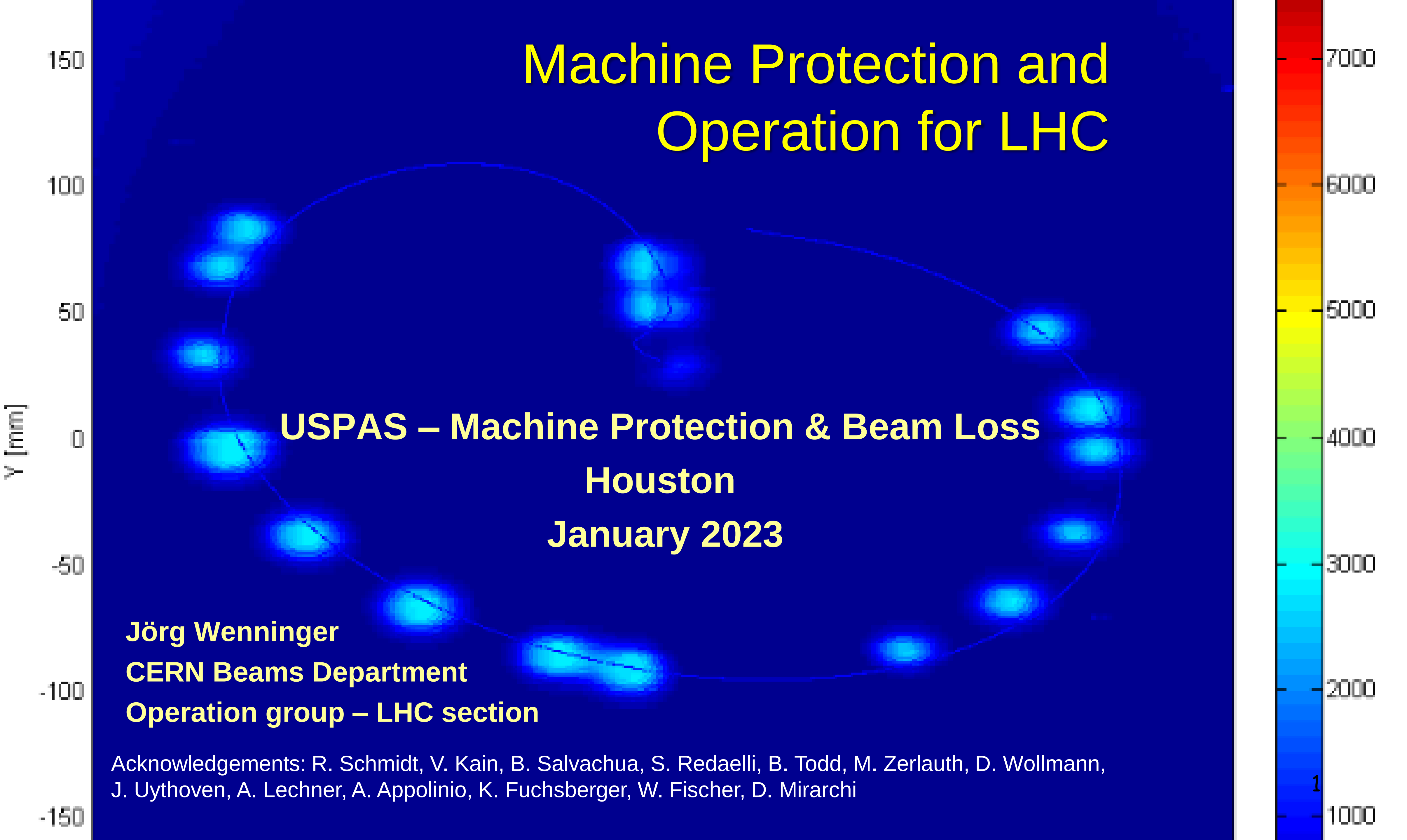


Machine Protection and Operation for LHC

USPAS – Machine Protection & Beam Loss

Houston

January 2023

Jörg Wenninger
CERN Beams Department
Operation group – LHC section

Acknowledgements: R. Schmidt, V. Kain, B. Salvachua, S. Redaelli, B. Todd, M. Zerlauth, D. Wollmann, J. Uythoven, A. Lechner, A. Appolinio, K. Fuchsberger, W. Fischer, D. Mirarchi

Introduction to LHC

Magnet powering and incident

Beam interlock system

Commissioning

Intensity ramp up

Beam losses and *very* special ultra-fast failures

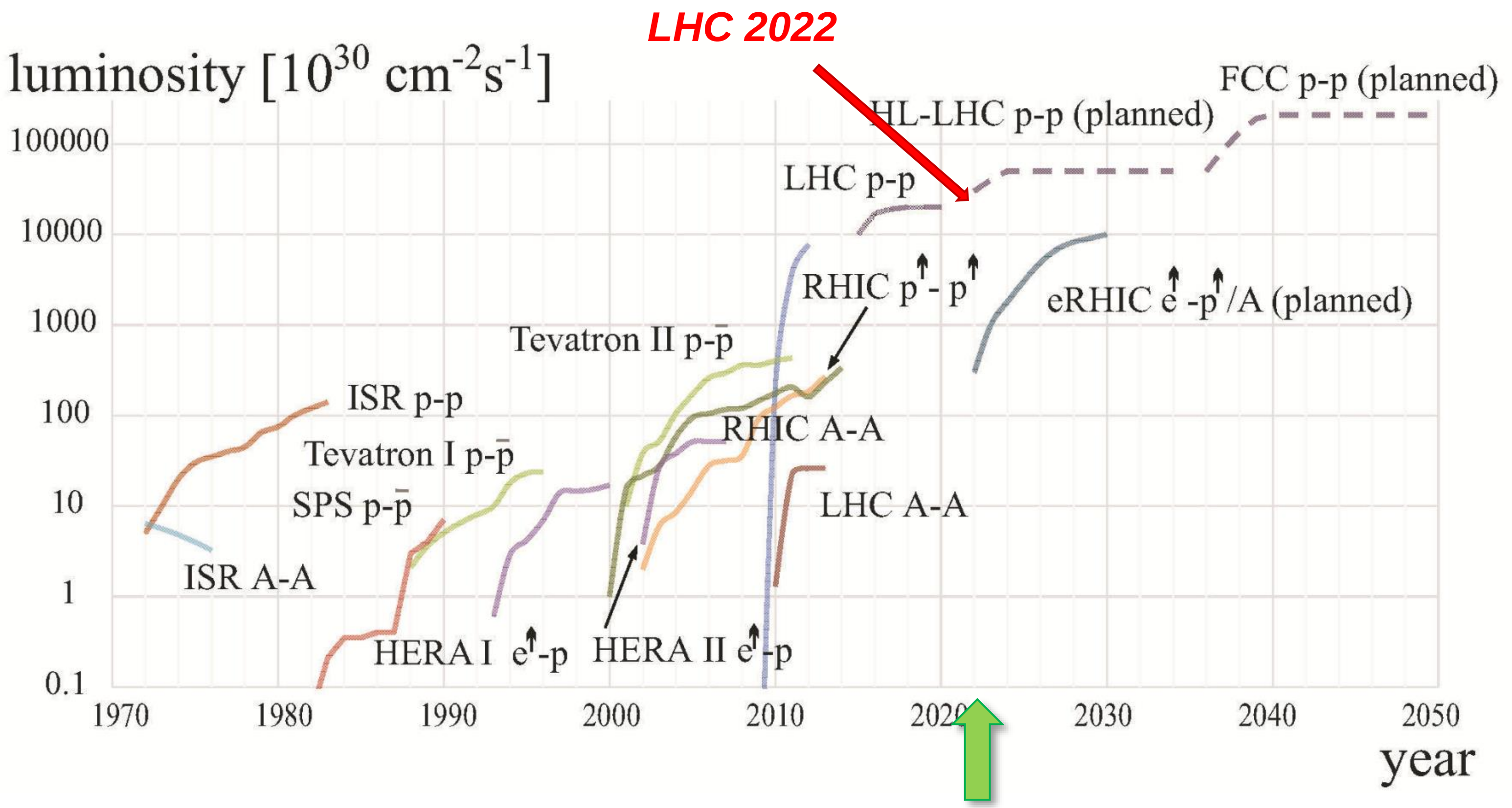
Machine protection diagnostics & software

Conclusions

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.

- *The luminosity gain is mainly achieved with very high beam intensity.*



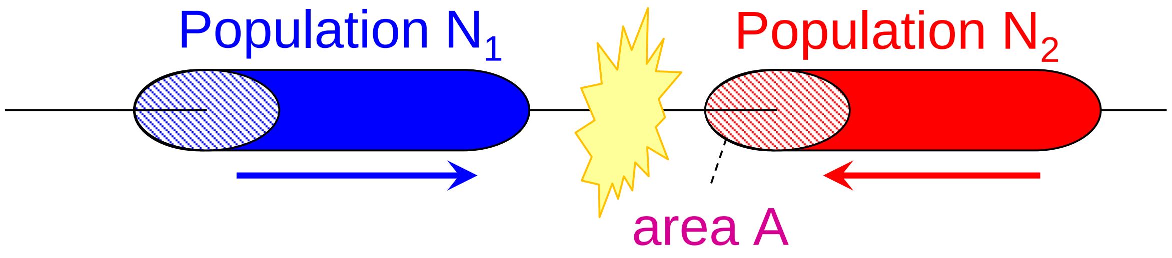
W. Fischer

Collider Luminosity

The key parameter for the experiments is the event rate dN/dt. For a physics process with *cross-section σ* it is proprotional to the collider **Luminosity *L***:

$$dN/dt = L\sigma$$

unit of L :
1/(surface × time)

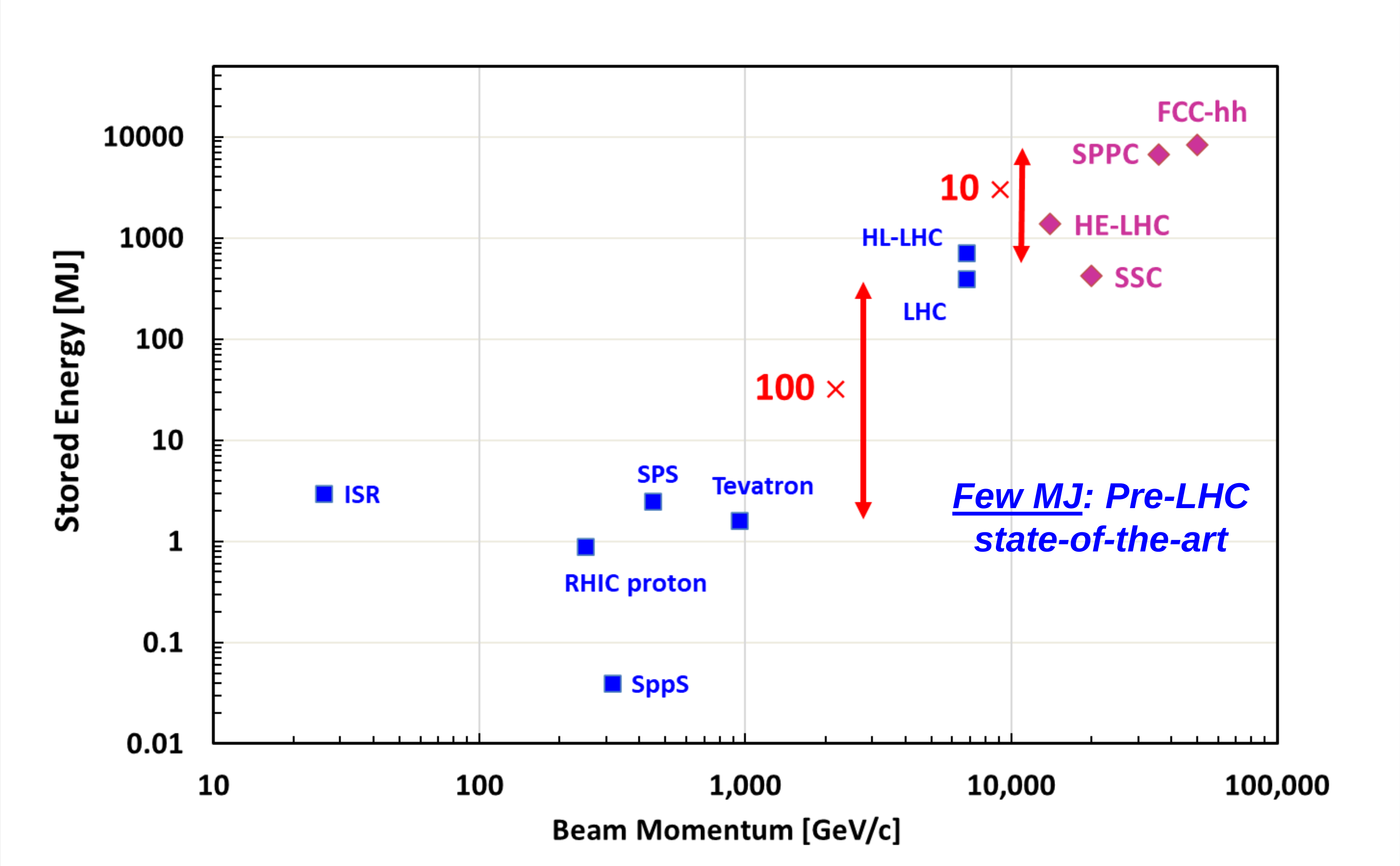


$$\text{Collision rate} \propto \sigma \times \underbrace{\frac{N1 \times N2}{A} \times \text{encounters/second}}_{L}$$

To maximize L we have to squeeze as many particles as possible into the smallest possible volume !

Stored energy: past – present – future

LHC pushed the stored energy from few MJ to > 100 MJ



HL-LHC: High Luminosity LHC, startup in 2029 (evolution of LHC).

SSC: Super Conducting Super collider, US project canceled in 1993

HE-LHC: High Energy variant of LHC (2x energy) – not pursued anymore.

FCC-hh: Future Circular Collider (100 km) hadron version, > 2060?

SPPC : Chinese version of FCC-hh.

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.

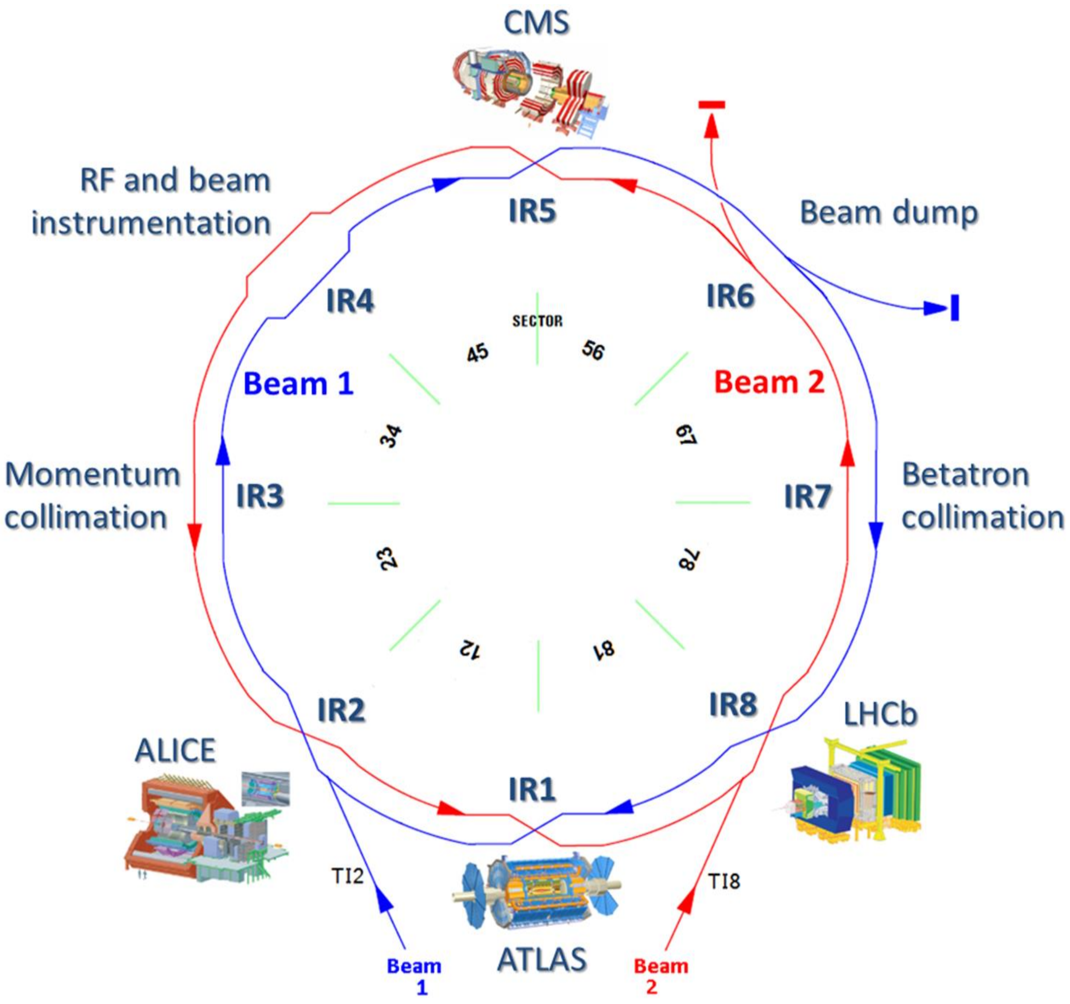
2-in-1 magnet design with separate vacuum chambers.

2 COUPLED rings.

Injection at 450 GeV, operation at 6.5 TeV since 2015.

The beam intensity (number bunches) is very high thanks to the double ring layout – modern '**factory**' design.

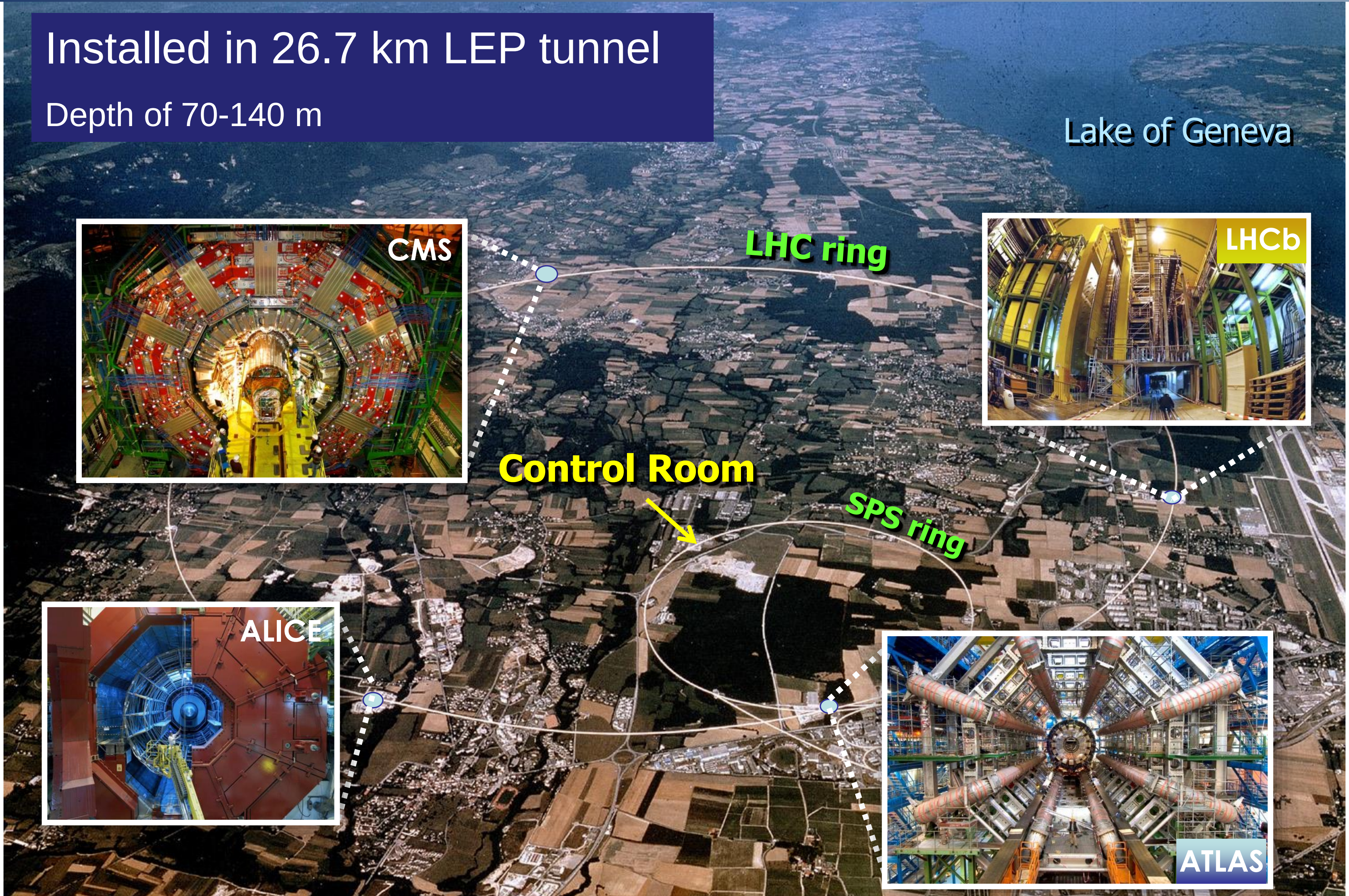
The LHC can be operated with protons and ions (so far Pb_{208})



LHC layout


Installed in 26.7 km LEP tunnel
Depth of 50-170 m
Lake of Geneva
LHC ring
Control Room
SPS ring

LHC layout

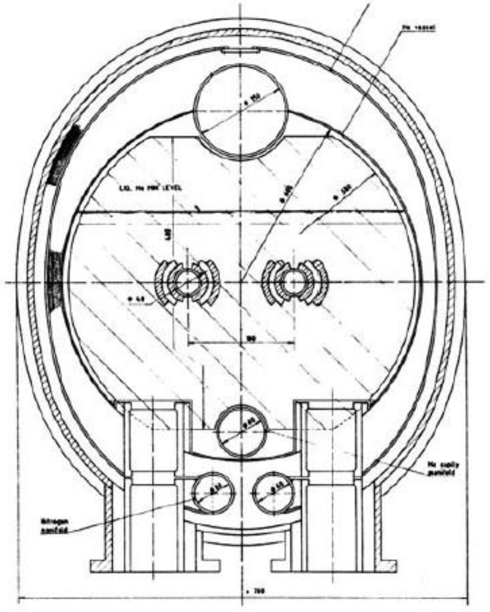


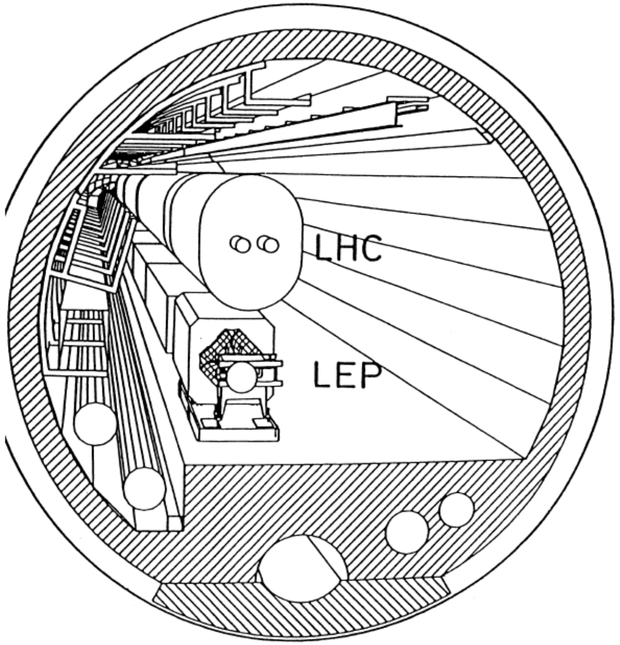
Installed in 26.7 km LEP tunnel
Depth of 70-140 m
Lake of Geneva
CMS
LHC ring
LHCb
Control Room
SPS ring
ALICE
ATLAS

