Machine Protection and Operation for LHC

Joint Accelerator School,

Newport News,

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Introduction to LHC

Masking

Commissioning

Intensity ramp up

Beam losses

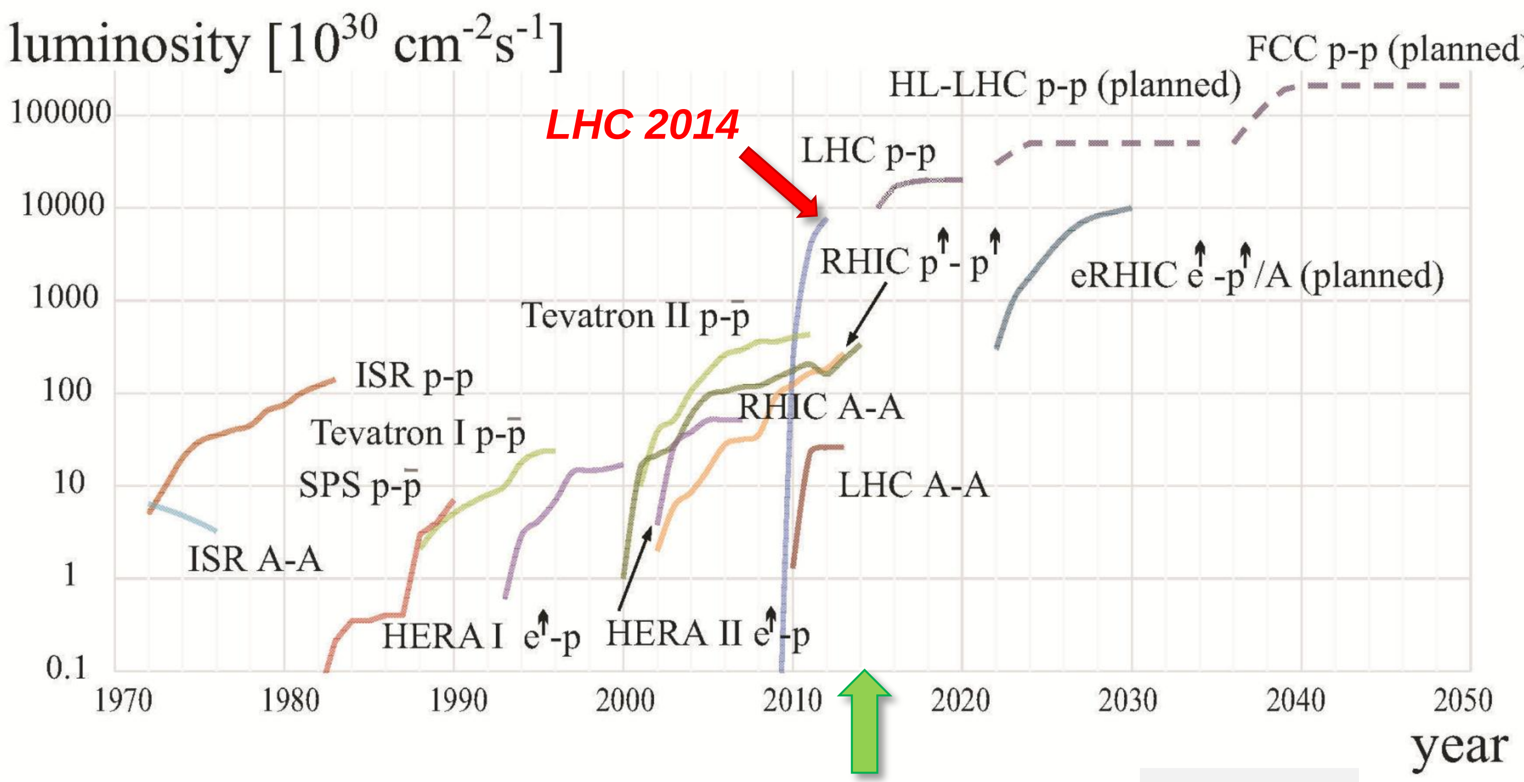
Machine protection diagnostics & software

Availability

Conclusions

Hadron colliders

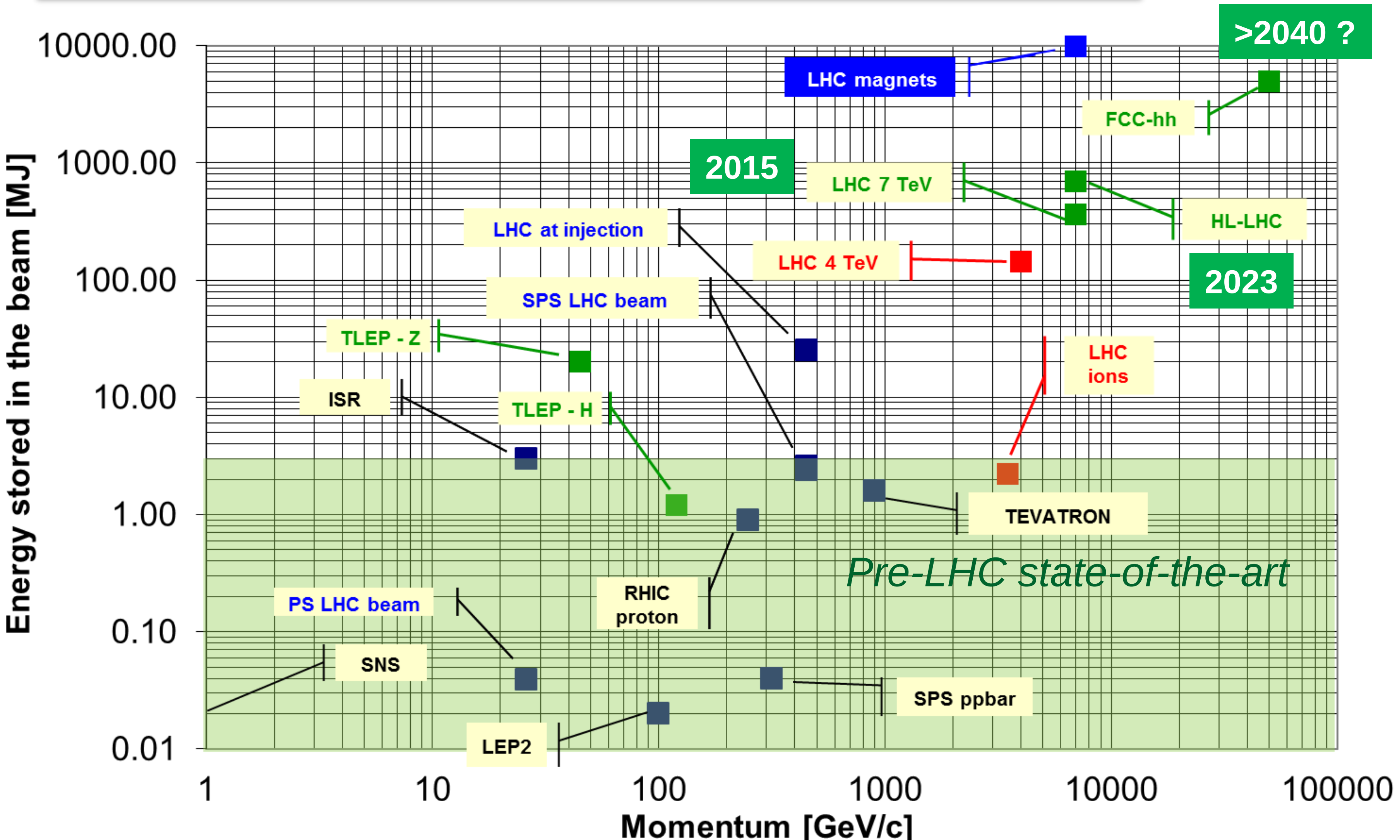
- The LHC is the latest in the series of the large hadron colliders after the ISR, SPS, Tevatron, HERA and RHIC.
- The LHC pushes the luminosity frontier by a factor ~25 and the energy frontier by a factor ~7 (soon !).
  - *Higher energy and much higher beam intensity.*



W. Fischer

Stored energy: past – present – future

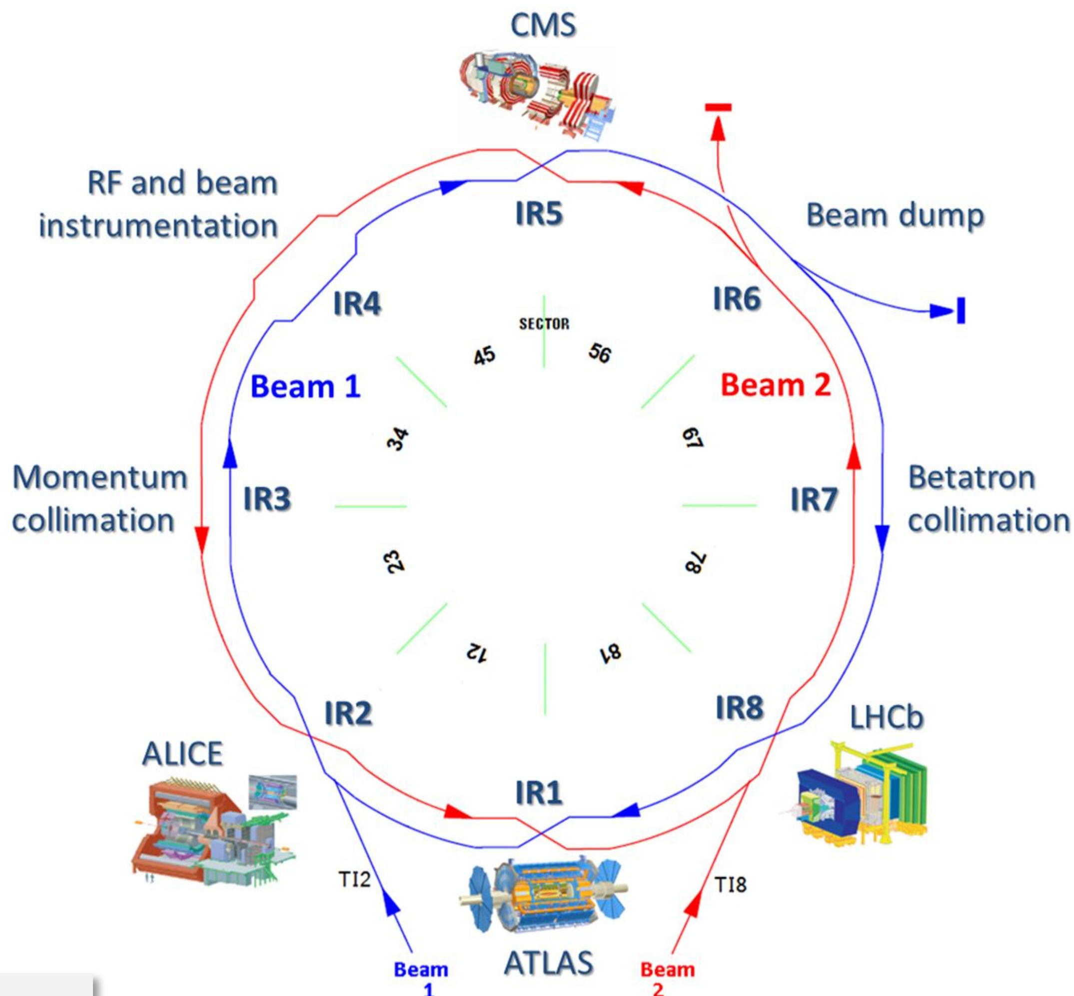
LHC pushes the stored energy from few MJs to > 100 MJs



LHC overview

- Total length 26.66 km, in the former LEP tunnel.
- 8 arcs (sectors), ~3 km each.
- 8 straight sections of 700 m.
- beams cross in 4 points.

- 2-in-1 magnet design with separate vacuum chambers.
- **2 COUPLED rings**.
- Injection at 450 GeV, operation at 4 TeV (6.5 TeV in 2015).



The LHC can be operated with protons and ions (so far Pb_{208})

LHC layout

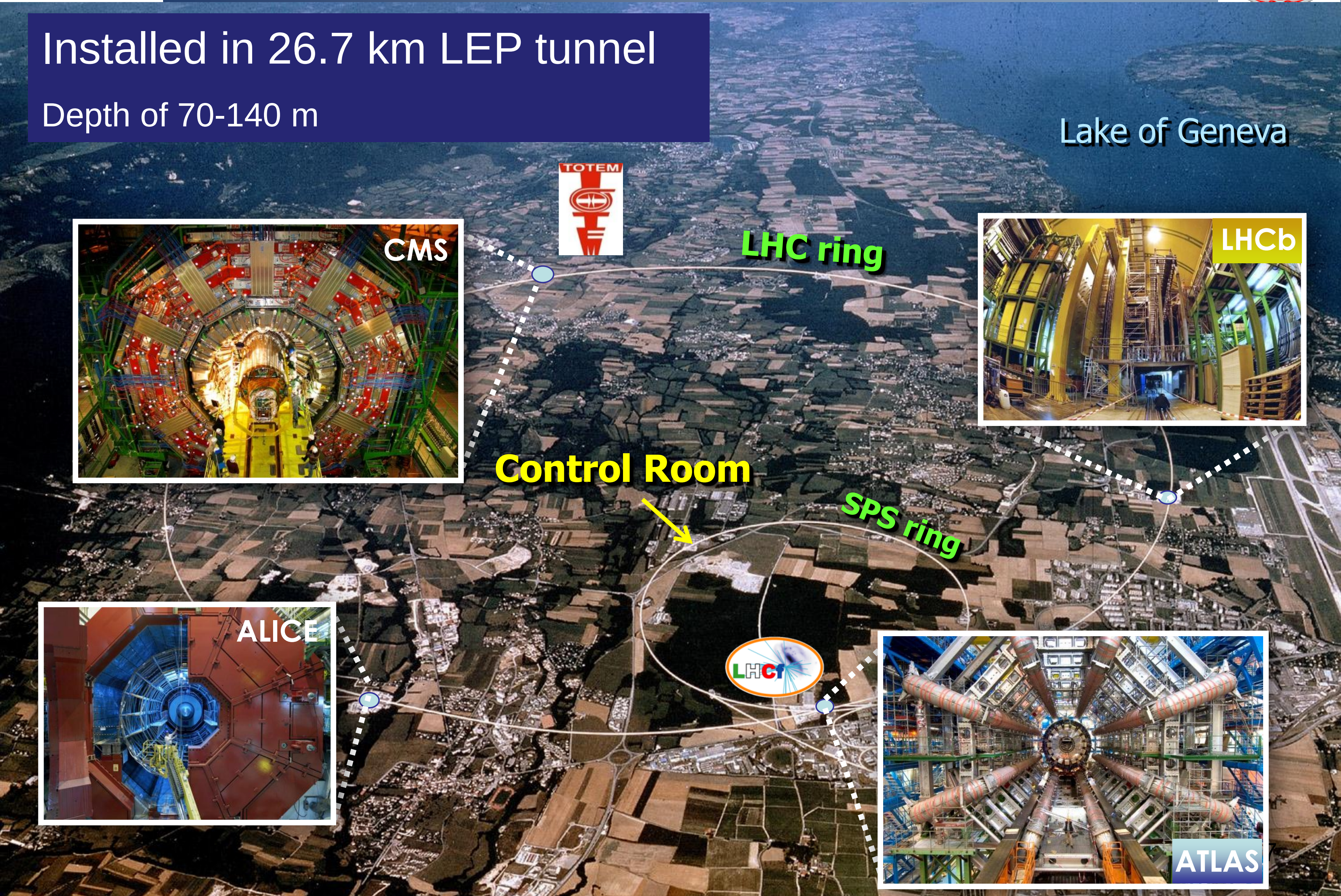
Installed in 26.7 km LEP tunnel

Depth of 50-170 m

LHC layout

Installed in 26.7 km LEP tunnel

Depth of 70-140 m

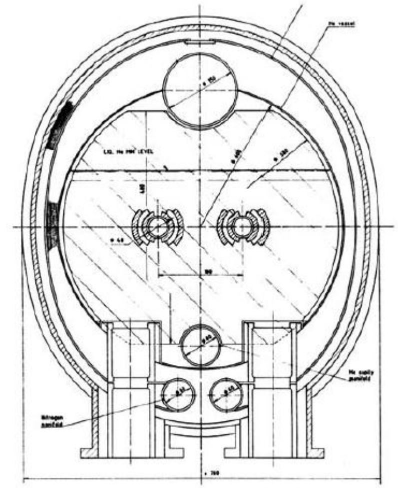


Challenges and choices

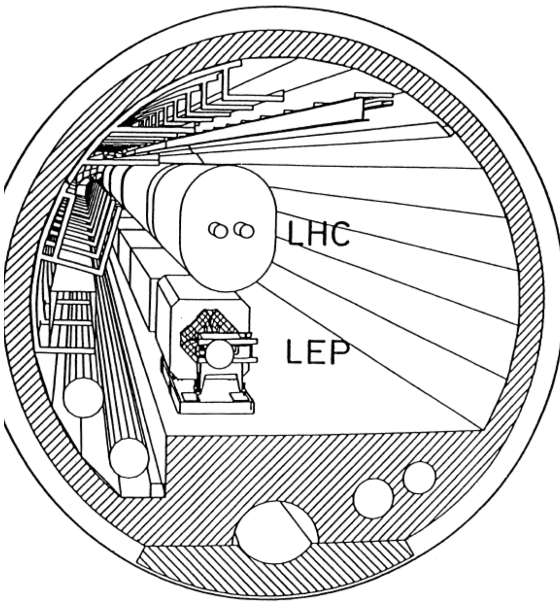
- High magnetic fields – 8T,

  ⇒ super-conducting magnets
- 2 in 1 magnet design,
- Superfluid Helium,
- Luminosity ~1×10^{33} cm^{-2}s^{-1}

  ⇔ limit to 4 pp collisions ('events') / bunch crossing !



1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

The parameters remained rather stable over time, except for luminosity (and intensity):

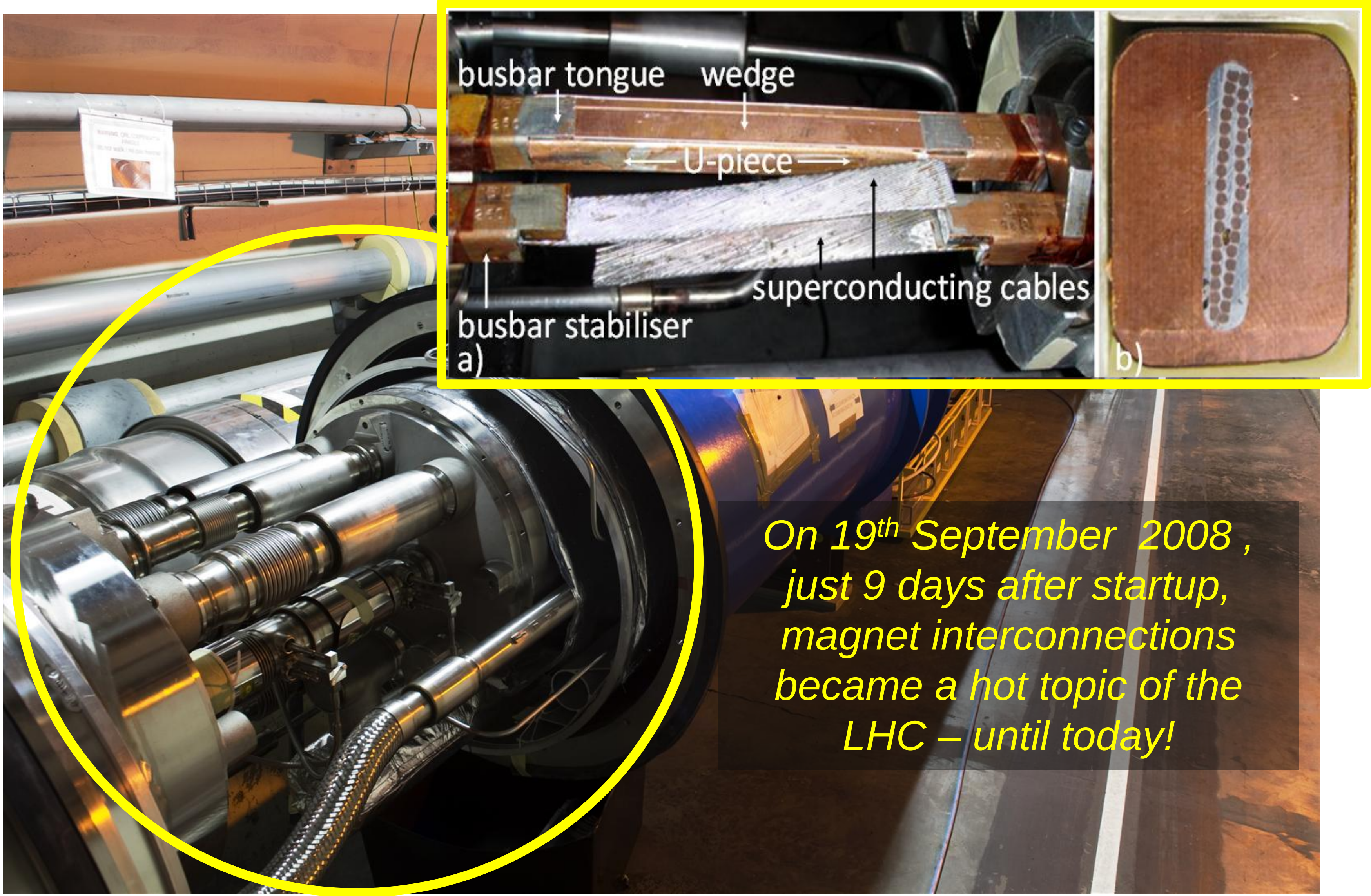
- Luminosity was pushed to ~1×10^{34} cm^{-2}s^{-1} to compete with SSC.

  The SSC was cancelled in 1994, but the high luminosity was kept !

  High luminosity → MPS !!

LHC incident 19th September 2008

LHC magnet interconnection



On 19th September 2008, just 9 days after startup, magnet interconnections became a hot topic of the LHC – until today!

The most serious machine incident

LHC incident on September 19th 2008

- Last commissioning step of one out of the 8 main dipole electrical circuit in sector 34 : ramp to 9.3kA (5.5 TeV).
- At 8.7kA an electrical fault developed in the **dipole bus bar** located in the interconnection between quadrupole Q24.R3 and the neighboring dipole.

  Later correlated to a local resistance of ~220 nΩ – nominal value 0.35 nΩ.
- An electrical arc developed which punctured the helium enclosure.

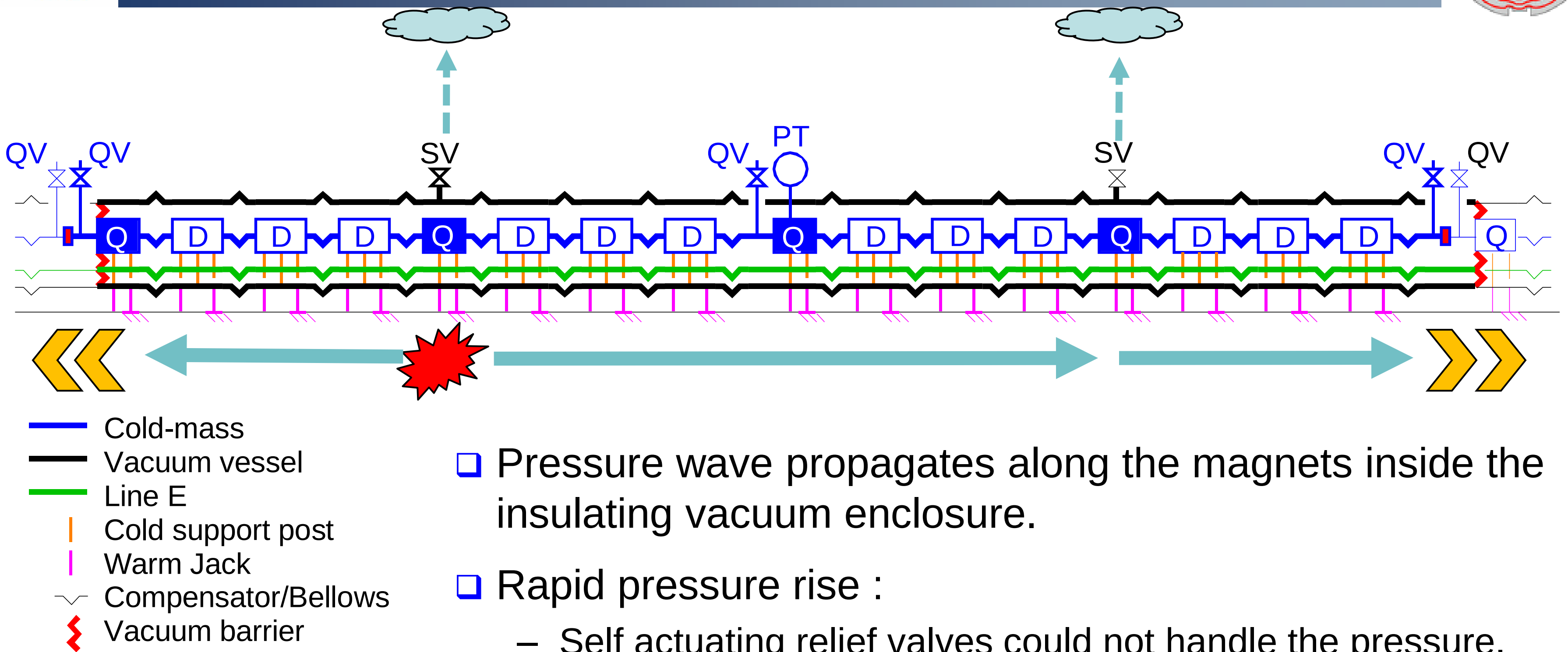
  Secondary arcs developed along the arc.

  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.
- Large amounts of Helium were released into the insulating vacuum.

  In total 6 tons of He were released.

This incident involved magnet powering, but no beam!

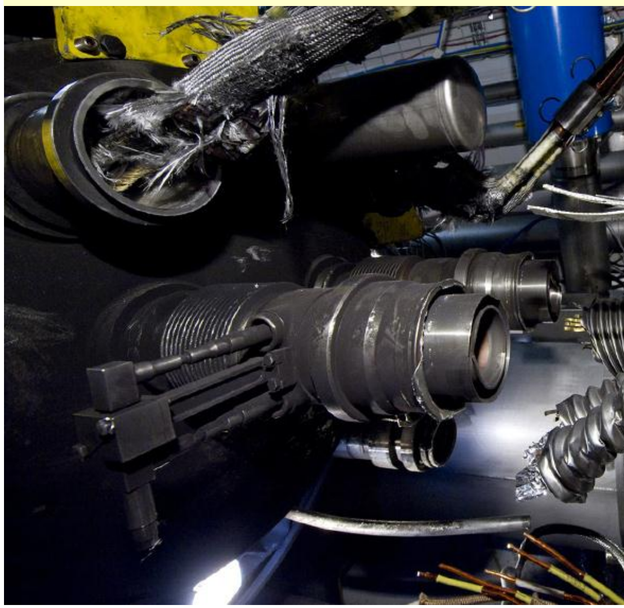
Helium pressure wave



- ❑ Pressure wave propagates along the magnets inside the insulating vacuum enclosure.
- ❑ Rapid pressure rise :
  - Self actuating relief valves could not handle the pressure.
    designed for 2 kg He/s, incident ~ 20 kg/s.
  - Large forces exerted on the vacuum barriers (every 2 cells).
    designed for a pressure of 1.5 bar, incident ~ 8 bar.
  - Several quadrupoles displaced by up to ~50 cm.
  - Connections to the cryogenic line damaged in some places.
  - Beam vacuum to atmospheric pressure.

Release of 600 MJ at LHC

The Helium pressure wave damaged ~600 m of LHC, polluting the beam vacuum over more than 2 km.



Arcing in the interconnection

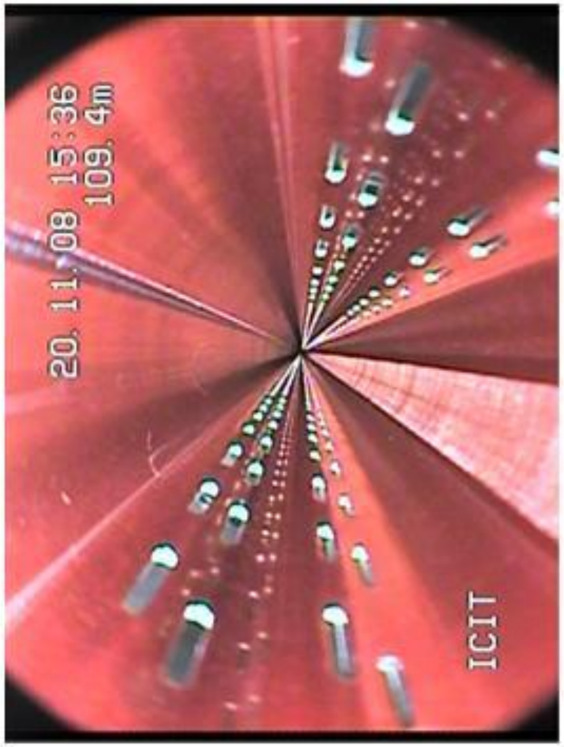
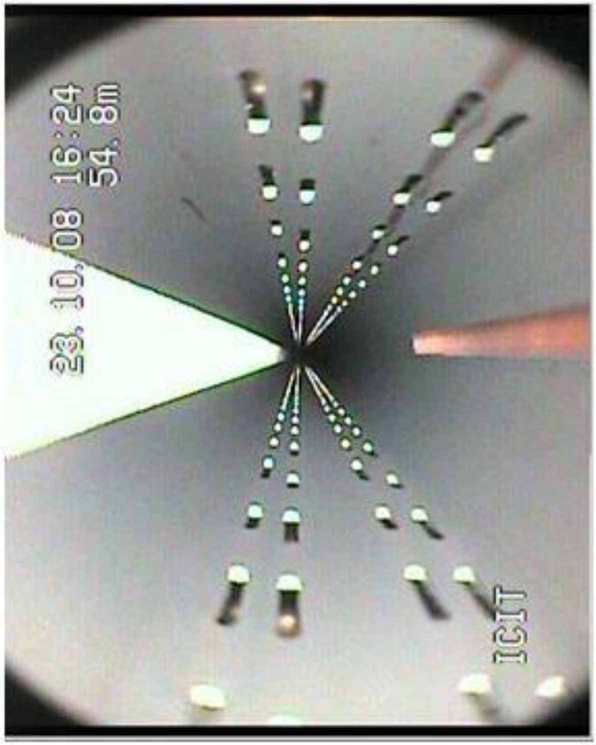
Over-pressure

Magnet displacement

53 magnets had to be repaired

Collateral damage : beam vacuum

Beam vacuum affected over entire 2.7 km length of the arc.

Beam screen with clean Copper surface.	Beam screen contaminated with multi-layer magnet insulation debris.	Beam screen contaminated with sooth.
		
	≈ 60% of the chambers	**≈ 20% of the chambers**

Consequences

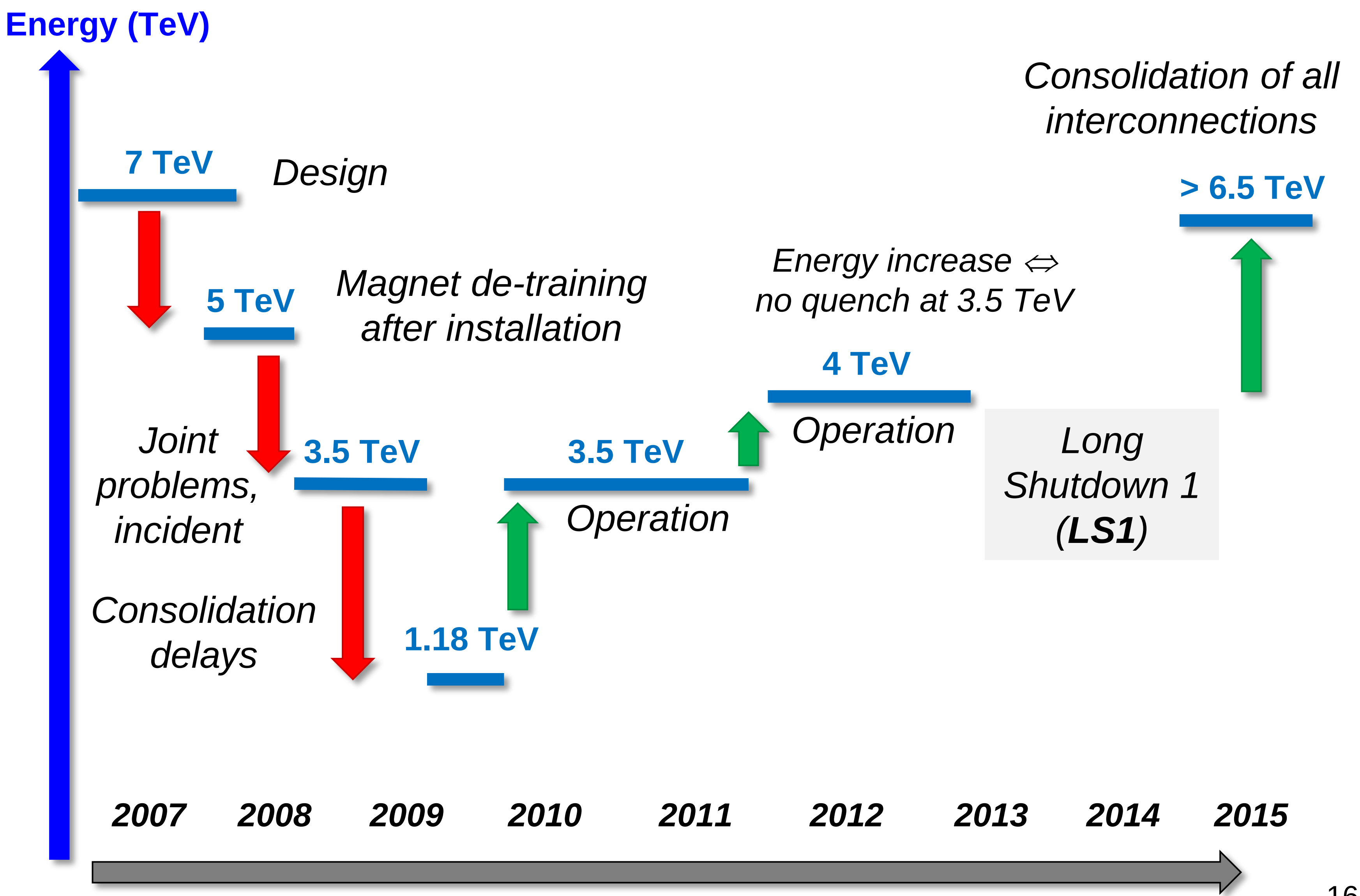
- Machine down for more than 1 year for repair and re-commissioning,
- **Major upgrades to protection system of the magnets** (surveillance of the bus-bars),

see lecture by H. Pfeffer

- Major upgrades to pressure release and magnet anchoring,
- Limitation of the machine energy to 3.5 (later 4) TeV instead of 7 TeV,
- Almost 2 years long shutdown (2013-2014) to repair all magnet interconnections.

