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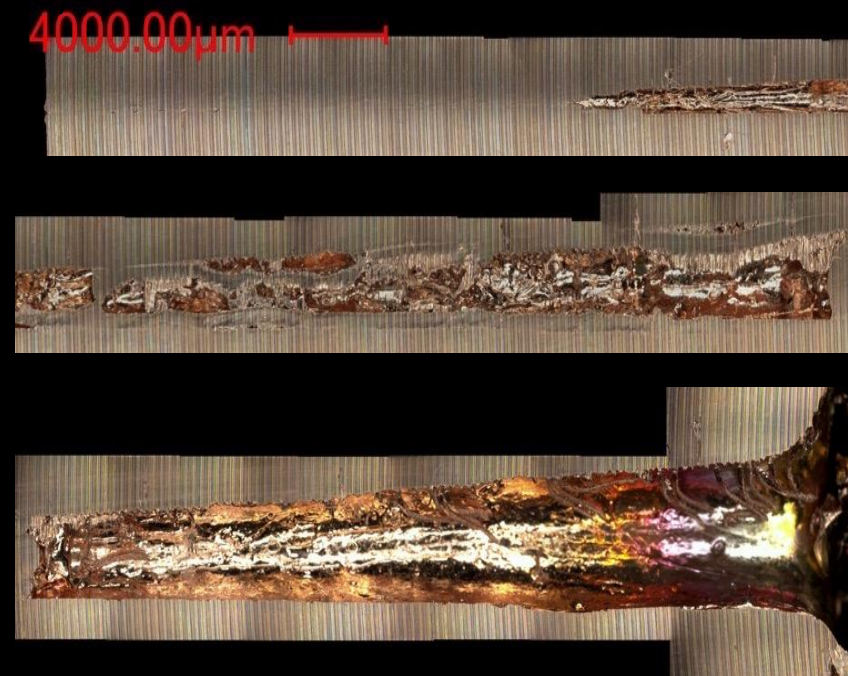

Machine Protection

Basics of Accelerator Physics and Technology, 04-20 May, 2021

Markus Zerlauth with acknowledgements to M. Lamont, R. Schmidt, D. Wollmann, J. Wenninger and many other CERN colleagues

Outline

- Introduction
- Stored energy & interaction with matter
- Machine protection design
- Example from LHC
- The unexpected
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Safety in 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 and its upgrade project HL-LHC
  - Linear e+e- colliders
  - Future Circular Colliders study (FCC)
- 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

Risks and machine protection

- Protection is required since there is (always!) 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

	A 1/10000 Years	B 1/1000 Years	C 1/100 Years	D 1/10 Years	E 1/1 Year
5 Catastrophic	1	2	3	4	5
4 Major	0	1	2	3	4
3 Severe	0	0	1	2	3
2 Minor	0	0	0	1	2
1 Slight	0	0	0	0	1

>> The higher the risk, the more protection and/or mitigation becomes important !

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Technological Challenges – LHC example

…To see the rarest events…
LHC needs high luminosity of 10^{34} [$cm^{-2}s^{-1}$]
→ 3 x 10^{14} p per beam

Collisions generate PetaBytes of data Per year

particle fluence near machine demands radiation-tolerant electronics

… to get 7 TeV operation…
LHC needs 8.3 Tesla dipole fields with circumference of 27 kms (16.5 miles)

World's largest machine

… to get 8.3 Tesla …
LHC needs super-conducting magnets <2°K (-271°C)
with an operational current of ≈13kA
cooled in super fluid helium
maintained in a vacuum

1 ppm

10x less pressure than on moon surface

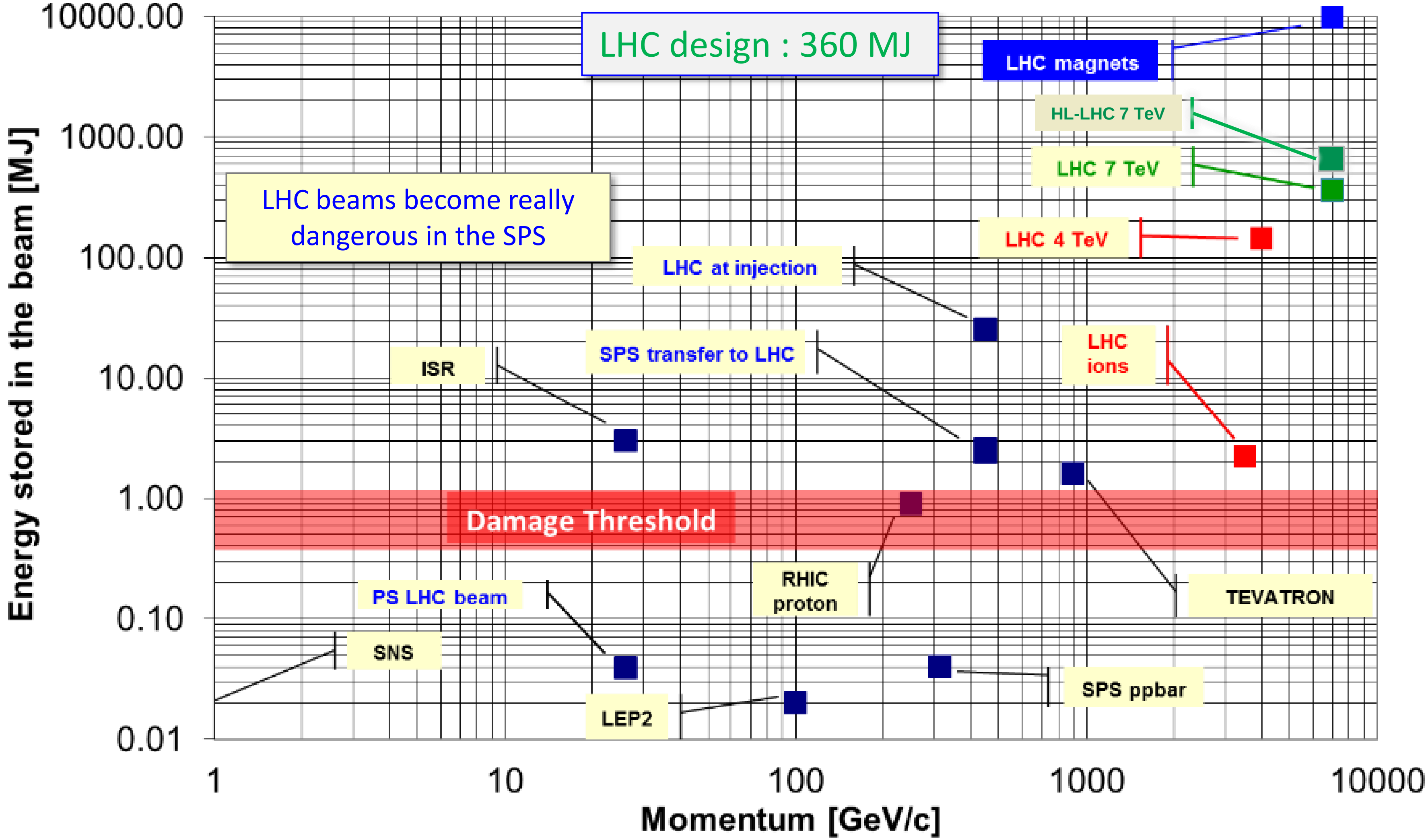
two orders of magnitude higher than others

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ

A magnet will QUENCH with milliJoule deposited energy

Accelerators at the Energy Frontier



Relevant parameter for MPS

- Momentum of the particle
- Energy stored in the beam
  - 360MJ per beam in the LHC
    when fully filled with 2808 bunches
- Particle type
  - Activation of material is mainly an issue for hadron accelerators
- Beam power (CW vs pulsed)
- 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

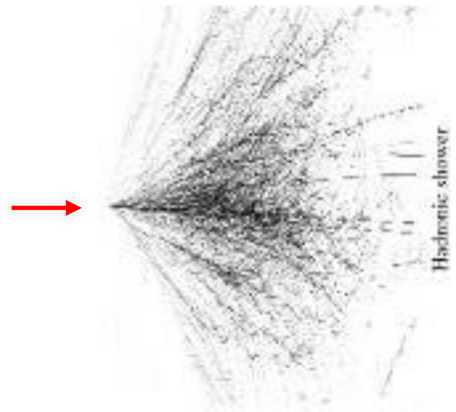
15 kg of chocolate

Energy stored in Magnet Powering System of the LHC

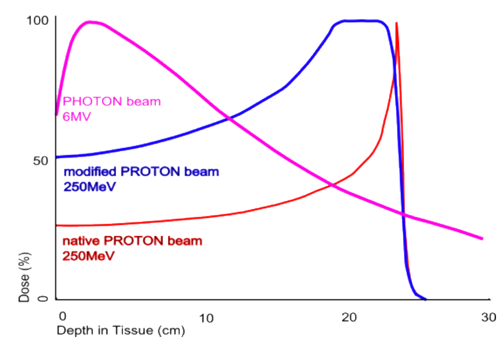
$$E_{kin}(v = 27\ \text{kn}) \approx E_{LHC\ main\ circuits}(@6.5\ \text{TeV})$$

Beam loss in materials

- Lost particles induce 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 several meters

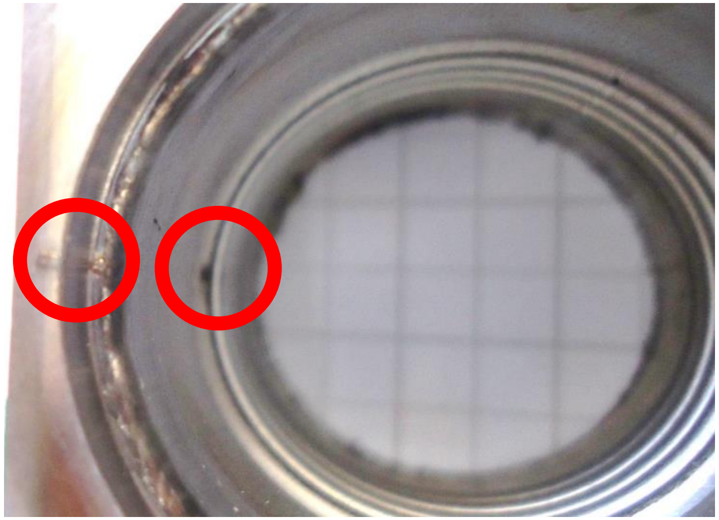


- The energy deposition leads to a temperature increase, and for very fast losses to shock waves and to plastic deformation
  - Material can melt, vaporize, deform or lose its mechanical properties
  - Limited risk for some 10 kJ, large risk for some MJ
  - Equipment becomes activated due to beam losses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

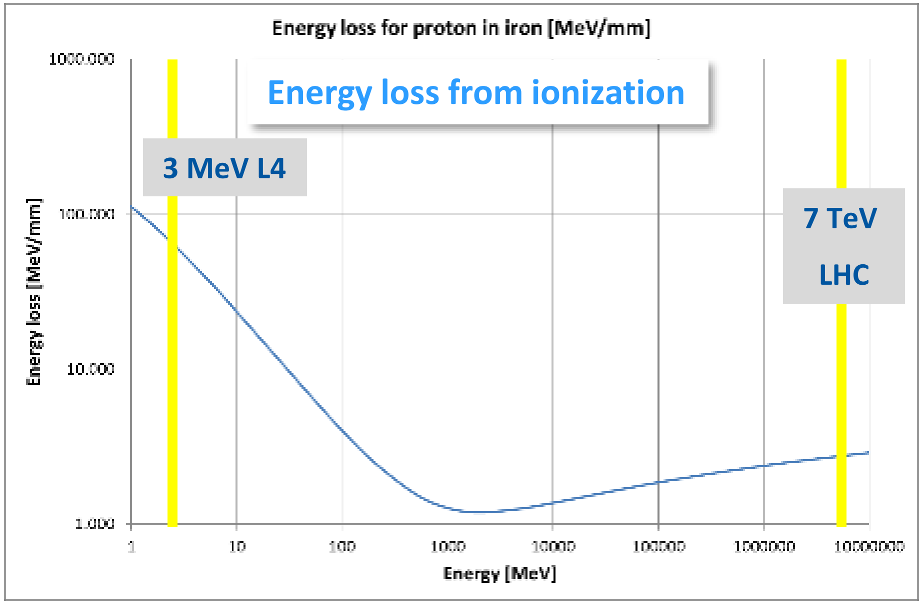


Small but already dangerous

- ❑ Damage @ Linac4 with a 3 MeV beam – vacuum leak.
- ❑ Failure combination:
  - Beam misaligned
  - Unlucky magnet setting
  - Aperture limitation at bellow