LHC challenges and choices

Initial design choices:

- High magnetic fields – 8T,
  - *⇒ super-conducting magnets*
- 2-in-1 magnet design,
- Superfluid Helium,
- Luminosity ~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

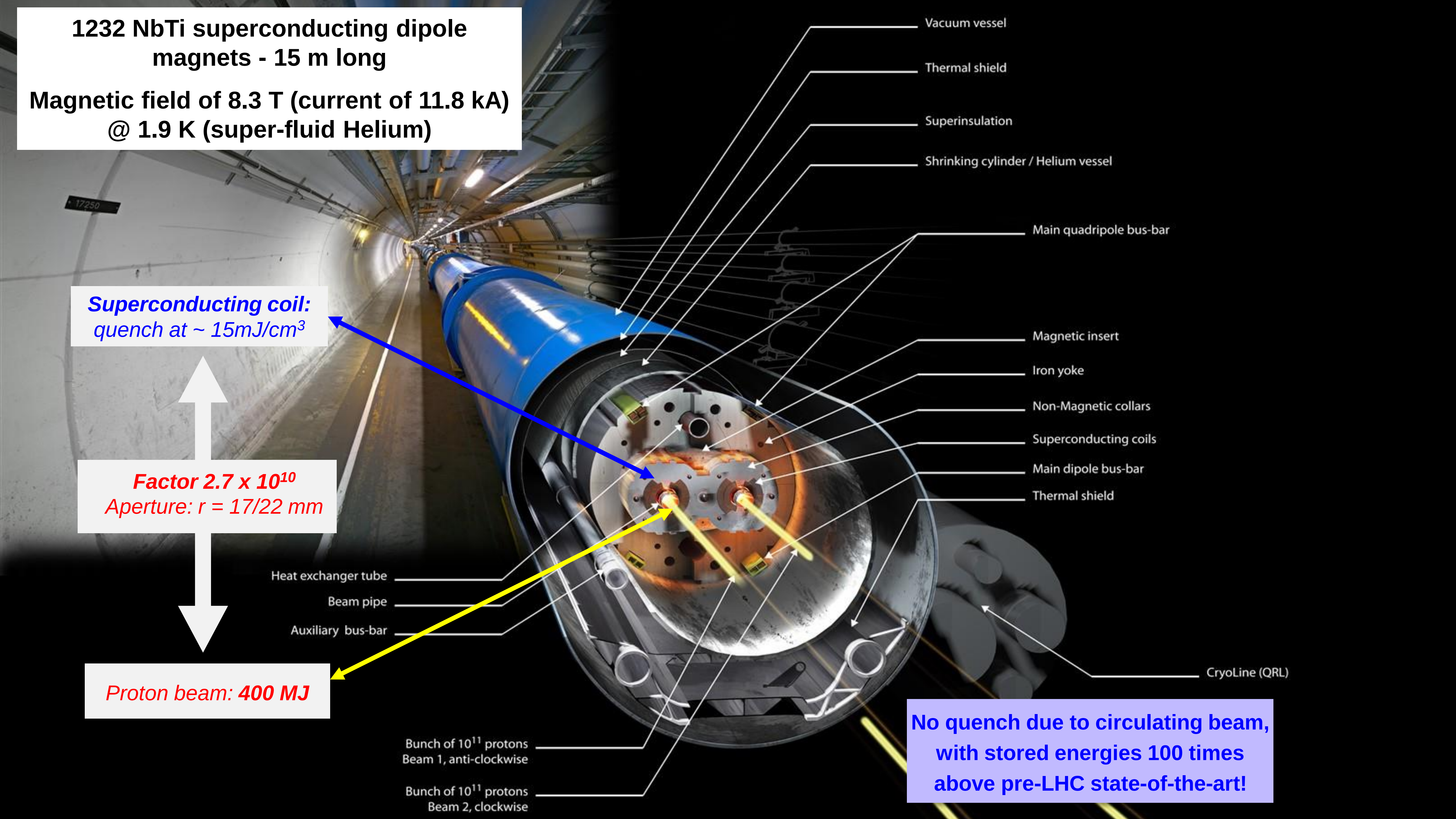
held at Lausanne and Geneva,
21–27 March 1984

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

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

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

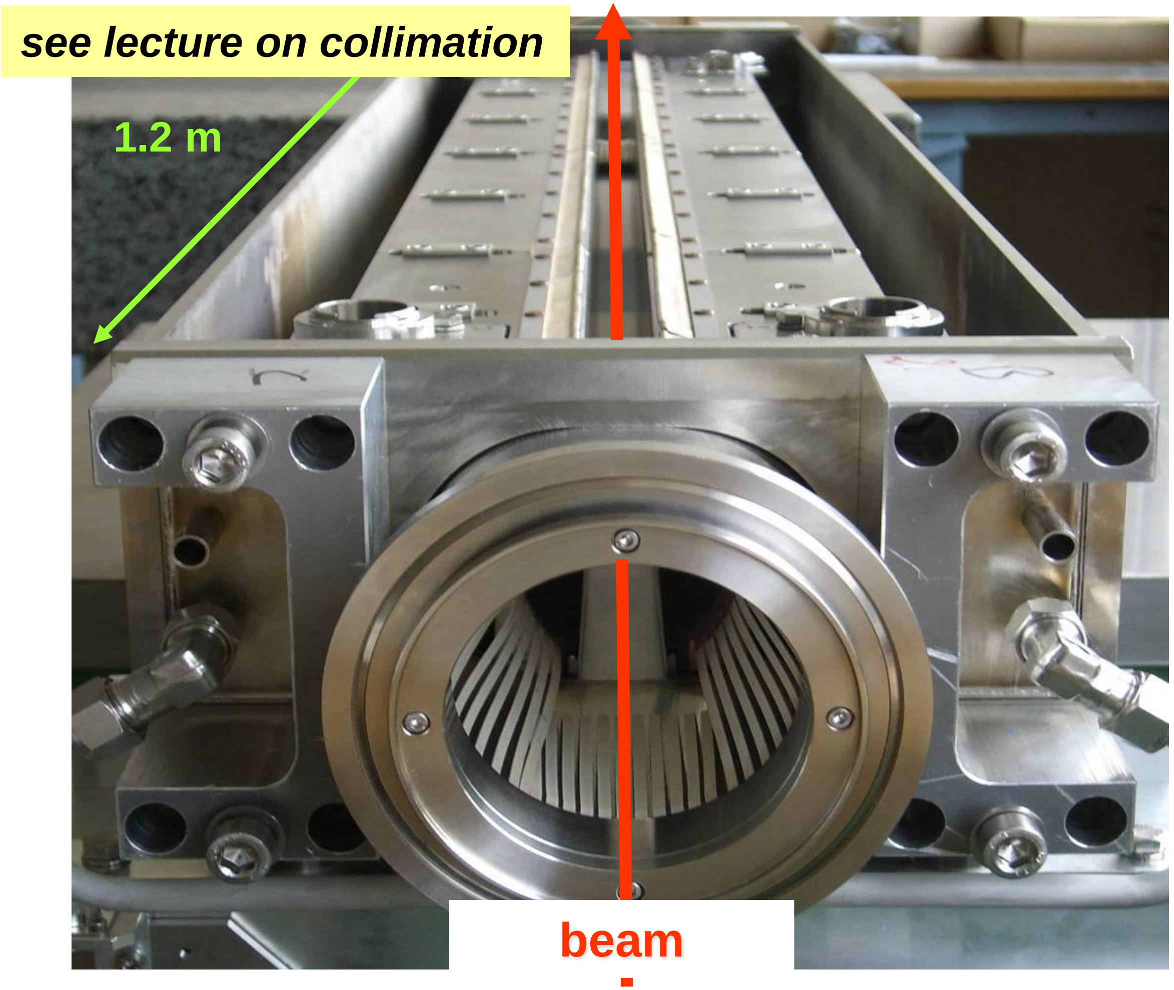
High luminosity → high intensity → MPS !!


1232 NbTi superconducting dipole magnets - 15 m long
Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)
Superconducting coil: quench at ~ 15mJ/cm3
Factor 2.7 x 1010
Aperture: r = 17/22 mm
Proton beam: 400 MJ
No quench due to circulating beam, with stored energies 100 times above pre-LHC state-of-the-art!
Vacuum vessel
Thermal shield
Superinsulation
Shrinking cylinder / Helium vessel
Main quadripole bus-bar
Magnetic insert
Iron yoke
Non-Magnetic collars
Superconducting coils
Main dipole bus-bar
Thermal shield
CryoLine (QRL)
Heat exchanger tube
Beam pipe
Auxiliary bus-bar
Bunch of 1011 protons Beam 1, anti-clockwise
Bunch of 1011 protons Beam 2, clockwise

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.*

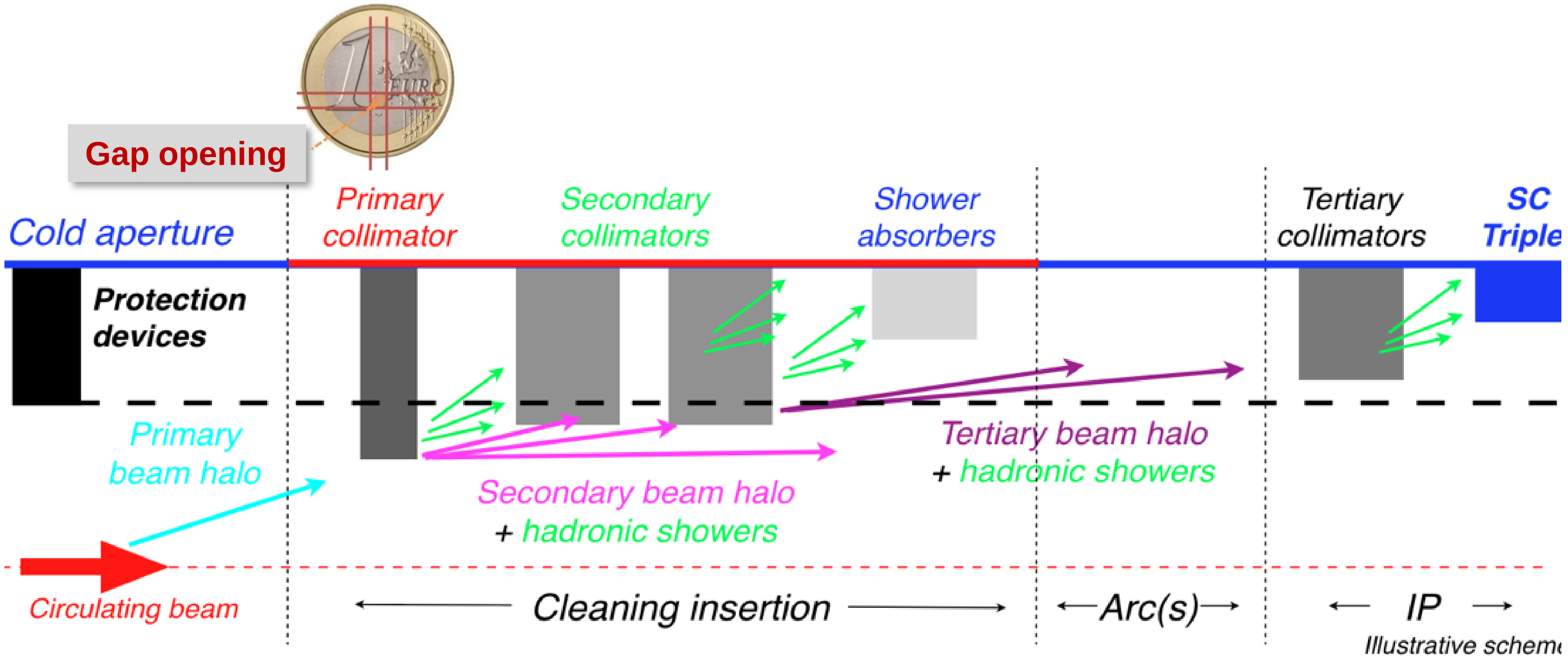


Over ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

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– 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.
- No quench with circulating beam (only during injection or dedicated quench tests).

Beam loss monitoring

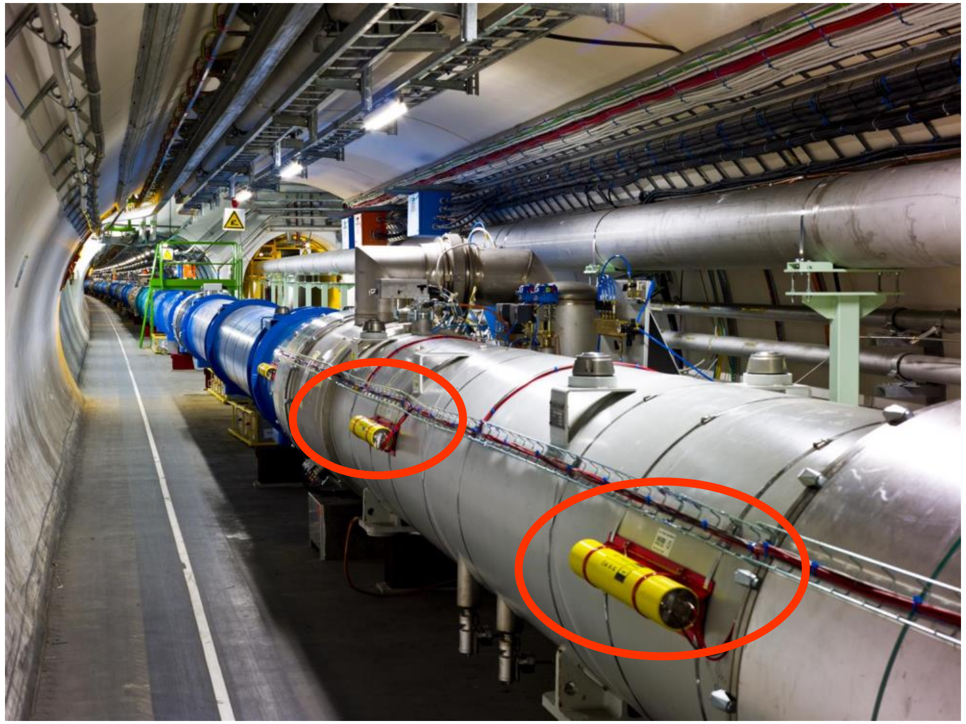
Ionization chambers are used to detect beam losses at LHC:

- Very fast reaction time ~ ½ turn (40 μs)
- Very large dynamic range (> 10^6)

~**4000** chambers (BLMS) are distributed over the LHC to detect beam losses and trigger a beam abort !

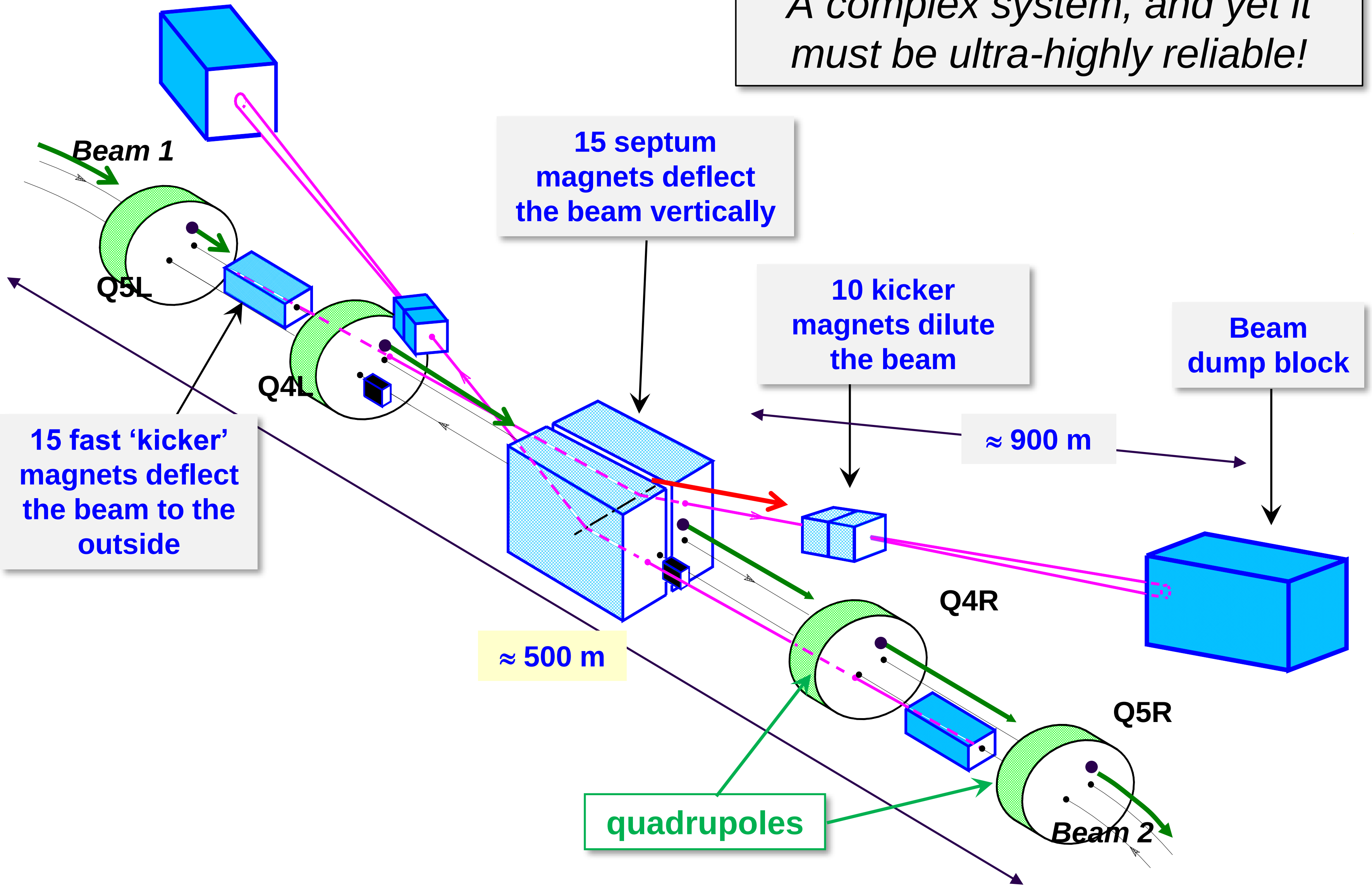
- Each individual monitor can dump the beam.

BLMs cover almost all failures for failure time constant of ~ at least few turns (few 0.1 ms)



LHC beam dumping system

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



Dump line to dump cavern

Dump cavern

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.

see lecture on collimation

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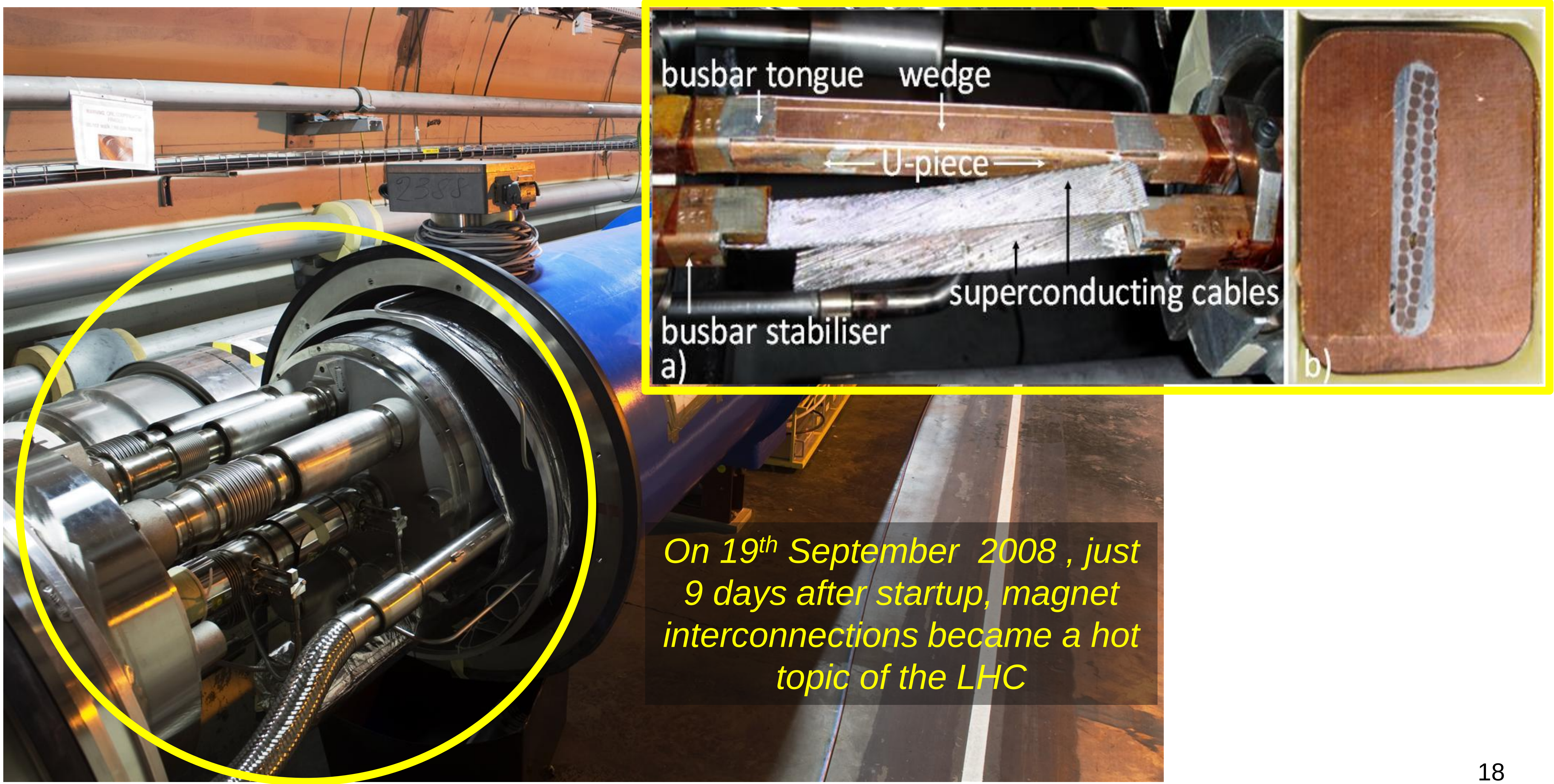
LHC magnet interconnection



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

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.

