Machine Protection

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Operation group – LHC section

Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

The unexpected

Summary

Safety at accelerators - definitions

Accelerators, as all other technical systems, must respect some general principles with respect to safety:

- Protect the people (legal requirements).
- Protect the environment (legal requirements).
- Protect the equipment (asset management).
  - Without beam : superconducting magnets, high power equipment, power cables, normal conducting magnets, RF systems, etc.
  - **With beam: damage caused by beams.**
- Those 3 aspects may be coupled in some circumstances!

This presentation on "Machine Protection" is focused on equipment protection from damage caused by <u>beams</u>.

Trends in modern accelerators

All major accelerator projects are pushed to new records.

- Higher beam energy and intensity:
  - Hadron colliders – LHC.
  - Linear e+e- colliders.
  - CERN Future Circular Colliders study.

Frequent mixing of super-conducting magnets/RF and high power beams

- Higher power and brightness:
  - Neutron spallation sources.
  - Neutrino physics.
  - Synchrotron light sources (synchrotron light power).

>> the energy (density) stored in the beams increases !

In many modern projects machine protection aspects have a large impact on (or may even dominate) design and operation

Modern accelerators

- High power accelerators – from some 10 kW to above 1 MW.
  - Neutron spallation sources (SNS, ISIS).
  - High power/high duty cycle machines (PSI cyclotron, JPARC).
- High energy hadron colliders and synchrotrons.
  - LHC and its upgrades.
  - Synchrotrons for fixed target experiments (SPS).
- e+e- colliders.
  - B-factories (KEKB, super-KEKB).
- Synchrotron light sources.
  - High power photon beams.
- Linear colliders/ Free Electron Lasers (FEL).
  - SLAC linac, ILC, CLIC, FLASH, XFEL.
- Energy recovery linacs.
- Medical accelerators.
  - The patients !

Risks and protection

- Protection is required since there is some risk.

Risk = probability of an accident

x consequences (in Euro, downtime, radiation doses).

- Probability of an uncontrolled beam loss:
  - What are the failures that lead to beam loss into equipment?
  - What is the probability for the failure modes?
- Consequences:
  - Damage to equipment.
  - Downtime of the accelerator for repair.
  - Activation of material, dose to personnel.

>> The higher the risk, the more protection becomes important !

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Summary

- Momentum of the particle
- Particle type

  Activation is mainly an issue for hadron accelerators.

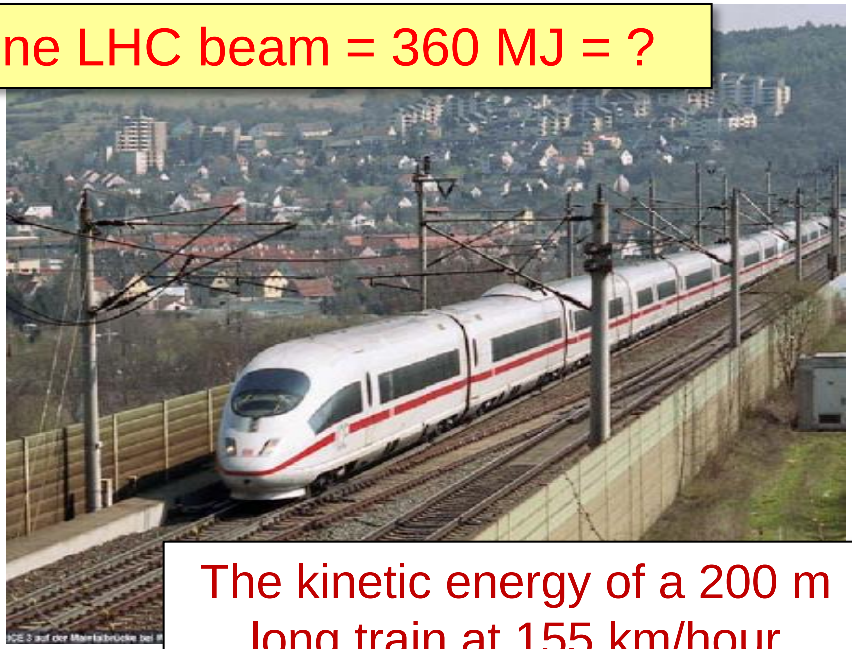
- Energy stored in the beam

  1 MJ can heat and melt 1.5 kg of copper.

  1 MJ = energy stored in 0.25 kg of TNT.

- Beam power
- Beam size
- Time structure of beam

One LHC beam = 360 MJ = ?



The kinetic energy of a 200 m long train at 155 km/hour

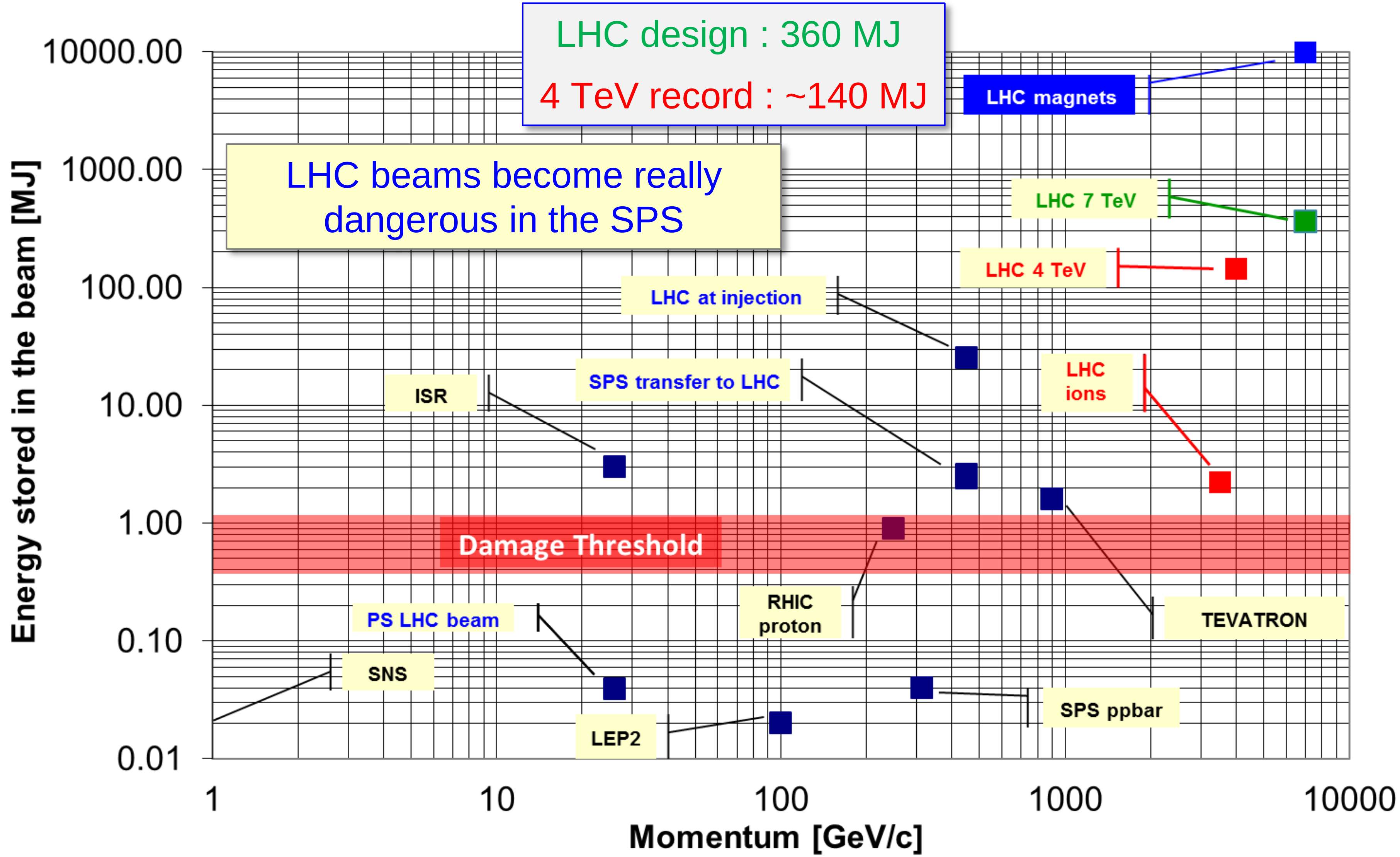
90 kg of TNT

8 litres of gasoline

15 kg of chocolate

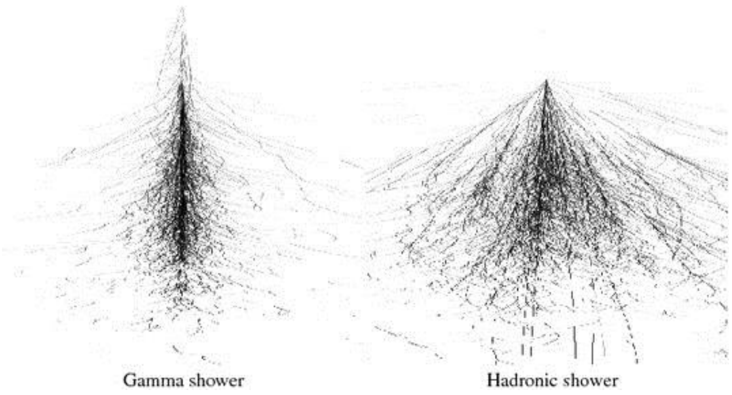
Key factor :
how easily and how fast the energy is released !!

Stored energy chart



Beam loss in materials

- Lost particles induced particle cascades in materials they traverse.
  - The peak energy deposition can be deep in the material at the maximum of the hadron / electromagnetic shower.
  - Particle showers from hadrons with energies of 100's of GeV to some TeV have a penetration depth of some meters.

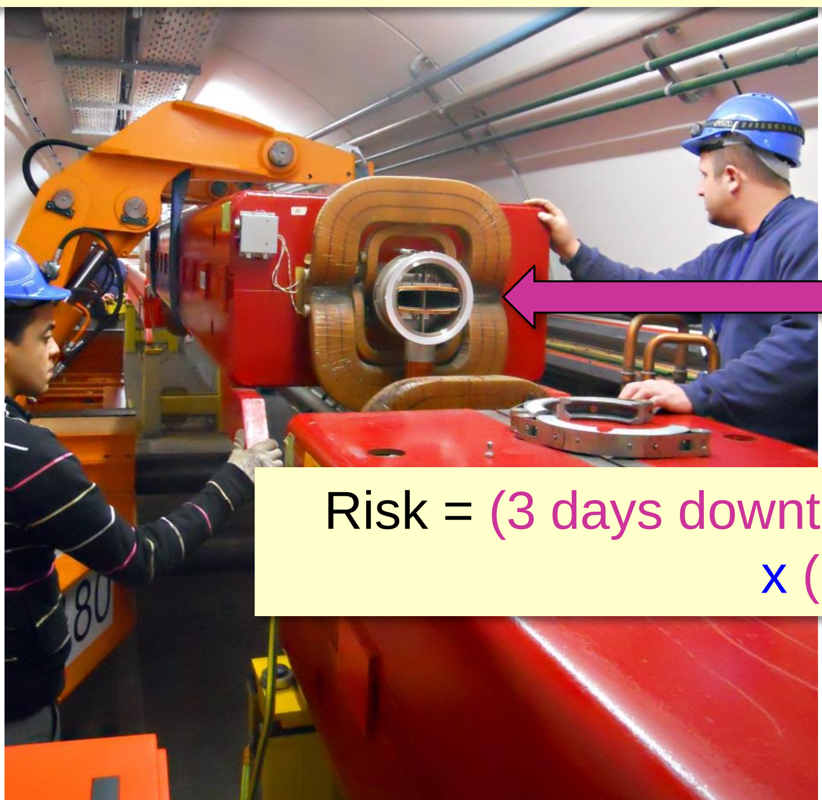


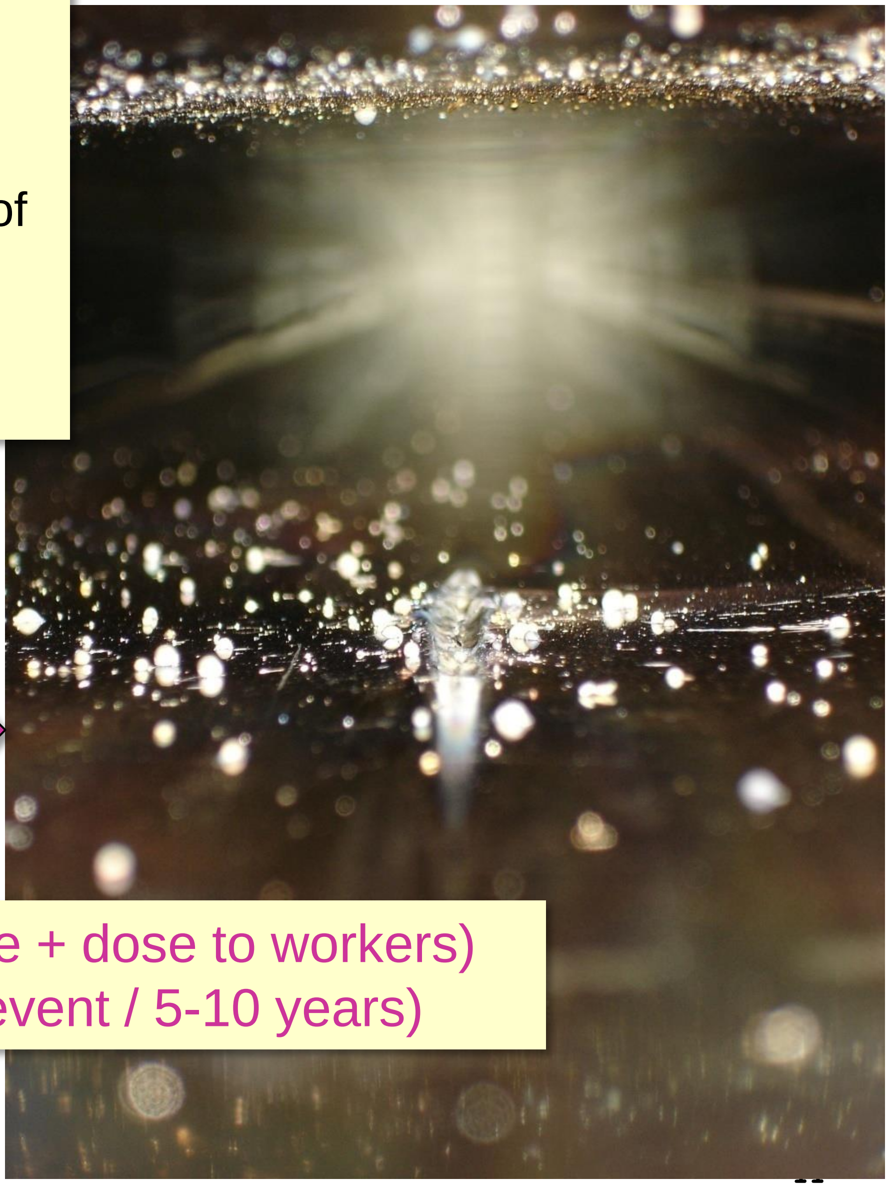
- The energy deposition leads to a temperature increase, and for very fast losses to shock waves and to plastic deformation.
  - Material can melt, vaporize, deform or lose its mechanical properties.
  - Limited risk for some 10 kJ, large risk for some MJ.
  - Equipment becomes activated due to beam losses.
  - Superconducting magnets can quench (become normal-conducting).

