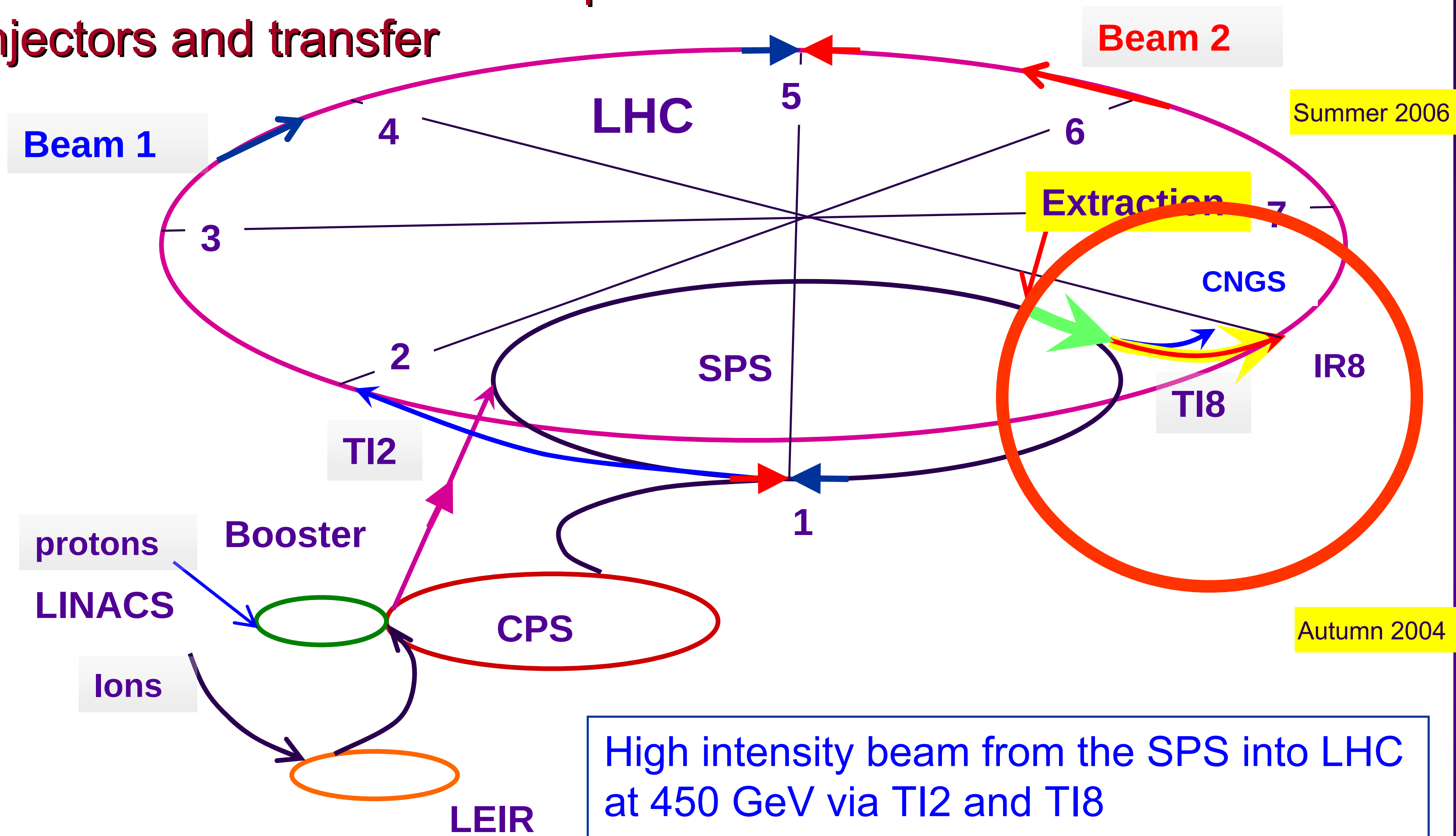
eight arcs (sectors)

eight long straight sections (about 700 m long)

three of the four non-experiment insertions for systems to protect the accelarator



The CERN accelerator complex: injectors and transfer



High intensity beam from the SPS into LHC at 450 GeV via TI2 and TI8

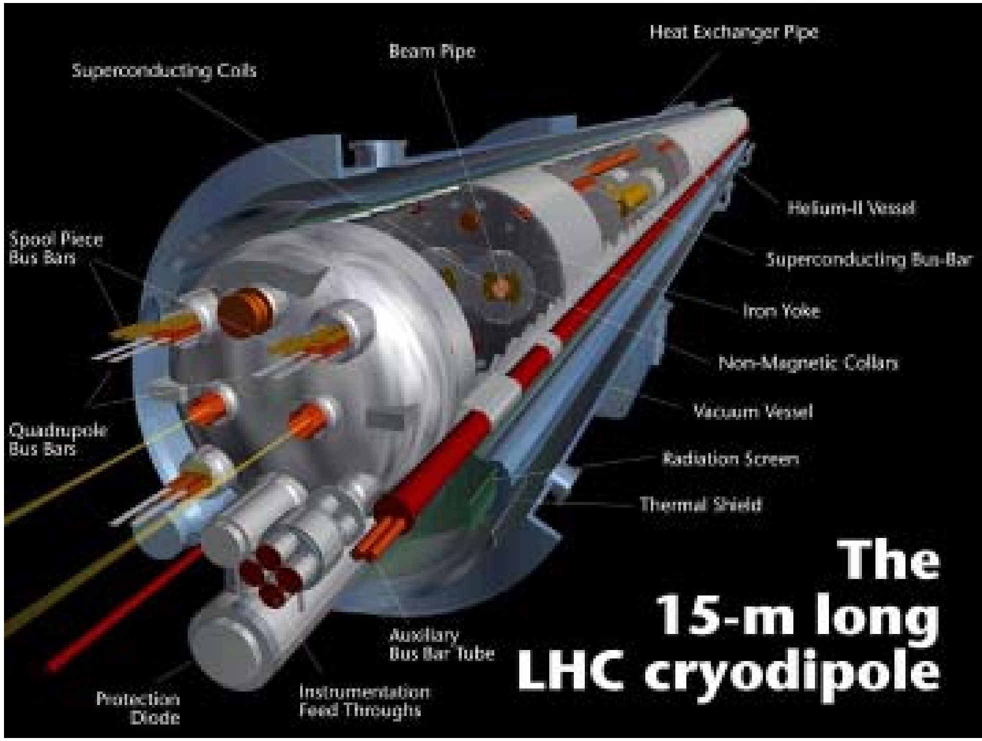
Transfer lines: 2 • 3 km

LHC accelerates from 450 GeV to 7 TeV

Status: LHC Large Distributed Systems

Superconducting magnets
Cryogenics
Vacuum system
Powering system

Dipole magnets for the LHC

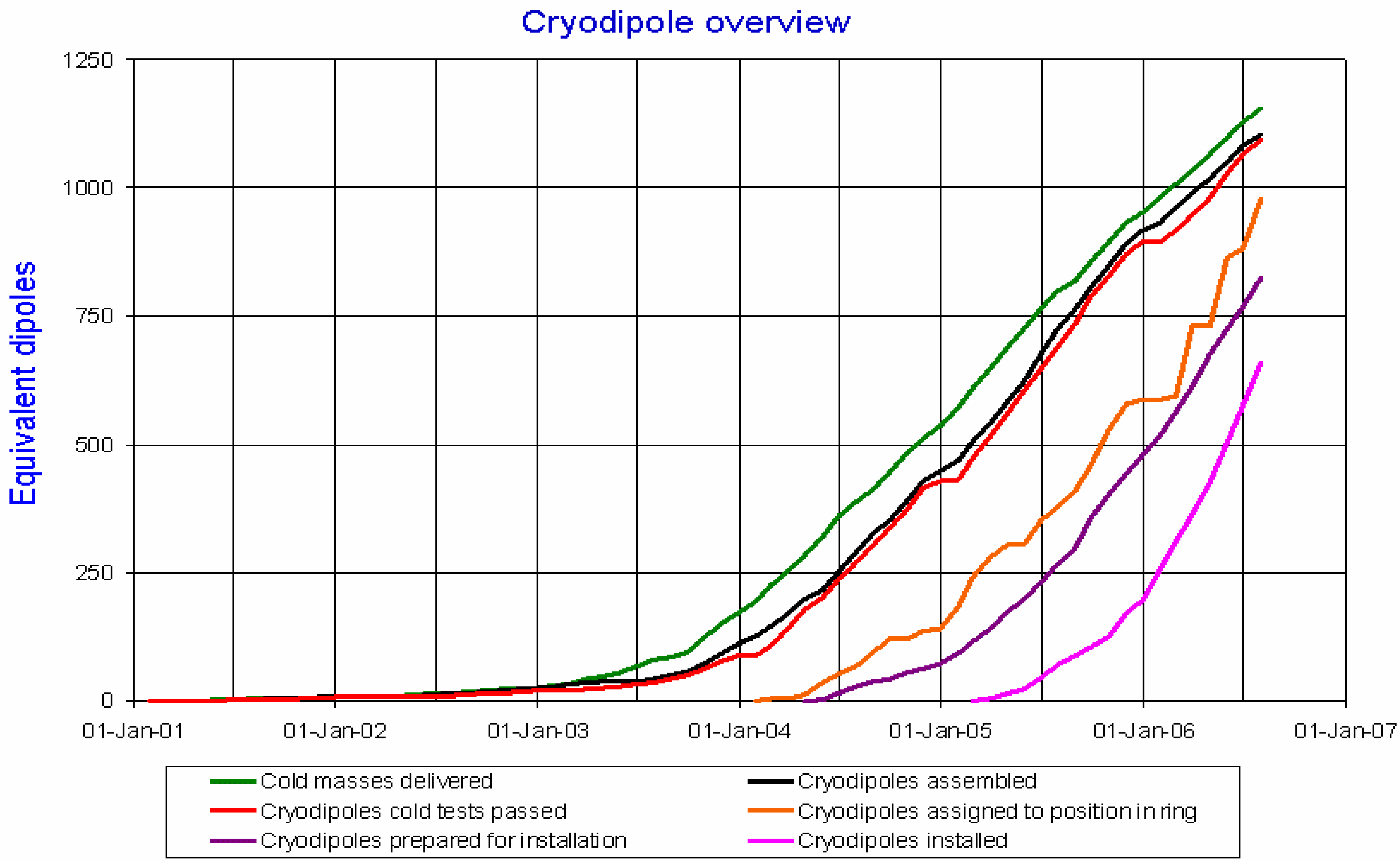


1232 Dipolmagnets
Length about 15 m
Magnetic Field 8.3 T
Two beam tubes with an opening of 56 mm

Cryodipole overview

LHC Progress Dashboard

Accelerator Technology Department



Updated 31 Jul 2006

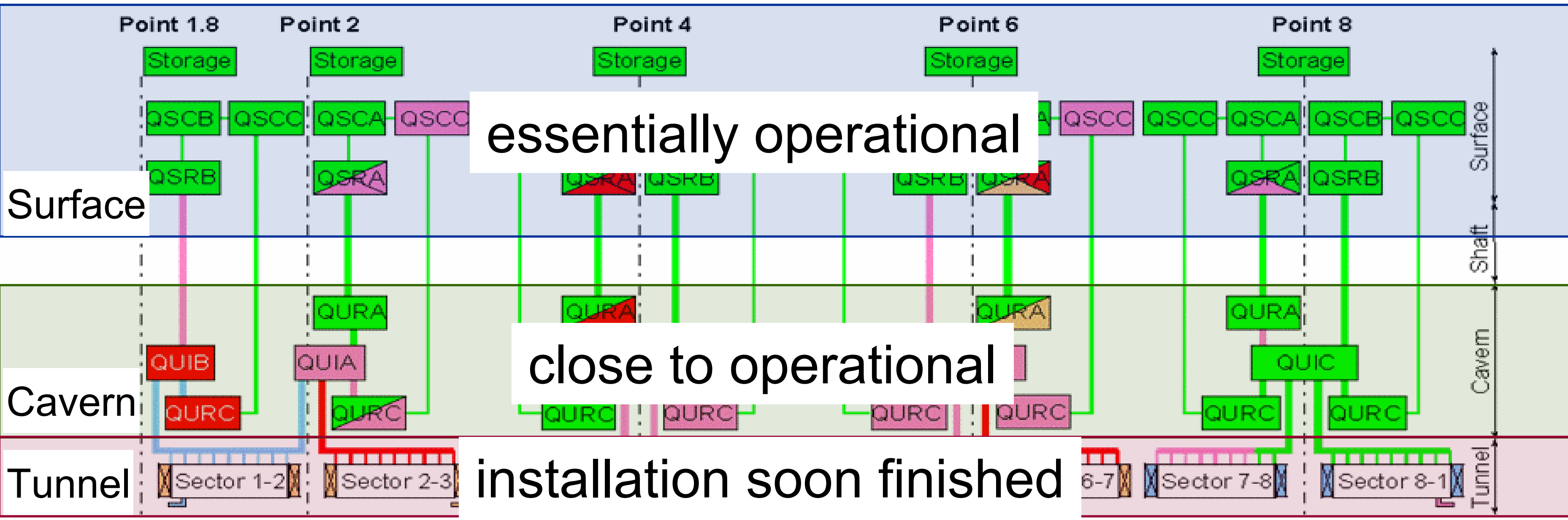
Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM

Cryogenic system

LHC Progress Dashboard

Accelerator Technology Department

Cryogenics overview



Legend

Cryogenic Distribution Line

QSC_(A,B,C): Warm Compressor Station
QSR_(A,B): Surface 4.5 K Refrigerator Cold Box
QURA: Underground 4.5 K Refrigerator Cold Box
QURC: 1.8 K Refrigeration Unit Cold Box
QUI_(A,B,C): Cryogenic Interconnection Box

Electrical Feed Box

Superconducting Link

Commisionned & accepted

Delivered / Under installation

Ordered (Contract placed)

Under commissioning

Under fabrication

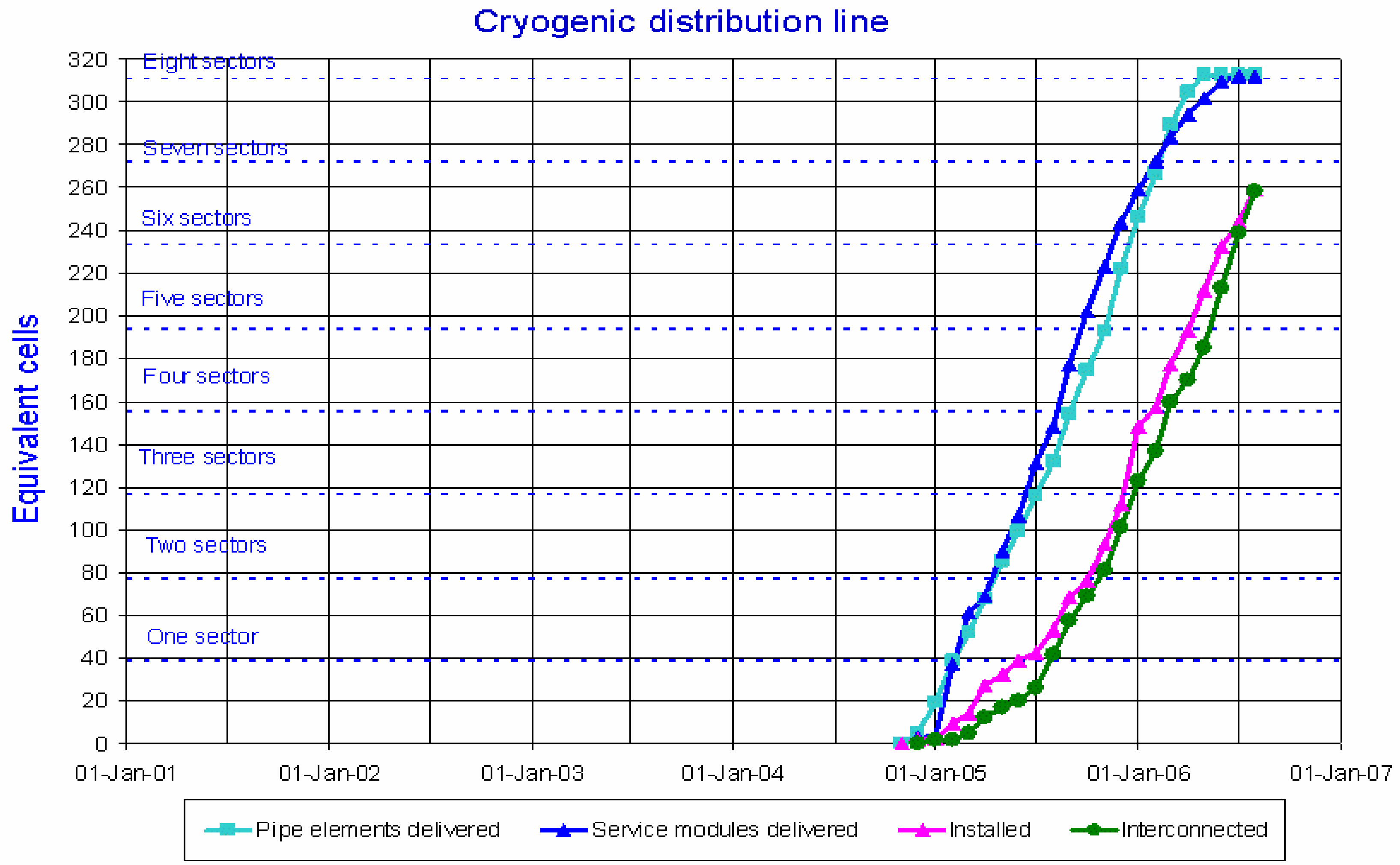
Under definition

Updated 30 Apr 2006 Data provided by L. Tavian AT-ACR

Cryogenic distribution line

LHC Progress Dashboard

Accelerator Technology Department



Updated 31 Jul 2006 Data provided by G. Riddone AT-ACR

First cryodipole lowered on 7 March 2005

Tunnel logistics

Transport in the tunnel with an optical guided vehicle

about 1600 magnets to be transported for 20 km

at 3 km/hour

Transfer on jacks

Hardware commissioning

“Hardware commissioning”
Commissioning of the (large) technical systems

Commissioning of all technical systems that do not require beam

- about 10000 magnets (most of them superconducting)
- 26 km cryogenic distribution line
- 26 km cryogenic magnets
- 4 vacuum systems, each 27 km long
- > 1700 magnet powering circuits with power converters (60A to 13000kA)
- Quench protection and powering interlock systems