JB Lallement



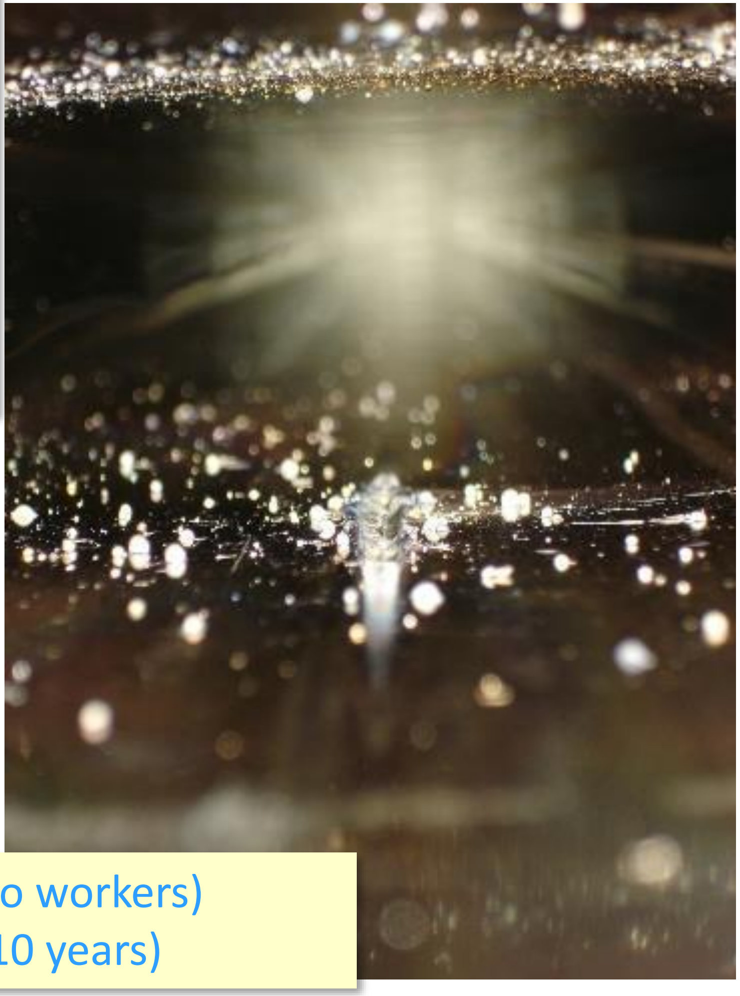
At such low energies, the local energy loss per proton is very high

$\Rightarrow$ Damage after some integration time

SPS dipole magnet

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.



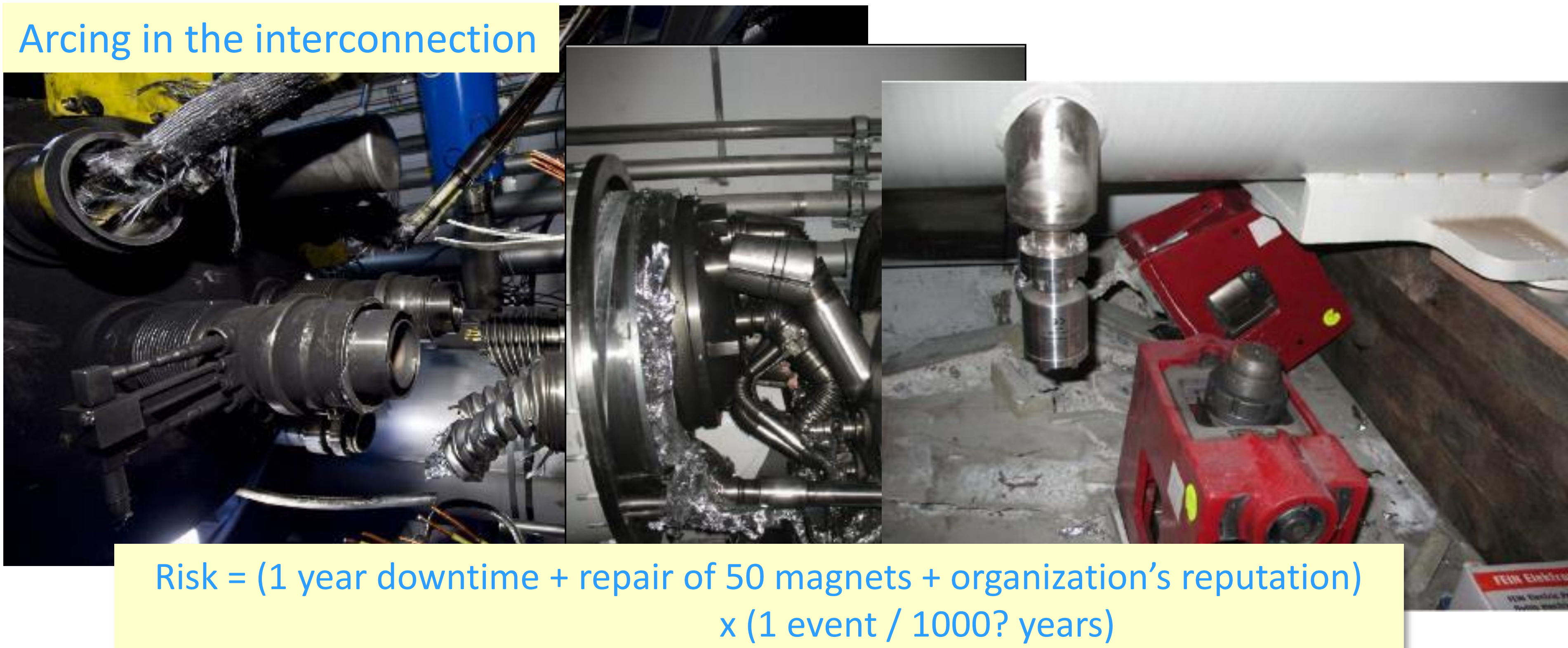
Risk = (3 days downtime + dose to workers)
x (1 event / 5-10 years)

Release of 600MJ at the LHC

The 2008 LHC accident happened during test runs <u>without beam</u>.

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.

Arcing in the interconnection



Risk = (1 year downtime + repair of 50 magnets + organization’s reputation)
x (1 event / 1000? years)

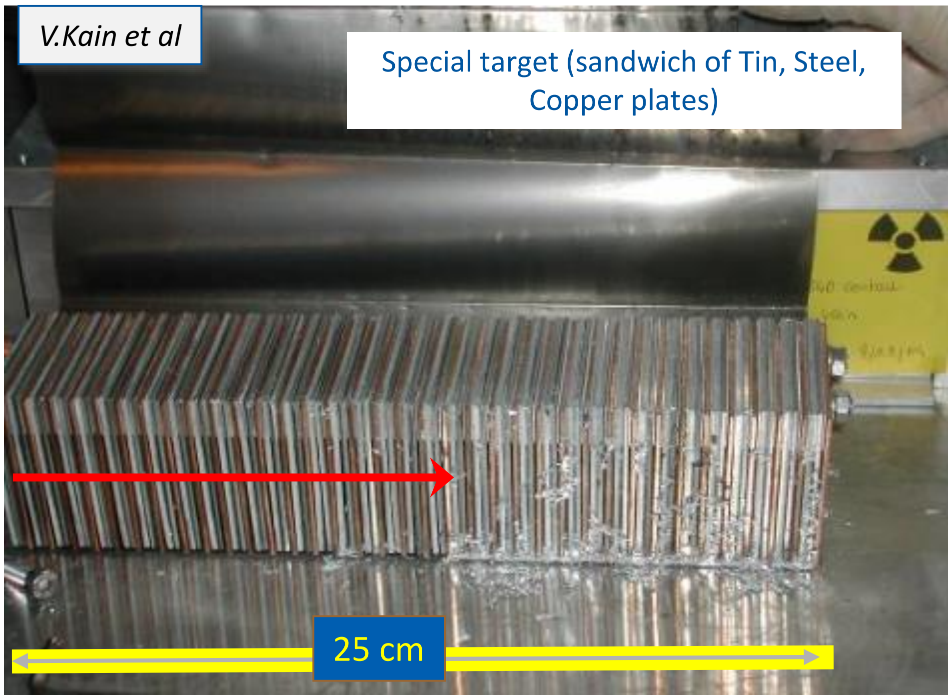
Controlled damage tests for MP

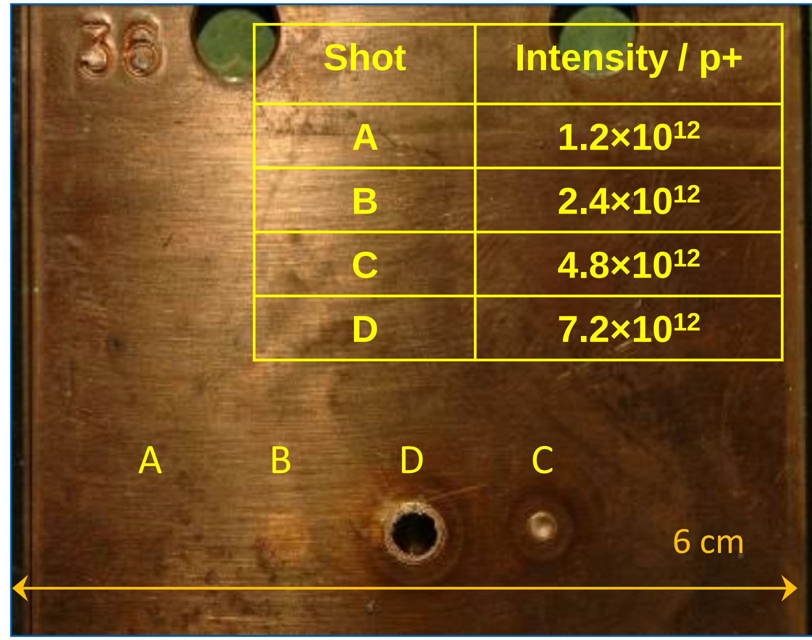
- In the past decade a lot of effort was invested to better understand the interaction of high energy / high density beams with matter.
- Experiments:
  - Ad-hoc experiments for the LHC
  - Construction of a dedicated test facility at CERN (HiRadMat @ SPS)
- Modeling and comparison with tests.
  - Many matter phases (solid, liquid, plasma), 'hydro-dynamic-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 450GeV

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.



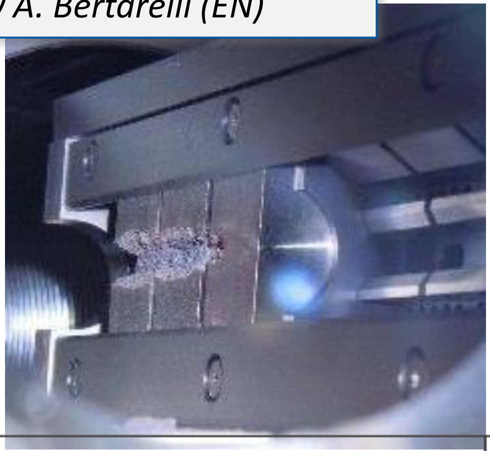


Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

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

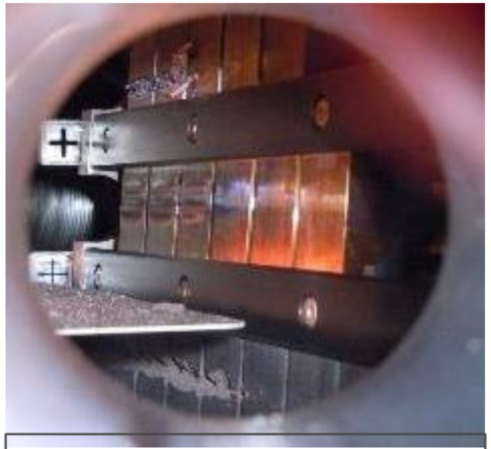
HiRadMat tests – new materials

Courtesy A. Bertarelli (EN)

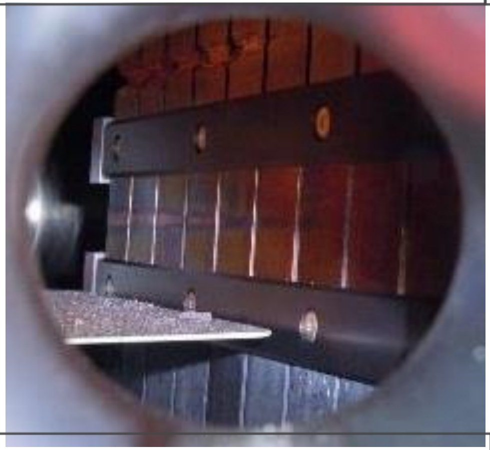


Inermet 180, 72 bunches

Molybdenum, 72 & 144 bunches



Glidcop, 72 bunches (2 x)