- Commissioning and early operation in ‘easier’ conditions (3.5-4 versus 7 TeV) – lower fields, magnets less subject to quenching.

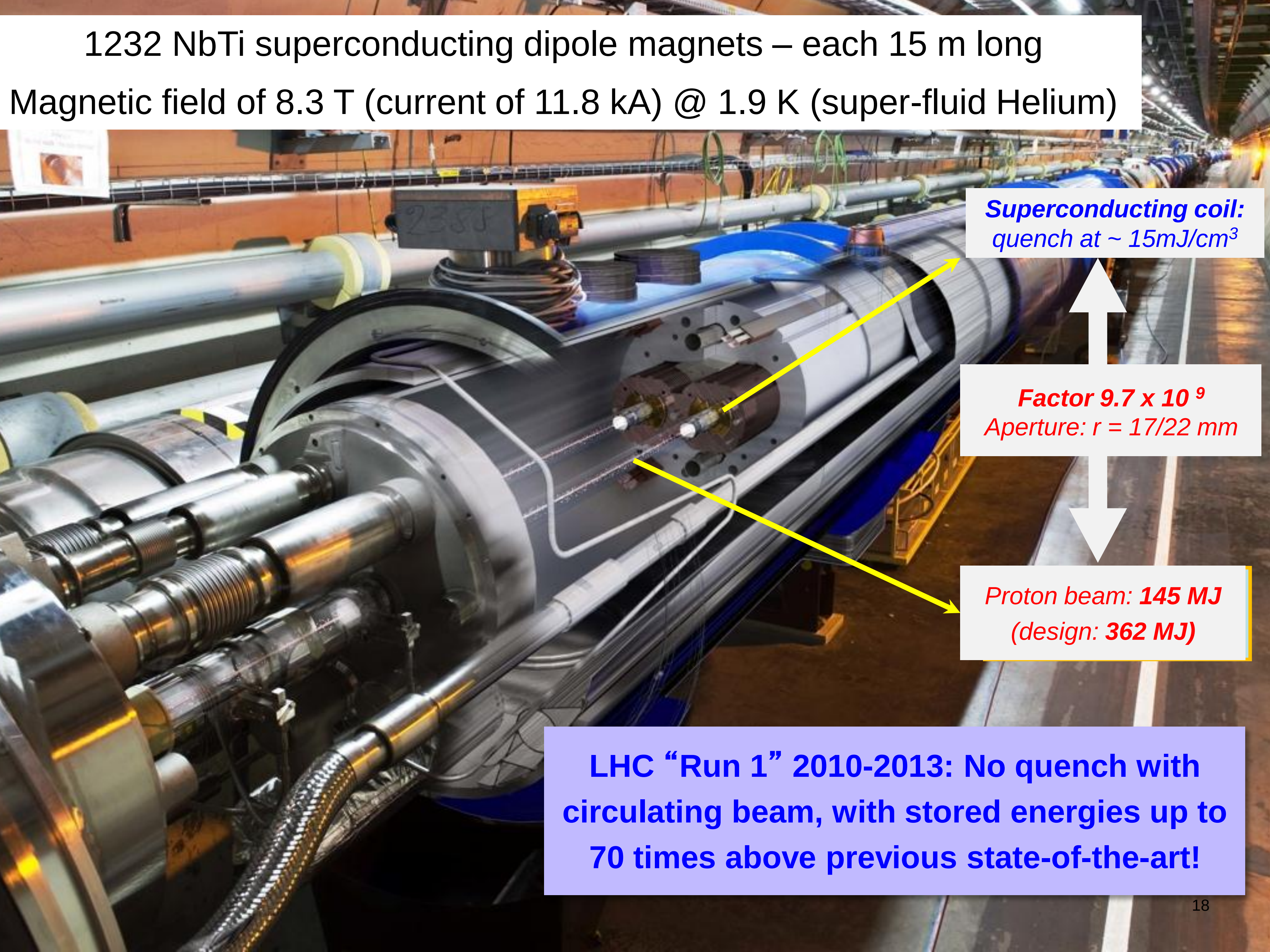
LHC energy evolution



Introduction to LHC

1232 NbTi superconducting dipole magnets – each 15 m long

Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)

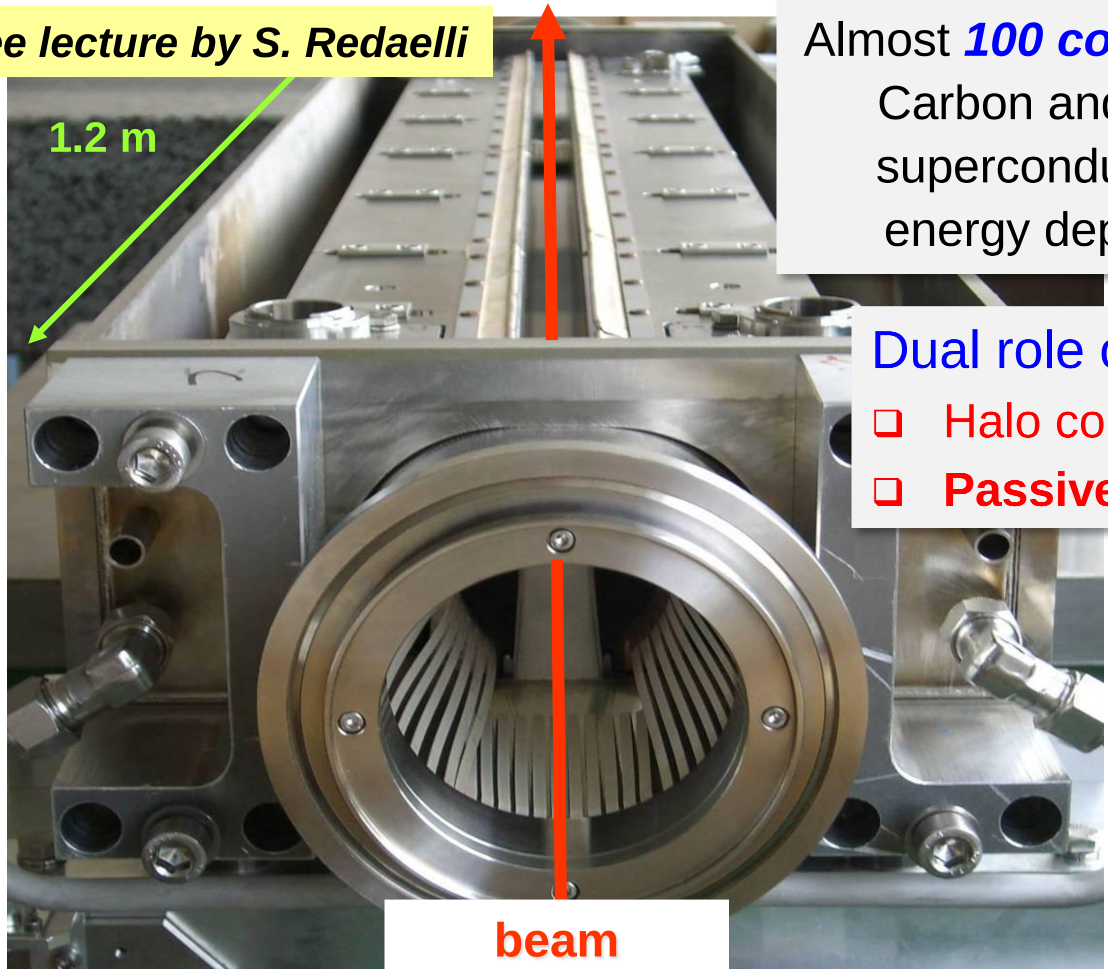


LHC “Run 1” 2010-2013: No quench with circulating beam, with stored energies up to 70 times above previous state-of-the-art!

Beam collimation (cleaning)

- The LHC requires a complex multi-stage collimation system to operate at high intensity.
  - *Previous hadron machines used collimators only for experimental background conditions.*

see lecture by S. Redaelli

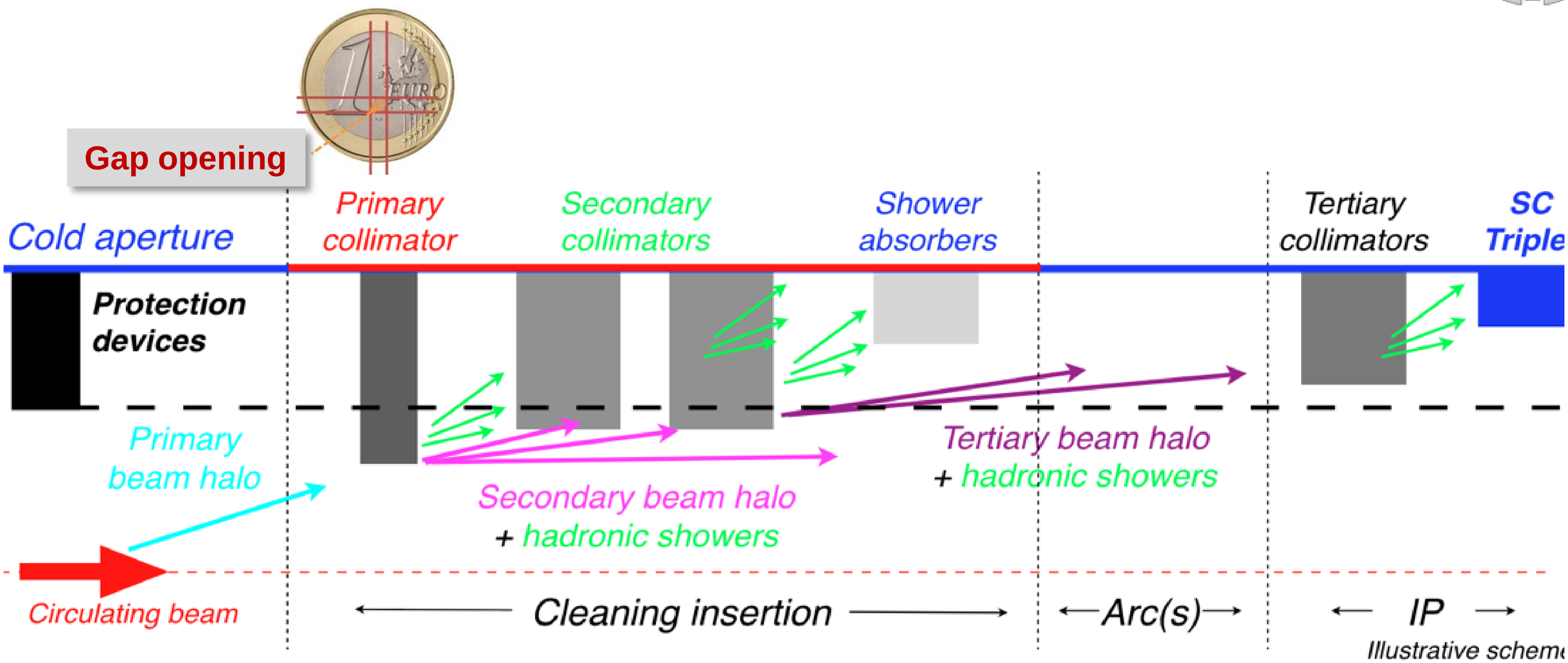


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

Dual role of collimators:

- Halo collimation (cleaning)
- **Passive protection** of the machine

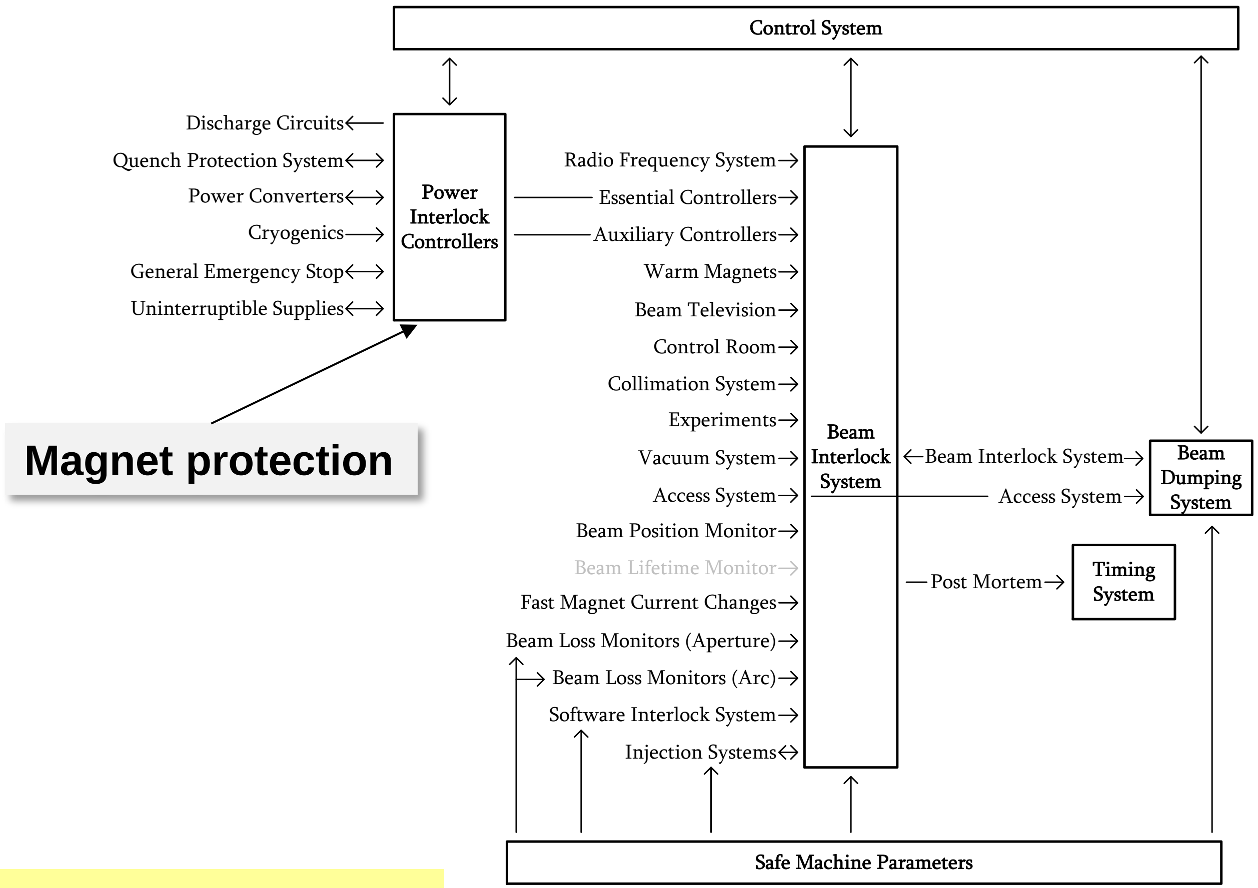
Collimation system



- To be able to absorb the energy of the 7 TeV proton, the LHC requires a multi-stage collimation system – primary, secondary, tertiary.
- The system worked perfectly so far – thanks to excellent beam stabilization and machine reproducibility – only one full collimation setup / year.
  - ~99.99% of the protons that were lost from the beam were intercepted.

MPS inputs

- The LHC beam interlock system (BIS) has 189 inputs from client systems (including injection).
- Behind each input that can be many individual tests / interlocks.

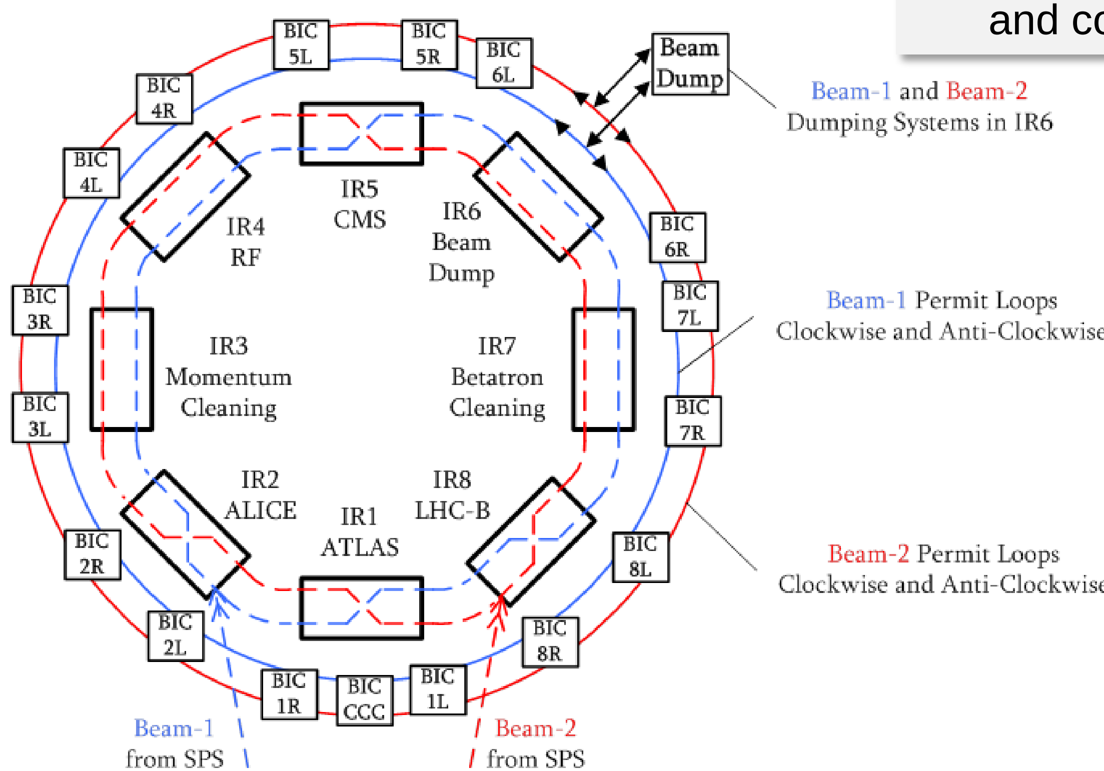


see lecture by R. Schmidt

Geographical BIS layout

see lecture by R. Schmidt

Loop signal propagation in clockwise and counter-clockwise directions



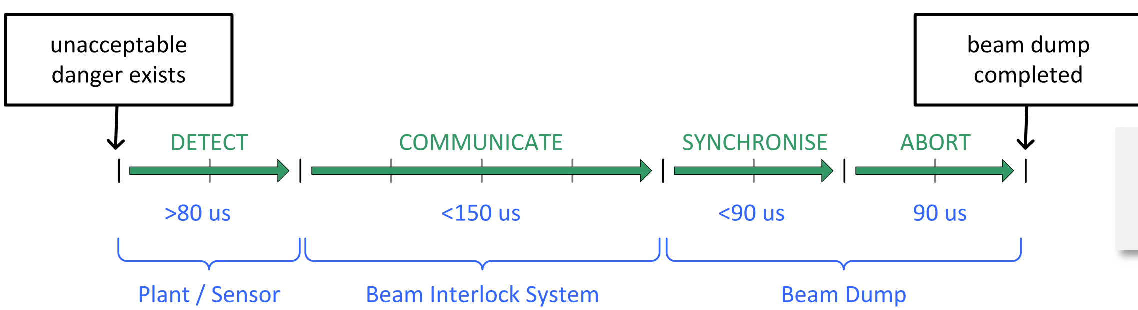
4 beam permit loops

2 permit loops / beam

Direct link to LHC injection and SPS extraction

→ no beam permit

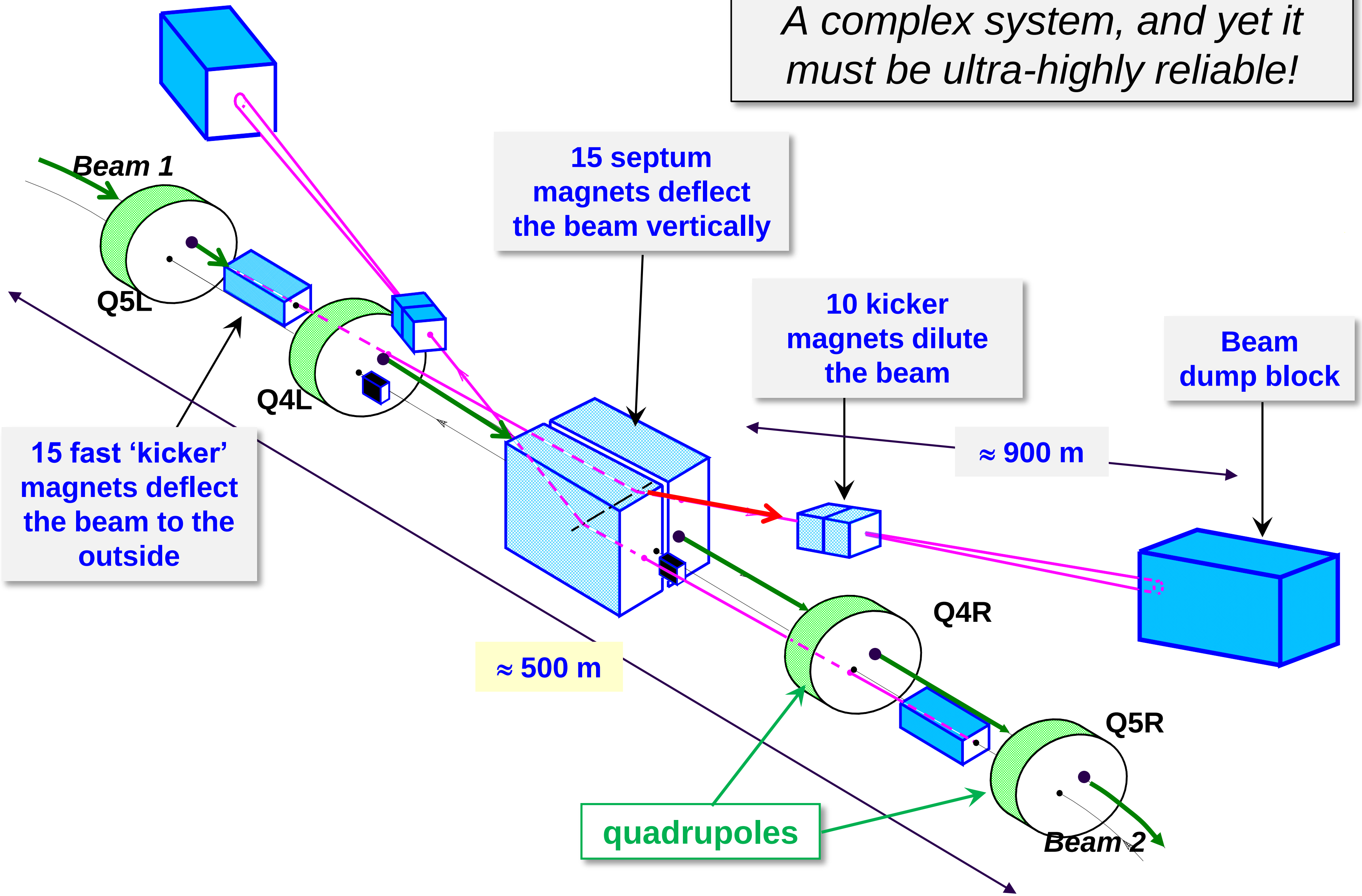
→ no injection/extraction



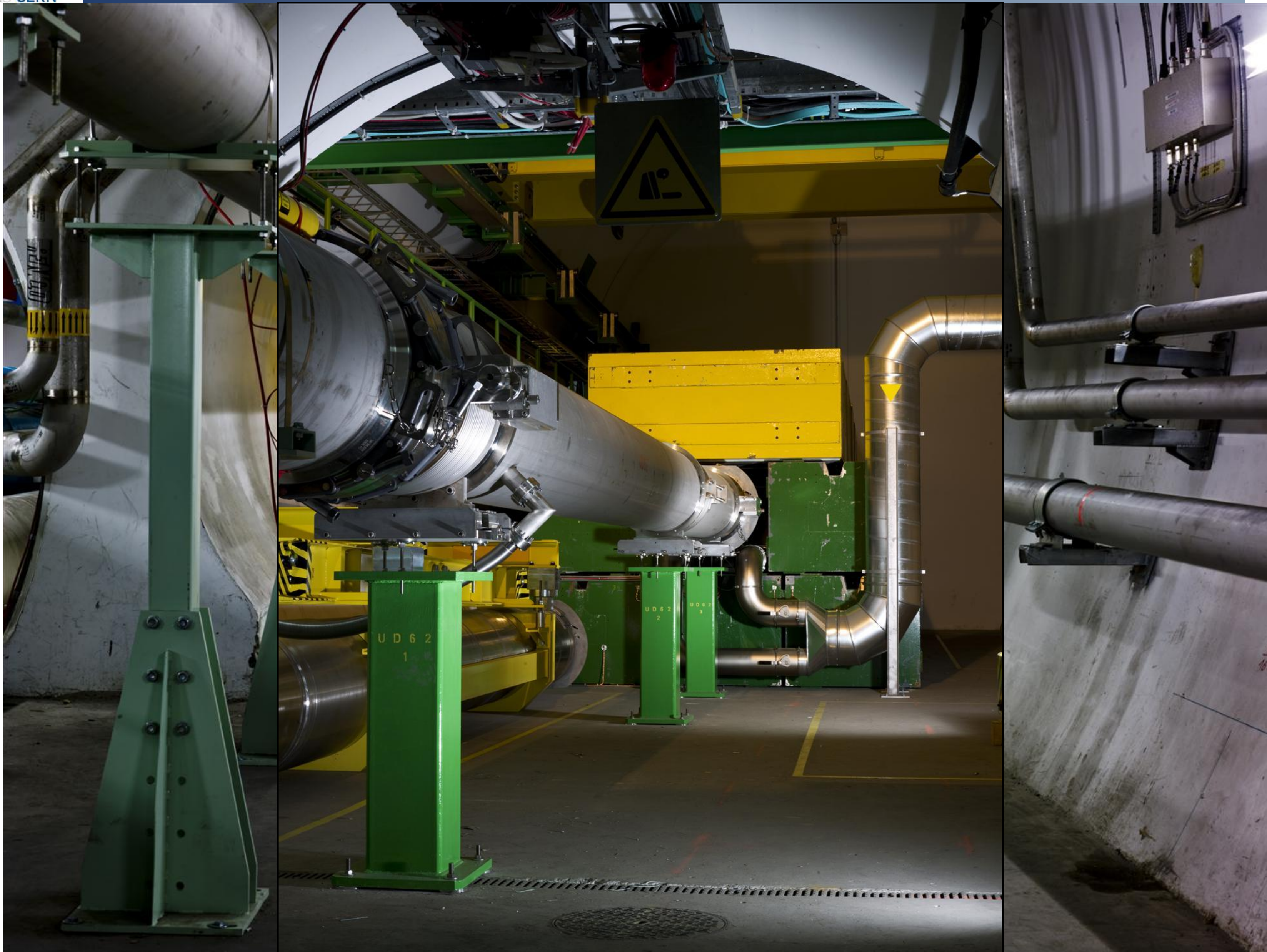
At the LHC the dump delay can reach ~3 turns – ~300 μs

LHC beam dumping system

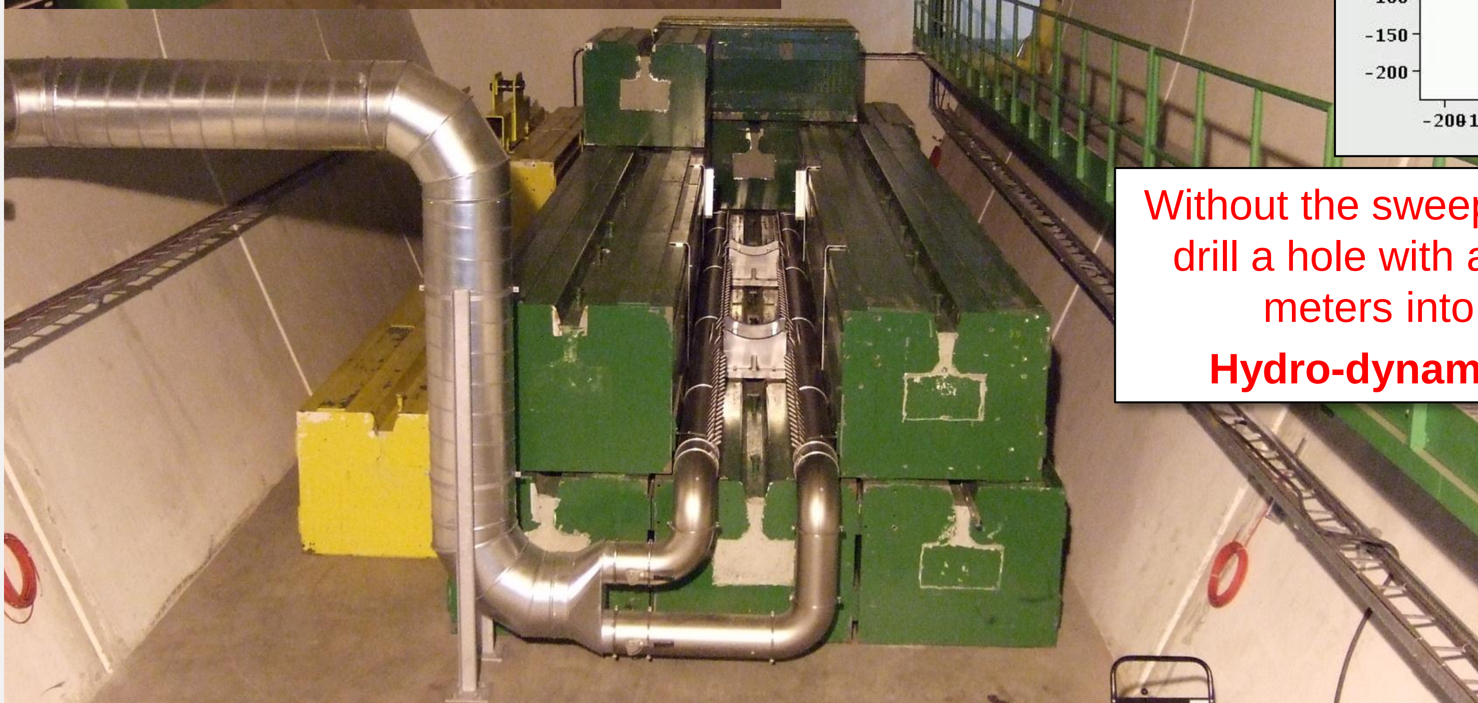
A complex system, and yet it must be ultra-highly reliable!



LHC dump line

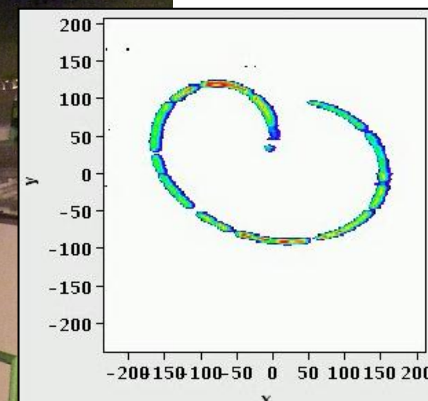


The LHC dump block



The dump block is the only LHC element capable of absorbing the nominal beam.

The beam is swept over dump surface to lower the power density.



Without the sweep the beam could drill a hole with a depth of a few meters into the block !

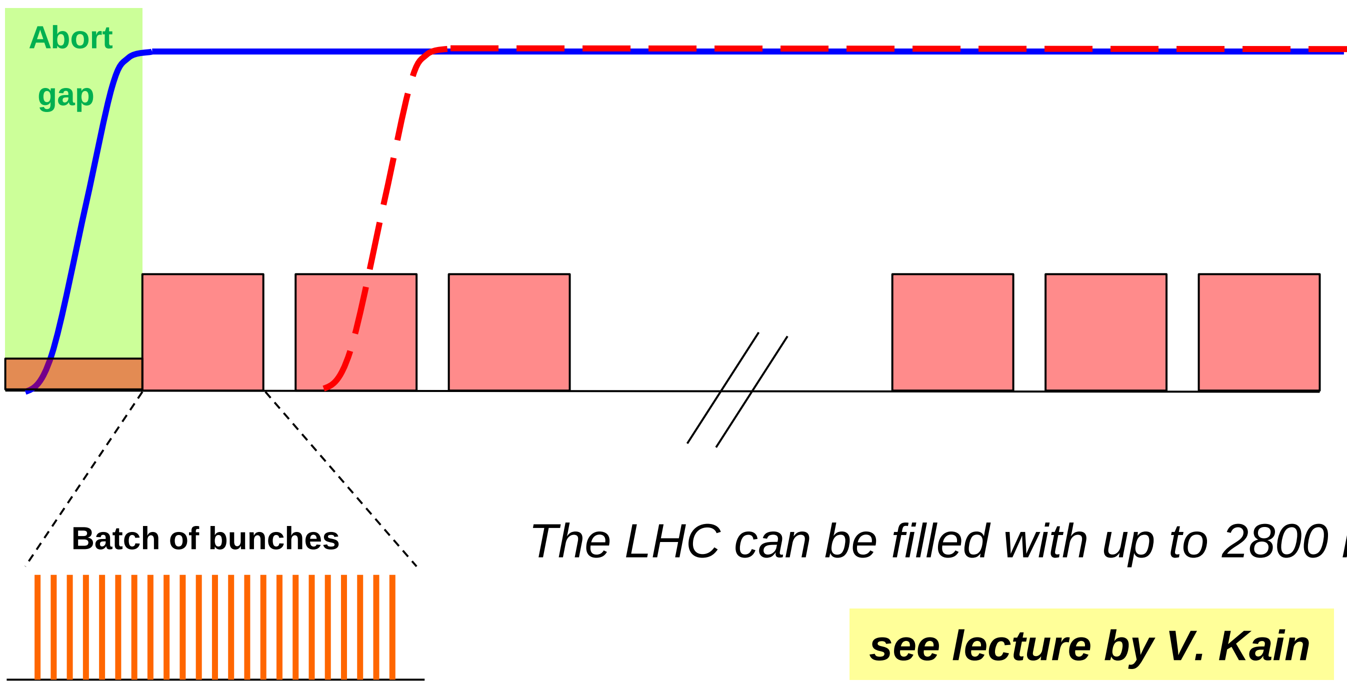
Hydro-dynamic tunnelling

25

Beam dump sychronization

- The beam dump must be accurately synchronized to the **beam abort gap** to avoid spreading beam across the aperture during the kicker rise-time.
- The 3 μs long **beam abort gap** must be … free of beam !
- Possible failure modes:
  - The abort gap fills with beams (RF fault, debunching, injection error),
  - The kicker synchronization fails,
  - A kicker fires spontaneously (not synchronized).