> 10000 electronics crates for operation and protection

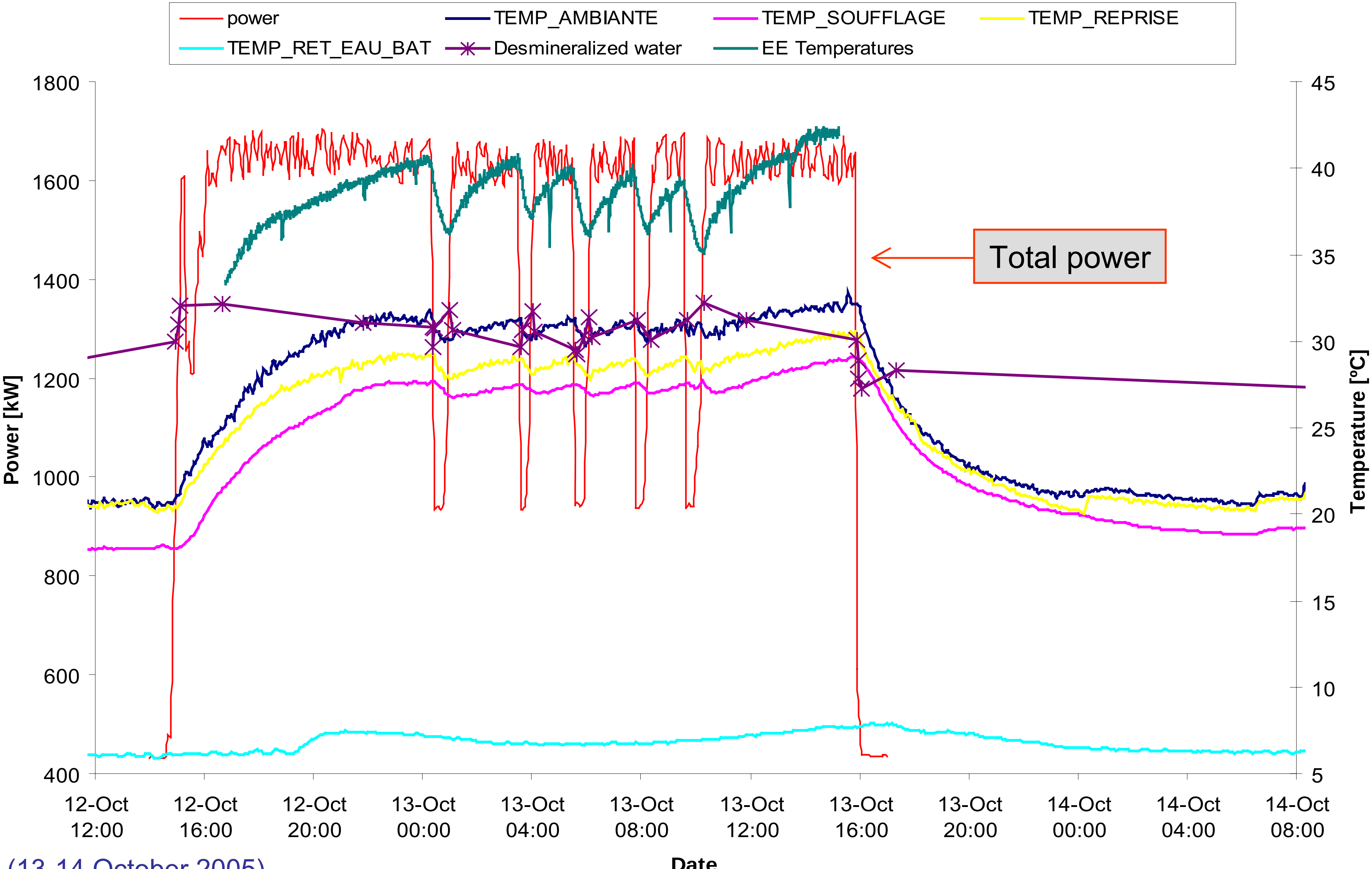



Power converters installed and commissioning on short circuits started in tunnel

- 81 power converters in UA83
- 156 kA and 1.2 MW dissipated: PCs and Cables

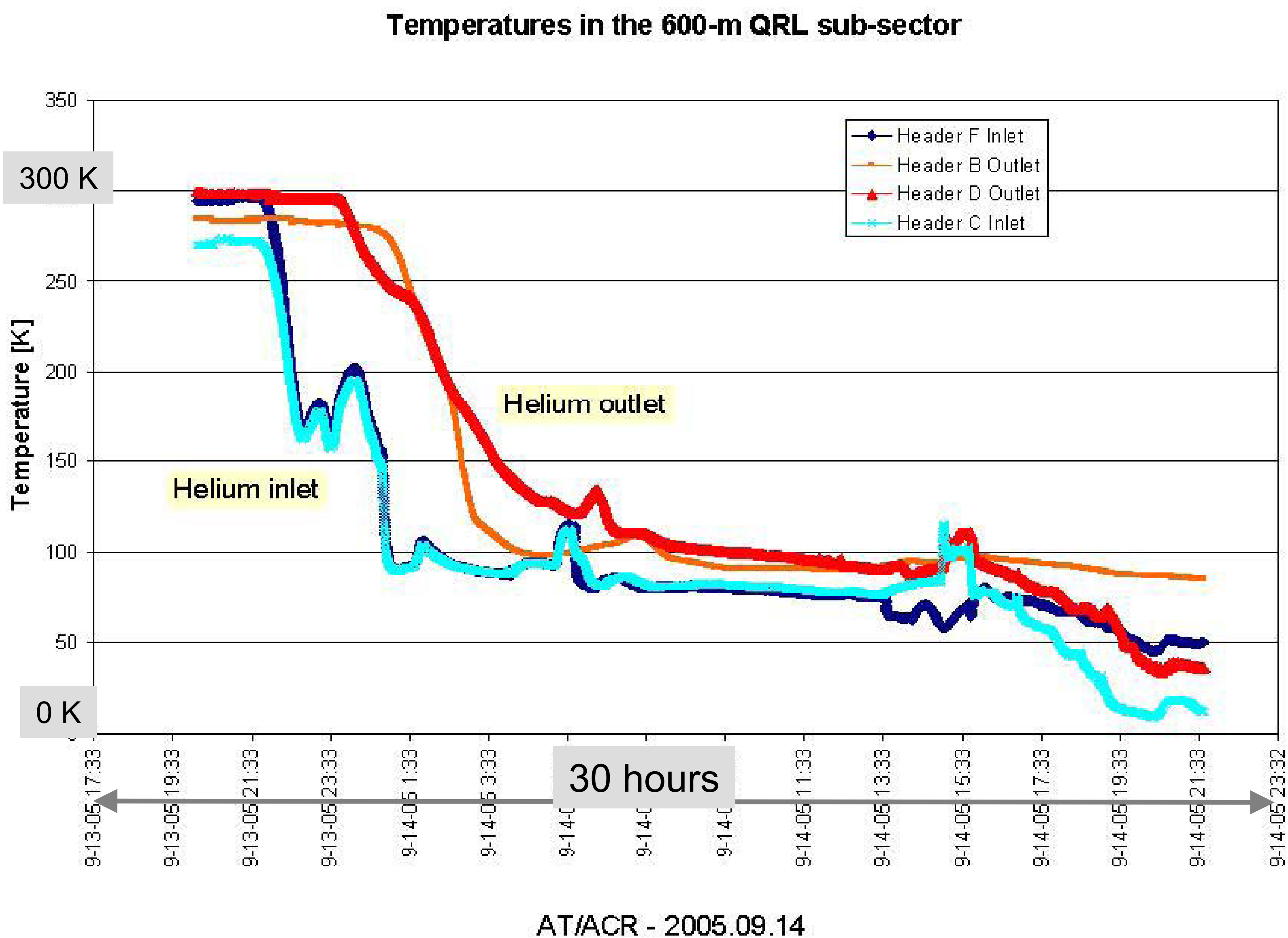
F.Bordry, 11-2005

24h endurance test of power converters and electrical network



(13-14 October 2005)

Cool down of the cryogenic distribution line

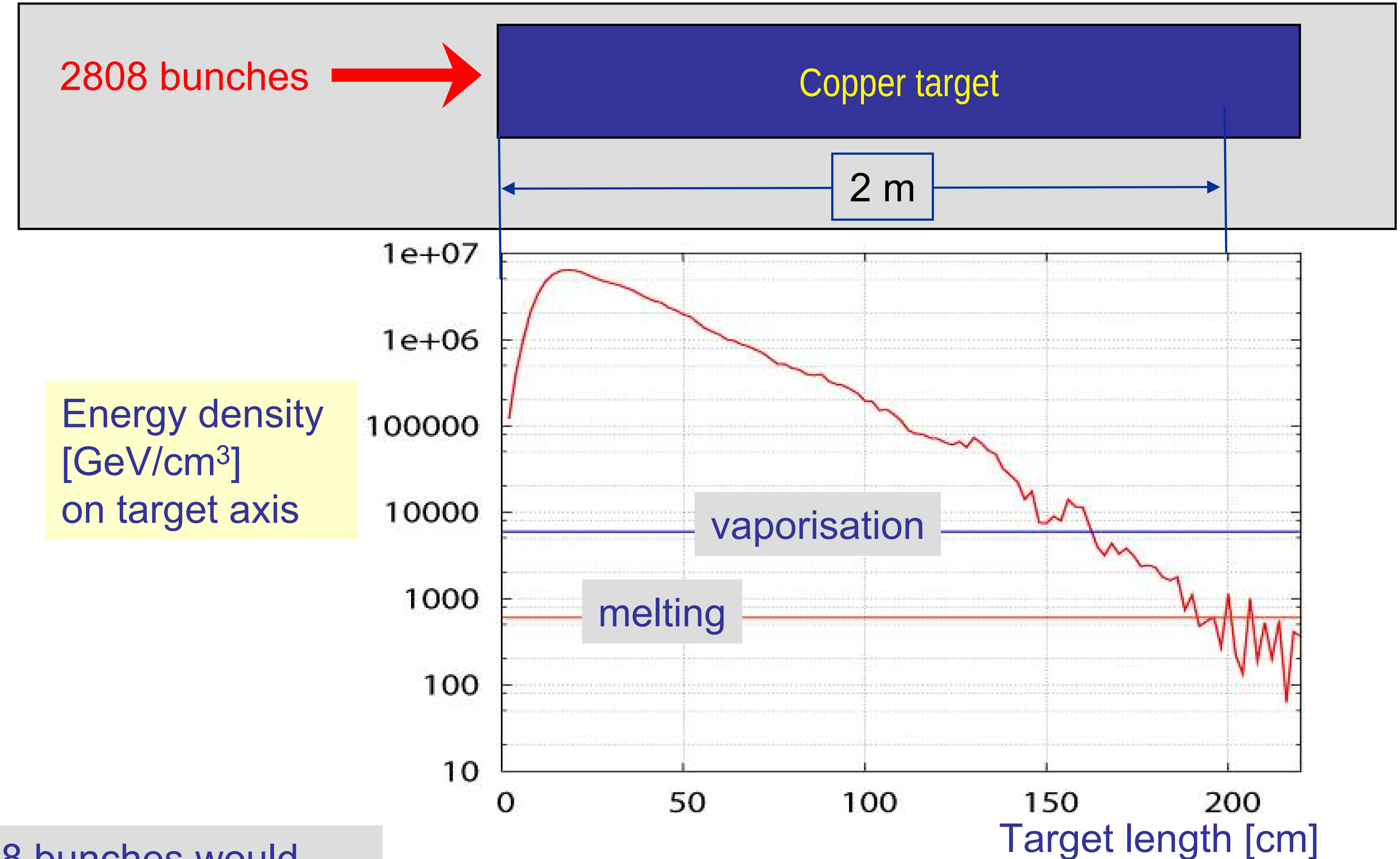


Status summary

- Magnet production well advanced – last magnets to be finished by end September
- Installation and interconnections in progress, ~800 cryomagnets are in place
- Powering system: commissioning started
- Cryogenics
  - **large part finished and operational (e.g. cryoplants)**
  - **QRL being installed and partial commissioning started**
- Other systems (RF, Beam injection and extraction, Beam instrumentation, Collimation, Interlocks, Controls)
  - **essentially on schedule for first beam in autumn 2007**
- Injector complex ready

Machine protection

Full LHC 7 TeV beam deflected into copper target



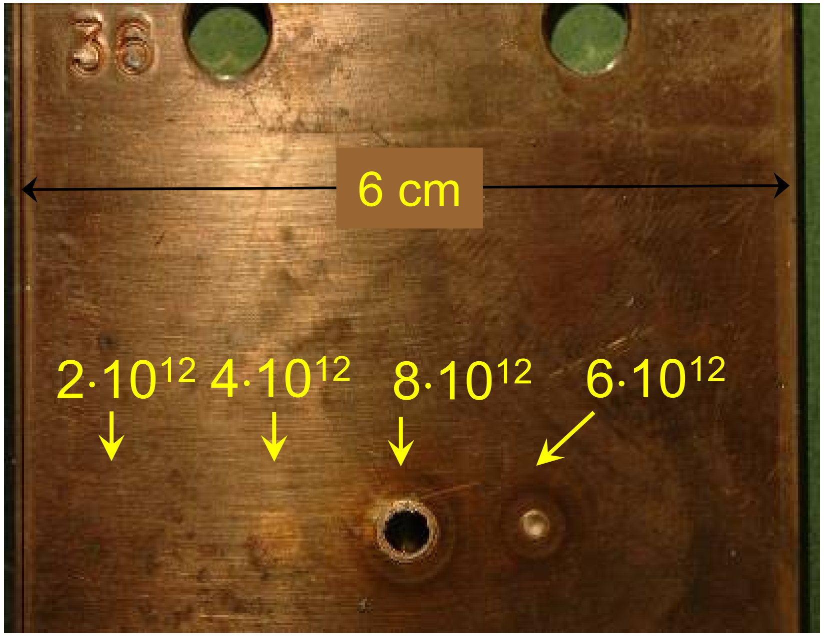
2808 bunches would travel up to ~30 m into a copper target

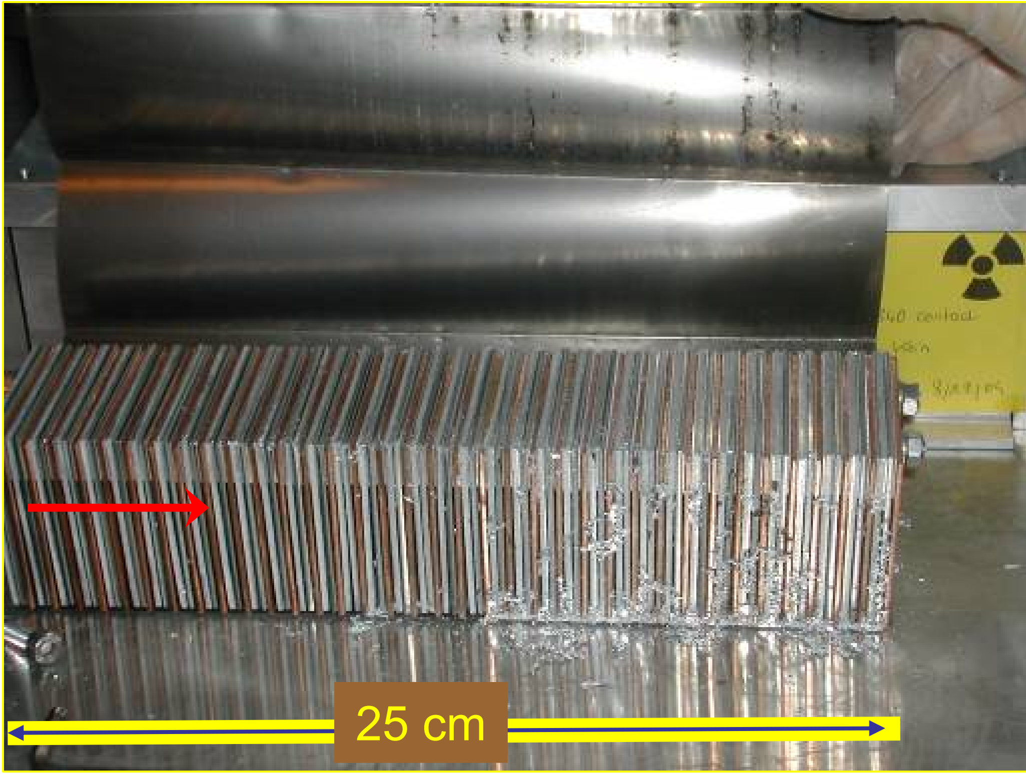
N.Tahir (GSI) et al.

SPS experiment: Beam damage at 450 GeV

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

- $2 \cdot 10^{12}$ protons
- below damage limit





0.1 % of the full LHC beam

V.Kain

Machine protection for three phases of operation

Beam transfer from SPS to LHC (or to CNGS)

- Energy of a batch from SPS to LHC: 2.4 MJ

Circulating beams: detection in case of failure or if beam becomes unstable

- Energy of the LHC beam from ~MJ (injection) up to 362 MJ (7 TeV)
- Inform beam dumping system to extract beam

Extraction of beam into the beam dump blocks

- Energy of the LHC beam between ~MJ (injection) up to 362 MJ (7 TeV)
- Extraction at end of fill and in case of emergency
- The only component that can stand a loss of the full beam is the beam dump block - all other components would be damaged: beams must always be extracted into beam dump blocks
- Beam with a lifetime of less than 10 min must be dumped (7 TeV)

Beam losses and time constant

min ... hours

ms ... sec

μs

time

accidental beam losses

Very slow beam losses (lifetime 0.2 hours or more)

Cleaning system to limit beam losses around the ring

Operation is acceptable

Slow beam losses (several seconds – 0.2 hours)

Fast beam losses (5 ms – several seconds)

Very fast beam losses (some turns to some milliseconds)

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

Failure leading to beam loss within one turn or less

At extraction from SPS, via transfer and injection until beams are circulating in LHC

- 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 (larger kicks)
- Failure when extracting the beams

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 interlocked 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 - FMCM)

4) Protect in case of beam goes astray

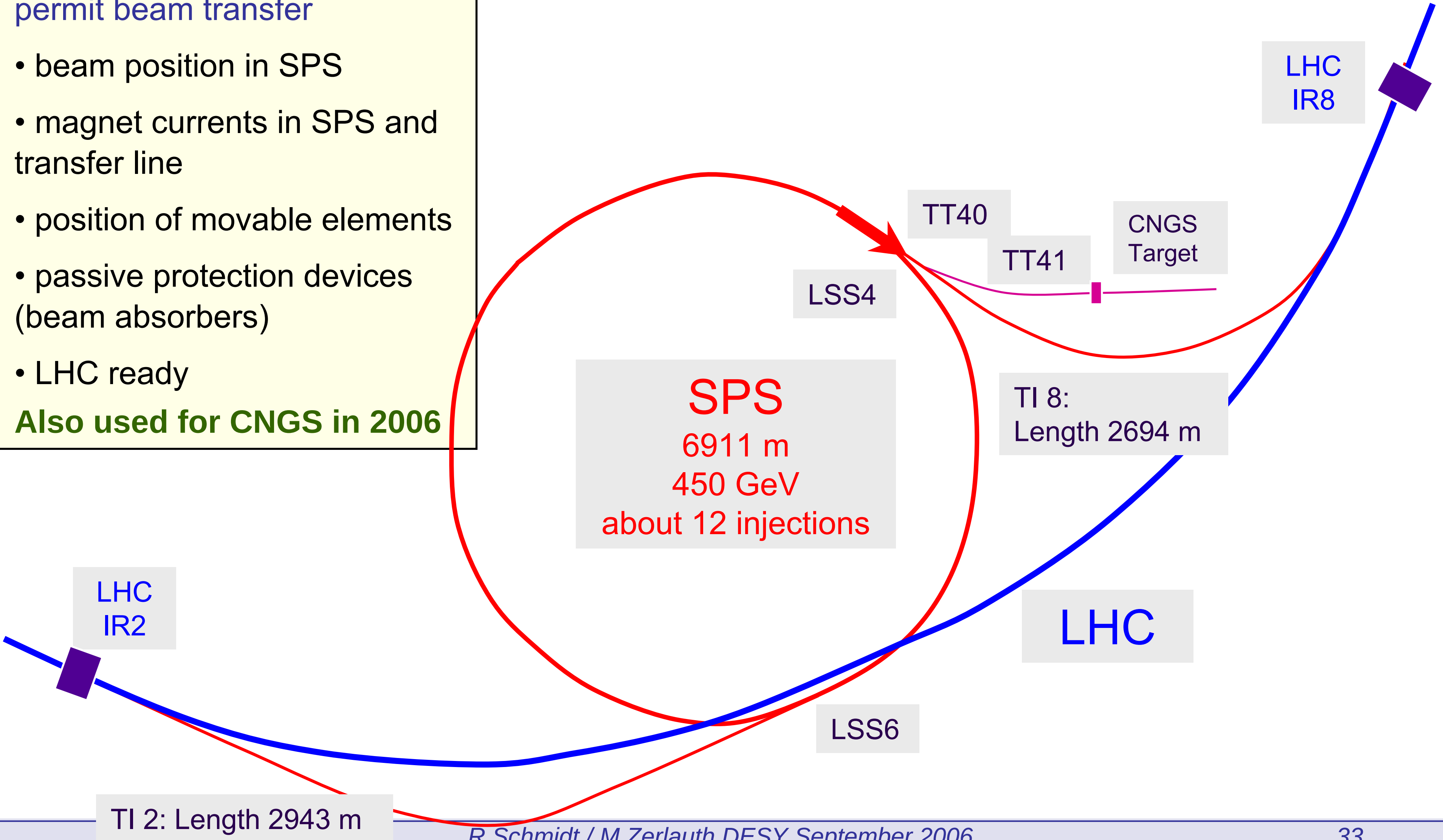
- beam absorbers for single turn failures

