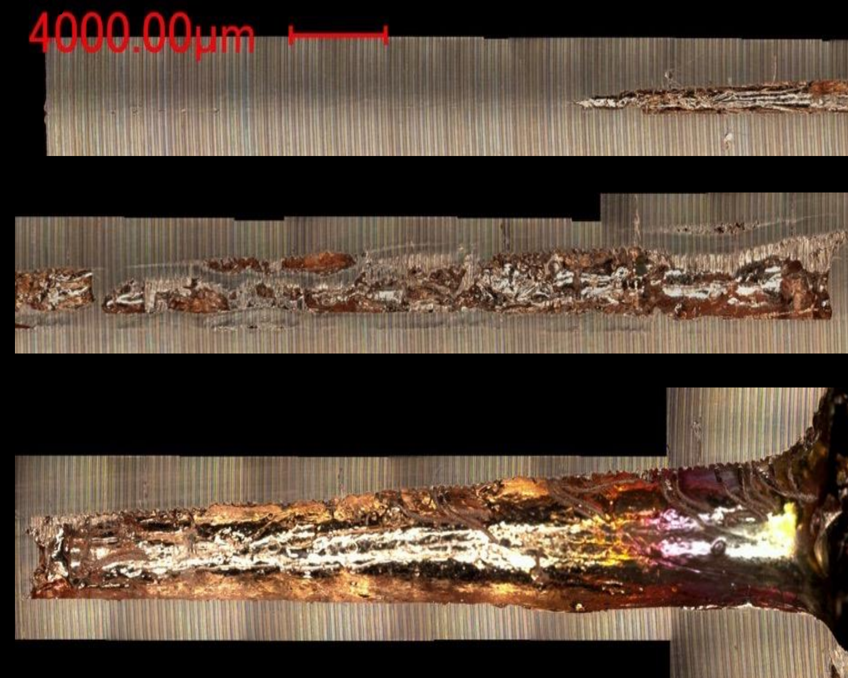
CERN







Machine Protection

Basics of Accelerator Science and Technology at CERN

Markus Zerlauth with acknowledgements to M.Lamont, R.Schmidt, 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 beams.

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.
- 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.

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

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Technological Challenges

...To see the rarest events...

LHC needs high luminosity of 10^{34} [$cm^{-2}s^{-1}$]

Collisions generate PetaBytes of data Per year

3×10^{14} p per beam

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

1 ppm

cooled in super fluid helium

maintained in a vacuum

10x less pressure than on moon surface

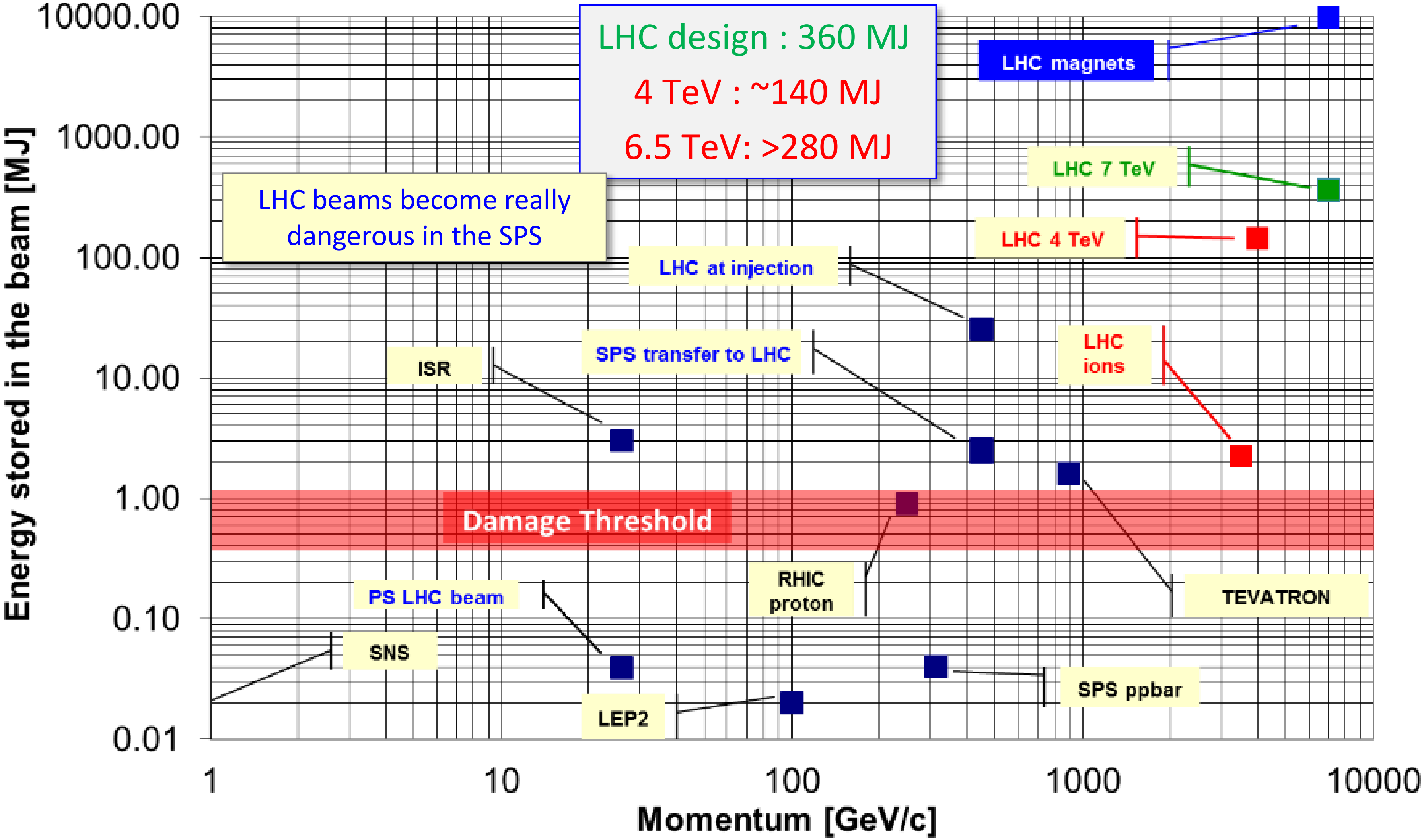
two orders of magnitude higher than others