Copper-Diamond 144 bunches

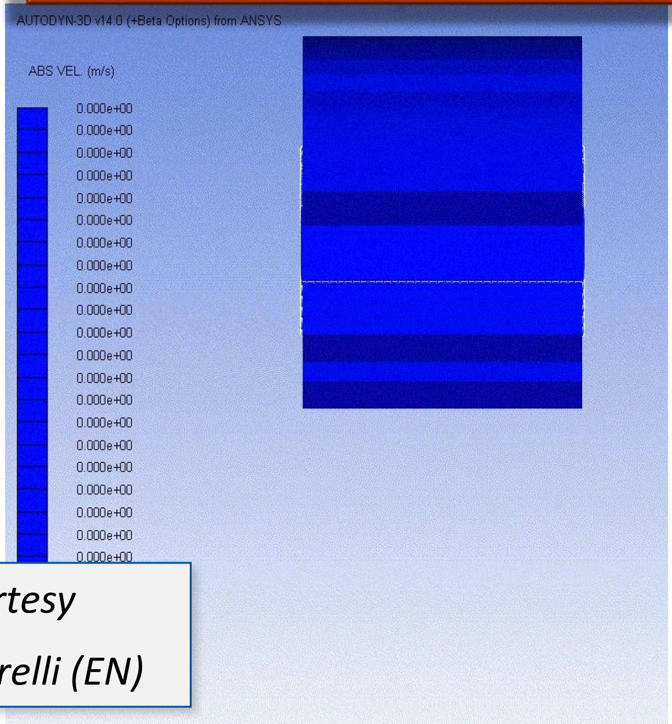
Molybdenum-Copper-Diamond 144 bunches

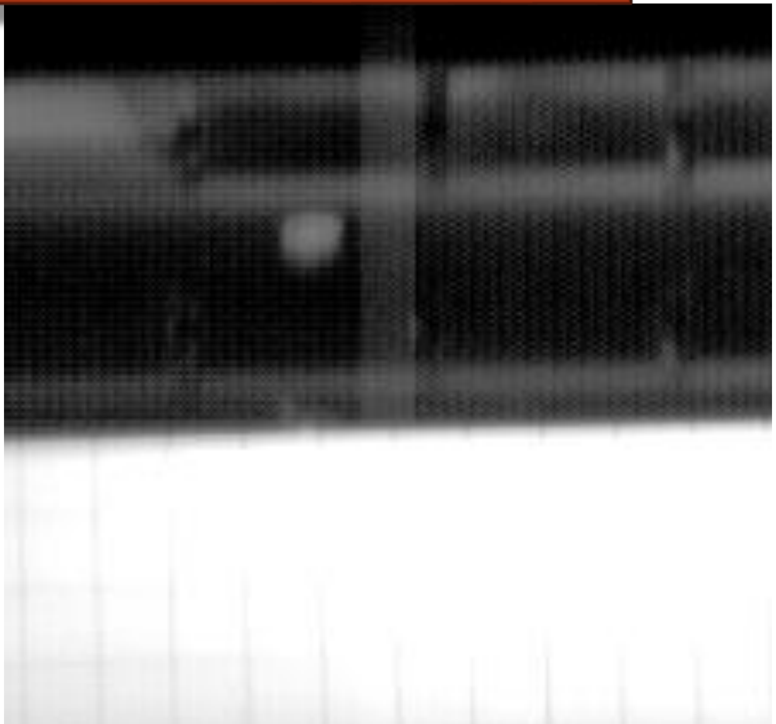
Molybdenum-Graphite (3 grades) 144 bunches

HighRadMat test with high intensity

Inermet : comparison between simulation and experiment

Beam



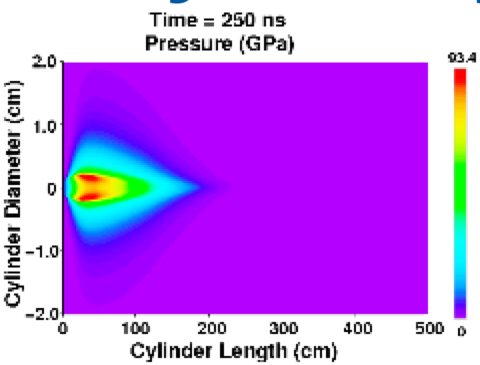


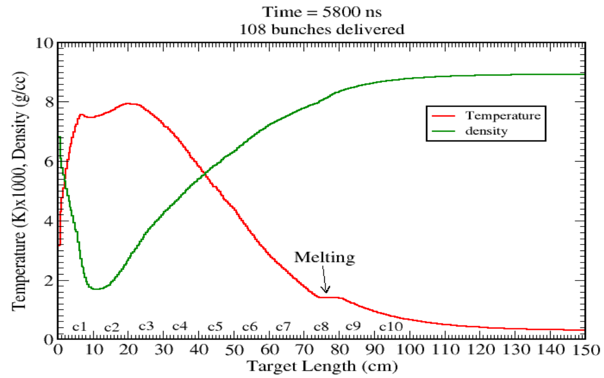
Courtesy

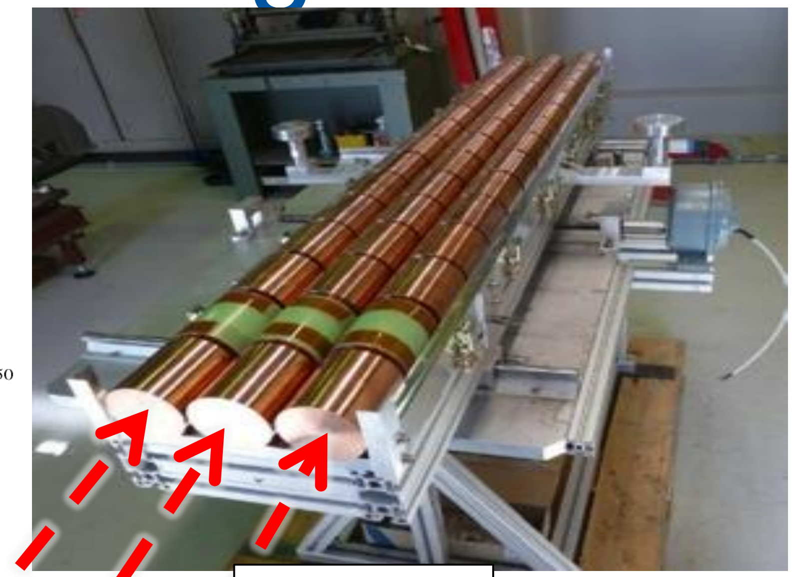
A. Bertarelli (EN)

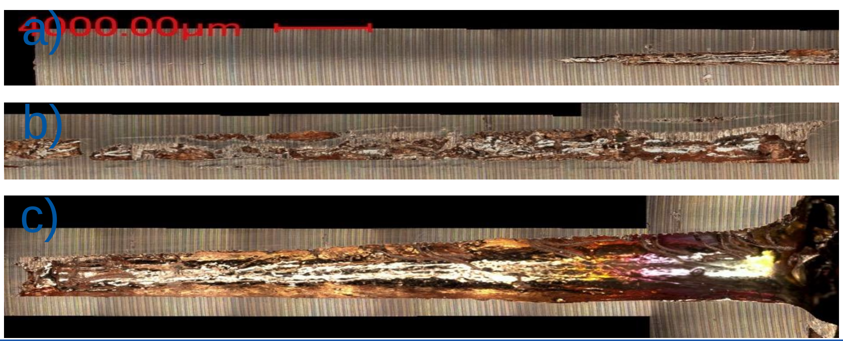
Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

Hydrodynamic tunneling









Target 3
440GeV/c
144b
s = 0.2mm

Target 2
440GeV/c
108b
s = 0.2mm

Target 1
440GeV/c
144b
s = 2mm

- Excellent agreement between simulations and experimental results – proving existence of hydrodynamic tunneling process in case of the LHC beam (~ 35 m in copper).

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Main objectives of MP^3 design

- **P**rotect the machine

  Highest priority is to avoid damage of the accelerator

- **P**rotect 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

- **P**rovide the evidence

  Clear (post-mortem) diagnostics must be provided when:

  - the protection systems stop operation,
  - something goes wrong (failure, damage, but also 'near misses')

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/circulating 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 vs 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 in circular machines

	Time scale	
❑ Single turn (single-passage) beam loss ○ Failures of kicker magnets (injection, extraction kicker magnets). ○ Transfer failures between two accelerators or from an accelerator to a target station.	ns -µs	**High reliability** **Passive protection**
❑ Very fast beam loss (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 milli-seconds	µs-ms	**Active Protection** **Passive protection**
❑ Fast beam loss	10 ms - s	
❑ Slow beam loss	many s	

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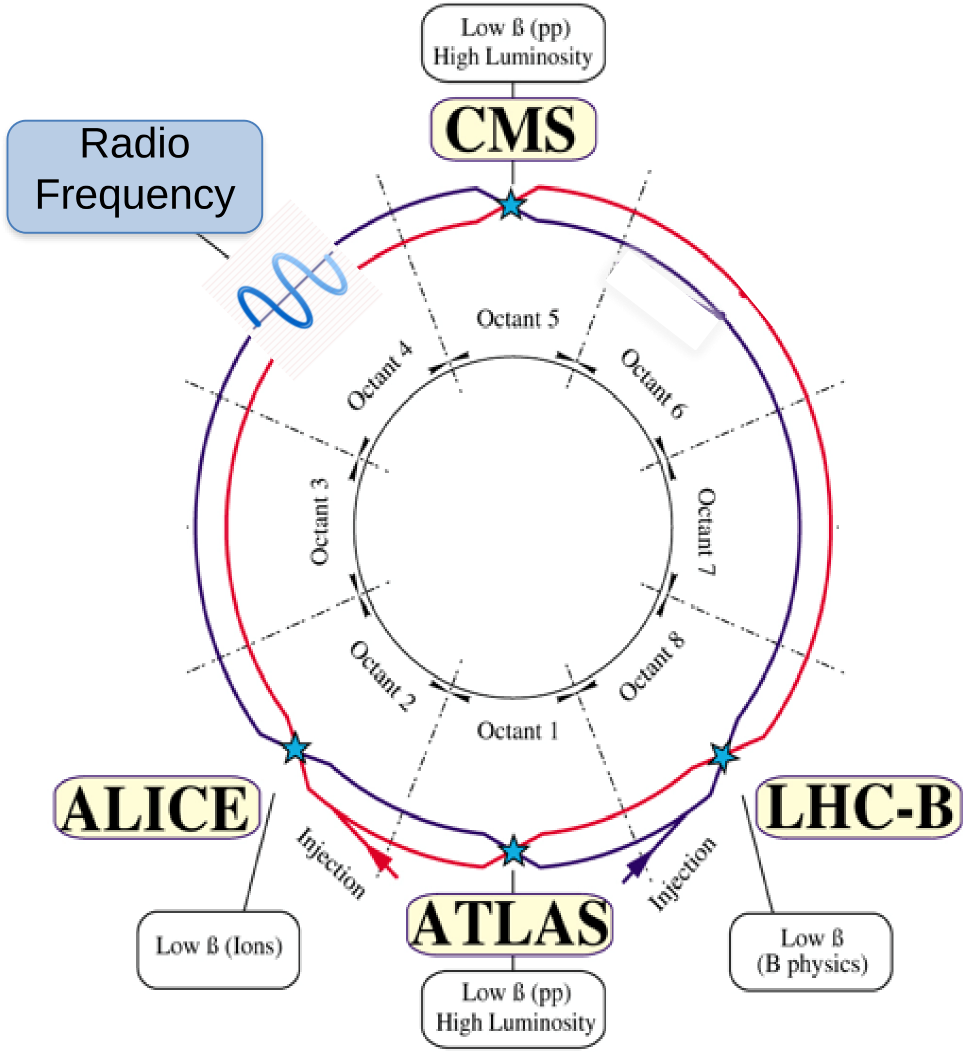
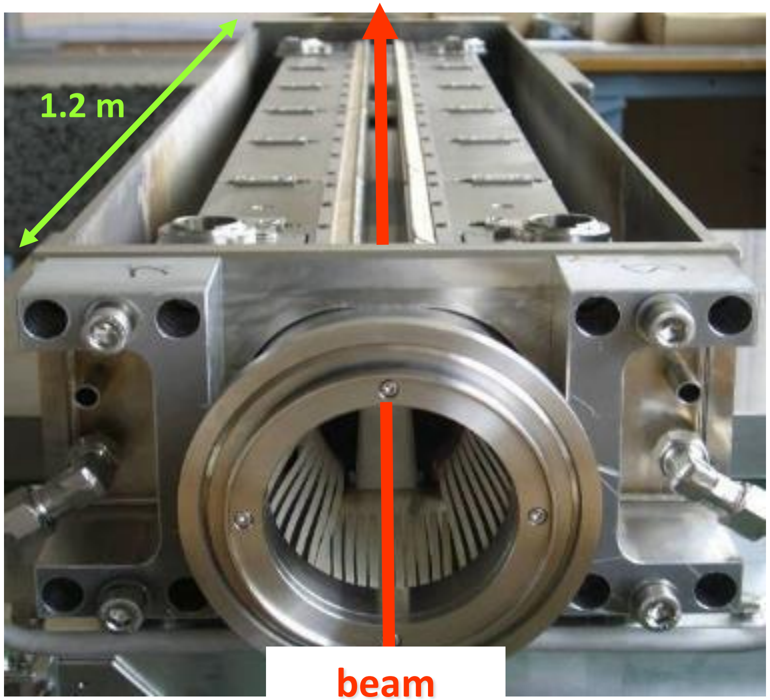
LHC and its Design Parameters

	design
Beam energy	7 TeV
transv. norm. emittance	3.75 μm
beta*	0.55 m
IP beam size	16.7 μm
bunch intensity	1.15×10^{11}
luminosity / bunch	3.6×10^{30} cm^{-2}s^{-1}
# bunches	2808
bunch spacing	25 ns
beam current	0.582 A
rms bunch length	7.55 cm
crossing angle	285 μrad
“Piwinski angle”	0.64
luminosity	10^{34} cm^{-2}s^{-1}