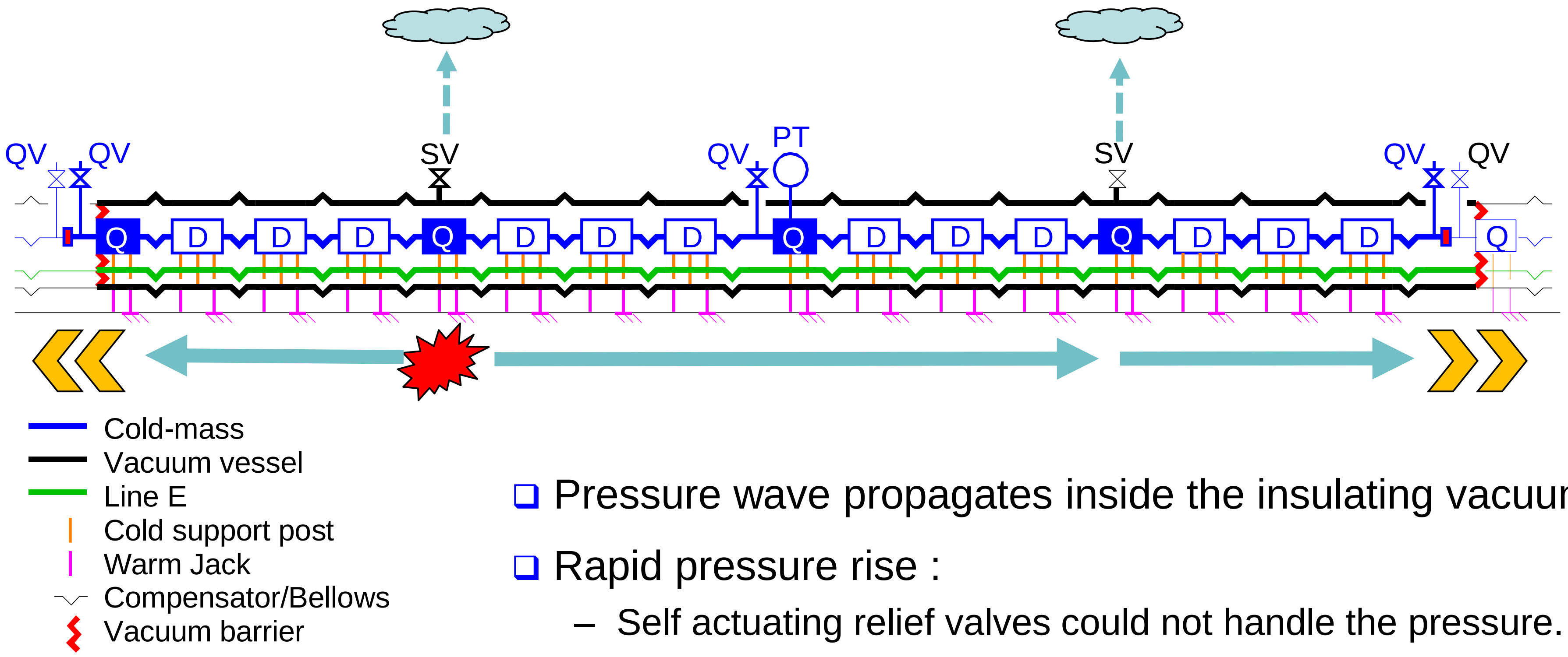
  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.

- Large amounts of Helium were released into the insulating vacuum.

  In total 6 tons of He were released.

This incident involved magnet powering - no beam!

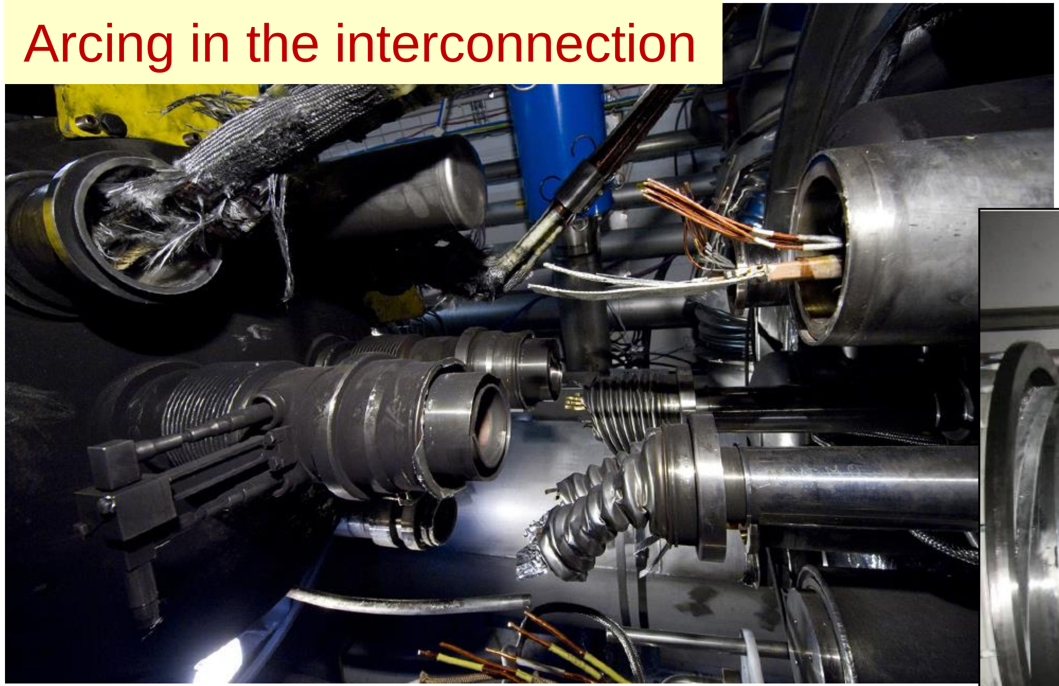
Helium pressure wave

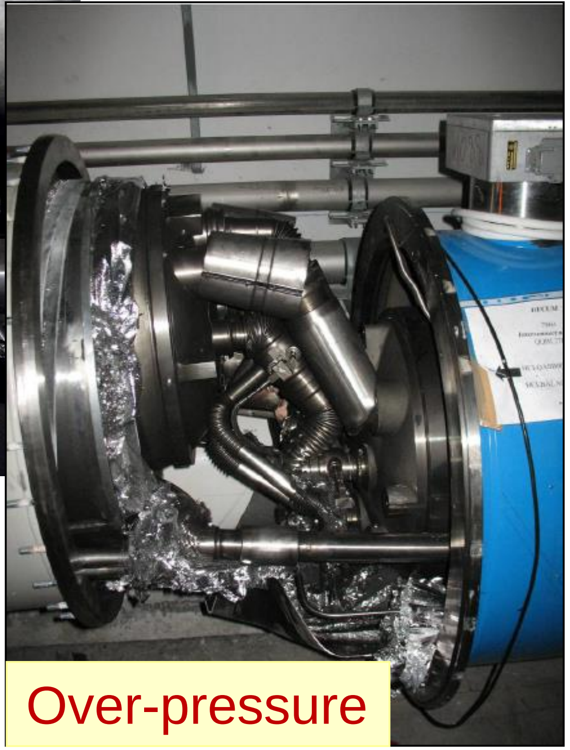


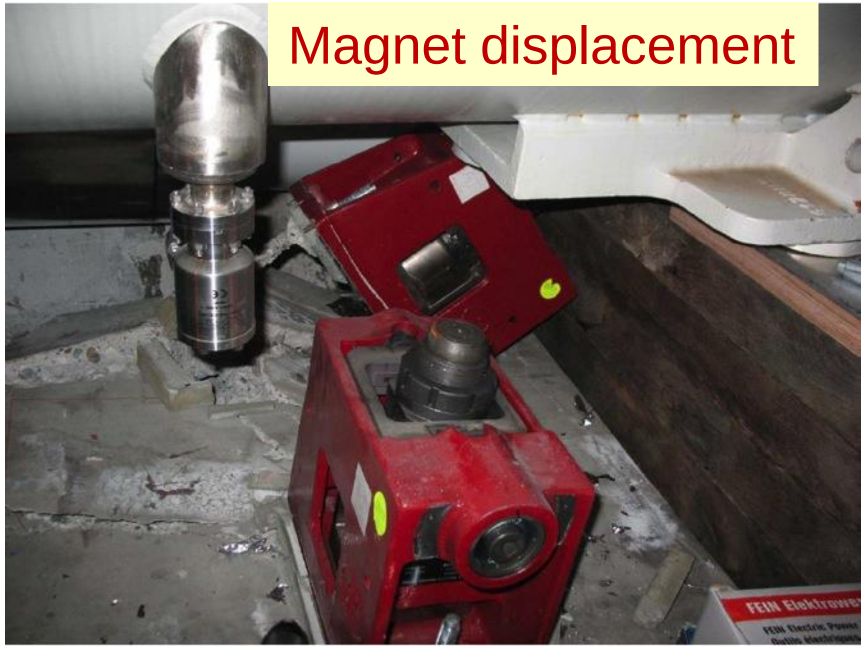
- Pressure wave propagates inside the insulating vacuum enclosure.
- Rapid pressure rise :
  - Self actuating relief valves could not handle the pressure.
    designed for 2 kg He/s, incident ~ 20 kg/s.
  - Large forces exerted on the vacuum barriers (every 2 cells).
    designed for a pressure of 1.5 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.

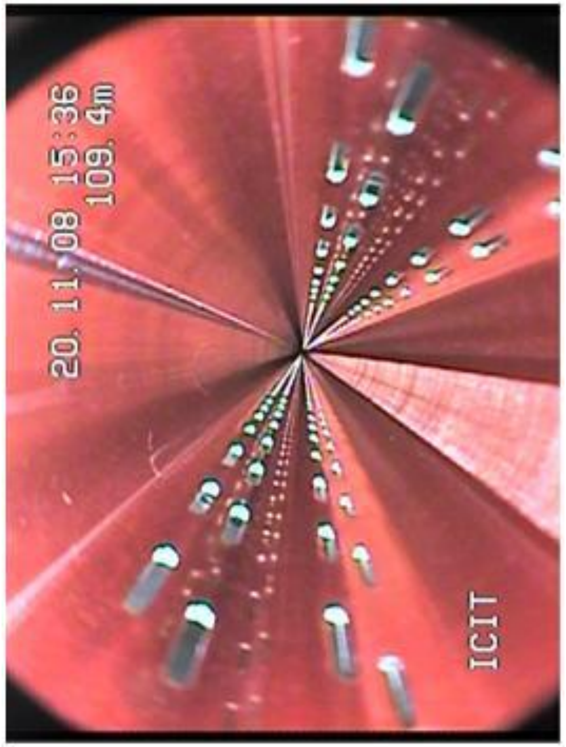
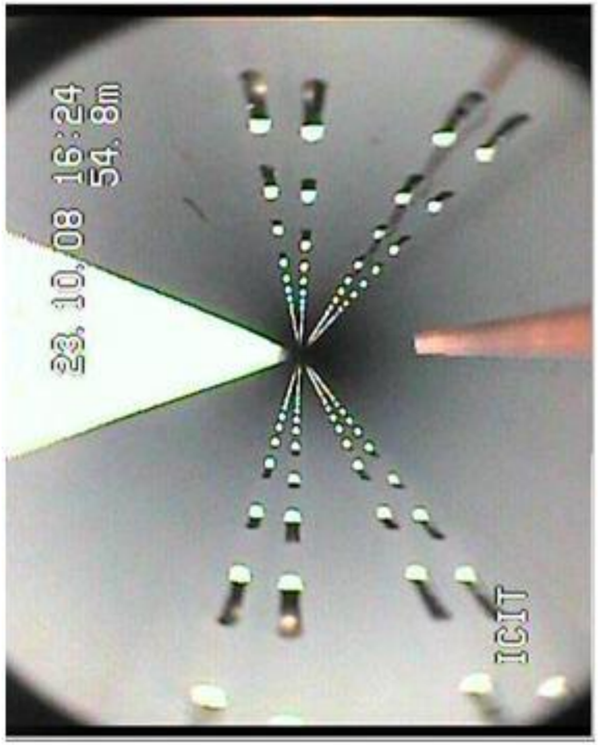

Arcing in the interconnection


Over-pressure


Magnet displacement

53 magnets had to be repaired

Beam vacuum affected over the entire 2.7 km length of the concerned 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).

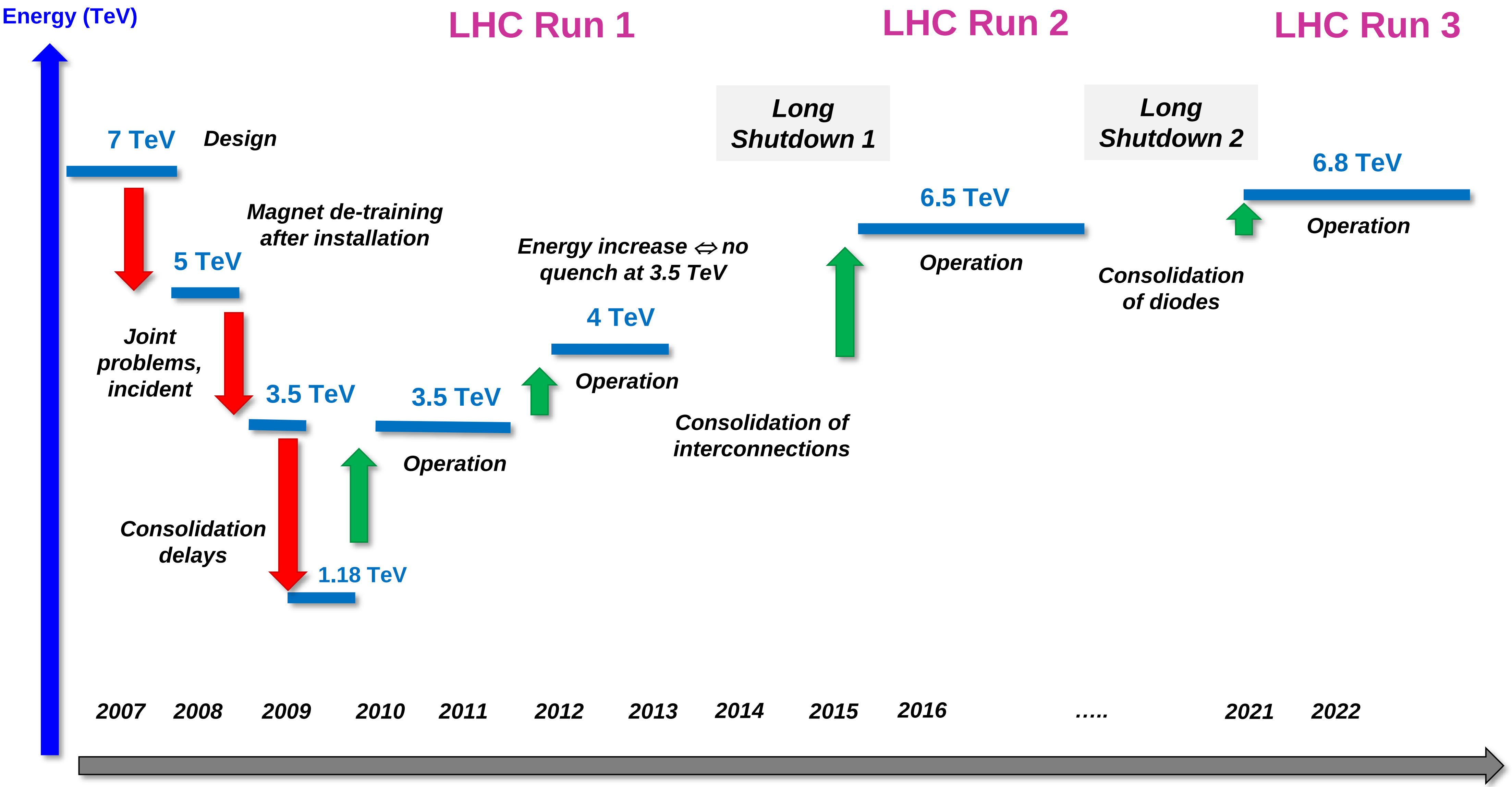
Major upgrades to pressure release systems and magnet anchoring.

Limitation of the machine energy to 3.5 / 4 TeV instead of 7 TeV for 3 years.

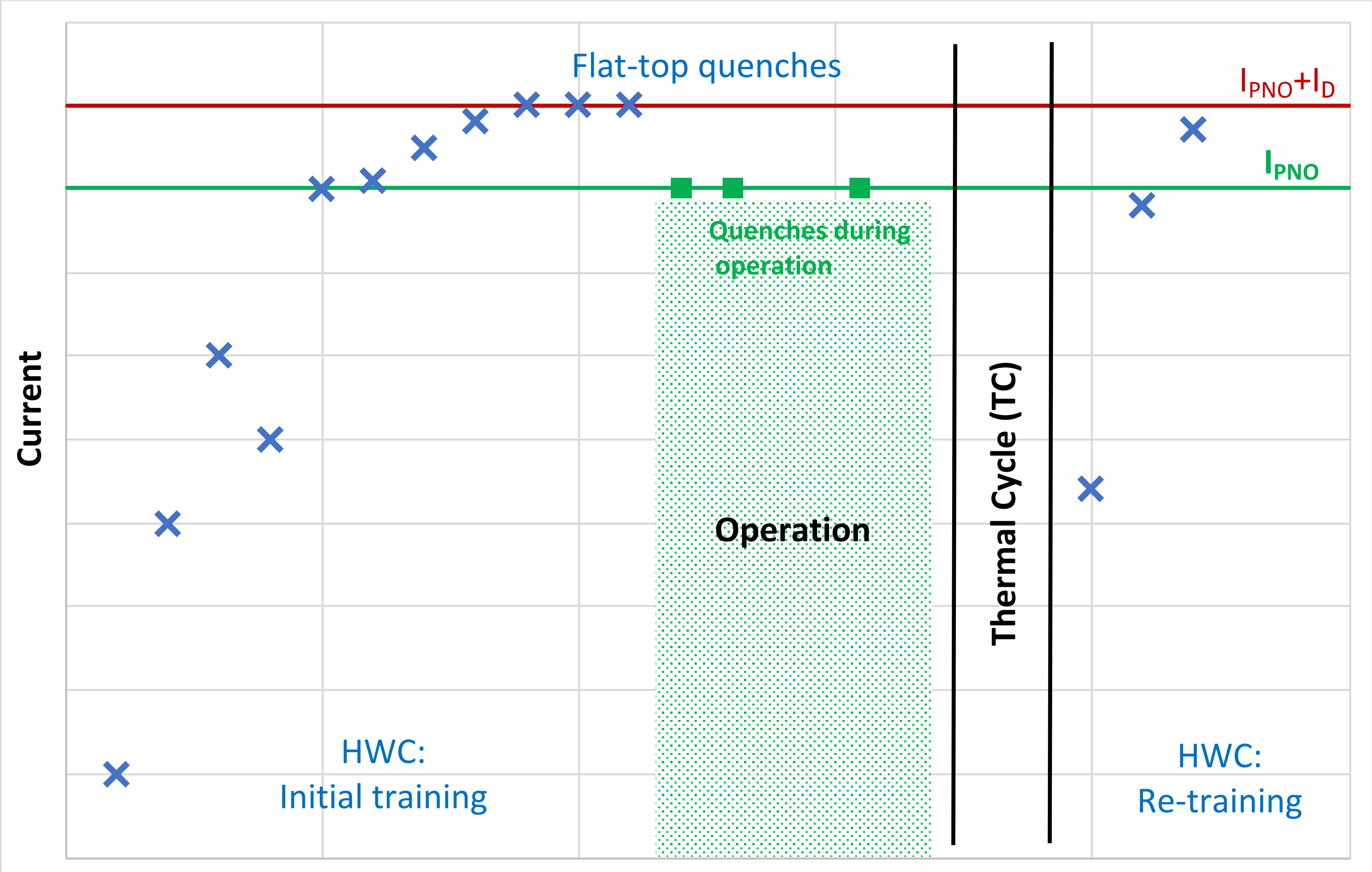
Almost **2 years of shutdown** (2013-2014) to repair all magnet interconnections (30% of them were completed redone) and prepare the machine for > 6.5 TeV.

The incident was so severe because it had not been considered during the design !

LHC beam energy evolution



Super-conducting magnet training



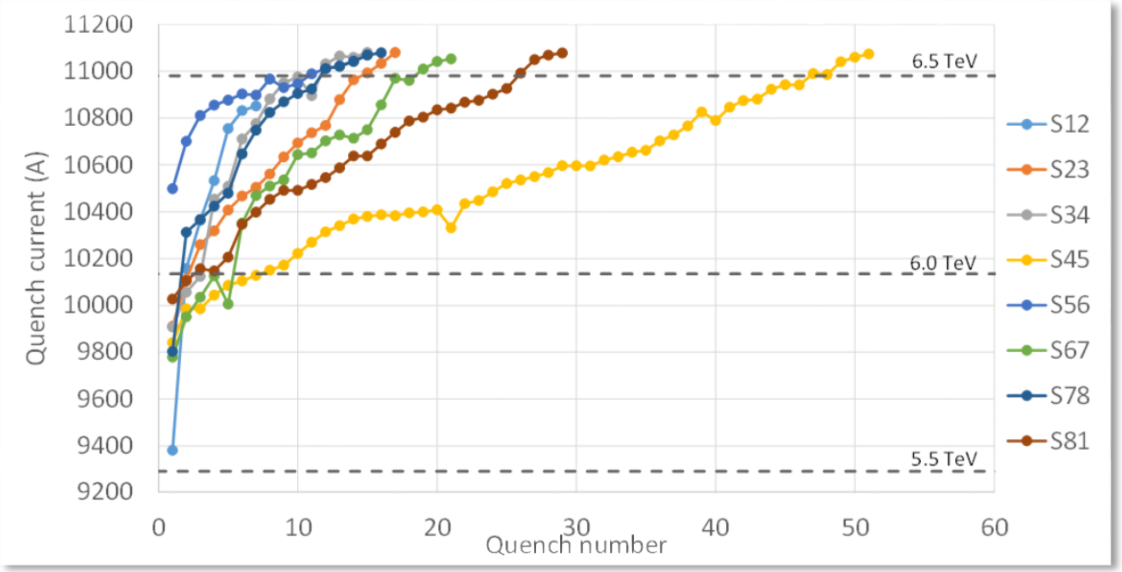
The **LHC dipole magnets** unfortunately suffer from '**de-training**' after warm up to room temperature.

Run 2 (2015-2018): **150 training quenches** required to reach **6.5 + ε TeV** (ε = operational margin).

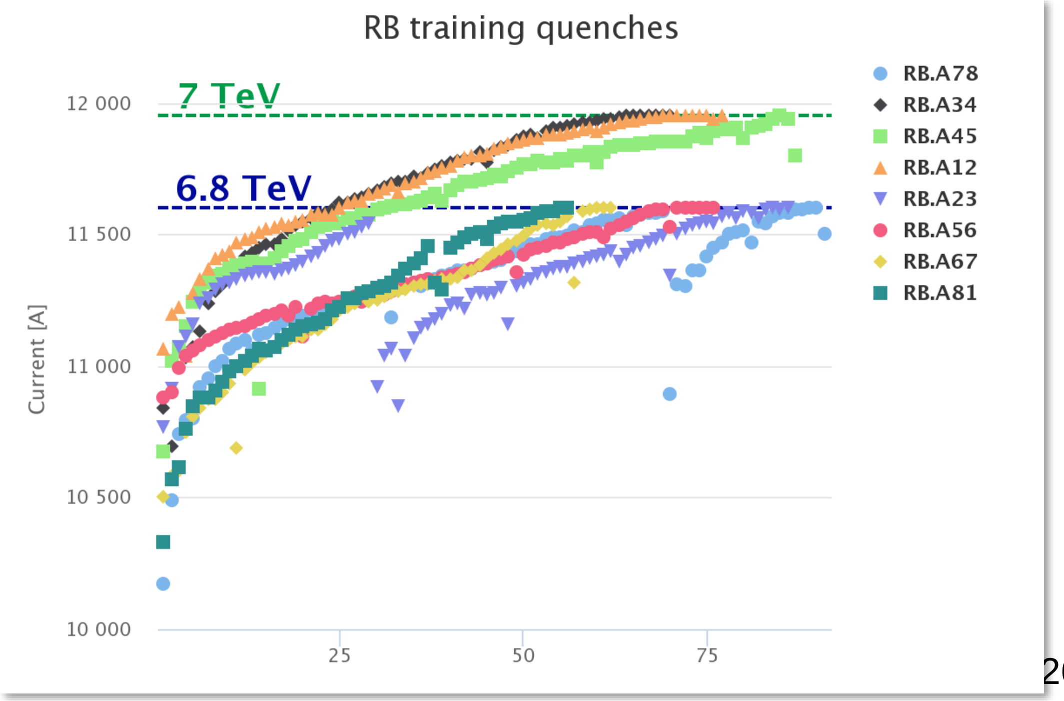
Run 3 (2022-2025): **600 training quenches** required to reach **6.8 + ε TeV**.