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ

A magnet will QUENCH with milliJoule deposited energy

The LHC at the Energy Frontier



Relevant parameter for MPS

- ❑ Momentum of the particle
- ❑ Particle type
  - Activation of material is mainly an issue for hadron accelerators.
- ❑ Energy stored in the beam
  - 360MJ per beam in the LHC
    when fully filled with 2808 bunches
- ❑ Beam power
- ❑ Beam size
- ❑ Time structure of beam

90 kg of TNT

8 litres of gasoline

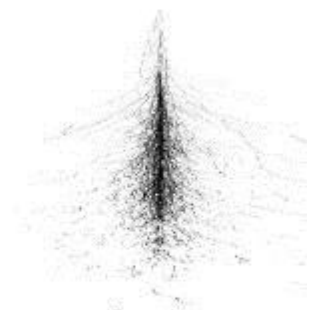
15 kg of chocolate

Energy stored in Magnet Powering System of the LHC

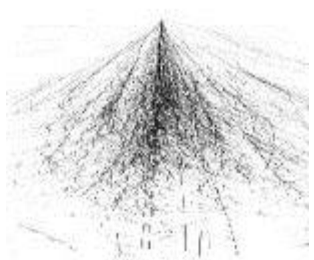
$E_{kin}(v = 27\ \text{kn}) \approx E_{\text{LHC main circuits}}\ (@6.5\ \text{TeV})$

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)