From uncontrolled damage tests…

A real case from the 2008 SPS run !

- Impact on the vacuum chamber of a 400 GeV beam of 3×10^{13} protons (**2 MJ**).
- Event is due to an insufficient coverage of the SPS MPS (known !).
- Vacuum chamber to atmospheric pressure, downtime ~ 3 days.





Risk = (3 days downtime + dose to workers) x (1 event / 5-10 years)

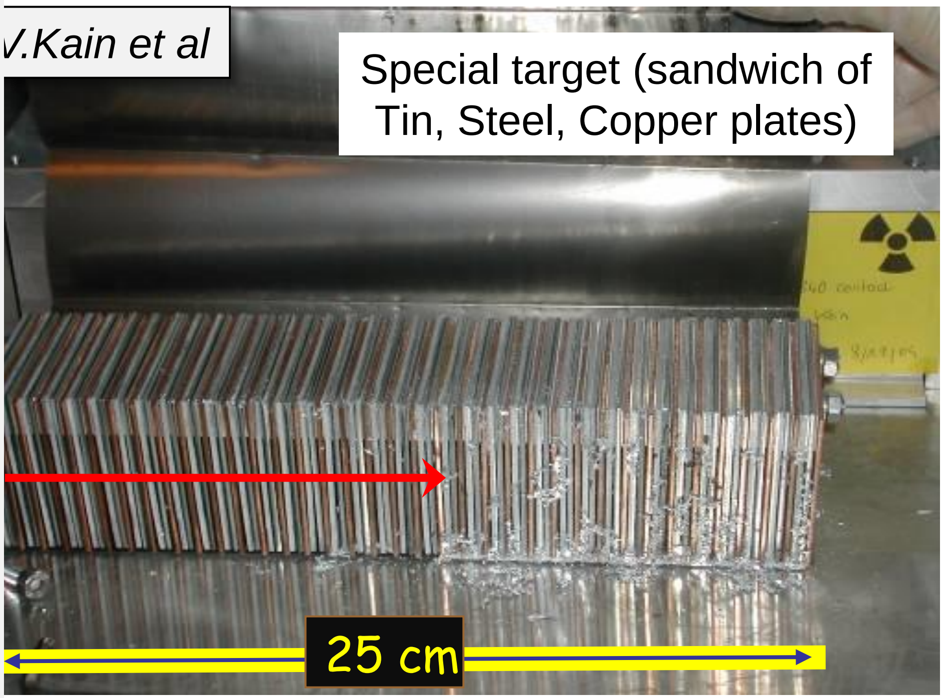
…to controlled damage tests

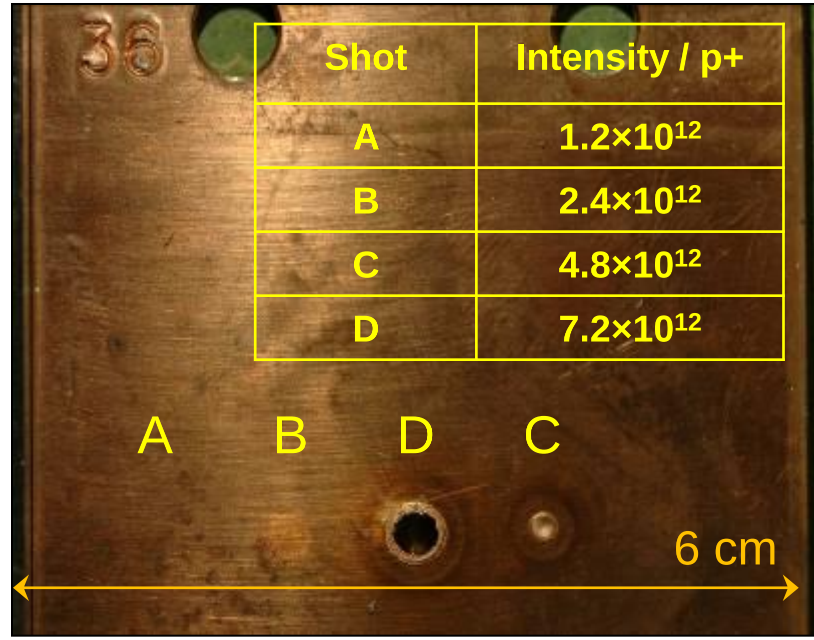
- In the past decade a lot of effort was invested to better understand the interaction of high energy / high density beams with matter.
- Experiments:
  - *Ad-hoc experiments for the LHC,*
  - *Construction of a dedicated test facility at CERN (HiRadMat @ SPS).*
- Modeling and comparison with tests.
  - *Many matter phases (solid, liquid, plasma), 'hydro-codes'.*
- Some outcomes:
  - ✓ Validation of LHC carbon collimator robustness,
  - ✓ Validation of damage thresholds for LHC injection energy,
  - ✓ Validation of simulation codes,
  - ✓ Search for more robust material.

SPS experiment : damage at 450 GeV

Controlled SPS experiment / protons.

- Energy 450 GeV,
- Beam area σ_x x σ_y = 1.1 x 0.6 mm^2,
- Damage limit for copper at 2×10^{12} p.
- No damage to stainless steel.



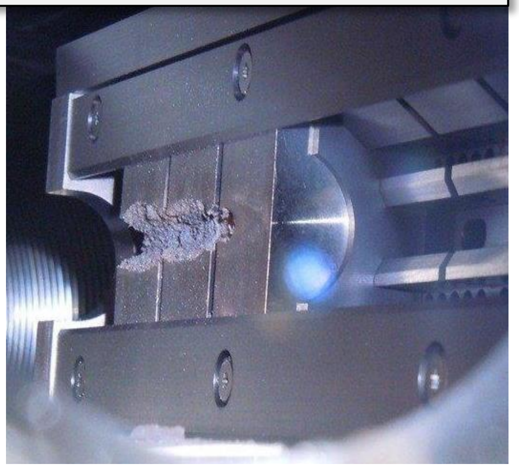


Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

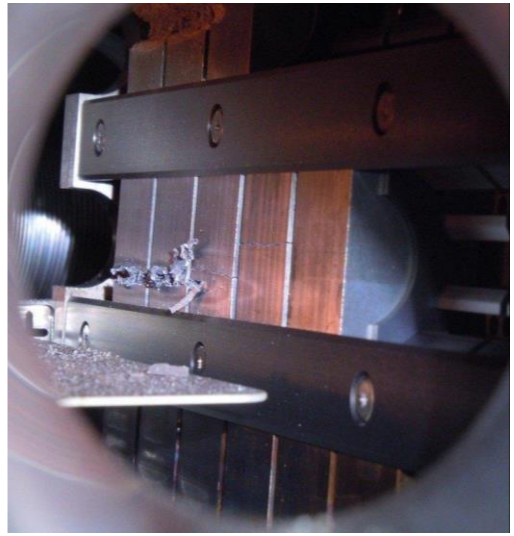
- Damage limit is ~200 kJ, < 0.1 % of a nominal LHC beam.
- Impact D: ≈ 1/3 of nominal LHC injection.

HiRadMat tests – new materials

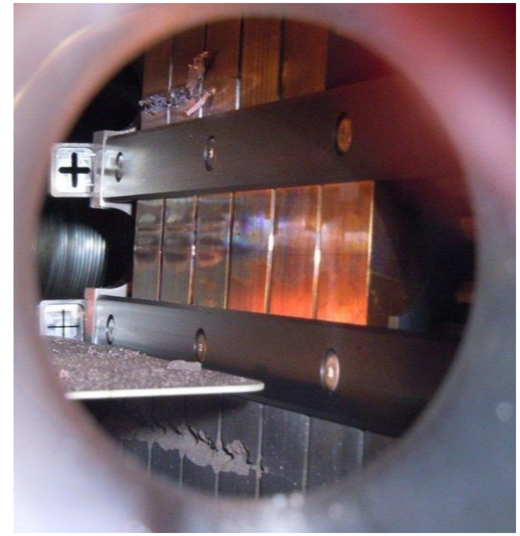
Courtesy A. Bertarelli (EN)



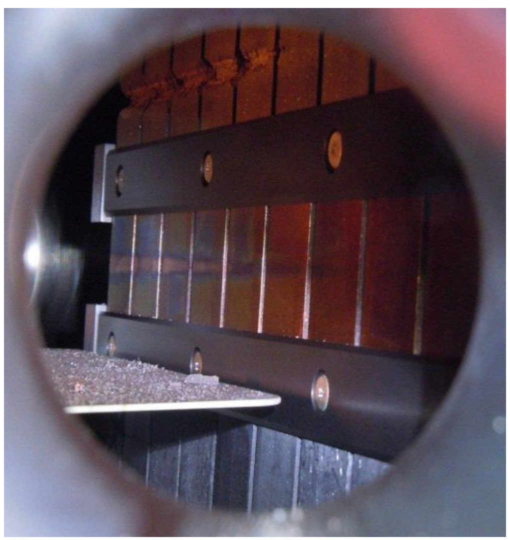
Inermet 180, 72 bunches



Molybdenum, 72 & 144 bunches

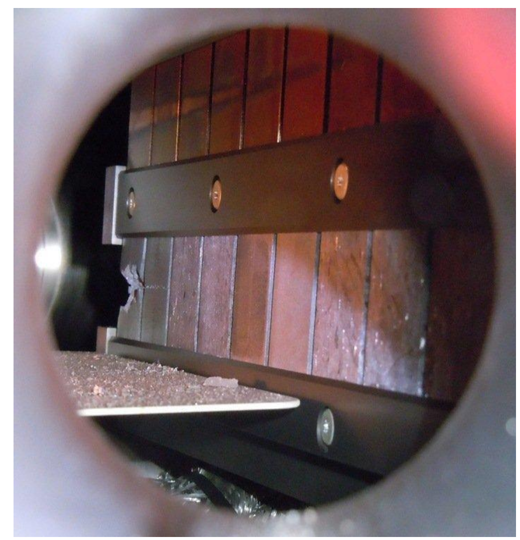


Glidcop, 72 bunches (2 x)



Copper-Diamond 144 bunches

Molybdenum-Copper-Diamond 144 bunches

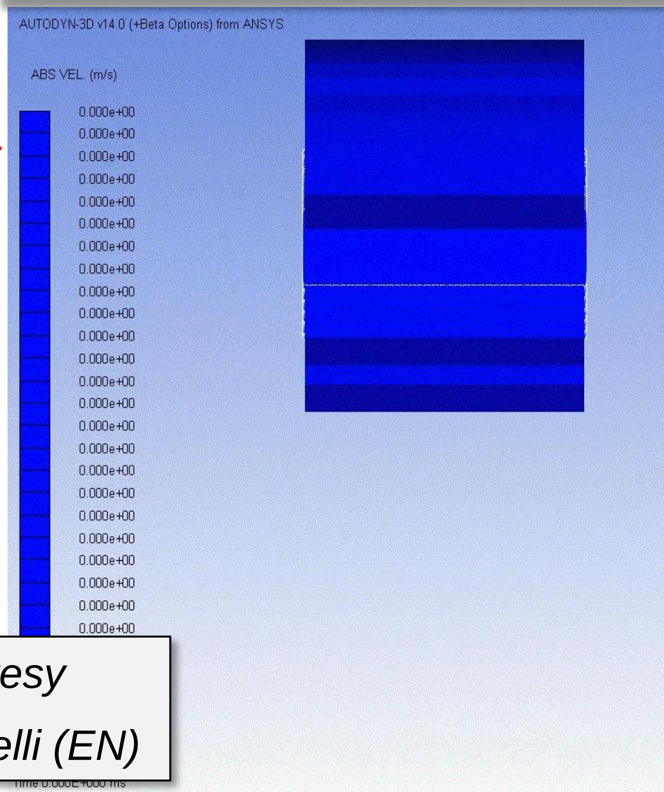


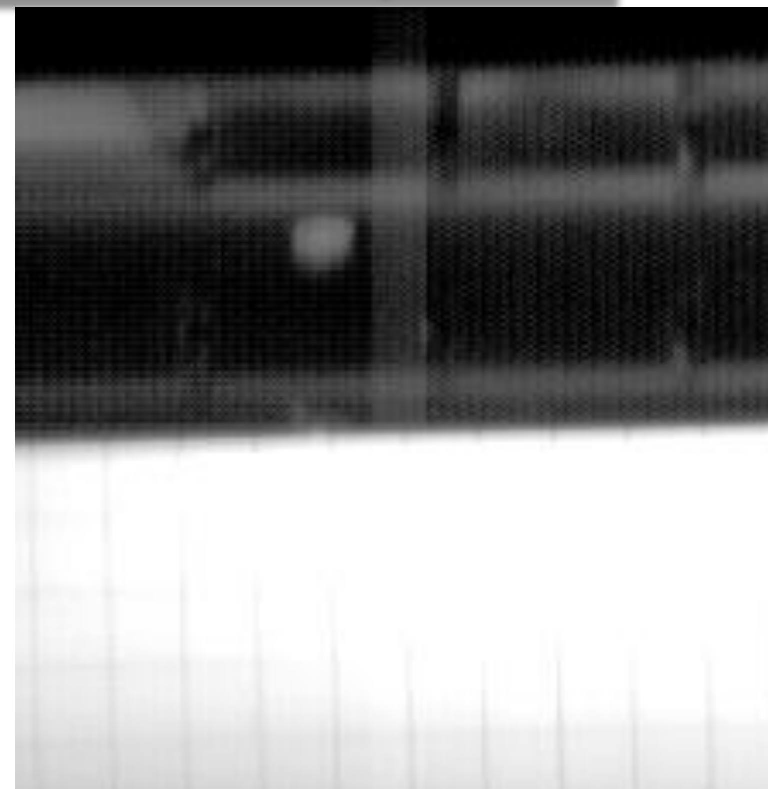
Molybdenum-Graphite (3 grades) 144 bunches

HRMT14: high intensity tests

Inermet : comparison between simulation and experiment

Beam





Courtesy

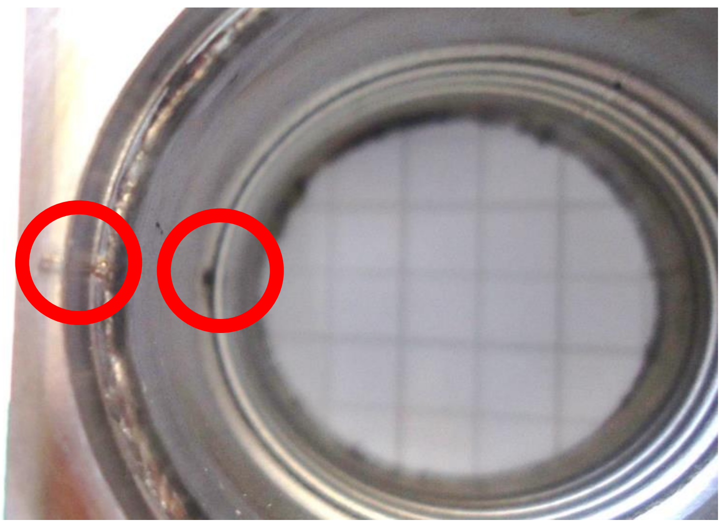
A. Bertarelli (EN)

Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

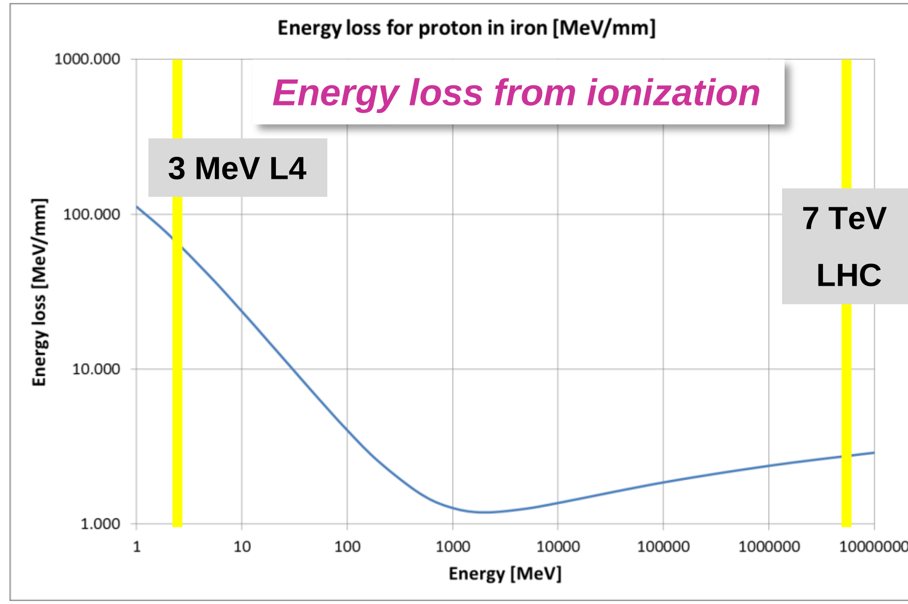
Small…but dangerous

- Damage @ Linac4 with a 3 MeV beam – vacuum leak.