Asynchronous dump failure

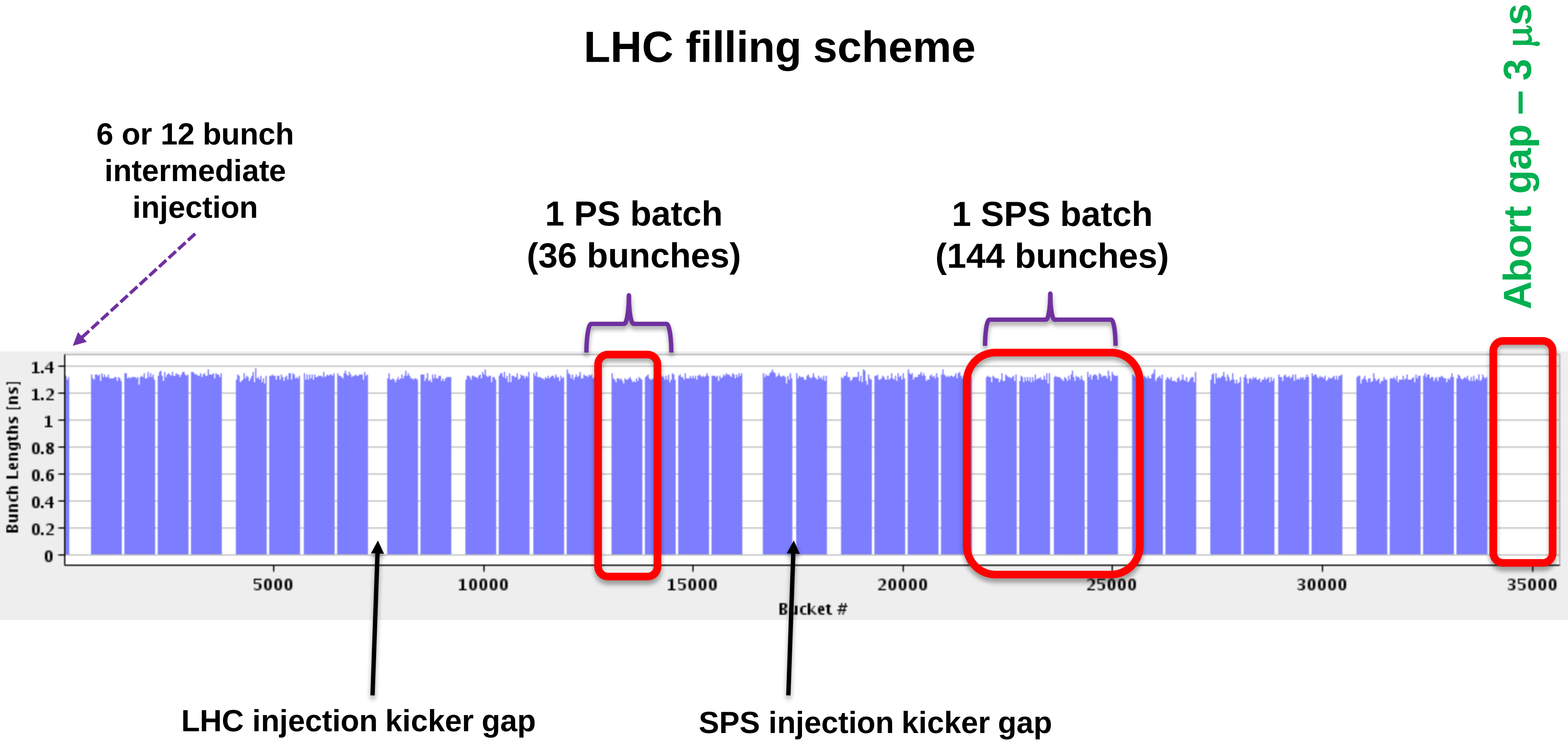


The LHC can be filled with up to 2800 bunches

see lecture by V. Kain

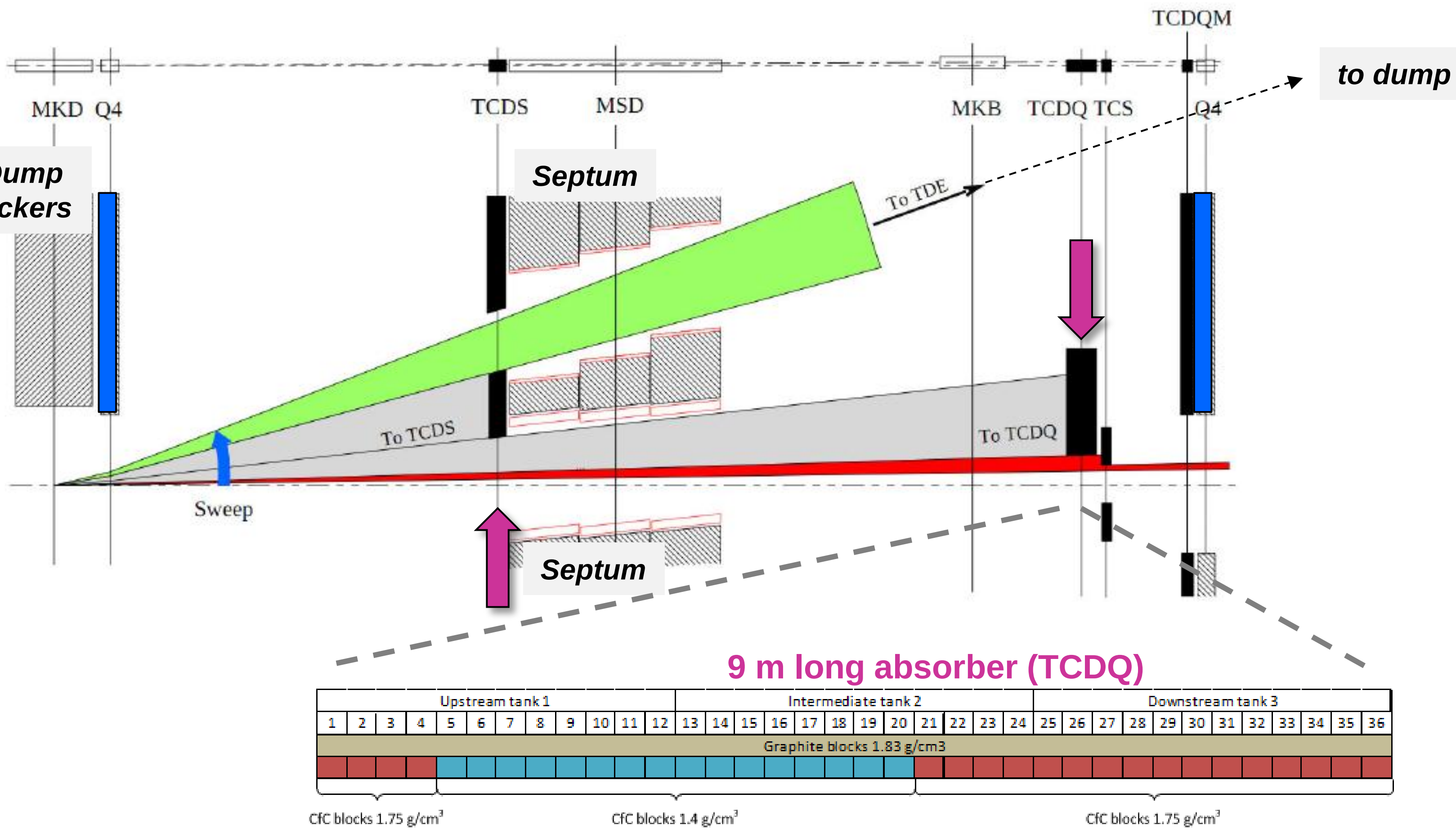
LHC filling and kicker synchronization

- Kickers magnets have to rise their field in the gaps between the circulating beam.
- The trigger and reference frequencies are generated by the RF system.



Asynchronous dump: passive protection

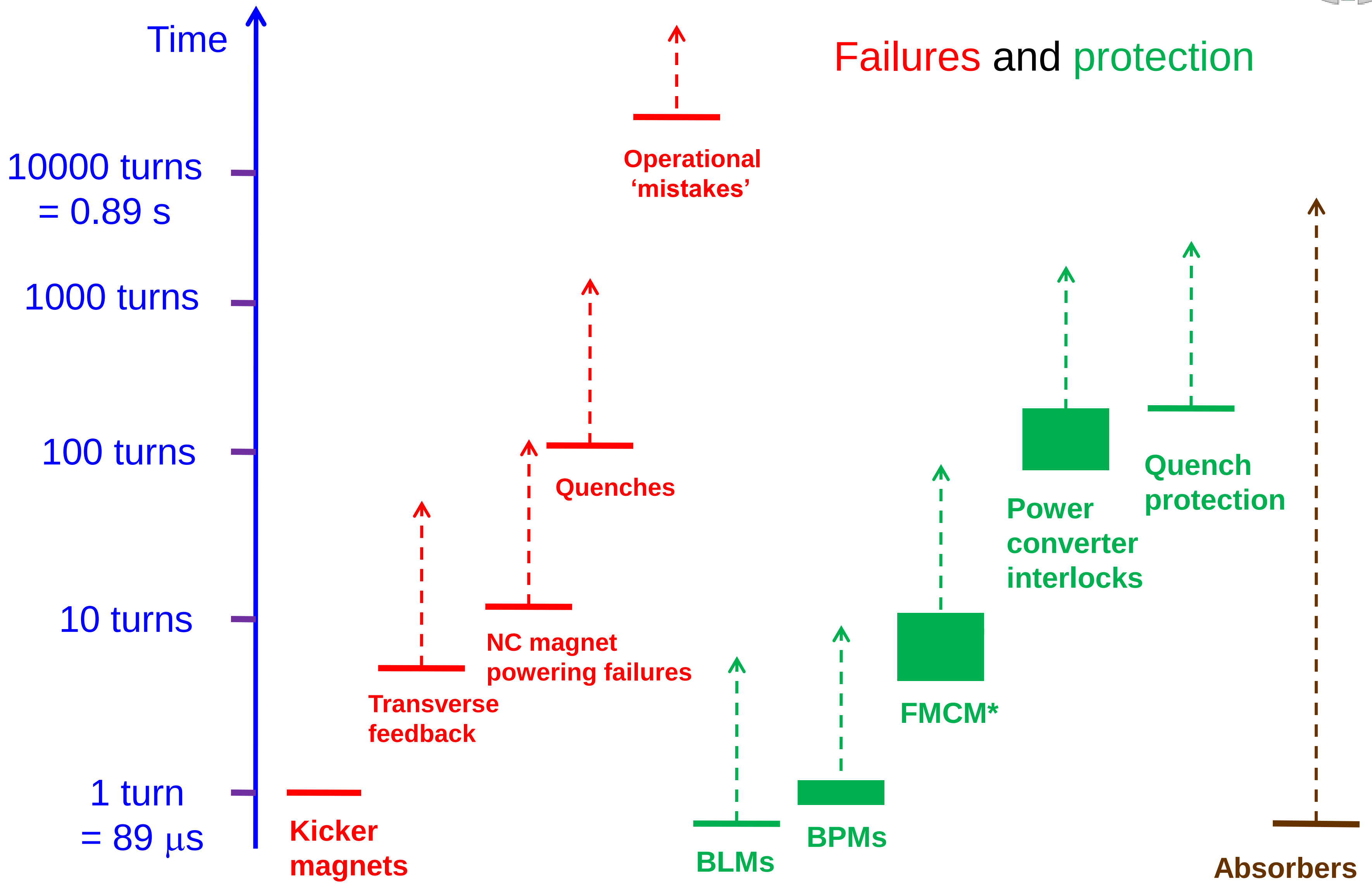
- Two large absorbers in front of the extraction septum (TCDS) and in front of the first SC magnet (TCDQ) protect the LHC against damage / quench from asynchronous dumps & beam in the abort gap.



Asynchronous dump: active protection

- The asynchronous dump is the '*ultimate*' unavoidable failure at the LHC – must to protect the machine **PASSIVELY**.
- Dump kicker powering, synchronization and triggering are designed to exclude out-of-synch triggers with high reliability.
  - *A spontaneous trigger of a switch expected at a rate ~ 1 / year.*
  - *So far none has been observed during high intensity operation (1 with a pilot bunch), but the system operated at reduce high voltage (4 TeV instead of 7 TeV).*
- Injection kicker synchronization → no injection into the abort gap.
  - *Link between dump and injection system.*
- Abort gap monitoring (using synchrotron light) and abort gap cleaning.
  - *Cleaning with transverse feedback system (excitation of the bunch positions corresponding to the abort gap → collimators).*

Failure timescales @ LHC



* *FMCM: Fast Magnet Current change Monitor for fast detection of powering failures*

If it does not work

- In case the operator request a beam dump trigger and it does not work…. Nobody wants to be on that shift !
  - We have foreseen emergency actions (depends on why it did not work).
  - Only for dumps that are initiated by the operation crew !

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LHC Project Document No.
LHC-OP-MPS-000x v1.0

CERN Div./Group or Supplier/Contractor Document No.
BE/OP/LHC/MPP

EDMS Document No.
1166480

Date: 2012-03-26

MPS Procedure

THE LHC MACHINE PROTECTION SYSTEM

PROCEDURE IN CASE OF NON-WORKING DUMP TRIGGER

Abstract

This document describes the procedure that should be followed by the operations crew in case the programmed beam dump does not work.

Introduction to LHC

Masking

Commissioning

Intensity ramp up

Beam losses

Machine protection diagnostics & software

Availability

Conclusions

Masking – the safe beam concept

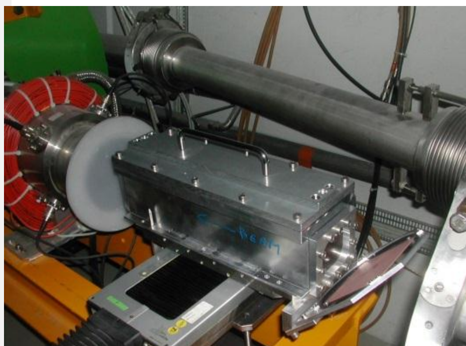
- Already at the design phase of the LHC MPS the need of masking interlocks in certain phases was recognized.
  - *Flexibility for commissioning and setting up.*
- To avoid masking interlocks by raising thresholds, opening tolerances for many components (risk of errors during the reversal), the concept of **Safe Beam** was introduced.
  - A safe beam should not be able to damage accelerator components.
  - The corresponding intensity limit depends on the beam energy (and emittance). It also depends on the material !
    - But a Safe Beam may quench magnets!
    - The Safe Beam must be defined for a reference material: Copper is used for the LHC.

see lectures by A. Bertarelli, V. Kain & R. Schmidt

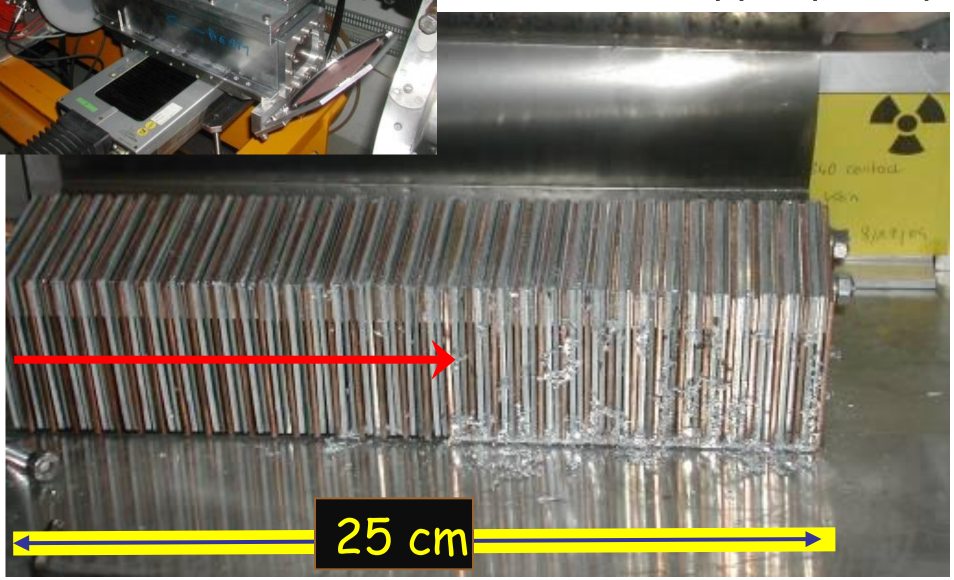
SPS experiment : damage at 450 GeV

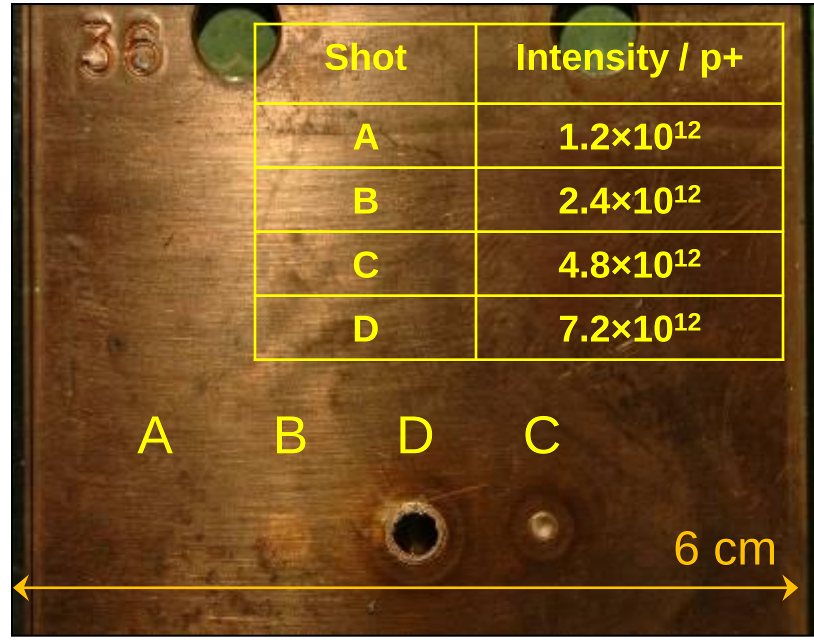
Controlled SPS experiment / protons.

- Energy 450 GeV,
- Beam area $\sigma_x \times \sigma_y = 1.1 \times 0.6\ \text{mm}^2$,
- Damage limit for copper at 2×10^{12} p.
- No damage to stainless steel.



Special target (sandwich of Tin, Steel, Copper plates)





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

- Damage onset is ~200 kJ, < 0.1 % of a nominal LHC beam.
- Impact D: ≈ 1/3 of a nominal LHC injection.

Safe Beam Flag for LHC

- The simulations predicted the scaling law with beam energy E:
  - *Larger energy deposition → scaling ~ 1/E,*
  - *Smaller emittance → beam area ~ 1/E,*
  - *Longer showers (~ log E) → some dilution.*

$$\Rightarrow \quad I_{SB}(E) = I_{SB}^{450\mathrm{GeV}}\left(\frac{450\,\mathrm{GeV}}{E}\right)^{1.7}$$

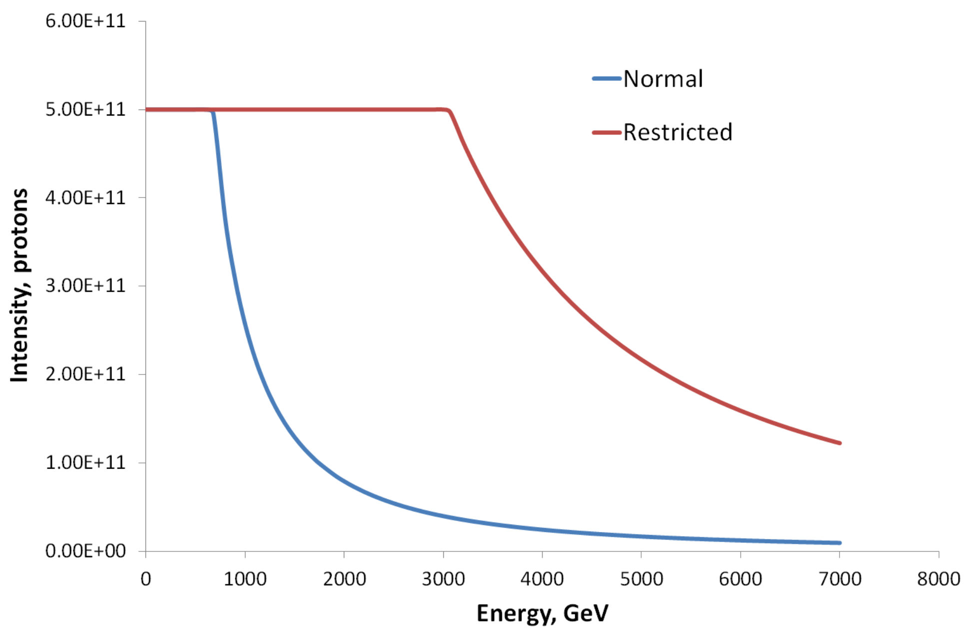
- This equation was implemented in a dedicated Safe Machine System (SMP). The SMP system is connected to reliable BCTs and energy sources (based on the dipole fields – 4-fold redundancy).
  - *Generates the **SBF (Setup Beam Flag)** → distributed to the BIS.*
  - SBF true = setup beam → 'maskable' channels can be masked.
  - SBF false = unsafe beam → no channel may be masked.
- The beam interlock system is configured to allow masking certain classes of interlocks (maskable) when the SBF is true.

And then operation starts…

- When LHC operation started, it was realized setting up the machine accurately required nominal bunch intensities N ~ 10^{11} p/b.
  - *Quality of the BPM measurements – beam instrumentation !*
- But the SBF limit is below that value at 4 TeV (3×10^{10} p/b) and 7 TeV (10^{10} p/b). To provide sufficient commissioning flexibility while maintaining a good level of safety, we had to be able to relax the limit.
  - ***Defined a relaxed limit*** *(another equation), but with restricted usage.*
  - *Accepted a limited increase of the risk in order to improve setup quality.*

Only MPS experts can switch between the SBF equations

SBF was rename **Setup** (and **not Safe**) Beam Flag since there is a residual risk of damage!



Introduction to LHC

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Organization at LHC

- The MPS activities of the LHC were organized since 2000 inside a Machine Protection Working Group (later changed to Machine Protection Panel - MPP).
  - *Design and follow up of implementation, issues and performance,*
  - *Collaboration of all groups concerned by MPS.*

- With the startup approaching an *executive body* was created, the *restricted MPP* (*rMPP*) with representatives of the core MPS system.

- The rMPP takes decisions related to MPS (example : BLM threshold changes) and steers the intensity ramp up of the machine.
  - Recommendations are submitted to the CERN management.
  - In general the recommendations are accepted.

Commissioning - procedures

- Before the machine startup, procedures were developed for the commissioning of the machine protection sub-systems.
- The procedures contain test descriptions and frequency of tests (after stop or intervention).
- The procedures were translated into a series of individual tests to be performed on the machine:
  - *Without beam,*
  - *With beam – if required for different intensity steps.*

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LHC Project Document No.
AB-NOTE-07-01
CERN Div./Group or Supplier/Contractor Document No.
AB/CO/MI
EDMS Document No.
889281

Date: 10 JANUARY 2009

MPS Commissioning Procedure

THE COMMISSIONING OF THE LHC MACHINE PROTECTION SYSTEM

MPS ASPECTS OF THE BEAM INTERLOCK SYSTEM COMMISSIONING

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LHC Project Document
LHC-OP-MPS-
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MPS Commissioning Procedure

THE COMMISSIONING OF THE LHC MACHINE PROTECTION SYSTEM

MPS ASPECTS OF THE POWERING INTERLOCK SYSTEM COMMISSIONING

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LHC Project Document No.
LHC-OP-MPS-0003.v3
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889343

Date: 2009-03-25

MPS Commissioning Procedure

THE COMMISSIONING OF THE LHC MACHINE PROTECTION SYSTEM

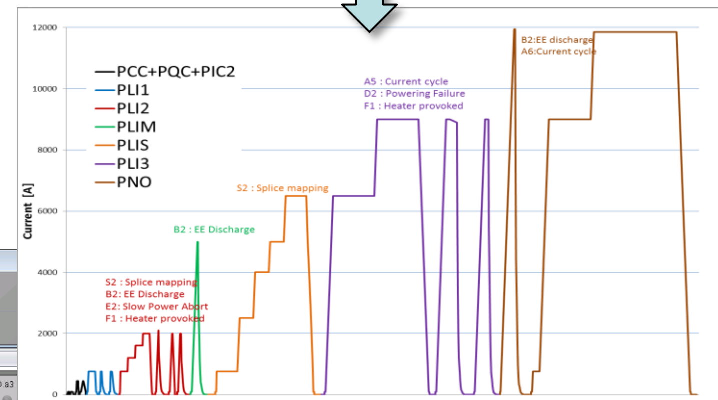
MPS ASPECTS OF THE INJECTION PROTECTION SYSTEM COMMISSIONING

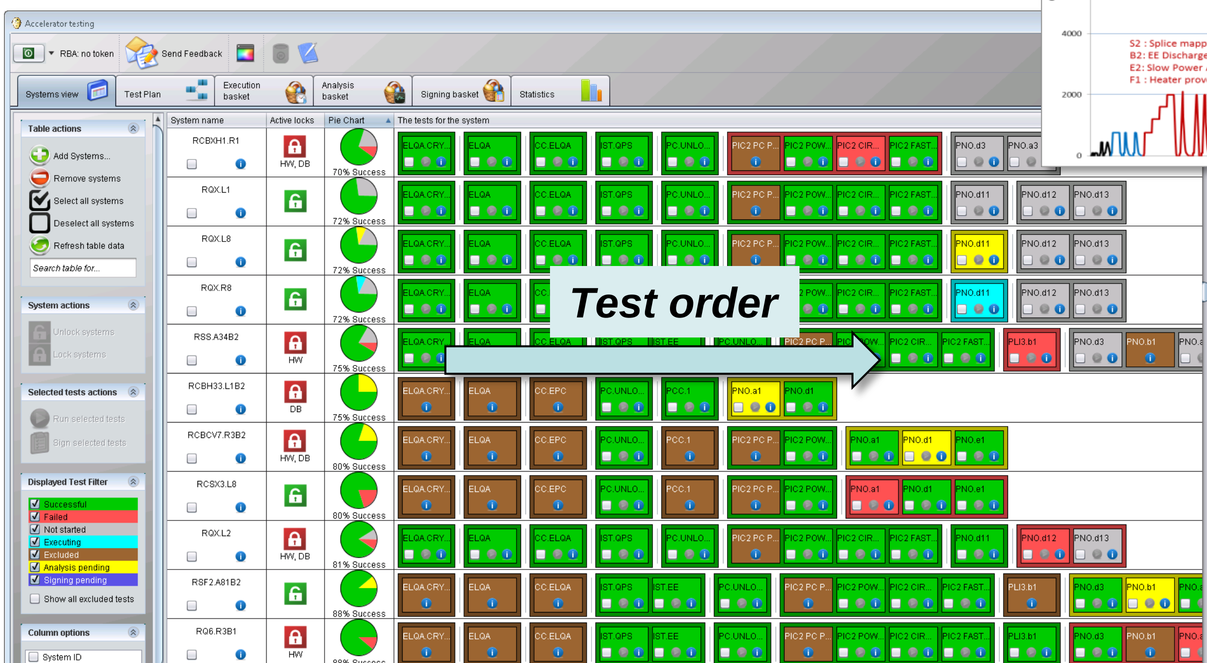
Tracking

- The tests are currently documented and tracked on a WEB page.
- One MPS expert is in charge of checking that all tests required for a certain machine phase are have been executed by the experts.
  - *Note that it is generally the system expert that executes the tests for his system – no independence.*
- This simple mechanism must & will be improved. In fact the new concept exists but could not yet be implemented.

Automated powering tests

- The powering tests that are used to commission the LHC super-conducting magnet system are a good example of how to track and automate test.
  - *Predefined and agreed test sequences,*
  - *Automated execution of the tests that are ready,*
  - *Test sequence blocked until tests are signed,*
  - *Tracking of results – one cannot forget a step!*





encoding in a test sequence

1 block = 1 test

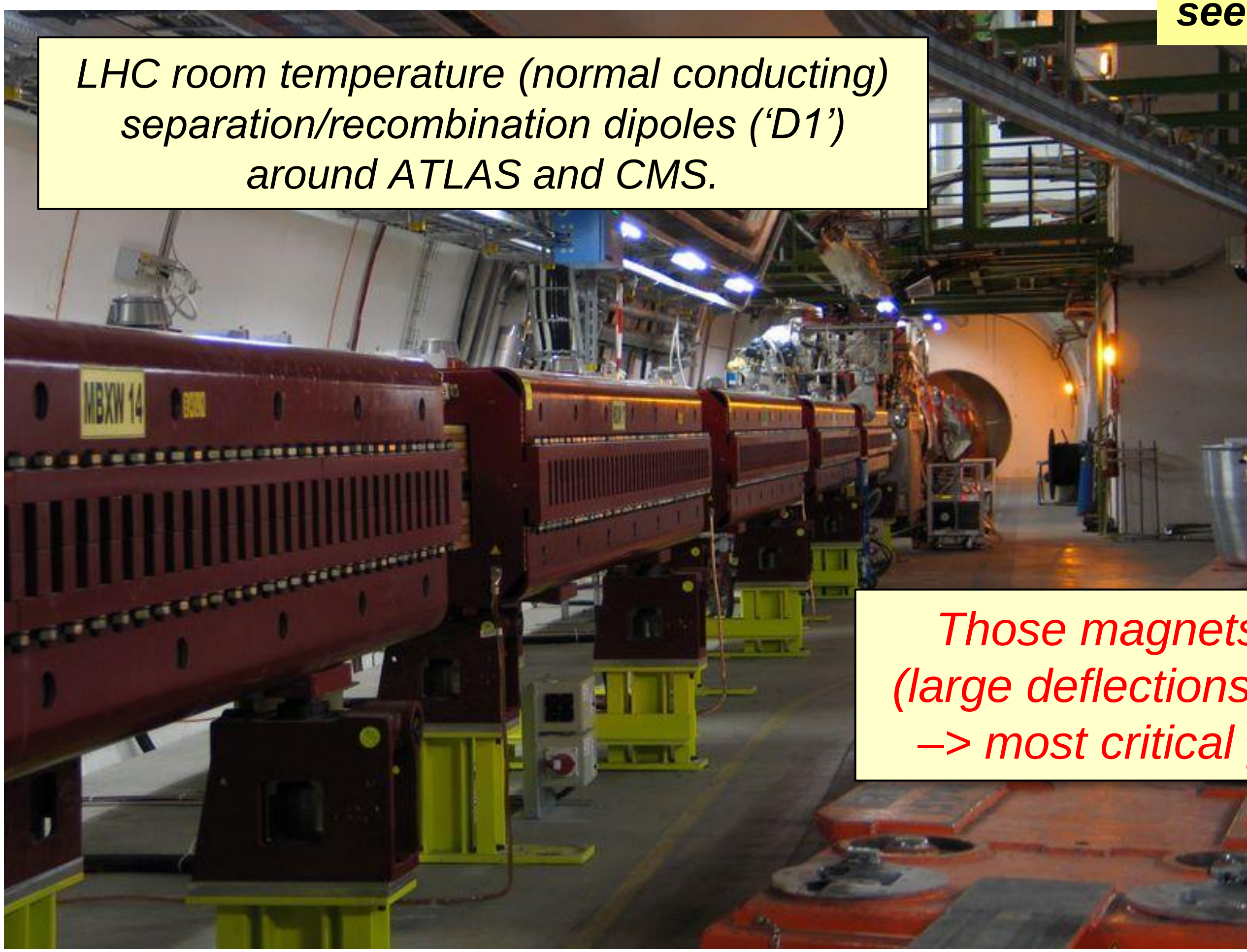
This is where we want to implement for MPS soon…

Commissioning example @ LHC

- We take the example of some of the few normal conduction magnets of the LHC. Those magnets are used to re-combine the 2 LHC beams near an experiment (from two to a single vacuum chamber).

see lecture by R. Schmidt

LHC room temperature (normal conducting) separation/recombination dipoles ('D1') around ATLAS and CMS.

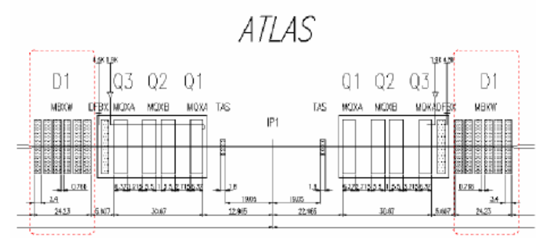


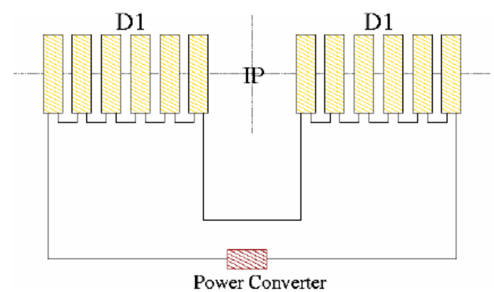
Those magnets are very strong (large deflections) and they are fast –> most critical powering failure !