Gamma shower

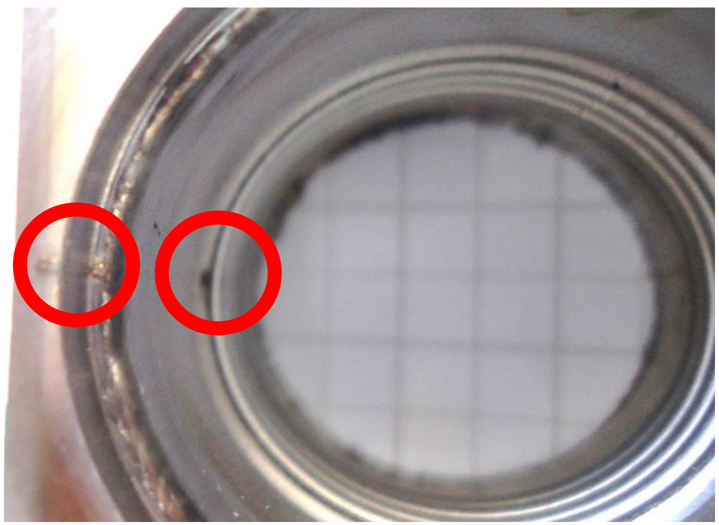


Hadronic shower

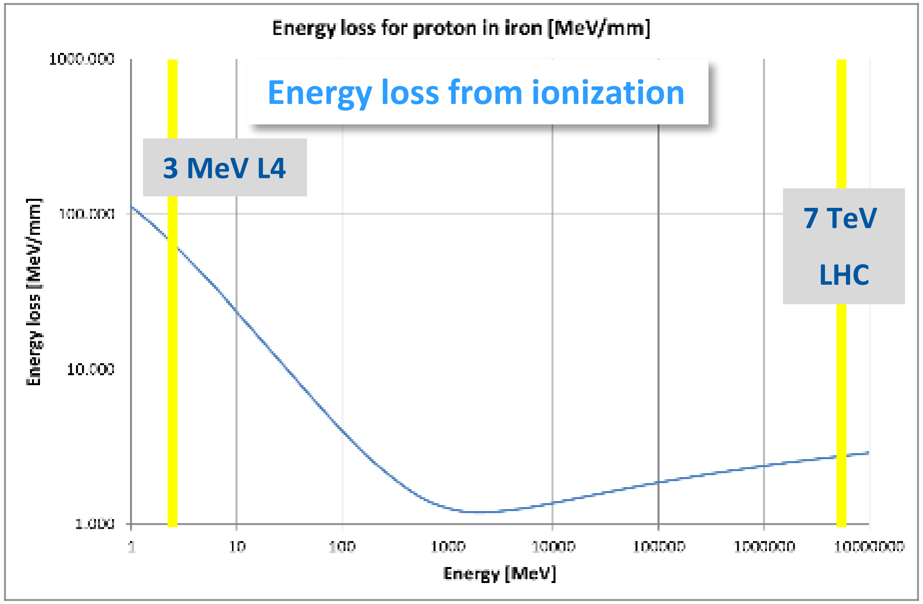
Small but already dangerous

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

- ❑ Failure combination:
  - Beam misaligned
  - Unlucky magnet setting
  - Aperture limitation at bellow



JB Lallement



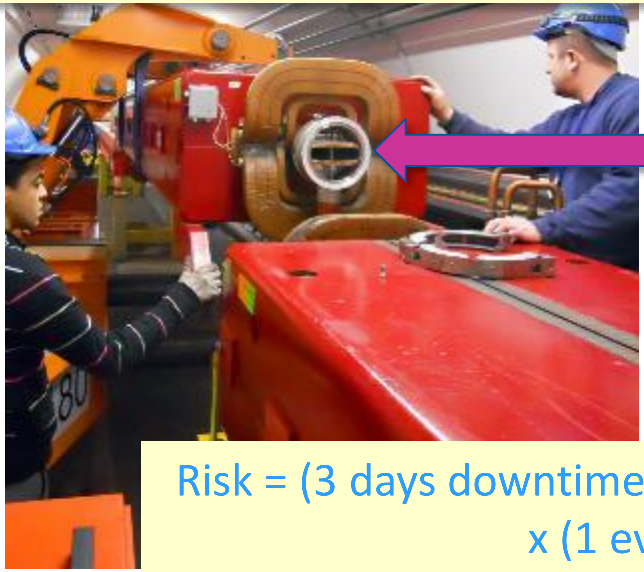
At such low energies, the local energy loss per proton is very high

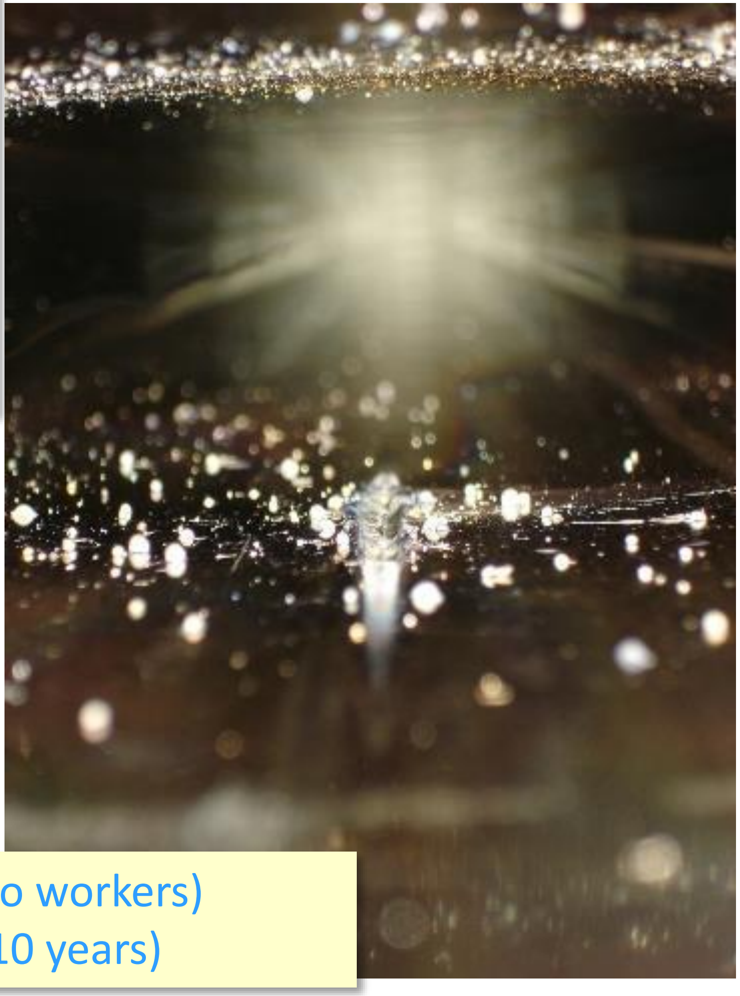
$\Rightarrow$ Damage after some integration time

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.