Safe beam transfer from SPS to LHC

Monitoring: if parameters inside predefined window, permit beam transfer

- beam position in SPS
- magnet currents in SPS and transfer line
- position of movable elements
- passive protection devices (beam absorbers)
- LHC ready

Also used for CNGS in 2006



Circulating beams: failures leading to beam losses within many turns that require 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
- Others

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

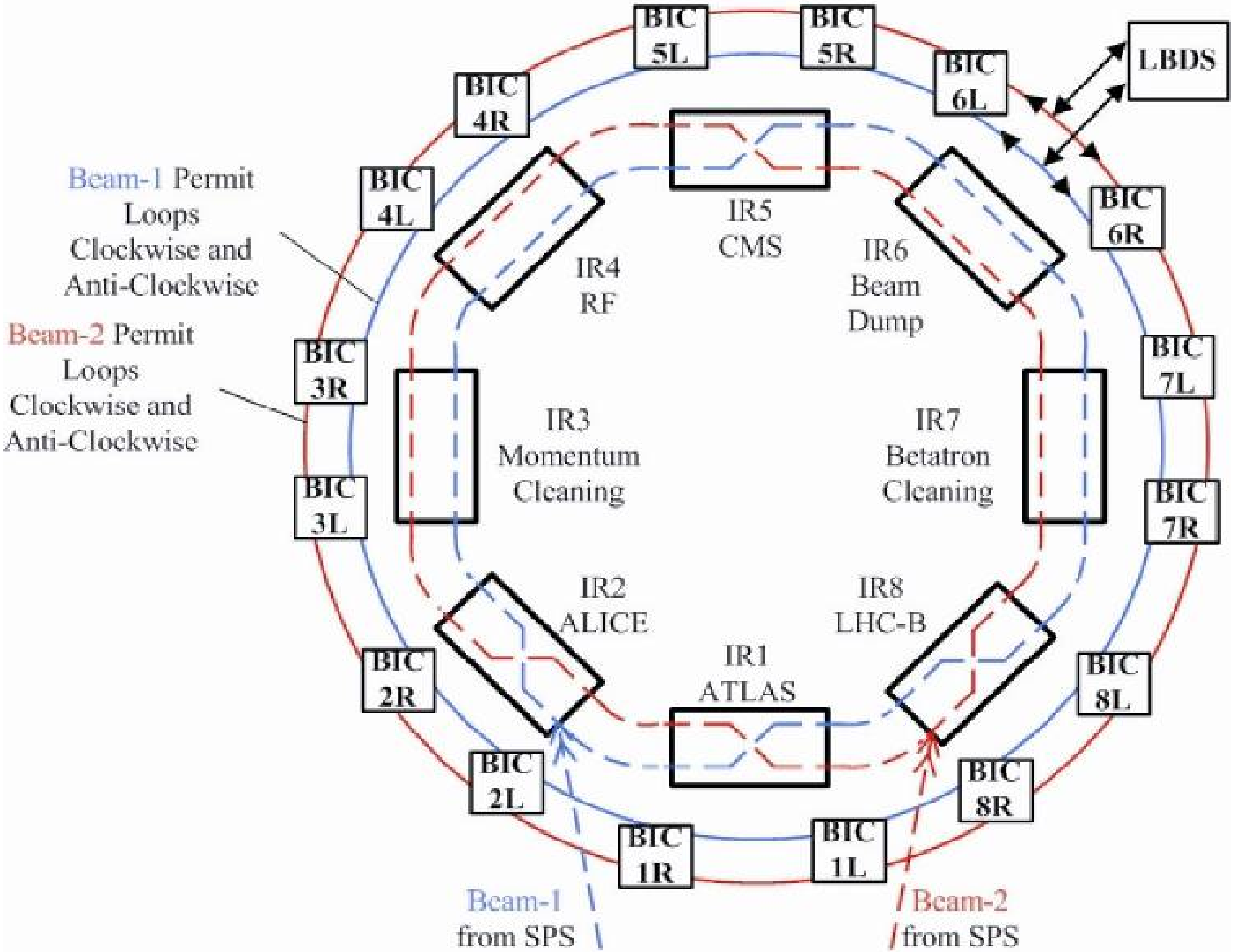
No single failure should lead to equipment damage

- 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

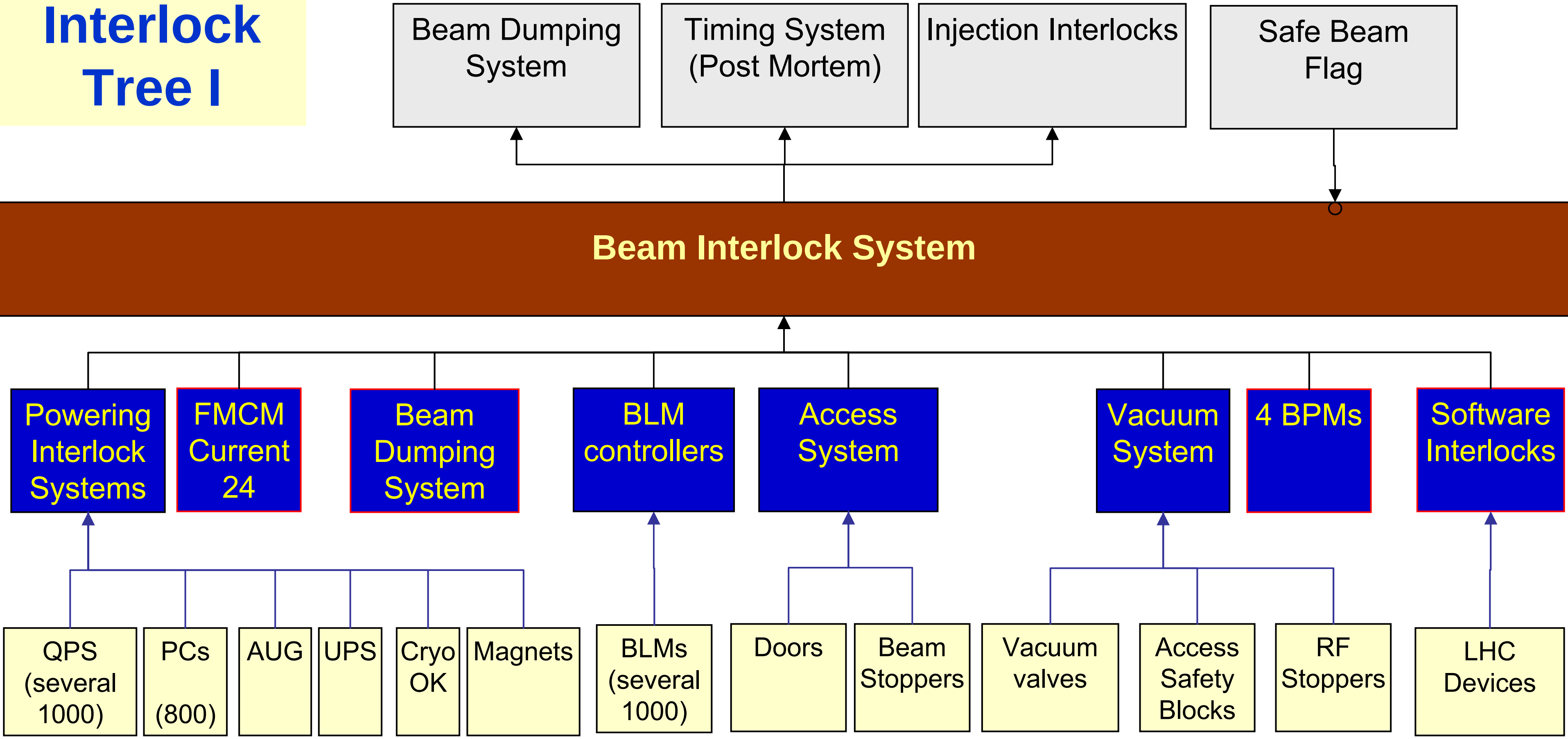
No erroneous manipulation on protection systems should compromise the accelerator safety (e.g. swapping two cables)

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

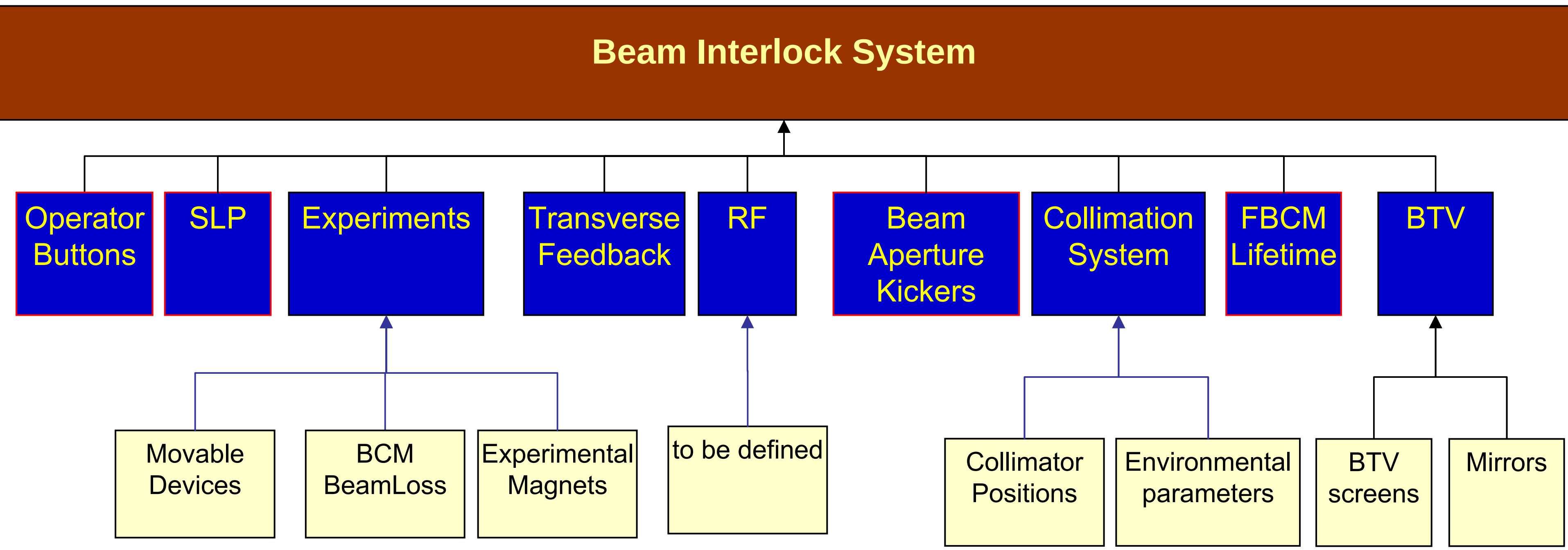
Beam Interlock System



Interlock Tree I



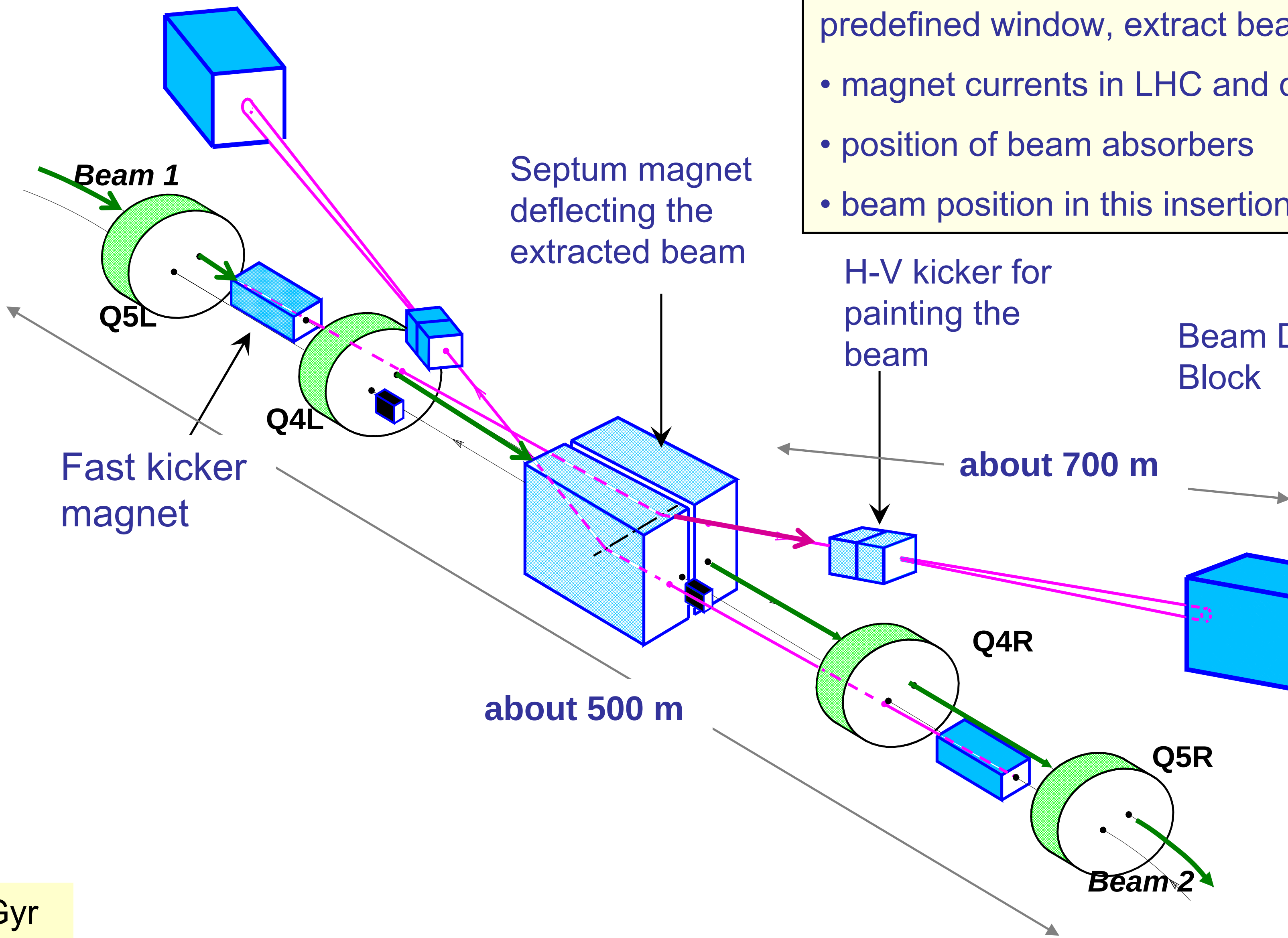
Interlock Tree II



Safe extraction of beam into beam dump blocks

Monitoring: if parameters outside predefined window, extract beam

- magnet currents in LHC and dump line
- position of beam absorbers
- beam position in this insertion



M.Gyr

Beam Loss Monitors

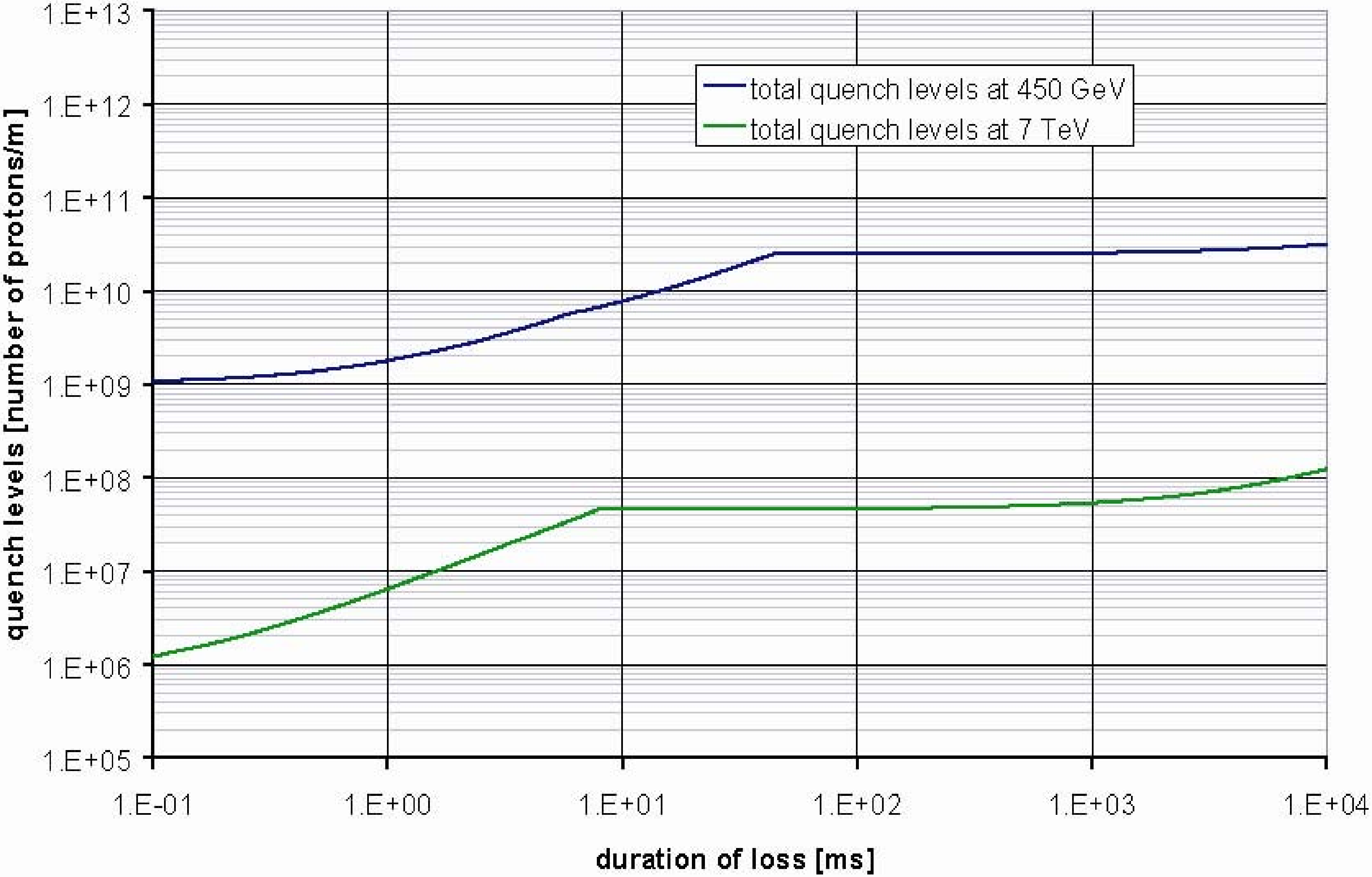
Very fast beam losses

- Collimators are limiting the aperture during all phases of LHC operation
- Several 100 beam loss monitors at all aperture restrictions continuously measuring beam losses
  - Losses can be detected within less than a turn
  - Aperture limitations are essentially collimators