Commissioning example @ LHC (2)

- Failure simulation.
  - *12 magnets are powered in series.*
  - *Large betatron function when squeezed (β > 2000 m) → large orbit changes.*
  - *Short time constant τ = 2.5 seconds (B is the magnetic field):*

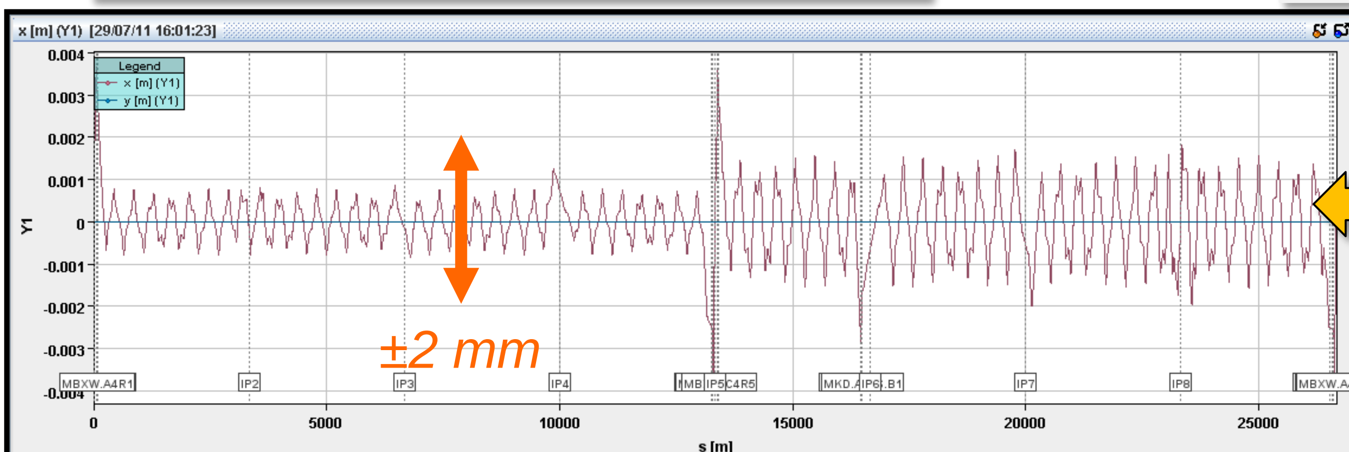
$$B(t) = B_0 e^{-t/\tau}$$





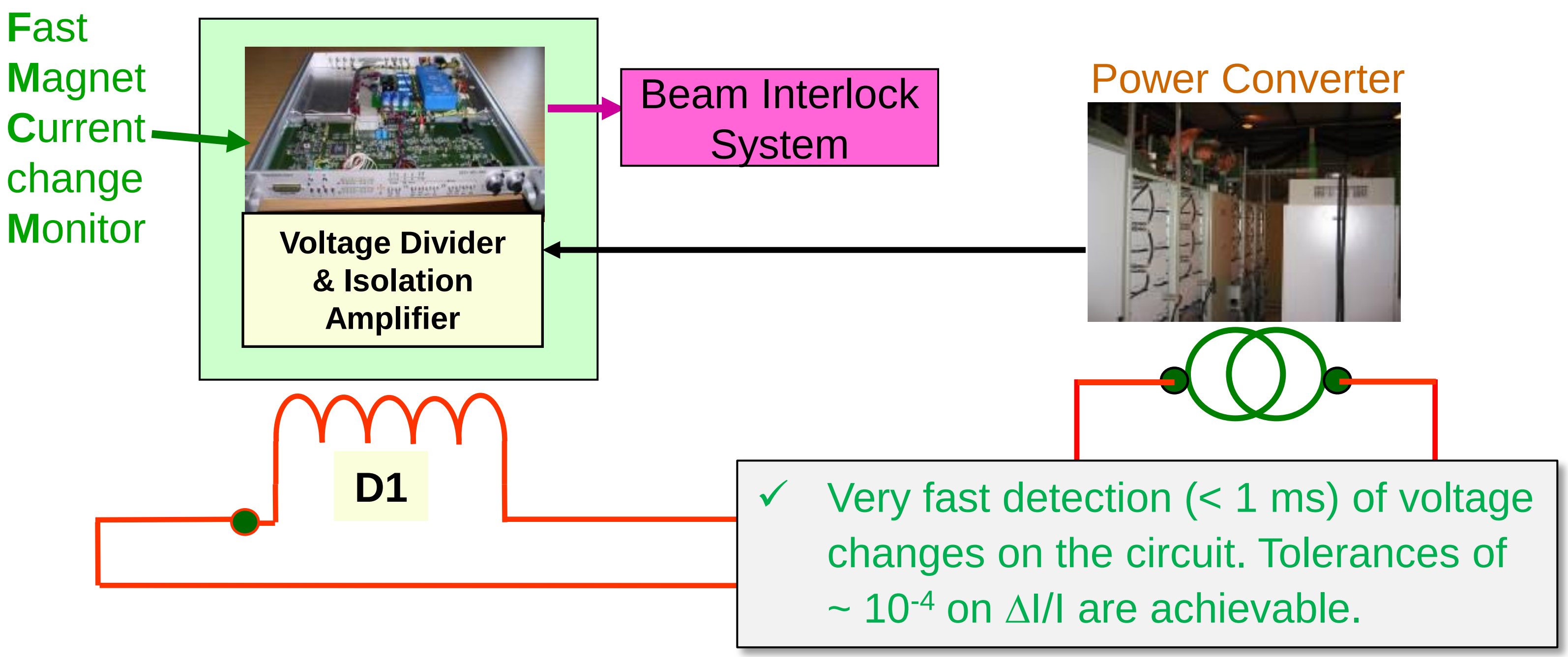
*Simulated orbit change along the LHC ring a few **milliseconds** after failure.*

LHC collimator opening



Commissioning example @ LHC (3)

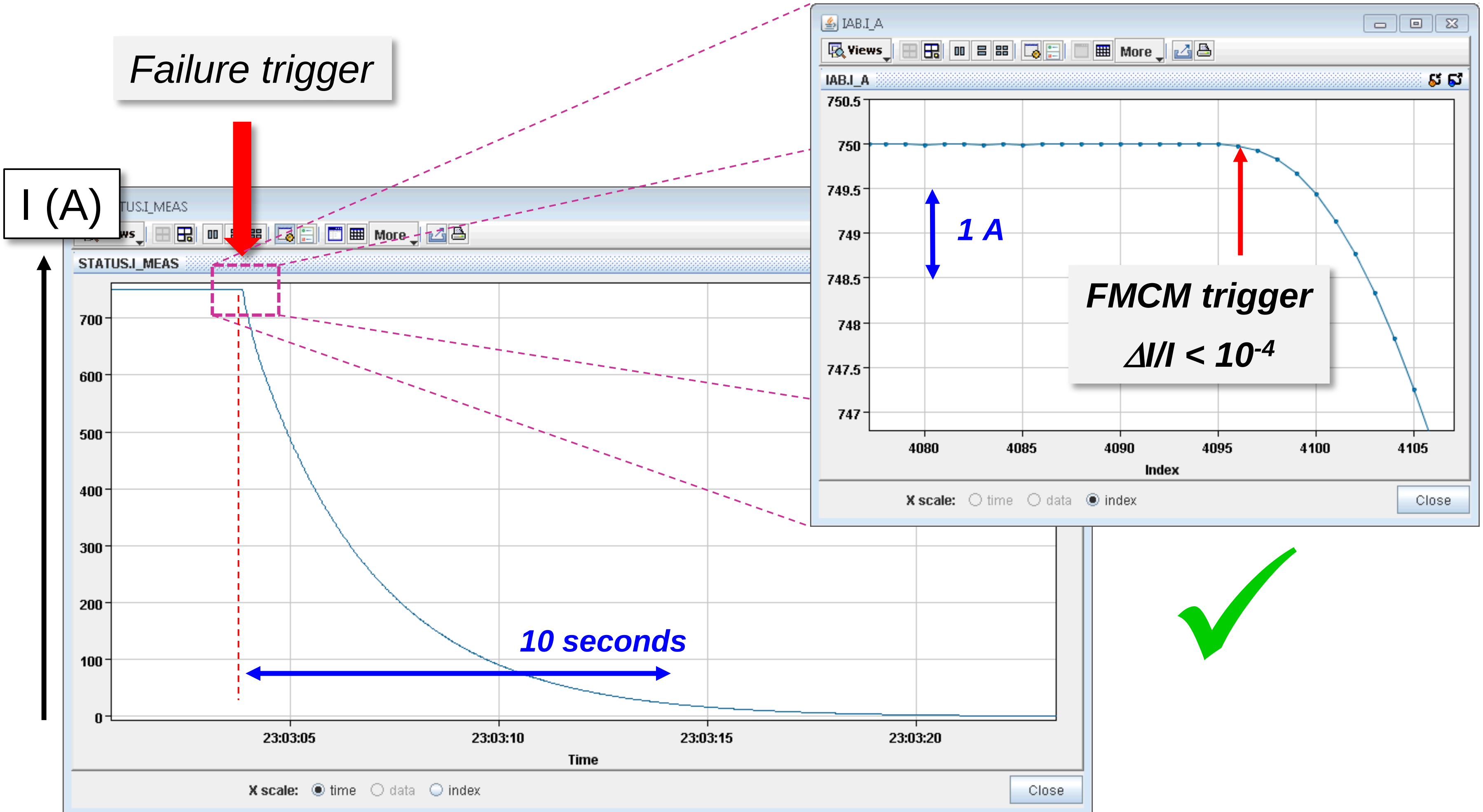
- The failure simulations indicated an absence of redundancy (only beam loss monitors) and the need for very short reaction times for BLMs → we wanted an extra-layer of protection at the equipment level.
- This triggered the development of so-called FMCMs (Fast Magnet Current change Monitor) that provide protection against fast magnet current changes after powering failures - CERN - DESY collaboration.



✓ Very fast detection (< 1 ms) of voltage changes on the circuit. Tolerances of ~ 10^{-4} on $\Delta I/I$ are achievable.

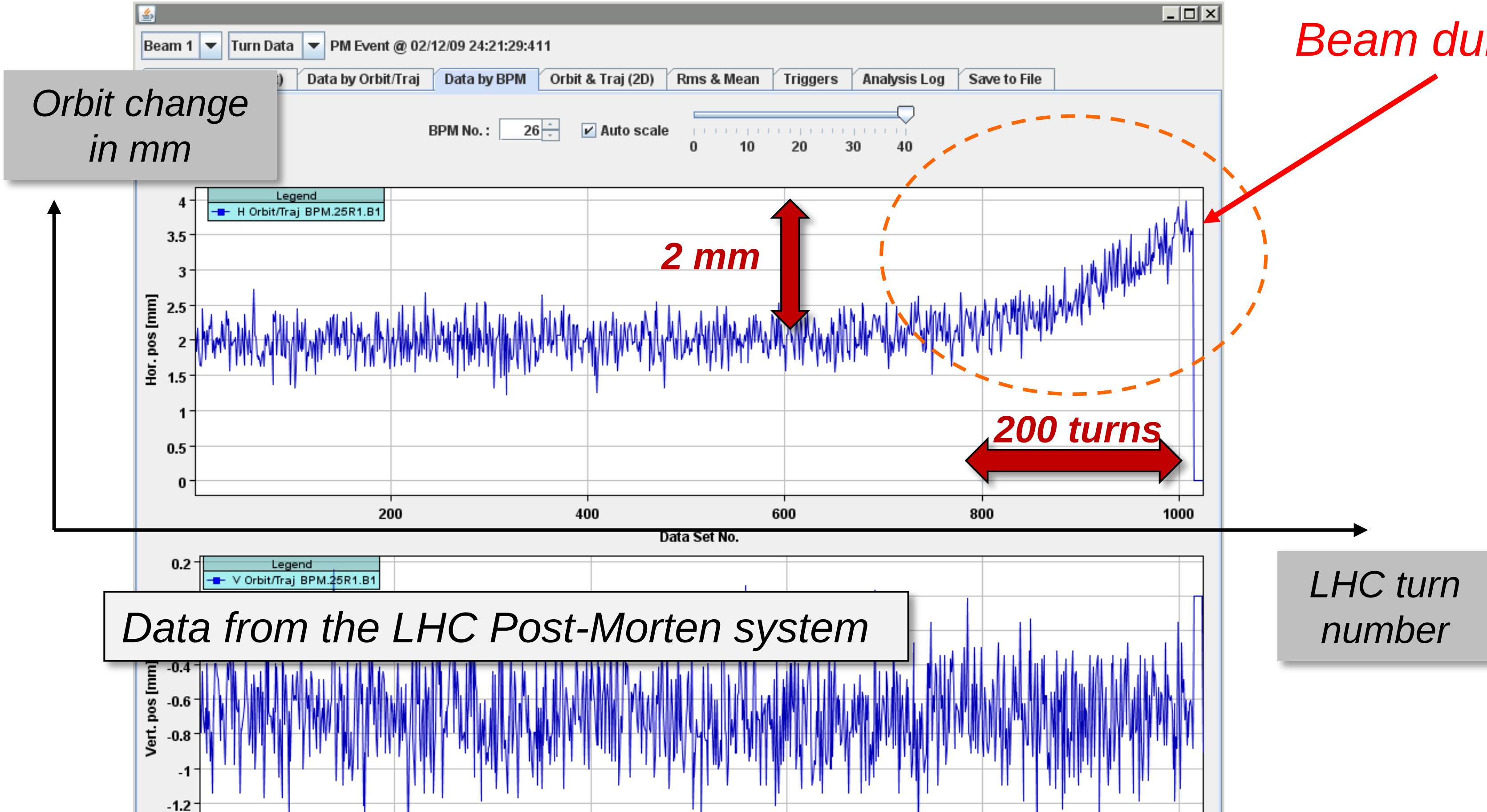
Commissioning example @ LHC (4)

- Test failure of PC and FMCM reaction – **NO BEAM.**
  - *Switch off D1 PC – simulated failure.*



Commissioning example @ LHC (5)

- Test with real beam – FMCM masked out.
  - *Low intensity ('safe') test beam.*
  - *Switch off D1 PC – simulated failure.*
  - *Beams dumped by the LHC BLMs when beams hit the collimators.*

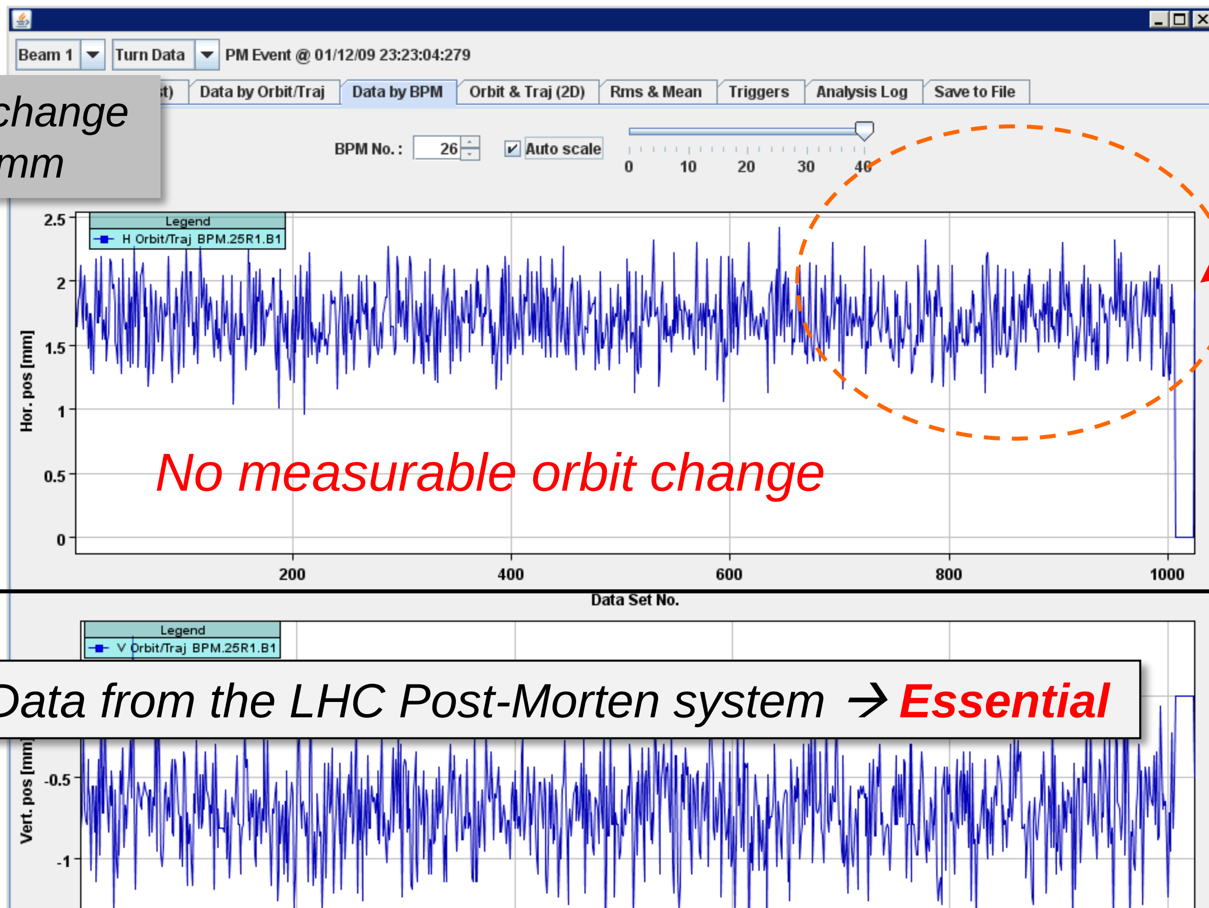


- Test with real beam – with FMCM active
  - *Low intensity ('safe') test beam.*
  - *Switch off D1 PC – simulated failure.*
  - *Beam dumped by FMCM.*

✔

Orbit change in mm

Beam dump !

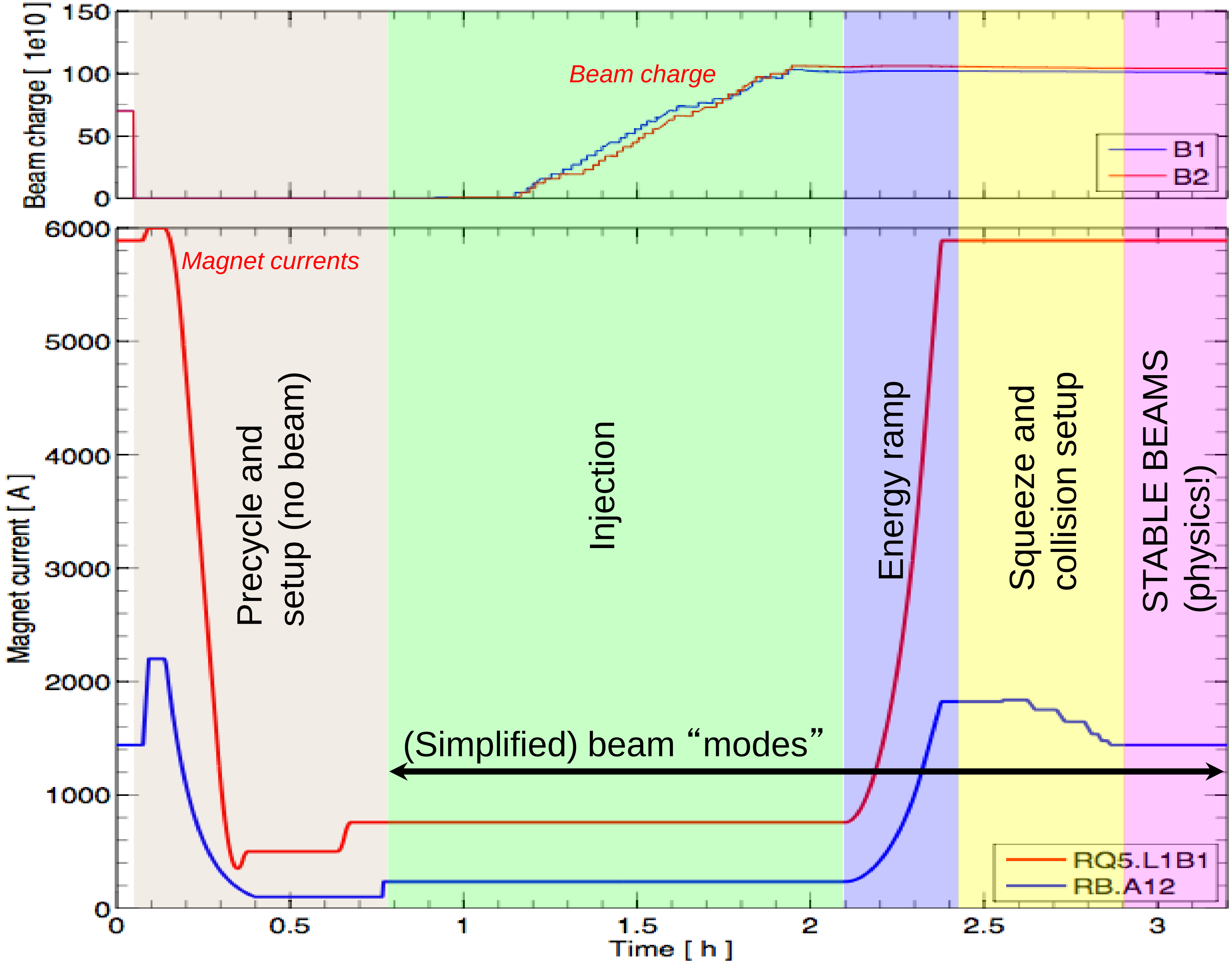


No measurable orbit change

*Data from the LHC Post-Morten system → **Essential***

LHC turn number

LHC operational cycle (in 2010)



Beam commissioning sequence

- First turn, CO, capture
- 450 GeV
- Ramp
- Squeeze & collisions
- Optics corrections
- MPS commissioning
- Injection setup & validation
- Collimation setup & validation
- Stable collisions and intensity ramp up

Injection

- Transfer line setup
- Injection steering
- Injection protection
- Transfer line collimation
- Injection protection validation

Ring collimation

- Collimation 450 GeV
- Ramp settings
- Collimation 6.5 TeV
- Collimator setup squeeze & collisions
- Loss maps

Beam dump

- Setup 450 GeV
- Setup 6.5 TeV
- Dump protection
- Dump protection validation

- Machine protection activities are an integral part of LHC beam commissioning.
  - *~25% of the commissioning time for MPS related activities.*
  - *Total low intensity commissioning after a long shutdown lasts between 2 and 3 months !*

Setup quality assurance

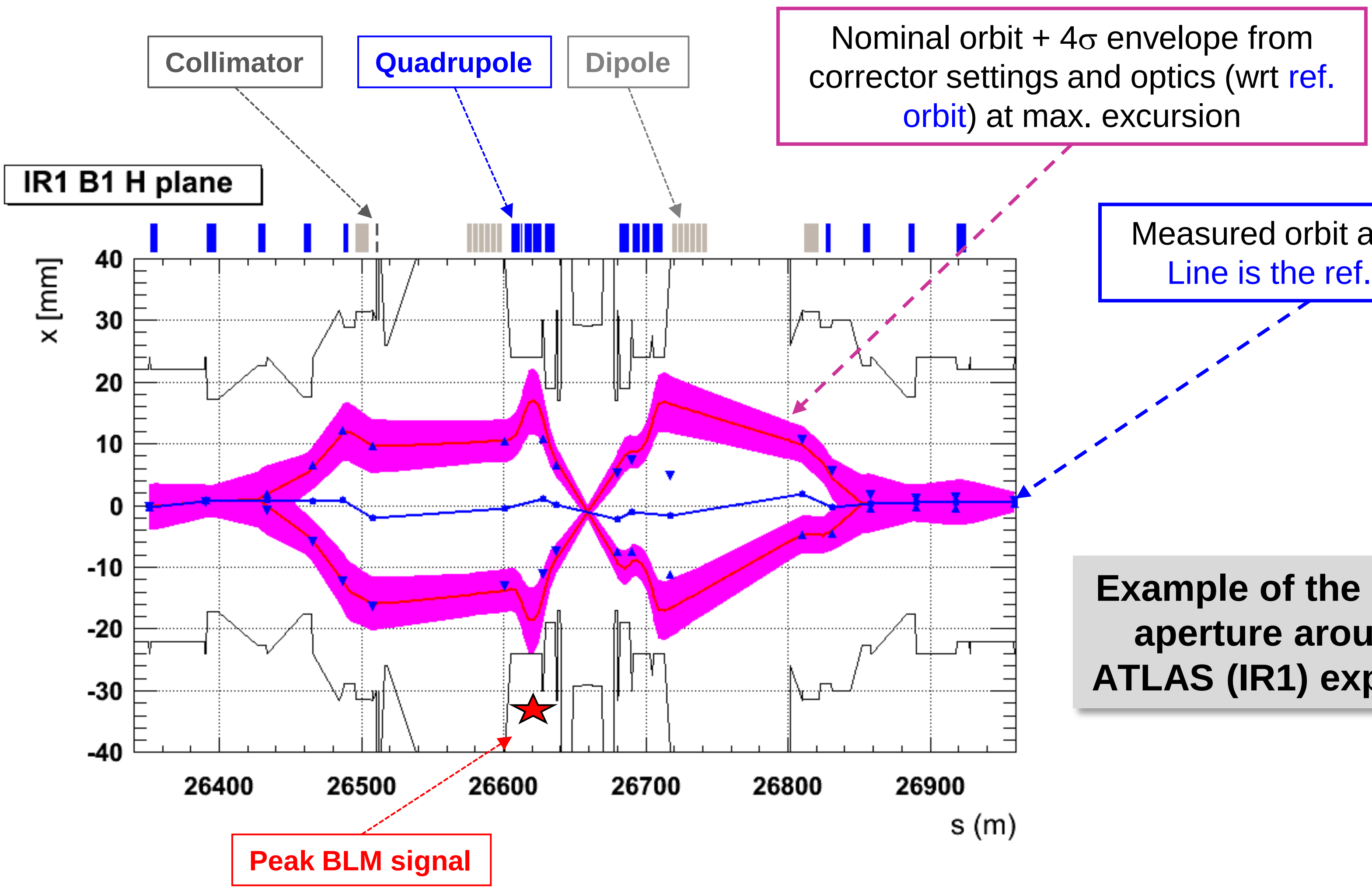
- Protecting the aperture passively with collimators and absorbers is a key ingredient for operating the LHC safely at high intensity.
  - *All failures affecting the machine on a global scale (global orbit, optics, emittance etc perturbation) should be intercepted by a protection device.*
  - *Dual role of collimators for beam cleaning (→ performance and quench prevention) and MP (passive protection).*

- A proper LHC machine setting up involves:
  - *A well corrected orbit,*
  - *A well corrected optics (betatron functions),*
  - *A good knowledge of the aperture bottlenecks (after orbit and optics correction).*
    - Measurement of the global aperture,
    - Measurement of critical local apertures (for example around the experiments).

All along the machine cycle – from injection to collisions

Local aperture measurement

- The primary collimator is used to define a clear edge of the beam (4σ).
- The beam is scanned until losses appear locally.

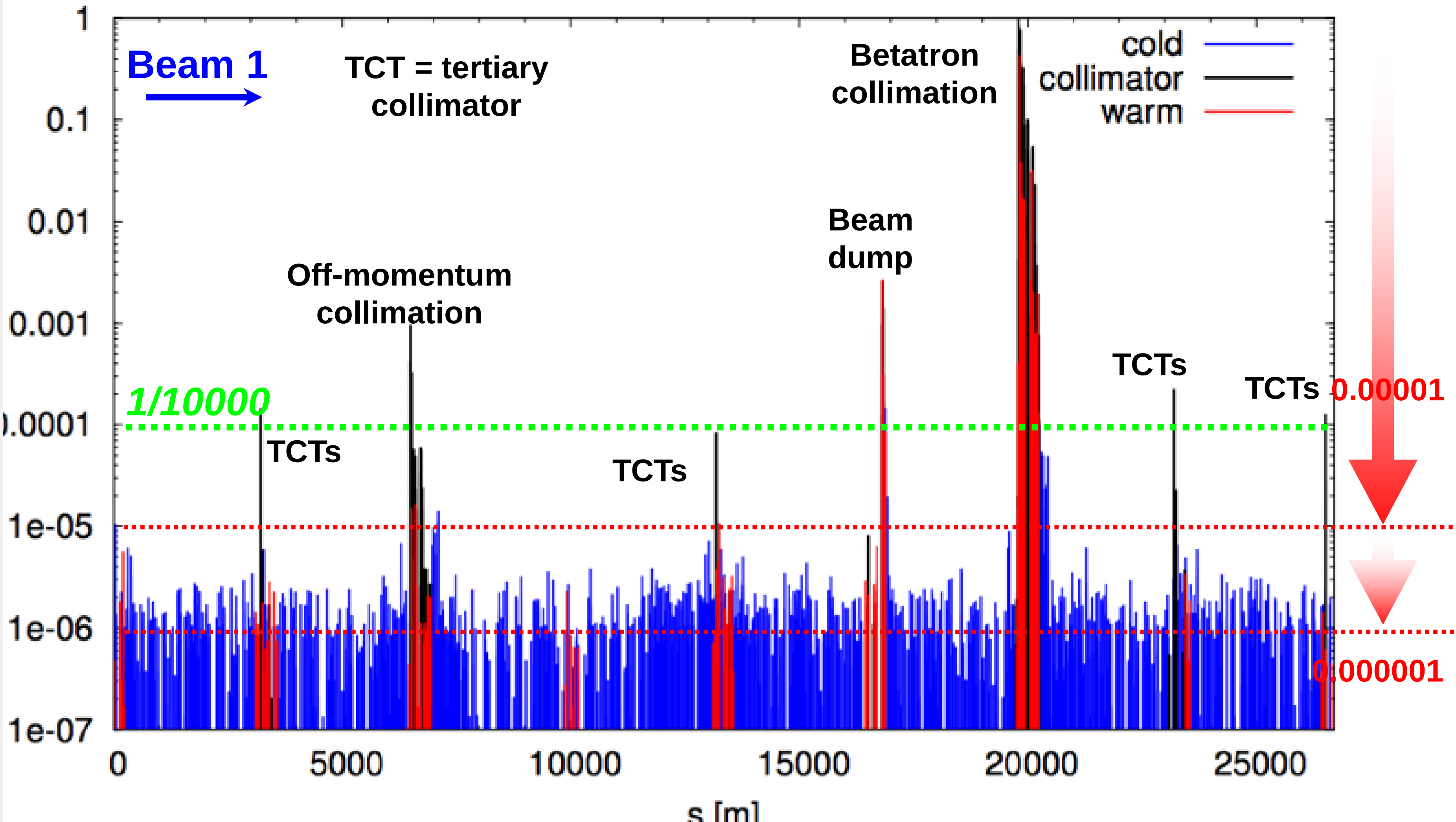


Example of the injection aperture around the ATLAS (IR1) experiment.

MPS Quality Assurance

- During machine setup collimators and absorbers are aligned around the closed orbit with appropriate retractions.
  - *The orbit must be reproducible at the level of 50-100 μm ($\Leftrightarrow$ 1/4 σ).*
- The machine setup (orbit, optics, aperture, protection devices) is then validated by a campaign of *loss maps* and *simulated asynchronous beam dump tests*.
  - **Loss map**: the beam emittance is blown up in a controlled way with a transverse feedback (noise) until losses are observed. The loss distributions provides a *validation of the collimator alignment & hierarchy*.
  - **Simulated asynchronous dump test**: a low intensity is debunched (switch off RF) and a beam dump is triggered. The beam present in the region of the abort gap mimics the effect of an asynchronous dump. The loss distribution along the ring provides a *validation of the dump protection alignment*.

Loss map example



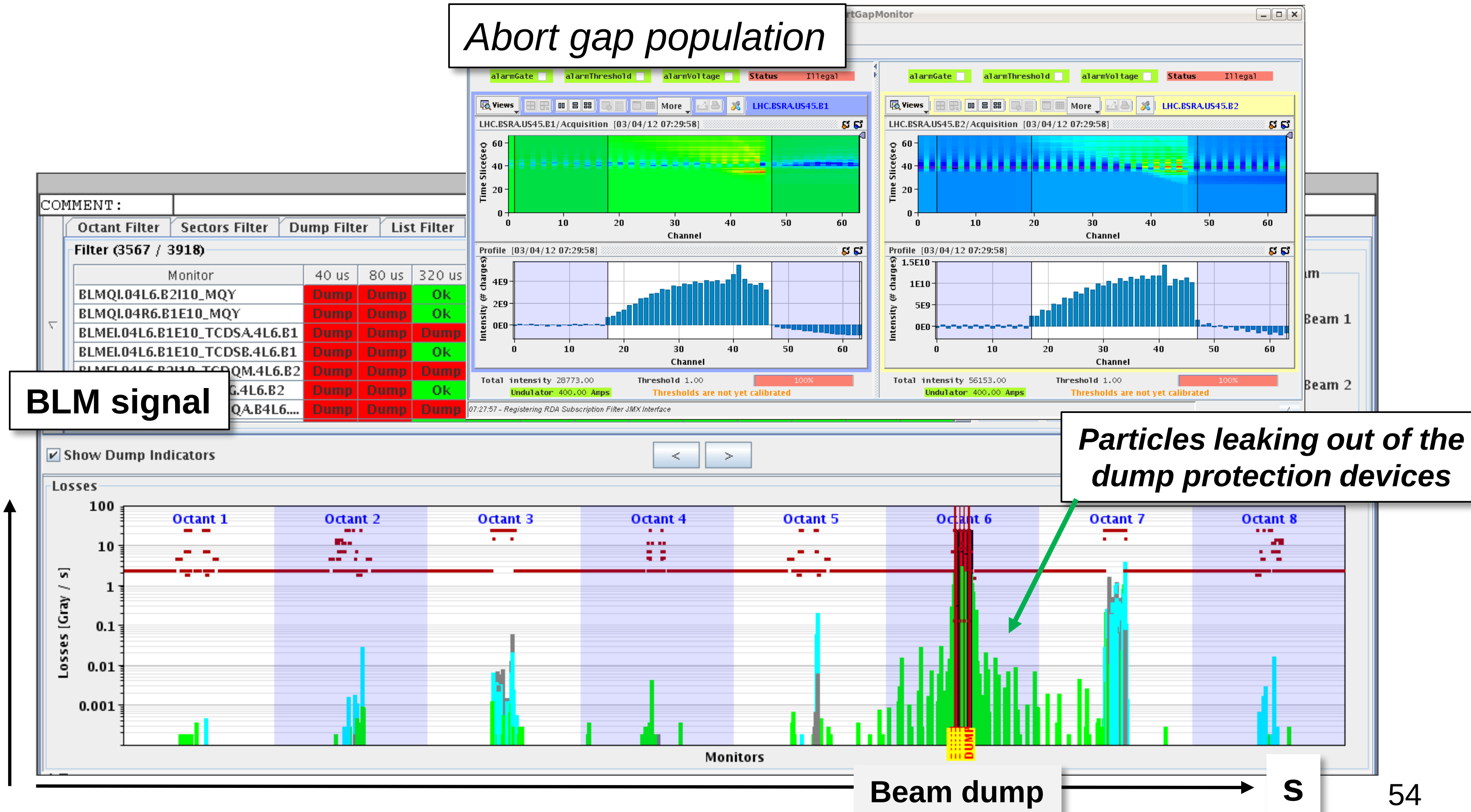
B. Salvachua

Note: not all collimator hierarchy issues can be identified in this loss map !

see lecture by S. Redaelli

Asynchronous beam dump test

For the asynchronous beam dump test the particle population in the abort gap is observed with synchrotron light, gated on the abort gap.