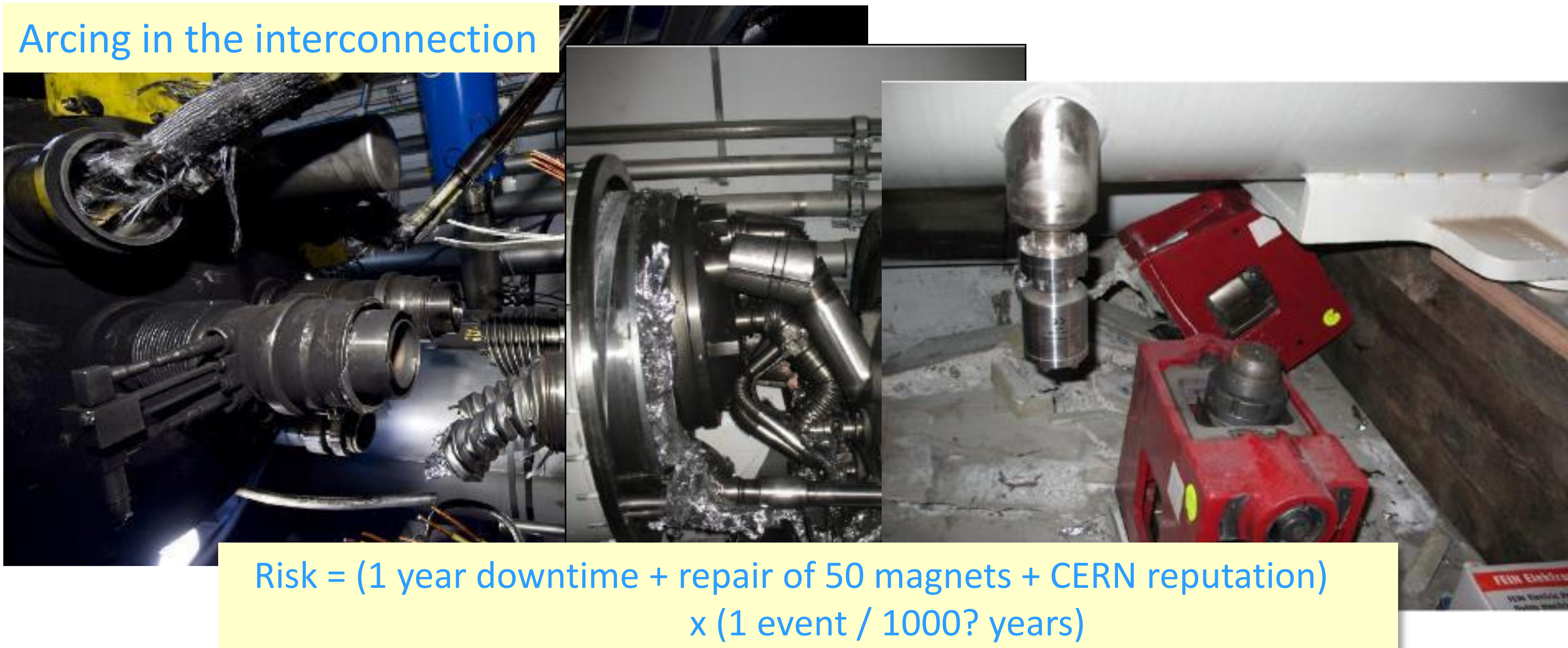
Risk = (3 days downtime + dose to workers)
x (1 event / 5-10 years)

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 + CERN reputation) x (1 event / 1000? years)