- Two faults occurred during training (inter-turn short and diode fault), warm up and repair of the sectors.
- Objective of 7 TeV was lowered to 6.8 TeV following those two faults.

Training to 6.5 TeV



Training to 6.8 TeV



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LHC MPS design

To design the LHC MPS a systems approach was used:

- *Break up the LHC into logical systems, identify failure modes,*
- *Estimate failure properties (time constants, beam loss rates etc) and identify protective measures,*
- *Establish a classification of failure types and of the most critical failures,*
- ***Ensure that for the most critical failures there is more than one protection level.***

We did not immediate build long failure trees for every element – too much effort and time.

- *This was limited to a number of critical systems like beam loss monitoring , beam interlock and beam dumping systems to design internal redundancy, monitoring needs etc.*

Such a system level approach to safety is now becoming much more common for **complex systems** – 'STPA approach (Systems-Theoretic Process Analysis).

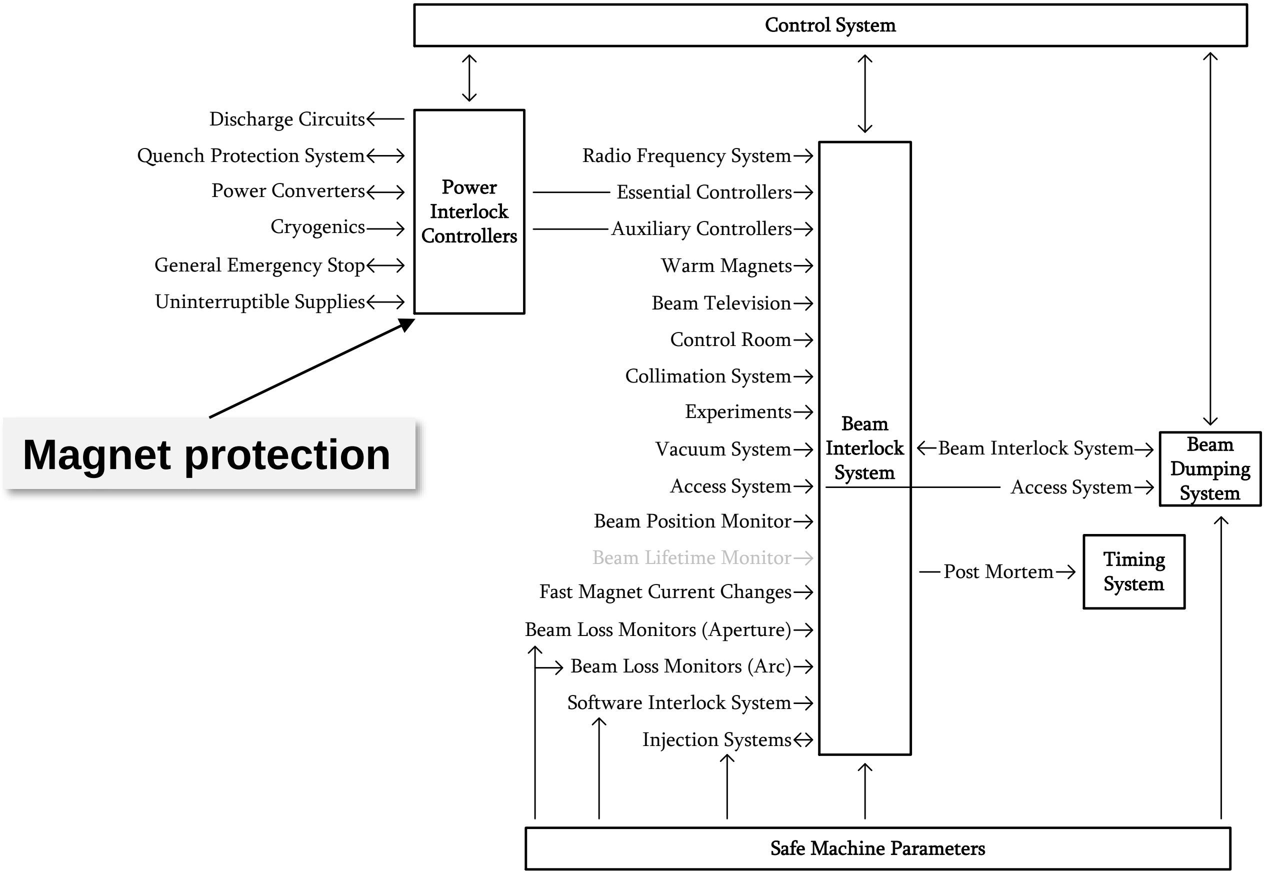
R. Schmidt et al., New J. Phys. 8 (2006) 290. http://dx.doi.org/10.1088/1367-2630/8/11/290

MPS inputs

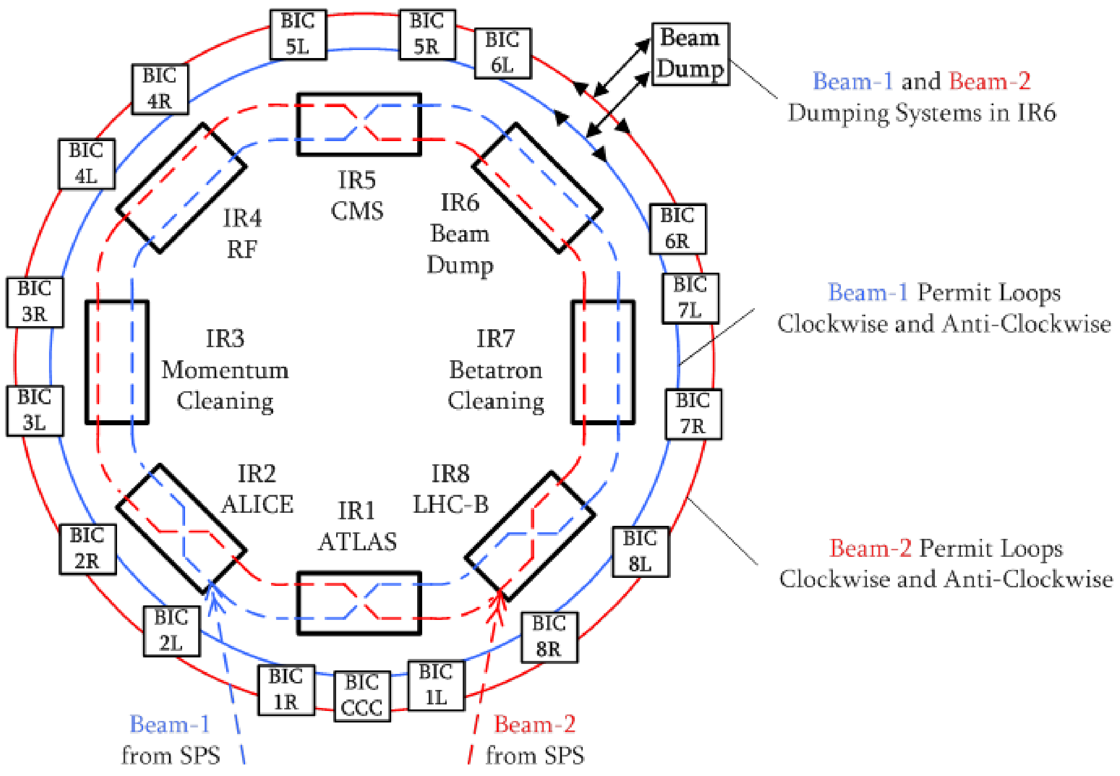
The LHC beam interlock system (BIS) has ~200 inputs from client systems.

Behind each input there can be many individual tests / interlocks.

- *For example, the BLM or super-conducting magnet protection systems provide an aggregated interlock signal for covering typically 1/8 to 1/16 of the LHC.*



Beam Interlock System layout



17 distributed **Beam Interlock Controller** (**BIC**) units with up to 14 client inputs.

The BIC units are connected together by optical fibre links – **beam permit loops (BPL)**.

There are 4 independent BPLs, 2 BPLs for each beam.

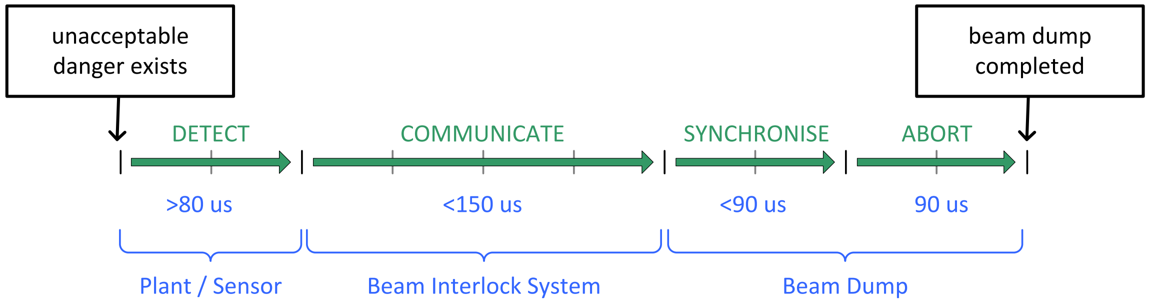
The loops of the 2 beams can be coupled together.

For each beam, the loop signals propagate in clockwise and anti-clockwise directions.

Reduces the time delay to the dump.

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

Revolution period 89 μs



Masking – the safe beam concept

During the design phase of the LHC MPS the **need for masking interlocks** 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 **Setup Beam (= almost safe, low risk)** was introduced.

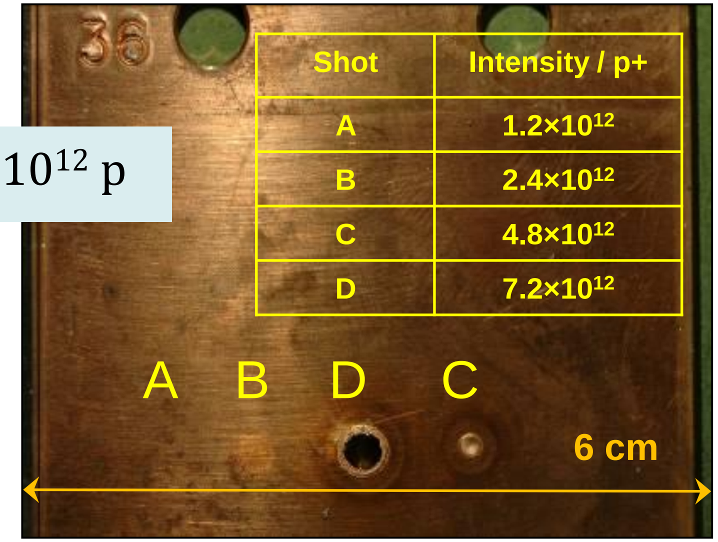
- A setup beam should not be able (or have low risk) to damage accelerator components.
- The corresponding intensity limit depends on the beam energy (and emittance). It also depends on the material !
  - But a Setup Beam may quench magnets!
  - The Setup Beam must be defined for a reference material: Copper is used for the LHC.

Setup Beam Flag for LHC

A combinations of “damage experiments” and simulations were used to predict the scaling with beam energy E:

- *Larger energy deposition → scaling ~ 1/E.*
- *Smaller emittance → beam area ~ 1/E.*
- *Longer showers (~ log E) → some dilution.*

$$I_{SB}^{450GeV} = 10^{12}\ \text{p}$$



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

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

This equation was implemented as a table in a **Safe Machine System** (SMP). The SMP is connected to reliable/redundant 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.

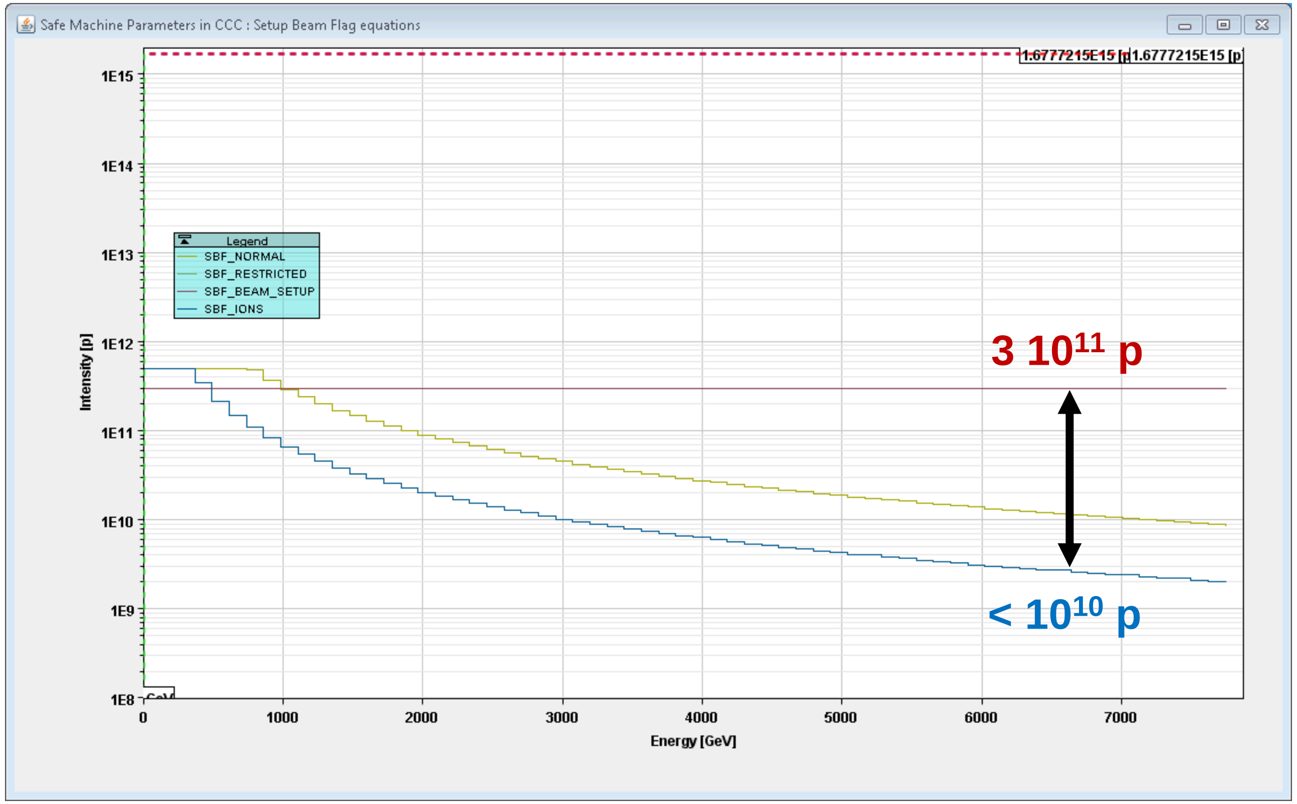
And then operation starts…

During operation setting up the machine accurately required bunches with nominal intensities N ~ 10^{11} p/b.

- *Quality of the BPM measurements – beam instrumentation !*

Because the SBF limit was below that value above 3 TeV, it was decided to relax the limit in some cases.

- ***Defined a relaxed limit*** *(another equation) with restricted usage.*
- *Accepted a limited increase of the risk in order to improve setup quality.*



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Commissioning - procedures

Before the machine startup, procedures were developed for the commissioning of the machine protection sub-systems.

- *Updated regularly to reflect changes in the systems or new tests.*

The procedures contain test descriptions and frequency of tests.

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.*

CERN
CH-1211 Geneva 23
Switzerland

EDMS NO.	REV.	VALIDITY
889281	3.0	RELEASED

REFERENCE
LHC-OP-MPS-0004

LHC

Date: 2016-04-21

MPS COMMISSIONING PROCEDURE

MPS Aspects of the Beam Interlock System Commissioning

ABSTRACT:
This document describes the tests that will be carried out to validate the operation of the Beam Interlock System for the LHC. It covers tests that must occur in each of the key phases of the commissioning of the Machine Protection System.
A prerequisite of these tests is that the Individual System Tests of the Beam Interlock System have been carried out. These prerequisite steps are labelled before each of the commissioning tests.

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896390	4.0	RELEASED

REFERENCE
LHC-OP-MPS-0005

LHC

Date: 2016-02-12

MPS COMMISSIONING PROCEDURE

MPS Aspects of the Powering Interlock System Commissioning

ABSTRACT:
This document describes the set of tests which will be carried-out to validate for operation the machine protection aspects of the **LHC Powering Interlock system (PIC)**. The area concerned by these tests extends over the whole LHC machine for each of the two LHC beams.

These tests include Hardware Commissioning, machine check-out and tests with beam.

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889343	5.0	RELEASED

REFERENCE
LHC-OP-MPS-0003

LHC

Date: 2022-07-05

MPS COMMISSIONING PROCEDURE

MPS Aspects of the Injection Protection System Commissioning

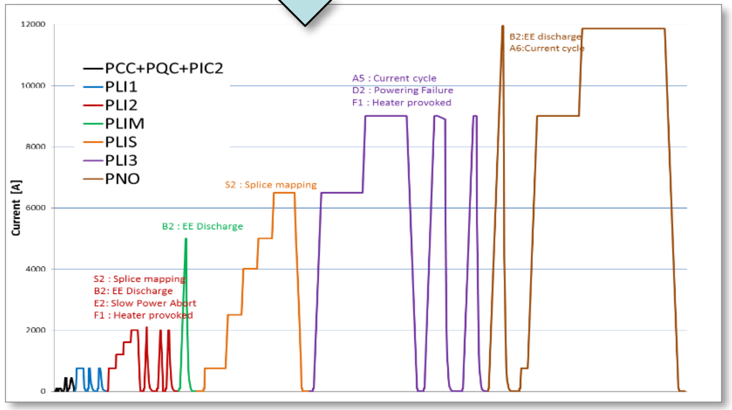
ABSTRACT:
This document describes the set of tests which will be carried out to validate for operation the machine protection aspects of the LHC Injection Protection system. The area concerned by these tests extends over the LHC injection regions (including SPS extraction) for each of the two LHC beams.

These tests include Hardware Commissioning, machine check-out and tests with beam.
This is the updated version for LHC Run 2, starting 2015.

Automated testing

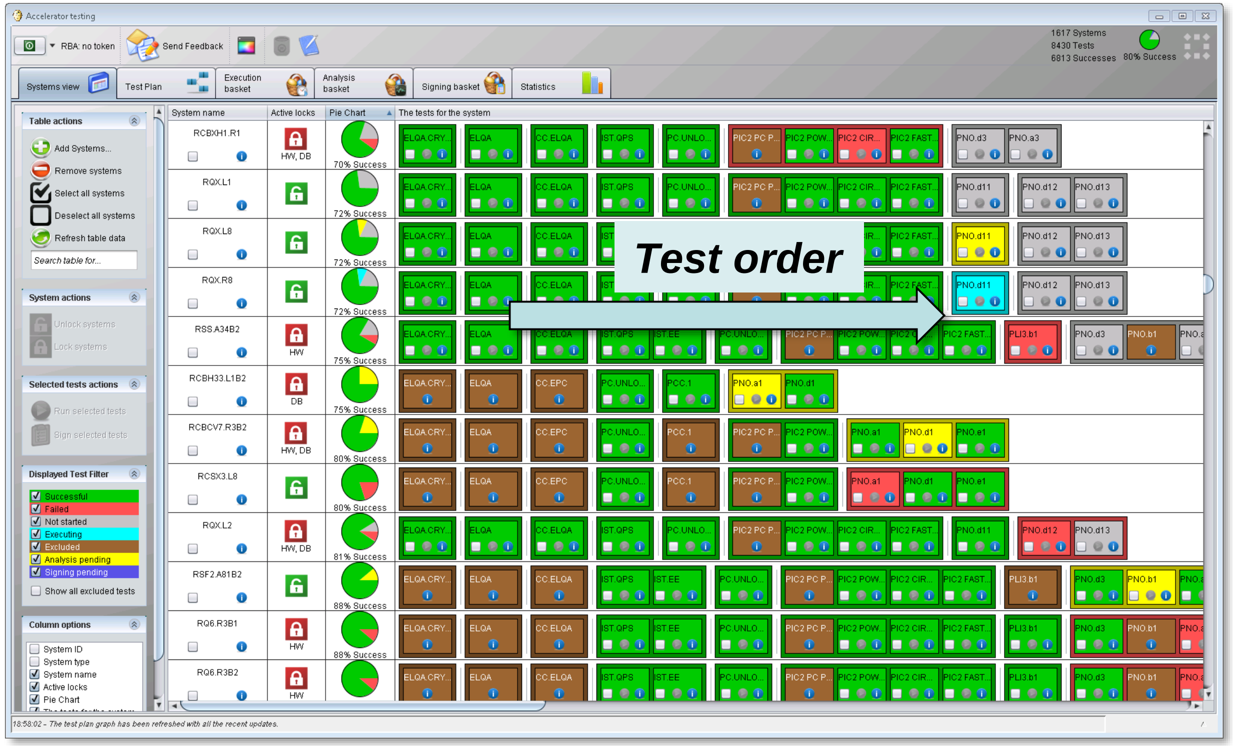
The powering tests that are used to commission the LHC super-conducting magnet system are a good example of how to track and automate test.