- Failure combination:
  - *Beam misaligned,*
  - *Unlucky magnet setting,*
  - *Aperture limitation at bellow.*



JB Lallement



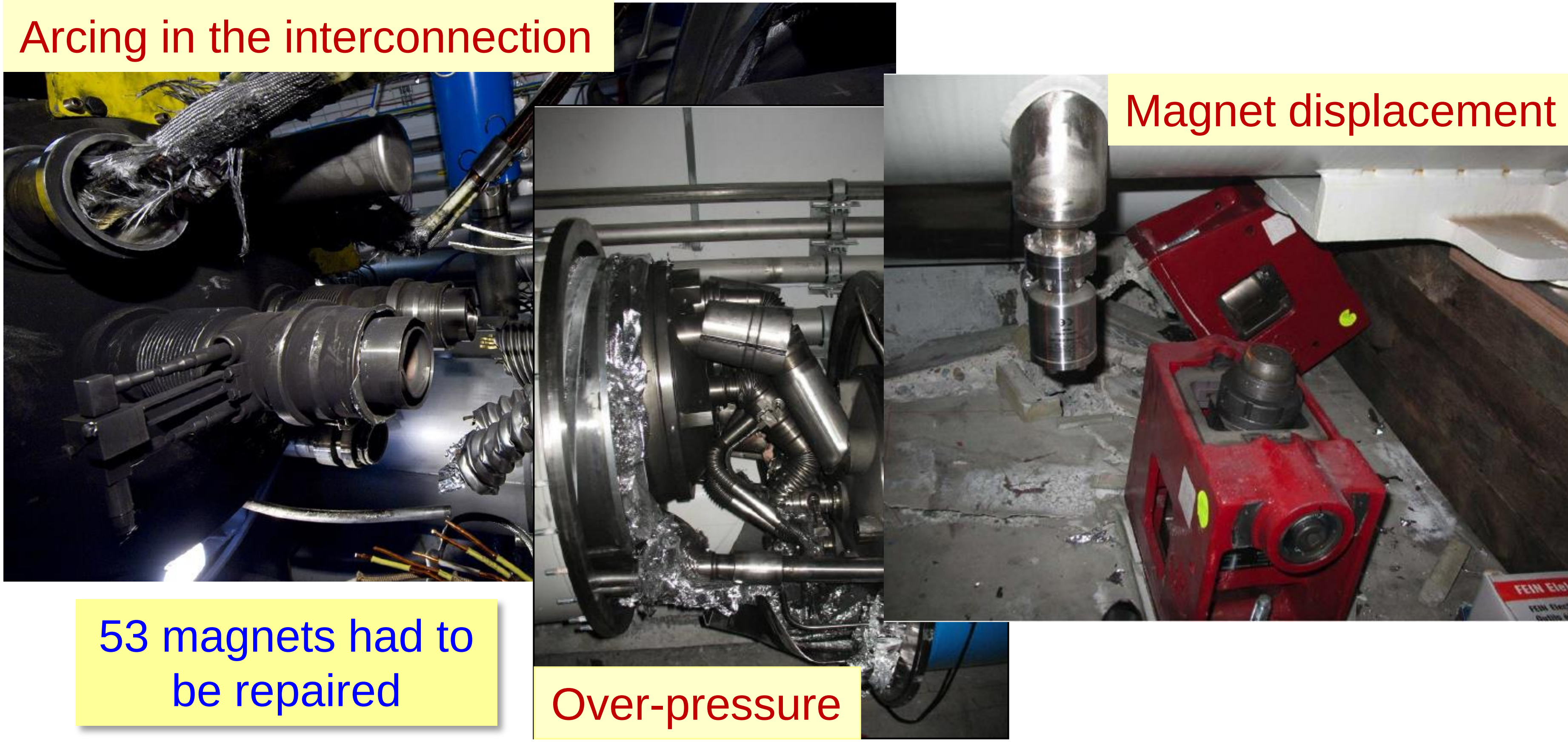
At such low energies, the local energy loss per proton is very high

$\Rightarrow$ Damage after some integration time

Release of 600 MJ at LHC

The 2008 LHC accident happened during test runs without beam.

A magnet interconnect was defect and the circuit opened. An electrical arc provoked a He pressure wave damaging ~600 m of LHC, polluting the beam vacuum over more than 2 km.



53 magnets had to be repaired

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Modern Machine Protection System : P^3

- **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').

Beam loss

In accelerators, particles are lost due to a variety of reasons: beam gas interaction, losses from collisions, losses of the beam halo, …

- Some (continuous) beam losses are inherent to the operation of accelerators.
  - *Taken into account during the design of the accelerator.*
  - *Max. loss rates may be given by the design:*
    - *Prevent magnet quenches (LHC).*
    - *Allow maintenance (residual contact radiation).*
- Accidental beam losses are due to a multitude of failures mechanisms.

Analysis and structure required !

Failure classification

- **Failure type:**
  - Hardware failure (power converter trip, magnet quench, AC distribution failure, object in vacuum chamber, vacuum leak, RF trip, ….).
  - Controls failure (wrong data, wrong magnet current function, trigger problem, timing system, feedback failure, ..).
  - Operational failure (chromaticity / tune / orbit errors, …).
  - Beam instability (high beam / bunch current).
- **Failure parameters:**
  - Damage potential.
  - Probability for the failure.
  - Time constant for beam loss.

→ *Mixture defines the risk and the criticality for MP*

- **Machine state (when failure occurs):**
  - Linac, beam transfer, injection and extraction (single pass).
  - Stored beam.

MPS design strategy

- Avoid a failure by design – if you can.
- Detect a failure at the hardware (equipment) level and stop operation – first protection layer.
- Detect the consequences of the failure on beam parameters (orbit, tune, losses etc) and stop operation – second protection layer.
- Stop beam operation.
  - *Inhibit injection,*
  - *Send beam to a dump,*
  - *Stop the beam by collimators / absorbers.*
- Elements of protection:
  - ✓ Equipment and beam monitoring,
  - ✓ Collimators and absorbers,
  - ✓ Beam dumps,
  - ✓ Interlock system linking different systems.

Passive and active protection

Passive protection

- Collimators.
- Masks.
- Absorbers.
- Dumps.

Obstacles to absorb the energy

Active protection

- Equipment surveillance.
- Beam observation.
- Extraction (dump) kickers.

Detection of a failure directly on the equipment or by its effects on the beam.

Modern MP systems usually require both passive and active protection to cover all failure cases.

Failure time scales – circular machines

Time scale

- Single turn (single-passage) beam loss — ns -µs
  - Failures of kicker magnets (injection, extraction kicker magnets).
  - Transfer failures between two accelerators or from an accelerator to a target station.

High reliability

Passive protection

- Very fast beam loss (µs - ms) — µs-ms
  - Multi turn beam losses in rings.
  - Large variety of possible failures, mostly in the magnet powering system, with a typical time constant of some 10 turns to many seconds
- Fast beam loss — 10 ms - s
- Slow beam loss — many s

Active Protection

Passive protection

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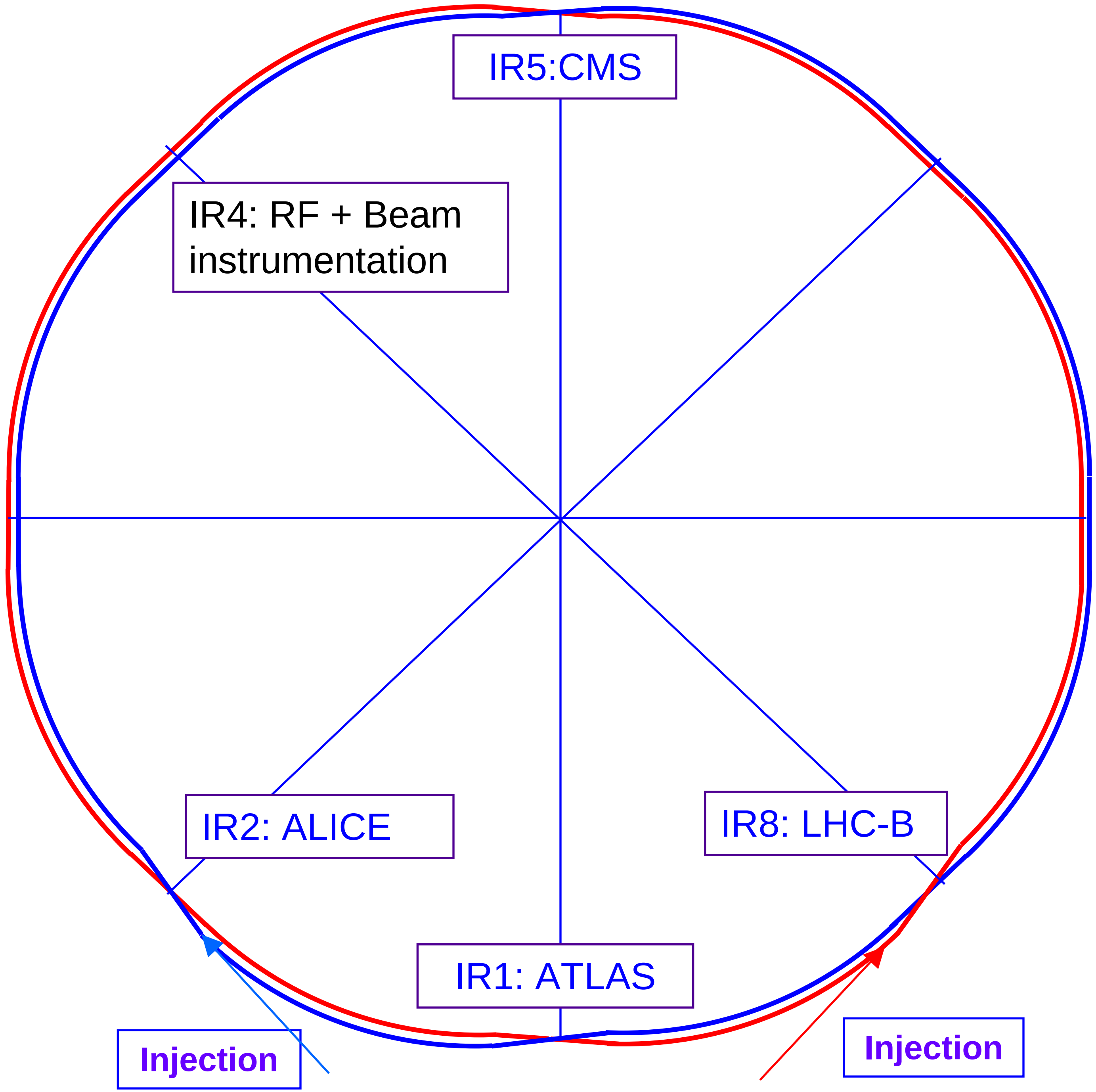
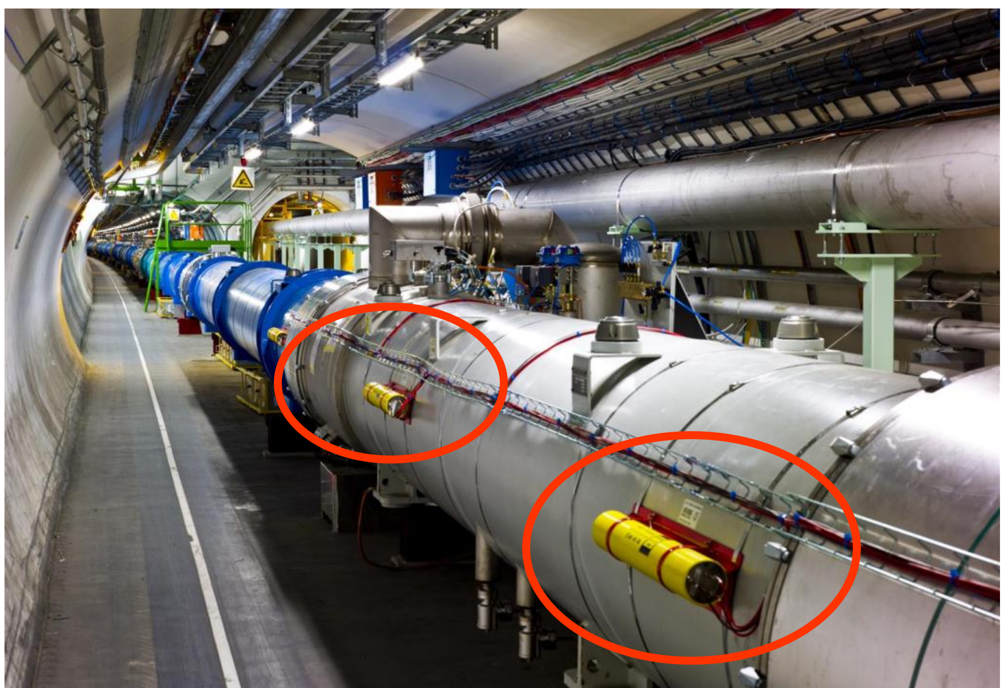
The LHC