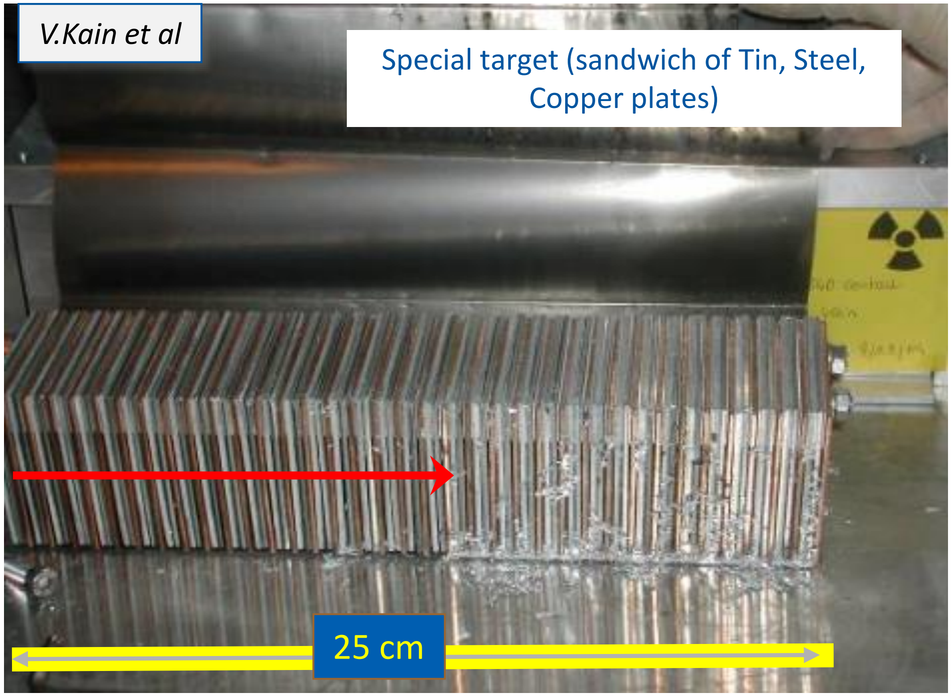
Controlled damage tests for MP

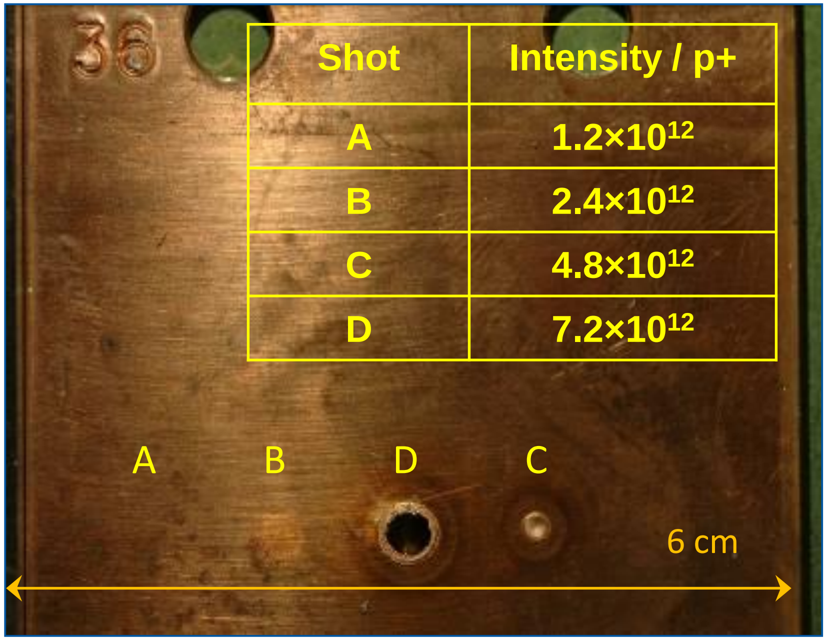
- In the past decade a lot of effort was invested to better understand the interaction of high energy / high density beams with matter.
- Experiments:
  - Ad-hoc experiments for the LHC
  - Construction of a dedicated test facility at CERN (HiRadMat @ SPS)
- Modeling and comparison with tests.
  - Many 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 $\sigma_x \times \sigma_y = 1.1 \times 0.6\ mm^2$,
- Damage limit for copper at 2×10^{12} p.
- No damage to stainless steel.



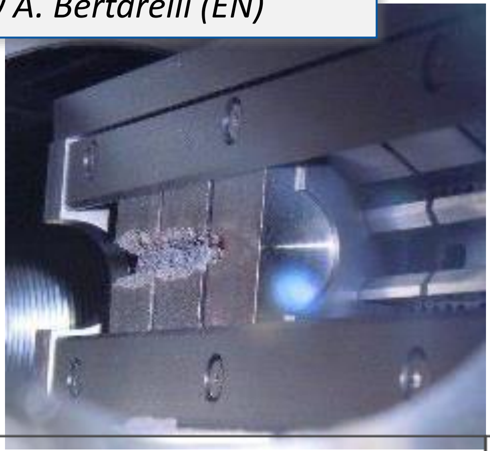


Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

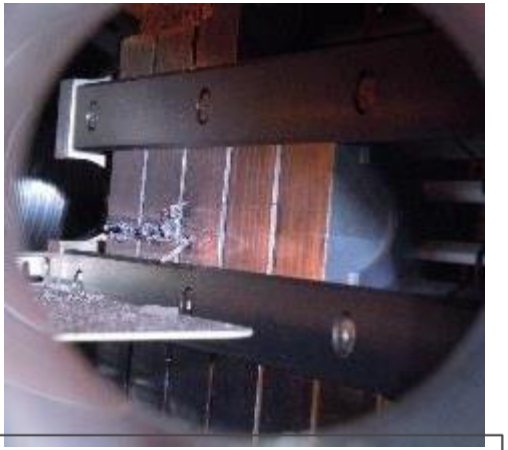
- Damage limit is ~200 kJ,
  < 0.1 % of a nominal LHC beam.
- Impact D: ≈ 1/3 of nominal LHC injection.