- *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!*

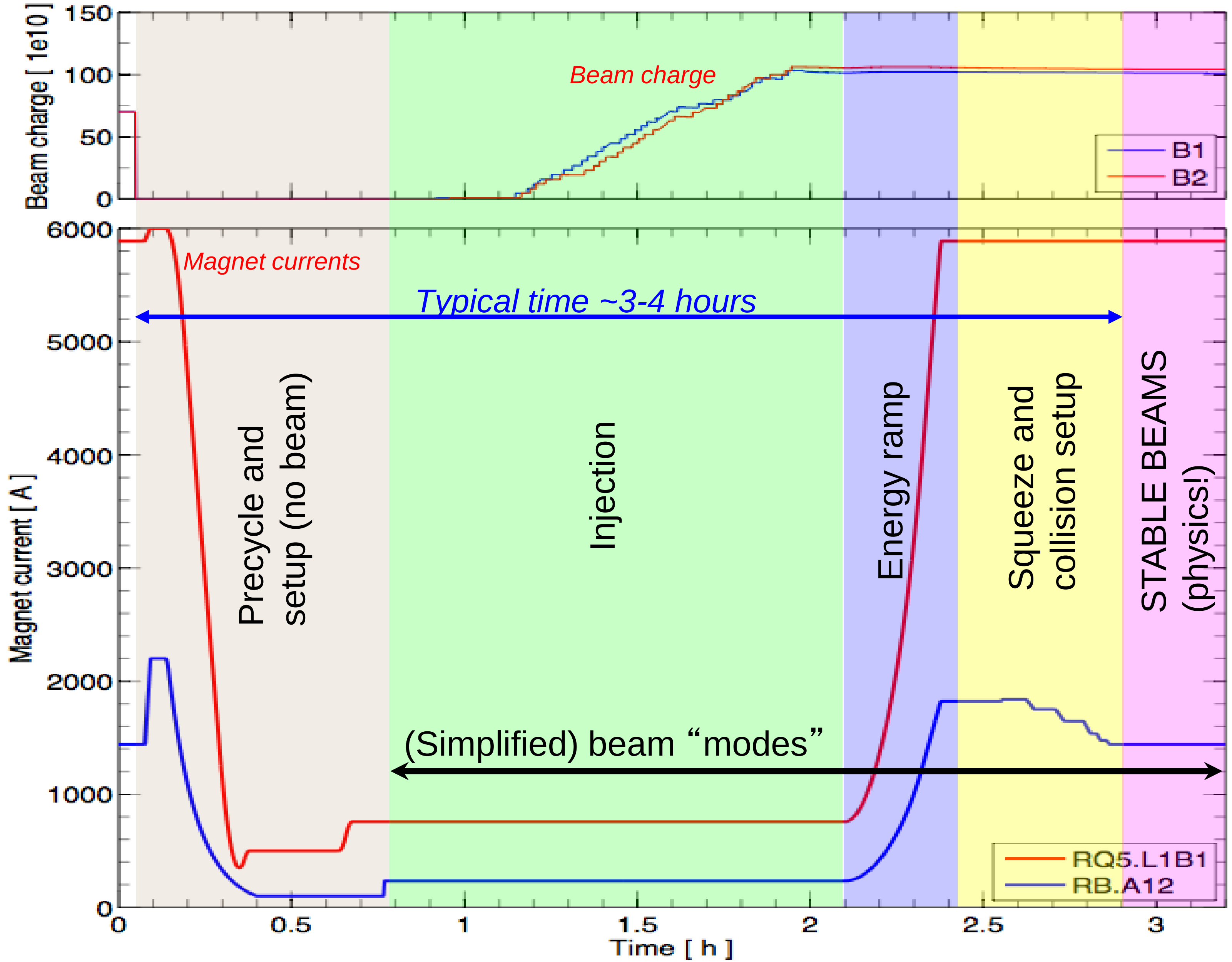


encoding in a test sequence

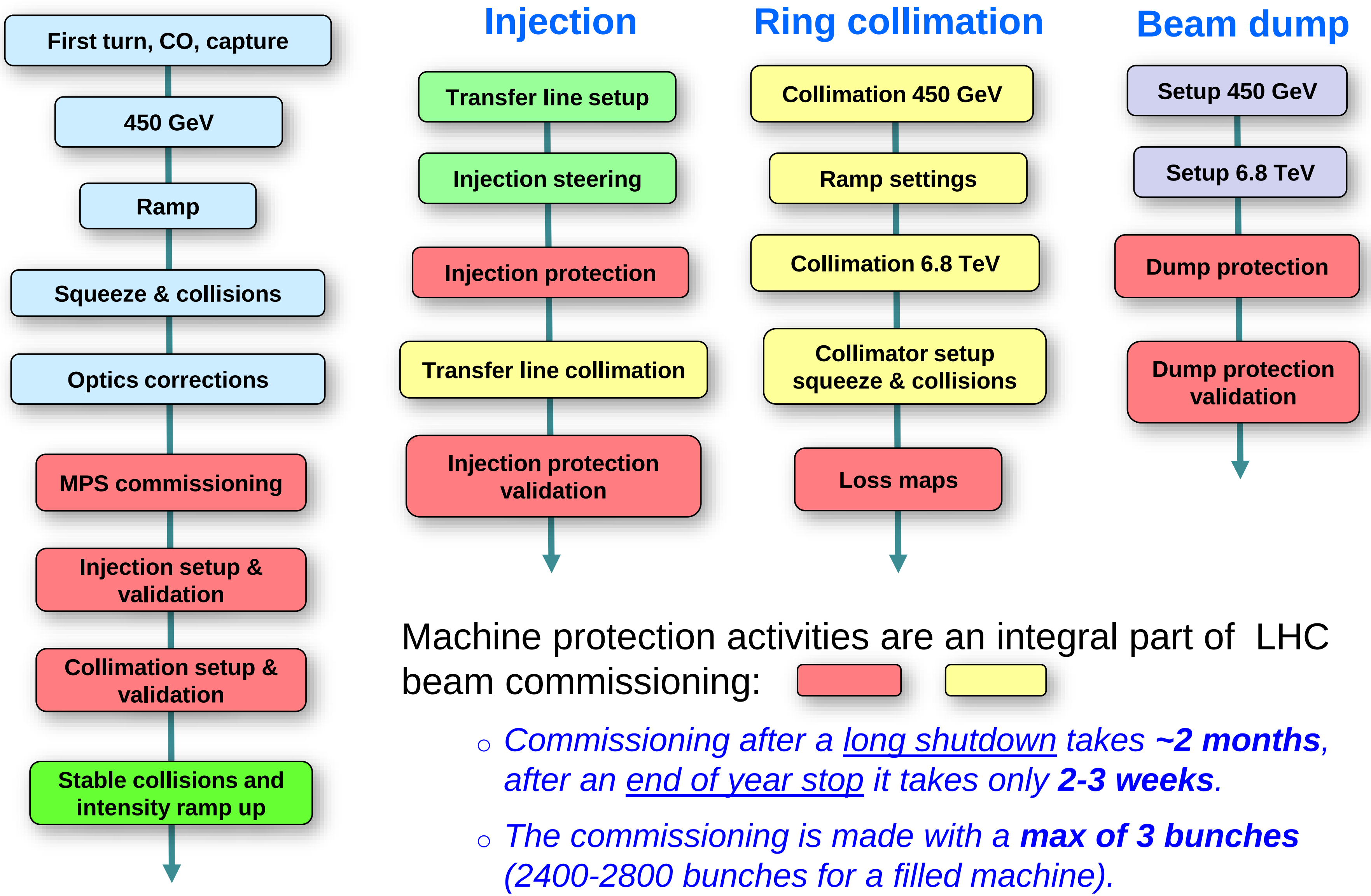
1 block = 1 test



LHC operational cycle



Beam commissioning sequence



Machine protection activities are an integral part of LHC beam commissioning:

- *Commissioning after a <u>long shutdown</u> takes **~2 months**, after an <u>end of year stop</u> it takes only **2-3 weeks**.*
- *The commissioning is made with a **max of 3 bunches** (2400-2800 bunches for a filled machine).*

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 (quench prevention) and MP (passive protection).*

Setting up the LHC machine for a run 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).

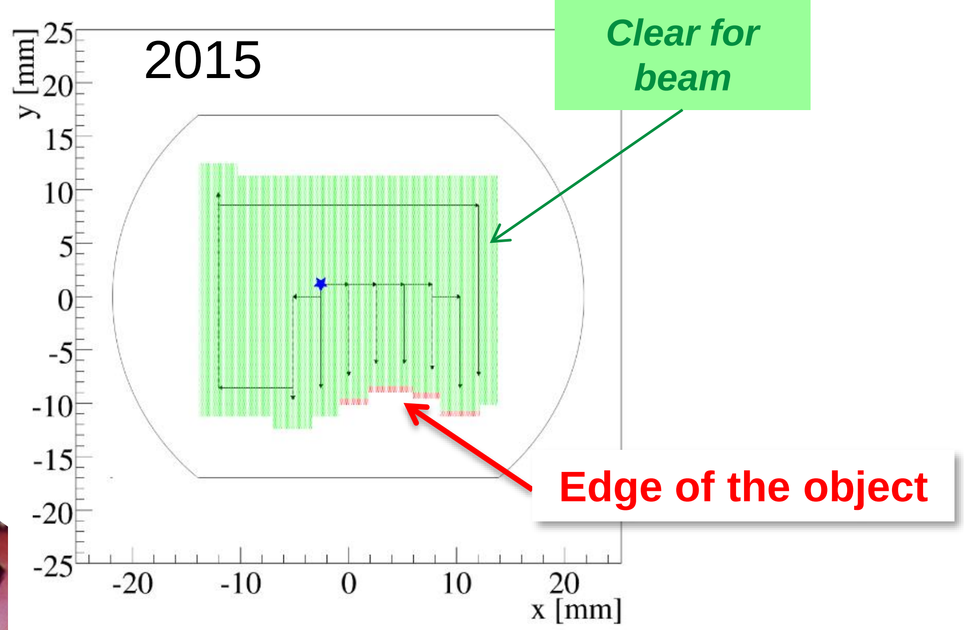
All along the machine cycle – from injection to collisions

Aperture restriction (1)

At the restart of the LHC ring 2015 following a 2-year shutdown, an **aperture restriction** was identified in an arc location.

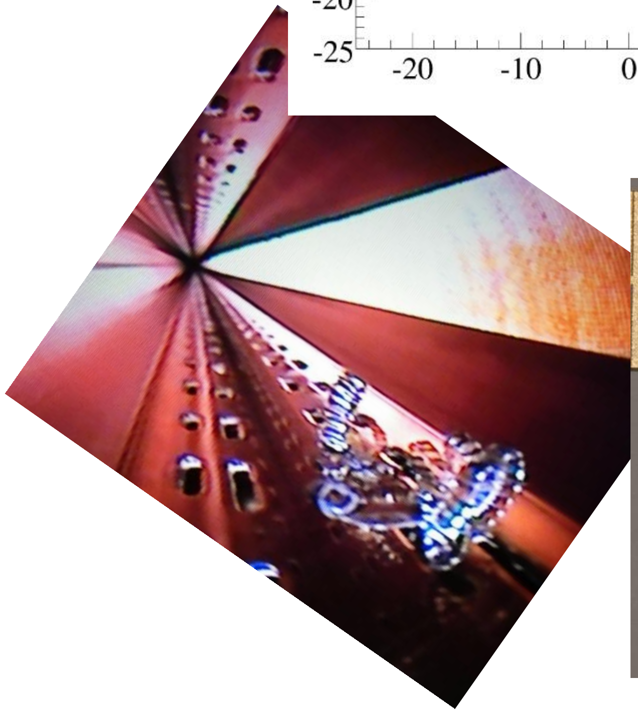
- Diagnosed as a '**thin**' object lying on the bottom of the vacuum chamber.

Fortunately, the restriction could be **mitigated by bumping the beam** around it, and **LHC operated during 4 years with this acceptable restriction**.



The object was recovered during shutdown 2019-2020: **polythene swarf**, a left-over from the installation of the vacuum chamber.

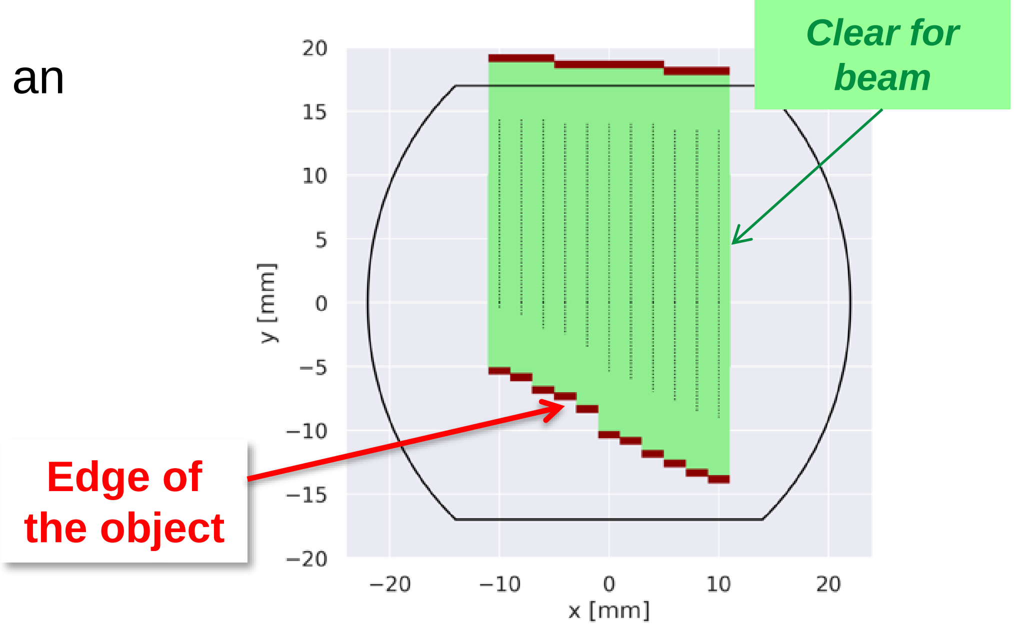
- Despite being so thin, such an obstacle generates sufficient losses to quench nearby magnets.
- **It is not possible to 'burn out' such an obstacle: the energy loss in the object is too small !**



Aperture restriction (2)

At the restart of the LHC in 2021 following a 2.5-year shutdown, an **aperture restriction** was again detected in one location.

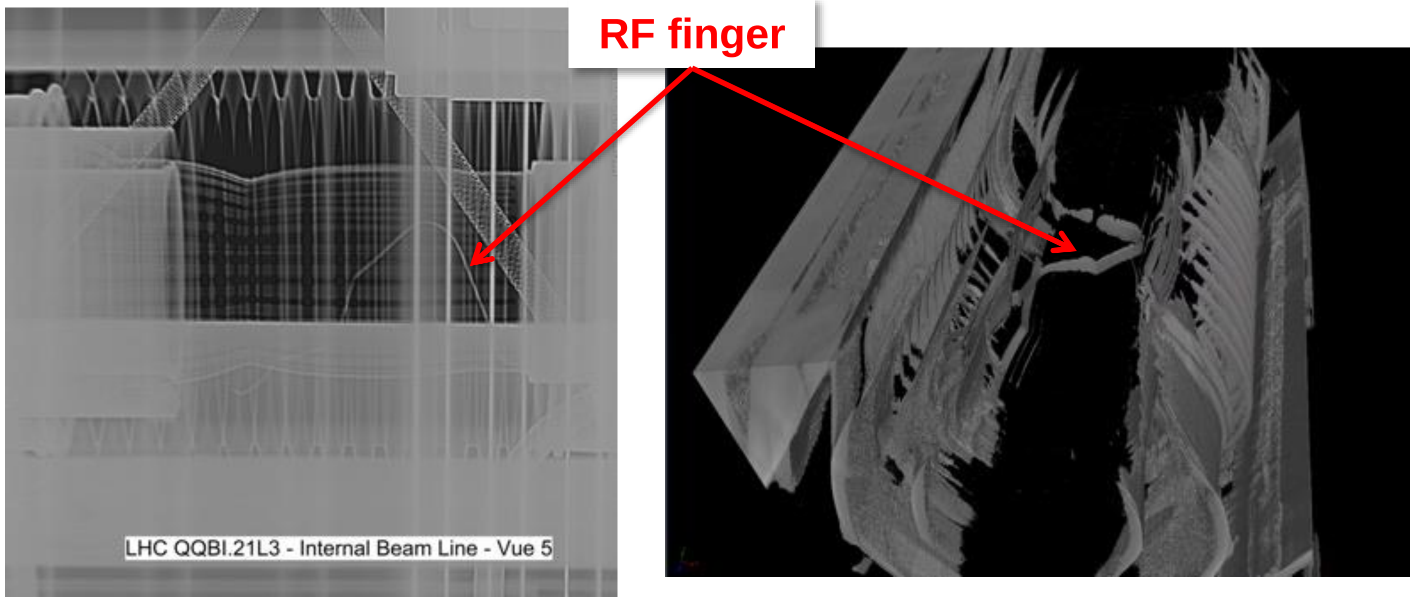
- **Severe restriction**, again a thin object in the lower part of the vacuum chamber.



X-rays and tomography reveal the presence of a **deformed RF-finger**.

- Decision to **warm-up the sector for repair**: high risk of over-heating of the finger by the beam (RF heating).

Duration of the intervention : 4 months.



MPS Quality Assurance

During machine setting up collimators and absorbers are aligned around the closed orbit with appropriate retractions.

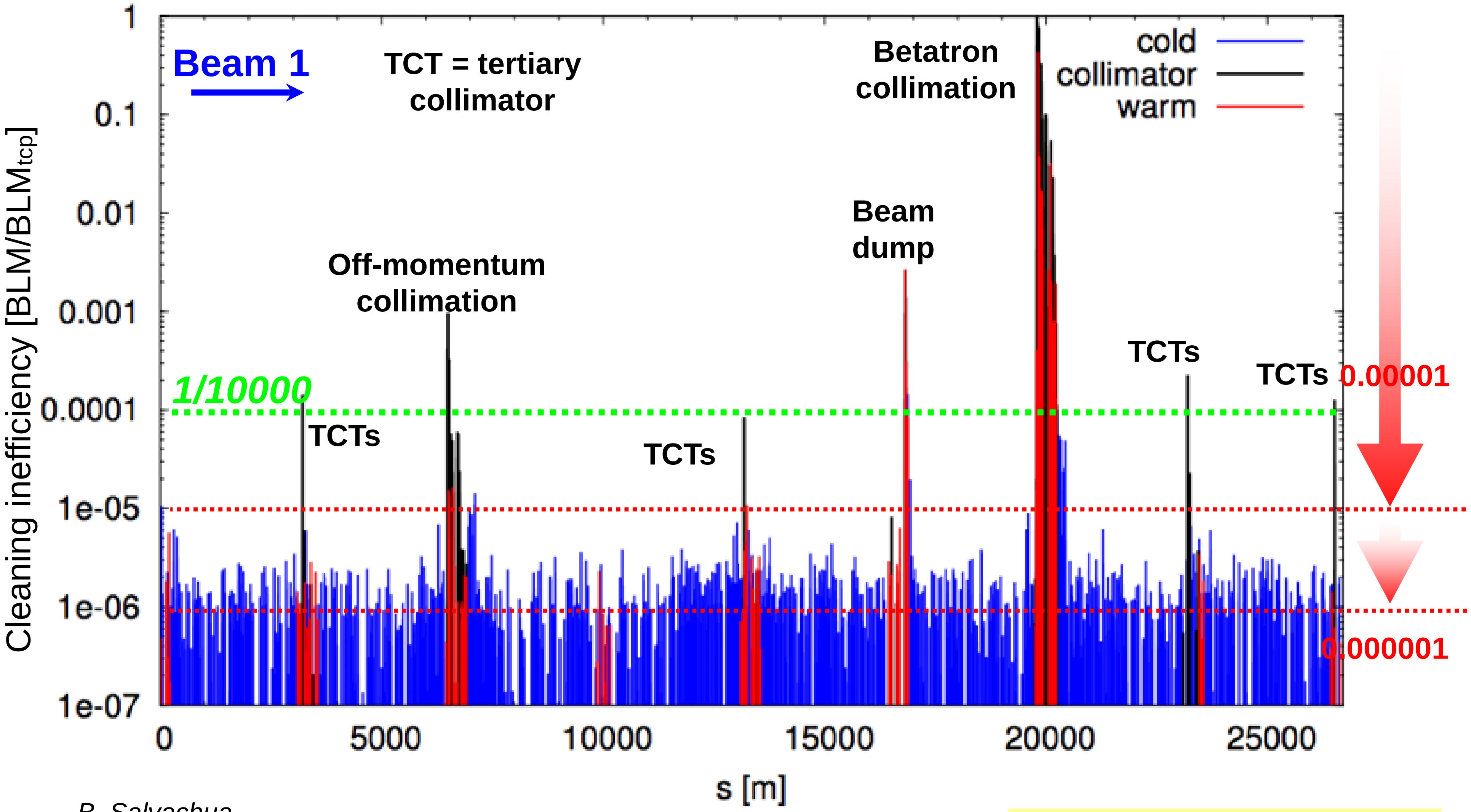
- *The orbit must be reproducible at the level of ~50 μm ($\Leftrightarrow$ 1/4 σ).*

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 de-bunched (RF switched off) 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.*

Those tests are repeated after every machine stop (~2x per yearly running period).

Loss map example



B. Salvachua

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

see lecture on collimation

Beam dump synchronization

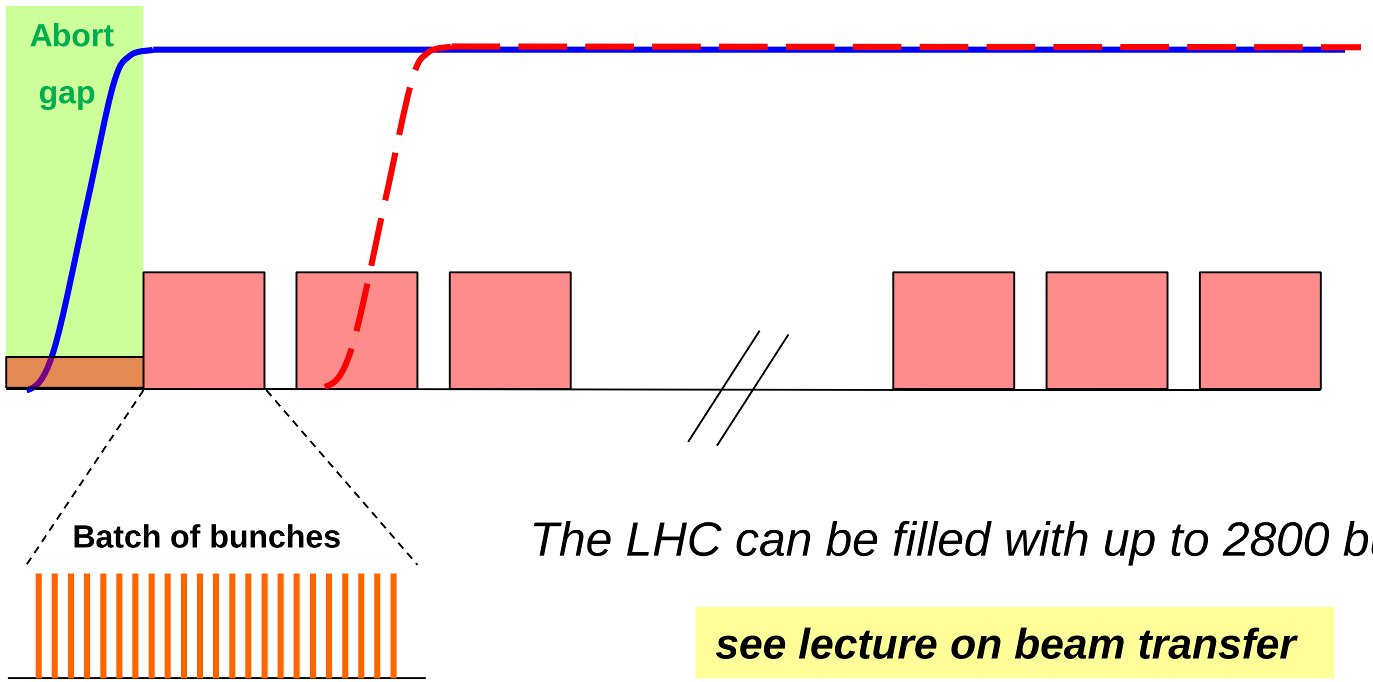
The beam dump must be accurately synchronized to the **beam abort gap** to avoid spreading beam across the aperture during the kicker rise-time.