Introduction to LHC

Masking

Commissioning

Intensity ramp up

Beam losses

Machine protection diagnostics & software

Availability

Conclusions

Increasing the energy

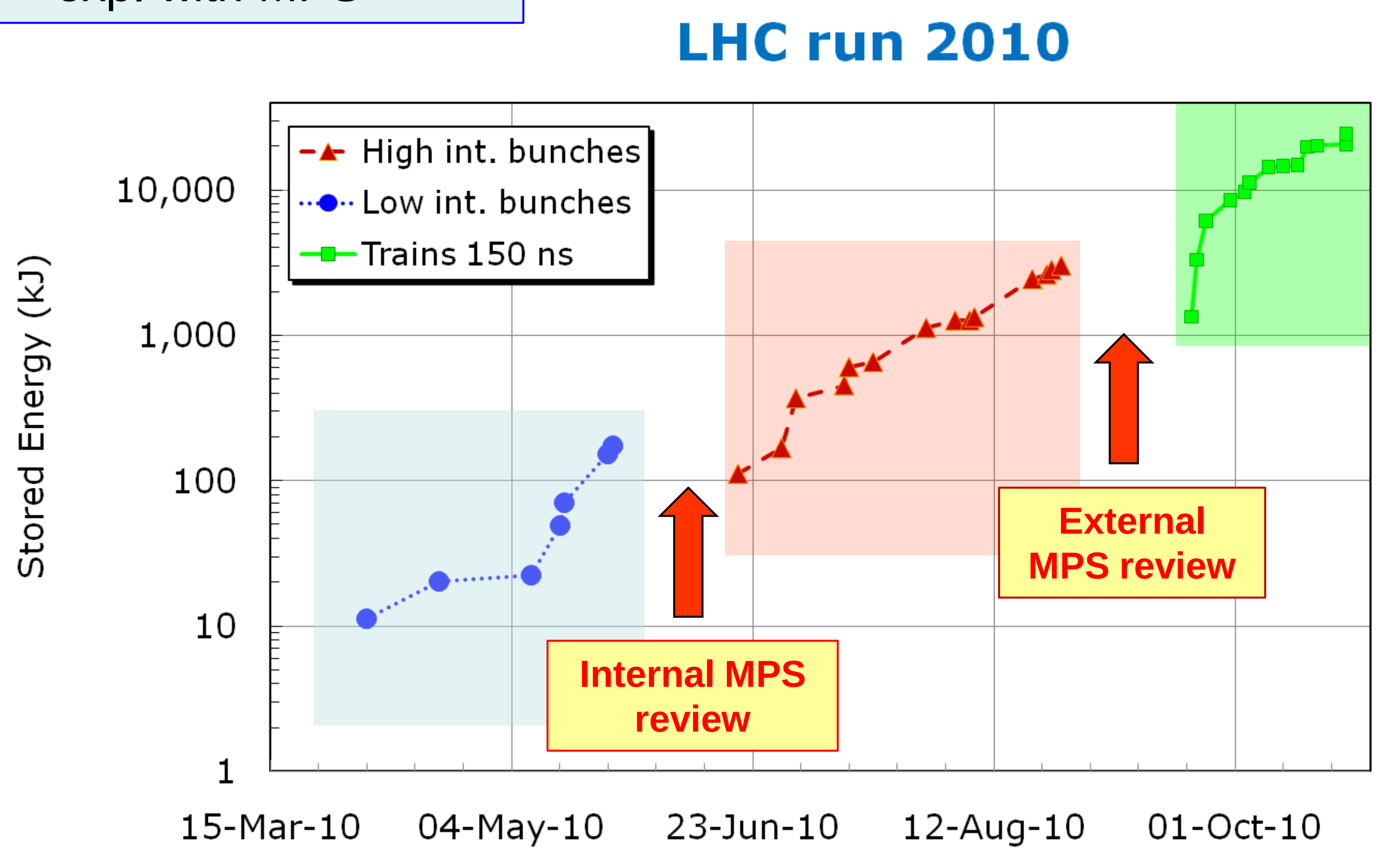
- The machine setup is always made with low intensity beams, max. of 3 bunches (out of 1500-3000).
  - **Setup with < 1/1000 of the nominal intensity! Challenge for instrumentation!**
- The intensity increase at the LHC is steered through the restricted Machine Protection Panel (*MPPr*).
  - *Defines the intensity steps and the requirements (checklists) to proceed with more bunches.*
- The plan for the first learning year in 2010 foresaw 3 phases:
  - *Low intensity for commissioning and early experience.*
  - *Ramp up to 1-2 MJ followed by a period of ~4 weeks at 1-2 MJ.*
    - ✓ Corresponded to state-of-the-art at the time !
  - *Move into 10's of MJ regime (World record).*

LHC stored energy – the first year

Low bunch intensity operation, first operational exp. with MPS

Ramping up to 1 MJ, stability run at 1-2 MJ

Breaking the records !



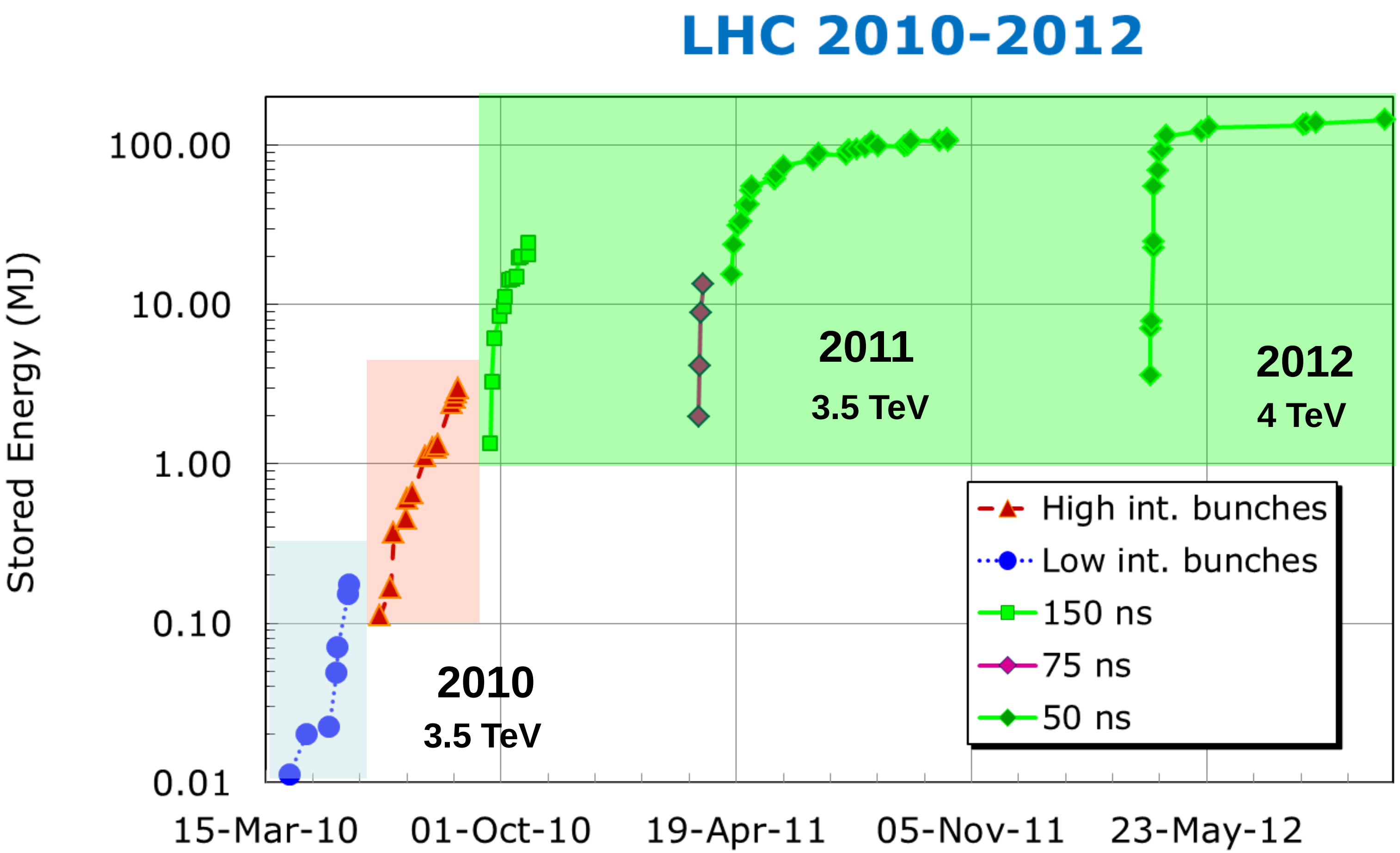
Two reviews of the MPS performance and issues !

LHC progress 2010-2012

Low bunch intensity operation, first operational exp. with LHC

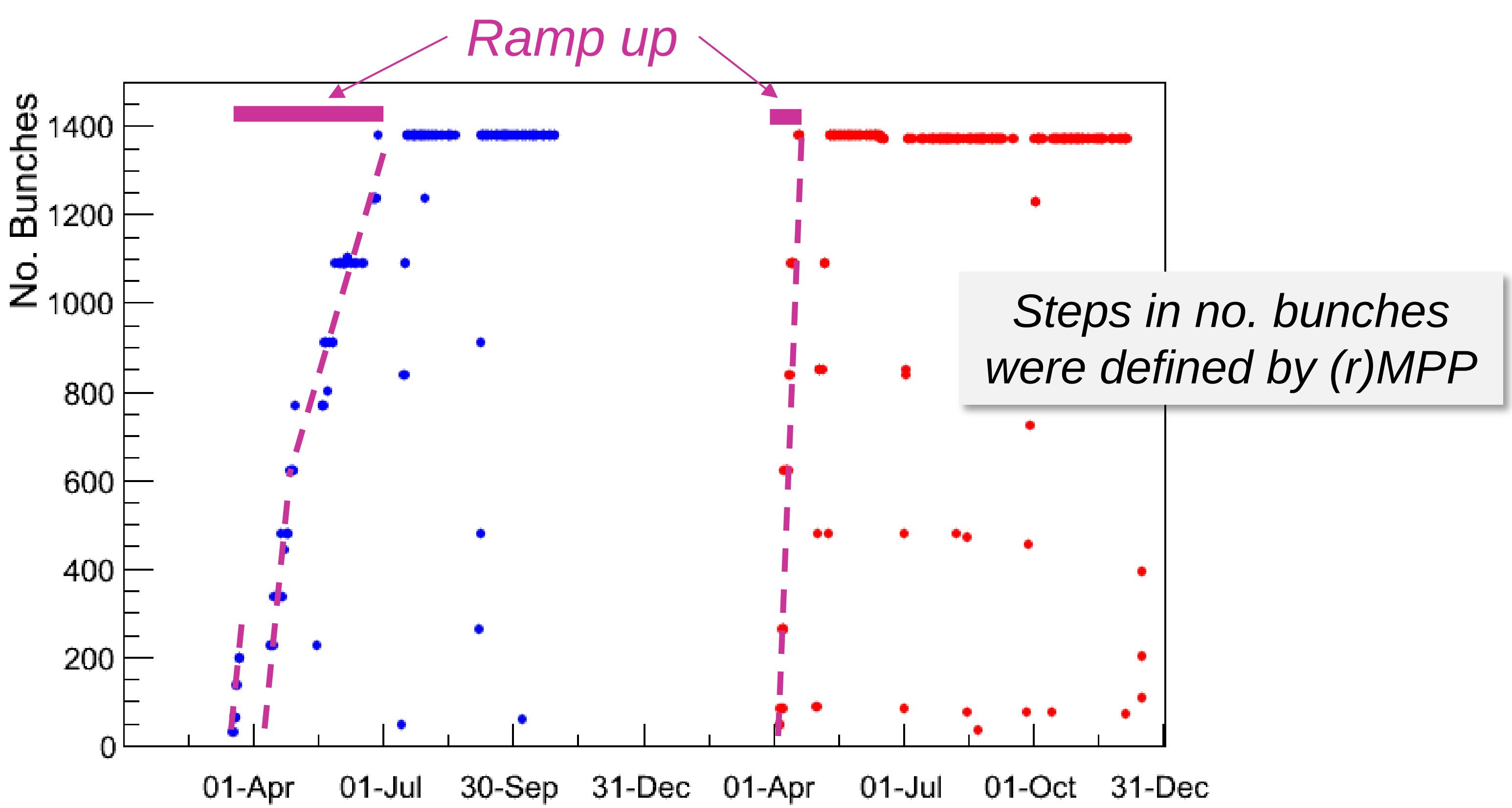
~1 MJ stored energy, learning to handle ‘intense’ beams

High luminosity operation !



Intensity ramp up details

- **2011** intensity ramp up took ~9 effective weeks – **11** intensity steps – rate dictated by operational (and not MP) issues from ~600 bunches.
  - *Losses & BLM thresholds (increase needed @ collimators), heating by the beam, beam stability etc.*
- **2012** intensity ramp up took 2 weeks – **7** intensity steps – experience !



LHC 2012 versus Design

	Design	2012
Collision energy:	7+7 TeV	4+4 TeV
Bunch spacing (ns):	25	50
Number of bunches k:	2808	1374
Number of particles per bunch N:	1.15×10^{11}	1.6×10^{11}
Beam emittance ε (μm):	3.75	2.3
Beam size at ATLAS/CMS (μm):	16	18
Circulating beam current:	0.58 A	0.42 A
Stored energy per beam:	360 MJ	140 MJ
Peak luminosity ($cm^{-2}s^{-1}$):	10^{34}	7.7×10^{33}

We aim to achieve (and exceed) design parameters in 2016 – except for the energy (6.5 TeV an not 7 TeV – magnet training).

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Beam as witness

- **During injection even a synchrotron is a linac**: injection of an intense beam may pose a serious risk or require a very important monitoring efforts (all power converters etc).

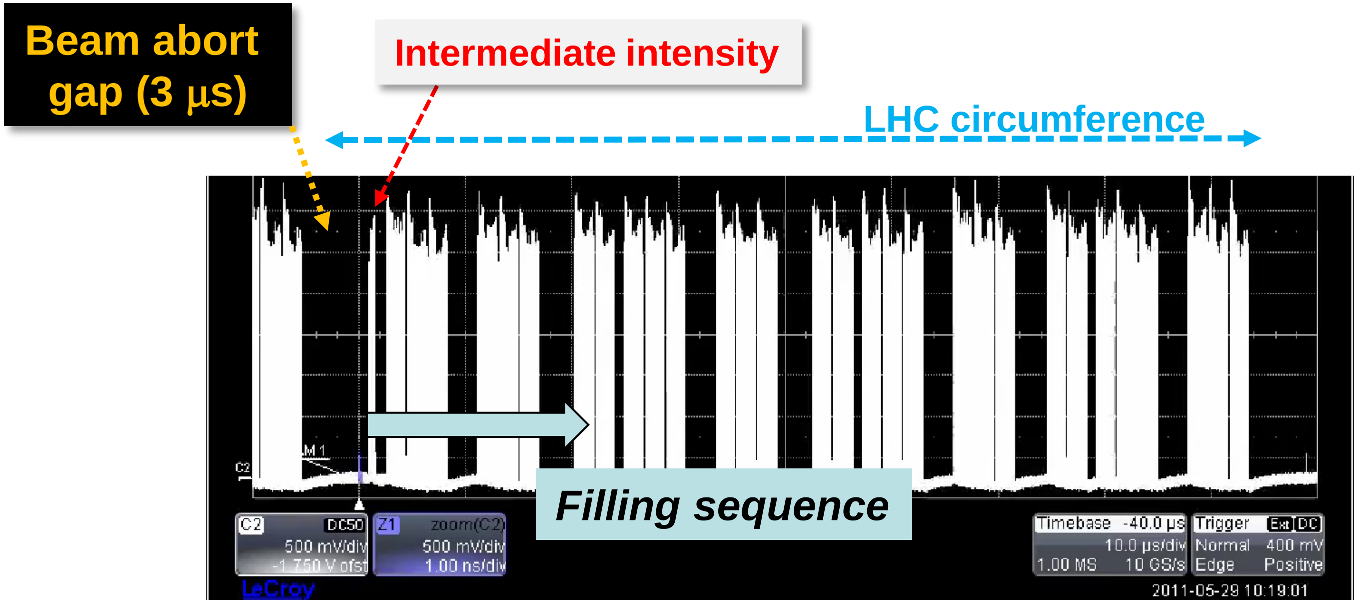
  see lecture by V. Kain

  ⇒ concept of 'witness' beam / bunch

- The LHC with nominal injection of 3 MJ (>> damage threshold) uses the ***beam presence*** concept.
  - *Only a probe bunch (typically 10^{10} protons, max 10^{11}) may be injected into an* ***EMPTY*** *ring.*
  - *High intensity injection requires a minimum beam intensity to be circulating → best check that conditions are reasonable – avoid failures happening on the first turn, before the MPS can react.*
  - ***Based on a highly reliable and redundant intensity measurement****: a flag indicating beam present (true/false) is transmitted to the extraction interlock system of the SPS injector where it is combined with a flag indicating that the SPS beam is a probe intensity (max 10^{11} p).*

Injection into LHC

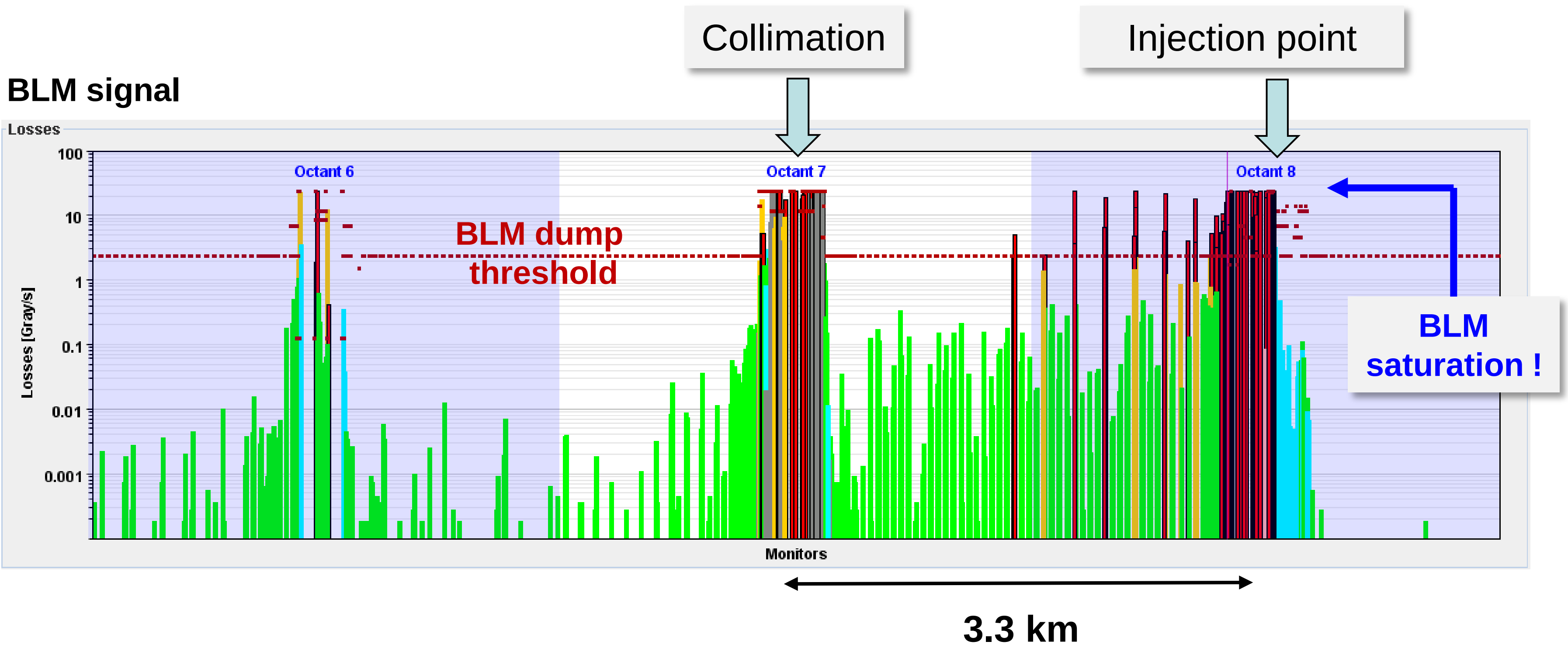
- Every injection phase of the LHC starts with the injection of a probe bunch (max 10^{11} p) into the empty ring.
- When a probe intensity is circulating, an intermediate intensity beam can be injected (max 2×10^{12} p).
  - *It is possible to over-inject on the probe bunch (which is kicked onto an injection protection device at the same time as the new beam is injected).*
- When the intermediate intensity is circulating, it is possible to inject a full intensity batch (up to 288 bunches of 1.3×10^{11} p/b).
- If the beam is dumped during the filling process → back to the beginning



Example for a LHC bunch pattern

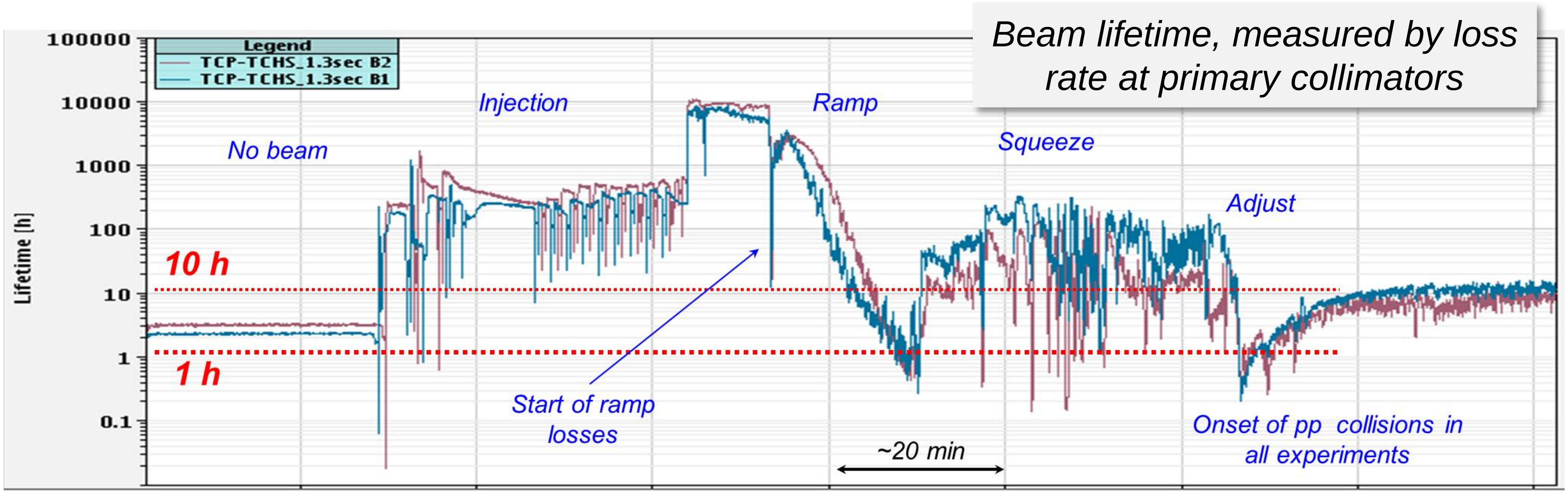
LHC example: stored - transfer

- Despite storing up to 140 MJ at 4 TeV, not a single superconducting magnet was quenched at the LHC with circulating beam – threshold ~ few 10's of mJ.
- Many magnets were however quenched at injection, mainly due to (expected) injection kicker failures (7 events in 2012).
  - *The beam (~2 MJ) is safely absorbed in injection dump blocks, but the shower leakage quenches magnets over ~1 km.*



Beam losses through the cycle

- Characteristic beam losses are observed in the various phases. They are part of regular operation and must be tolerated, even if one tries to minimize them.
  - ***Injection losses*** *(tails from injections, injection oscillations, de-bunched beam),*
  - ***Start of ramp losses*** *(uncaptured beam loss),*
  - ***Scraping on collimators*** *(gap changes, orbit and tune shifts),*
  - ***Loss of the beam halo*** *when beams start to collide (beam-beam effect),*
  - ***Losses due to the beam burn-off*** *– proportional to luminosity and performance.*



Example of a typical physics fill in 2012.

Courtesy B. Salvachua, S. Redaelli

see lectures on BLMs by B. Dehning & T. Shea

Losses during the LHC cycle

In 2012 the collimators were set closer to the beam in order to protect a smaller aperture → allowed smaller β and therefore beam size at the collision points → 60% higher luminosity.

⇒ strong impact on beam transmission & losses in the cycle

2011: losses are dominated by collisions.

Primary gap ~7.5σ (real beam size)

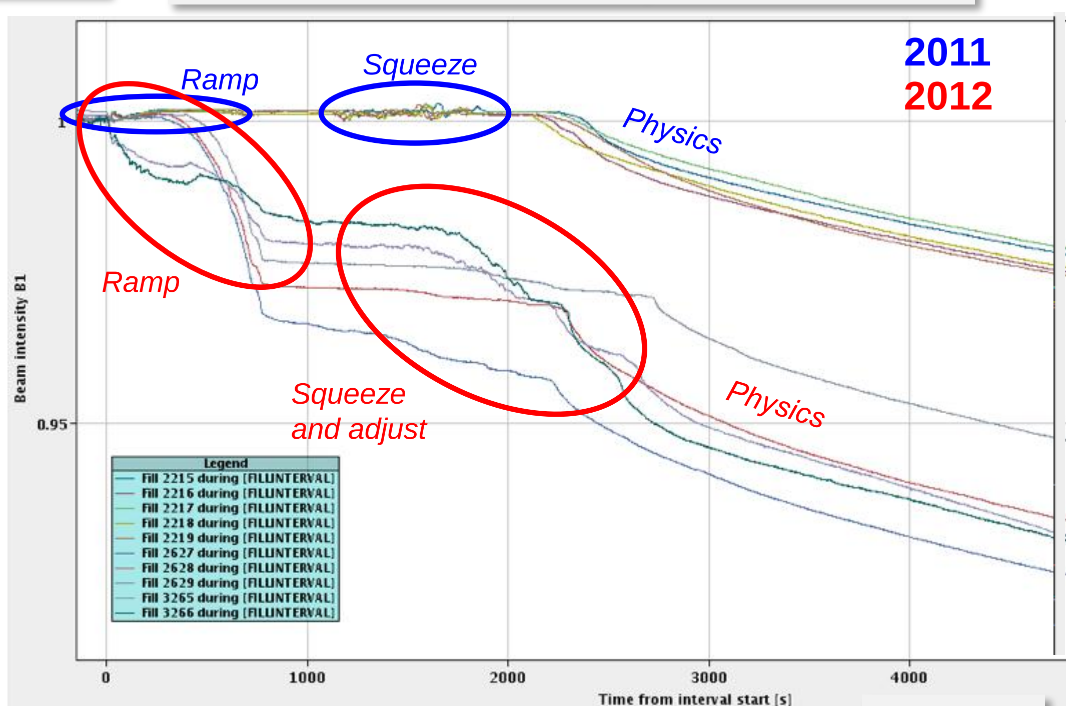
2012: beam losses at ramp end (scrapping), losses in the squeeze as more sensitive to orbit jitter.

Primary gap ~ 5.2σ (real beam size)

High halo population, ~MJs stored in the outer beam halo!

Intensity

Beam transmission from start of ramp for a few random fills



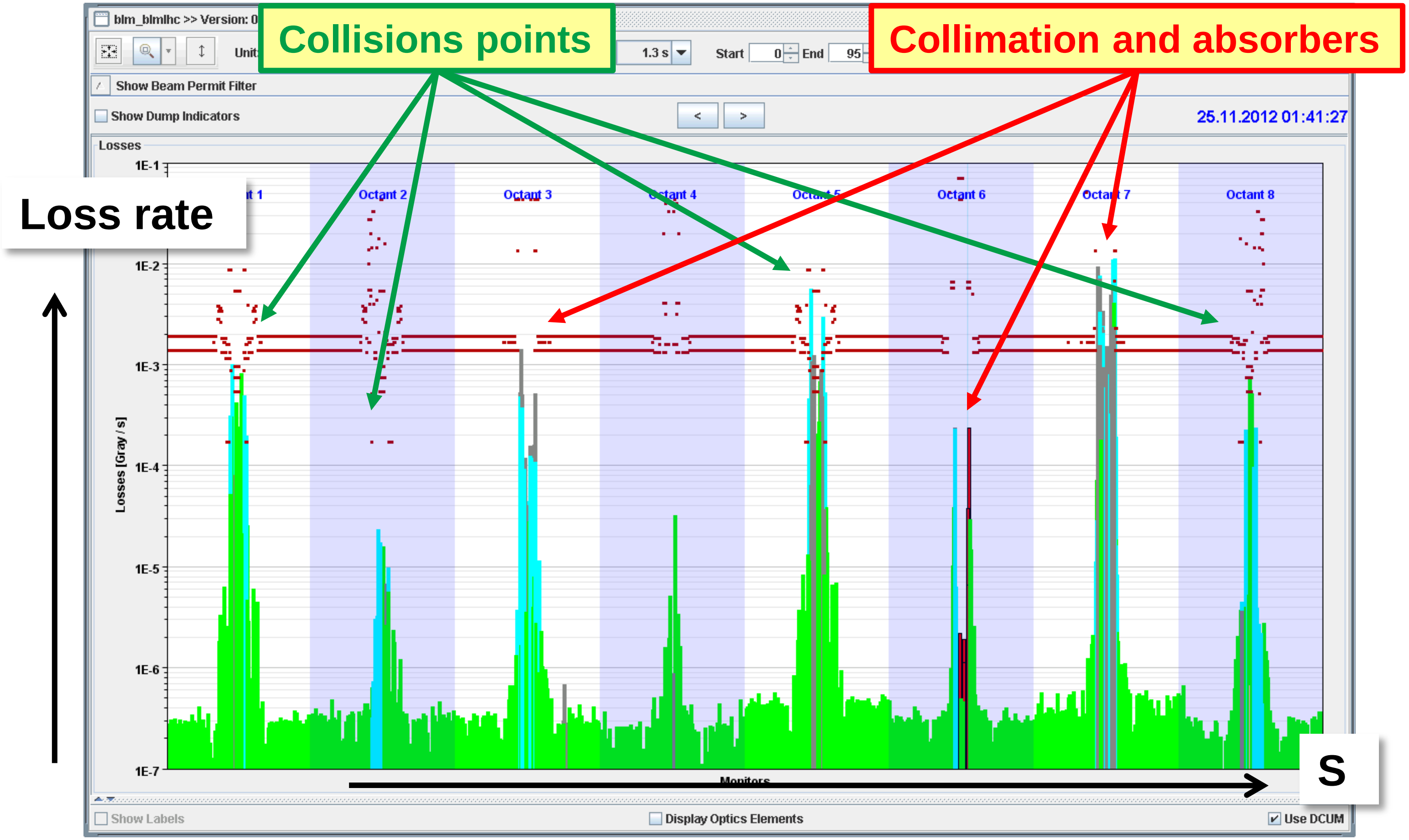
Time (s)

Courtesy B. Salvachua, S. Redaelli

Continuous beam losses at LHC

The BLM signals near the experiments are almost as high at the collimators (steady losses) due to the luminosity.