HiRadMat tests – new materials

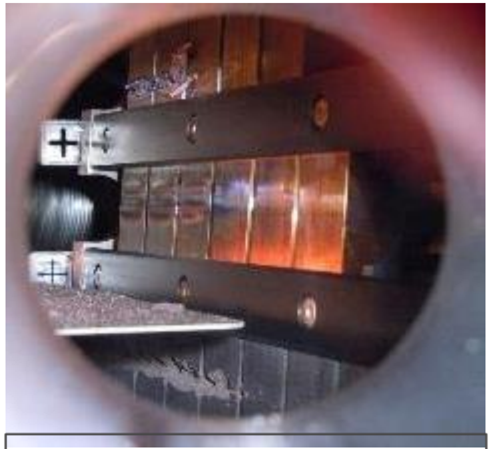
Courtesy A. Bertarelli (EN)



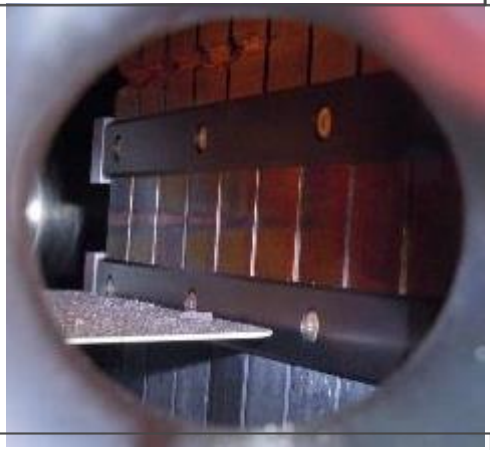
Inermet 180, 72 bunches



Molybdenum, 72 & 144 bunches



Glidcop, 72 bunches (2 x)



Copper-Diamond 144 bunches

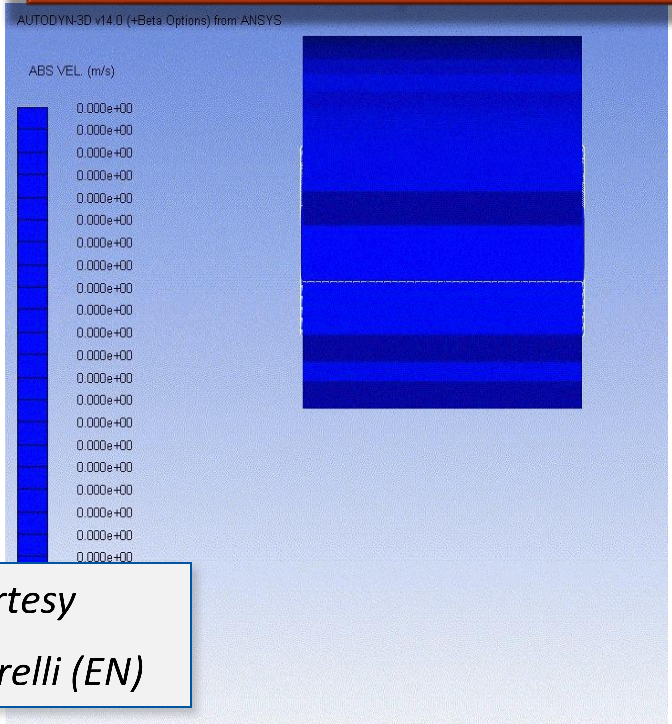
Molybdenum-Copper-Diamond 144 bunches

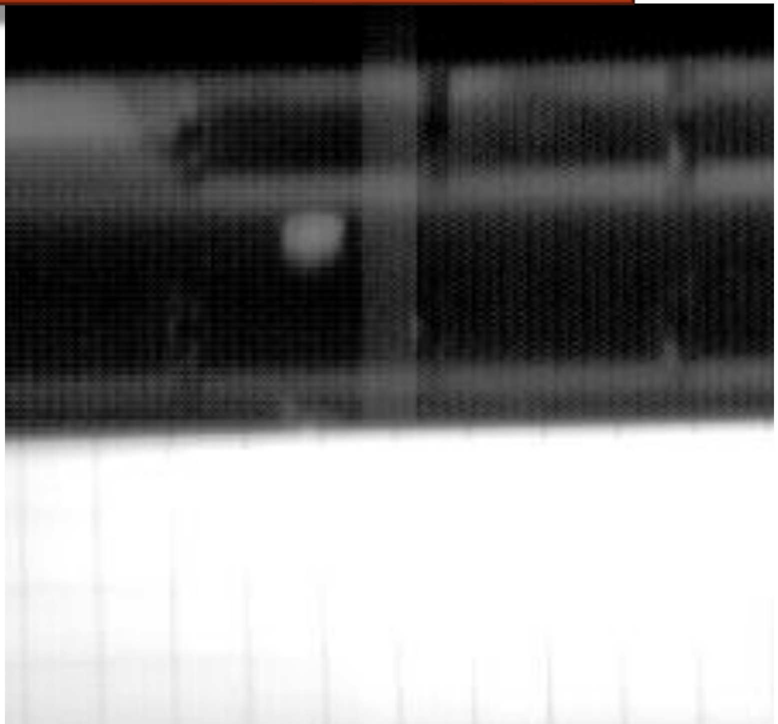
Molybdenum-Graphite (3 grades) 144 bunches