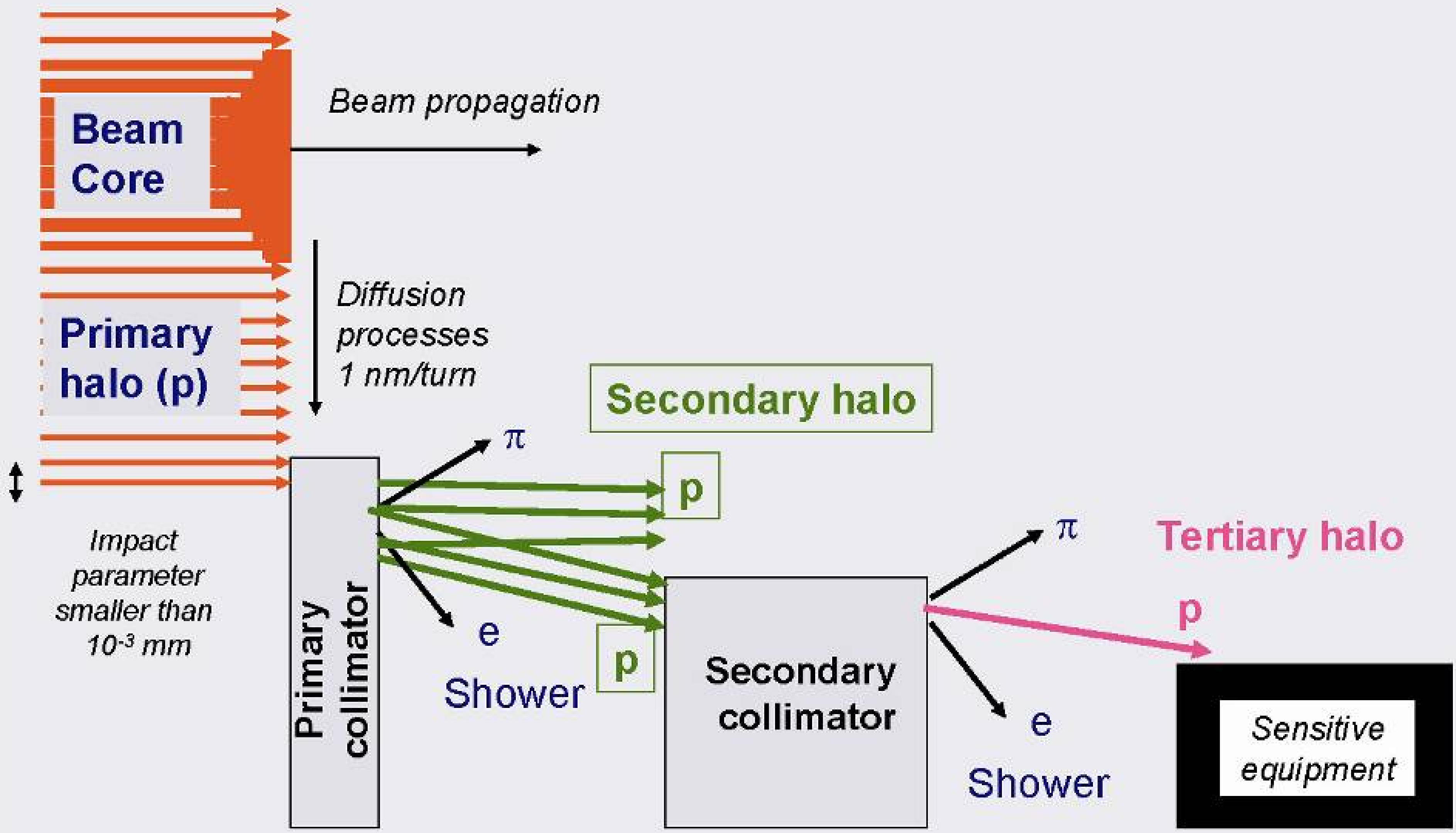
Fast or slow beam losses

- About 3000 beam loss monitors around the ring (mainly in arcs) continuously measure beam losses

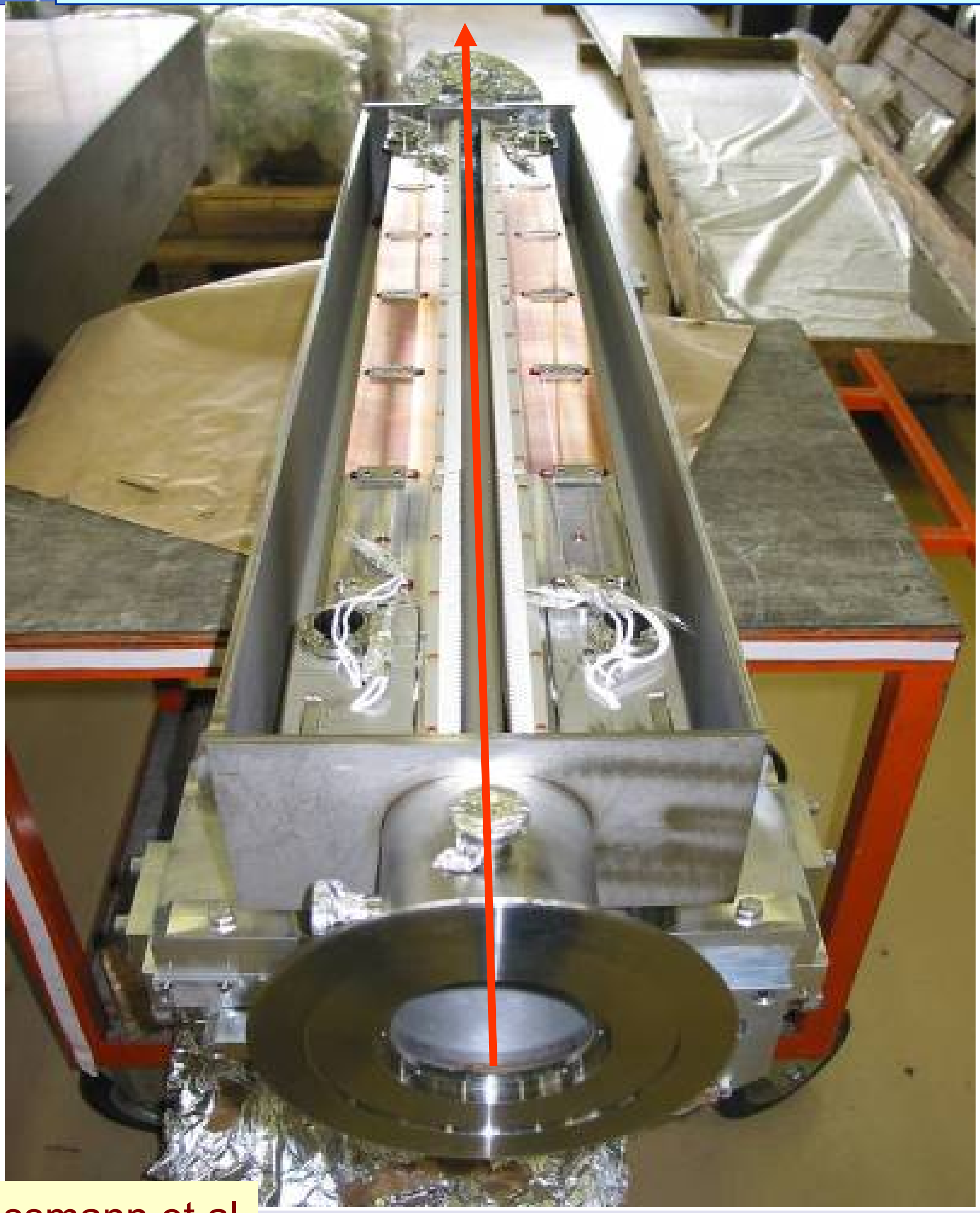
Calibration of Beam Loss Monitors and Quench levels



Cleaning system



The LHC Phase 1 Collimator

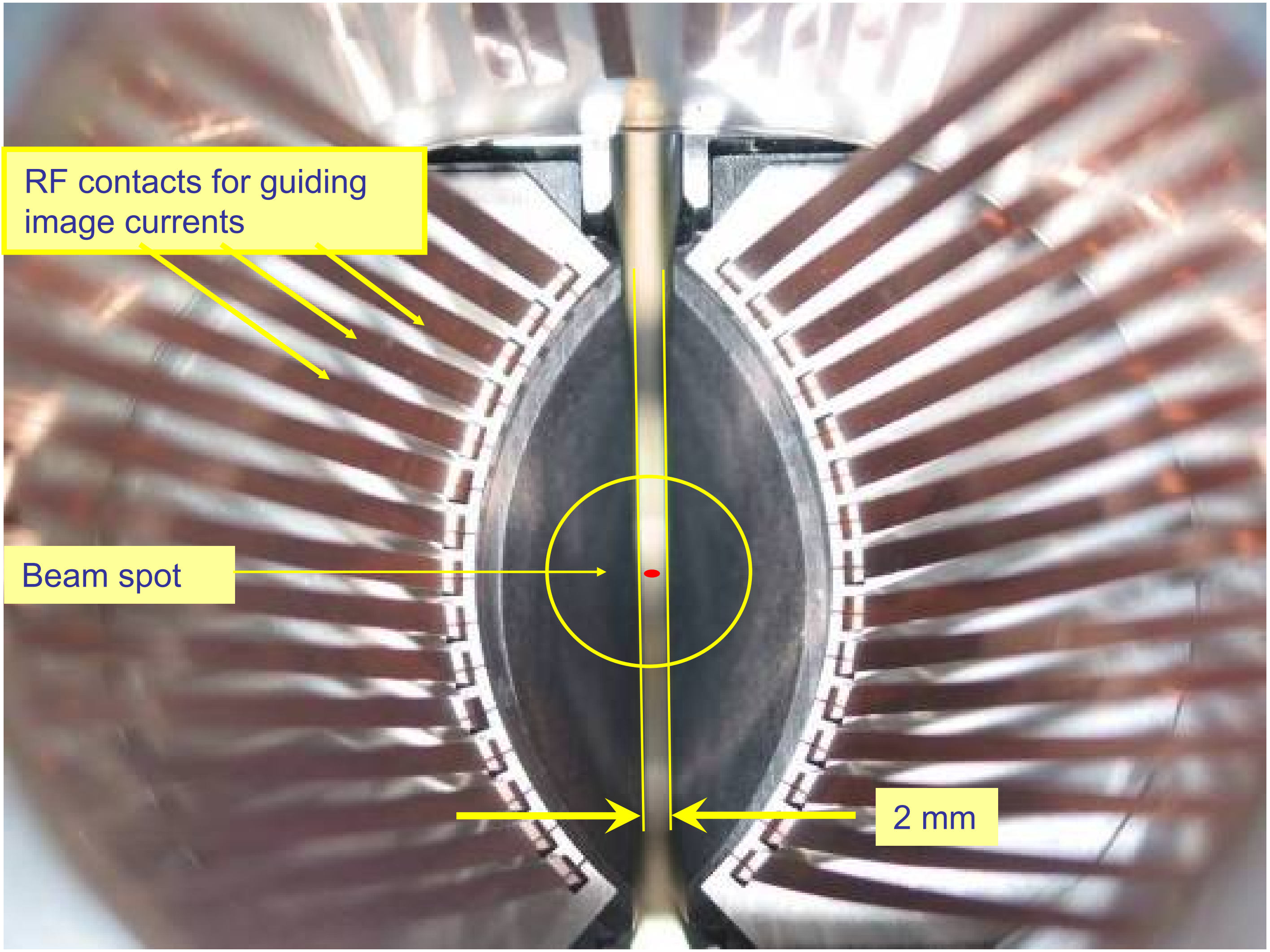


Vacuum tank with two jaws installed

Designed for maximum robustness:

Advanced Carbon Composite material for the jaws with water cooling!

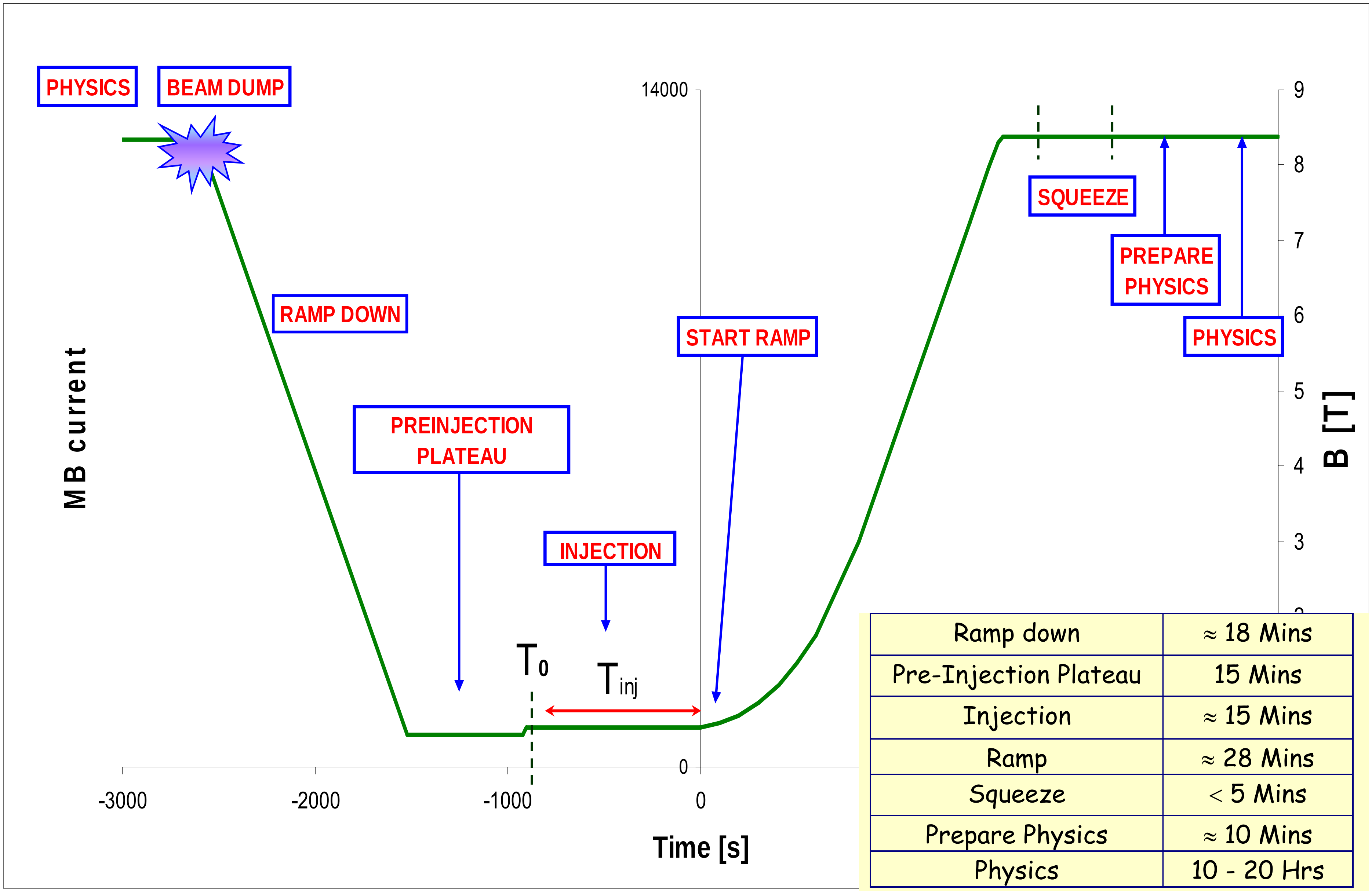
R.Assmann et al



R.Assmann et al

Outlook to operation

LHC operational cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

Beam commissioning: preparing for LHC

2006 : Restart all machines from new CCC (CERN - Control – Centre) operating all machines and technical service

CNGS - commissioning and operation with high intensity beam

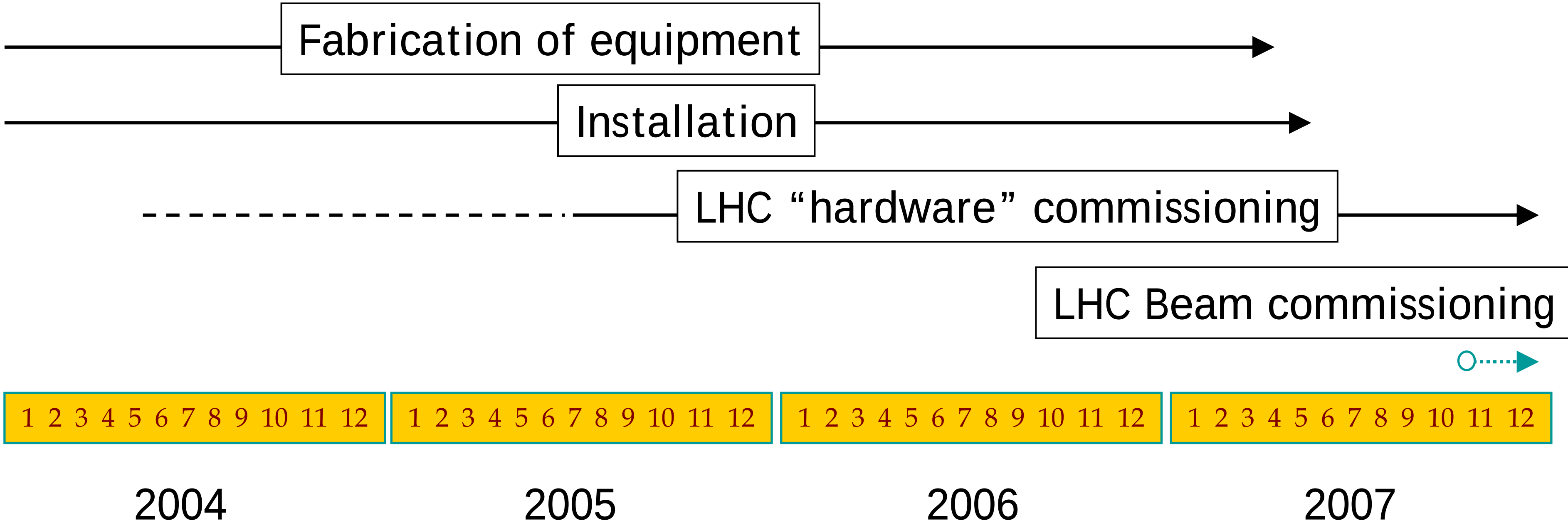
– operate with LHC type beam interlock sytem (identical hardware and software)
– input signals from users of the interlock system as for LHC injection
– learn procedures for safe operation