Beam collimation (cleaning)

- The LHC requires a complex multi-stage collimation system to avoid high energy particles to hit aperture limits and/or provoke quenches of sc magnets
  - *Previous hadron machines used collimators only for experimental background conditions.*

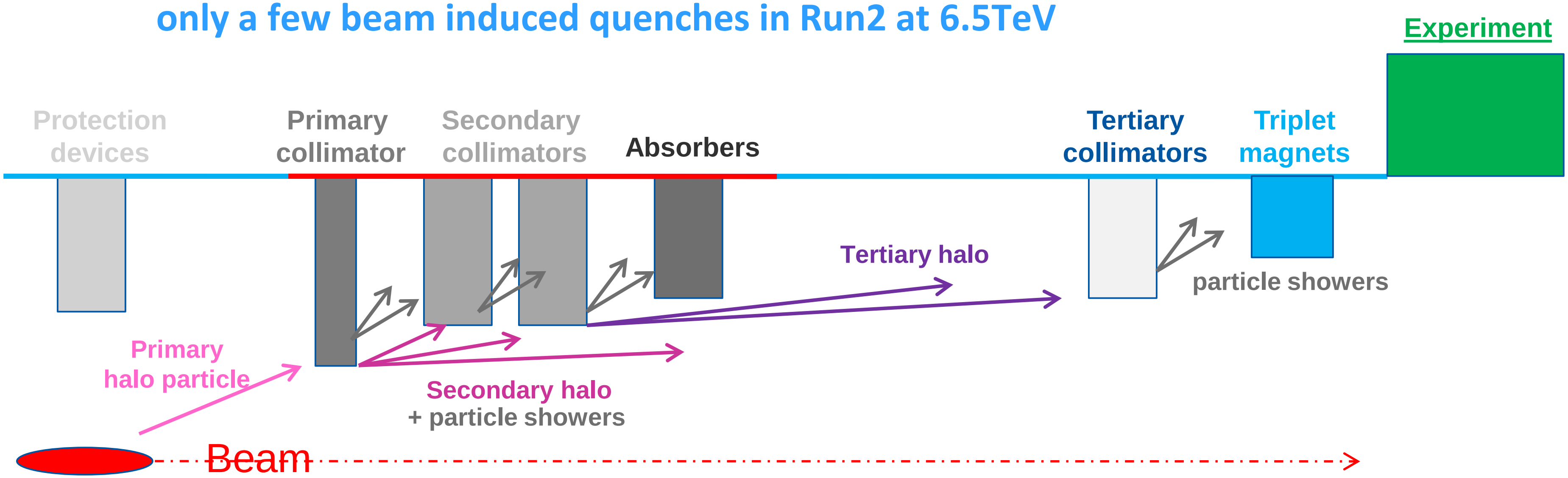


More than ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

Up to 360 MJ in each beam
versus
few mJ to quench a magnet

Collimation System

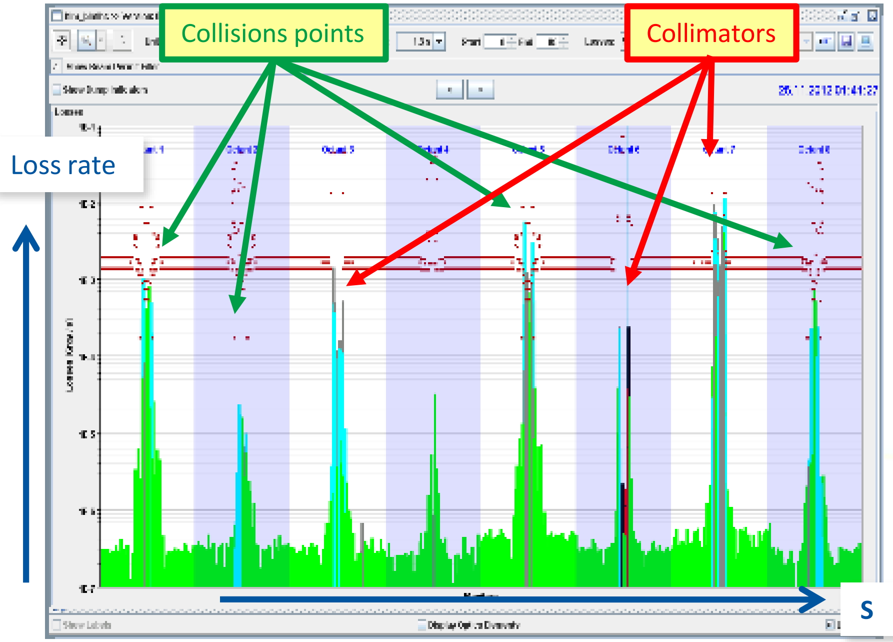
- To be able to absorb the energy of the (high energy) protons, the collimators are staged – primary, secondary, tertiary – multi-stage system.
- The system worked perfectly – also thanks to excellent beam stabilization and machine reproducibility – only one setup / year.
  - ~99.99% of the protons that were lost from the beam were intercepted.
  - **No magnet was quenched during Run1 operation at 3.5/4 TeV, only a few beam induced quenches in Run2 at 6.5TeV**

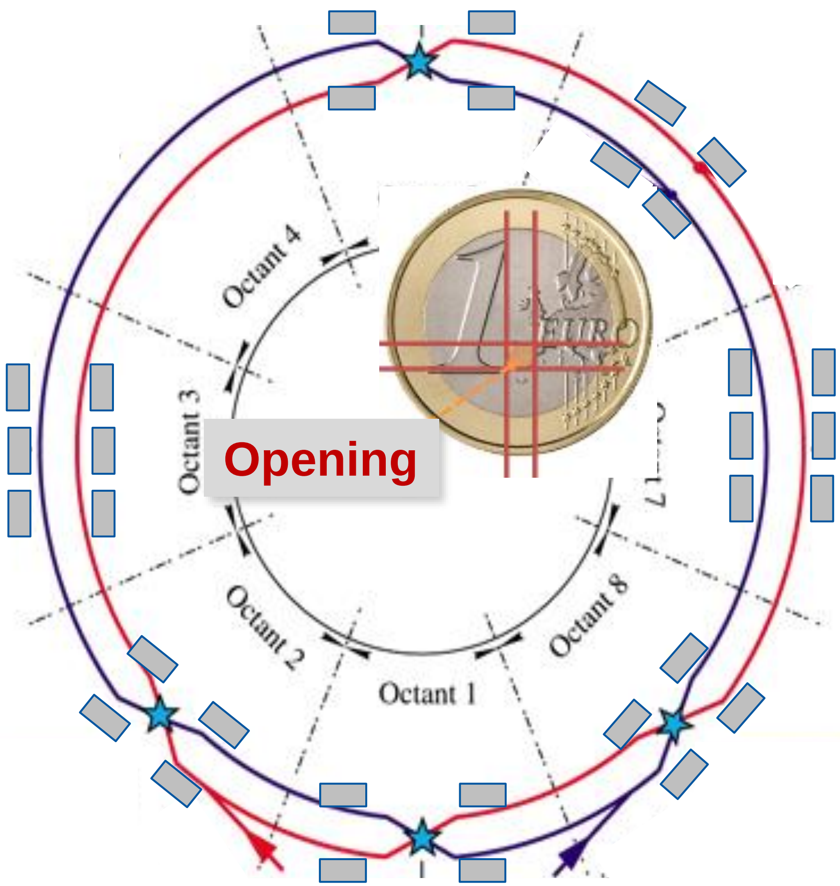


Collimators and continuous losses

100 x

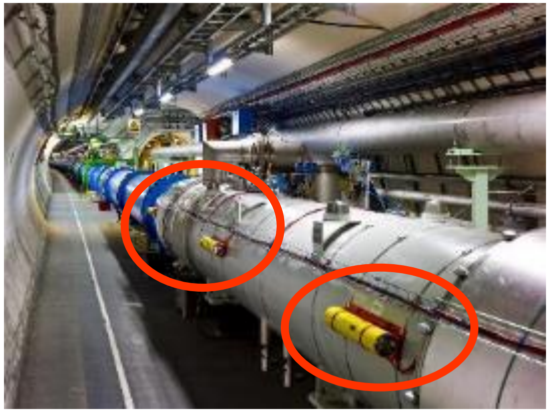
- The BLM signals near the experiments are almost as high as at the collimators (steady losses) due to the luminosity (in fact the physics at small angles not covered by the experiments !!)