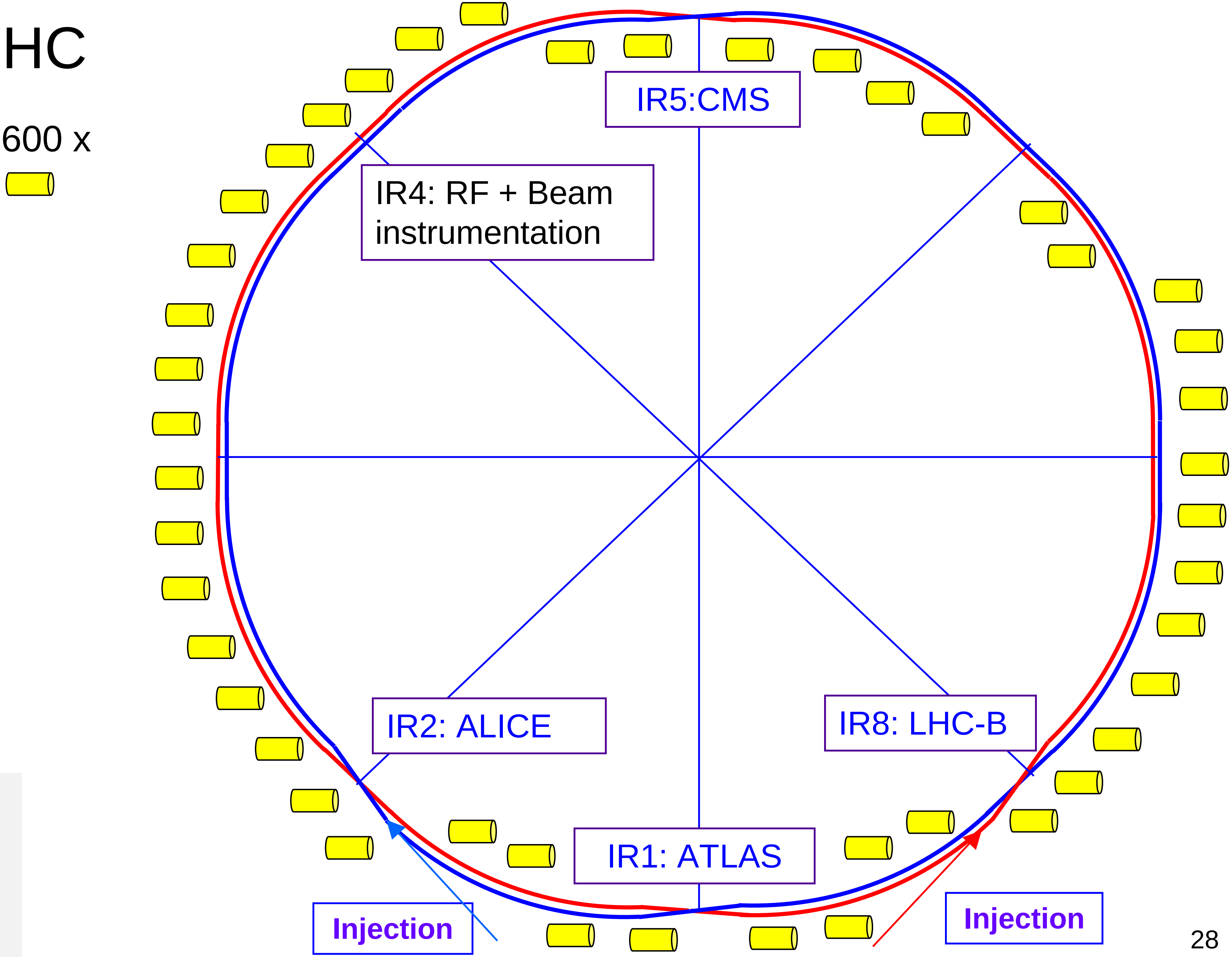

IR5:CMS
IR4: RF + Beam instrumentation
IR2: ALICE
IR8: LHC-B
IR1: ATLAS
Injection
Injection

- 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 !



LHC

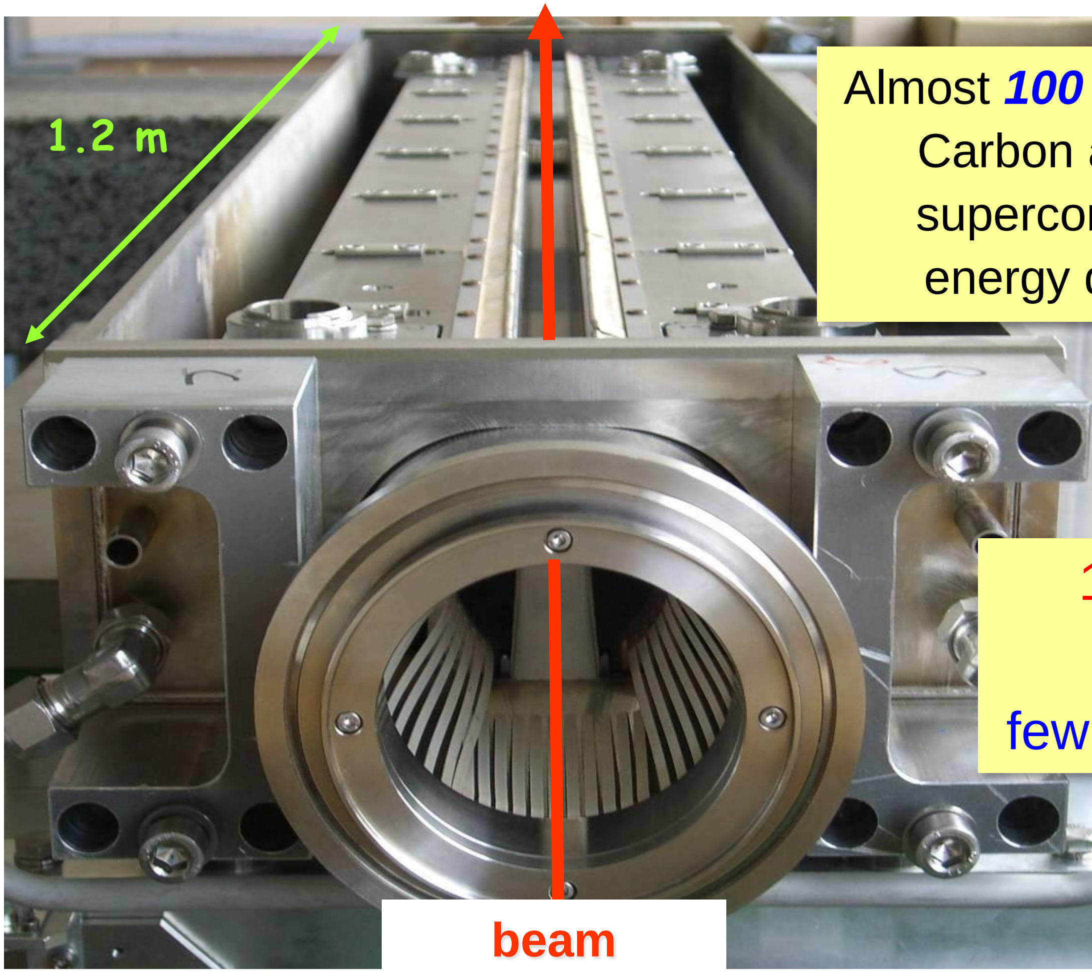
3600 x



IR5:CMS
IR4: RF + Beam instrumentation
IR2: ALICE
IR8: LHC-B
IR1: ATLAS
Injection
Injection

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.*

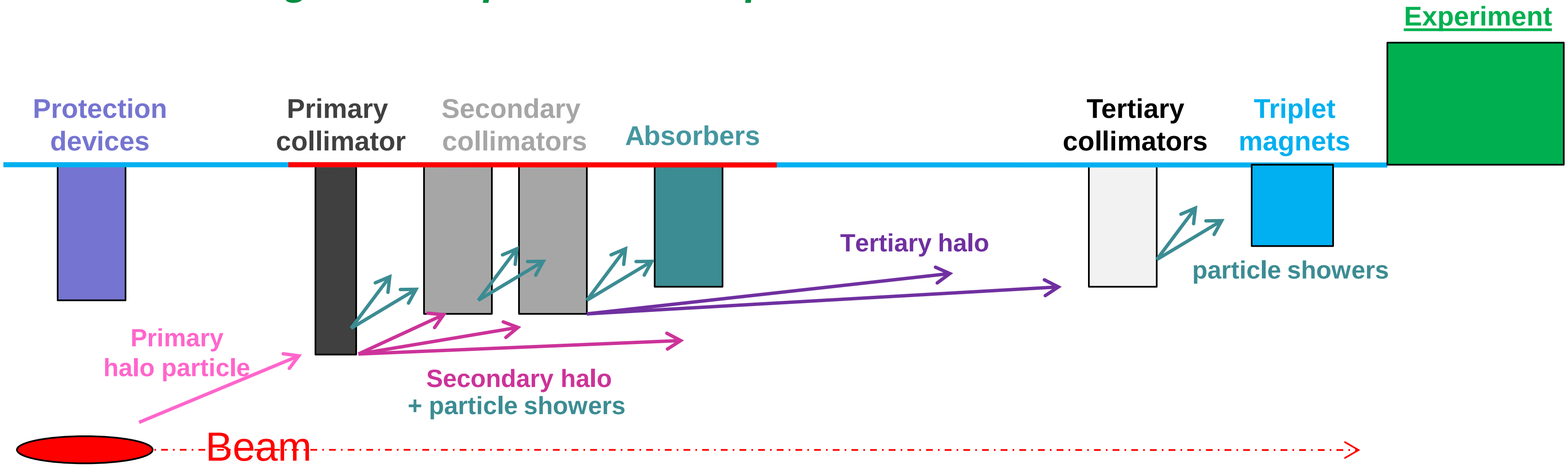


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

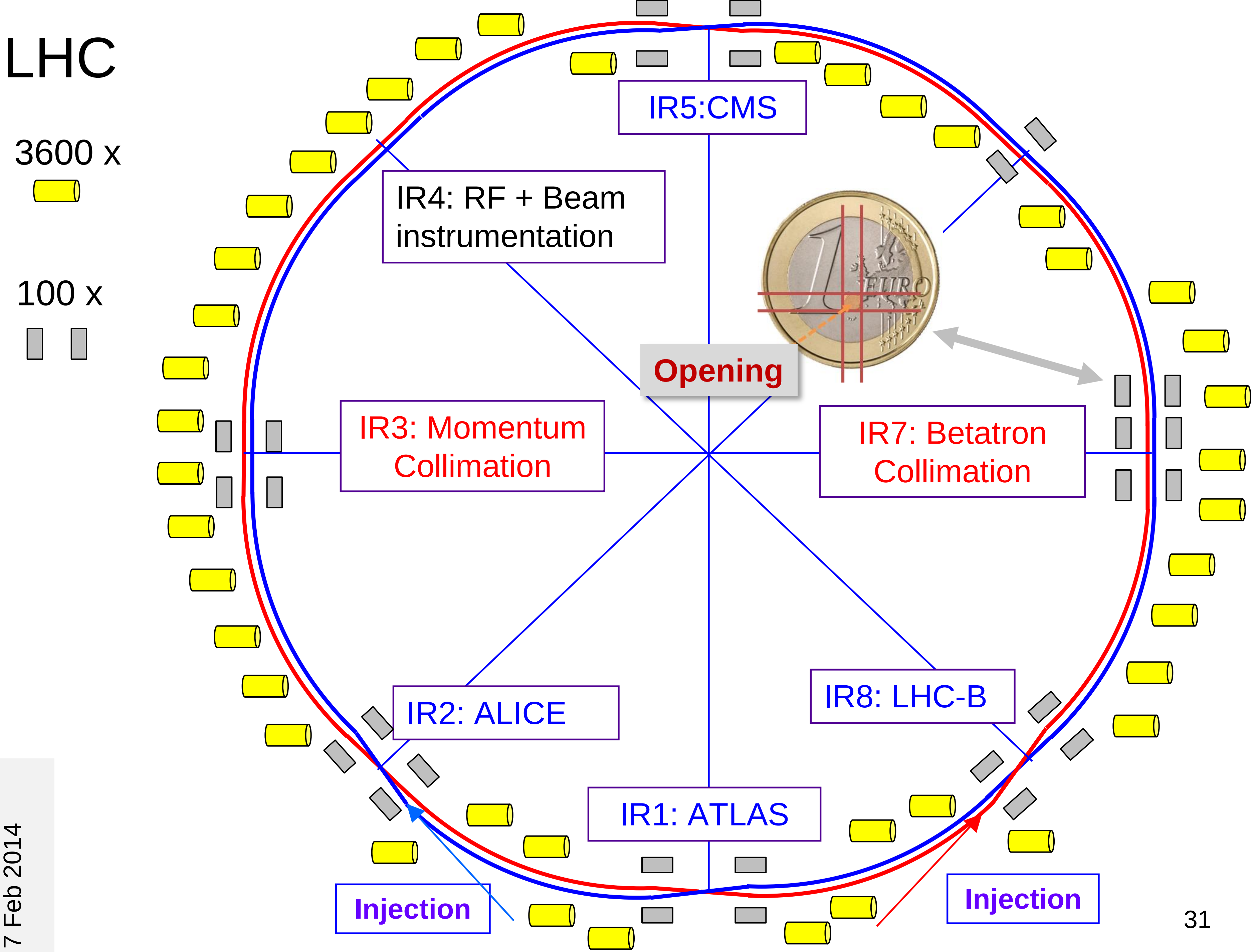
140 MJ in each beam
versus
few mJ to quench a magnet

Collimation system

- To be able to absorb the energy of the protons, the collimators are staged – primary, secondary, tertiary – multi-stage system.
- The system worked perfectly – also thanks to excellent beam stabilization and machine reproducibility – only one setup / year.
  - ~99.99% of the protons that were lost from the beam were intercepted.
  - ***No magnet was quenched in operation at 3.5/4 TeV.***