SPS machine studies, related to LHC

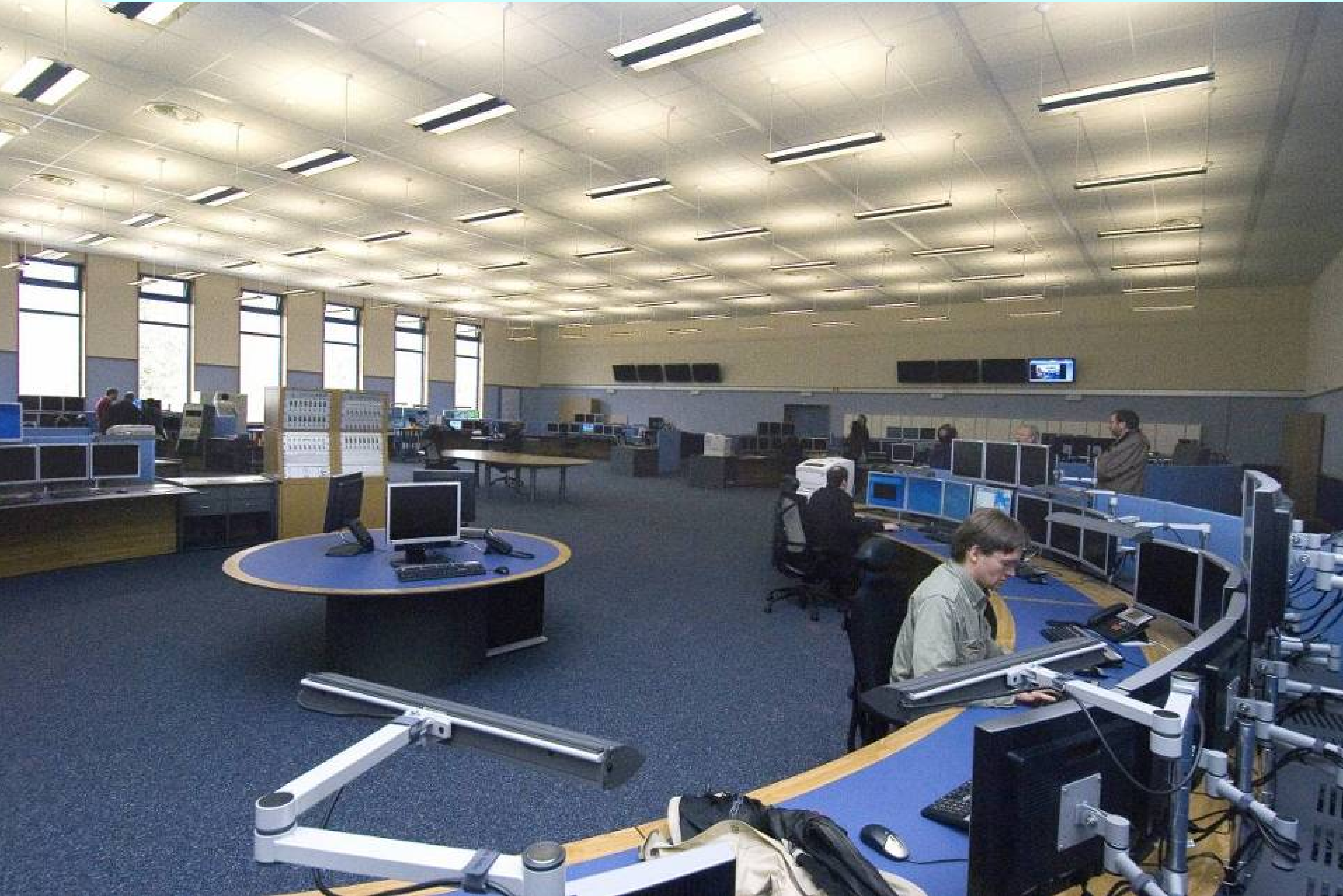
– intensity limits
– beam scraper commissioning
– collimator test

Recalling LHC status and challenges

- Enormous amount of equipment
- Complexity of the LHC accelerator
- New challenges in accelerator physics with LHC beam parameters pushed to the extreme



Beam commissioning: preparing for LHC



Conclusions

Conclusions

- We recognize that the planned schedule is very aggressive, given the complexity and potential for damage involved in the initial phases of operation.
- It will be important to understand the performance of the machine protection system, the collimation system and the orbit feedback system as well as cycle repeatability and adequate beta-beat control before proceeding to run with significant stored beam energy. Pressure to take shortcuts must be resisted.

Machine Advisory Committee, chaired by Prof. M. Tigner, June 2005

Acknowledgement

The LHC accelerator is being realised by CERN, supported by the CERN member states

Collaboration with institutes from many countries over a period of more than 20 years has been very fruitful

Main contribution come from the USA, Russia, India, Canada, special contributions from France and Switzerland

Industry plays a major role in the construction of the LHC

Thanks for the material from:

R.Assmann, R.Bailey, F.Bordry, L.Bottura, L.Bruno, H.Burkhardt, L.Evans, B.Goddard, M.Gyr, R.Ostojic, B.Puccio

LHC Powering System and Protection
&
some First Experience with
‘Magnetstrom-Alarmboxen’ (or FMCMs)
in CNGS

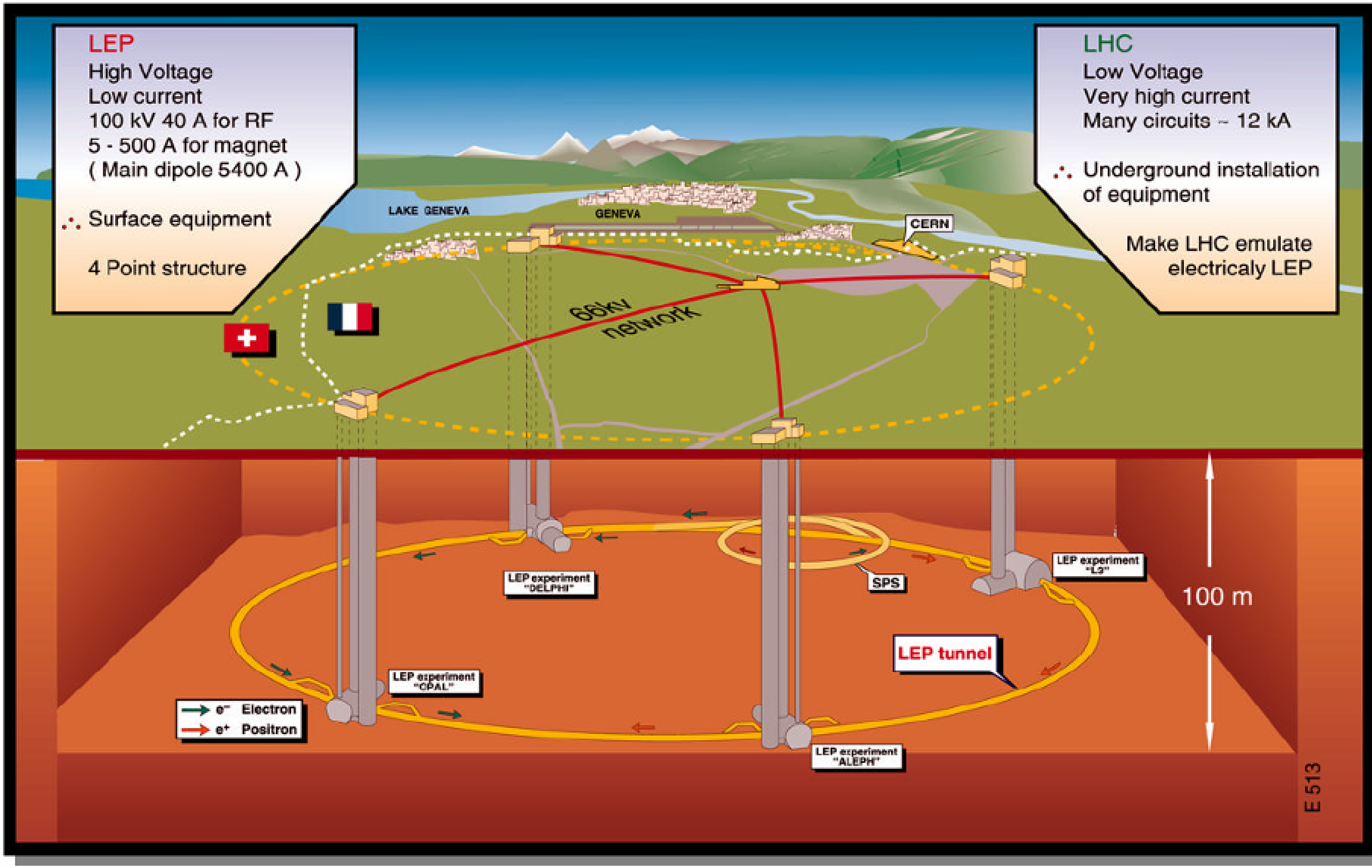
Acknowledgements: M.Werner, B.Closius,R.Schmidt, J.Wenninger, V.Kain,
B.Goddard and many others colleagues at DESY and CERN…

Outline

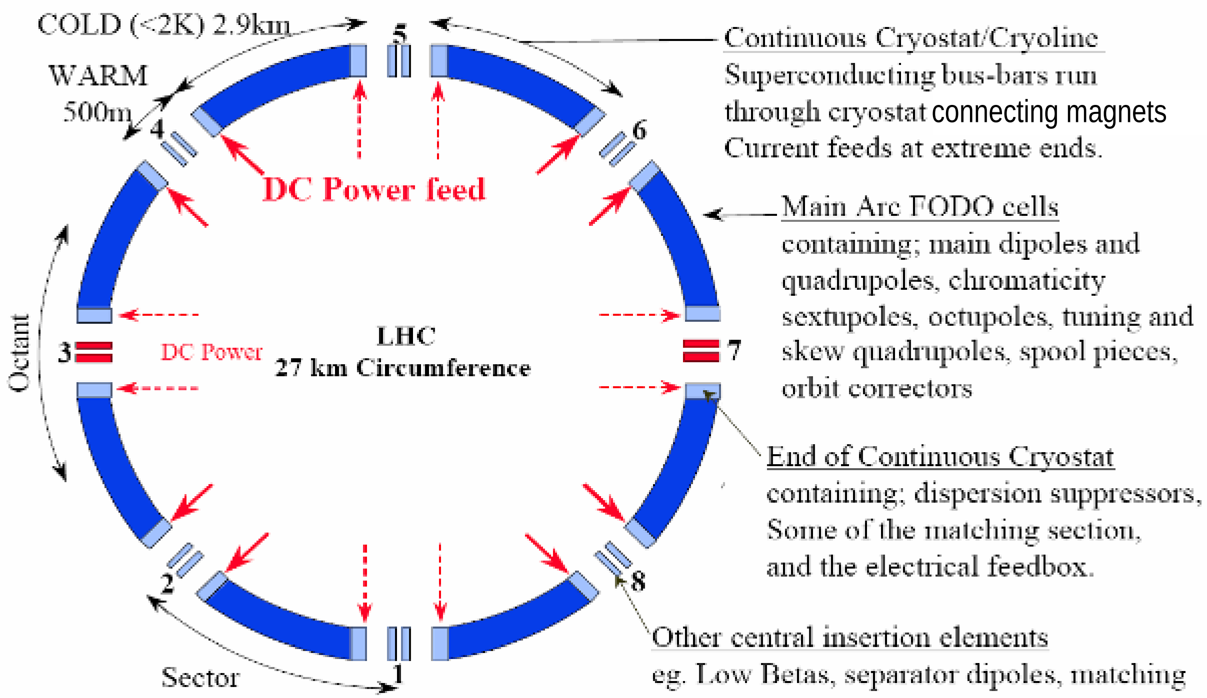
- Magnet Powering for the LHC and its injectors
- Powering and Protection of electrical circuits with normal conducting magnets
- Powering and Protection of electrical circuits with superconducting magnets
- Failure case of a magnet quench – Can we dump before beam losses occur?
- Fast Magnet Current Change Monitors providing additional protection for powering failures in nc magnets
- First experience and testing with FMCMs in CNGS

Powering of CERN accelerators

One out of the many LHC challenges – Correct and Safe Powering of magnets



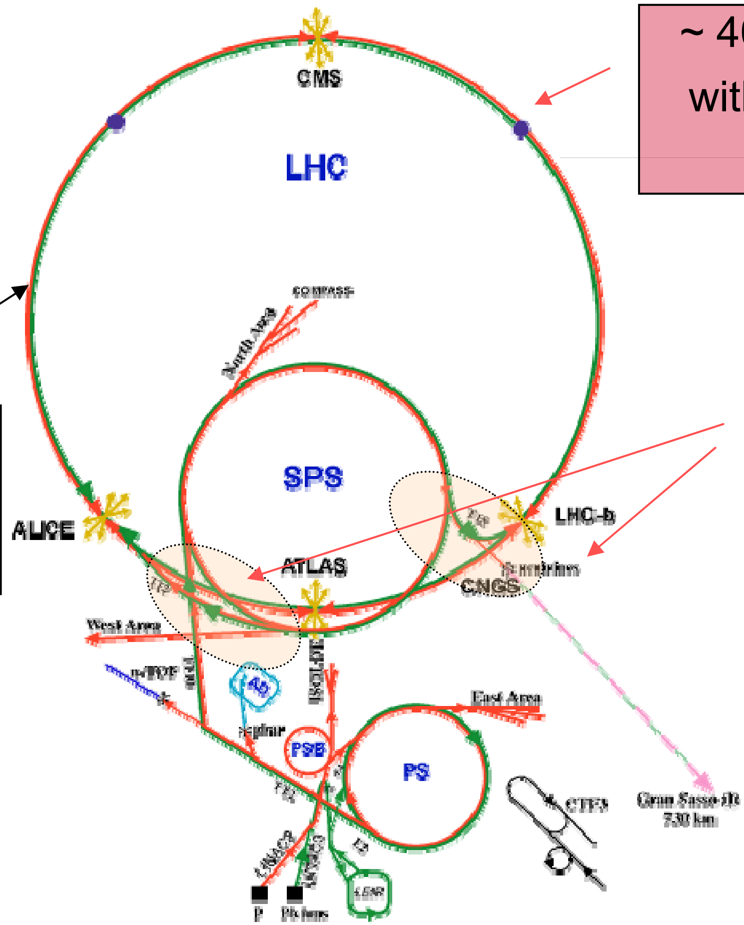
One of the LHC challenges – Correct and Safe Powering of magnets



- ➔ **8 fold symmetry for powering**
  - less energy in magnet chains
  - less build up voltages
  - easier installation, testing and commissioning
- ➔ **Complex powering layout, more powering equipment**
  - >1600 electrical circuits – 80000 high current interconnections
  - tracking from sector to sector

➔ Injector complex and SPS-LHC transfer lines built with normal conducting magnets (some 4000 circuits)

➔ LHC to 98% superconducting machine, only some 150 nc magnets in high luminosity and beam cleaning insertions (high radiation)



~ 40 electrical circuits with 150 nc magnets in the LHC

~1600 electrical circuits with 10 000 sc magnets in the LHC

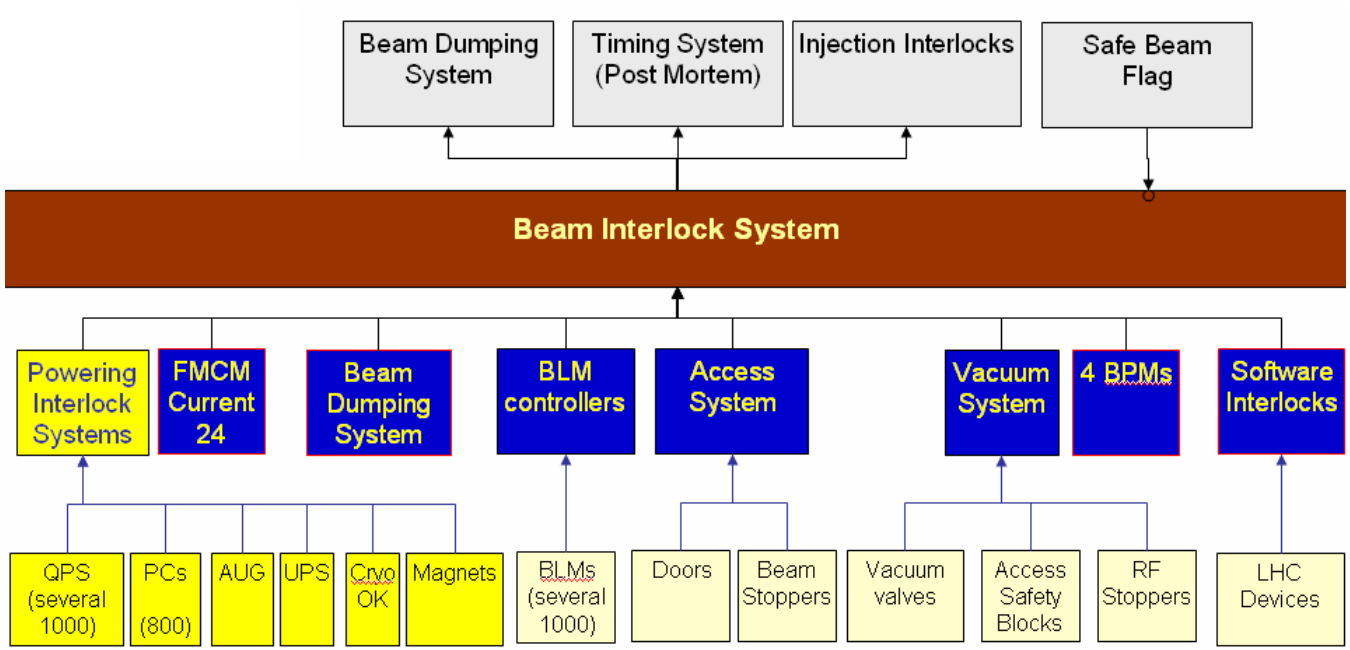
~ 25 electrical circuits with 800 nc magnets in SPS extractions lines & CNGS

Powering Interlocks

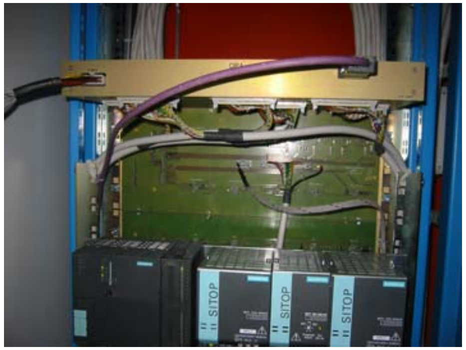
➔ Magnet powering system will account for a considerable fraction of beam dump requests due to (e.g. beam induced) magnet quenches, power converter failures, mains failures, etc..