- *At the experiments the BLM record collision debris – in fact the physics at small angles not covered by the experiments !!*

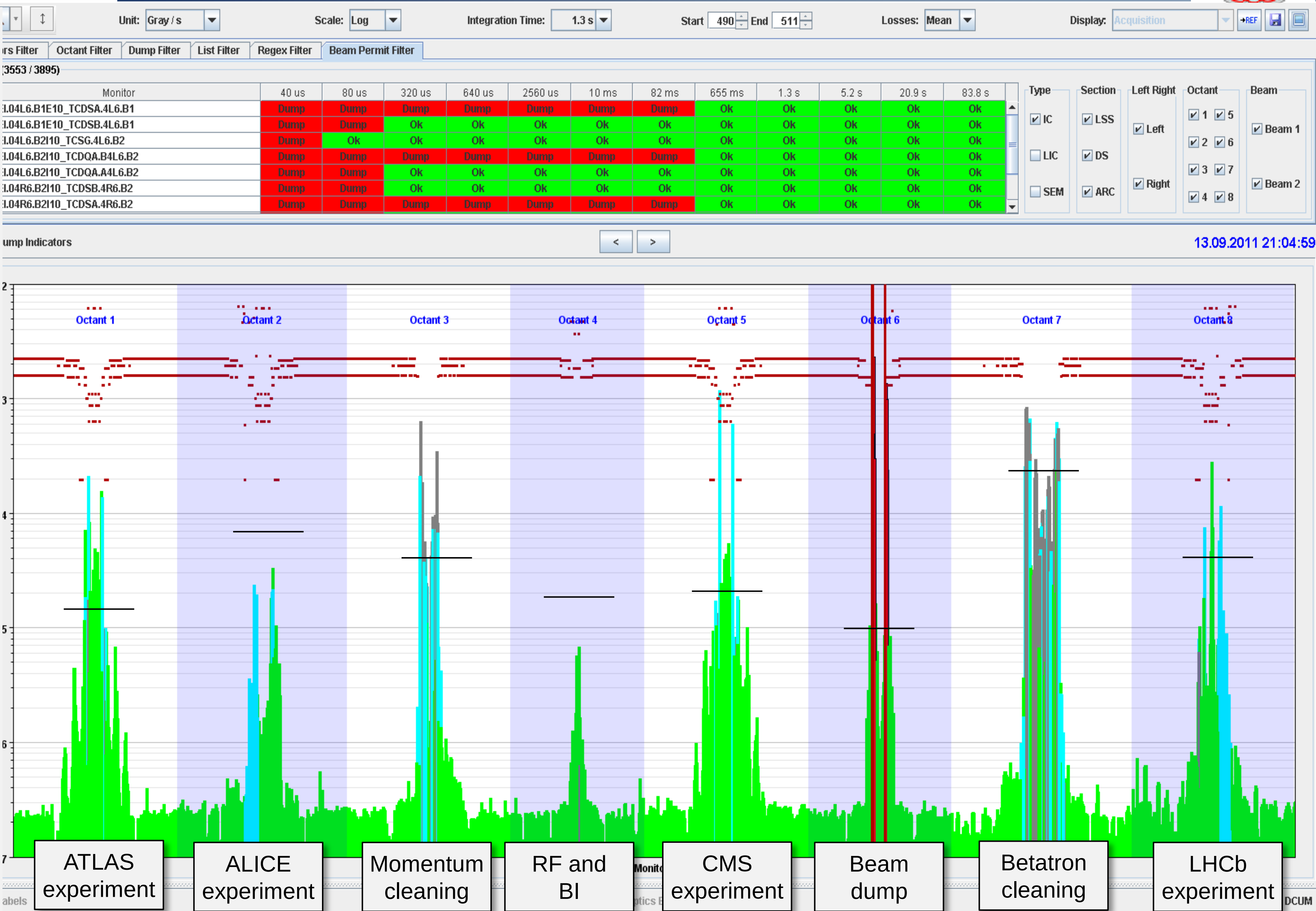


Setting thresholds - BLMs

- Threshold definition for BLMs installed in the LHC:
  - On superconducting elements: prevent quenches,
  - On room temperature elements: prevent damage.
  - In both case some (safety) margin is desired.
- Initial thresholds were set before LHC operation started based on rather coarse quench level estimates, GEANT, FLUKA and MARS simulations.
- During the first years of operation (→ 2012!) the thresholds were progressively adapted (many were increased) based on experience and on the beam intensity.
  - *Initially the thresholds on collimators were set to limit the average power loss significantly below the peak design power of 500 kW.*
- Quench tests with wire-scanners (nice point-like particle source), orbit bumps and short and high losses in the collimation area were used to determine more accurately the limits..

see lectures on BLMs by B. Dehning

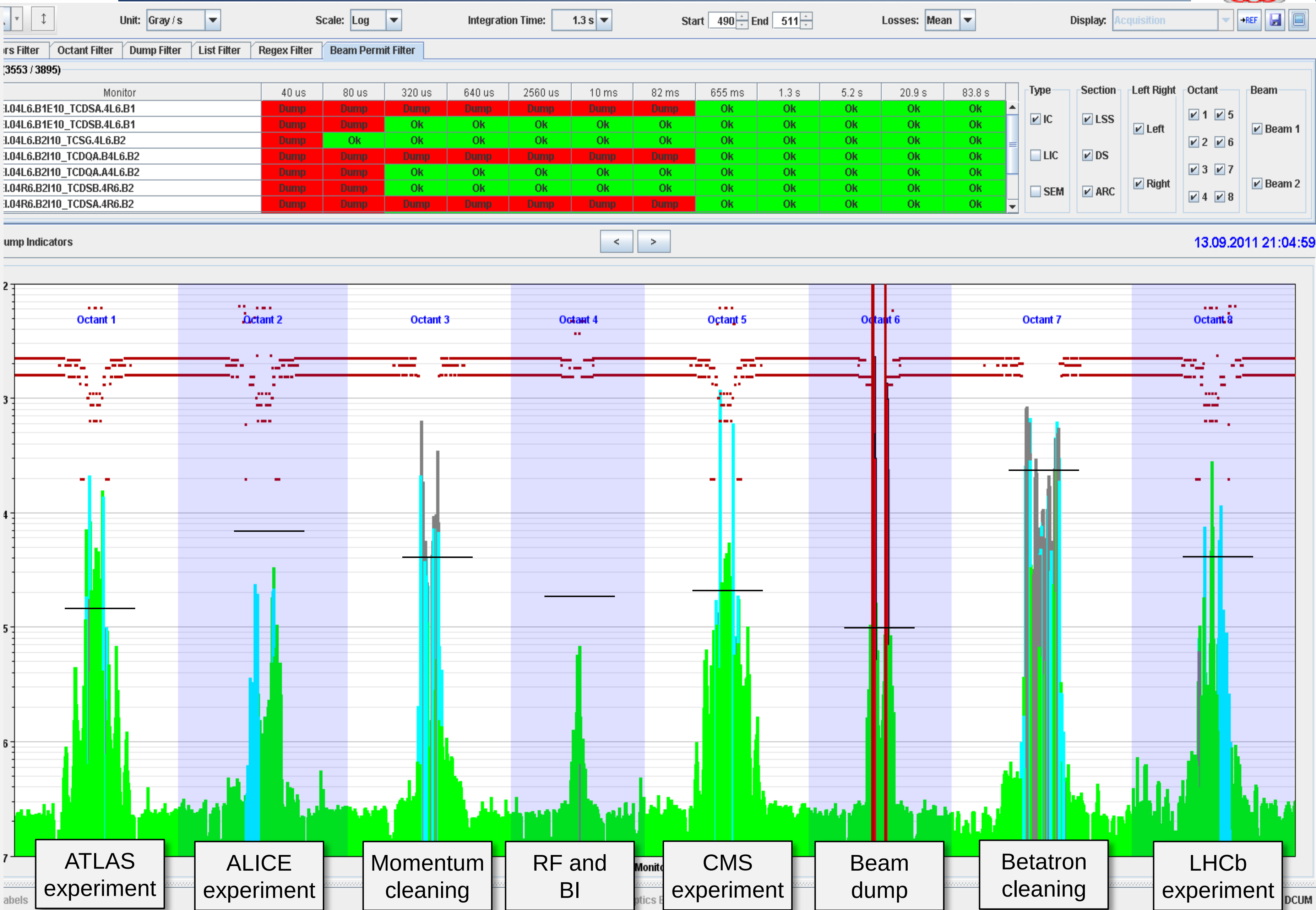
Continuous beam losses with collisions



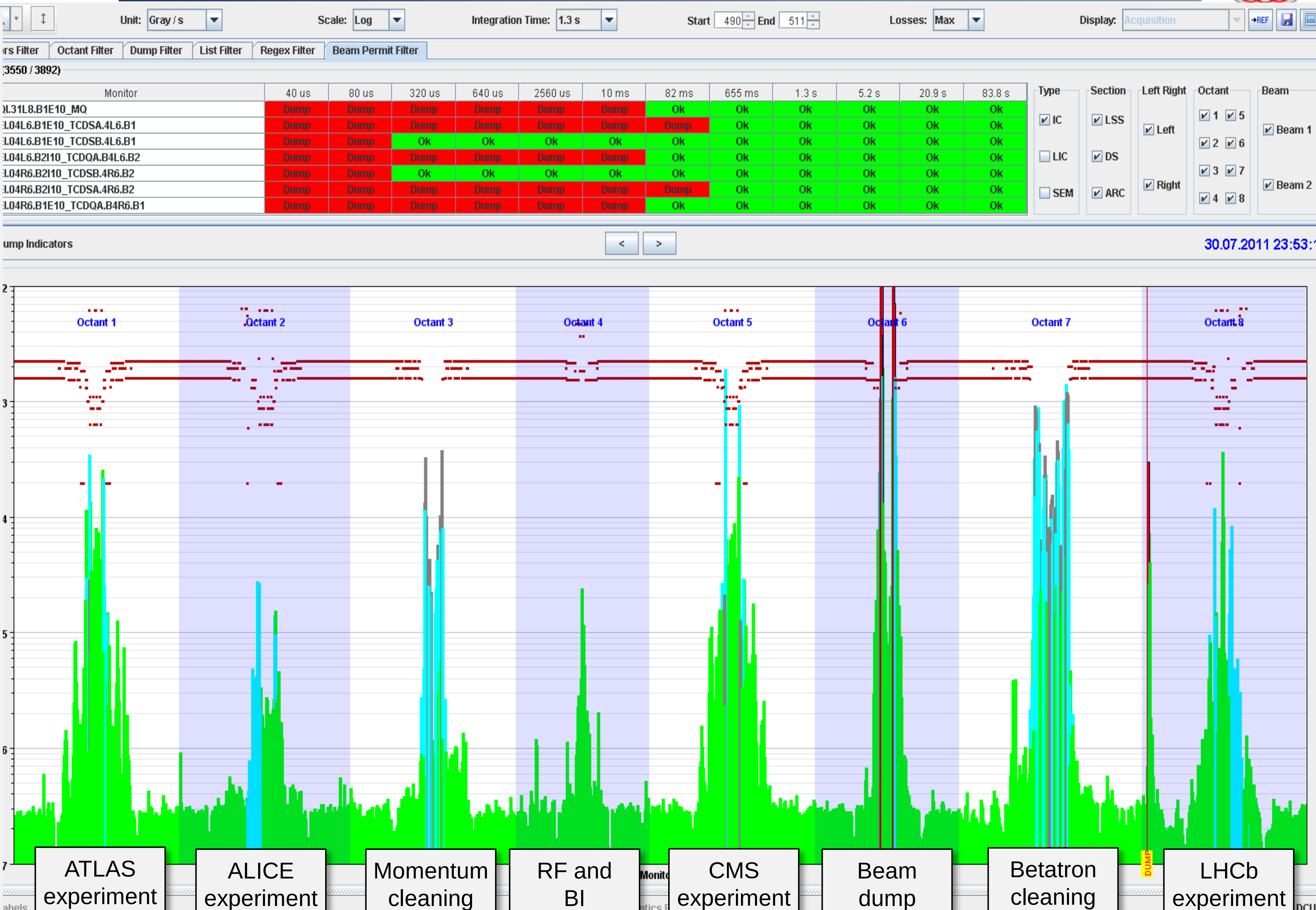
Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
1.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
1.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
1.04L6.B2I10_TCSG.4L6.B2	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
1.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
1.04L6.B2I10_TCDQA.A4L6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
1.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
1.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok

An object falls into the beam

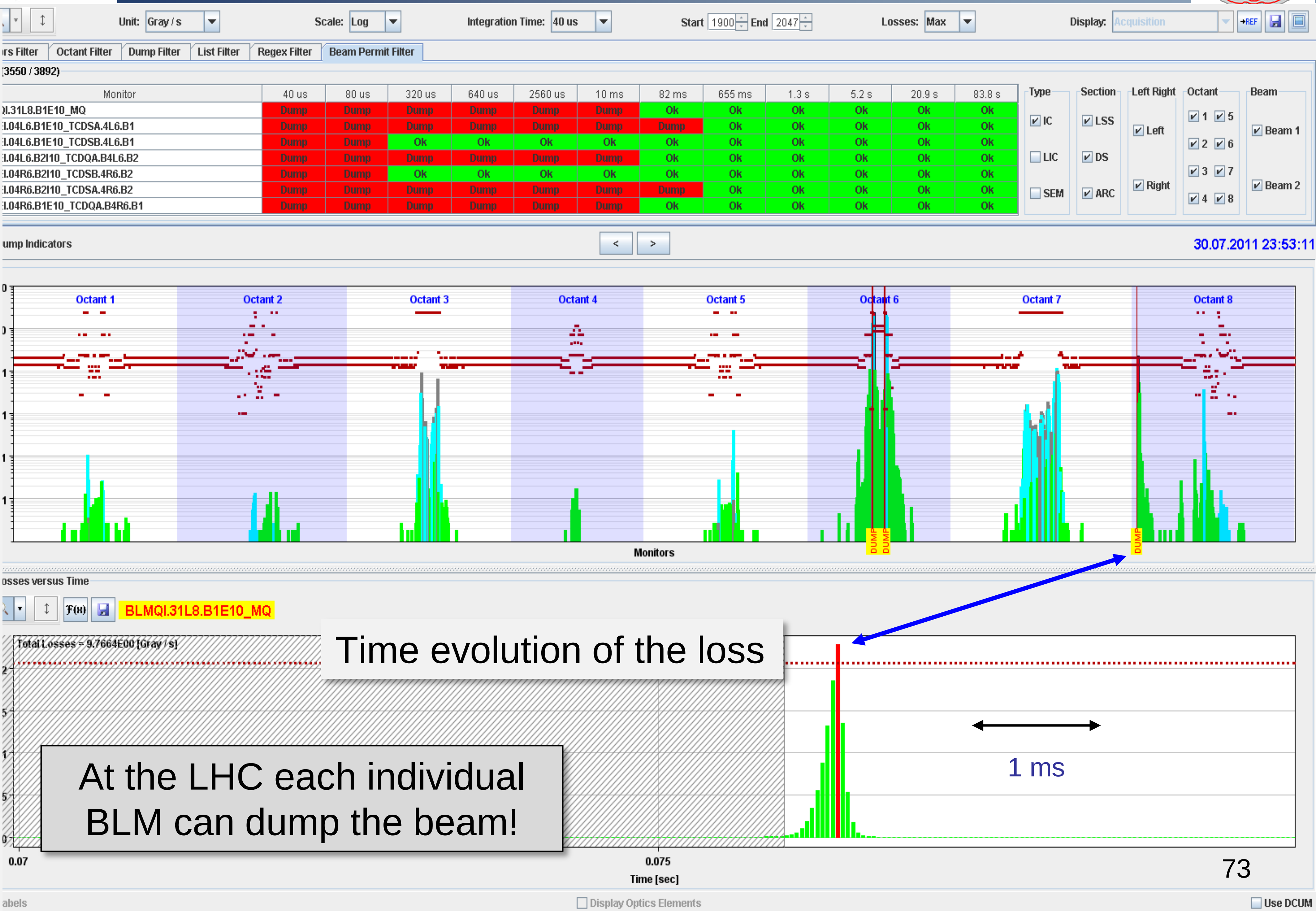
Continuous beam losses with collisions



Accidental beam losses with collisions



Accidental beam loss



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
I.31L8.B1E10_MQ	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
.04L6.B2I10_TCDQA.B4L6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
.04R6.B2I10_TCDSB.4R6.B2	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
.04R6.B2I10_TCDSA.4R6.B2	Dump	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok
.04R6.B1E10_TCDQA.B4R6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok

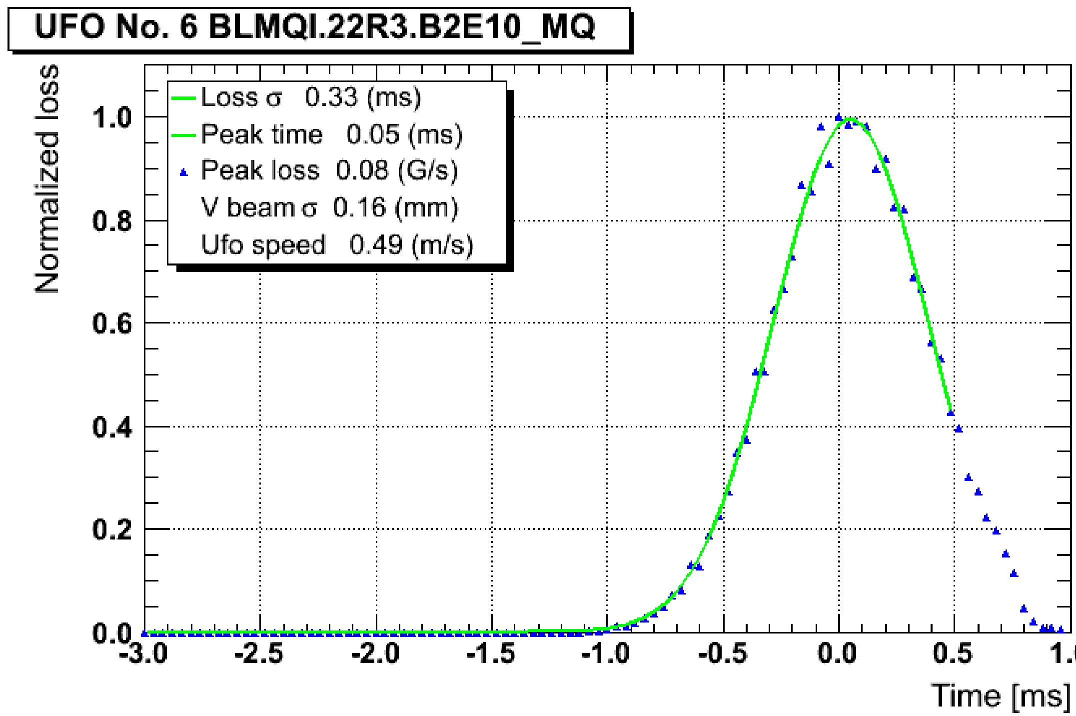
Time evolution of the loss

At the LHC each individual BLM can dump the beam!

Surprise, surprise !

- Very fast beam loss events (~ ms) mainly in supercondcting regions have been **THE SURPRISE** of LHC operation – nicknamed UFOs*.
  - *~20 dumps by such UFO-type events every year (2010-2012).*
- The signals are consistent with small (10’s μm diameter) dust particles ‘entering’ the beam.

Time evolution of a UFO-type loss

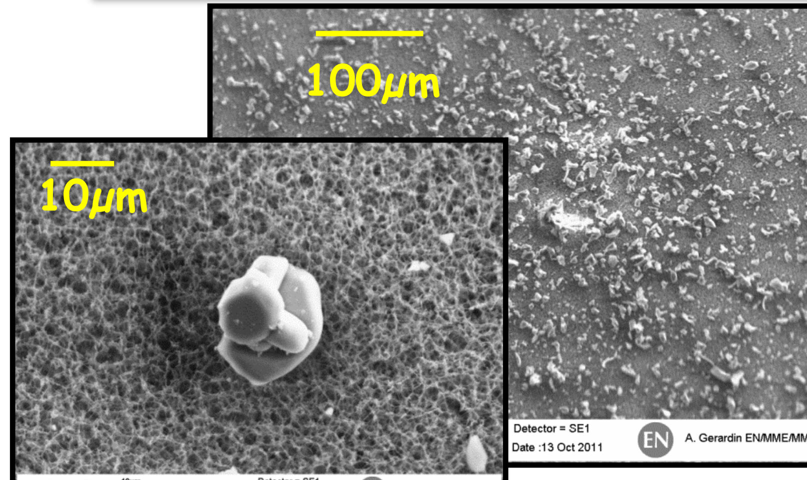


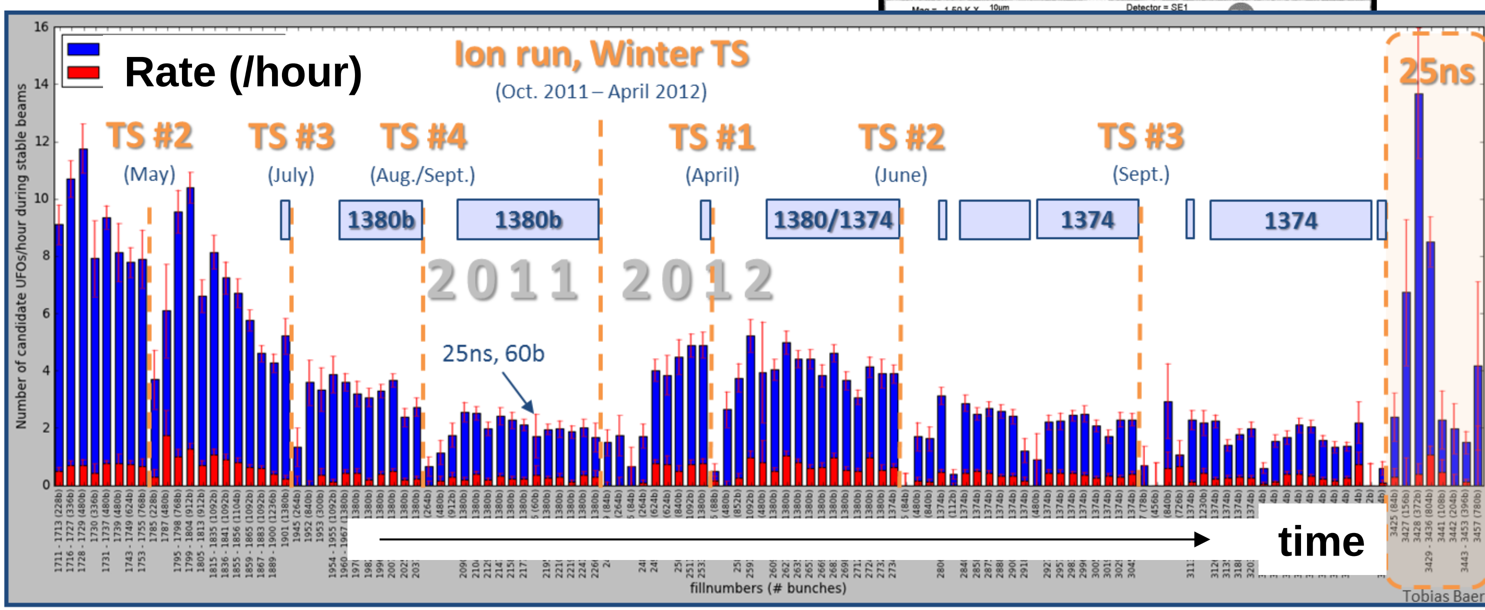
***:Unidentified Falling Object, acronym borrowed from nuclear fusion community**

UFO monitoring

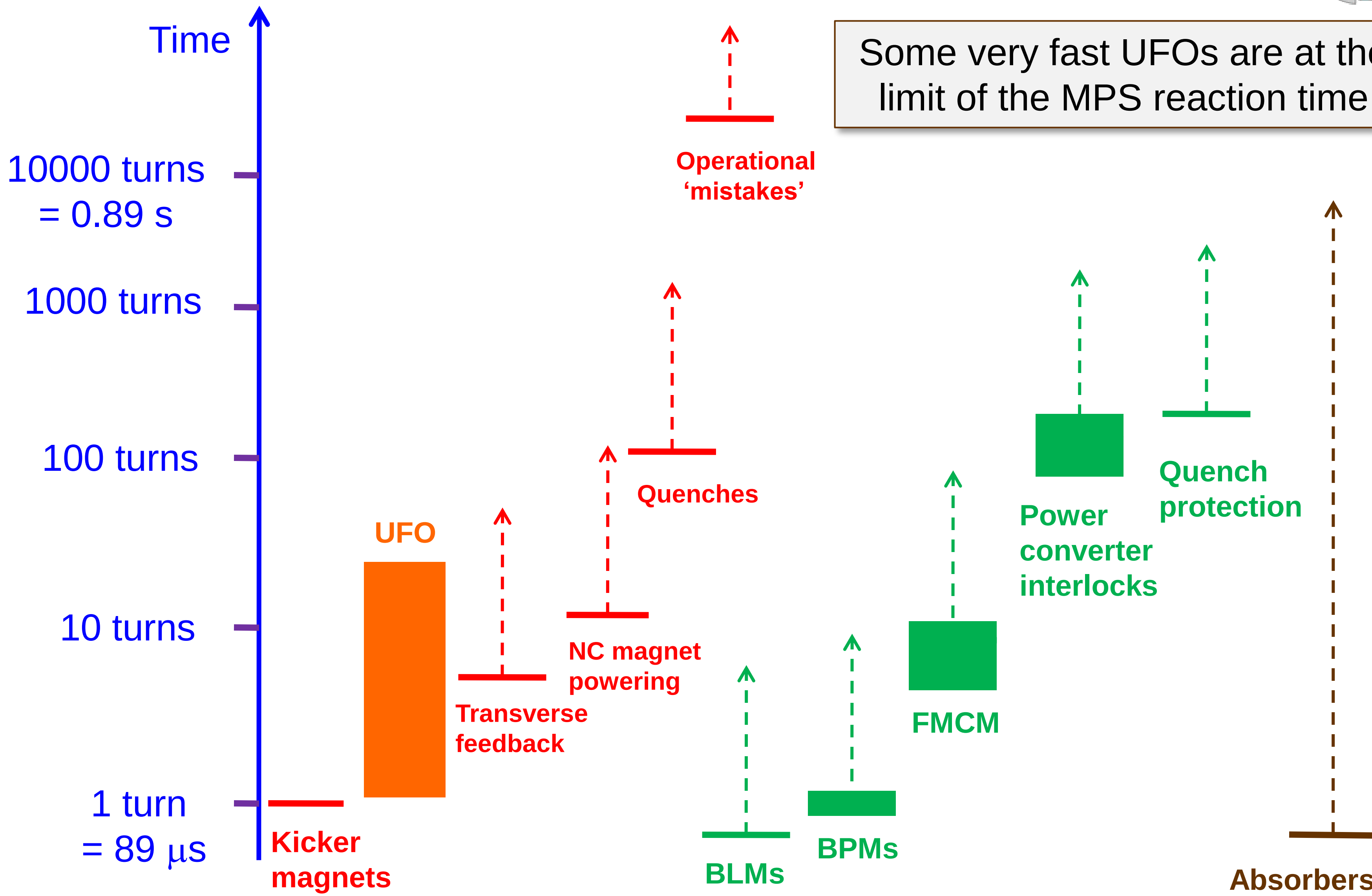
- Monitoring of UFO-like loss events was initiated. *The vast majority of events lead to losses below dump threshold.*
- For LHC injection kickers UFOs could be traced to Al oxide dust → cleaning campaign during the long shutdown.
- There is **conditioning** with beam:
  - The (non-dumping) UFO-rate drops from ~10/hour to ~2/hour over a year.

In the injection kickers UFOs were traced to Al oxide particles.





Timescales @ LHC

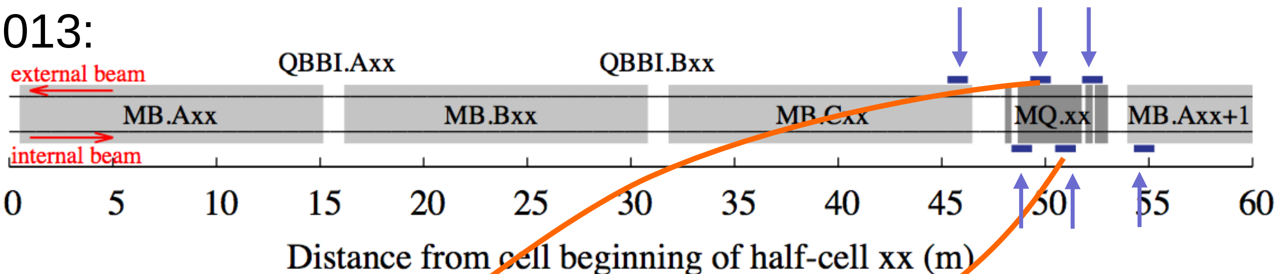


Some very fast UFOs are at the limit of the MPS reaction time

BLM relocation for UFOs

- To improve the sensitivity of the BLMs to UFO events, 2 out of 6 BLMs were relocated from the arc quadrupoles to the dipoles.
  - *Initial failure analysis: all faults are best observed at quadrupoles → in the arcs the BLMs were all installed at the quadrupoles.*

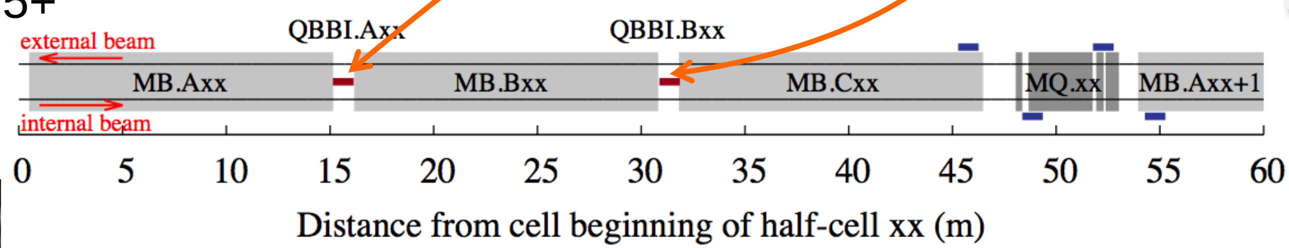
→ 2013:

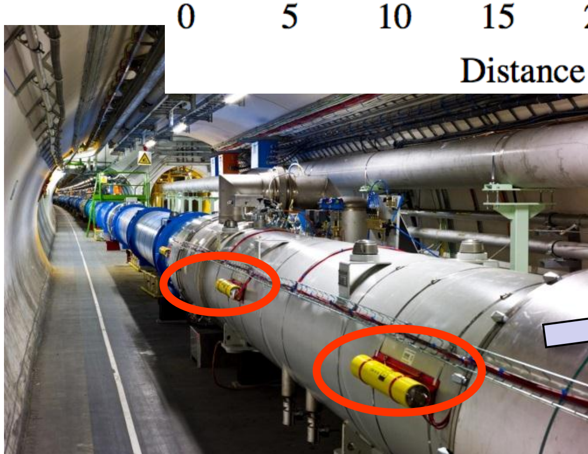


MB = dipoles

MQ = quadrupole

2015+



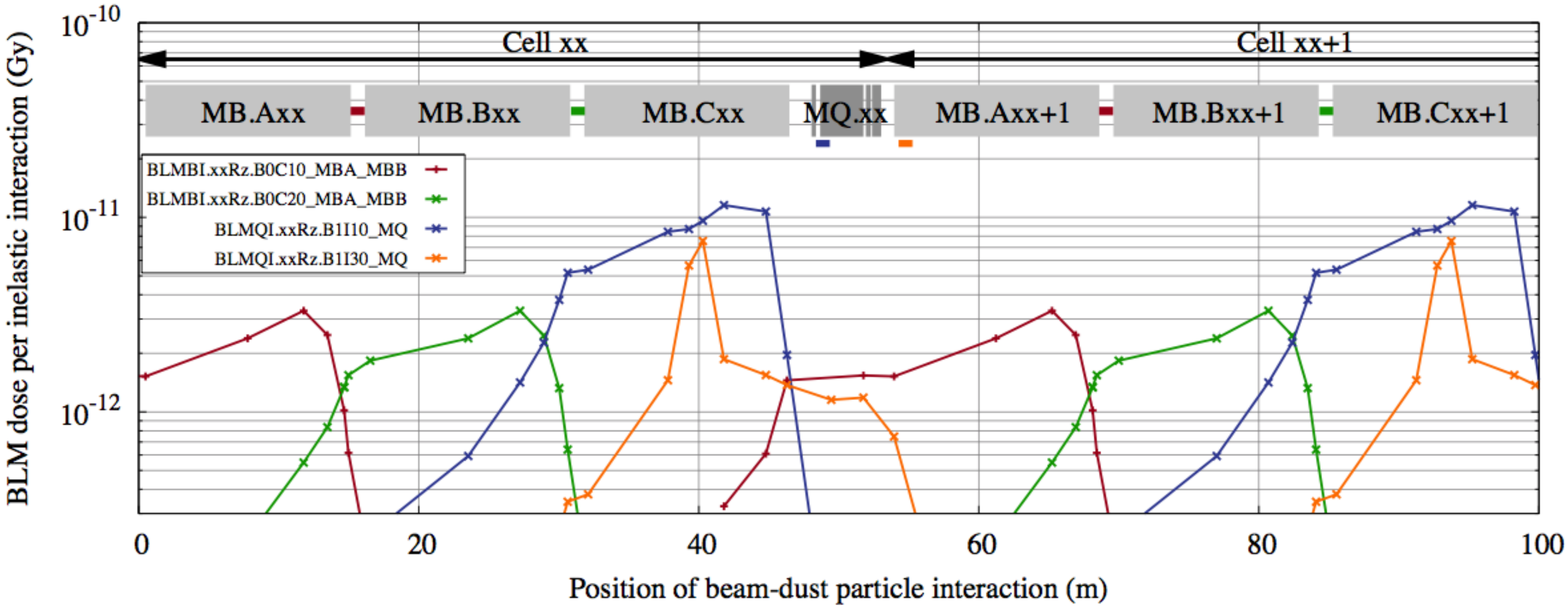


LHC half-cell

BLM relocation for UFOs

- The BLMs at the quadrupoles (blue and orange) are not sensitive to UFOs originating in 2 of the 3 dipoles (MB.Axx and MB.Bxx). The relocated BLMs cover the gap.
  - *Much improved monitoring and protection (quench prevention) capabilities for the coming 6.5 TeV run.*

Higher losses (energy) and lower quench thresholds !



Beam direction

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- **Protect the machine**
  - Highest priority is to avoid damage of the accelerator.

- **Protect the beam**
  - Complex protection systems reduce the availability of the accelerator, the number of "false" interlocks stopping operation must be minimized.
  - Trade-off between protection and operation.

- **Provide the evidence**
  - Clear (post-mortem) diagnostics must be provided when:
    - the protection systems stop operation,
    - something goes wrong (failure, damage, but also 'near miss').