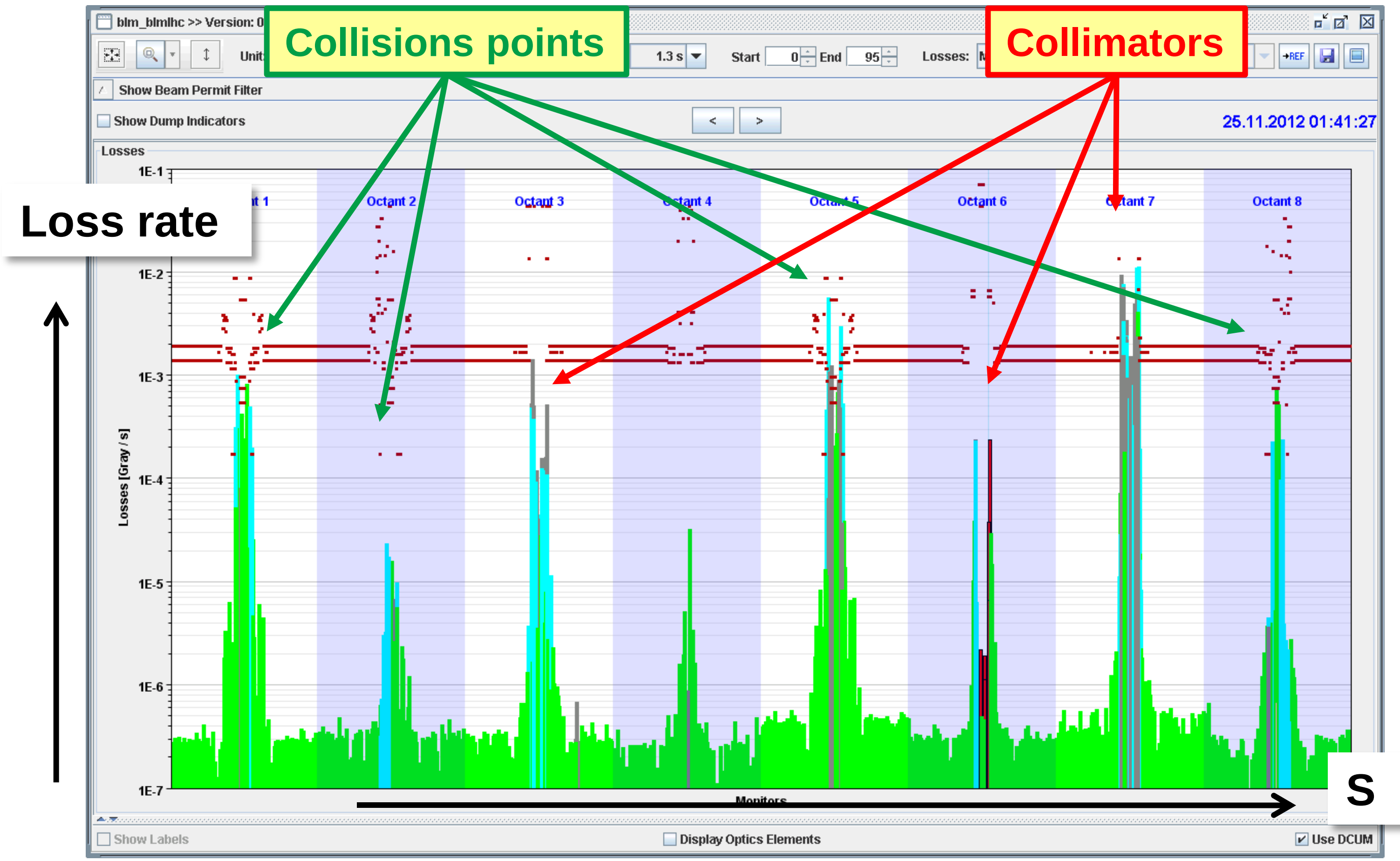
LHC



3600 x
100 x
IR5:CMS
IR4: RF + Beam instrumentation
Opening
IR3: Momentum Collimation
IR7: Betatron Collimation
IR2: ALICE
IR8: LHC-B
IR1: ATLAS
Injection
Injection

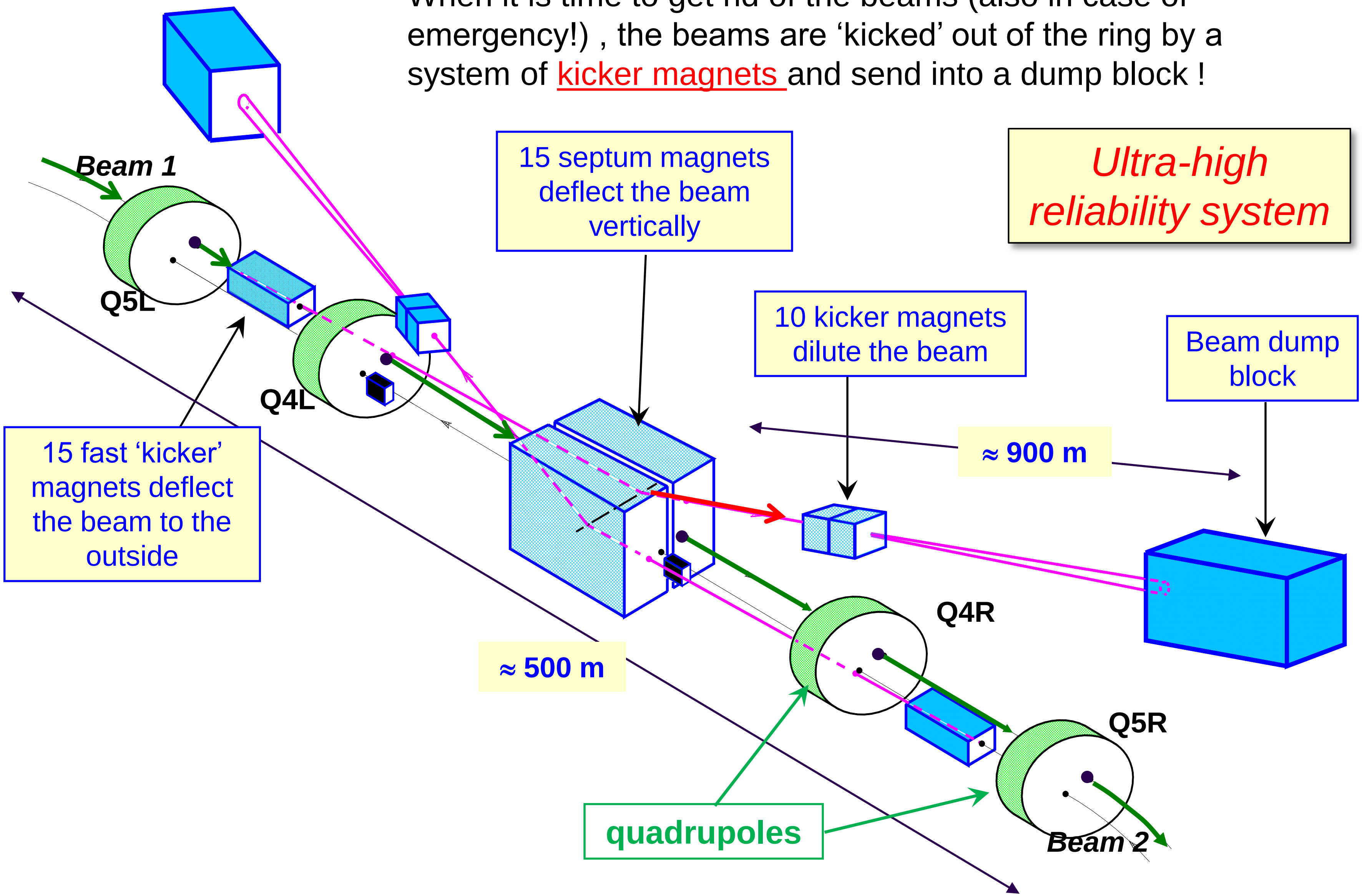
Continuous beam losses at LHC

- 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 !!*



LHC beam dumping system

When it is time to get rid of the beams (also in case of emergency!) , the beams are 'kicked' out of the ring by a system of kicker magnets and send into a dump block !

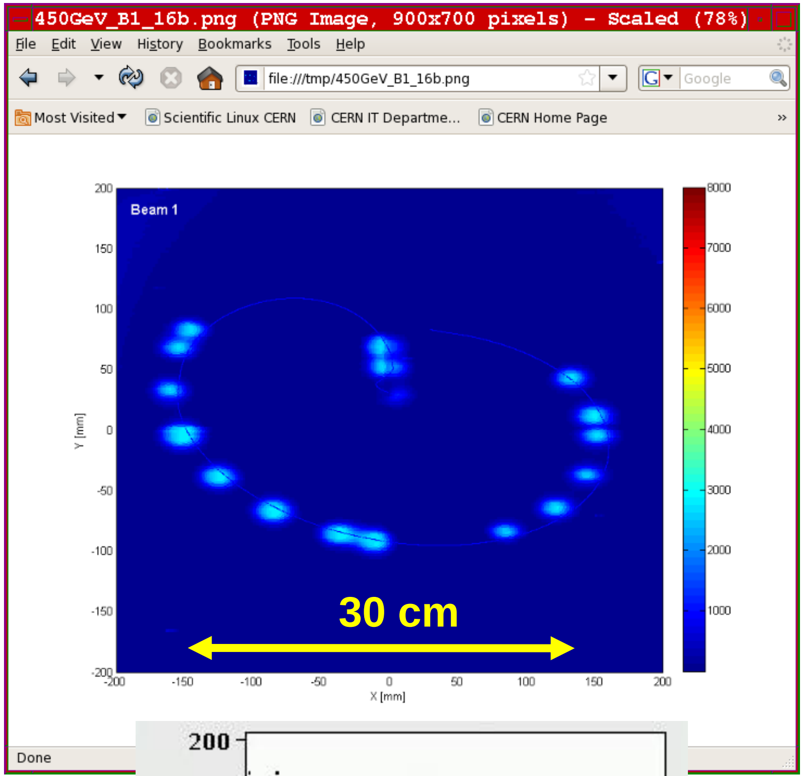


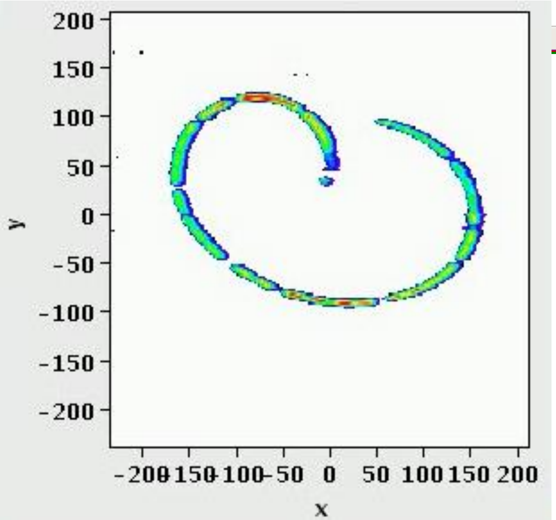
LHC dump line

The LHC dump block

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

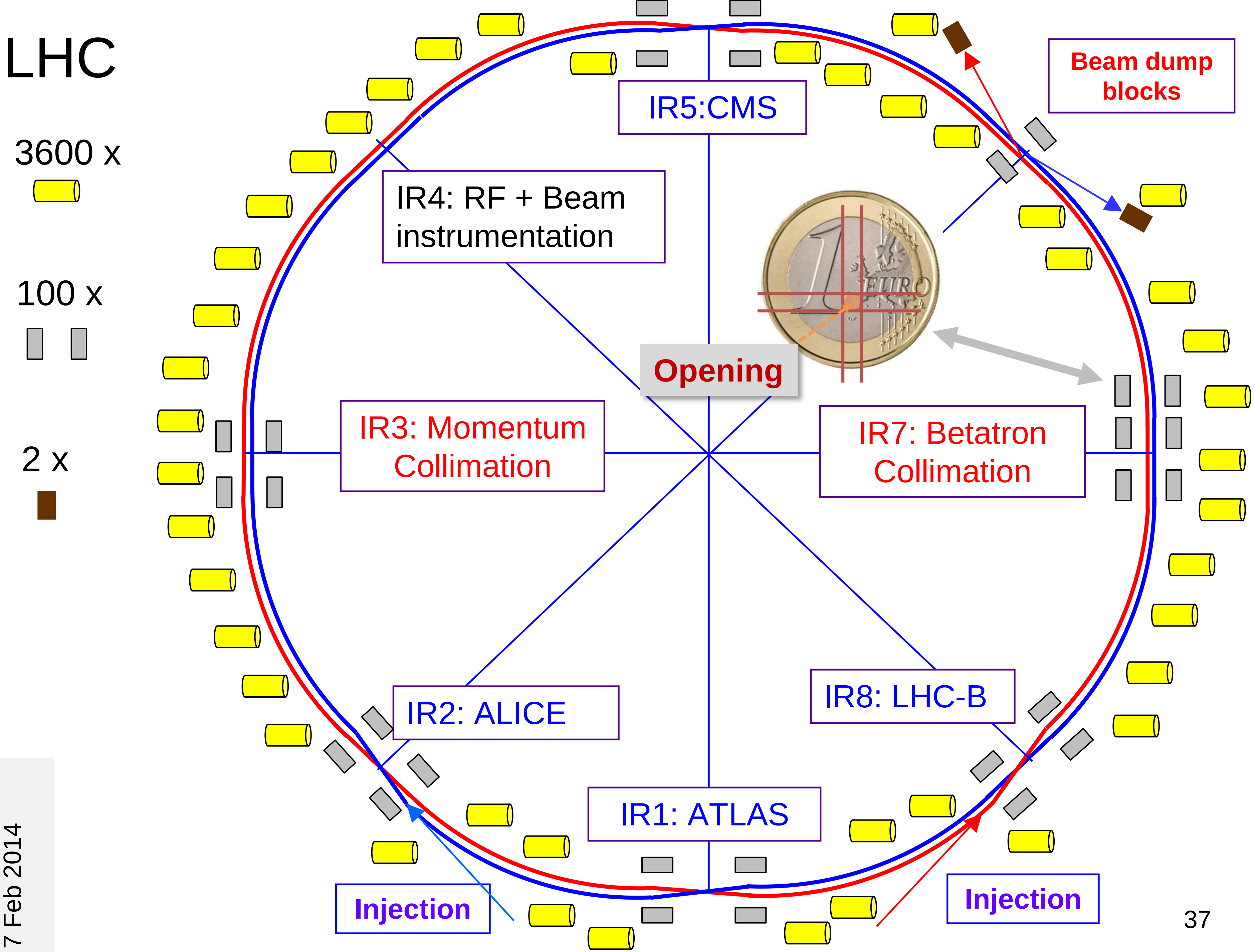
The end – for the beam !