➔ Due to its complexity and the requirement of flexibility (not all powering failures require beam dumps or extraction inhibits for TL), the powering interlock systems are separated from the beam interlock system

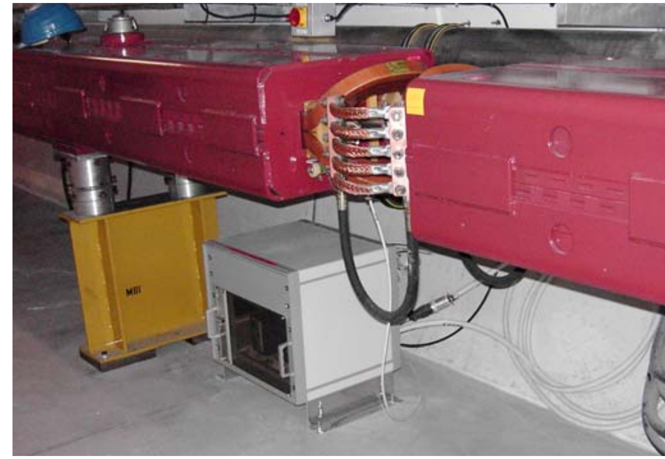
➔ Magnet powering and interlock systems in the SPS, transfer lines and the LHC are more or less identical (generic designs), with a progressive renewal of existing legacy



Powering Interlocks for sc and nc magnets



Powering Interlock Controller (PIC)



Warm Magnet Interlock Controller (WIC)

Protect electrical circuits with super conducting magnets (LHC)

HW Interfaces with quench protection system, converters, emergency stop, UPS

PLC Siemens S7-319

Real-Time (Response time ~1 msec)

Typical Powering Failures: Quenches, internal converter or cooling failures

Protect electrical circuits with normal conducting magnets (TI8/TI2, CNGS, LEIR, LHC, SPS, etc...)

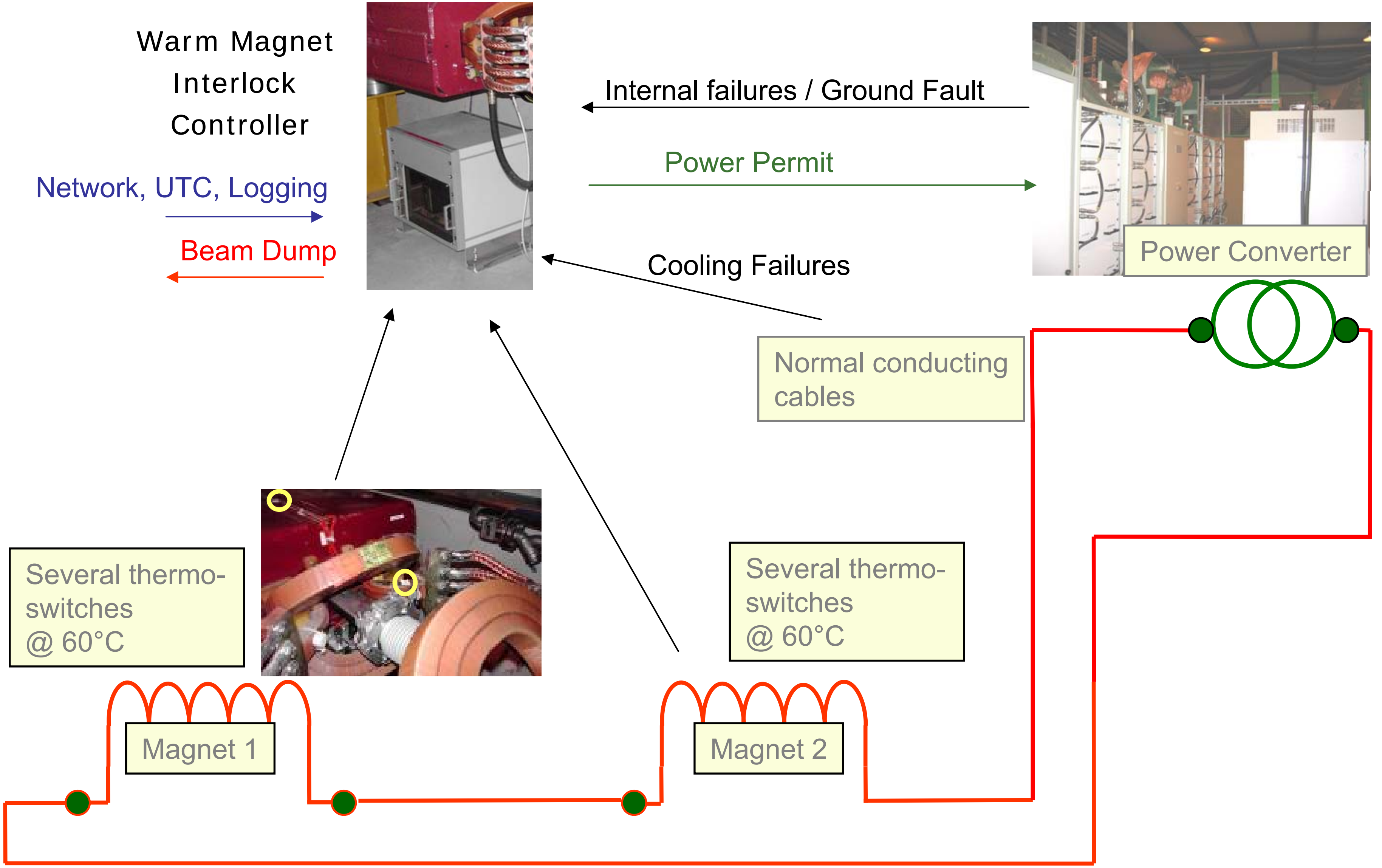
HW Interfaces with Magnets (Thermo-Switches) and power converters

PLC Siemens S7-300 (F-series for LHC)

Real-Time (Response time ~ sec)

Typical Powering Failures: Magnet overheating, internal converter failure

Protection mechanisms for normal conducting magnets / circuits



Injector chain

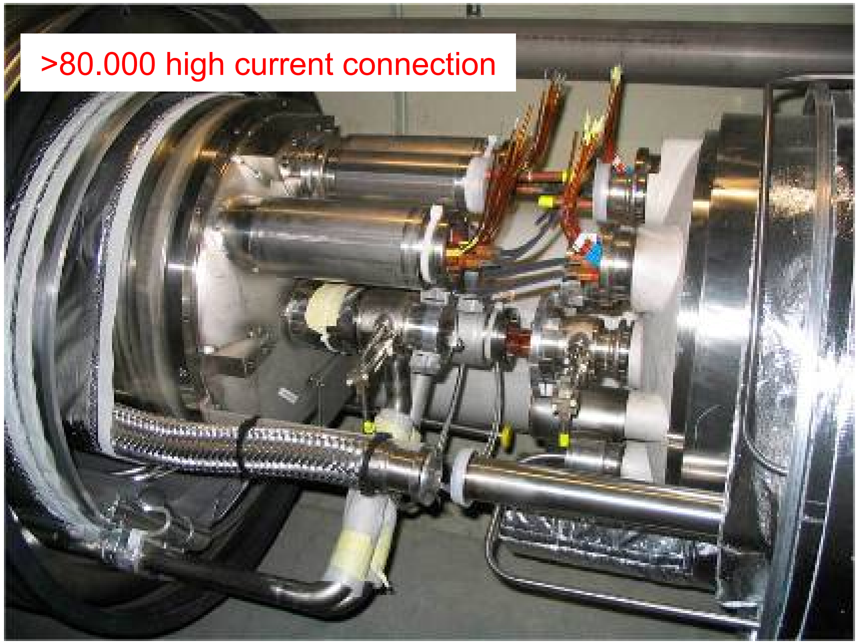
From the PS…

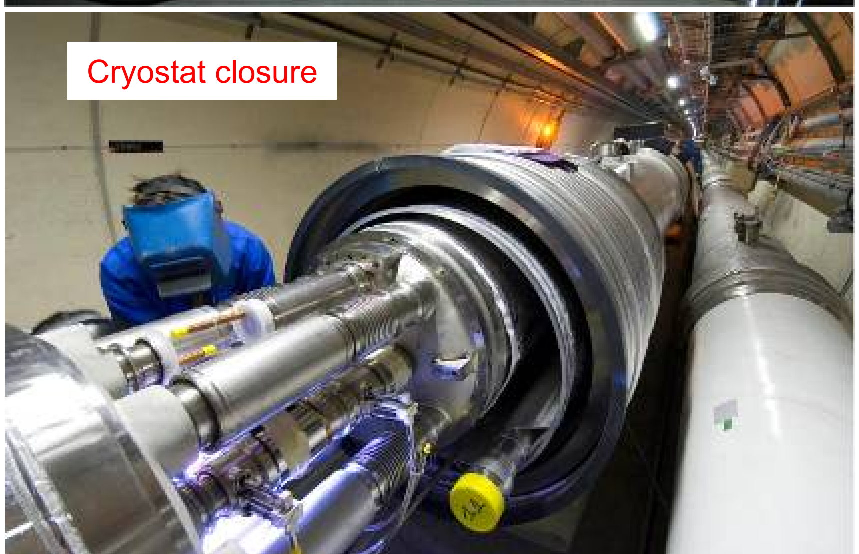
Through the SPS…

…into TI8 (beam 2 TL towards LHC)…

…and CNGS

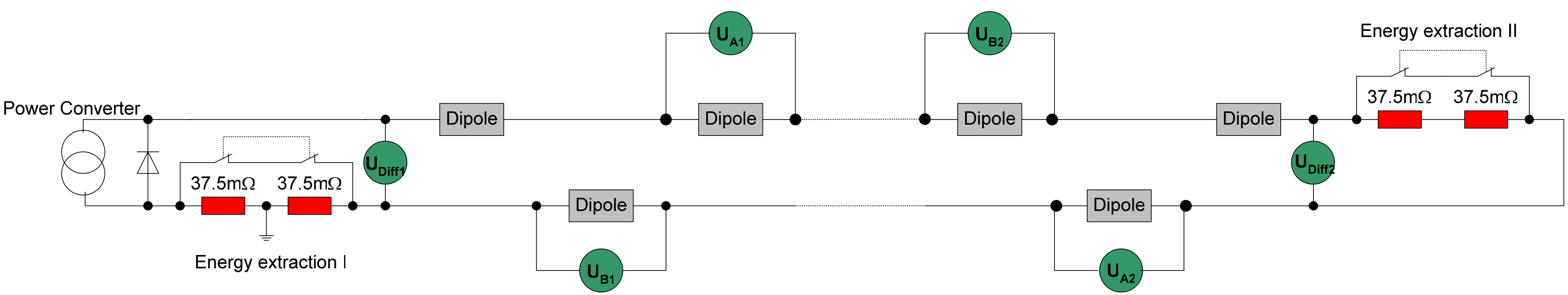
The LHC machine – Interconnections in the 8 arcs

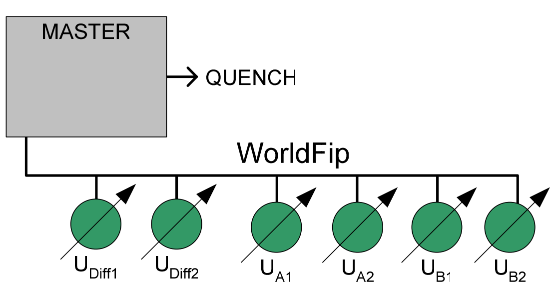




Protection of superconducting magnets

- More complex and faster protection systems than for nc magnets required
- Dedicated Quench Protection System for magnets, busbars and current leads (Fast DSP based systems and high precision system with low detection thresholds)
- Quench heaters, diodes and energy extraction systems to deal with high stored energies and long current decays

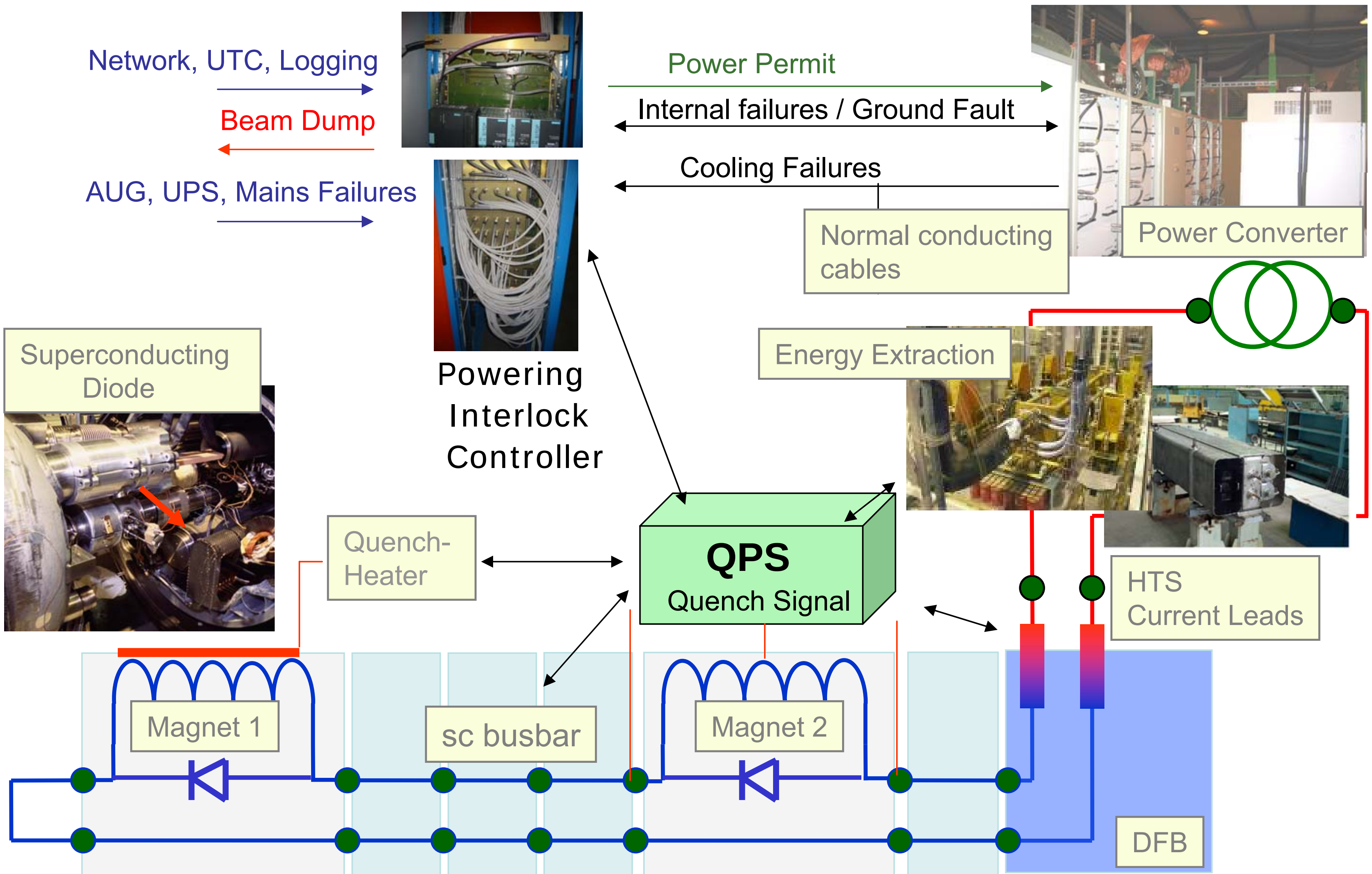




$$U_{Resistive}=U_{Diff1}-(U_{Diff2}+154*0.25*(U_{A1}+U_{A2}+U_{B1}+U_{B2}))$$

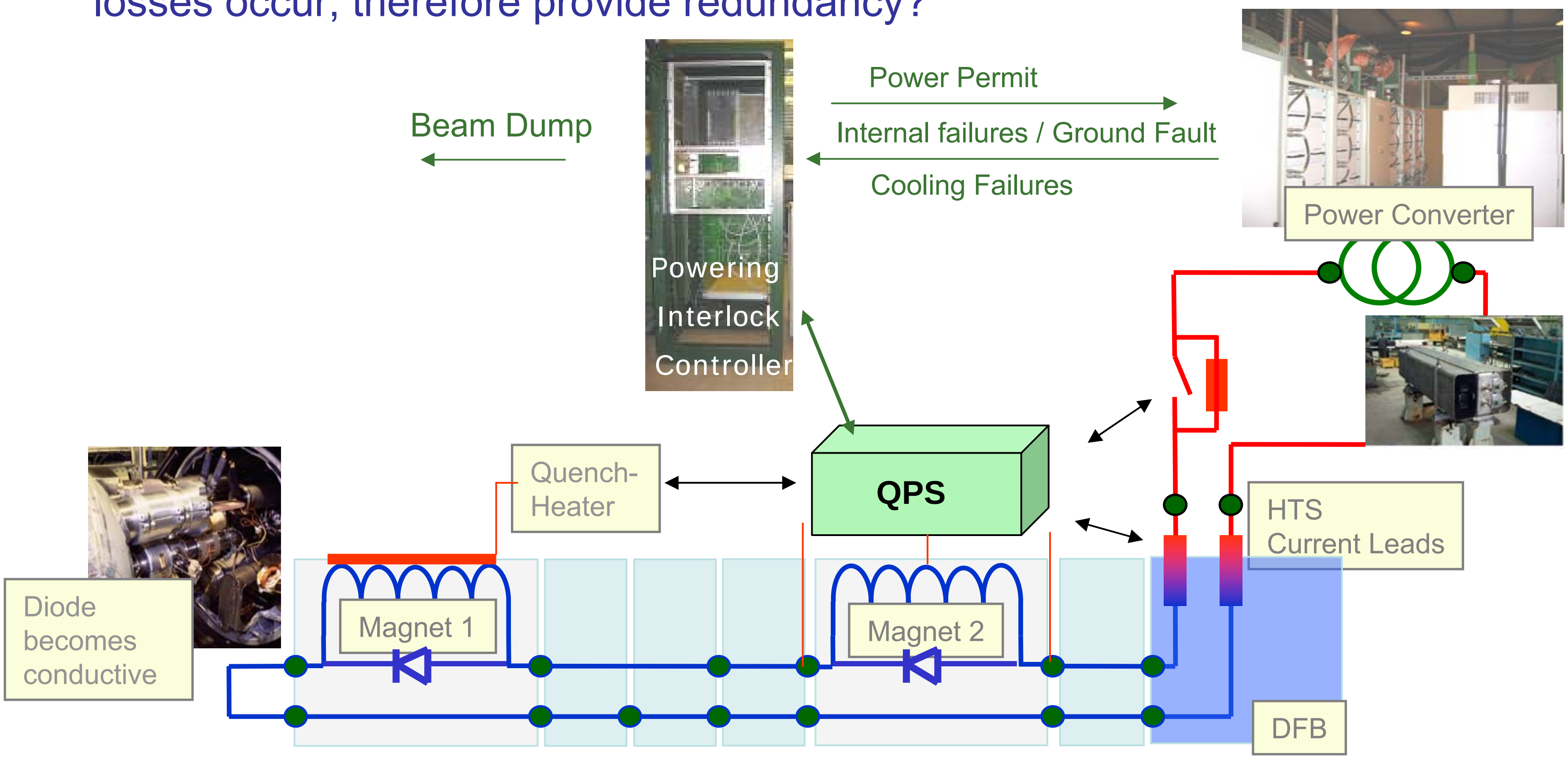
Courtesy R.Denz

Protection mechanisms for superconducting magnets / circuits

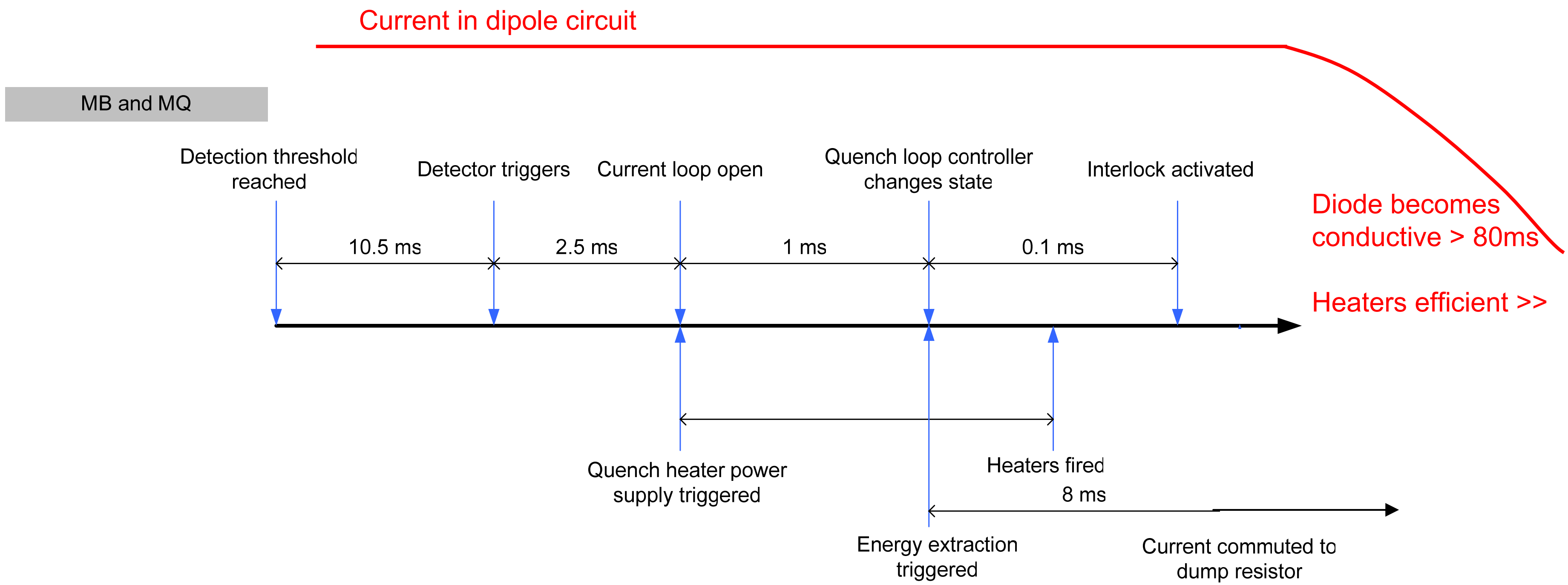


Failure case : Quench of a superconducting magnet

- ➔ Powering Interlocks mainly for equipment protection – can it help to protect the machine?
- ➔ Quenching of sc magnet due to e.g. beam losses -> detection by the QPS system
- ➔ Transmission of quench signal, firing of heaters and activation of EE system
- ➔ What comes first? Can the powering interlock dump the beam before beam losses occur, therefore provide redundancy?