HighRadMat test with high intensity

Inermet : comparison between simulation and experiment

Beam



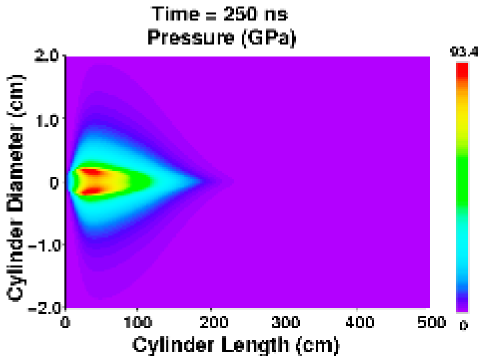


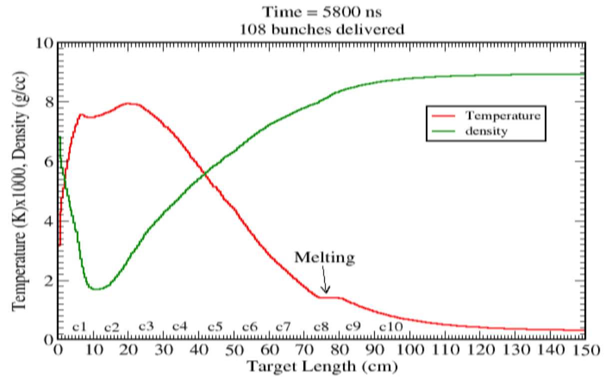
Courtesy

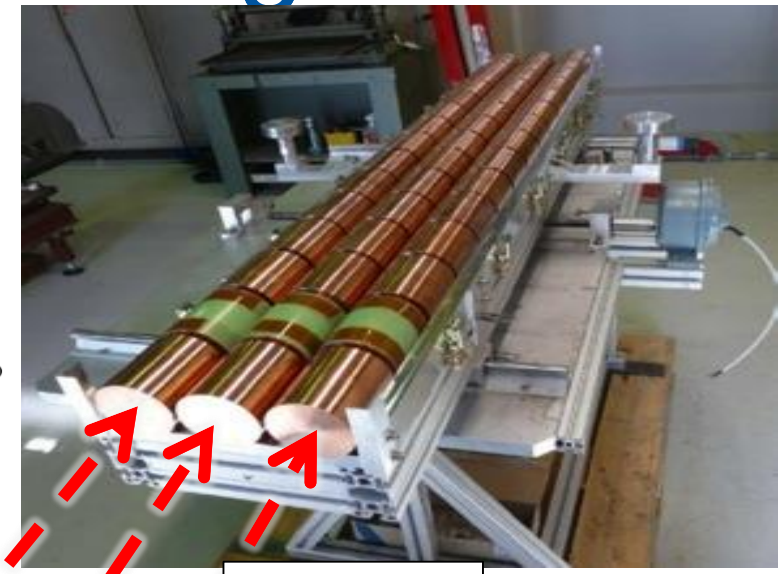
A. Bertarelli (EN)