- The dump is the only LHC element capable of absorbing the nominal beam.
  - *Beam swept over dump surface to lower the power density.*
- A beam screen installed in front of the dump provides monitoring of the dump execution.
  - *The shape of the beam impact is checked against prediction at each dump !*

LHC


3600 x
100 x
2 x
Beam dump blocks
IR5:CMS
IR4: RF + Beam instrumentation
Opening
IR3: Momentum Collimation
IR7: Betatron Collimation
IR2: ALICE
IR8: LHC-B
IR1: ATLAS
Injection
Injection

Failure analysis process – step (1)

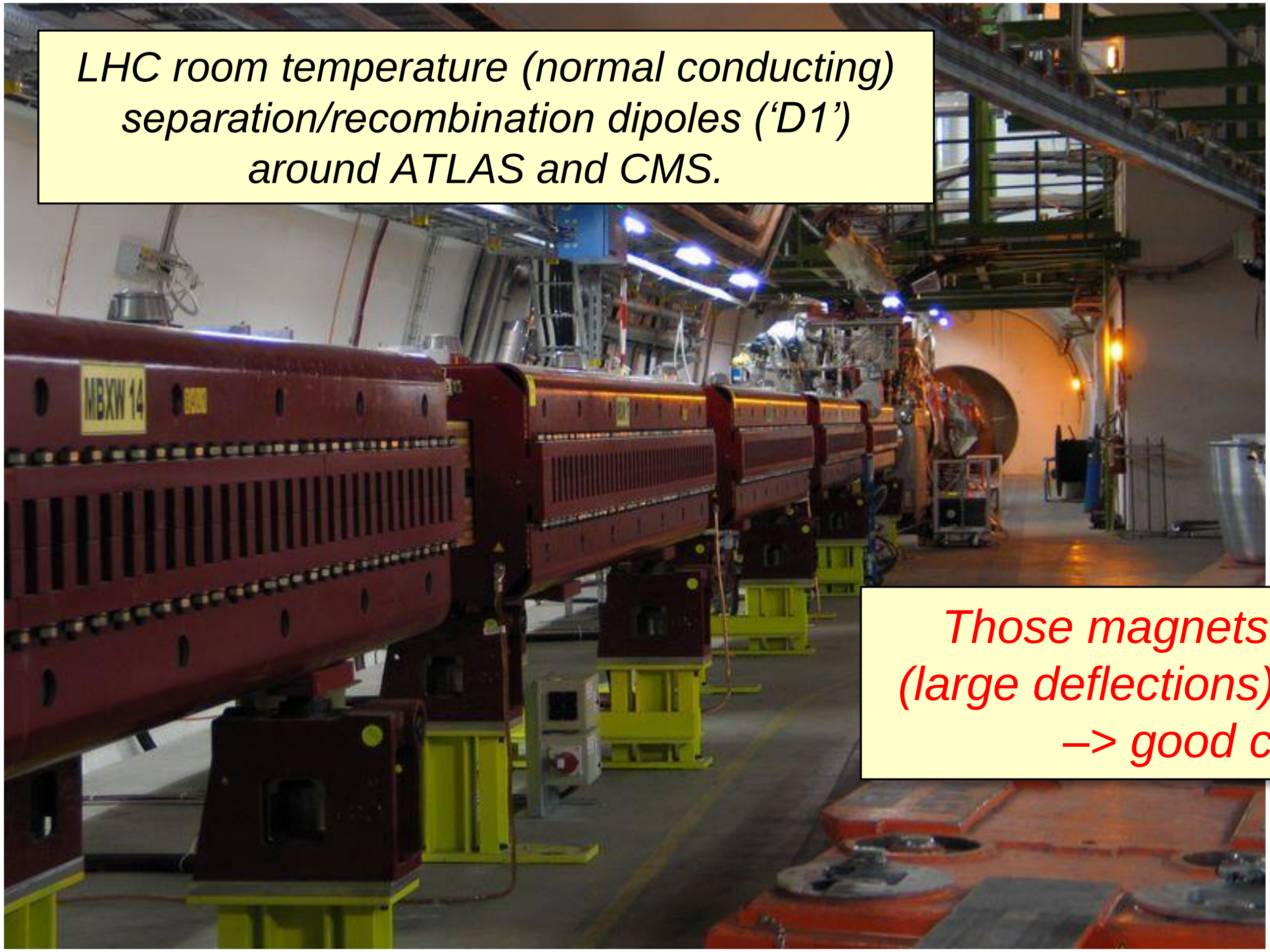
Let us pick an example for the LHC

- Step 1: Figure out what can go wrong…
  - *Requires good understanding of accelerator physics: how does a given element affect the beam?*
  - *Requires good understanding of the hardware: time scales, failure modes?*
  - *Requires a complete overview of all machine equipment that affect the beam.*
  - *The analysis must be done systematically for every system, from bottom up – including the software/controls.*

Failure analysis process – step (2)

- Step 2: Identify a critical element – the D1's.

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

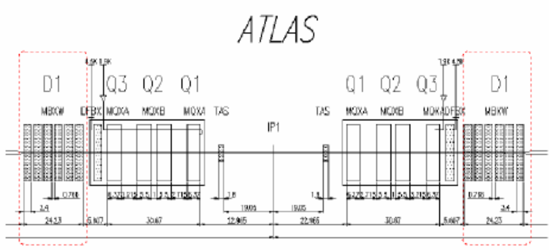


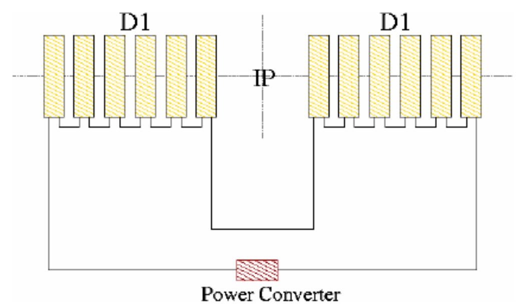
Those magnets are very strong (large deflections) and they are fast –> good candidates

Failure analysis process – step (3)

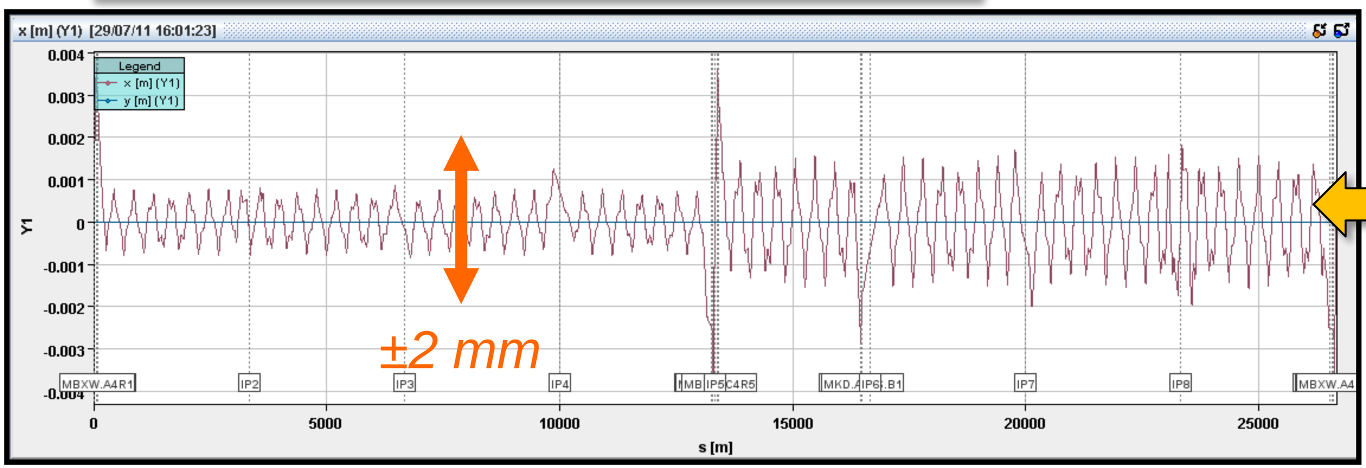
- Step 3: Simulate the failure.
  - *12 magnets are powered in series.*
  - *Large betatron function when squeezed (β > 2000 m) → large orbit changes.*
  - *Short time constant τ = 2.5 seconds (B is the magnetic field):*

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





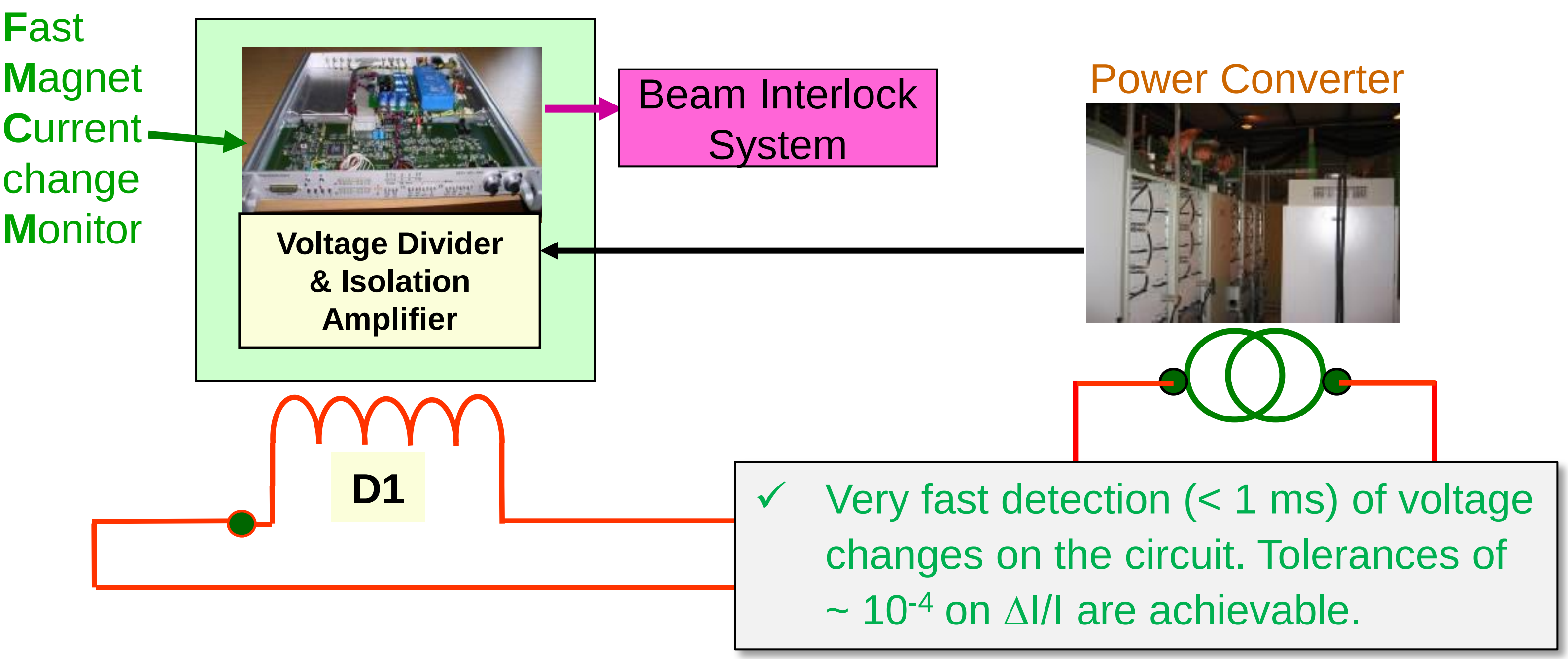
*Simulated orbit change along the LHC ring a few **milliseconds** after failure.*



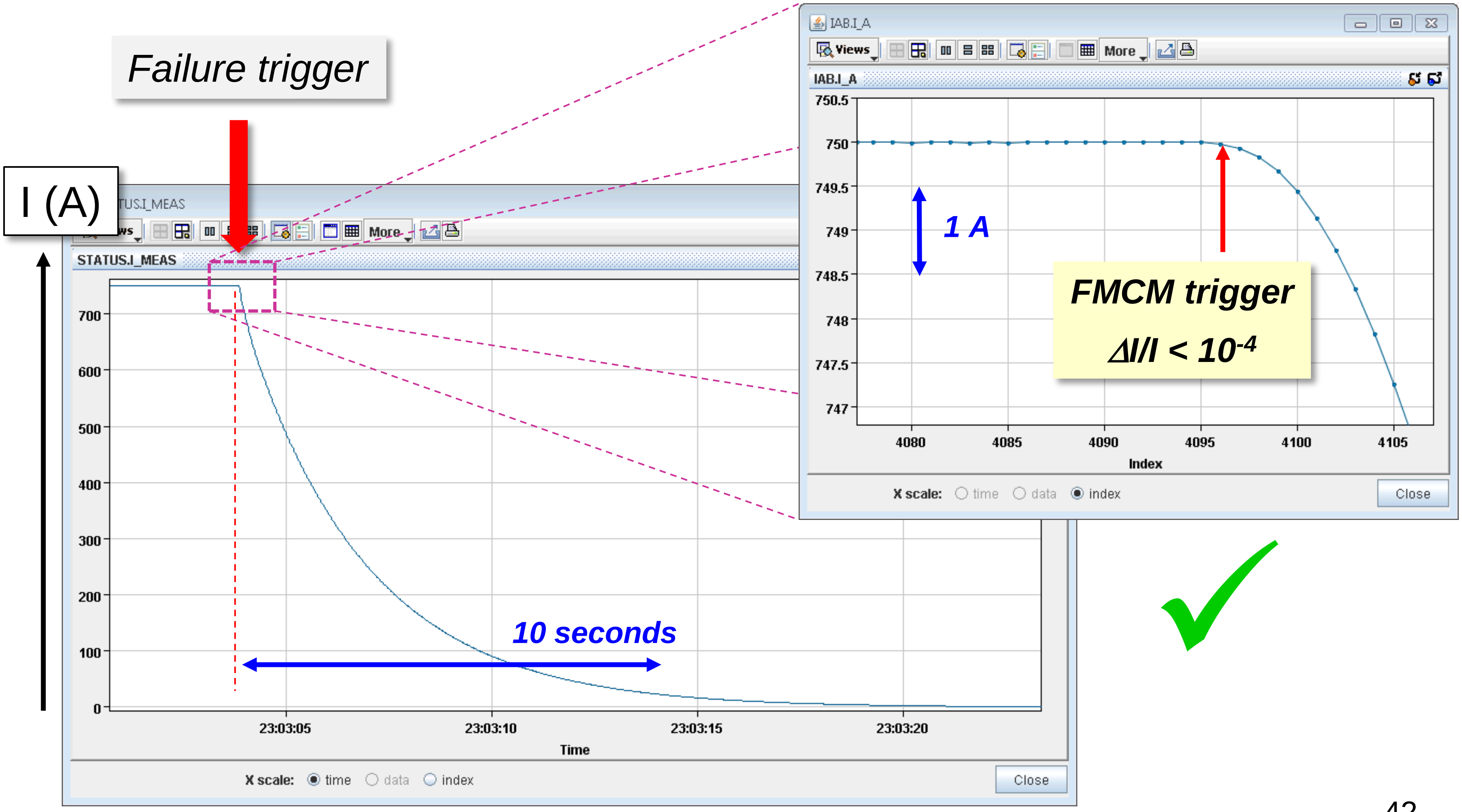
It does not fit !