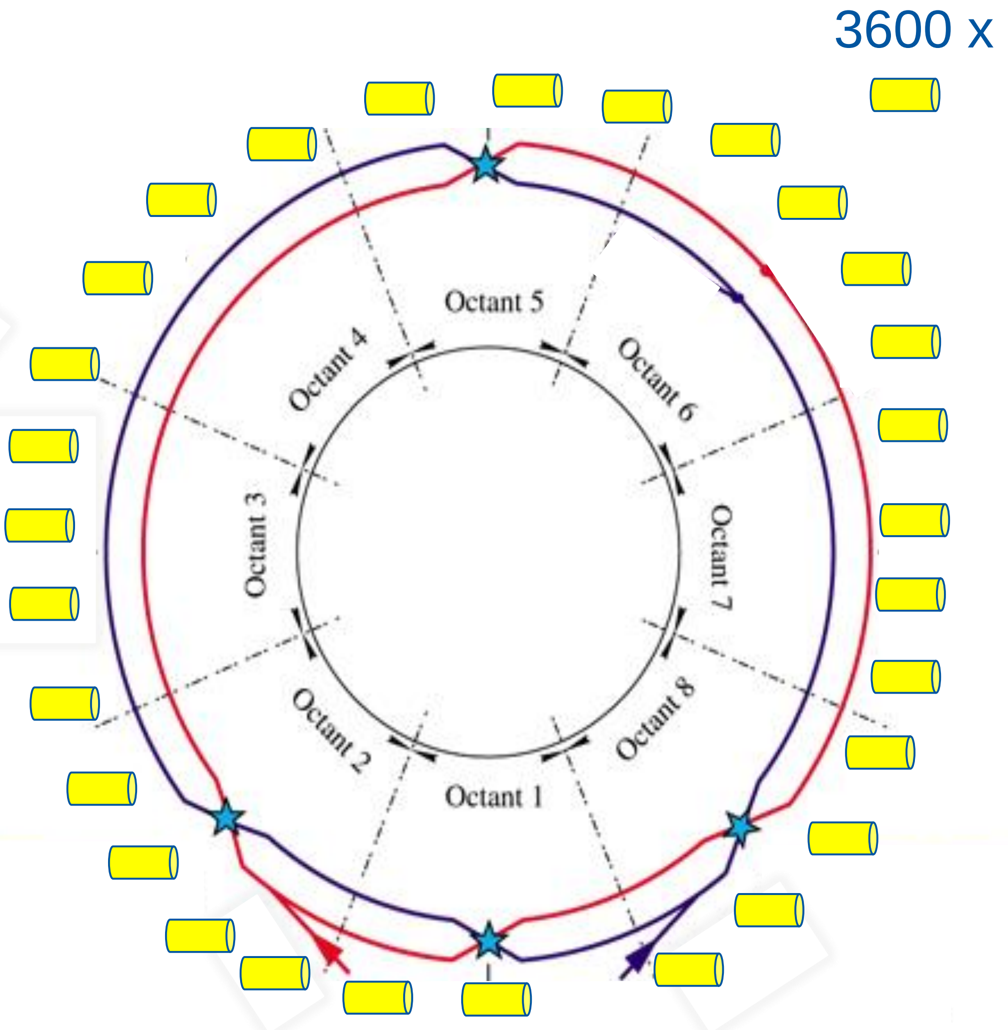




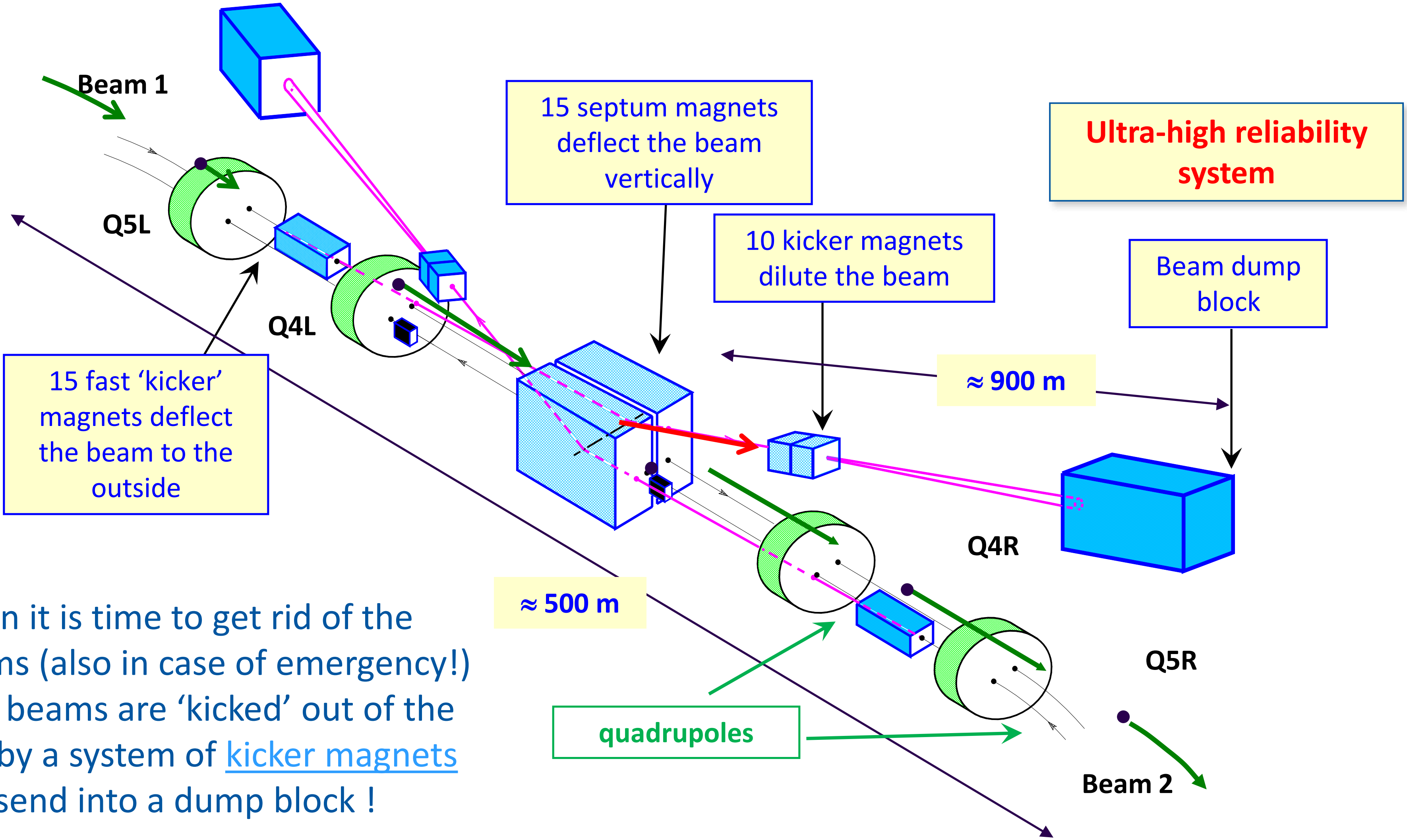
Beam Loss Monitors (BLMs)

- Ionization chambers are used to detect beam losses:
  - Very fast reaction time ~ ½ turn (40 us)
  - 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 beam dumping system

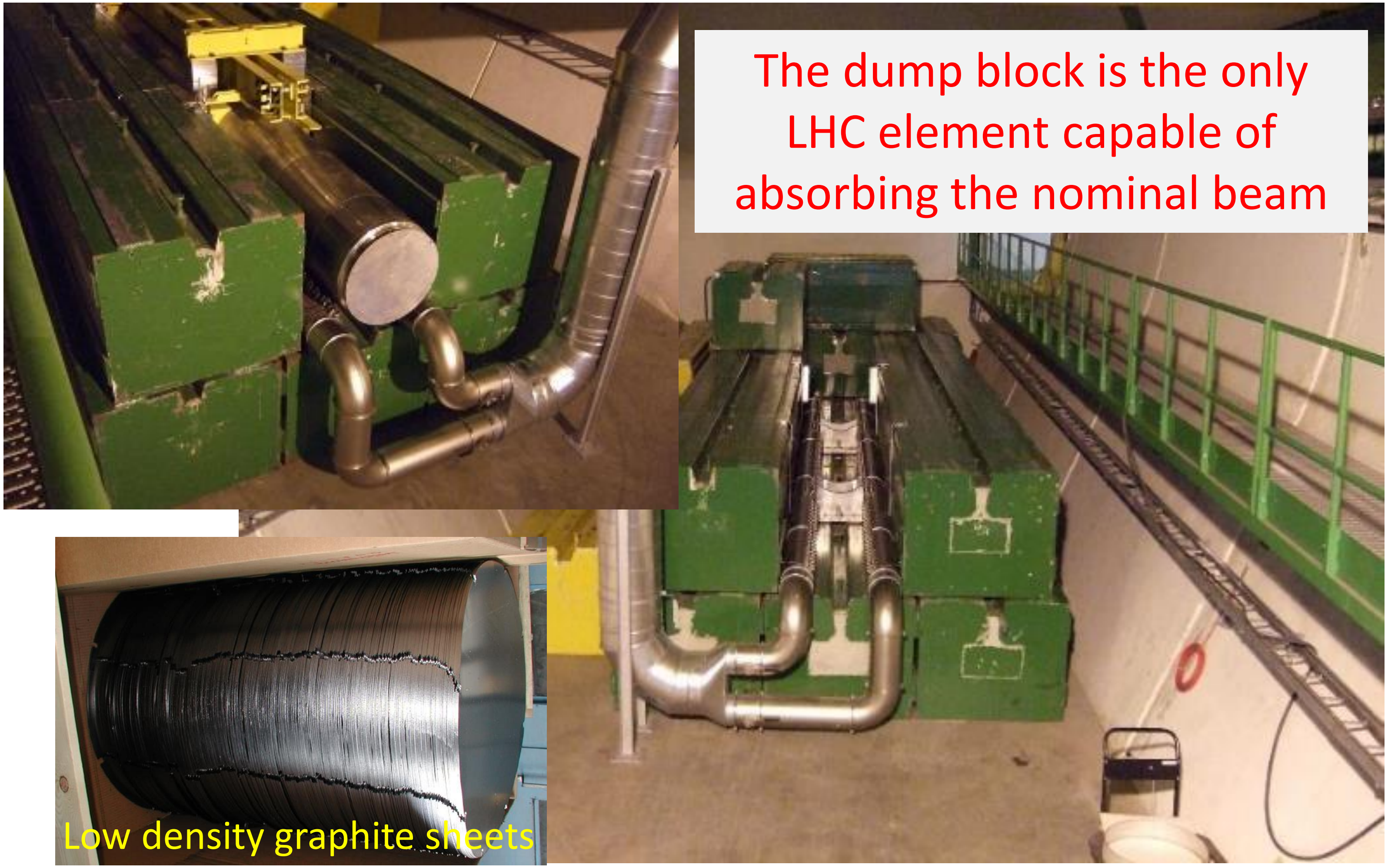


When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of [kicker magnets]() and send into a dump block !

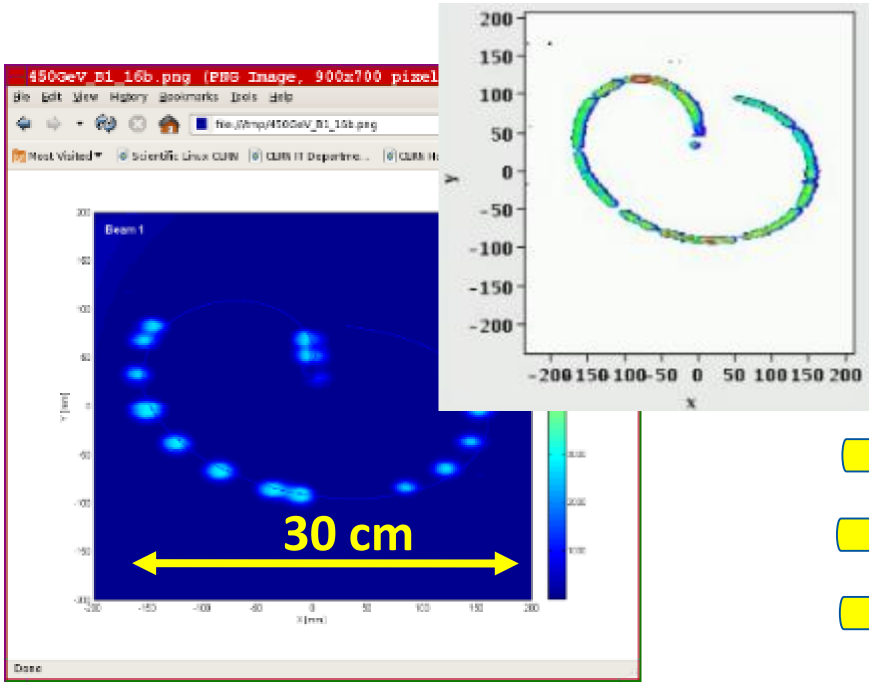
LHC dump line

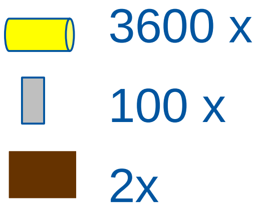
LHC dump block

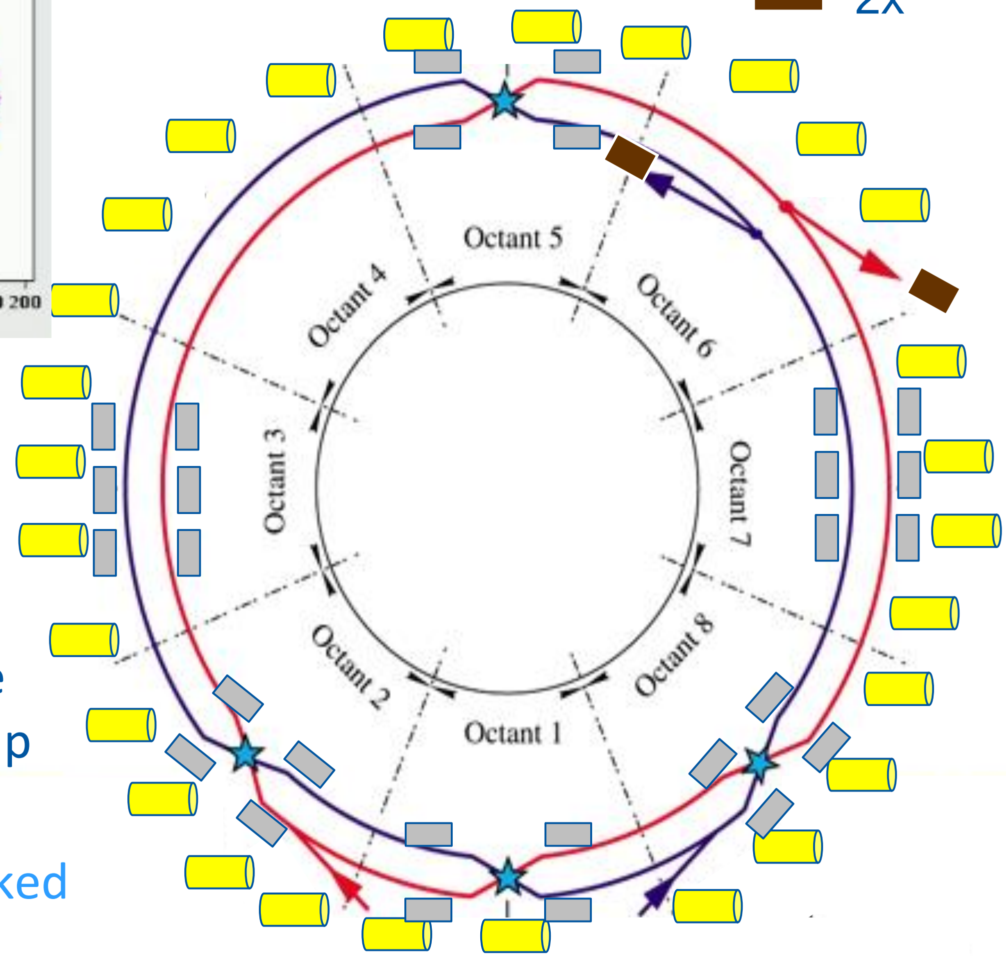
The dump block is the only LHC element capable of absorbing the nominal beam