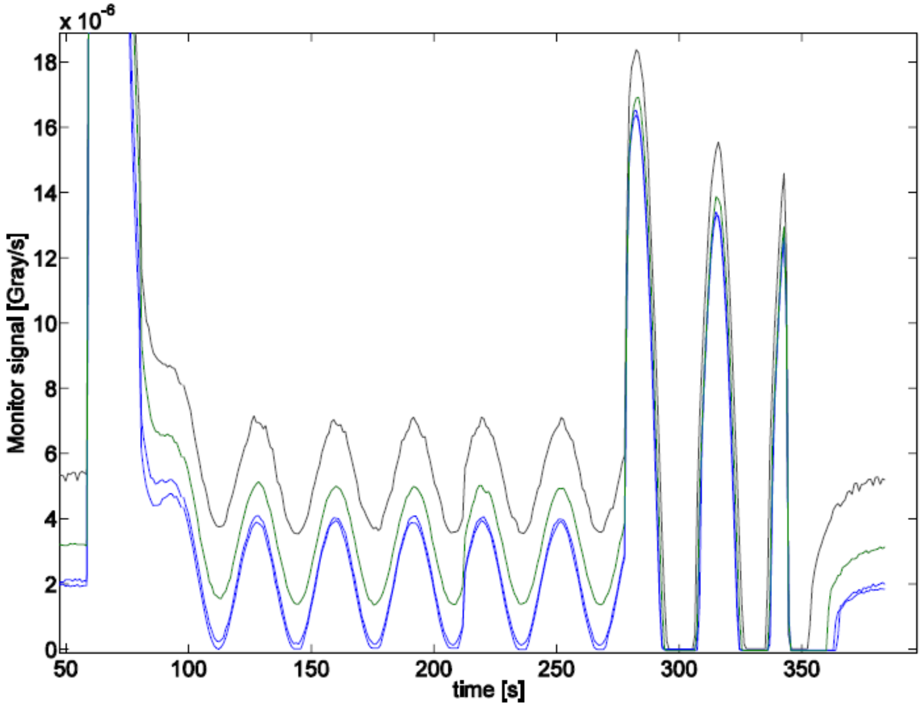
see lecture on by E. Carrone & T. Shea

Pre and Post-mission checks

- Automated checks of the MPS components as **pre-** or **post-flight checks** can ensure that the MPS functionality is not degraded.
- For colliders with long cycle times there are 2 types of checks that fit well into the cycle:
  - *Pre-flight checks before injection,*
  - *Post-flight checks on data collected during a fill/store or during the beam dump (Post-Mortem data).*
- Such tests can come in multiple forms:
  - *Test of MPS related settings, for example BLM thresholds.*
  - *Configuration checks of the beam interlock systems (all clients present and alive?).*
  - *Automated analysis of the faults and MPS reaction chain – mainly for the simplest and very frequent cases.*
  - *Automated analysis of the dump system action.*

Pre-flight checks

- Pre-flight checks and validations (after stops, interventions, before filling) are important to asses the good state of MPS elements.
  - *Interlock settings (actual settings versus DB reference).*
- LHC example: all LHC BLMs are tested between 2 fills.
  - *Signal/cable integrity by HV modulation,*
  - *Threshold consistency with respect to reference DB.*



Post-mission checks

- At the LHC the MPS is so critical that for every beam dump ***Post Operation Checks*** (***POCs***) are performed for the beam dump system based on Post-Mortem data (equipment and beam signals).
  - *Automatically triggered based on PM data.*
  - *Based on internal beam dump signals (IPOC), but also on external beam information (XPOC): intensities, losses, positions.*
  - *Asses that all signals are correct, no loss of redundancy…*

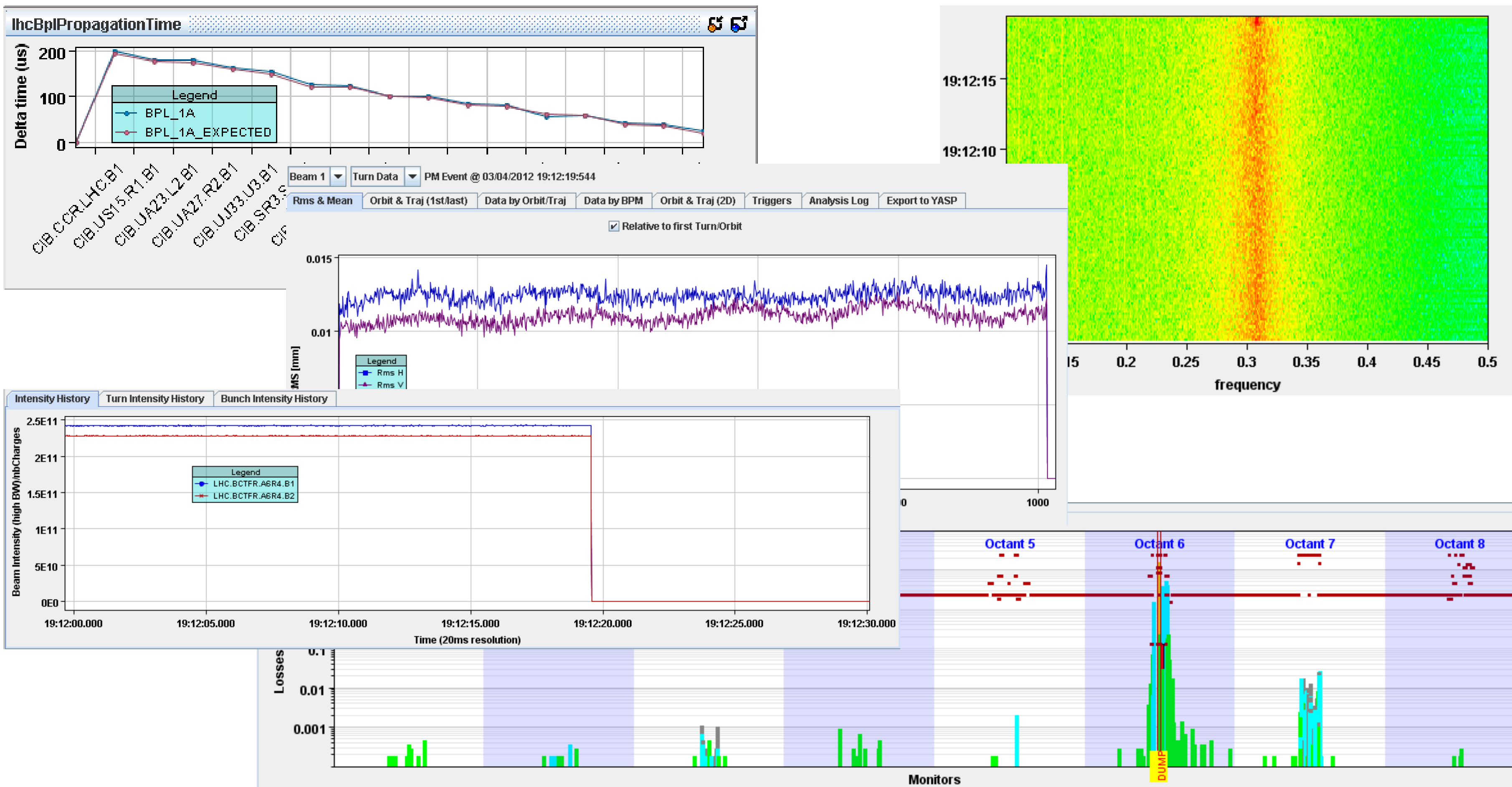
    → system is 'as good as new'.
  - *Complement to manual checks by operation crews.*
  - *Machine operation is stopped if the beam dumping system POCs fail → expert check required to restart.*
- The concept was so successful that it was **extended to injection**: automated check of each injection quality, interruption in case of losses, large trajectory excursions etc.

MPS diagnostics – post-mortem

- From the design of the LHC MPS post-mortem diagnostics was viewed as a key component in order to identify the root causes of beam dumps.
  - *All key systems implement a circular PM data buffer that is frozen and read-out when a beam dump is triggered.*
  - *Sampling frequencies range from μs – turn level to 10's of milliseconds.*
  - *Synchronization is critical to make sense of the data and define what came first !*
- For a large MPS the analysis can be tedious, automatic analysis tools are needed to help operators and MPS experts.
  - *LHC post-mortem size ~ 200 MB. Partially automated analysis.*
- After a LHC beam dump, **injection is blocked until the PM data is collected, pre-analyzed (automatic) and signed**.
  - *If the automated analysis identifies a critical problem, injection can only be released by a MPS expert.*
  - *The shift crews must sign the PM.*
  - *MPS experts re-analyse all PM events > injection energy within a few days – independent view, long term trends.*

Post-mortem GUI

- The LHC PM server and GUIs are JAVA based with standard interfaces to extract raw data and provided analyzed data.
  - *Many persons contribute to the analysis (experts, controls…).*
  - *The PM system also inserts an automatic entry in the LHC electronic logbook.*

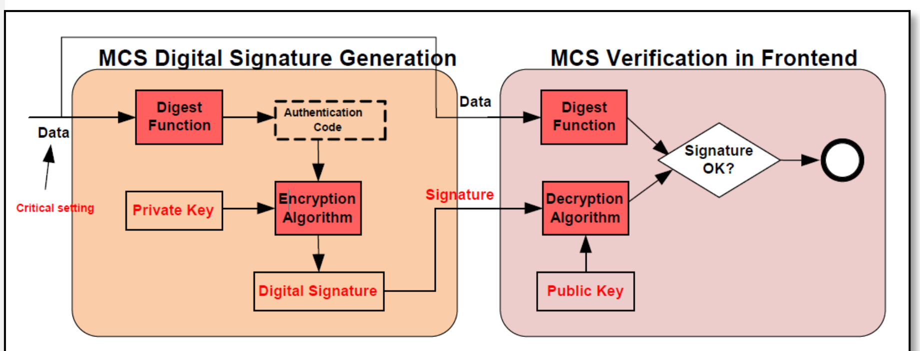


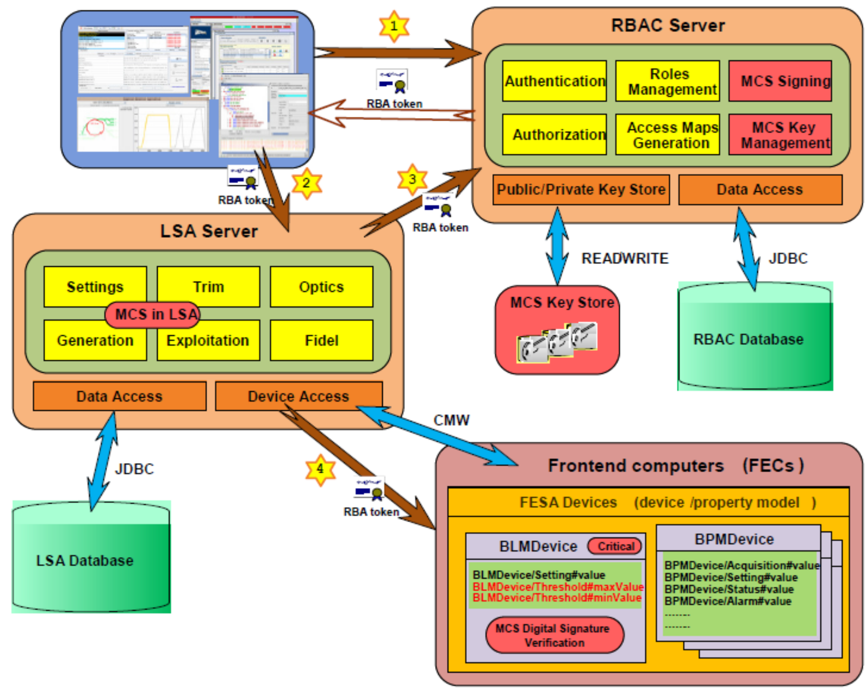
MPS settings (changes)

- Depending on its size, complexity and energy range an accelerator will have a large volume of MPS settings.
  - BLM thresholds, current references and tolerances etc
- Obviously someone has to set / introduce the values. Once there are in place there are two issues:
  - Who can change them, when and how?
  - How to make sure that the settings have not changed?
- There are various solutions that can be mixed:
  - 'Continuous' verification of the MPS settings.
    - For example before new injection phase.
  - Protection of the settings - only authorized experts can change them.
    - Access restrictions – at CERN: **Role Based Access Control (RBAC)**
    - **(Digital) signatures.**

Critical settings

- To protect MPS settings the concept of *Management of Critical Settings* (MCS) was developed for the LHC and its injection lines.
  - Fully embedded in the control middleware and settings management.
- A settings that is defined as critical has an associated **digital signature**.
  - The digital signature is generated at the moment when a setting is changed.
  - The setting and its digital signature are transmitted to the front end computer – a critical setting is only accepted with its valid digital signature.
  - Only a user that has to appropriate RBAC role (MPS expert, BLM expert etc) is able to generate the digital signature.

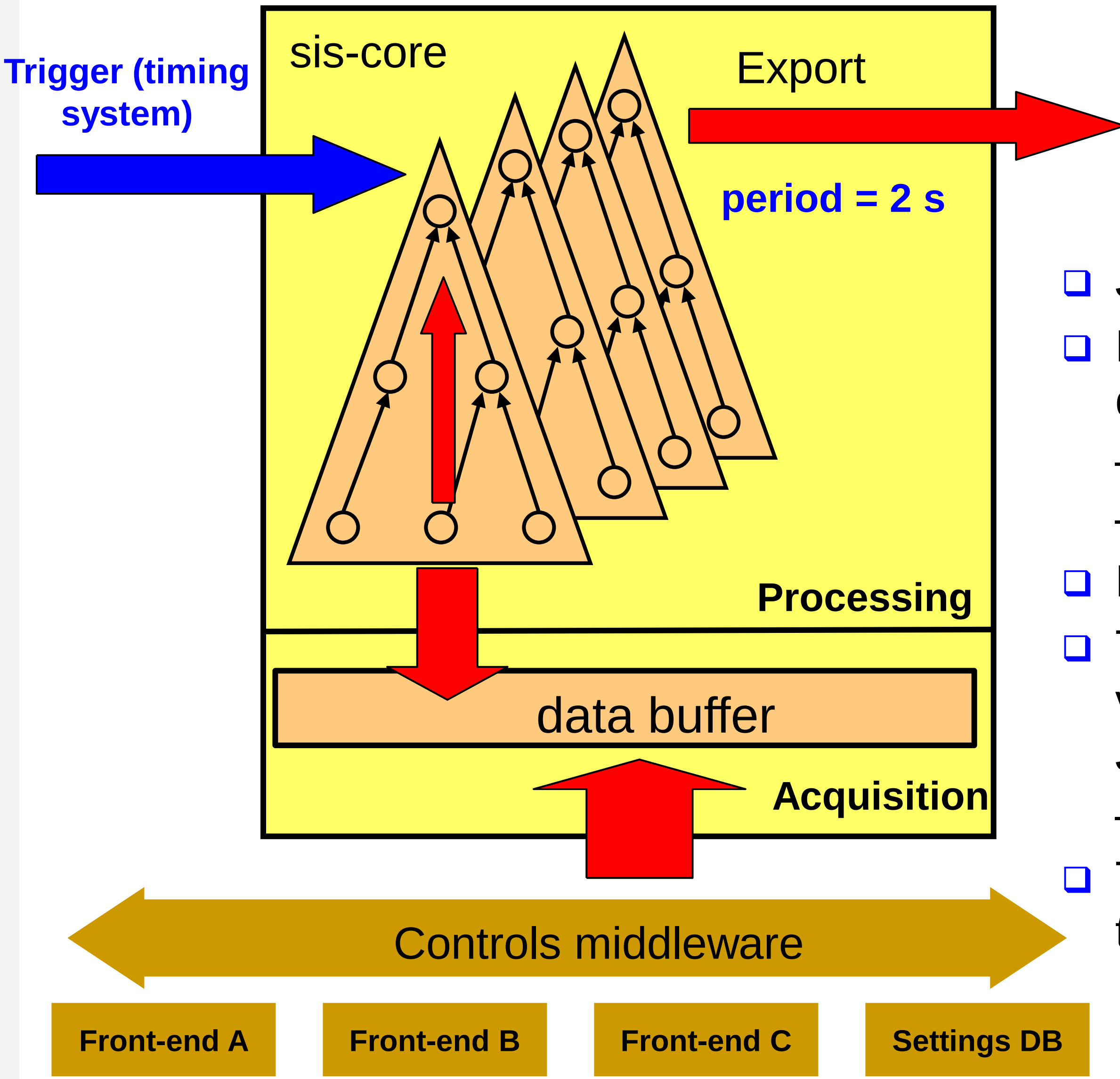




Software interlocks

- The LHC MPS has inputs from may system that operate **independently**. There is no (or very limited – timing system) information exchange between those systems.
- To implement interlocks on a global machine scale with correlation of data between any LHC system, a **Software Interlock System** was developed.
  - Global scale analysis and correlations among systems,
  - Correlation of injector data with LHC for injection,
  - Fast implementation for protection against unexpected issues.
- The SIS is by design rather slow (~ second) but it is **able to detect anomalies that could lead to problems in the 'near' future**, or prevent unnecessary beam dumps at injection.
  - ***'Soft'*** machine protection: prevent activation of the MPS.
    - For example: interlocking of the orbit (2000 readings), the steering magnets (~1000), soon to be expanded to all magnets.

SIS architecture



- JAVA core server.
- Large data buffer (~2500 devices and settings groups).
  - Access to entire device space.
  - Timeout and no-data policies.
- Many tests (> 5000).
- Tests can be defined as simple value comparisons or complex JAVA logic.
  - Evaluated every 2 seconds.
- Tests are organized in trees → top result is exported.

Introduction to LHC

Masking

Commissioning

Intensity ramp up

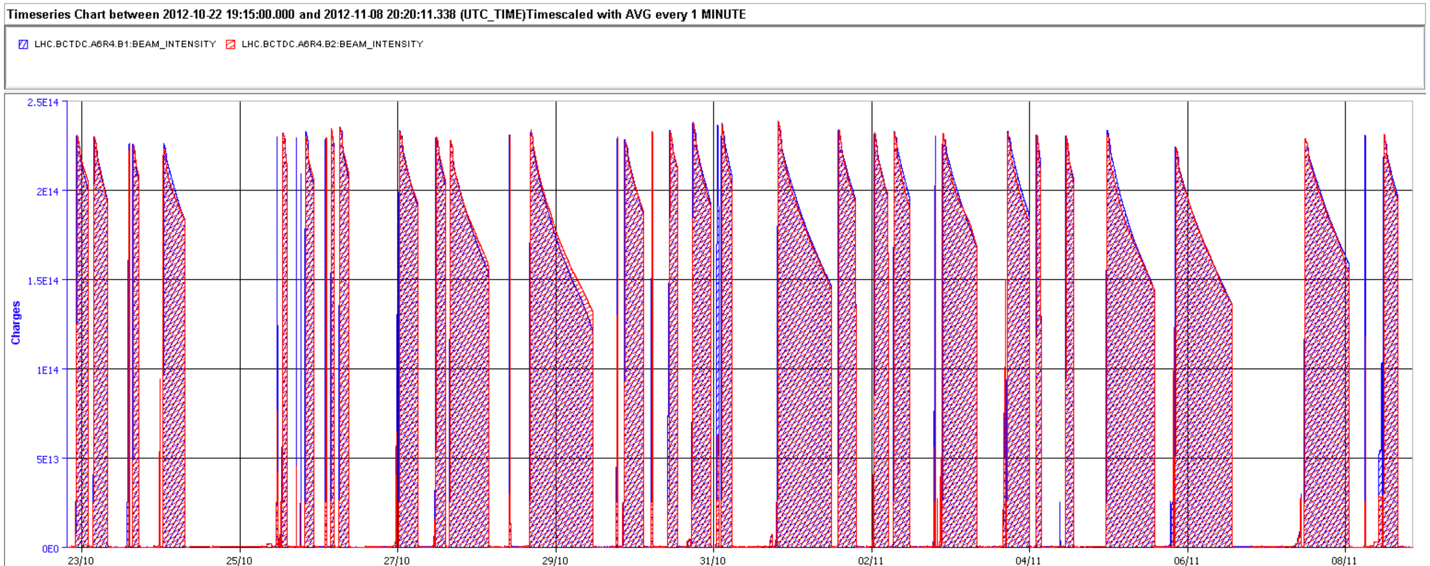
Beam losses

Machine protection diagnostics & sofware

Availability

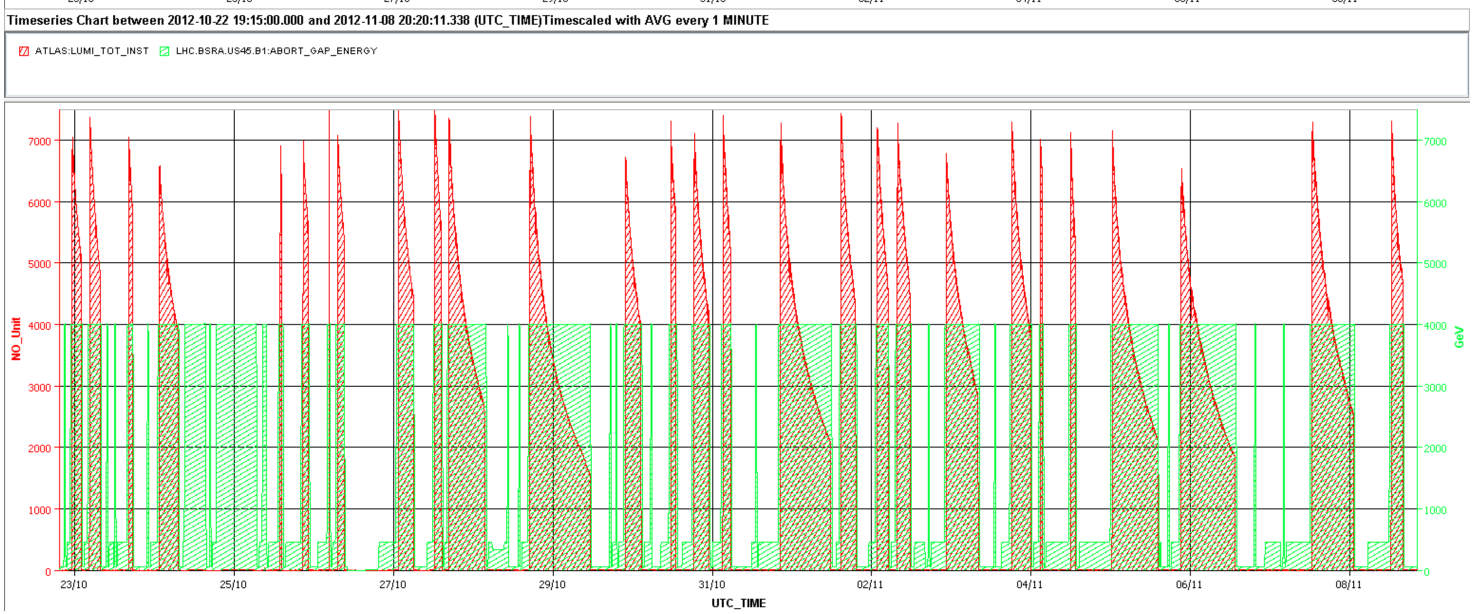
Conclusions

18 typical LHC days



Intensity B1

Intensity B2



Luminosity

Energy

Luminosity lifetime ~ 10 h

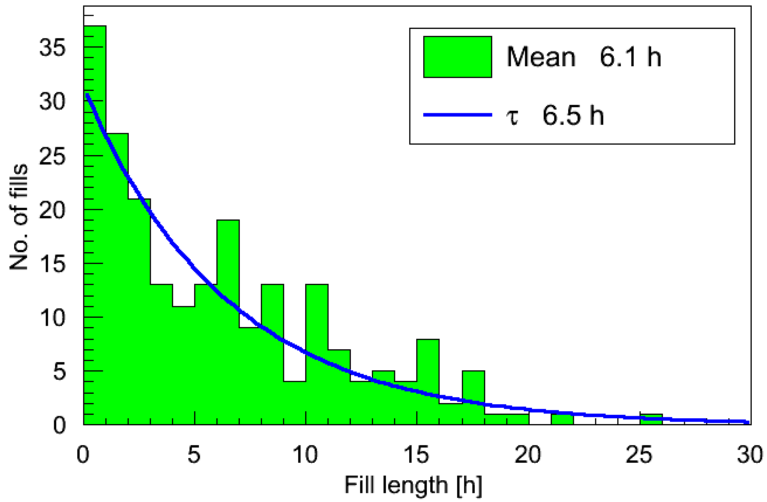
Machine availability

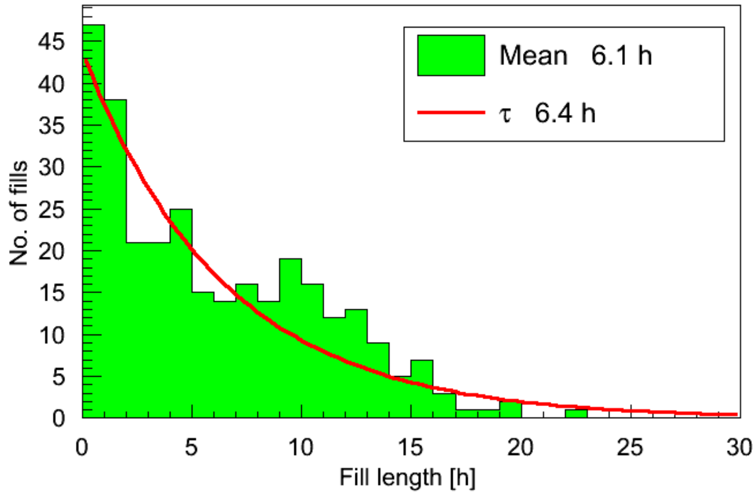
- Besides peak performance in terms of luminosity, the LHC performance depends on the time that is spent colliding beams stably at high energy – availability !

see lecture on by R. Willeke

- Ingredients:
  - Length of the stable collisions for each machine fill,
  - Time required to re-establish those conditions (turn-around time).

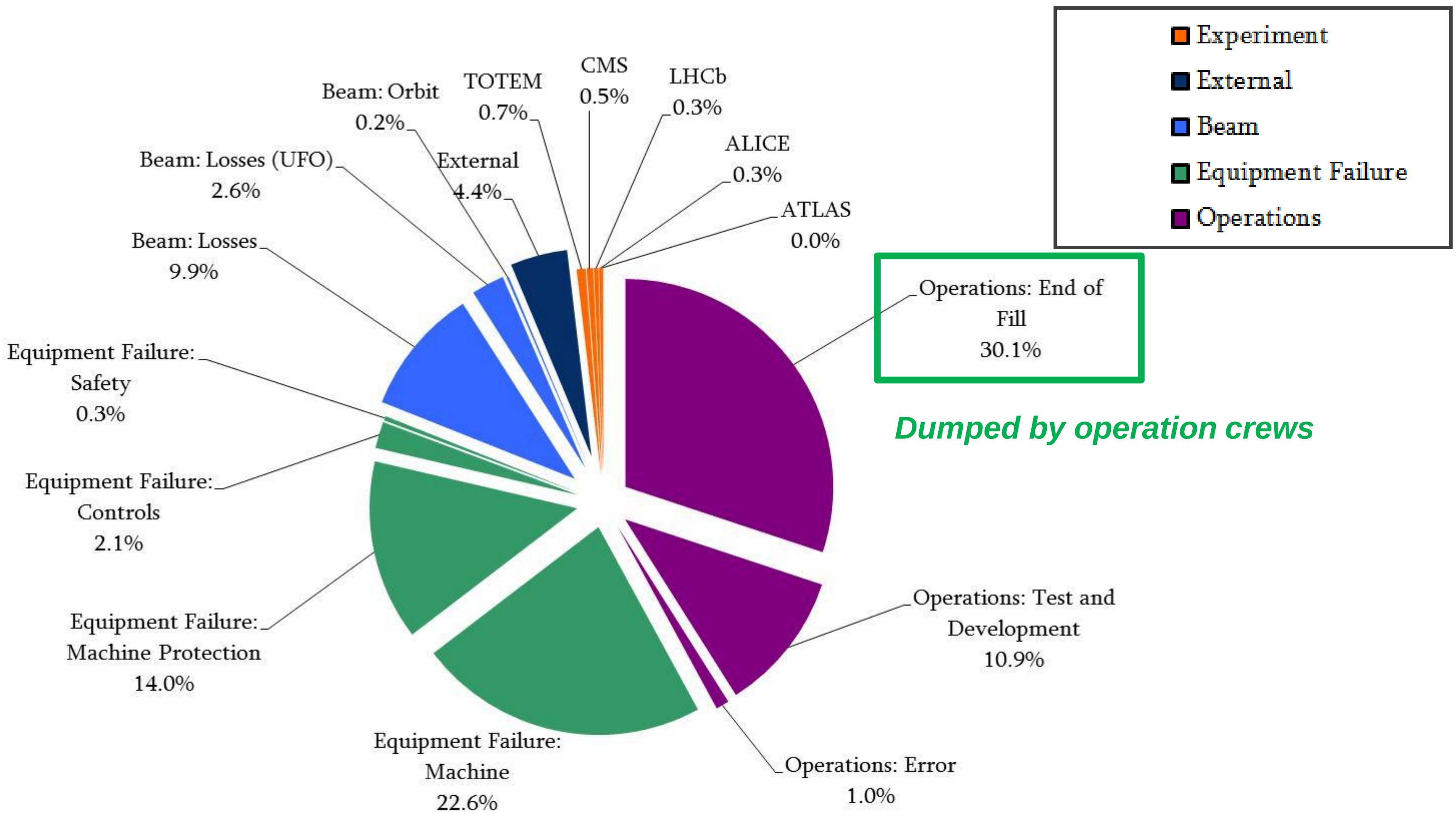
Distribution of fill length (collisions) for 2011 and 2012





The optimal length would be ~12 hours, why is it then so short?