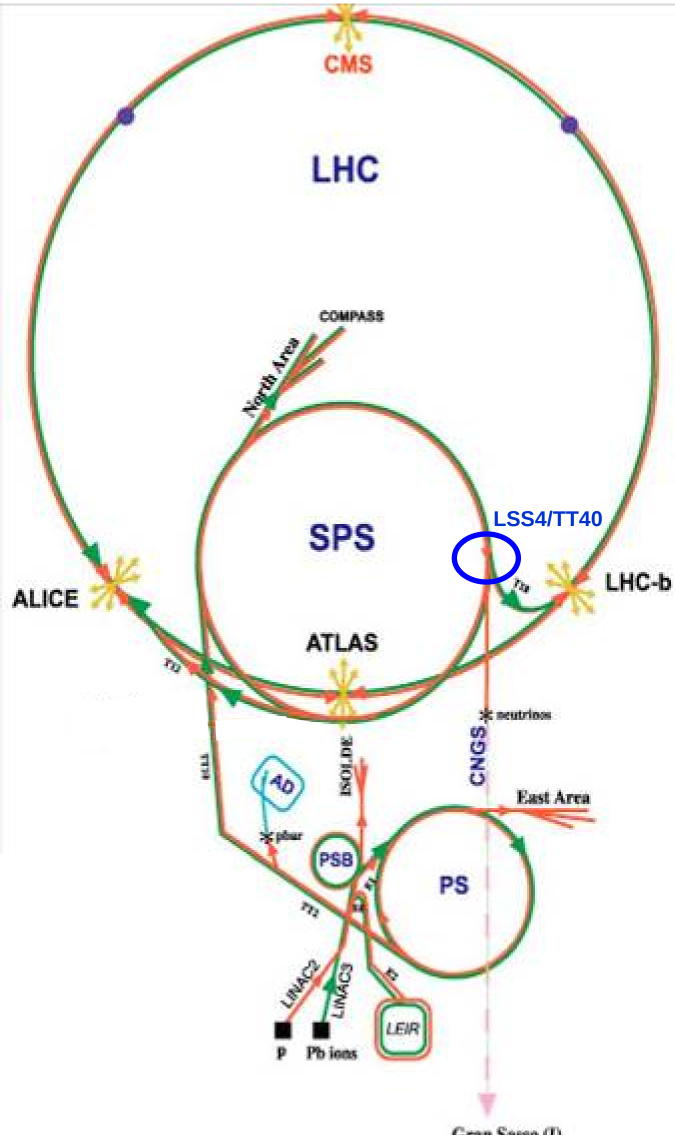
Quench detection time scales for quench of sc magnet

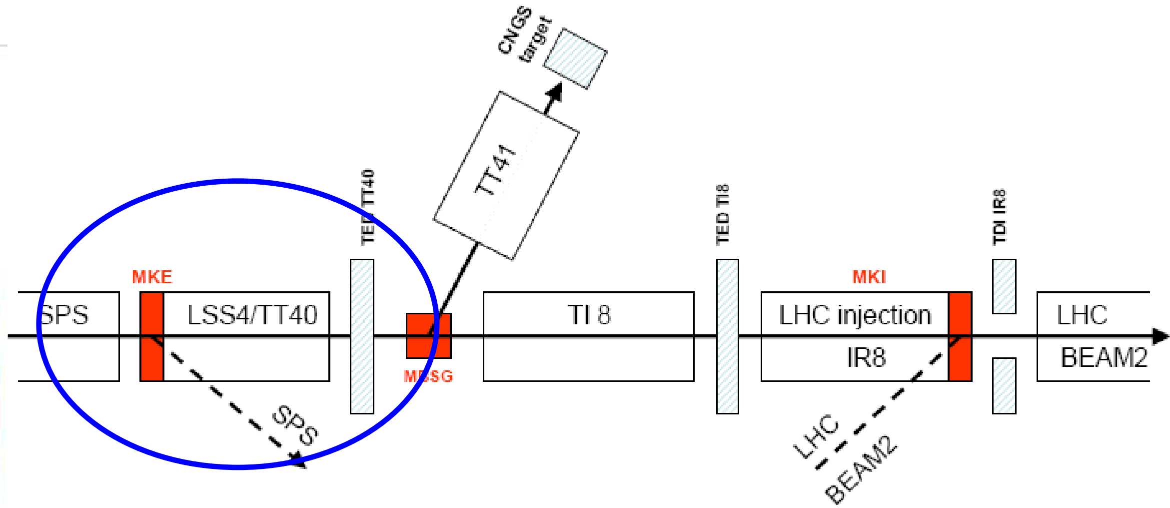


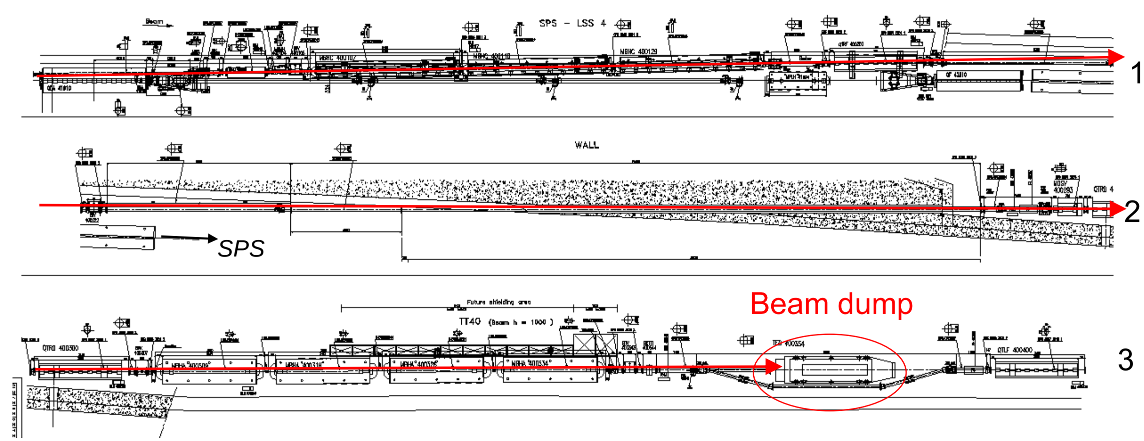
- ➔ Powering Interlock system requests a beam dump before the current in the dipole magnet starts decaying (all other sc magnets even less time critical)
- ➔ For most failure cases, the issued beam dump request provide redundancy to BLM's, as the fault is transmitted to the Beam Dumping System before beam losses occur
- ➔ For some failure cases (especially for the interlock system for nc magnets), the issued beam dump request will not be fast enough and other monitors (BLM etc) need to trigger the beam dump
- ➔ But, for injection/extraction failures neither the powering interlocks nor the BLM system can prevent damage (TT40 incident end of last year)

TT40 Incident – Powering Failures in nc magnets

TT40 incident end 2004 – Beam transfer from the SPS



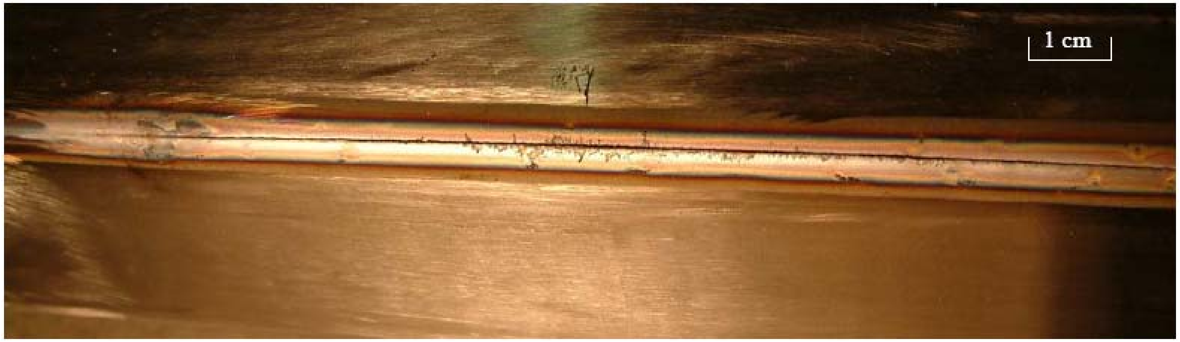


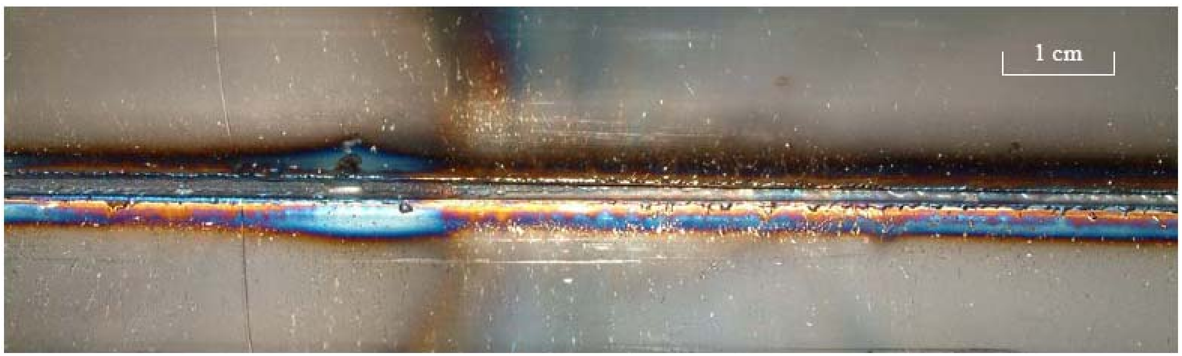


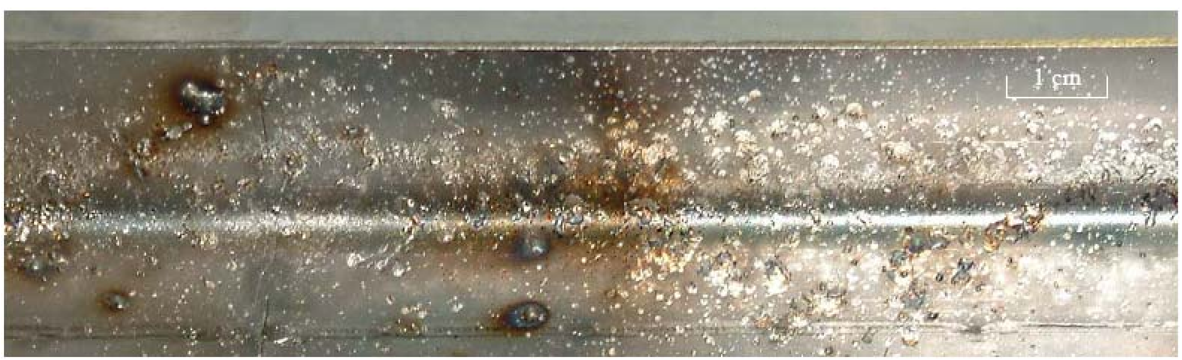
First 100m of TT40 transfer line (to movable beam dump)

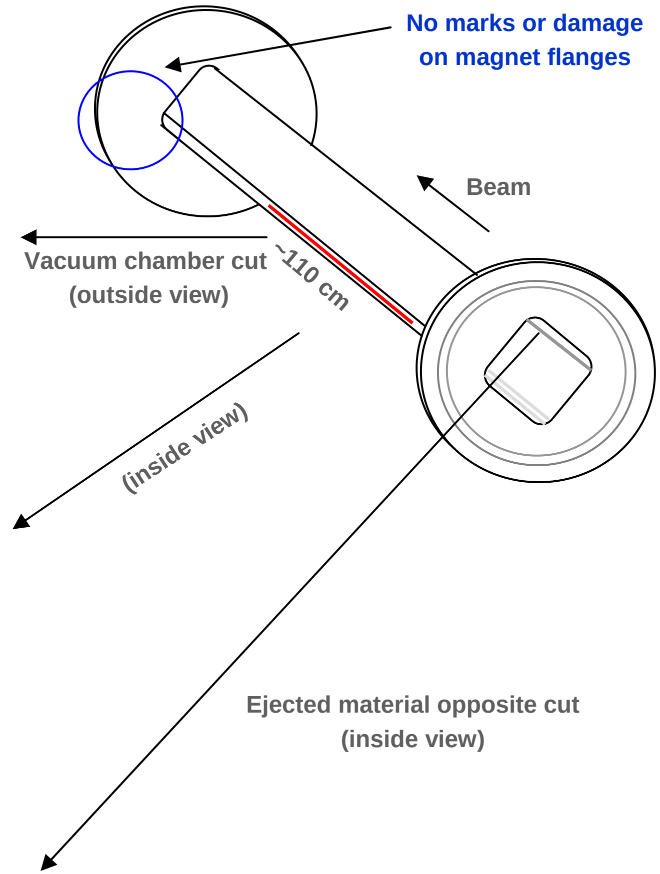
Courtesy B.Goddard

Inspection of damaged quad chamber





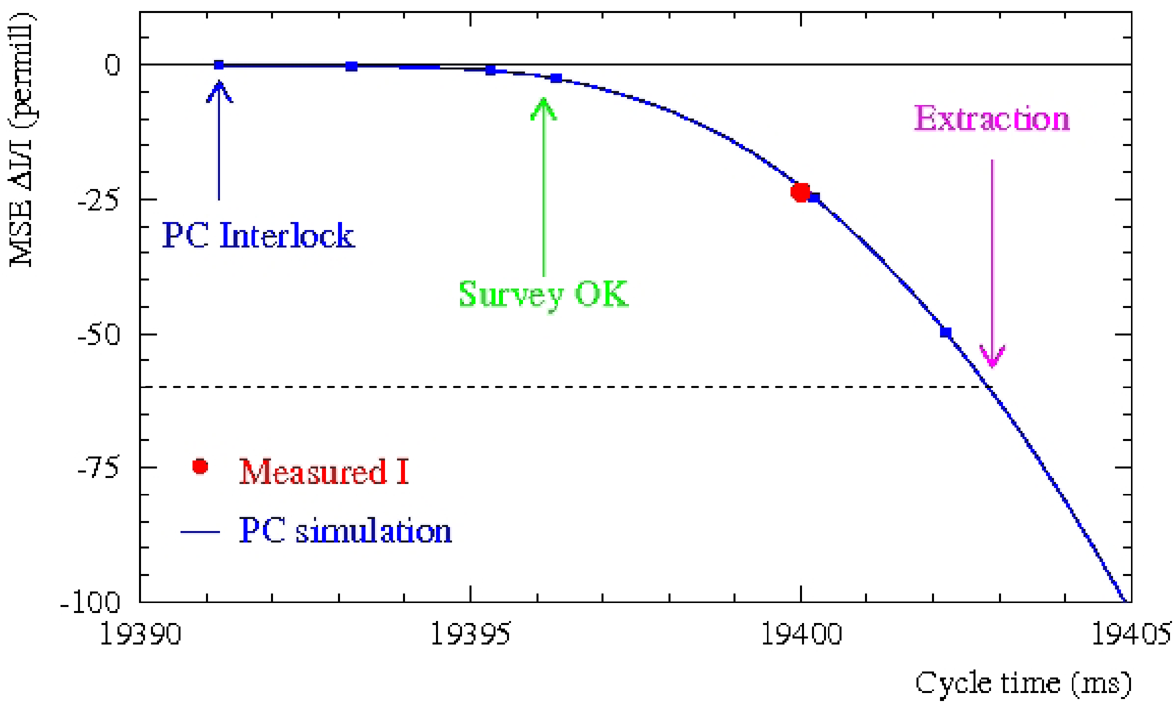




Courtesy B.Goddard

Reconstruction of sequence of events

- E - 13 ms: septum power supply tripped off, through EMC from beam via PLC;
- E - 7 ms: current surveillance measured -0.5% error → inside ±1% tolerance;
- E - 3 ms: current logged with -2.5% error;
- E: simulated current drop of -6% (c.f. -5.1% deduced from trajectory)