Failure analysis process – step (4)

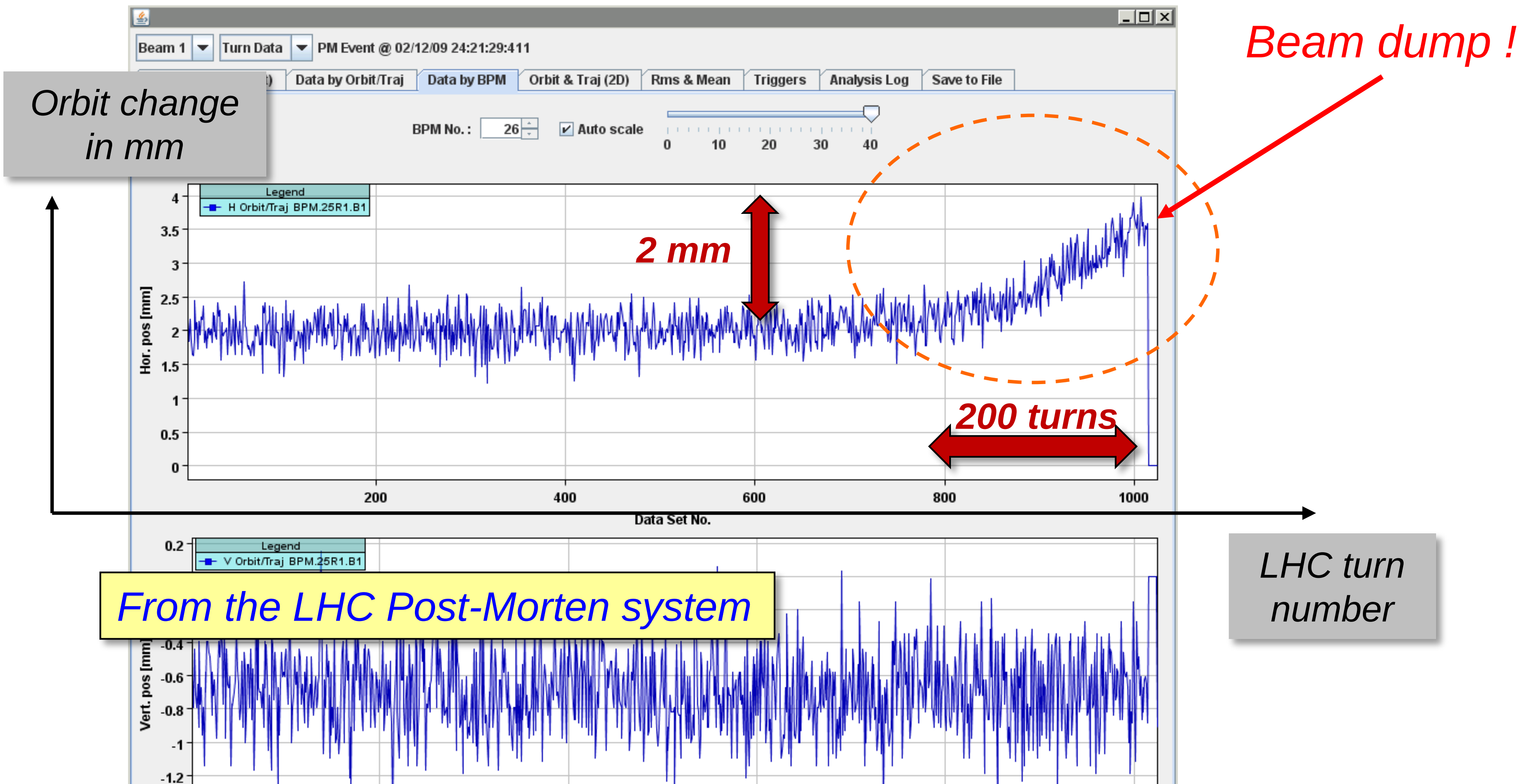
- The simulations indicate absence of redundancy (we only have beam loss monitors) and very short reaction times for BLMs → we want an extra-layer of protection at the equipment level.
- This analysis triggered the development of so-called FMCMs (Fast Magnet Current change Monitor) that provide protection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



- Step 5: Test failure of PC and FMCM reaction.
  - *Switch off D1 PC – simulated failure.*

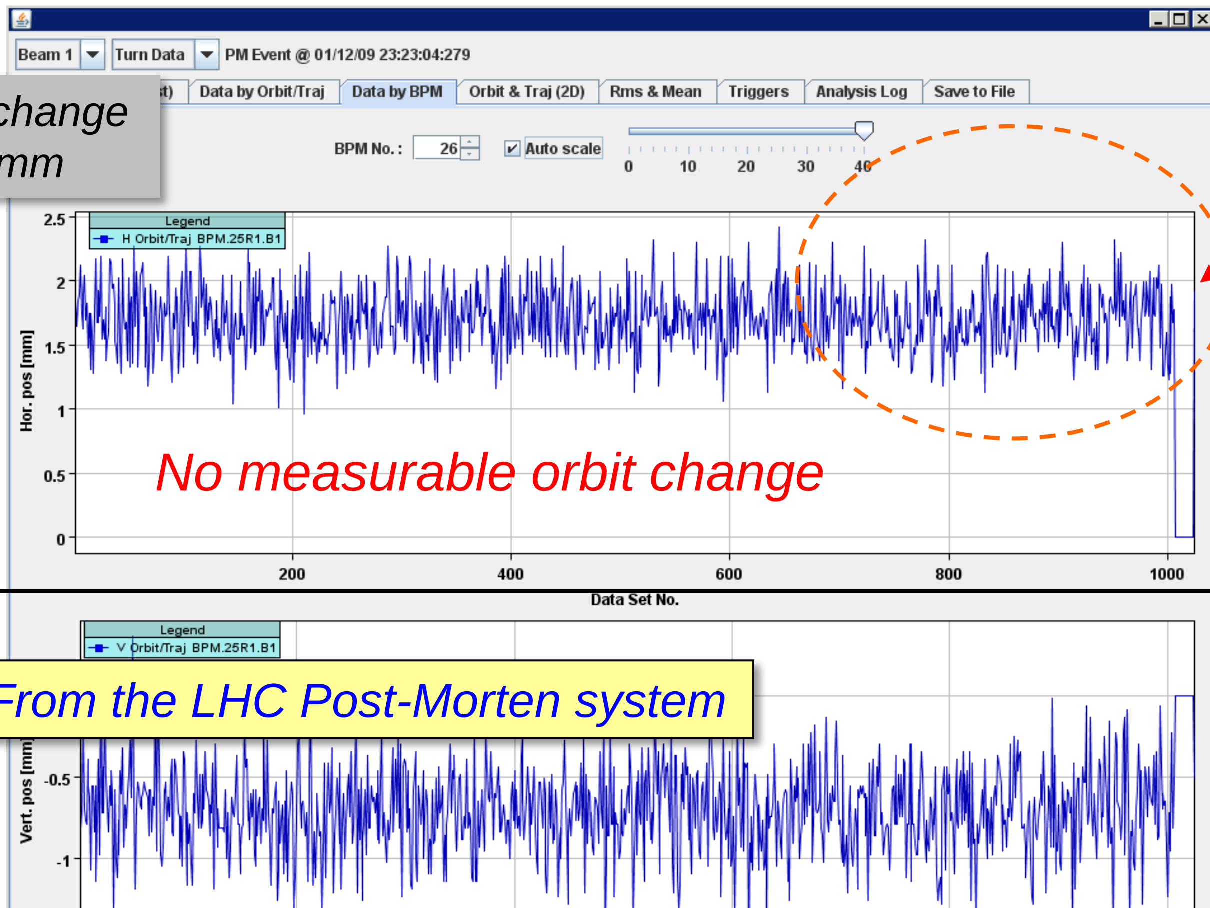


- Step 6: Real test with beam – no FMCM
  - *Low intensity ('safe') test beam.*
  - *Switch off D1 PC – simulated failure.*
  - *Beams dumped by the LHC BLMs when beams hit the collimators.*

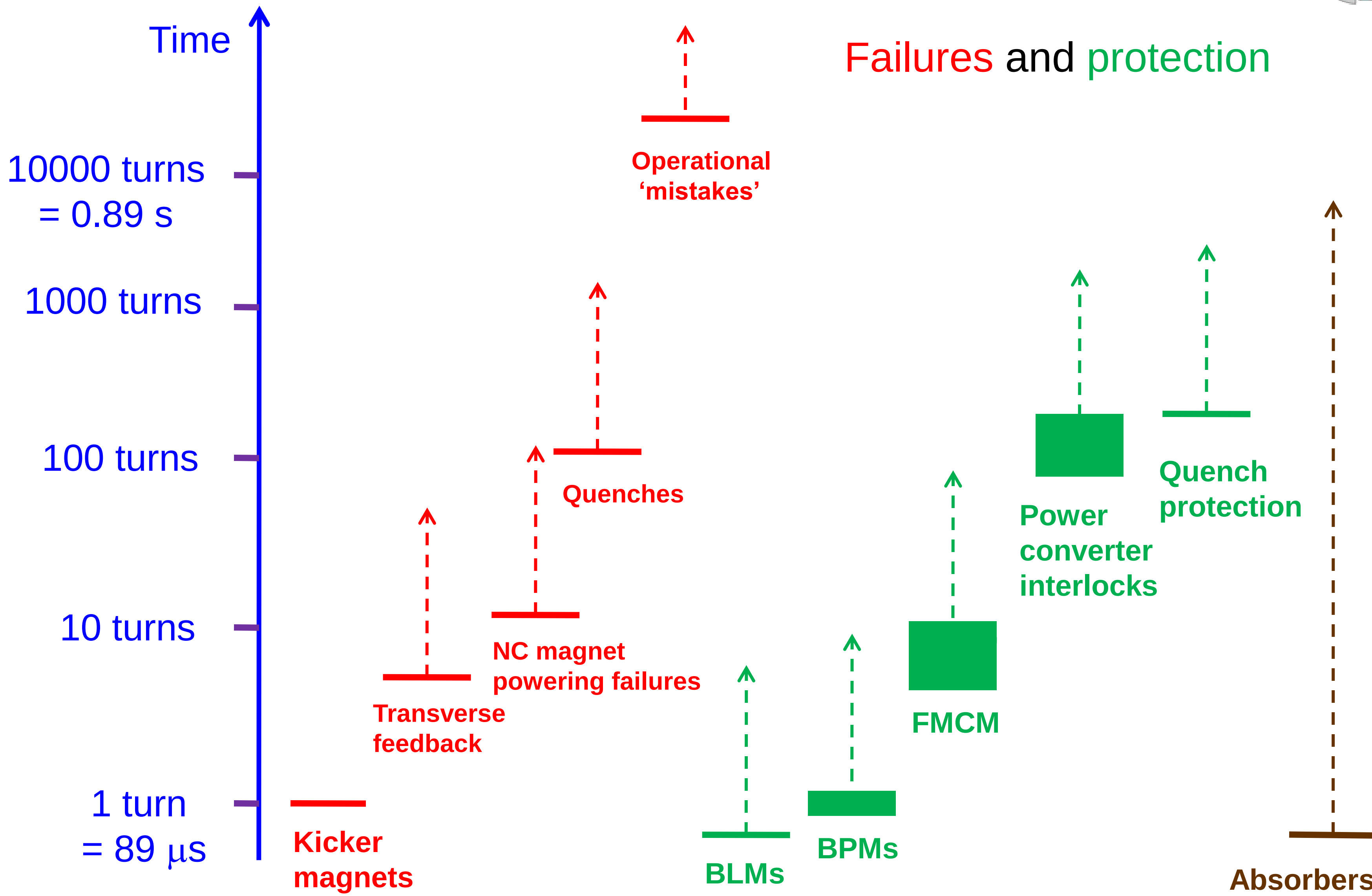


Failure analysis process – step (7)

- Step 7: Real test with beam – with FMCM
  - *Low intensity ('safe') test beam.*
  - *Switch off D1 PC – simulated failure.*
  - *Beam dumped by FMCM.*

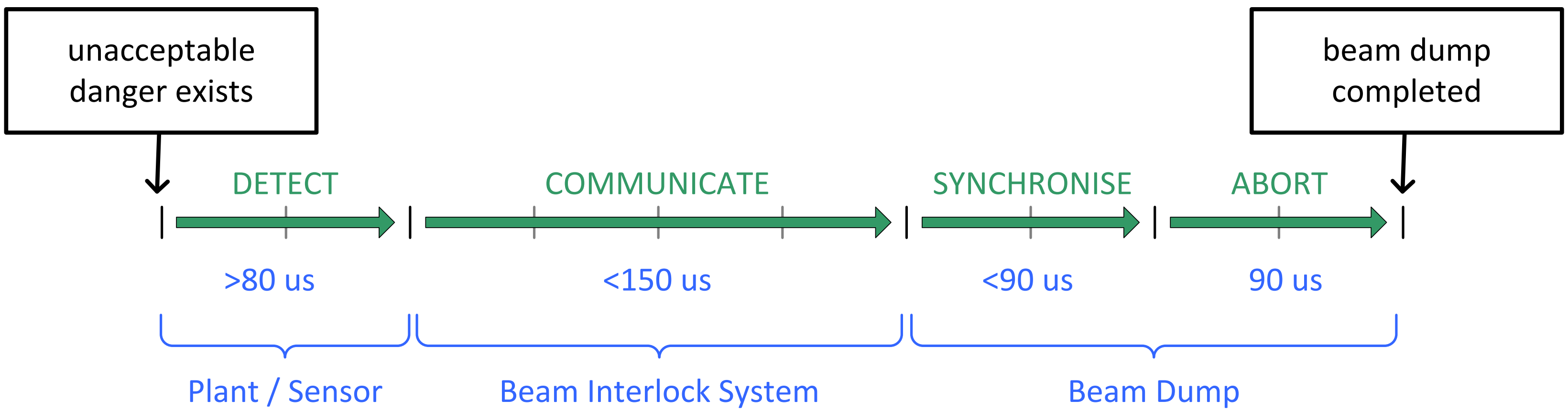


Timescales @ LHC



The beam's gone immediately isn't it?

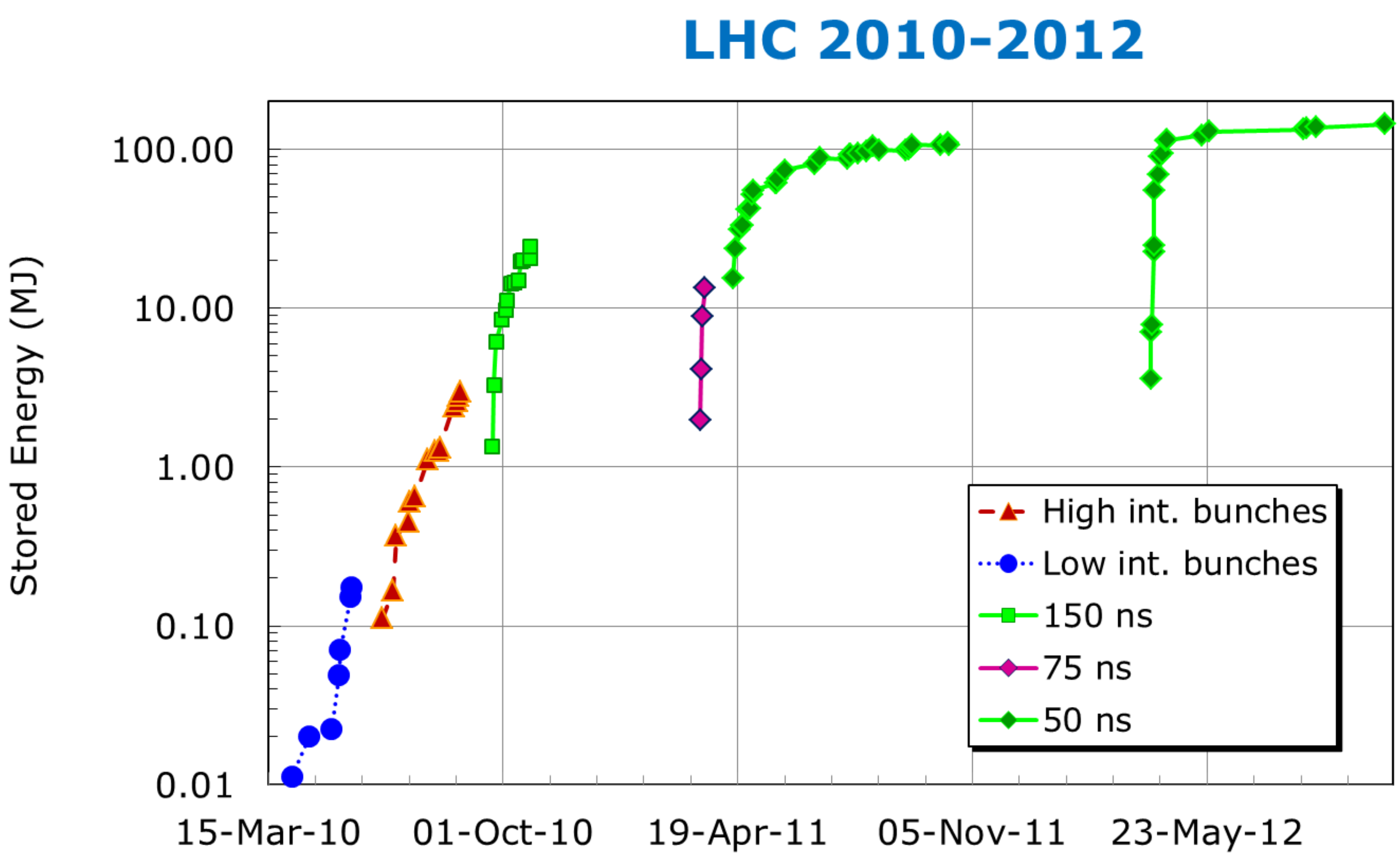
- Unfortunately even the best failure detection takes some time, the signal must be propagated to the dumping system, the dumping system must synchronize to the beam.
  - Unavoidable delay to fire the dump !