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***

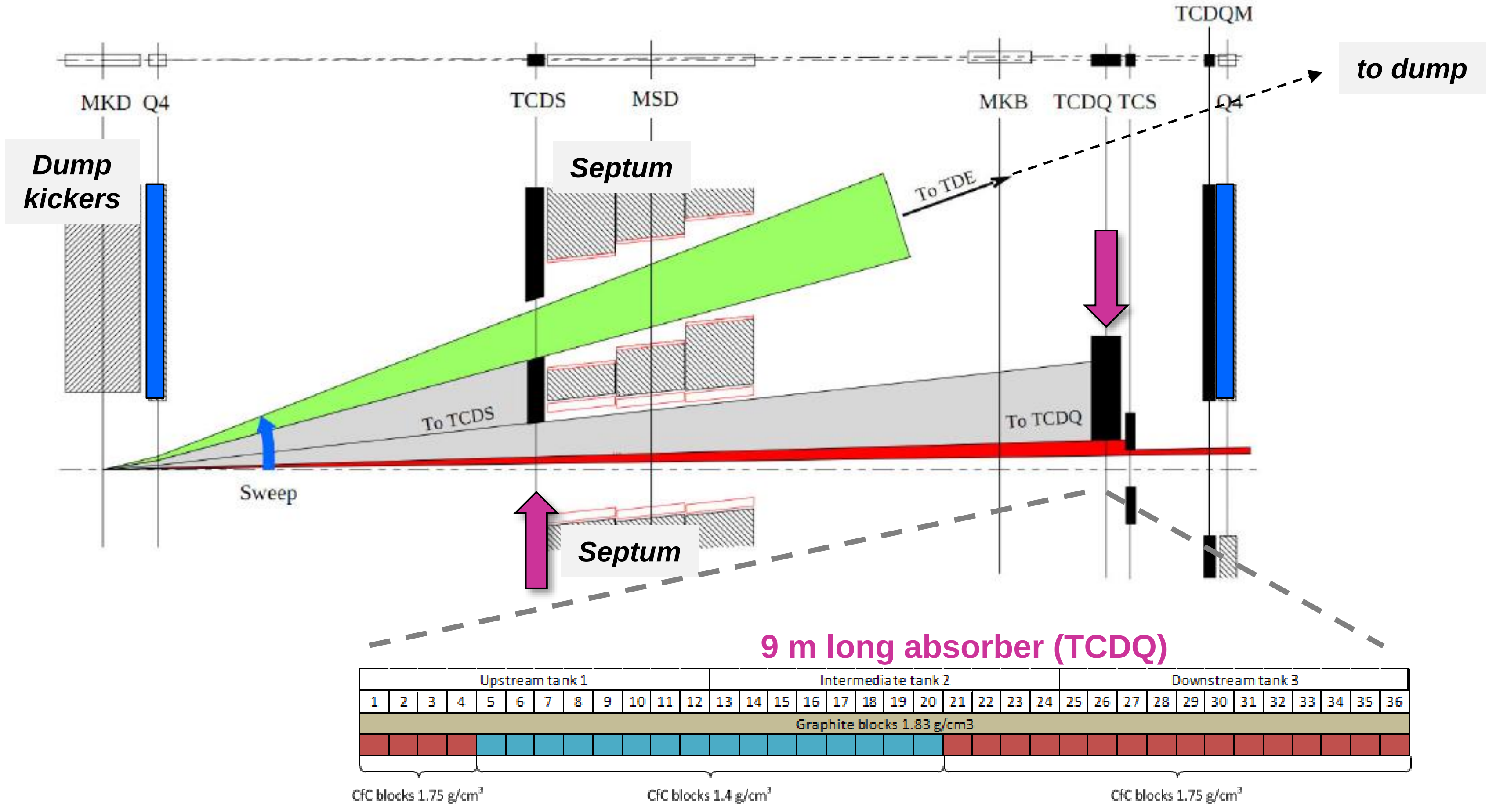


The LHC can be filled with up to 2800 bunches

see lecture on beam transfer

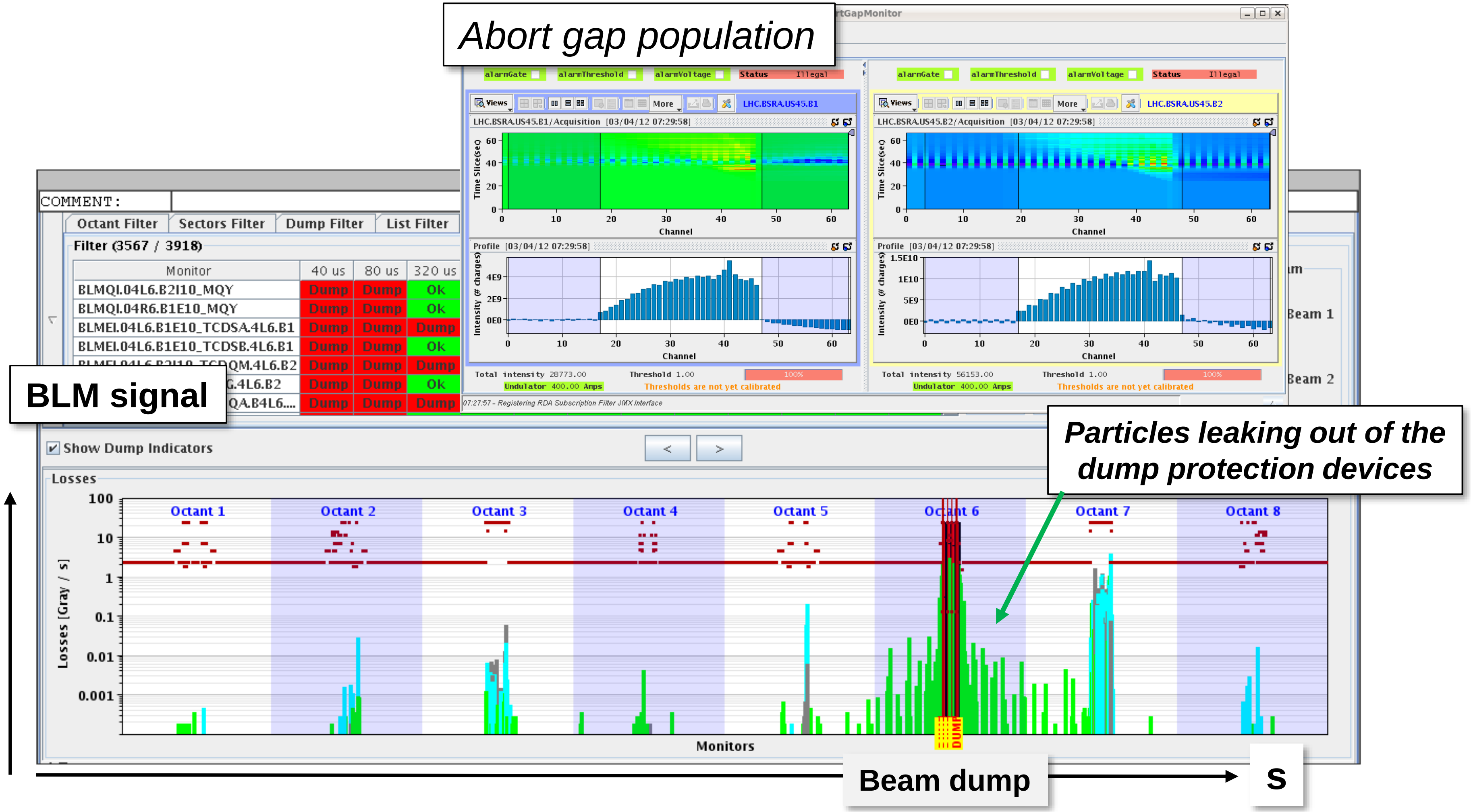
Asynchronous dump: passive protection

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 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.



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Increasing the energy

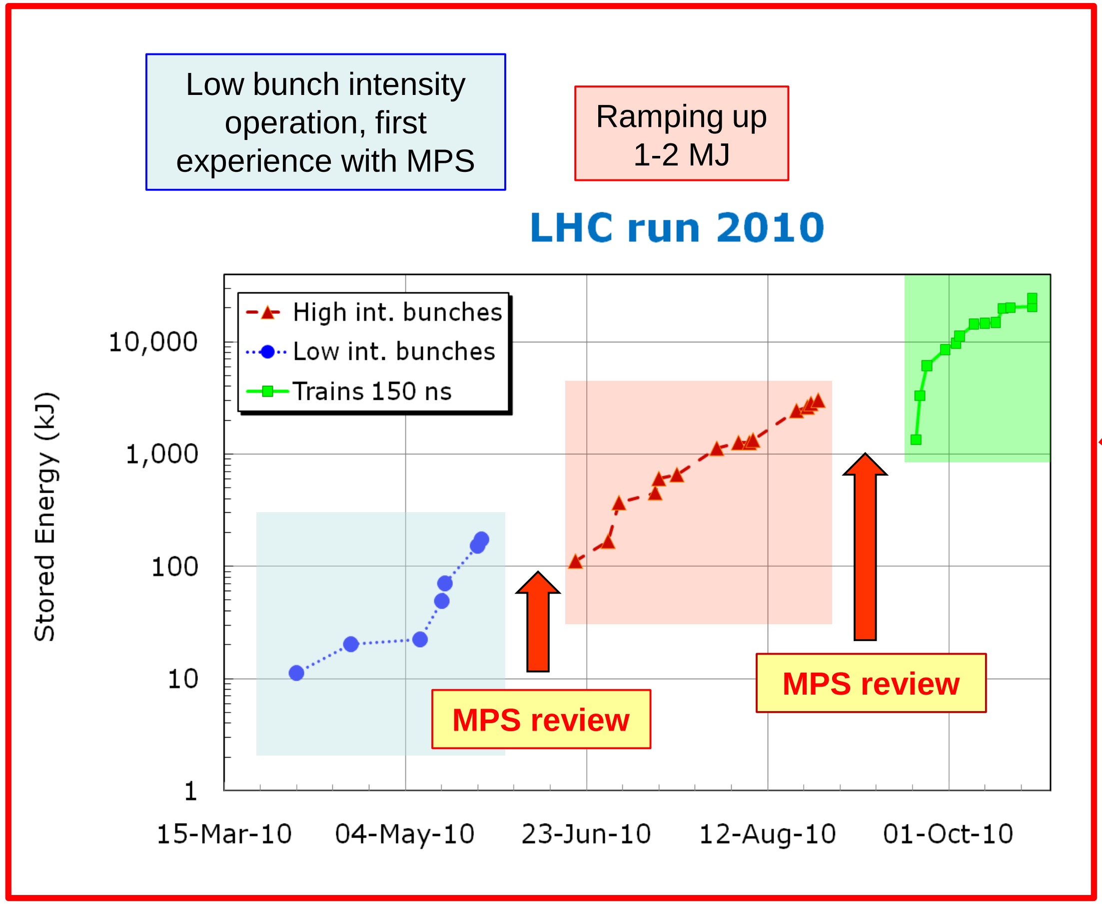
The LHC is always setup with low intensity beams, max. of 3 bunches (~2800 max).

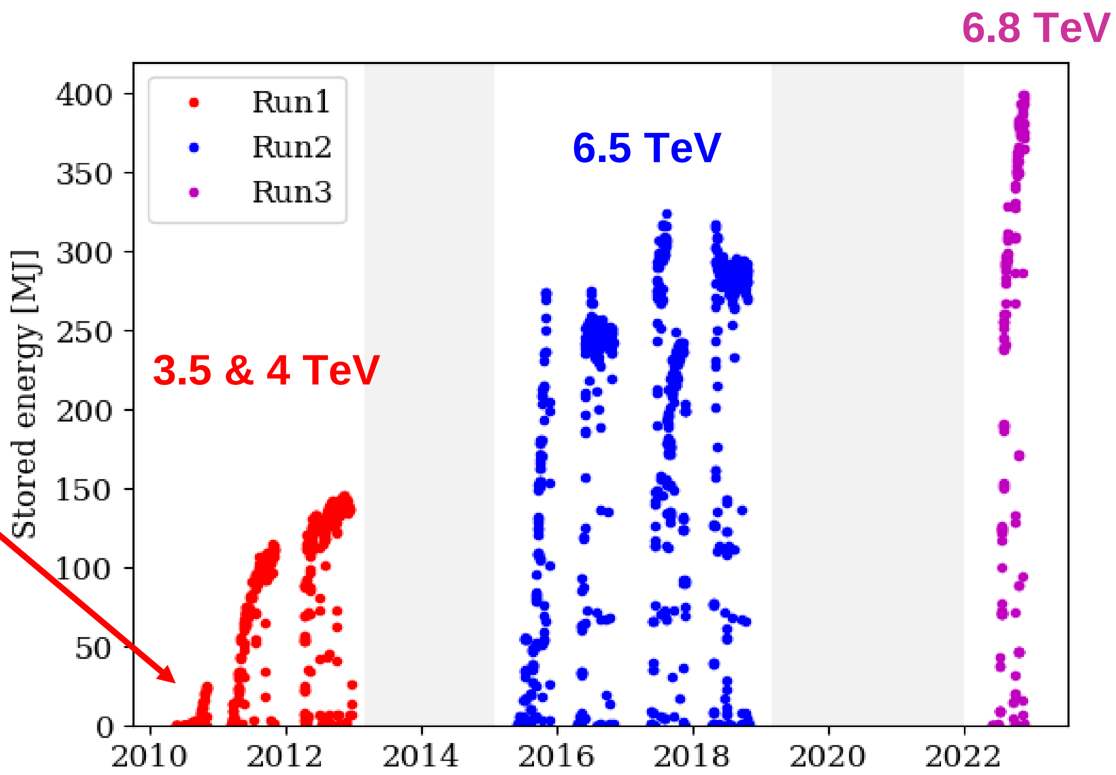
- **Setup with ~ 1/1000 of the nominal intensity: challenge for instrumentation.**

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 – new World record at that time !!.*

LHC stored energy

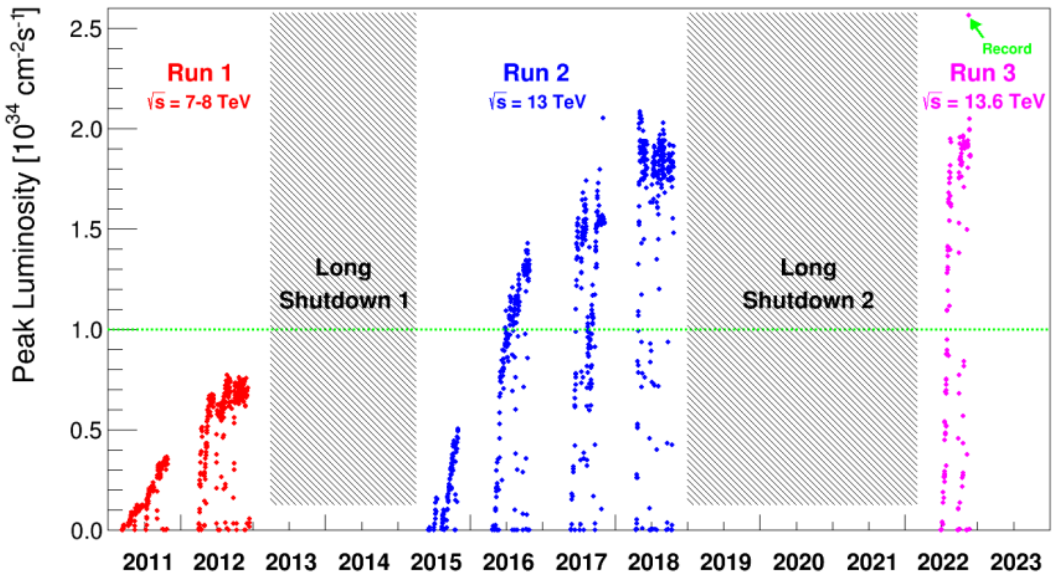


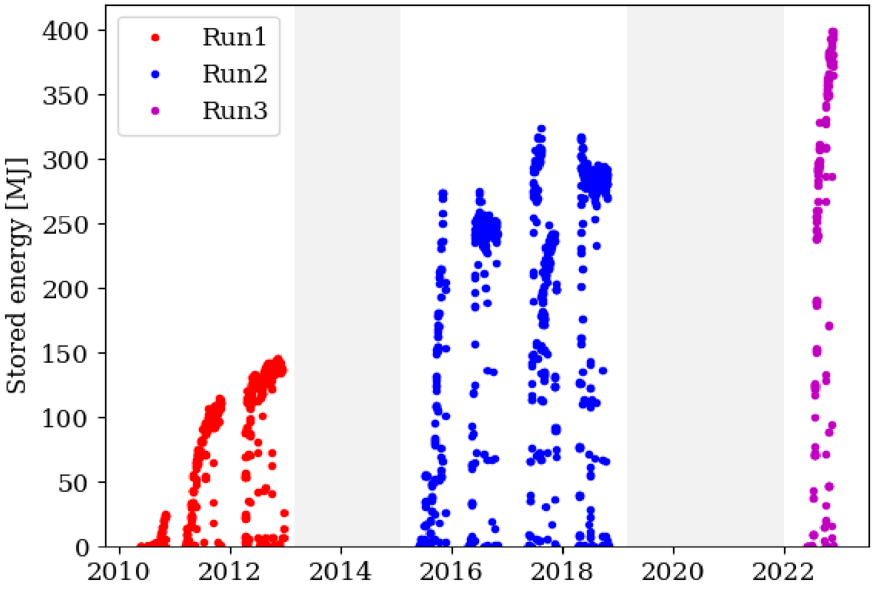


Stored beam energy and speed of commissioning evolved with experience, improved beam control, as well as higher beam energy and higher beam intensity.

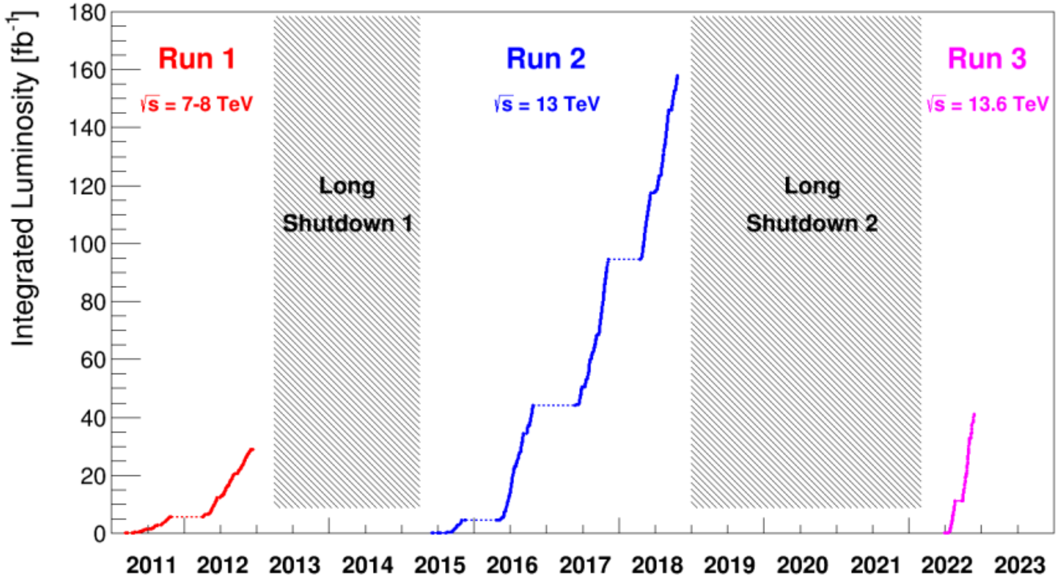
LHC stored energy and performance

Peak performance





Integrated performance



Availability

Typical machine availability is 75-80%.

Best performance of LHC for high intensity operation corresponds to **40-50% of the allocated time** spent **colliding stable beams**.

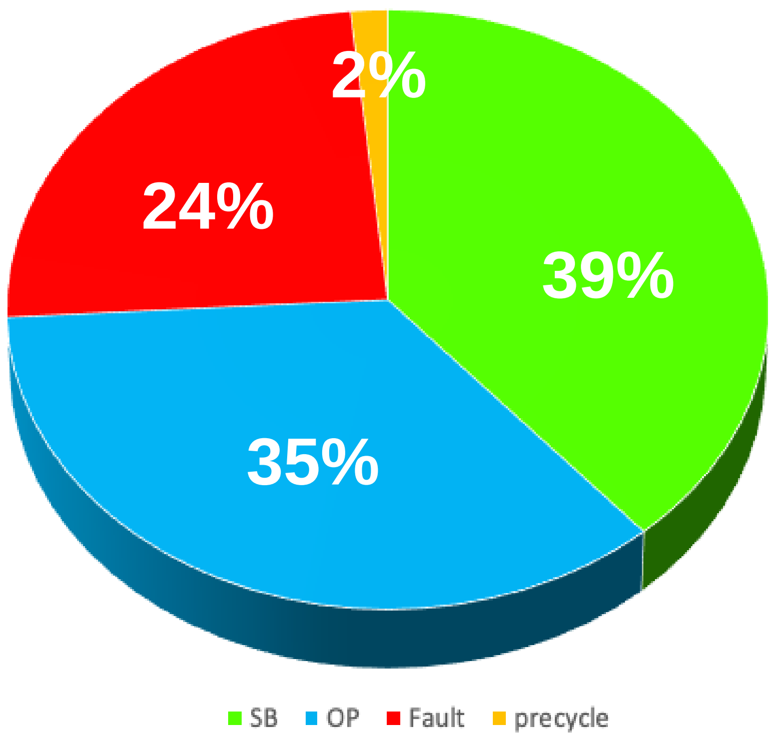
- Due to injection, ramp etc max value is ~ 85%.

Top five contributors to downtime:

- Injectors (no beam available!)
- Cryogenics
- Power converters
- Quench protection (→ part of MPS)
- Radio-frequency

2022 run

Machine availability = 76%



LHC 2022 versus Design

	Design	2022	
Collision energy:	**7+7 TeV**	**6.8+6.8 TeV**	**Training**
Bunch spacing (ns):	**25**	**25**	
Number of bunches k:	**2808**	**2450**	**Electron clouds**
Number of particles per bunch N:	**1.15×10^{11}**	**1.5×10^{11}**	
Beam emittance ε (μm):	**3.75**	**1.8**	
Beam size at ATLAS/CMS (μm):	**16**	**11**	
Circulating beam current:	**0.58 A**	**0.66 A**	
Stored energy per beam:	**360 MJ**	**400 MJ**	
Peak luminosity ($cm^{-2}s^{-1}$):	**10^{34}**	**2.5×10^{34}**	

Except for beam energy and number of bunches, all design parameters have been exceeded !

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Setting thresholds - BLMs

Threshold definition for BLMs installed in the LHC:

- On superconducting elements: prevent quenches,
- On room temperature elements: prevent damage.
- In both cases 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.

Ever since LHC started beam operation, **BLM thresholds were progressively adjusted and tuned** (many were increased) based on operational experience.

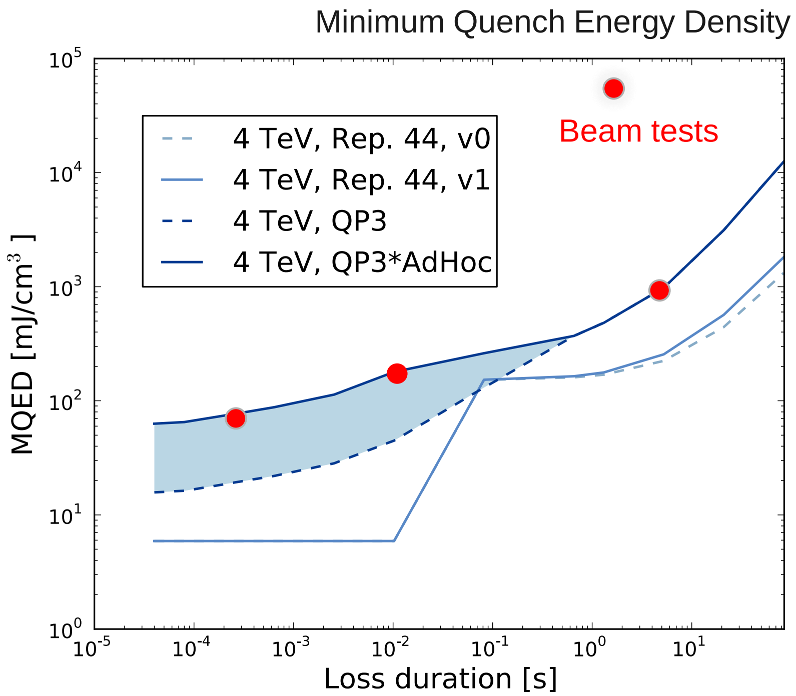
To determine quench levels in terms of BLM signals requires extensive simulations including loss scenarios, shower development and material properties.