The (ideal) end for each LHC beam

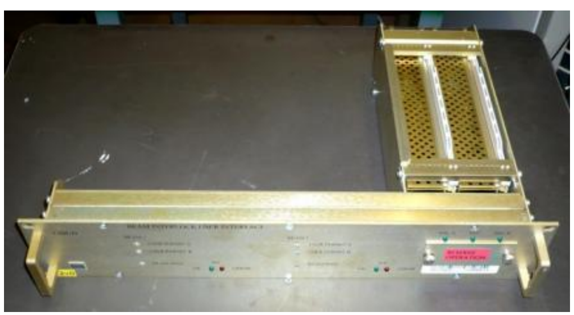






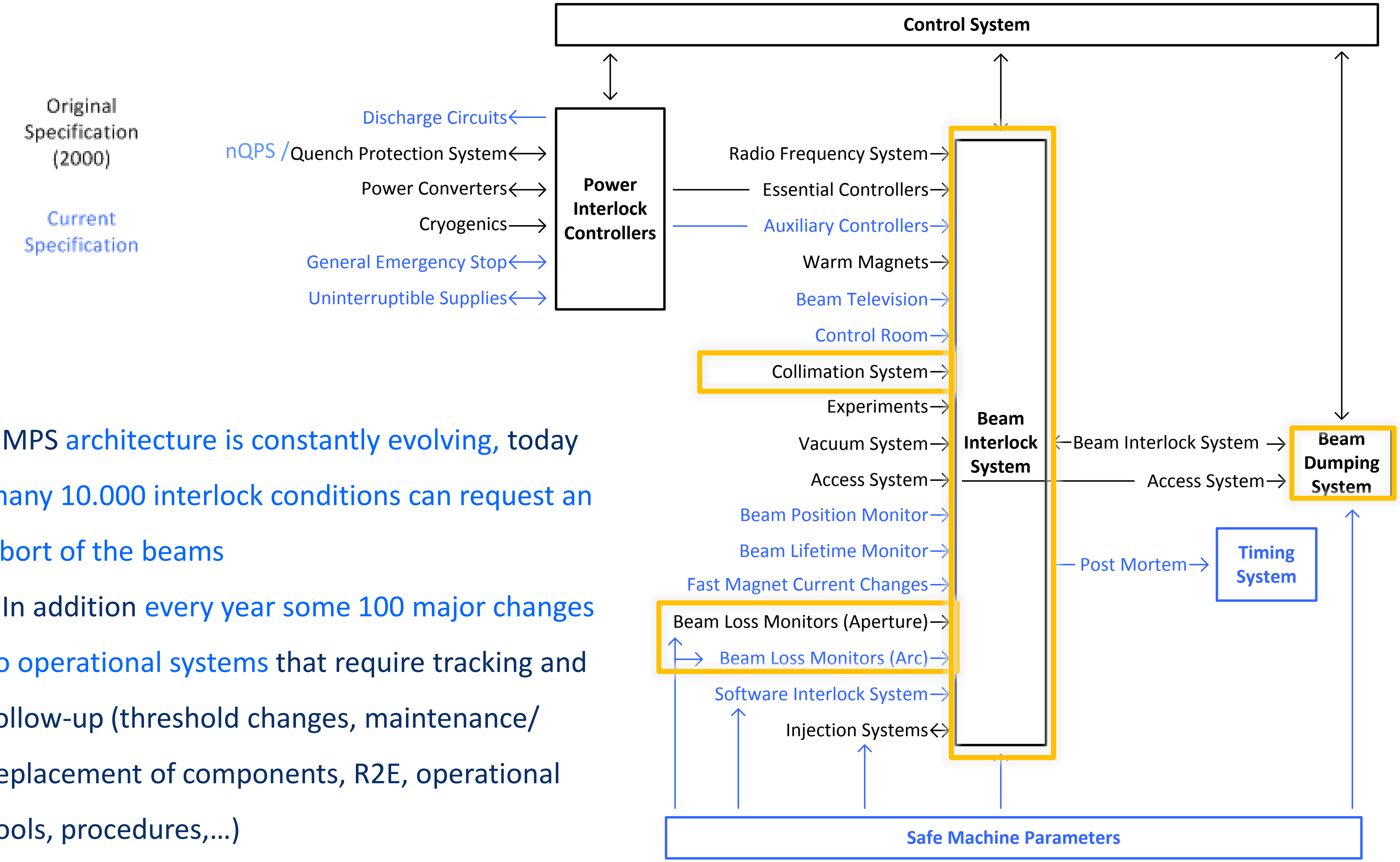
- A beam screen installed in front of the dump provides monitoring of the dump execution.
- The shape of the beam impact is checked against prediction at each dump !

Magnet and Beam Interlock Systems



Custom made electronics developments for fast and reliable concentration and transmission of protection actions

The MPS systems continue to learn as well



- MPS architecture is constantly evolving, today many 10.000 interlock conditions can request an abort of the beams
- In addition every year some 100 major changes to operational systems that require tracking and follow-up (threshold changes, maintenance/ replacement of components, R2E, operational tools, procedures,…)

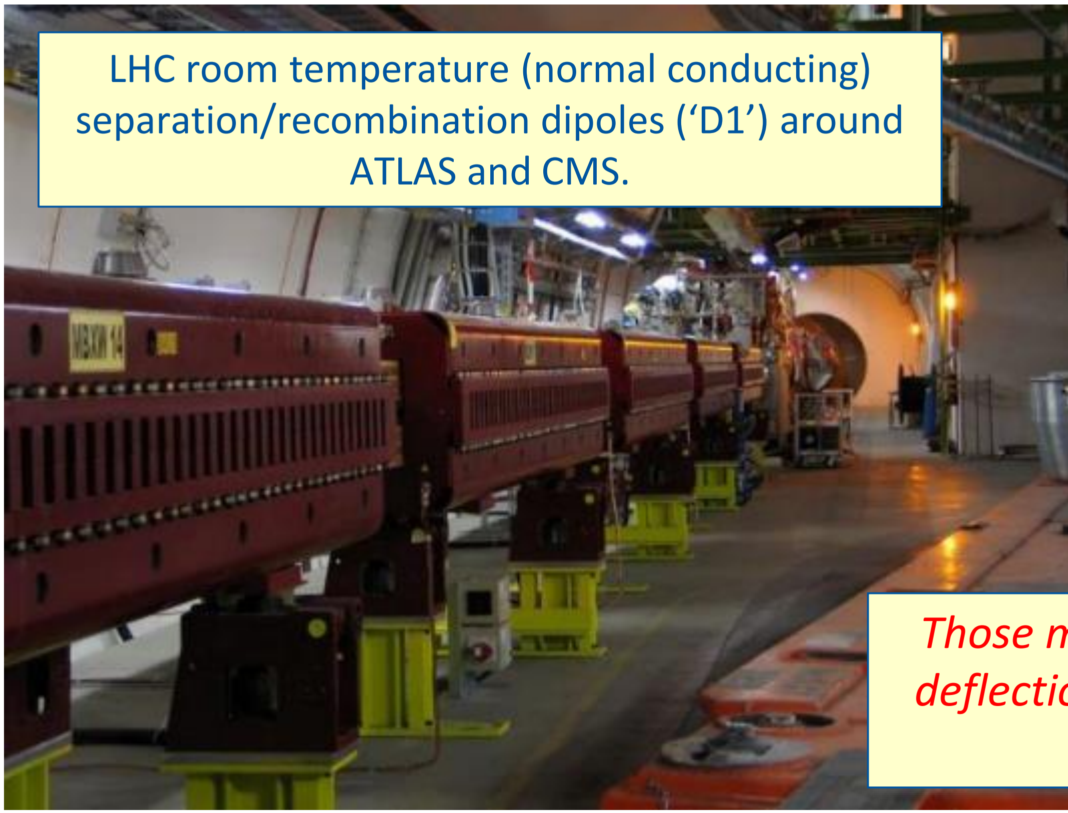
Failure analysis process – step 1

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

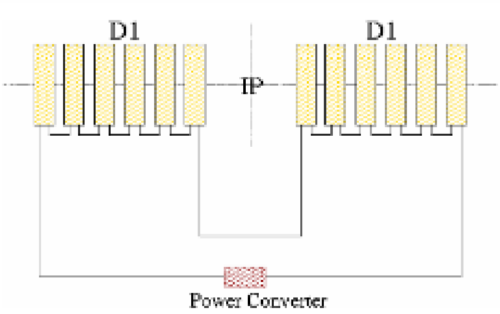
- Step 2: Identify a critical element – the D1's (separation/re-combination dipoles around the high luminosity experiments)



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

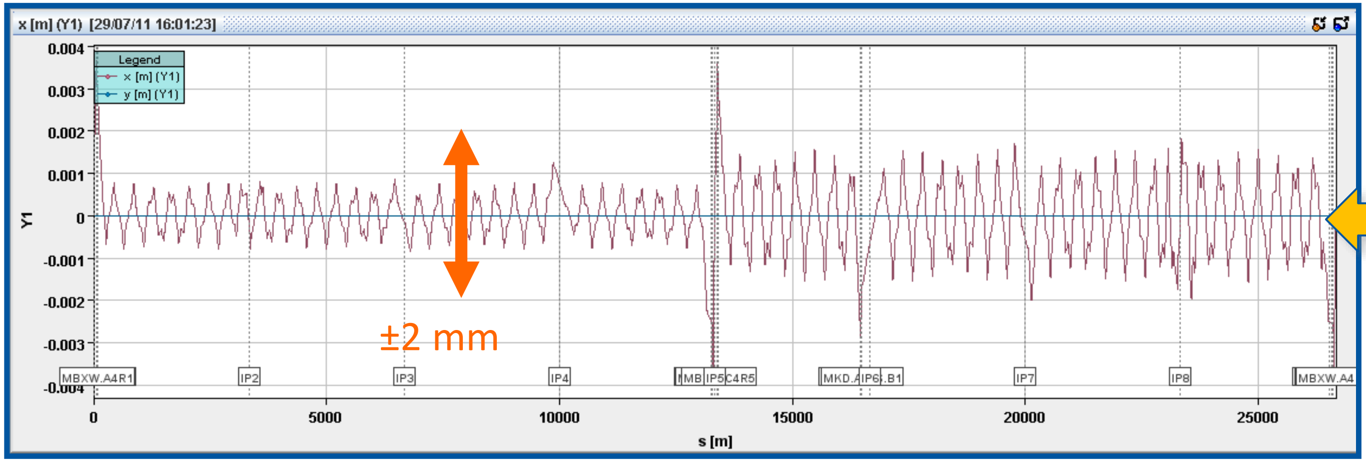
Those magnets are very strong (large deflections) and they are fast –> good candidates

Failure analysis process – step 3



- *Step 3: Simulate the failure.*
  - 12 magnets are powered in series.
  - Large betatron function when squeezed (b > 2000 m) → large orbit changes.
  - Short time constant t = 2.5 seconds (B is the magnetic field): $B(t) = B_0 e^{-t/\tau}$

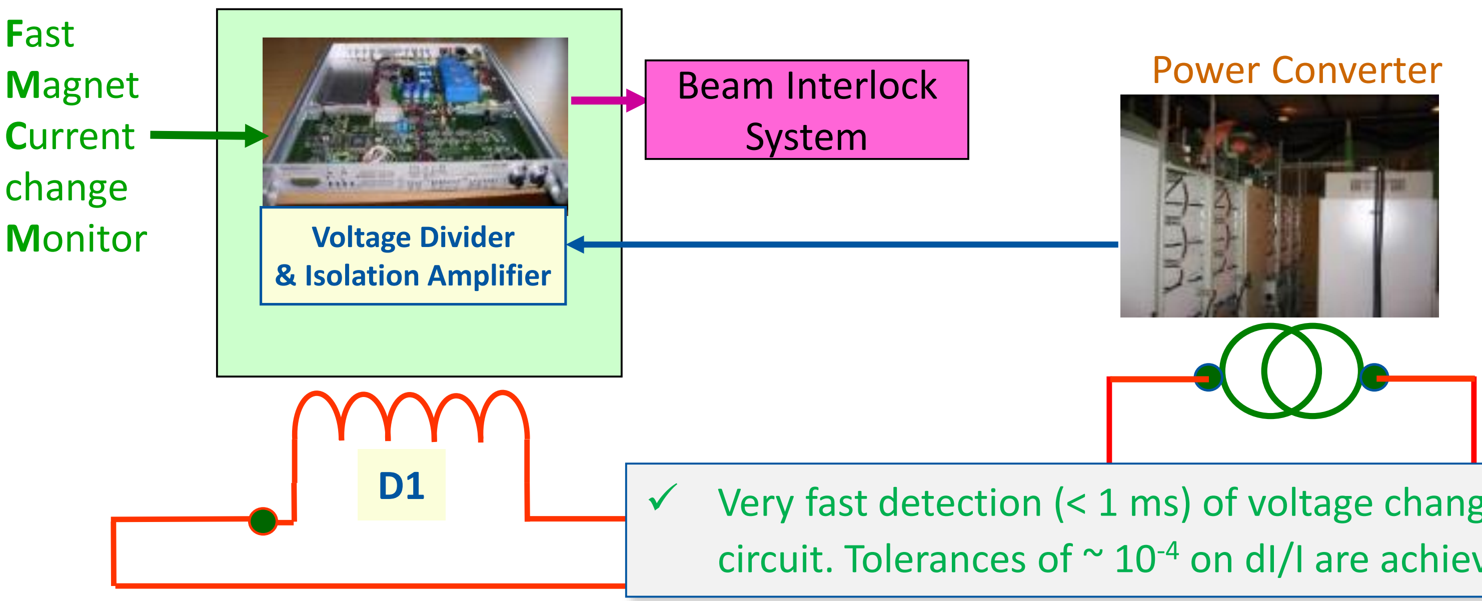
Simulated orbit change along the LHC ring a few **milliseconds** after failure.