Beam dump causes - 2012

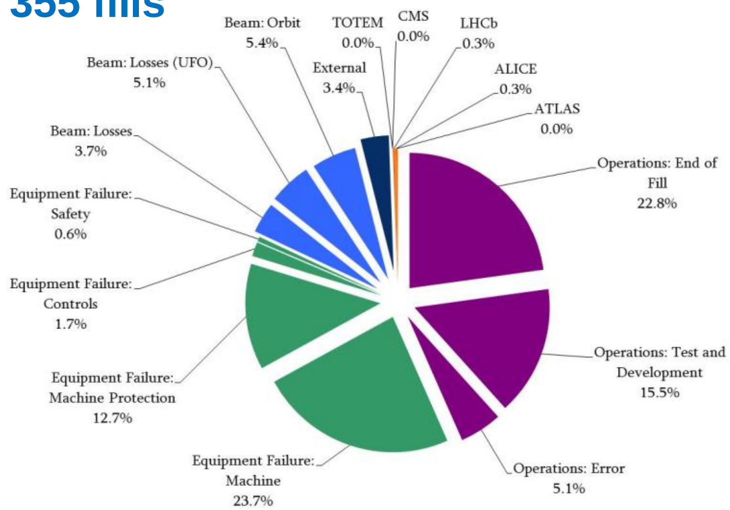


Dumped by operation crews

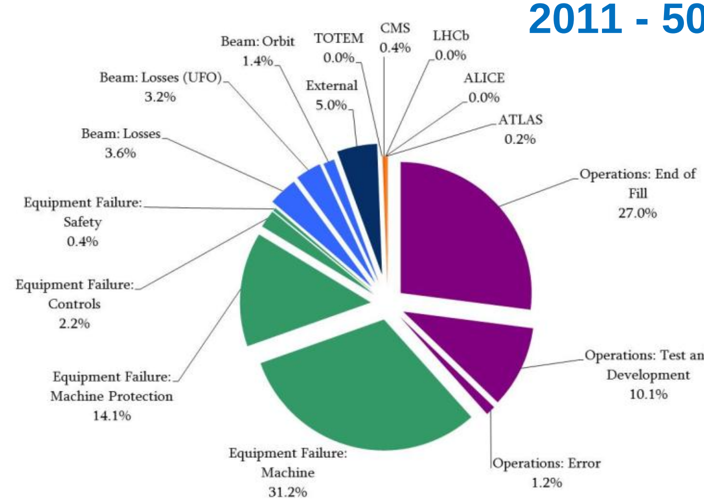
Beam dumps above injection energy

Beam dump causes

2010 - 355 fills



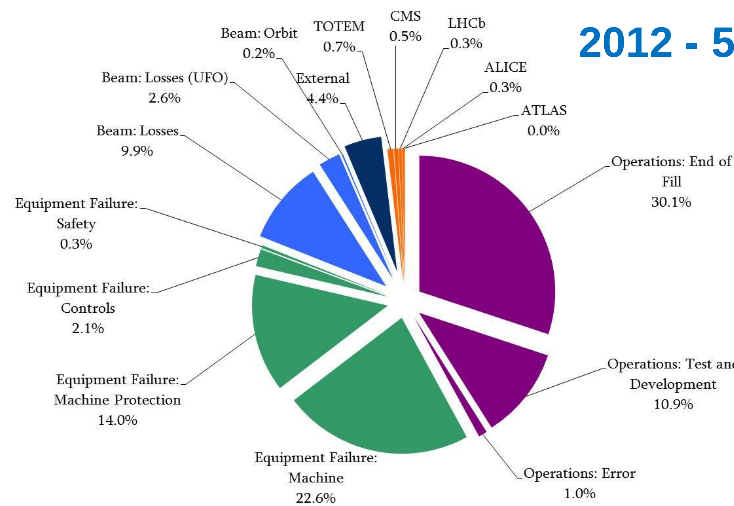
2011 - 503 fills



~14% of the beam dumps are due to the failures of MPS sub-systems:

- ***Quench protection system (radiation to electronics!) 65%***
- ***BLM system 13%***
- ***Beam dumping system 12%***
- ***Software interlock system 5%***
- ***Powering interlock system 2.5%***
- ***Beam interlock system 1.5%***

2012 - 585 fills



2010-2012: very similar statistics (coarse view)

Prediction versus observations

- A reliability working group predicted the rate of false dumps and the safety of the LHC MPS for 7 TeV operation before the LHC was switched on
- This can now be compared with observations.
  - *Attention: 4 TeV operation not exactly equivalent to 7 TeV !*

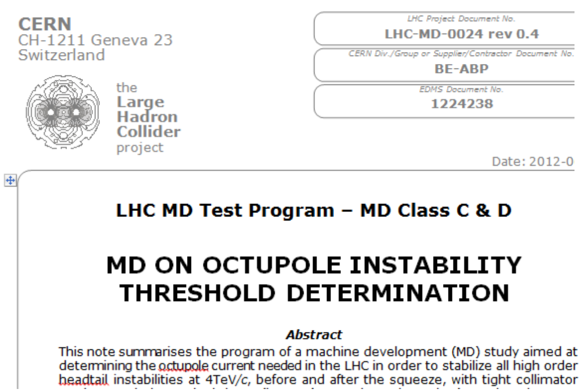
A. Apollonio

System	Predicted 2005	Observed 2010	Observed 2011	Observed 2012
Dump	6.8 ± 3.6	9	11	4
Beam interlock	0.5 ± 0.5	2	1	0
BLM	17.0 ± 4.0	0	4	15
Powering interlock (PIC)	1.5 ± 1.2	2	5	0
Quench protection (QPS)	15.8 ± 3.9	24	48	56

- The observations are ~ in line with predictions, but some failures do not match completely, in particular:
  - *Radiation to electronics was not included in predictions (⇔ PIC, QPS).*
  - *Optical fiber issues (BLMs).*

Machine experiments

- Machine experiments can be very exciting, but also risky periods for a machine – the machine may operate at some *distance from standard conditions*.
  - Collimator settings, orbit and optics may be changed etc
- At the LHC every experiment is categorized according to the foreseen changes to the machine and to intensity.
- Experiments using intensities > SBF limit have to write a detailed description of the changes to machines and the test procedure.
  - In many cases the analysis of the document helped improve the efficiency of the experiment by spotting 'impossible' things.
  - This encourages experimenters to think about options with smaller MP footprint – for example lower intensity – very efficient !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CH-1211 Geneva 23
Switzerland

the Large Hadron Collider project

LHC Project Document No.
LHC-MD-0024 rev 0.4

CERN Div./Group or Supplier/Contractor Document No.
BE-ABP

EDMS Document No.
1224238

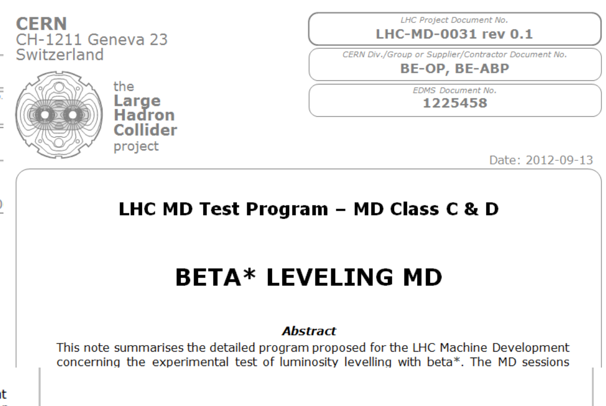
Date: 2012-0

LHC MD Test Program – MD Class C & D

MD ON OCTUPOLE INSTABILITY THRESHOLD DETERMINATION

Abstract

This note summarises the program of a machine development (MD) study aimed at determining the octupole current needed in the LHC in order to stabilize all high order headtail instabilities at 4TeV/c, before and after the squeeze, with tight collimator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BE-OP, BE-ABP

EDMS Document No.
1225458

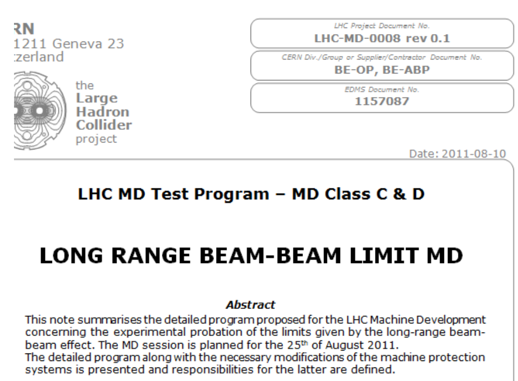
Date: 2012-09-13

LHC MD Test Program – MD Class C & D

BETA* LEVELING MD

Abstract

This note summarises the detailed program proposed for the LHC Machine Development concerning the experimental test of luminosity levelling with beta*. The MD sessions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LHC Project Document No.
LHC-MD-0008 rev 0.1

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BE-OP, BE-ABP

EDMS Document No.
1157087

Date: 2011-08-10

LHC MD Test Program – MD Class C & D

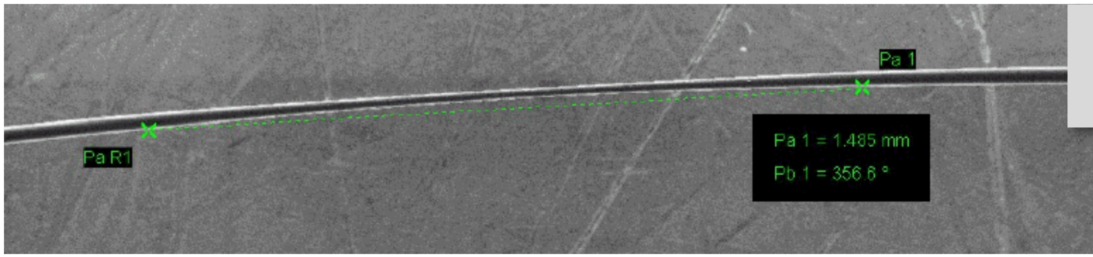
LONG RANGE BEAM-BEAM LIMIT MD

Abstract

This note summarises the detailed program proposed for the LHC Machine Development concerning the experimental probation of the limits given by the long-range beam-beam effect. The MD session is planned for the 25th of August 2011.
The detailed program along with the necessary modifications of the machine protection systems is presented and responsibilities for the latter are defined.

Summary : anything damaged?

- Wire-scanner damage during quench test – ‘deliberate’ action.

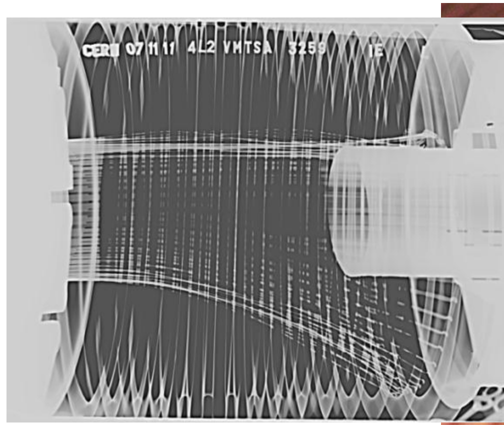


Carbon wire Ø reduction from 30 to 17 μm over a length ~ beam size.

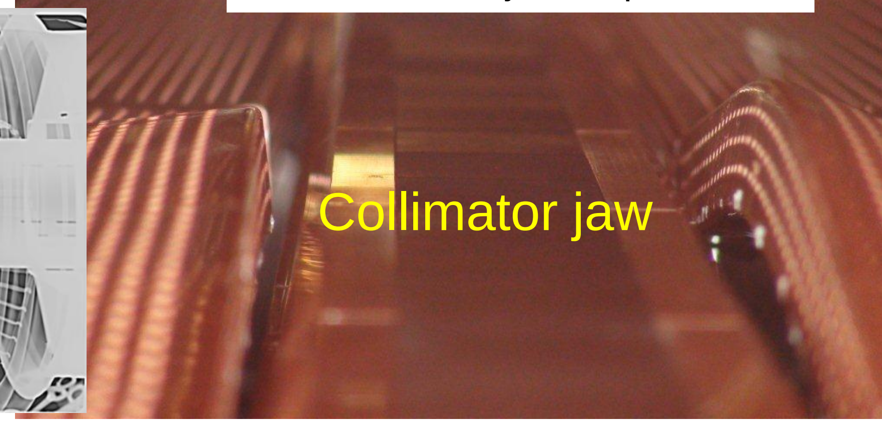
- Beam induced heating – lack of temperature monitoring – edge at MPS

Damaged mirror of the synchrotron light telescope

Damaged RF fingers



Damaged beam screen in a collimator for injection protection



- So far we were successful in protecting the machine !

Summary: outlook

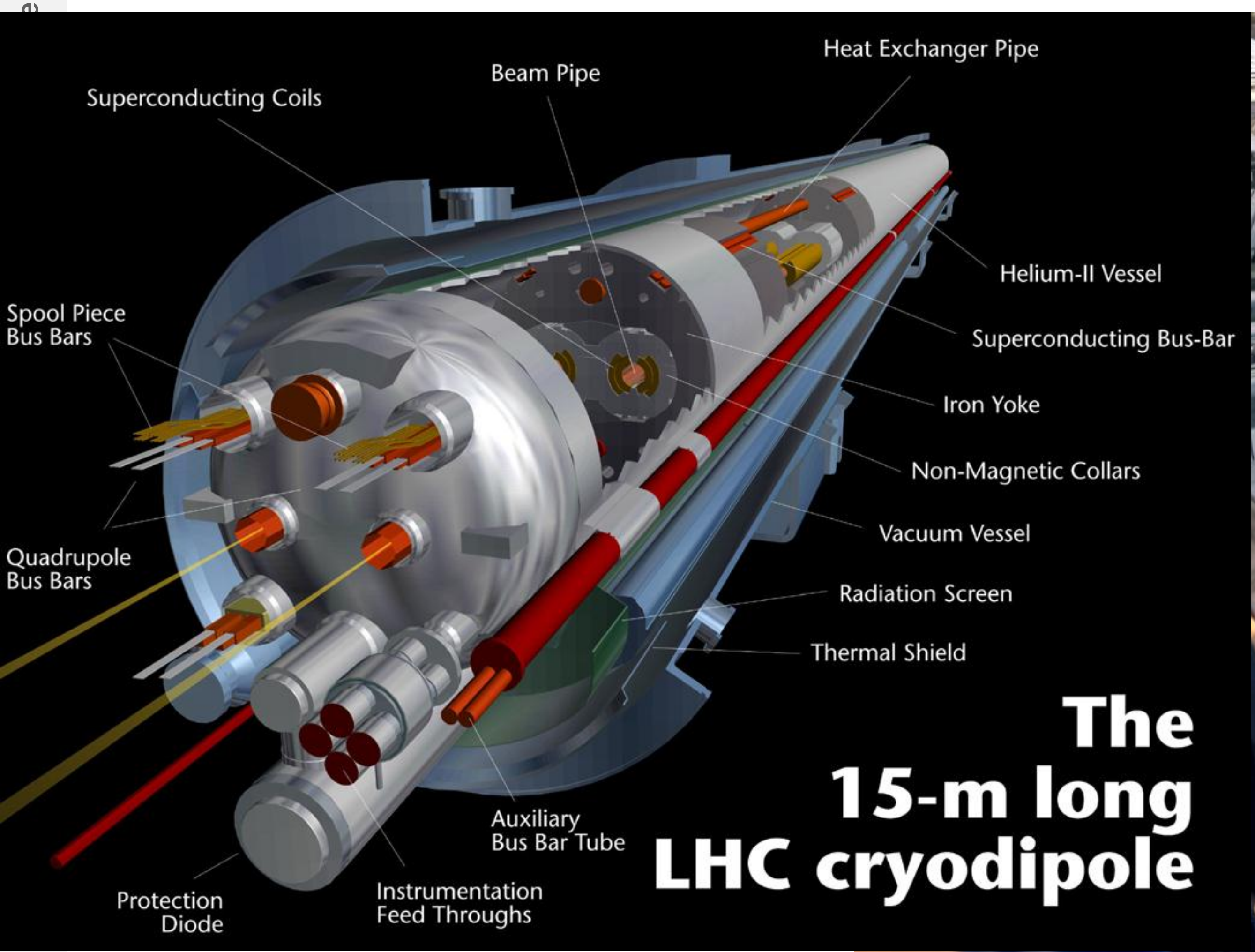
- Despite its huge stored energy and complexity the LHC was operated very successfully at 4 TeV.
- No component was damaged by a failure leading to beam loss – the MPS fulfilled its job!
- From 2015 the energy will be increased to 6.5 TeV: more energy in the beam, and 3-5 times lower quench thresholds.
    - *UFOs may give us some headache – BLM threshold tuning.*
- Now that operation of the LHC is stable, the focus is shifting more and more towards high(er) availability.
    - *MPS is also concerned.*

My colleagues from the experiment are eager to witness the next records!

Thank you for the attention!

Beautiful technology

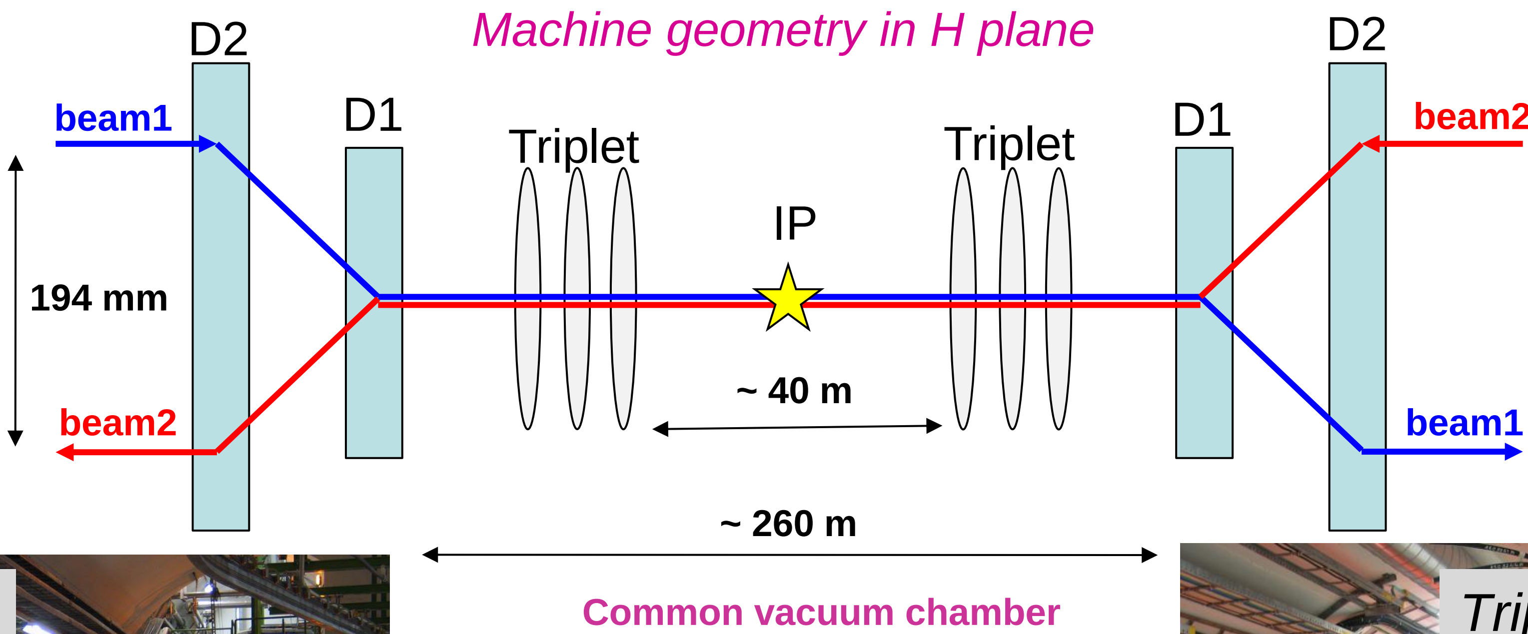
- 1232 NbTi superconducting dipole magnets – each 15 m long
- Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium).
  - *But they do not like beam loss – quench with few mJ/cm^3.*

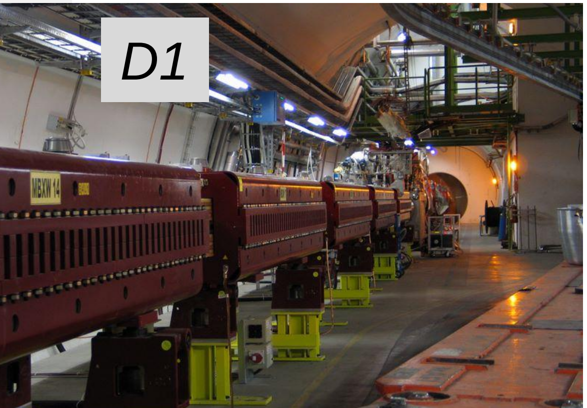


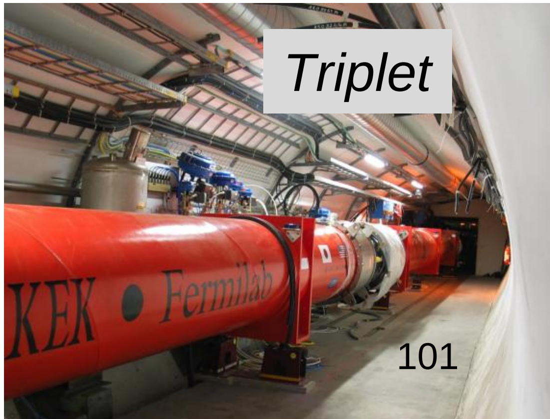
Interaction regions geometry

- In the IRs, the beams are first combined into a single common vacuum chamber and then re-separated in the horizontal plane,
- The beams move from inner to outer bore (or vice-versa),
- The triplet quadrupoles focus the beam at the IP.

D1,D2 : separation/recombination dipoles

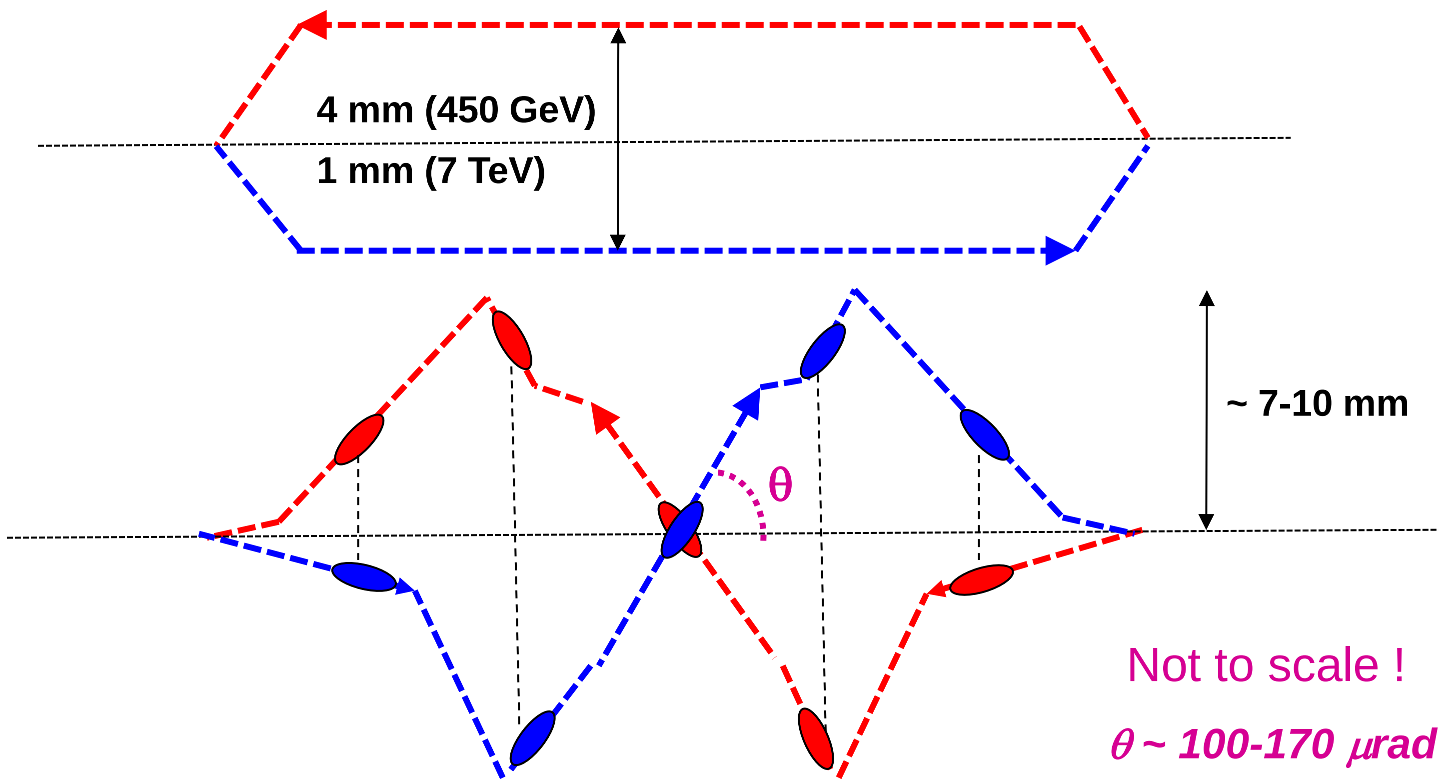






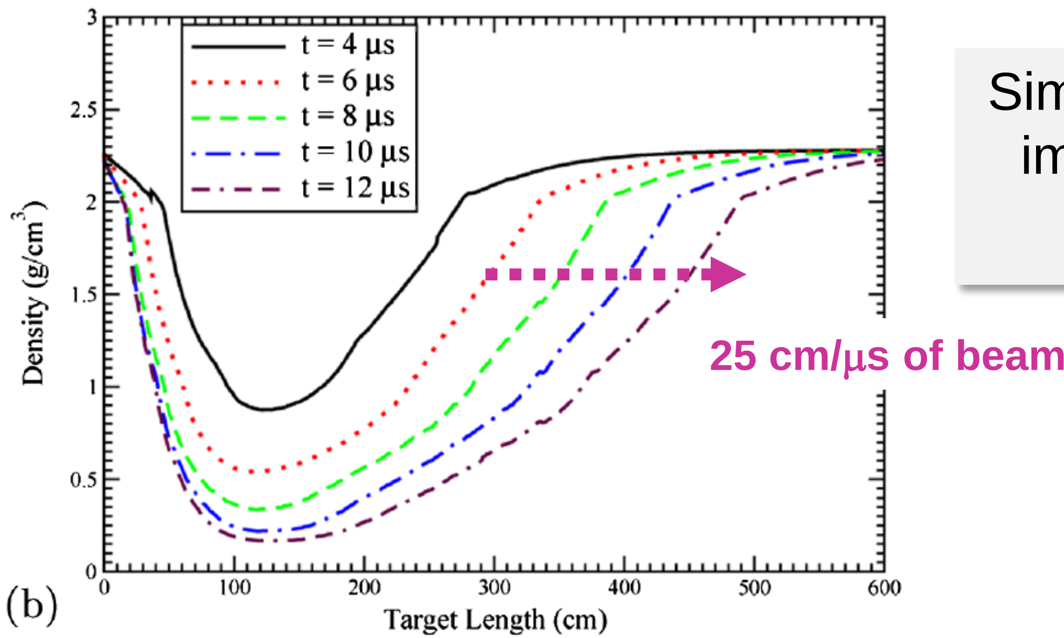
Separation and crossing

- Because of the tight bunch spacing and to prevent undesired parasitic collisions in the common vacuum chamber:
  - Parallel separation in one plane, collapsed to bring the beams in collision.
  - Crossing angle in the other plane (vertical for ATLAS, horizontal for LHCb).
  - Both extend beyond the common region.



Hydrodynamic tunneling

- The criticality of sweeping the beam over the dump surface is due to an effect called **hydrodynamic tunneling.**
- For high intensity beams made of long bunch trains **hydrodynamic tunneling** significantly increases the damage range in a material.
  - *Leading bunches melt the material and create a plasma, the following bunches see less material and penetrate deeper etc.*
  - ***The nominal LHC beam can perforate a ~20 m long Carbon target***.



Simulation of the LHC beam impacting a carbon target

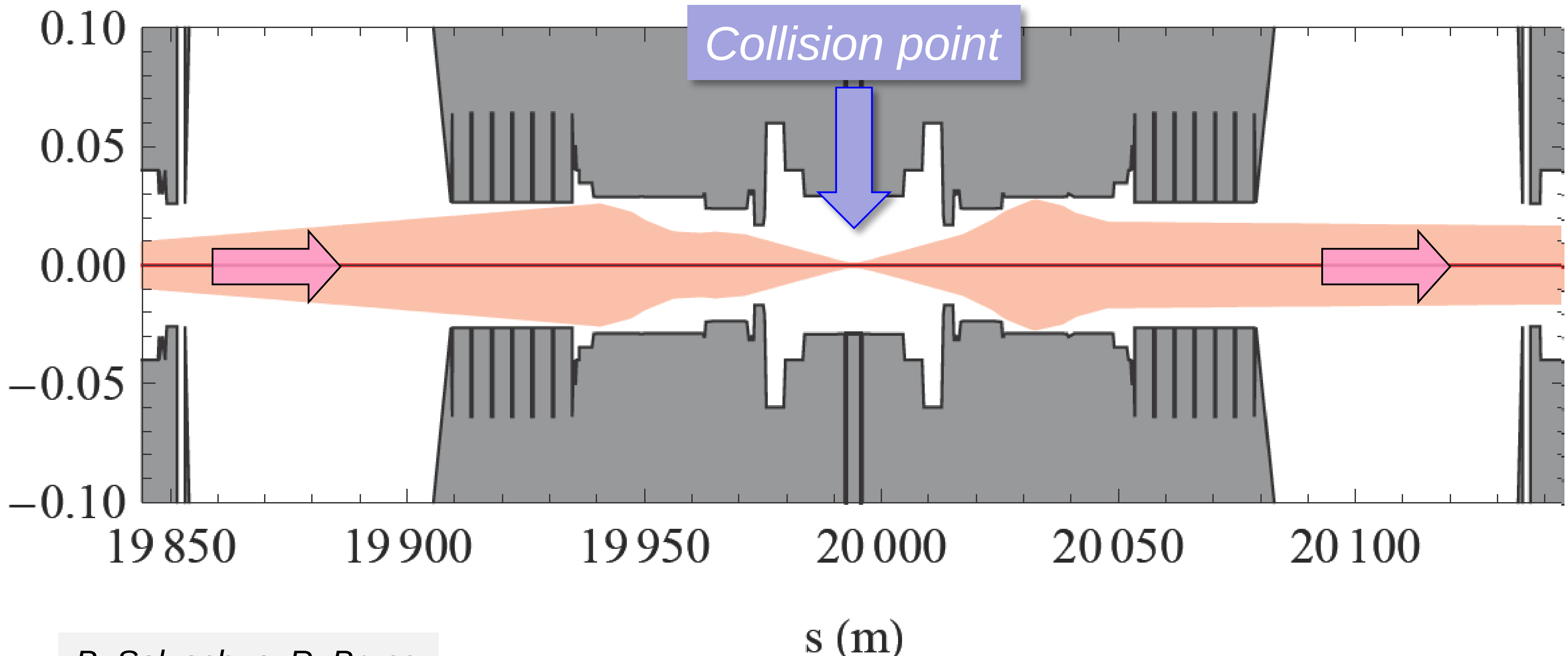
(no sweep !)

Penetration of ~20 m

see lecture by A. Bertarelli

Aperture 'evolution'

- At injection and with a optics that is not squeeze at the collision point, the LHC aperture limitations is far away from the experiments.
- As the beam size is squeeze at the IP, the aperture restriction moves towards the quadrupole magnets just around the experiments.
  - *Those quadrupoles are shadowed but tungsten collimators.*



B. Salvachua, R. Bruce

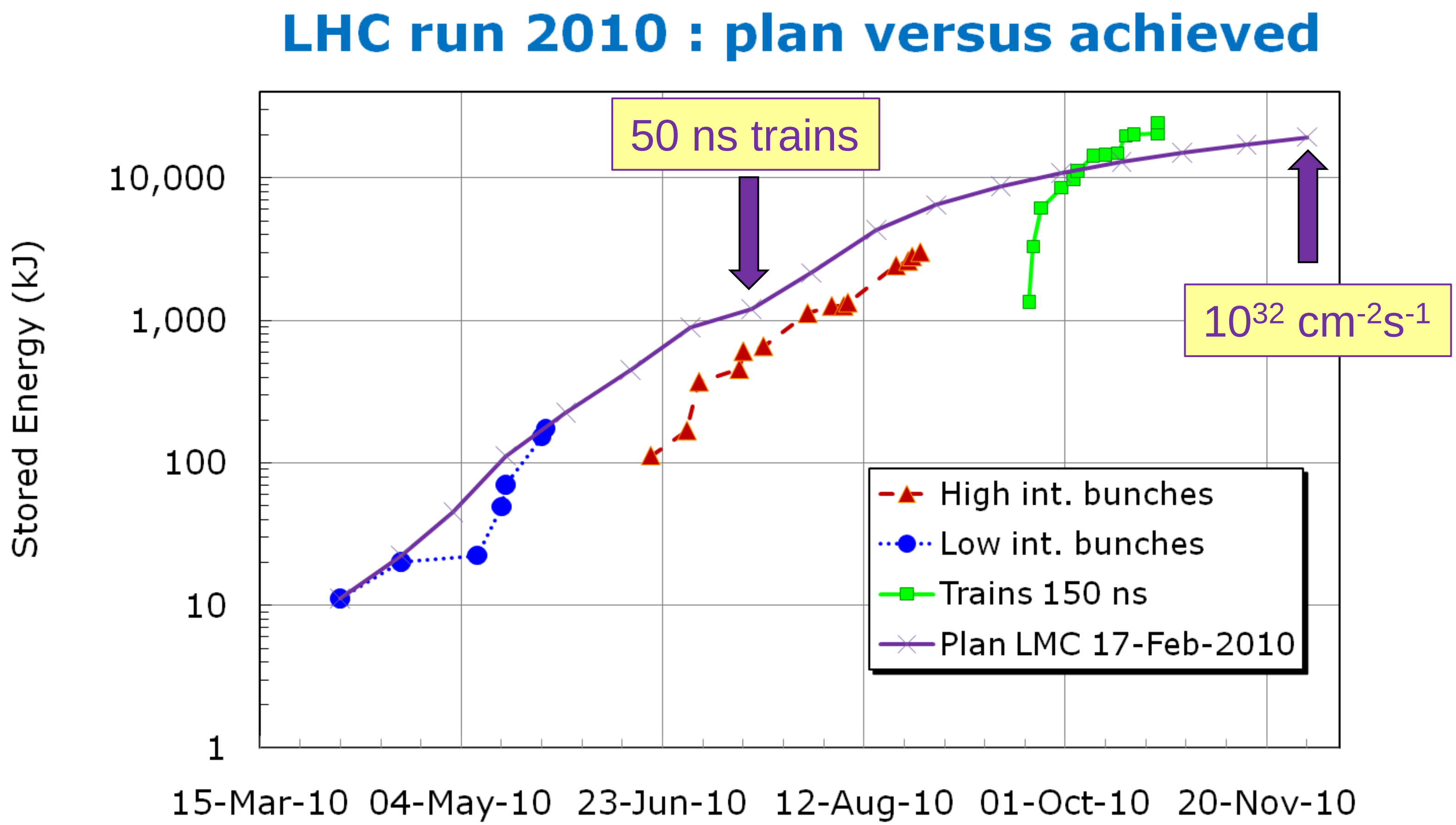
Plan (February 2010) versus reality

Plan:

- Commissioning 'in the shadow' of physics OP.
- 50 ns bunch spacing.

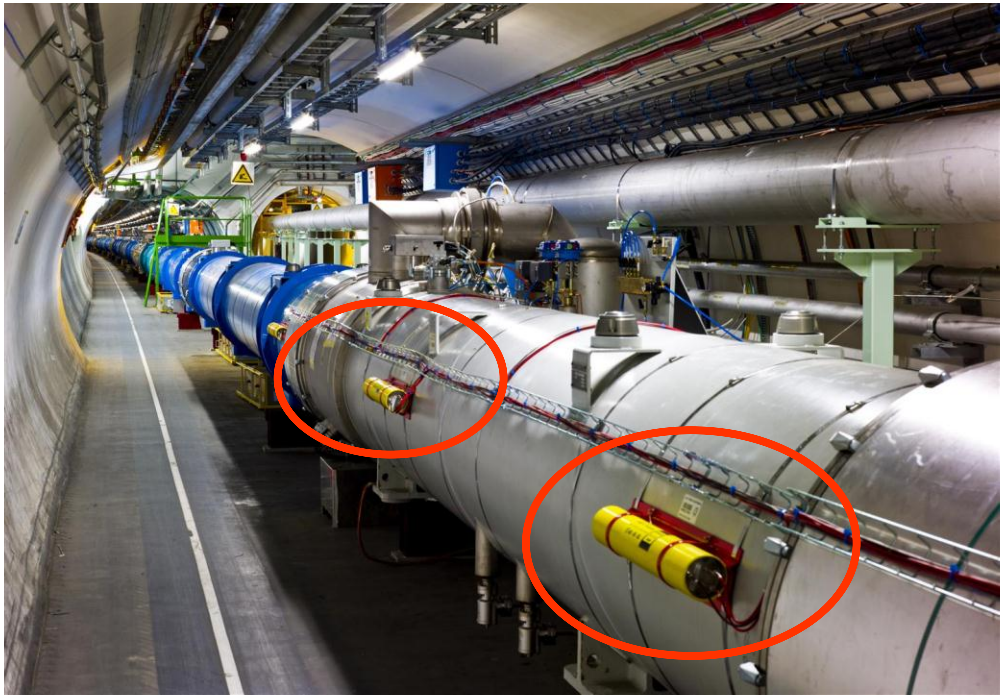
Reality:

- Higher bunch charge.
- Commissioning not transparent.
- Steeper slope (x4) in final phase since no problems were encountered.



Beam loss monitoring

- Ionization chambers are used to detect beam losses:
  - Very fast reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- ~**3600** chambers (BLMS) are distributed over the LHC to detect beam losses and trigger a beam abort !
- BLMs are good for almost all failures as long as they last ~ a few turns (few 0.1 ms) or more !



Comparison – high intensity target

- For comparison the intensity ramp up of the CNGS beam at the CERN SPS (~4x10^{13} p at 400 GeV, ~ 2 MJ) lasted 6 weeks in 2008, a few days in 2009.
  - *3 steps in intensity on target for initial ramp up in 2008,*
  - *Steered by 3 persons (for MP+OP, OP, target).*
- The rates depend a lot on the facility, its commissioning stage, 'emotional factors' & pressures etc.