- *Relate a BLM signal on the outside of a cryostat to the energy deposition deep in the magnet.*

The quench levels are delicate to determine theoretically due to the complex environment of the magnets.

- *The quench levels depend on the loss time scale:*
  - ***millisecond** : temperature margin of the cable,*
  - ***0.1 second** : cooling by helium inside the magnet,*
  - ***Steady state** : cooling power of cryogenic system.*

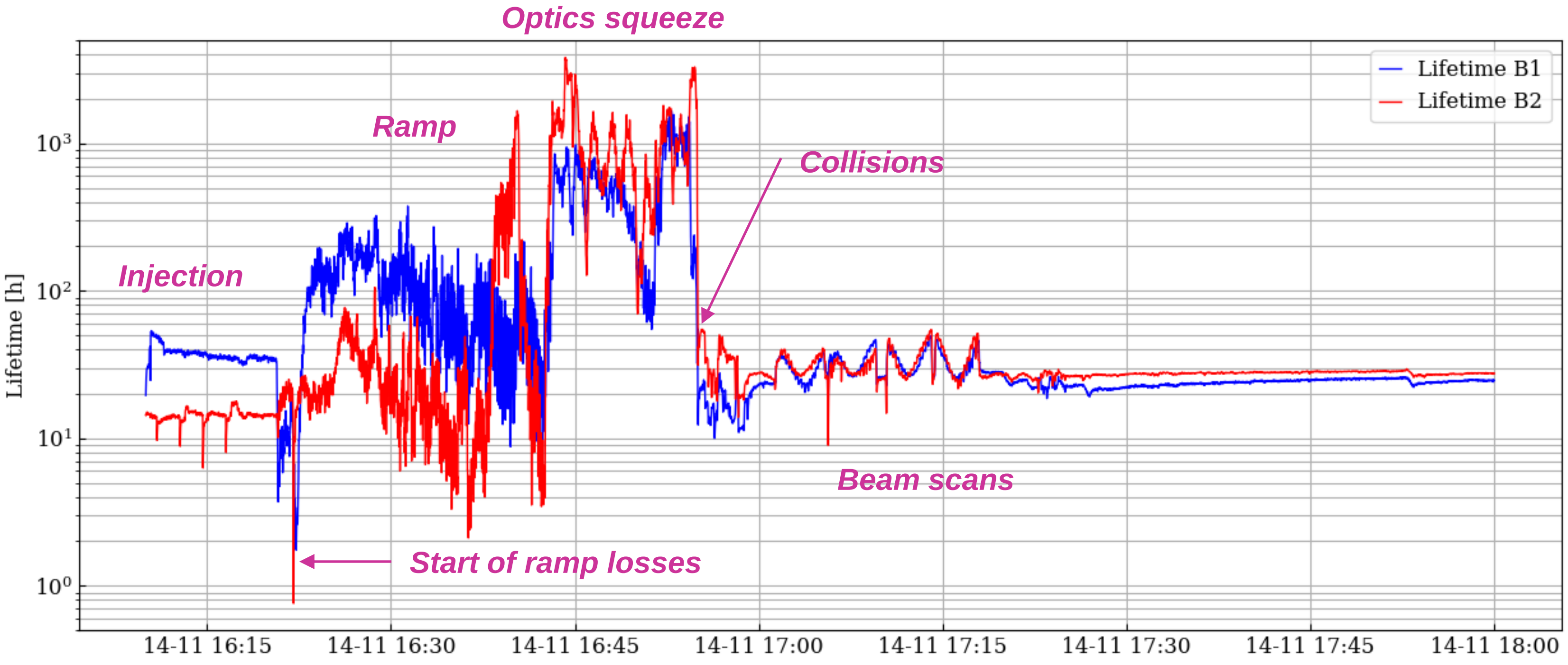
Quench levels were verified with dedicated beam experiments (mainly at 4 TeV) and with a few accidental beam induced quenches.



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.*

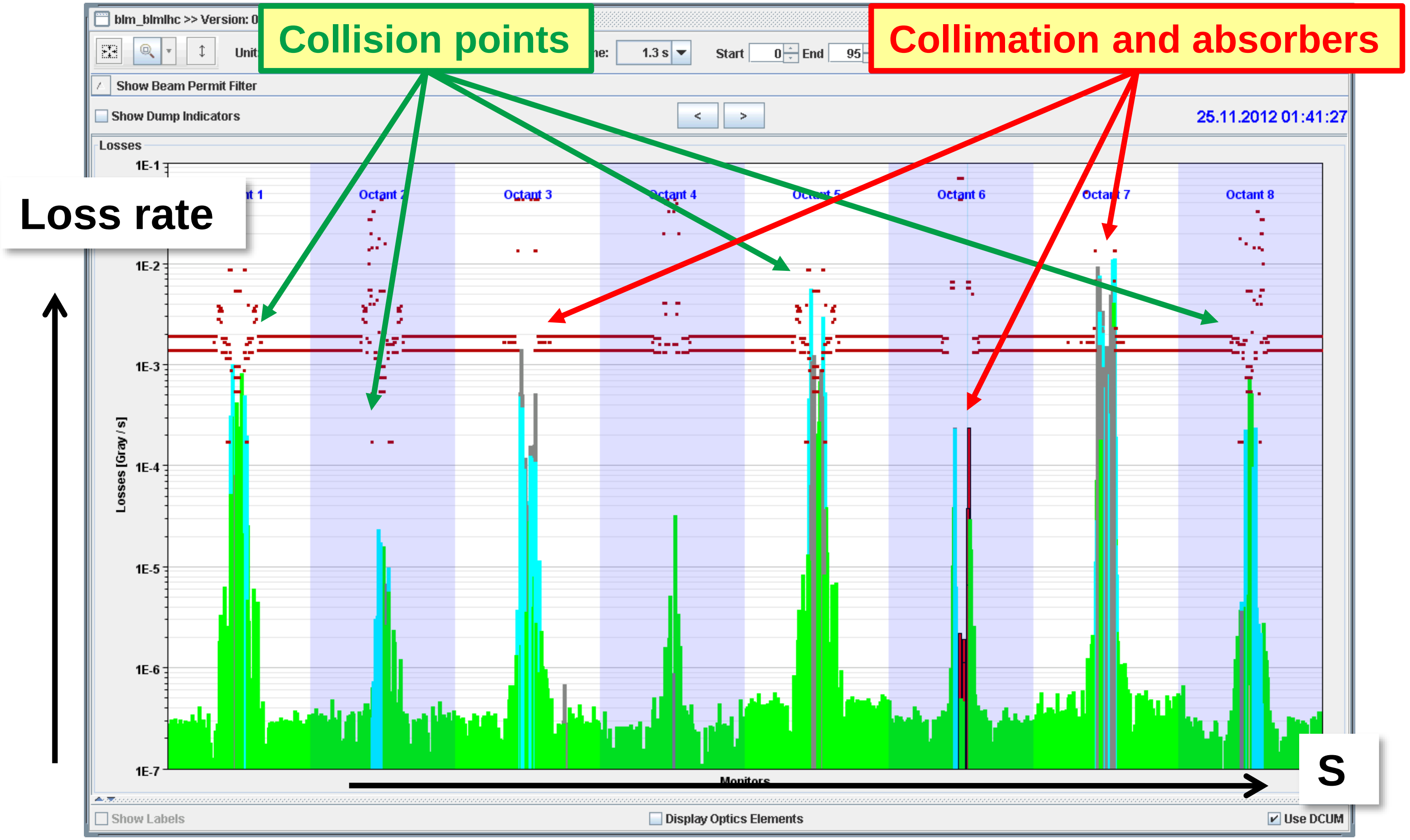


Beam lifetime, measured by loss rate at primary collimators

Continuous beam losses at LHC

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

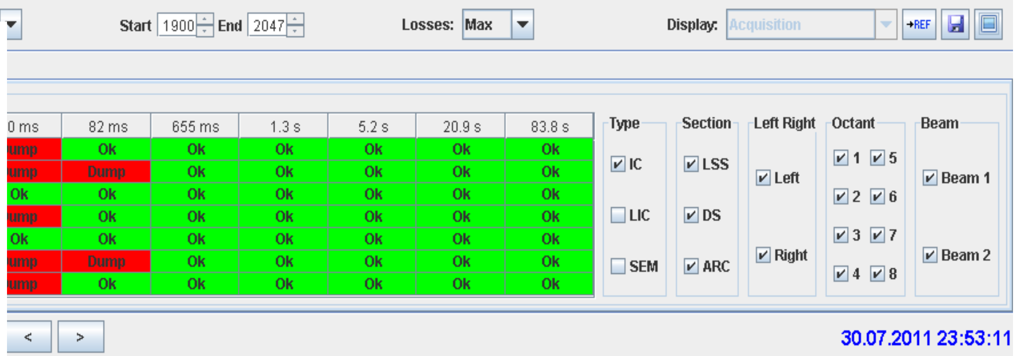
Around the experiments BLMs record collision debris: the small angle physics not covered by the experiments !!

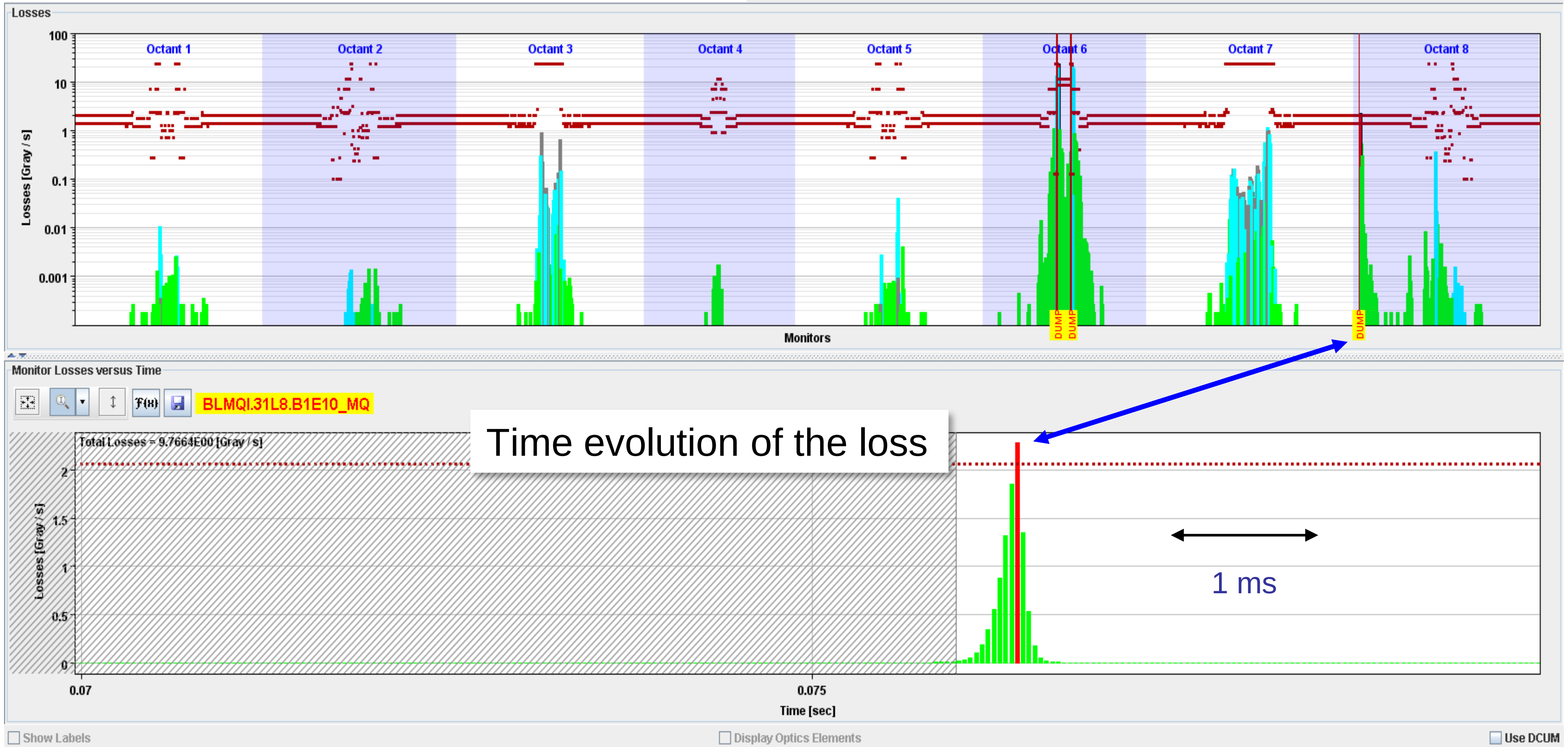


Unexpected beam losses…

As soon as the LHC intensity was increased in 2010, unexpected loss events started to occur.

- Very localized and short losses in arc section.
- Beam was completely stable.
- How could particles reach those locations?

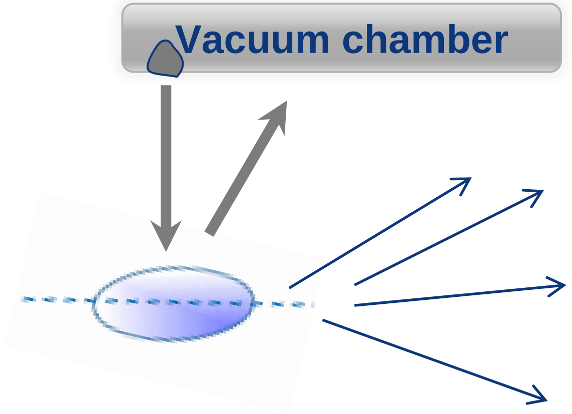




It was quickly realized that since **the beam was stable during such events and was not hitting the vacuum chamber**, it is the **"vacuum chamber that comes to the beam"**…**nicknamed UFOs**.

The most credible explanation for the **Unidentified Falling Objects** are **dust particles** that fall into the beam and generate beam losses due to inelastic collisions with the beam.

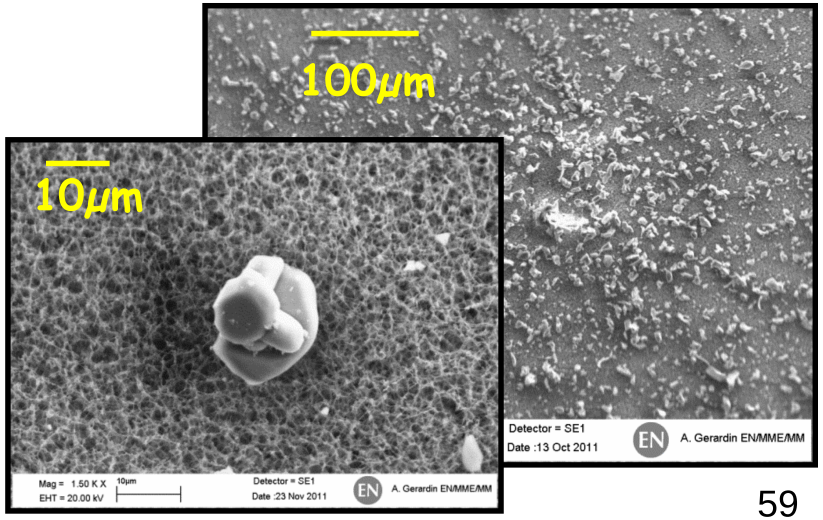
– The signals are consistent with small (10's μm diameter) dust particles.
– For LHC injection kickers that were initially a strong "source" of UFOs, the events could be traced to Al oxide dust → cleaning campaign solved the problem for those elements.



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

To note: **the vast majority of UFO events generates losses below BLM dump threshold →** no impact on operation.

The release mechanism of the dust is not understood.

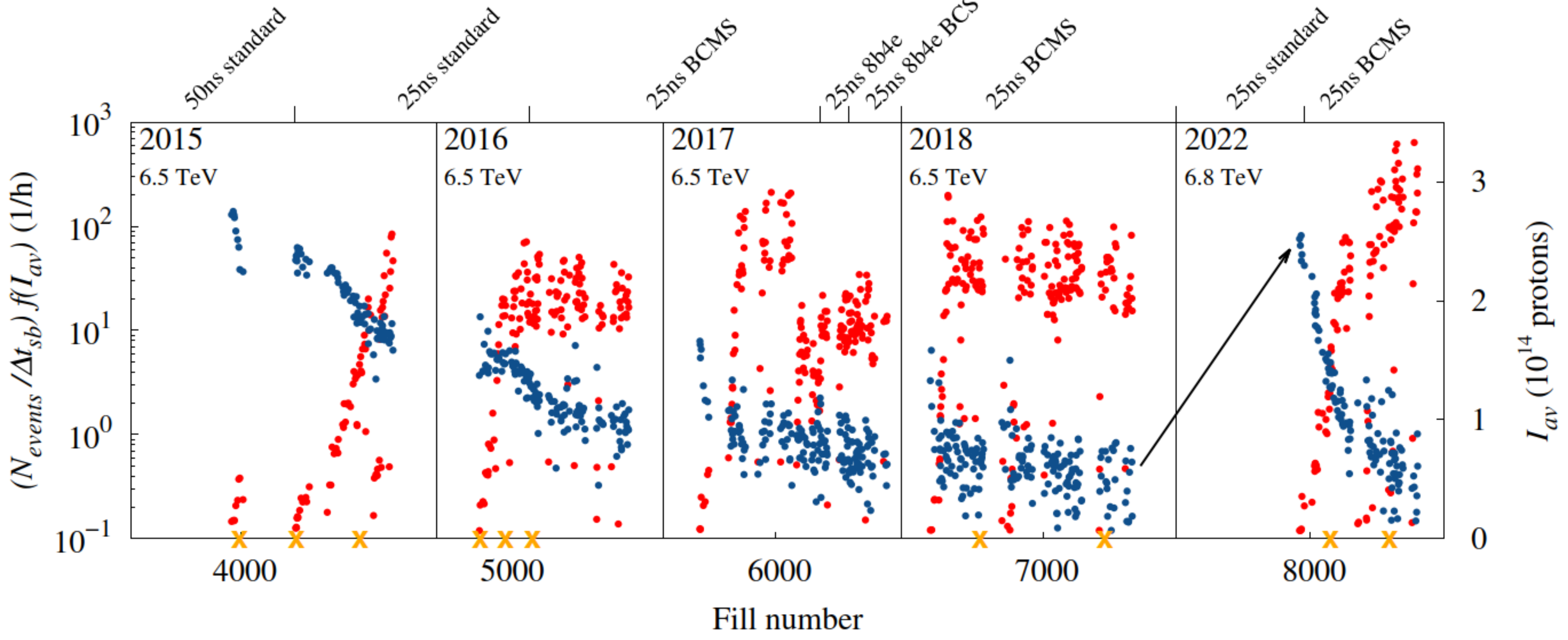


*A. Lechner et al., Phys. Rev. Accel. Beams **25**, 041001 (2022).*

Over long runs, the UFO rates decline to a vey low level, but after each longer shutdown, when the machine is opened, the rate resets again (2015, 2022).

- *In the year after a shutdown, important rate of beam aborts due to UFO beam losses (~20-30/y).*

70+ bunches:



Blue dots = **UFO rate**, red dots = **fill-averaged intensity**, orange crosses = **quench**

Even worse than UFOs

During the extended winter shutdown 2016-2017, one LHC sector (S12) was brought to room temperature to exchange a dipole with a inter-turn short.

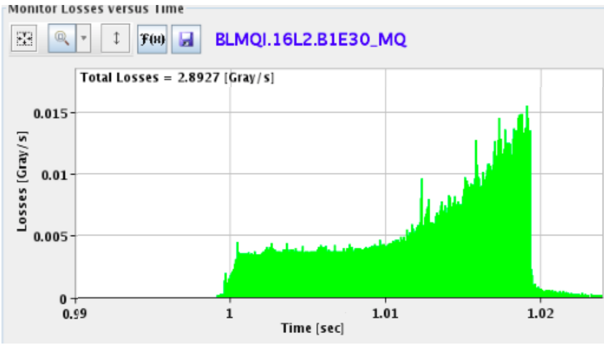
During the cool down an issue during the disconnection of vacuum pumps led to **an air inlet** (~few liters) **into the cold vacuum chamber**. The event and its consequences became only clear a few months later.

The air condensed as ice on the vacuum chamber.

In June 2017 **very strange beam loss events** were observed in conjunction with UFO-like losses in one cell coupled to beam instablities, eventually operation could only be sustained with limited beam intensity.

Partial warm up of the sector to 80K in the winter stop 2017-2018, pumping of the N2 gas present in the cell.

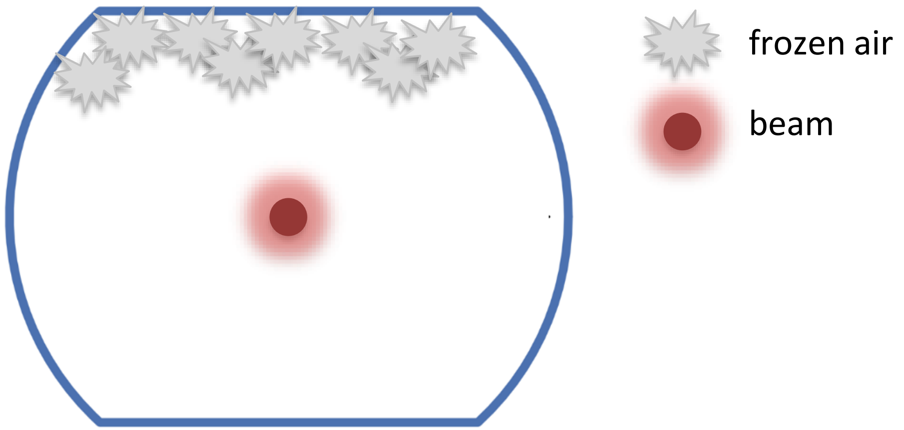
In 2018 the loss events are back, partial warm up was **insufficient to completely solve the problem**, but operation with higher intensity was possible.



10-20 msec

The problems in 16L2 is now understood to be caused by air frozen inside the beam chamber.

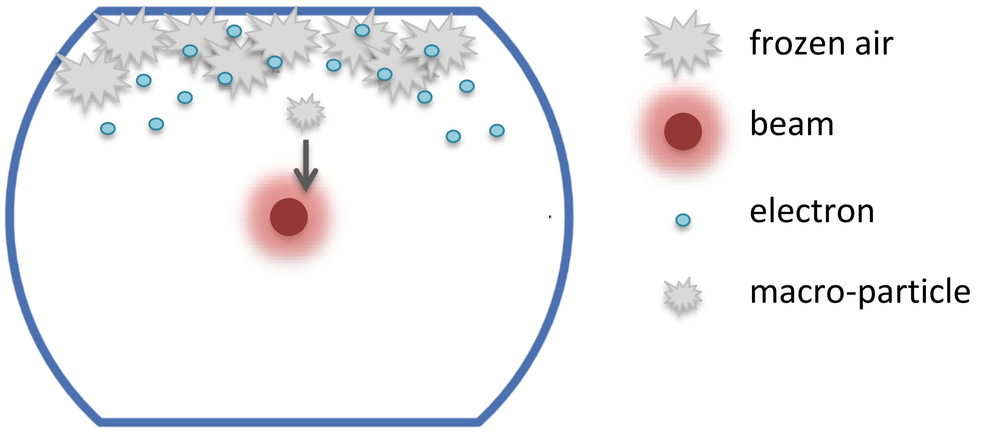
The following model could explain the sequence of events.