It does not fit !

Failure analysis process – step 4

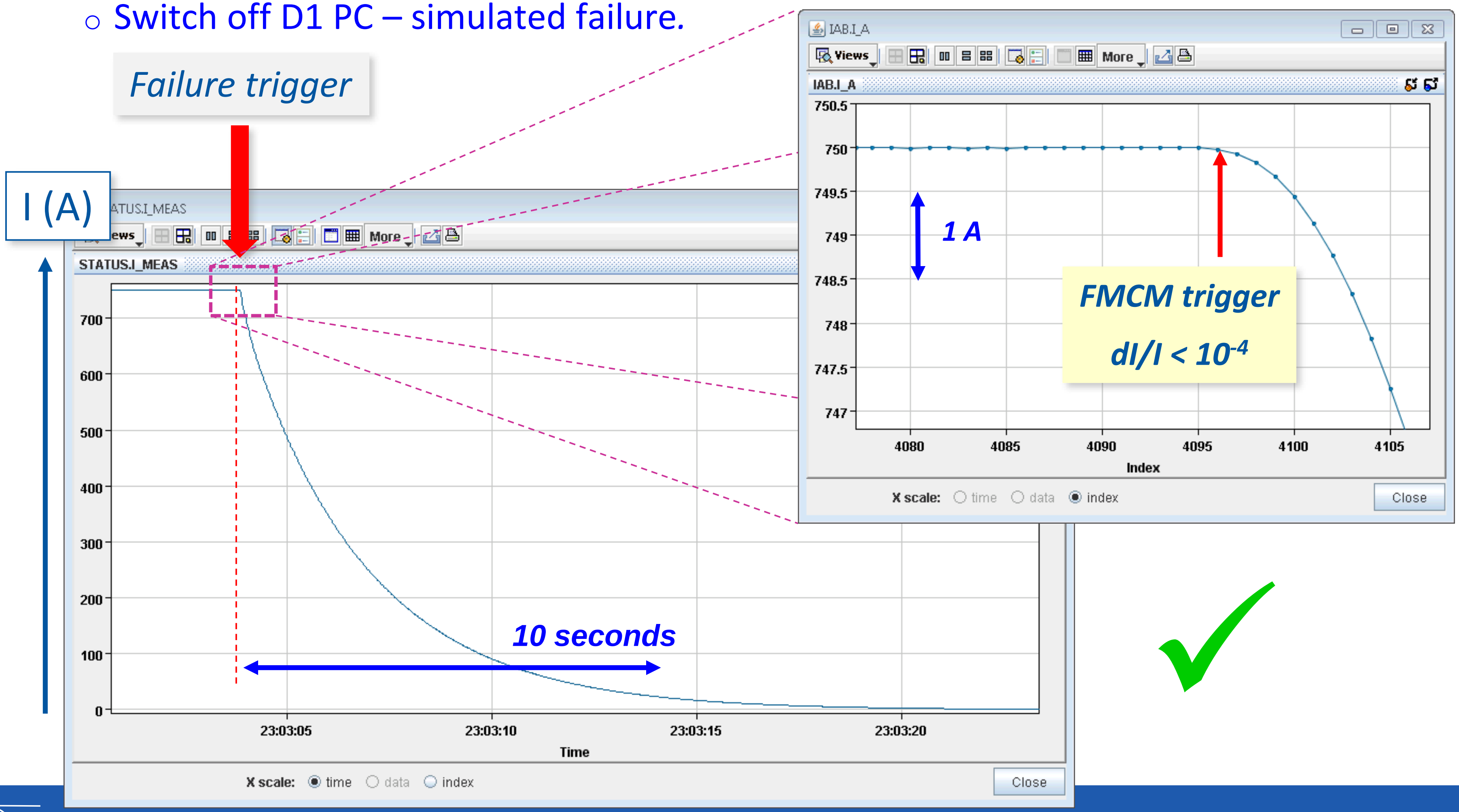
- *Step 4: Identify mitigation strategy*
  - The simulations indicate absence of redundancy (we only have beam loss monitors) and very short reaction times for BLMs → we want an extra-layer of protection at the equipment level.
  - This analysis triggered the development of so-called FMCMs (Fast Magnet Current change Monitor) that provide protection against fast magnet current changes after powering failures - CERN - DESY/Hamburg collaboration.



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

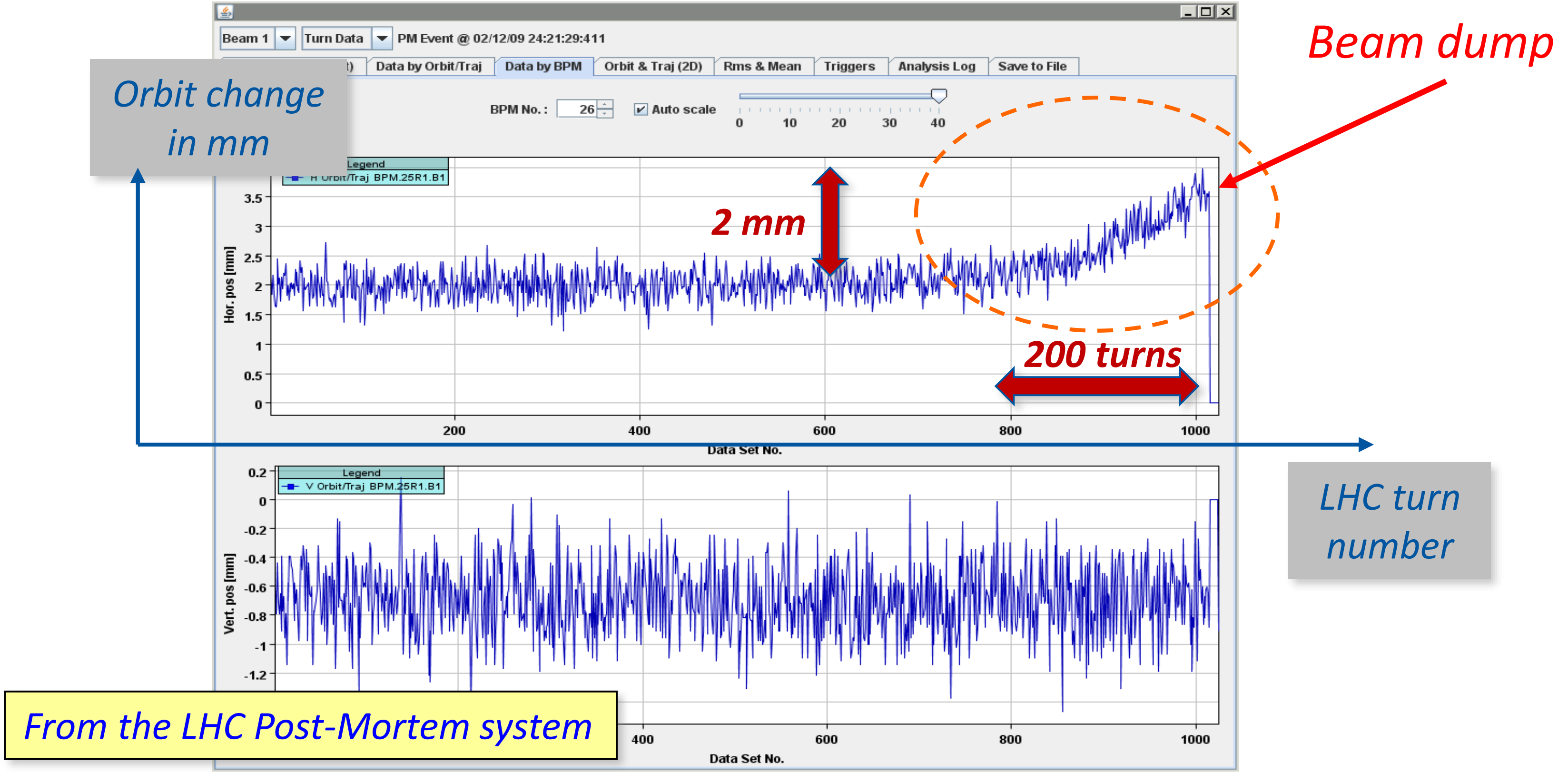
Failure analysis process – step 5

- Step 5: Commissioning and validation
  - Switch off D1 PC – simulated failure.



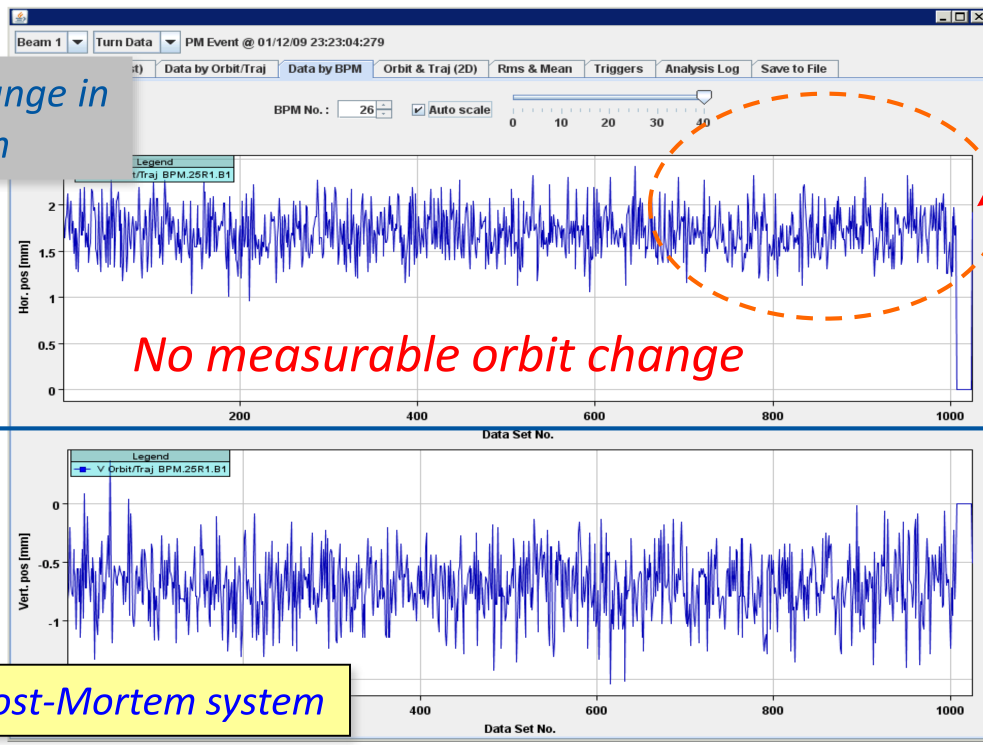
Failure analysis process – step 6

- 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.