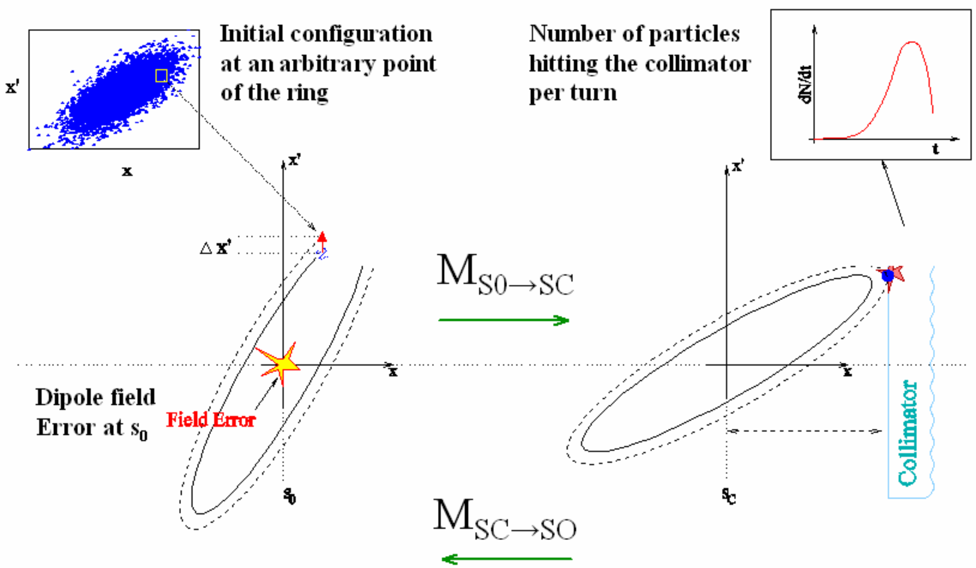
Courtesy B.Goddard

- ➔ TT40 incident triggered further studies of nc magnets in the TL (nc separation dipole D1 in LHC already known to be critical)
- ➔ Revealed around 25 circuits where the power converter surveillance (every 5-10ms) might not be sufficiently fast / accurate

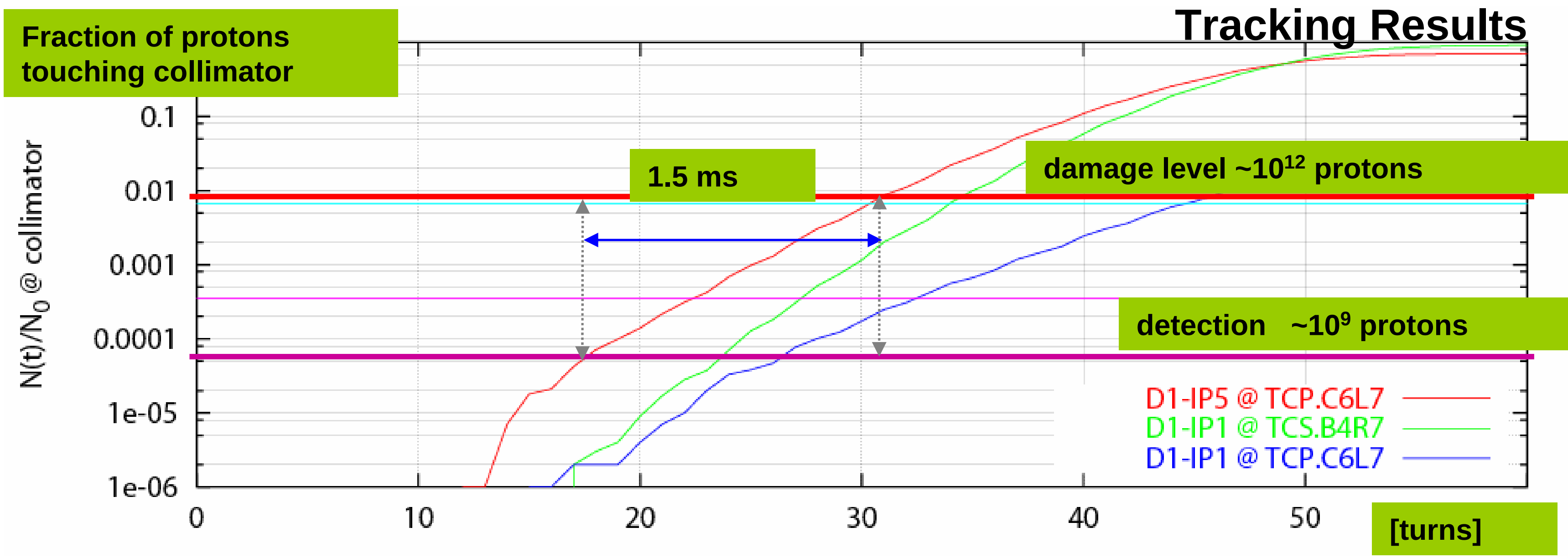
$$\Delta B_{error}(t) = B_0 \cdot (1 - e^{-t/\tau})$$

$$\Delta x'(t) = e/p \cdot \Delta B_{error}(t) \cdot l$$

With: τ ...*natural time constant*
e...electron charge
p...particle momentum
l...magnet length



Courtesy V.Kain



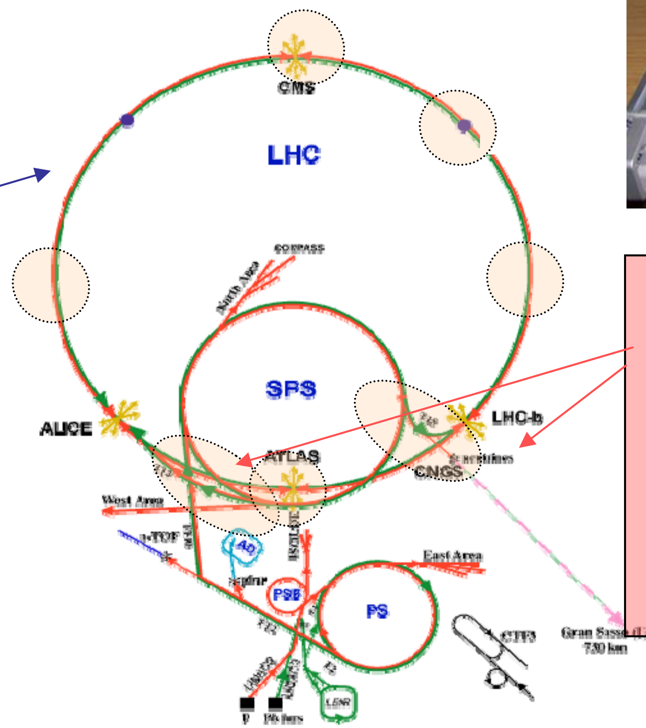
Power Converter Fault of normal conducting D1 in IR1 or IR5.
Assumption: Exponential decay: τ=2.5s

After 15 turns: ΔI = 0.05% in D1
After 30 turns: ΔI = 0.1% in D1
Threshold for FMCM: after 10 turns: ΔI = 0.035%,
required reaction time after detection: 10 turns

Courtesy V.Kain

Magnetstrom-alarme from DESY @ CERN and first experience in CNGS

Resulting FMCM Installations in the LHC and SPS-LHC TL



LHC

- D1 in IR1 and IR5
- Dump septa in IR6
- RD34, RQ4, RQ5 in IR3 and IR7

TI2, TI8, CNGS, TT41

- Septas (**MSE**, MSI, MST)
- MBB, **MBG, MBSG**
- MBI, MBHC
- MBIBH…

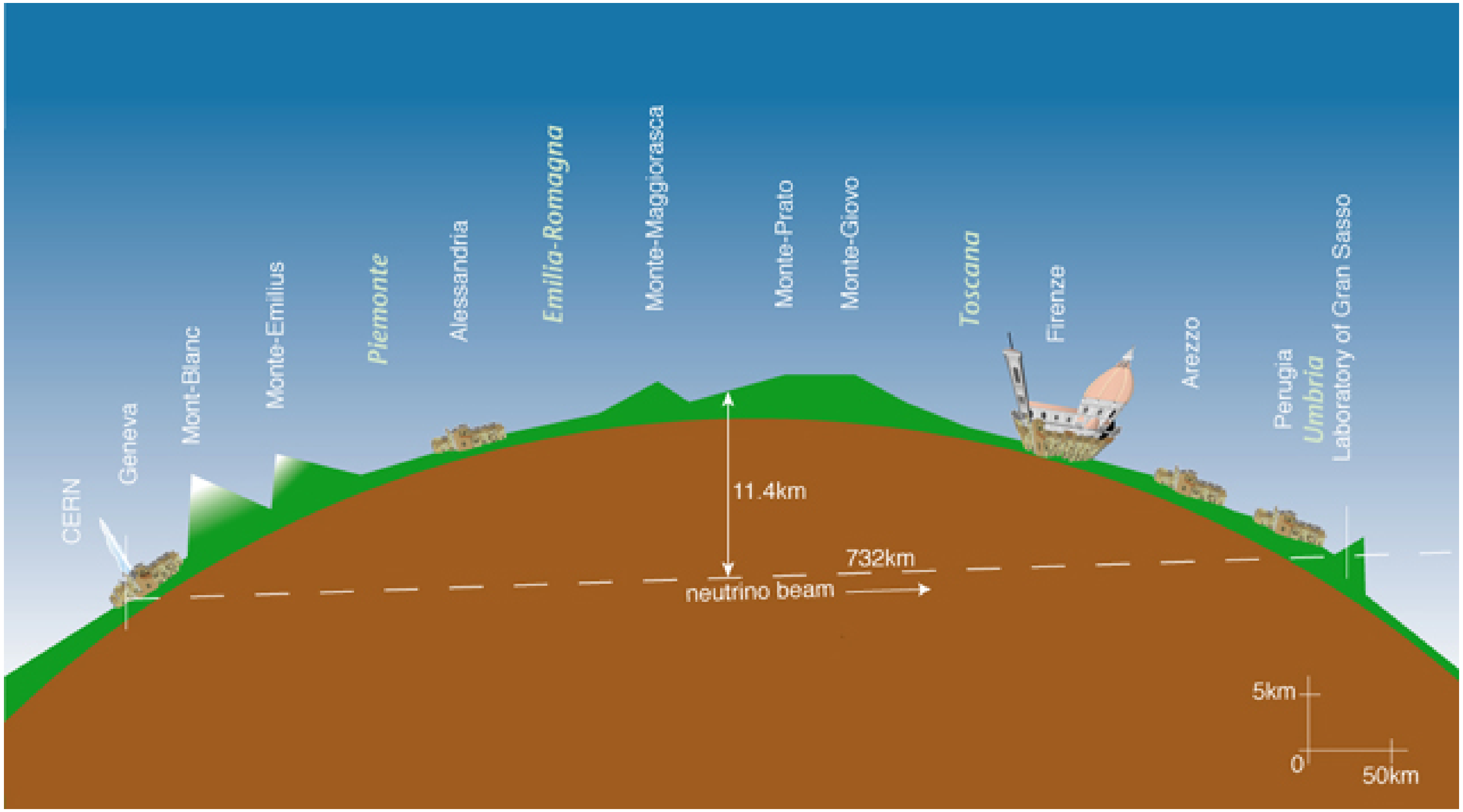
➔ Similar issues at DESY lead to the design of a 'Magnetstrom-Alarm-Box'

➔ Encouraging test results with DESY version on CERN test bench (D1 and MSE)

➔ Collaboration with DESY to adapt the existing design

➔ Three DESY (spare) units installed and commissioned for CNGS operation

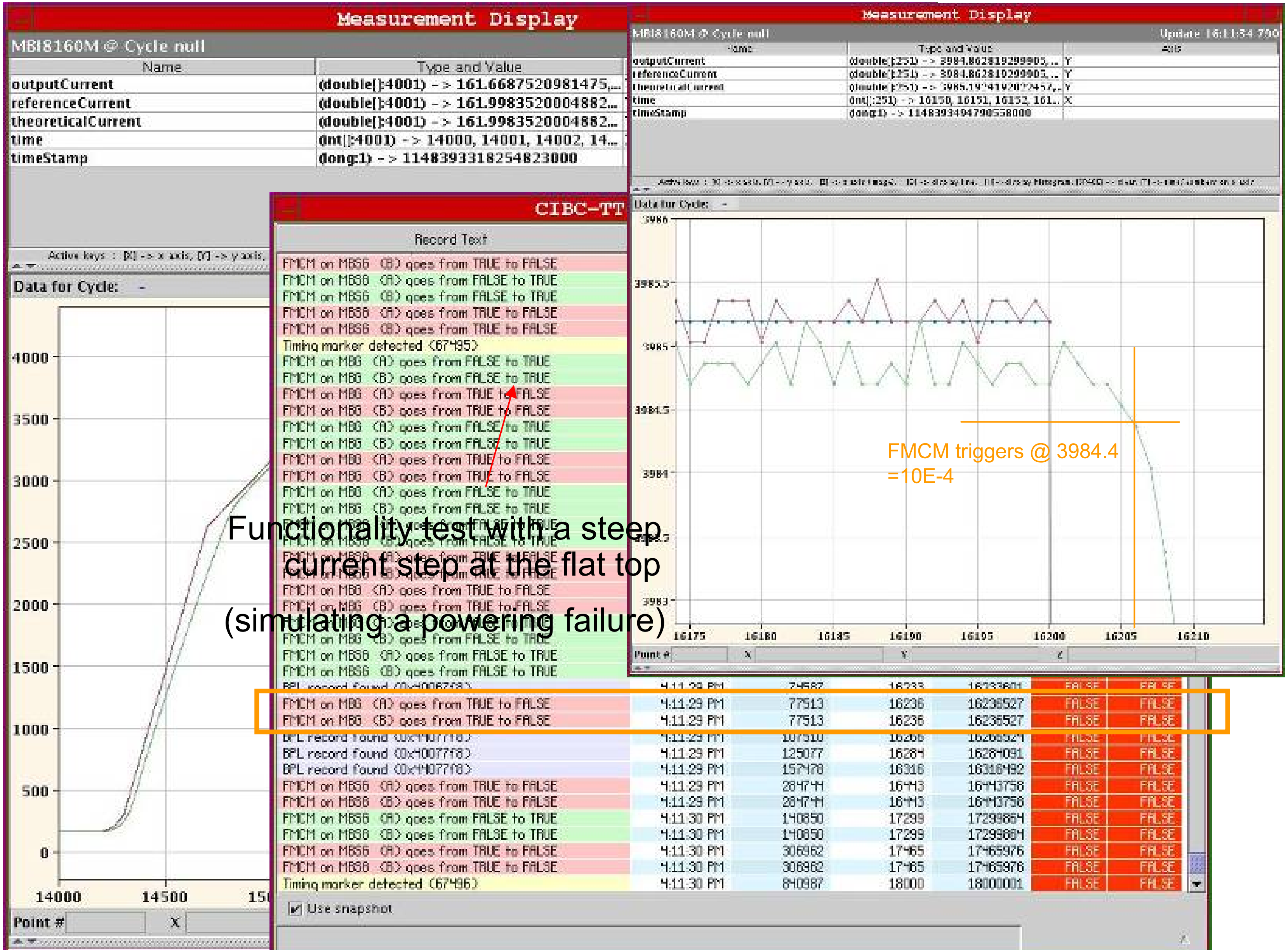
➔ Successfully operated for pulsing magnets during 3 initial CNGS runs



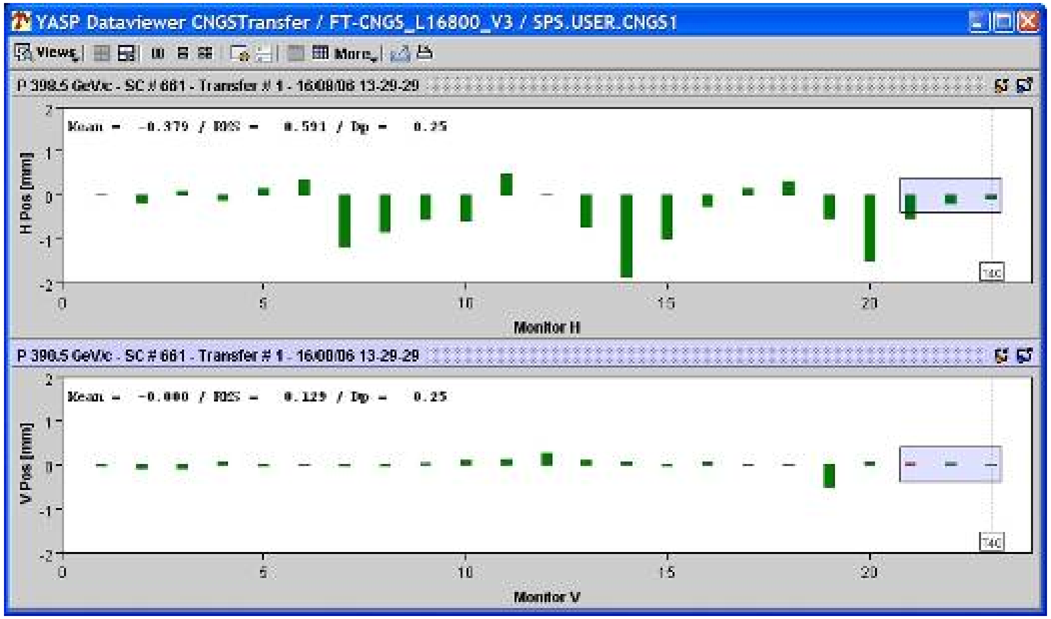
- Investigate Neutrino ‘oscillation’ (motivated by the results obtained at the Superkamiokande detector in Japan)
- Muon type neutrinos from the SPS will pass underground to the Gran Sasso National Laboratory (LNGS) in Italy, 730 km from CERN.
- LNGS is currently preparing to house huge detectors specially designed to detect the rare tau-neutrinos created by ‘oscillation’ from muon-neutrinos on the way between CERN and LNGS.


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
FMCM
Access shaft
PGCN
SPS/ECA4
55m
SPS tunnel
Extraction septa
Switching Magnet
Main Dipole Chain
TT41
LHC/TI8 tunnel
Target chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
TT41 transfer line
Hadron stop
and first muon detector
muons
neutrinos
Connection gallery
Second muon detector
neutrinos
to Gran Sasso
Target
06 / 2003
CERN-AC-DI-MM

MBG 4101M – Current Step of -1% on Flat Top



- After initial commissioning and setup without beam, beam trajectory measured with low intensity beam
- Failure positioned such that maximum current error is reached at extraction (and still not inhibited by the FMCM)
- Average beam trajectory (of some 10 good extractions) compared with erroneous extraction using some 20 BPM in the TL
- MSE Extraction septa: less than 2mm in the TL and 0.2mm on the target
- Dipole magnet chain: Peak excursions ~2 mm in TT41 (energy error) corresponding to a relative MBG strength change of ~2.5×10-4.



Tolerances for TL : ±4mm

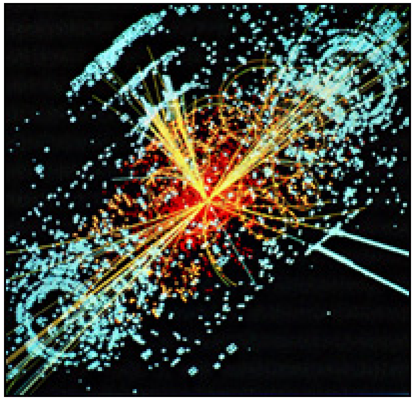
Tolerances on target: ± 0.5mm

LSS4 extraction

Target

Summary of FMCM experience in CNGS

- FMCM functionality validated for cycling magnets (producing extraction window rather than continuous beam permit)
  - 0.1‰ for MBG (0.6 ‰ required), 0.13‰ for MBSG (1.0 ‰ required), 1.5‰ for MSE (2.0 ‰ required)
  - Drawback are multiple extraction enables during ramp up
- Reproducible extraction windows for all three installations
- Simulations correlated and confirmed with beam excursion measurements
- Collaboration with DESY for the production of some 30 FMCMs will allow for additional safety during future CNGS and LHC operation, completing the existing powering interlock systems
- Outlook to operation 2007:
  - CNGS production runs starting in April/May
  - Commissioning of second SPS-LHC TL end of 2007
  - December 2007: LHC startup



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