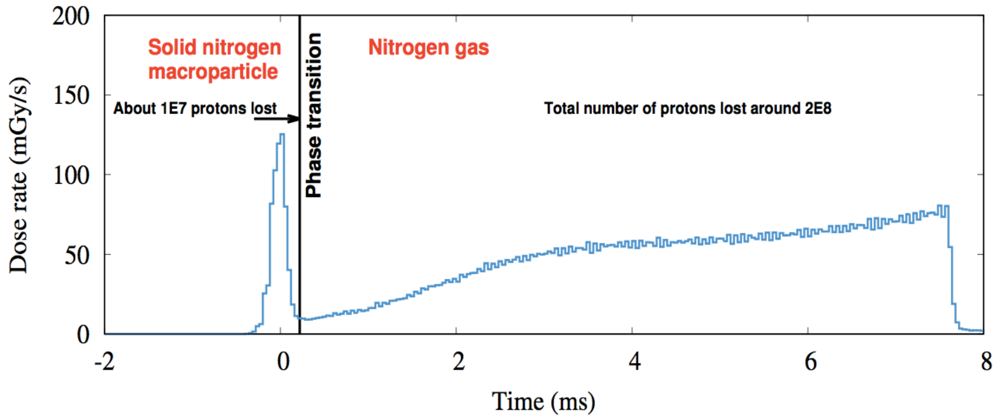
A model for the fast loss events (2)

A macro-particle of frozen air (N_2, O_2) is detached, triggered by the passage of the beam

The macro-particle interacts with the beam, generating a beam loss spike, and disintegrates due to the heat deposition from the beam



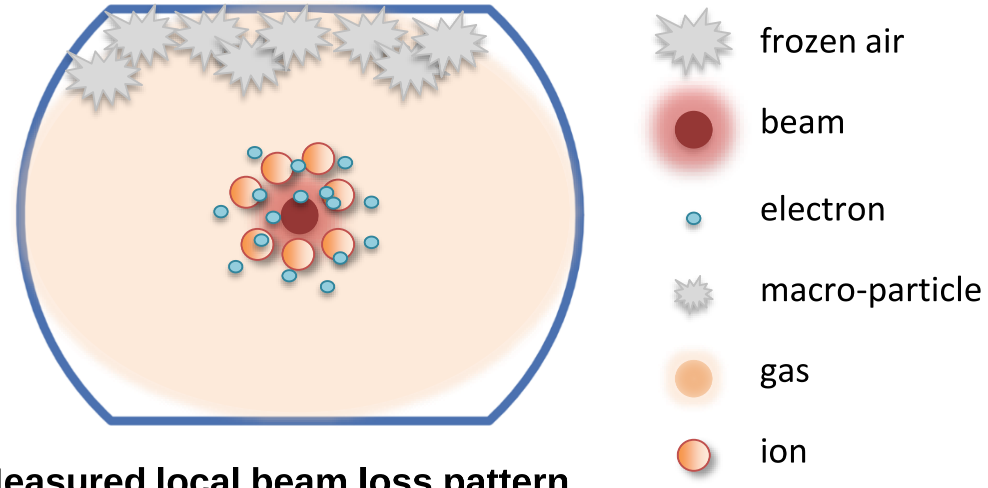
Measured local beam loss pattern



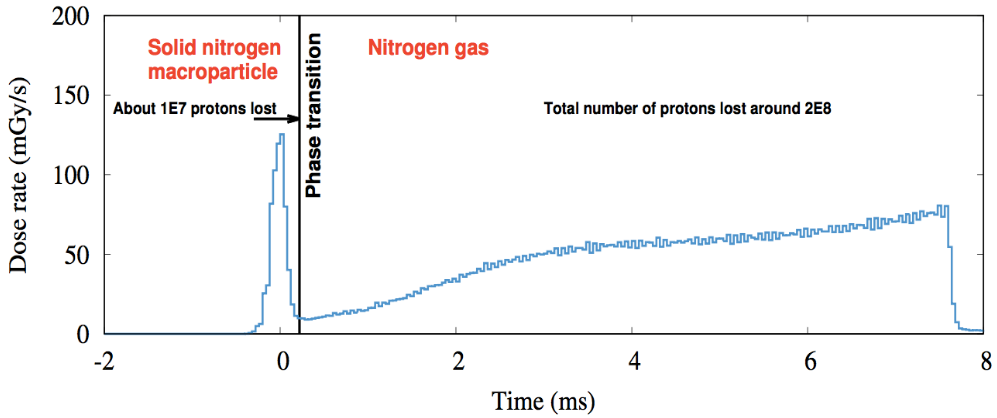
A model for the fast loss events (3)

Gas from the evaporated macro-particle fills the vacuum chamber

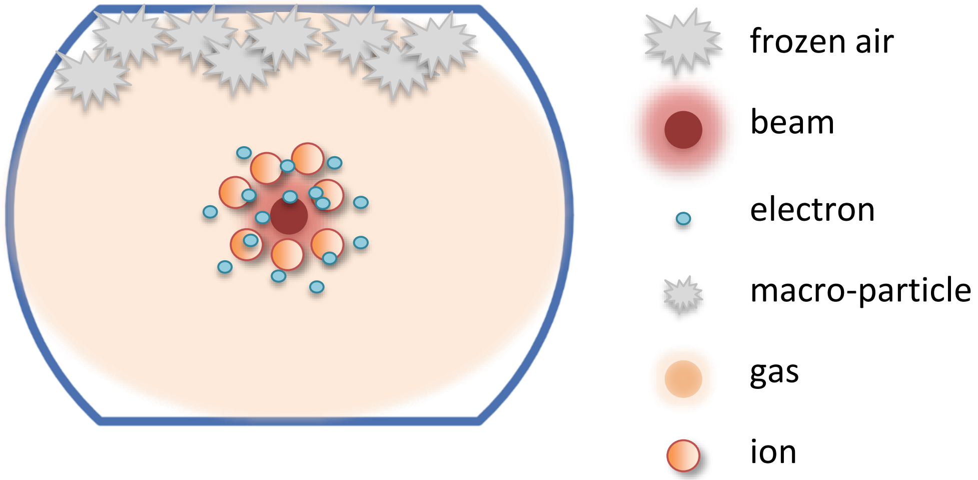
At the location of the beam a plasma is formed



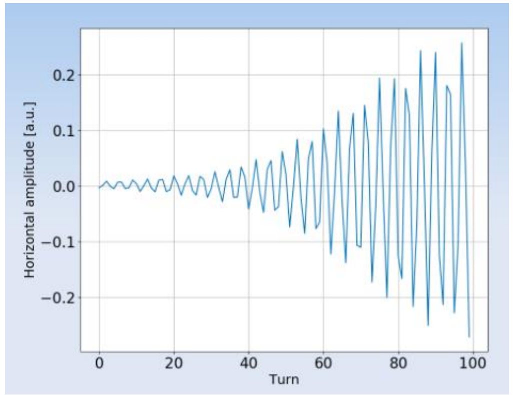
Measured local beam loss pattern



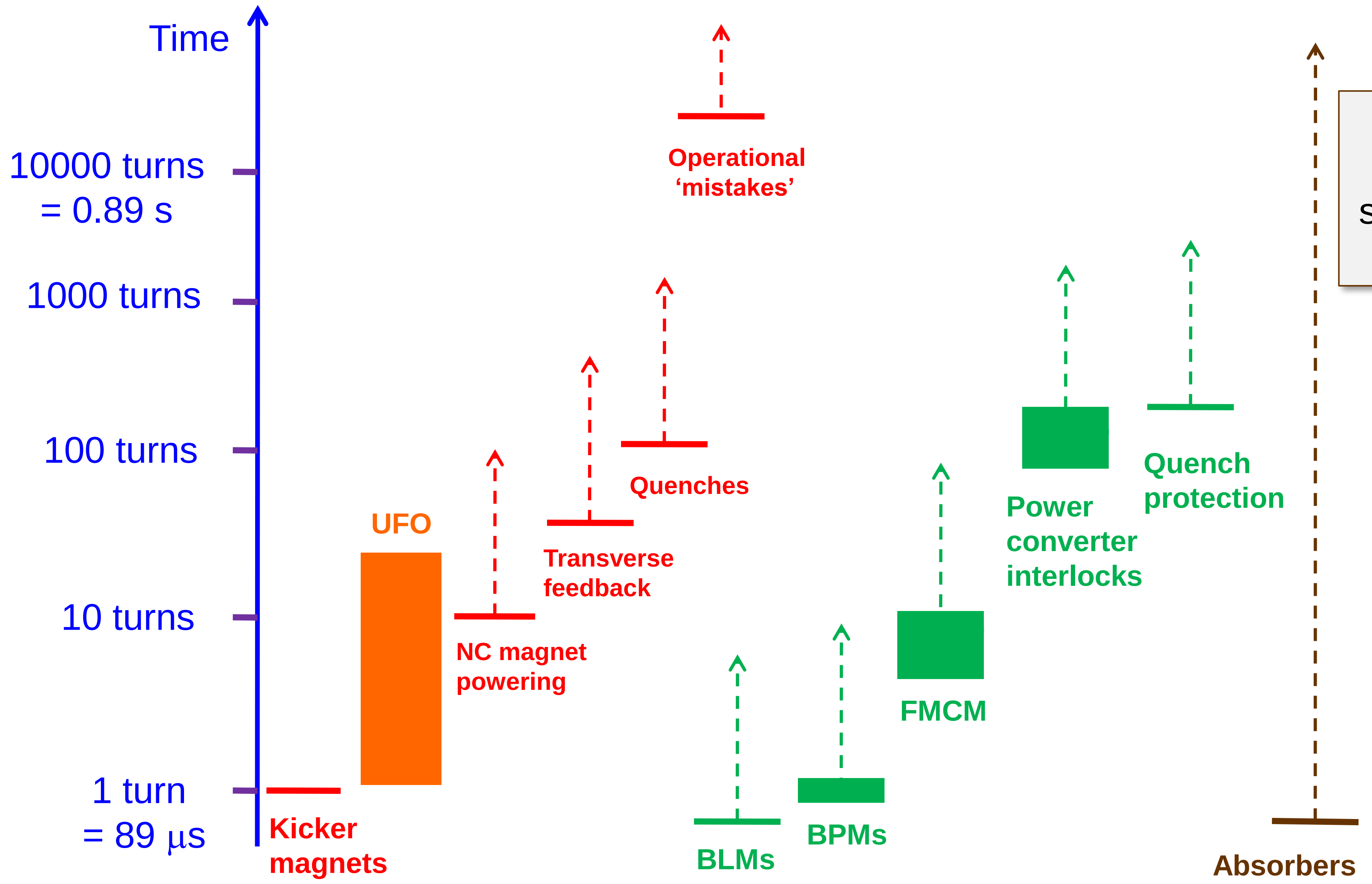
A model for the fast loss events (4)



The fast moving plasma electrons destabilize the beam that has to be dumped due to excessive losses at collimators



Growing transverse beam oscillations



For the fastest UFOs, only the quench protection system is able to protect the magnets

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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').

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:

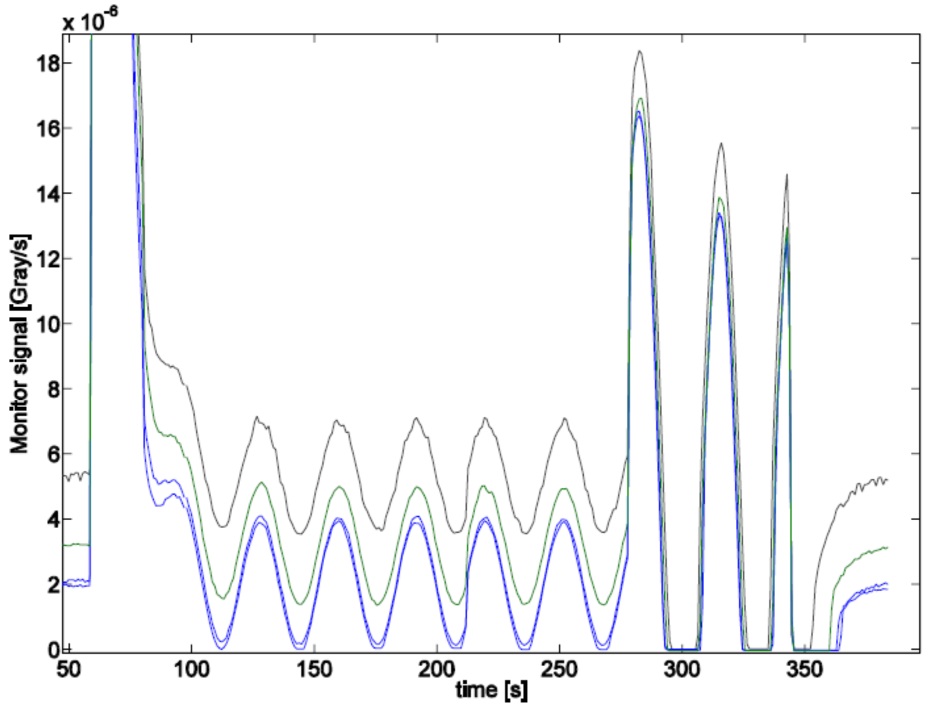
- *Test of MPS related settings, for example BLM thresholds.*
- *Configuration checks of the beam interlock systems (all clients present and alive?).*
- *Automated analysis of the faults and MPS reaction chain – mainly for the simplest and very frequent cases.*
- *Automated analysis of the dump system action.*

Pre-flight checks and validations (after stops, interventions, before filling) are important to assess the good state of MPS elements.

- *Interlock settings (actual settings versus DB reference).*

LHC example: all LHC BLMs are tested between two machine fillings.

- *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.*
- *Asses that all signals are correct, no loss of redundancy.*

  → system is 'as good as new'.
- ***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.

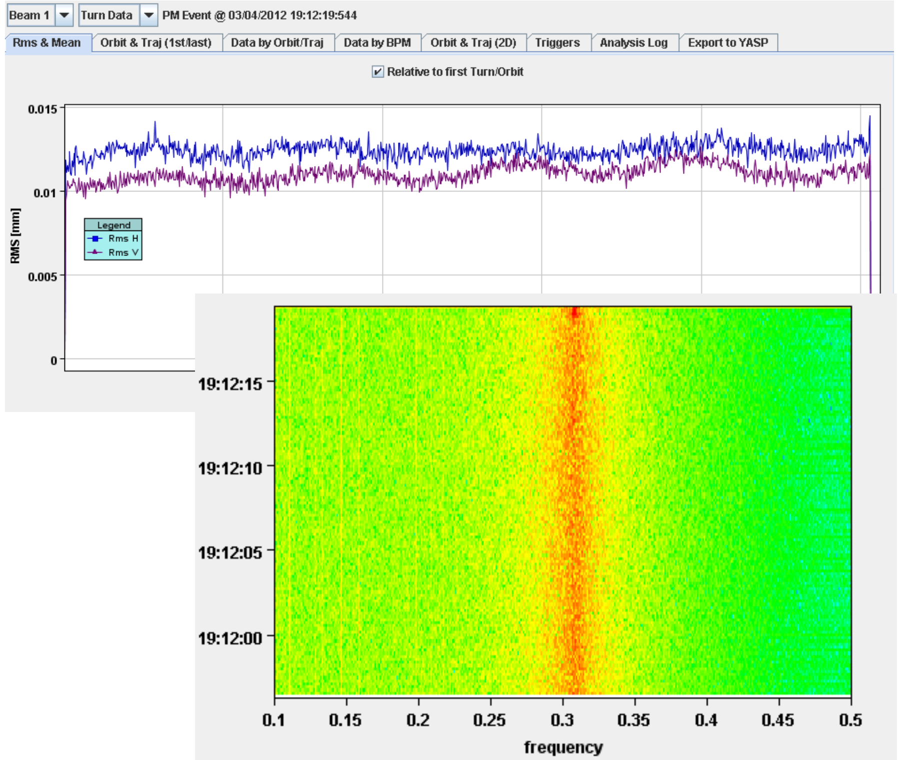
MPS diagnostics – post-mortem

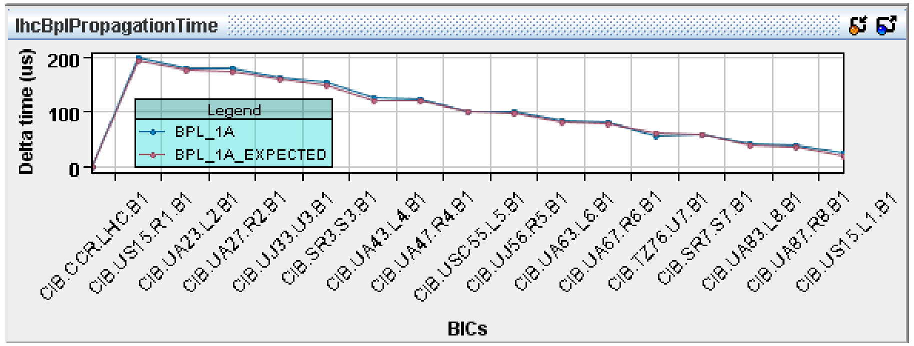
From the design of the LHC MPS post-mortem diagnostics was viewed as a key component in order to identify the root causes of beam dumps.

- *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 !*

After a 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 within a few days – independent view, long term trends.*





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

Someone must 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:

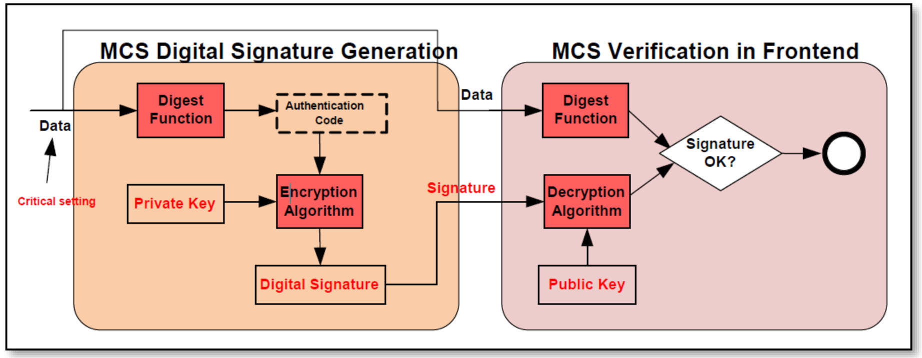
- ‘Continuous’ verification of the MPS settings.
  - For example, before new injection phase.
- Protection of the settings - only authorized experts can change them.
  - Access restrictions: **Role Based Access Control (RBAC)**
  - **(Digital) signatures.**

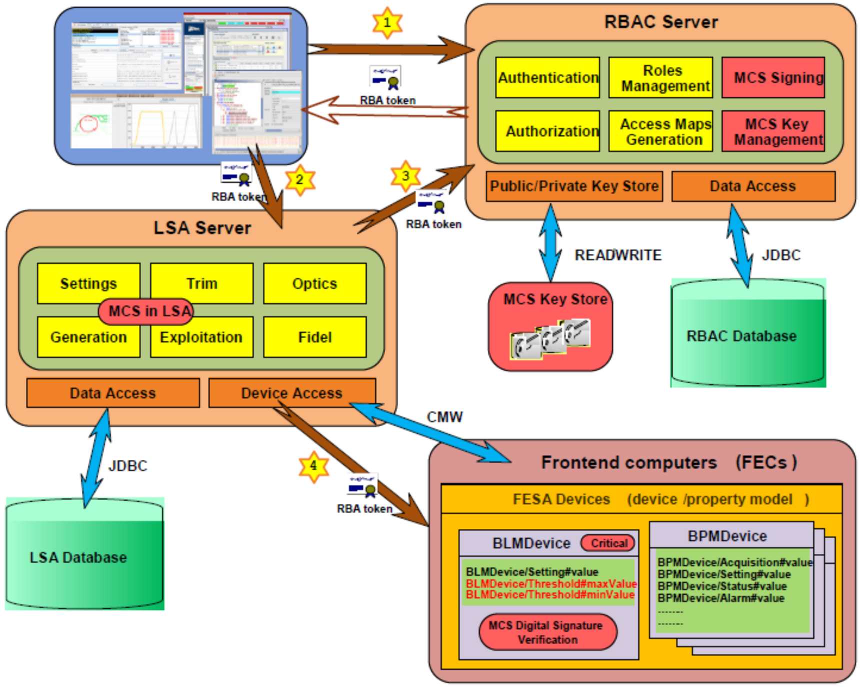
To protect MPS settings the concept of *Management of Critical Settings* (MCS) was developed for the CERN MPS.

- 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.





Summary

Despite its record stored energy and its complexity, the LHC was operated very successfully and with high intensity at 6.8 TeV.

No component was damaged by a failure leading to beam loss –the MPS fulfilled its role !

When you come now to the LHC control room, everything looks '***so simple***' and high intensity beams are injected, ramped and collided in an incredibly efficient and highly automated way.

When we started to look at LHC MP around the year 2000 it was by no means evident that the protection of the machine would work so well and be so efficient – this also includes the LHC collimation system.

- *The result of long and hard work, but also of efficient inter-disciplinary collaboration among many groups!*

Every injection phase of the LHC starts with the injection of a **probe bunch** (max 10^{11} p) into the empty ring – **enforced by HW signals**.

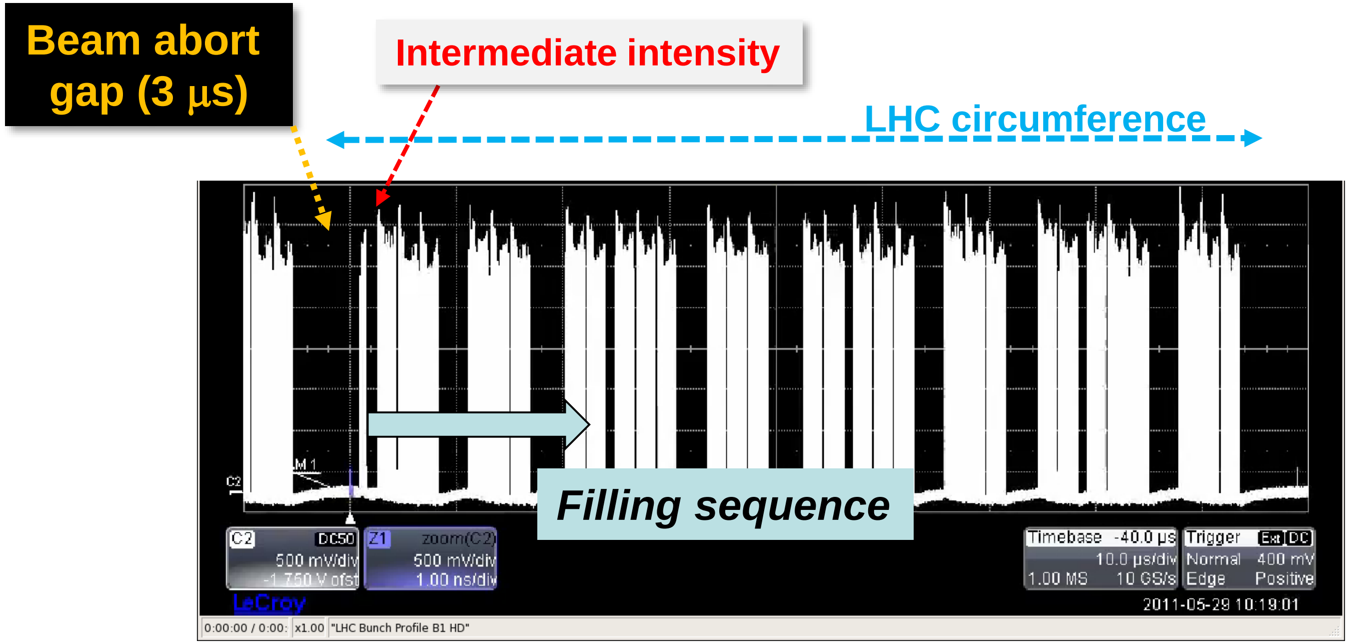
see lecture on beam transfer

When a probe bunch circulates, **an intermediate intensity** 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**.

If the beam is dumped during the filling process → back to the beginning.



Example for a LHC bunch pattern