Orbit change in mm

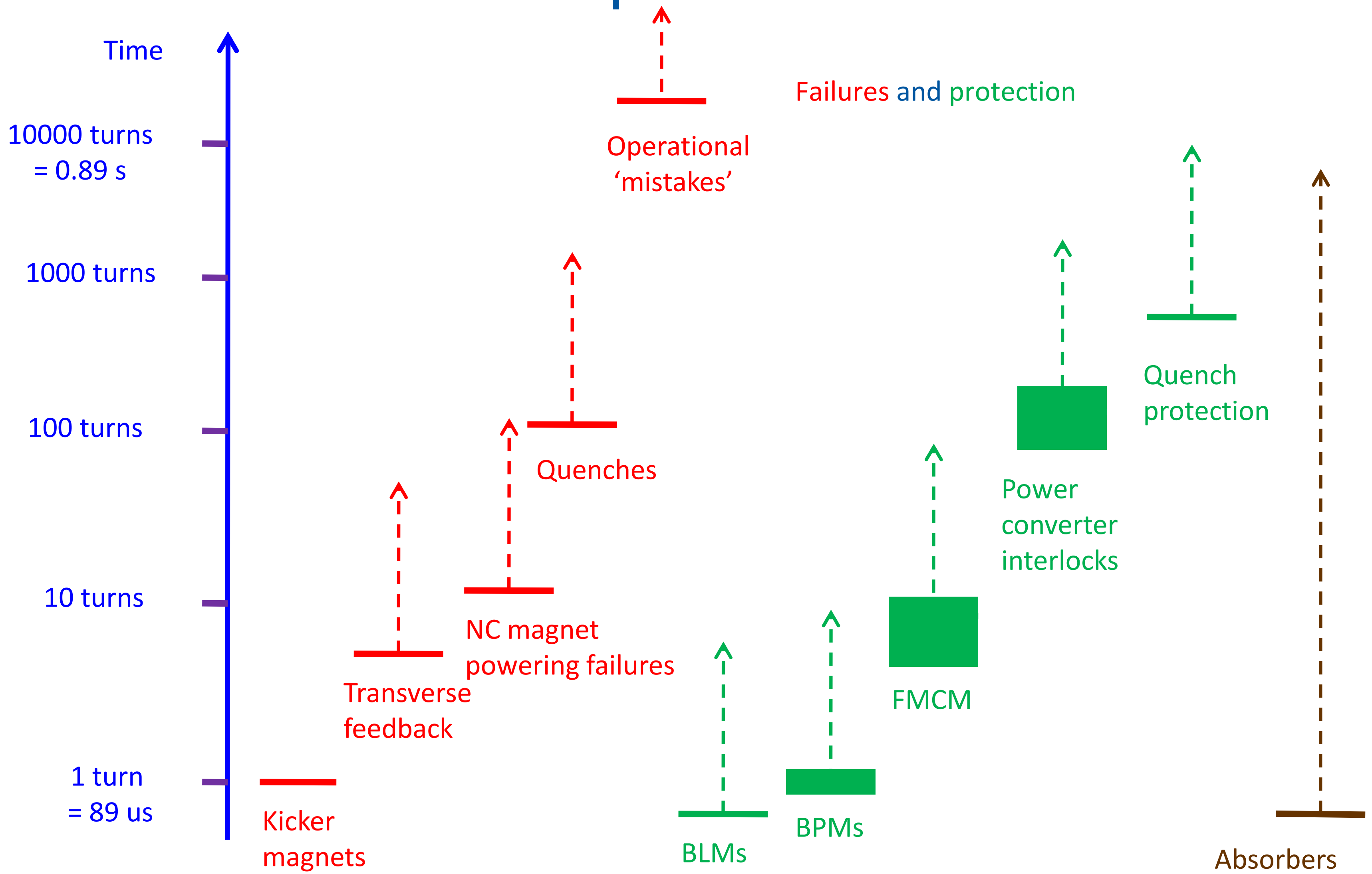
Beam dump !

No measurable orbit change

LHC turn number

From the LHC Post-Mortem system

Failure timescales + protection at the LHC



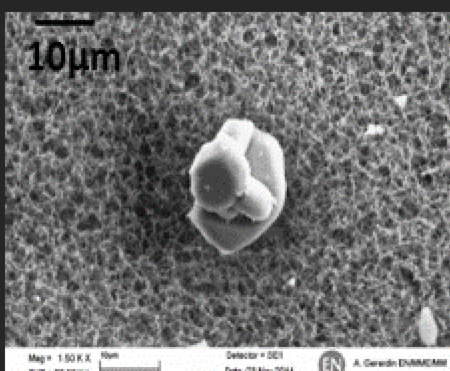
Outline

- Introduction
- Stored energy & interaction with matter
- Machine protection design
- Example from LHC
- The unexpected
- Summary

The less expected… 1/2

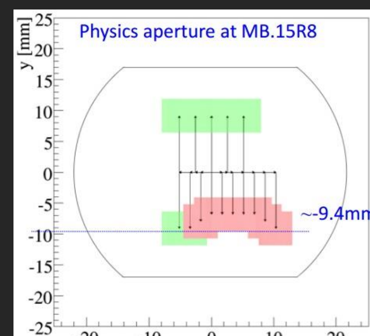
UFO

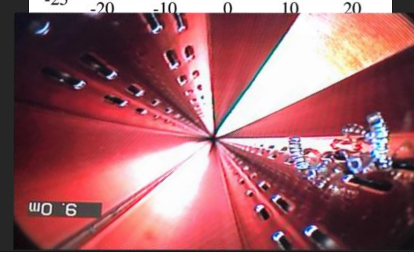
- (suspected) dust particles interacting with beam
- Beam losses and potential magnet quenches (quench limit at 7TeV)!
- Mitigated by threshold optimisation



ULO (Unidentified Lying Object)

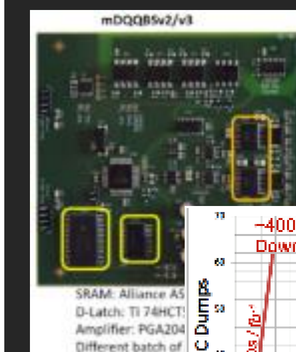
- Aperture limitation in LHC dipole magnet 15R8
- Mitigated by orbit bump

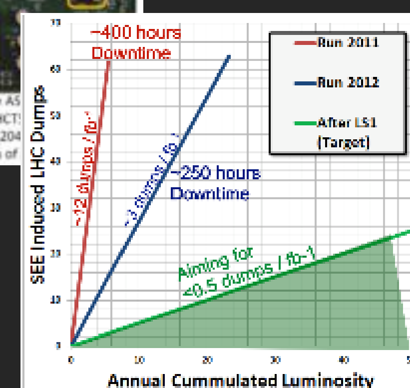




Radiation to electronics

- Non-rad hard components used in LS1 upgrade
- Mitigation measures (shielding, relocation…)





The less expected… 2/2

BIRDS & WEASELS

- Electrical fault in 66kV surface substation
- Mitigated by repair and additional protection

PS MAIN POWER SUPPLY

- Short in capacitor storage bank
- Mitigated by network reconfiguration and operation of rotating machine

SPS BEAM DUMP

- Limited to 96 bunches per injection
- 2076 (2200) bunches per beam cf. 2750
- Replacement during EYETS

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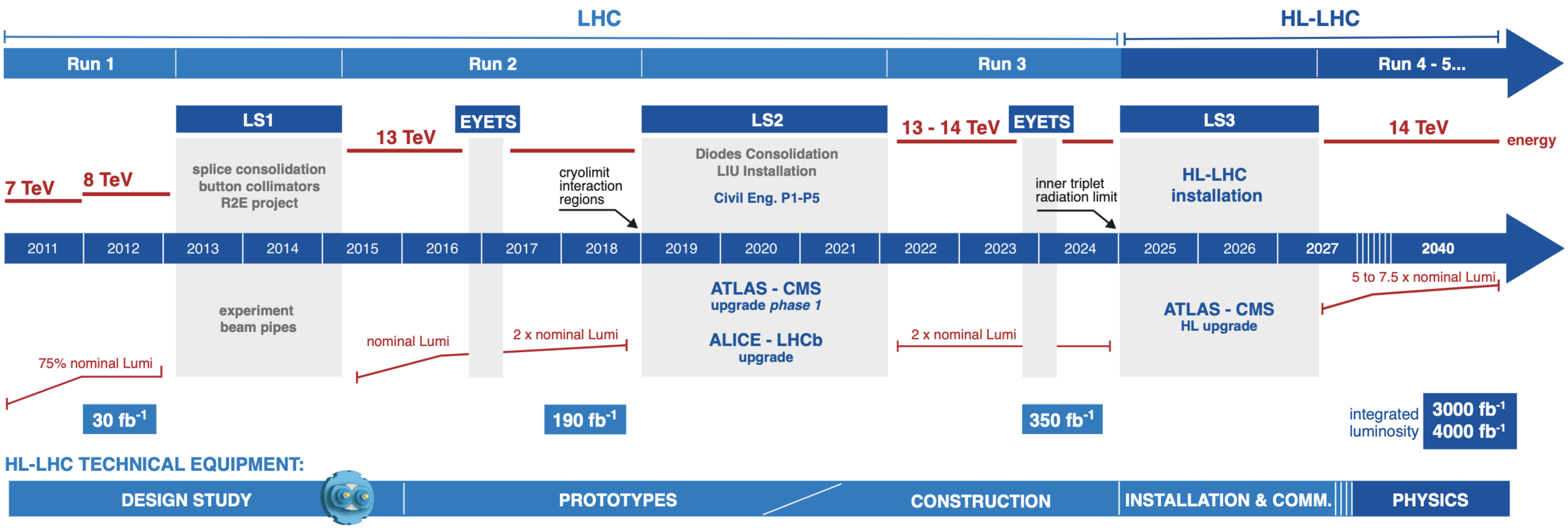
Summary

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.

LHC exploitation – past and upcoming

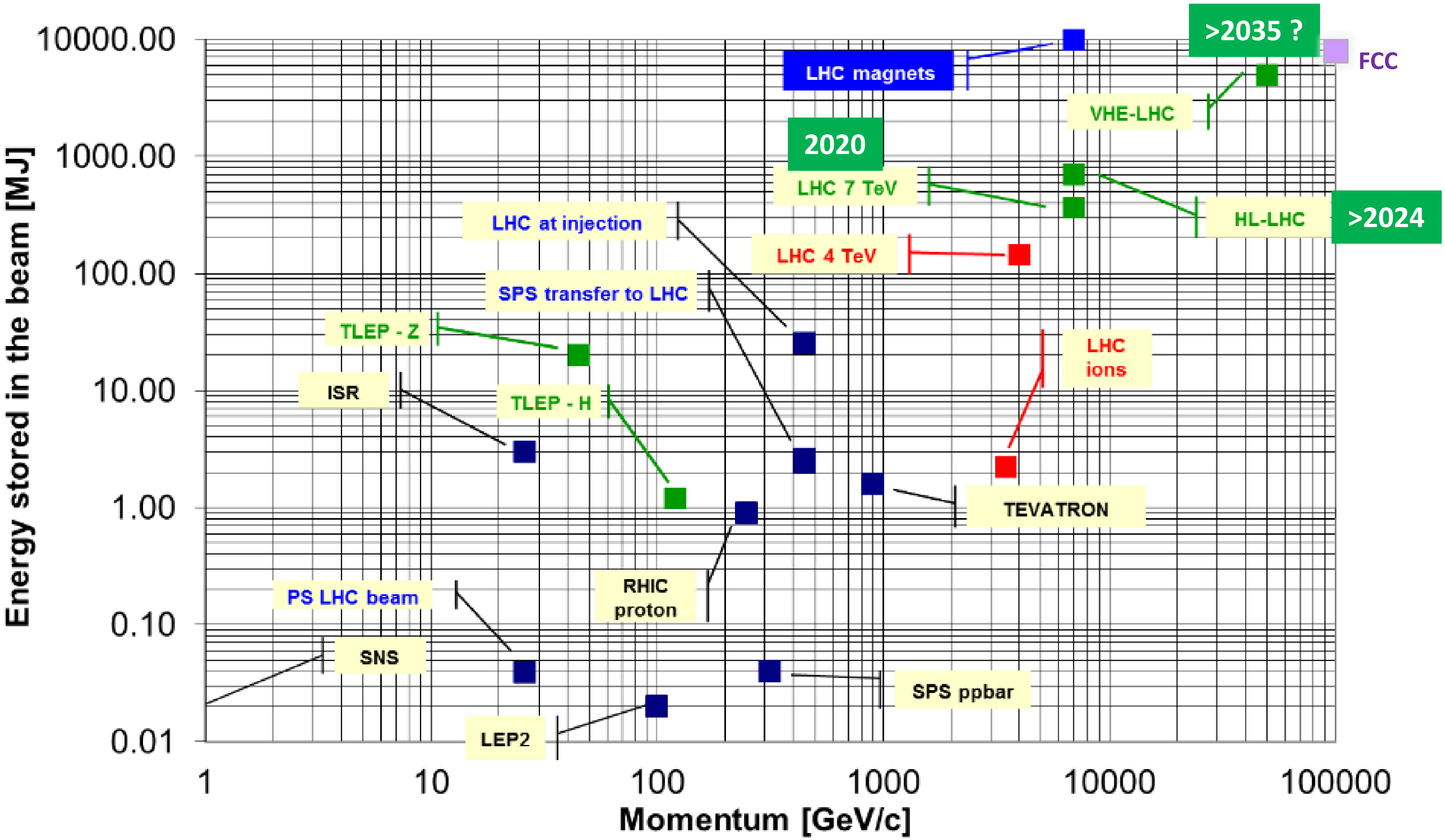


75ns / 50ns
1.5m -> 1m->0.6m

50ns / 25ns
0.8m -> 0.3m

- Excellent performance of LHC and its machine protection systems during first 7 years of commissioning and exploitation, allowing to exceed design luminosity by a factor 2
- Injector upgrade and HL-LHC projects will imply as well new MP challenges

Stored energies- the future



Thank you for your attention!
Questions ?