At the LHC the delay can be up to ~3 turns – ~300 μs.

Learning curve

- It took more than a year of commissioning and tuning (e.g. BLM thresholds) to reach the maximum intensity at 3.5/4 TeV



Introduction

Stored energy & interaction with matter

Machine protection design

Example from LHC

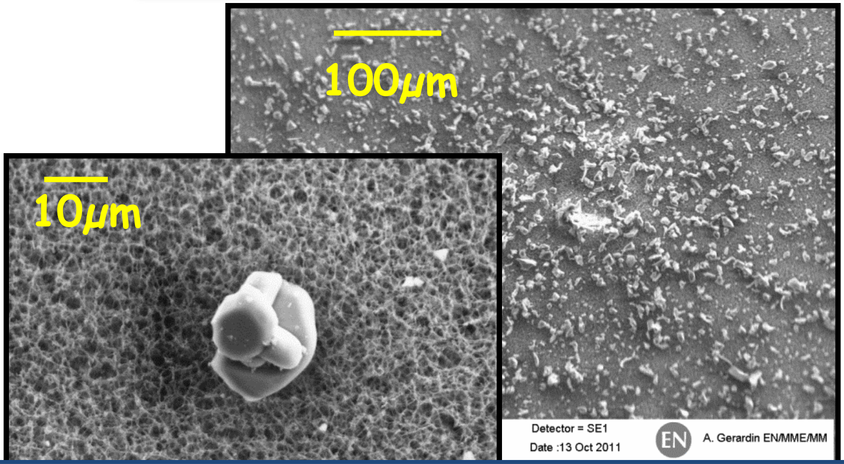
The unexpected

Summary

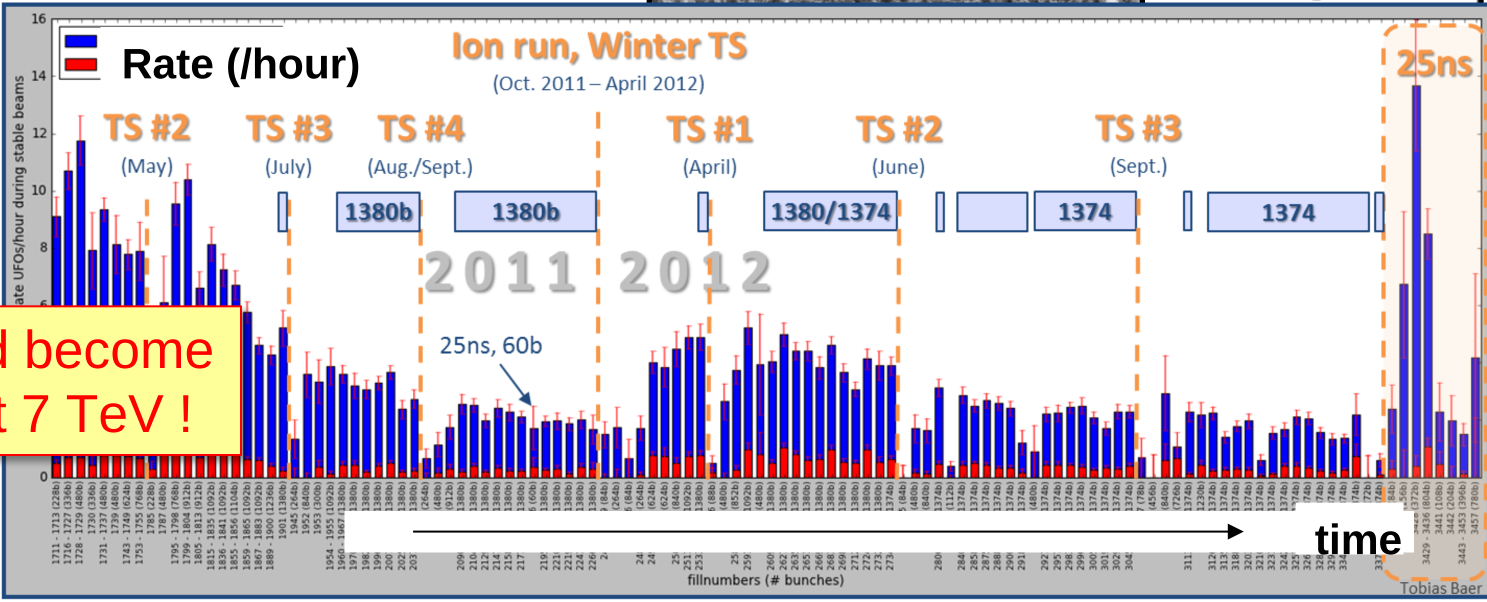
Surprising 'Unidentified Falling Objects'

- Very fast and localized beam losses were observed as soon as the LHC intensity was increased in 2010.
- The beam losses were traced to **dust particles falling into the beam** – '**UFO**'.
- If the losses are too high, the beams are dumped to avoid a magnet quench.
  - ~20 beams dumped / year due to UFOs.
  - We observe conditioning of the UFO-rate from ~10/hour to ~2/hour.

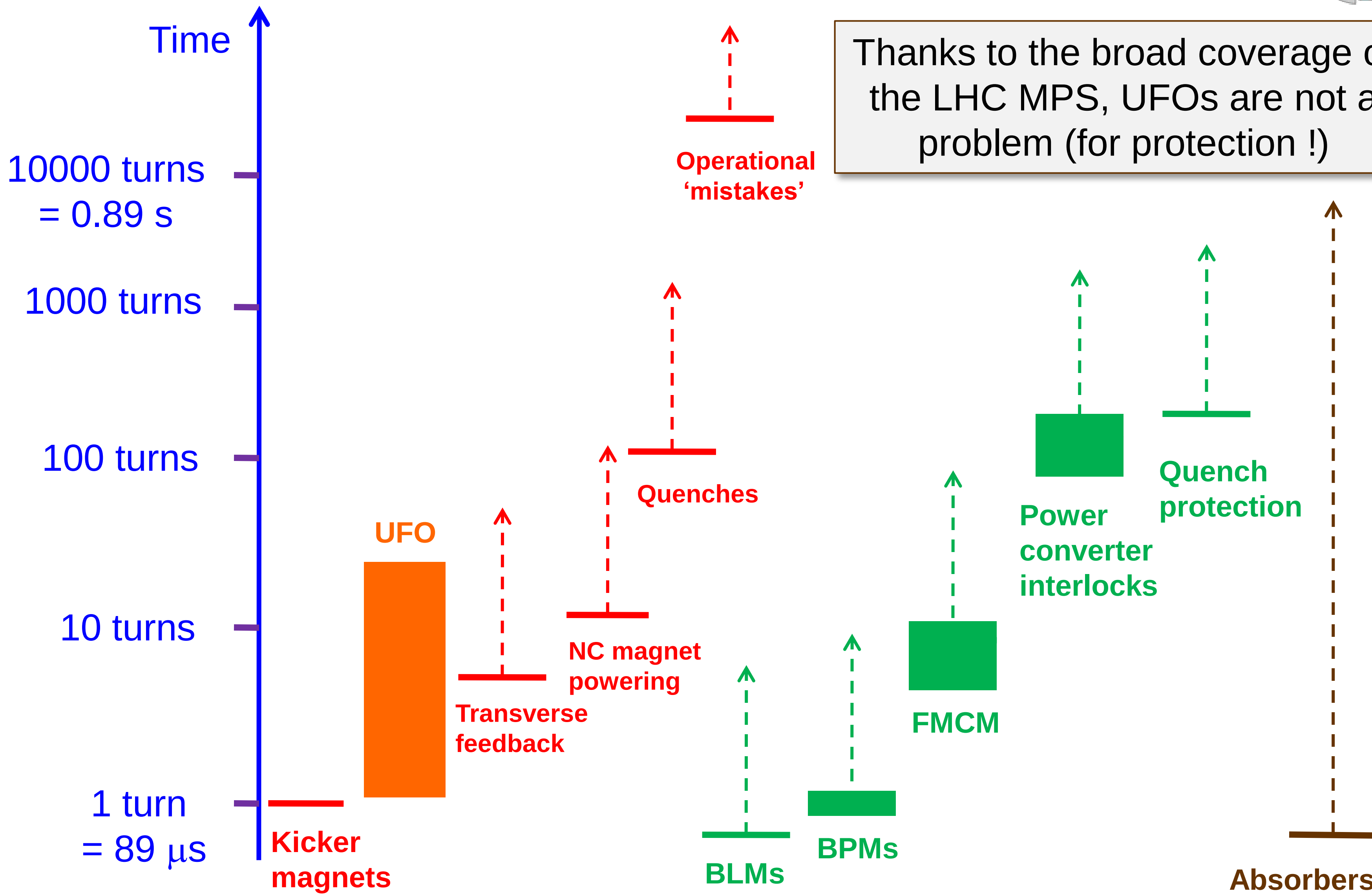
In one accelerator component UFOs were traced to Aluminum oxide particles.



UFOs could become an issue at 7 TeV !



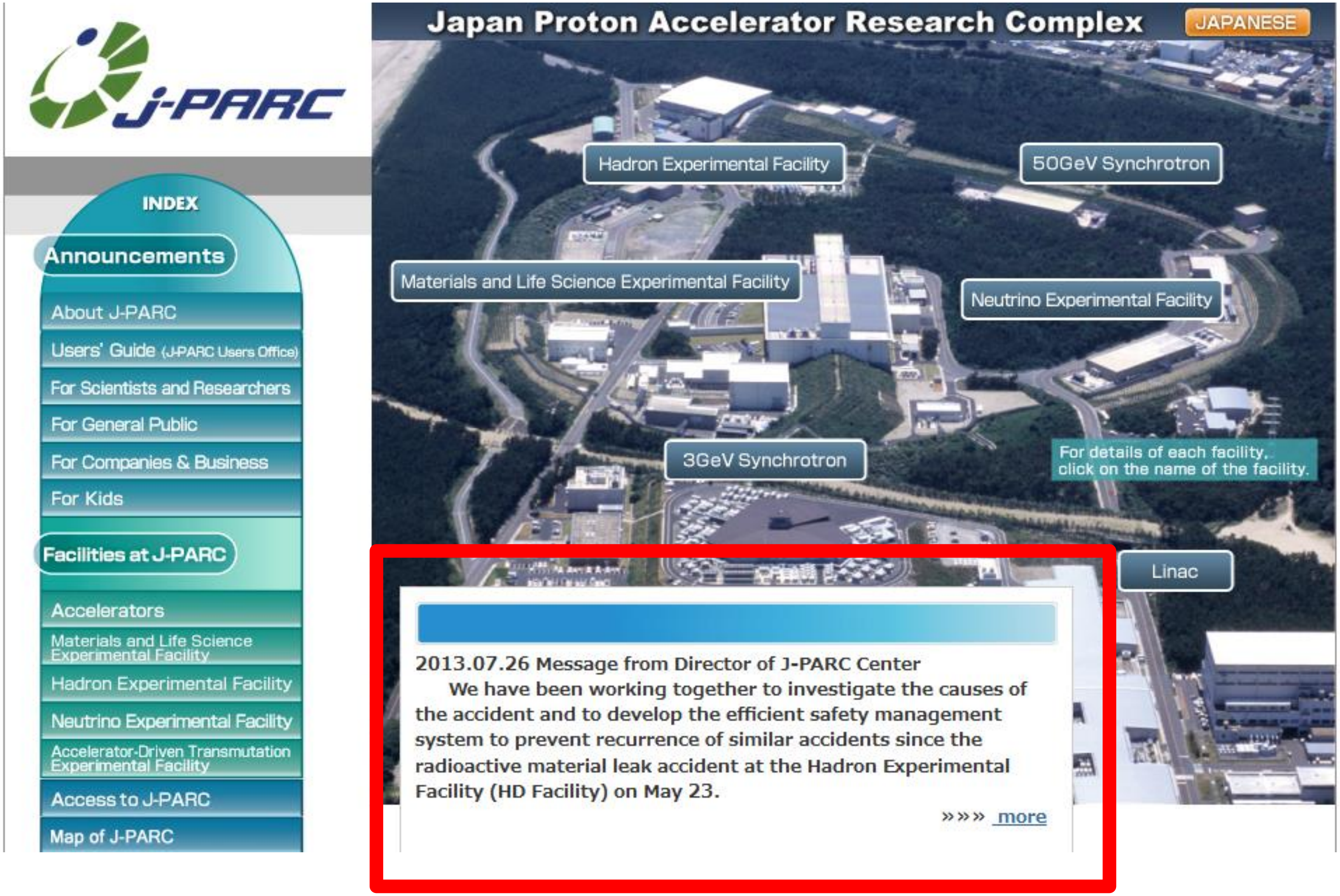
Timescales @ LHC



Thanks to the broad coverage of the LHC MPS, UFOs are not a problem (for protection !)

Incidents happen

JPARC home page – January 2014



JPARC incident – May 2013

- Due to a power converter failure, a slow extraction was transformed into a fast extraction.
  - *Extraction in milliseconds instead of seconds.*
- As a consequence of the high peak power a target was damaged and radio-isotopes were released into experimental halls.

  >> machine protection coupled to personnel protection !
- Investigations and protection improvements delayed the restart of the JPARC complex for ~7-8 months. JPARC is just restarting.

One insufficiently covered failure case had major consequences !

Summary

Machine protection:

- requires a comprehensive overview of all aspects of the accelerator (accelerator physics, operation, equipment, instrumentation),
- requires understanding the different failure types that could lead to uncontrolled beam loss,
- affects many aspects of accelerator construction and operation,
- must be an integral part of the machine design,
- is becoming increasingly important for future projects, with increased beam power / energy density and increasingly complex machines.

Stored energies – the future