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



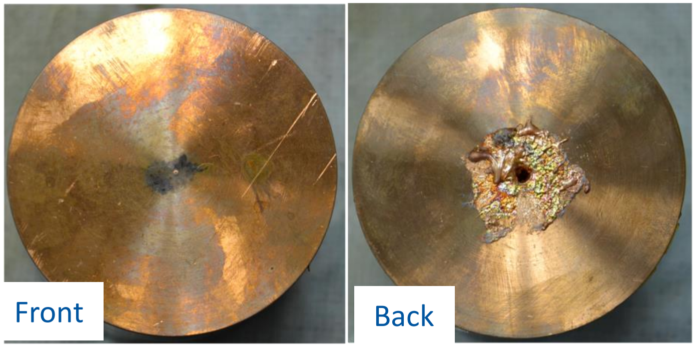


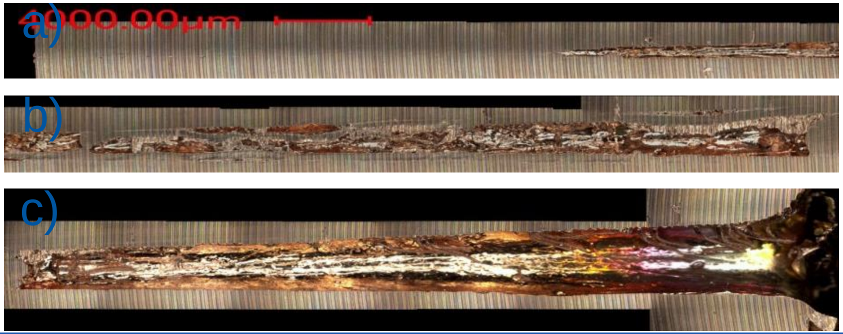


Target 3
440GeV/c
144b
s = 0.2mm

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 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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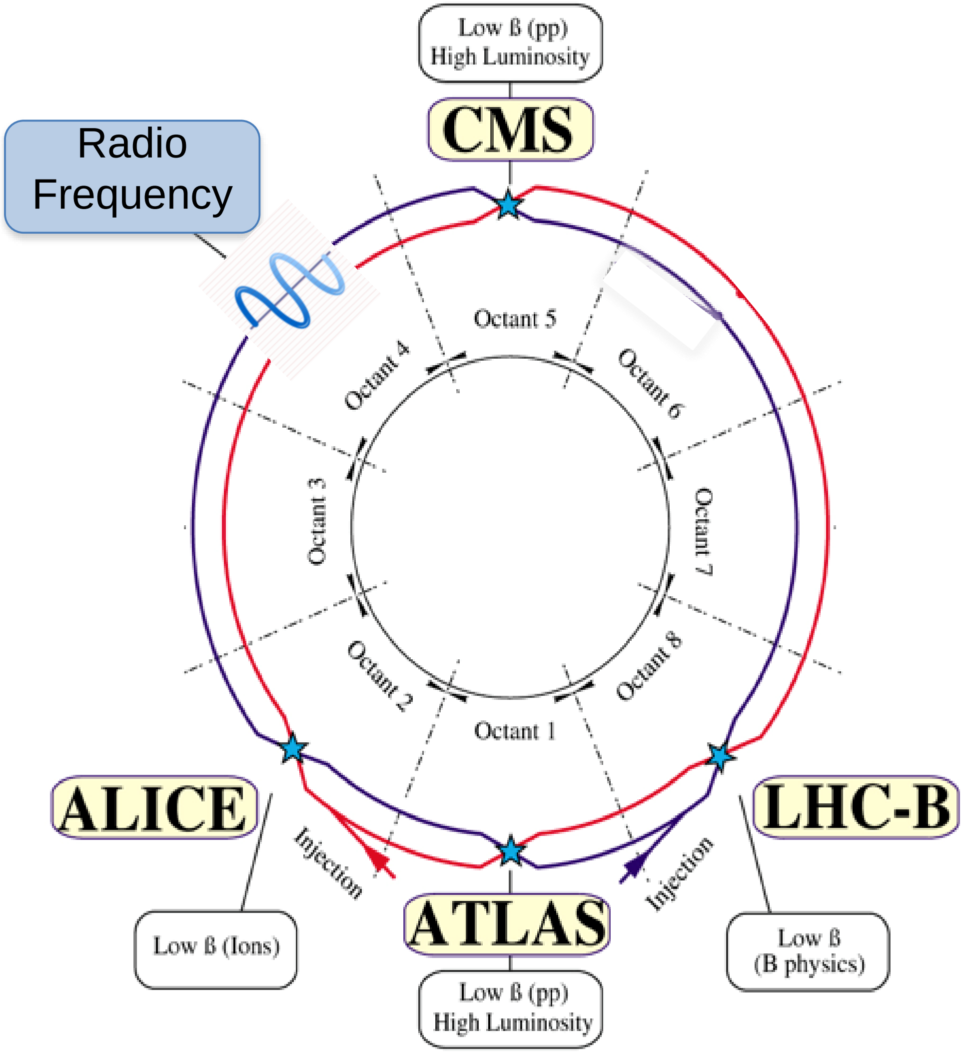
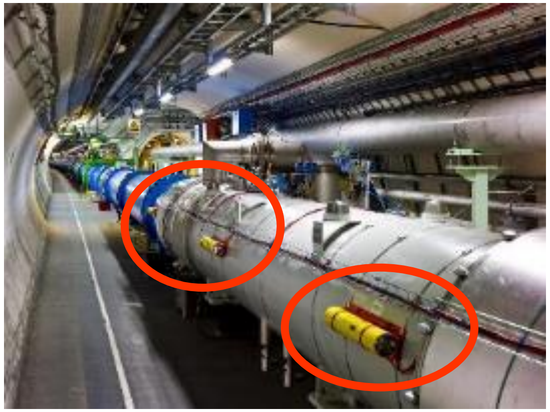
LHC and its Design Parameters

	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}

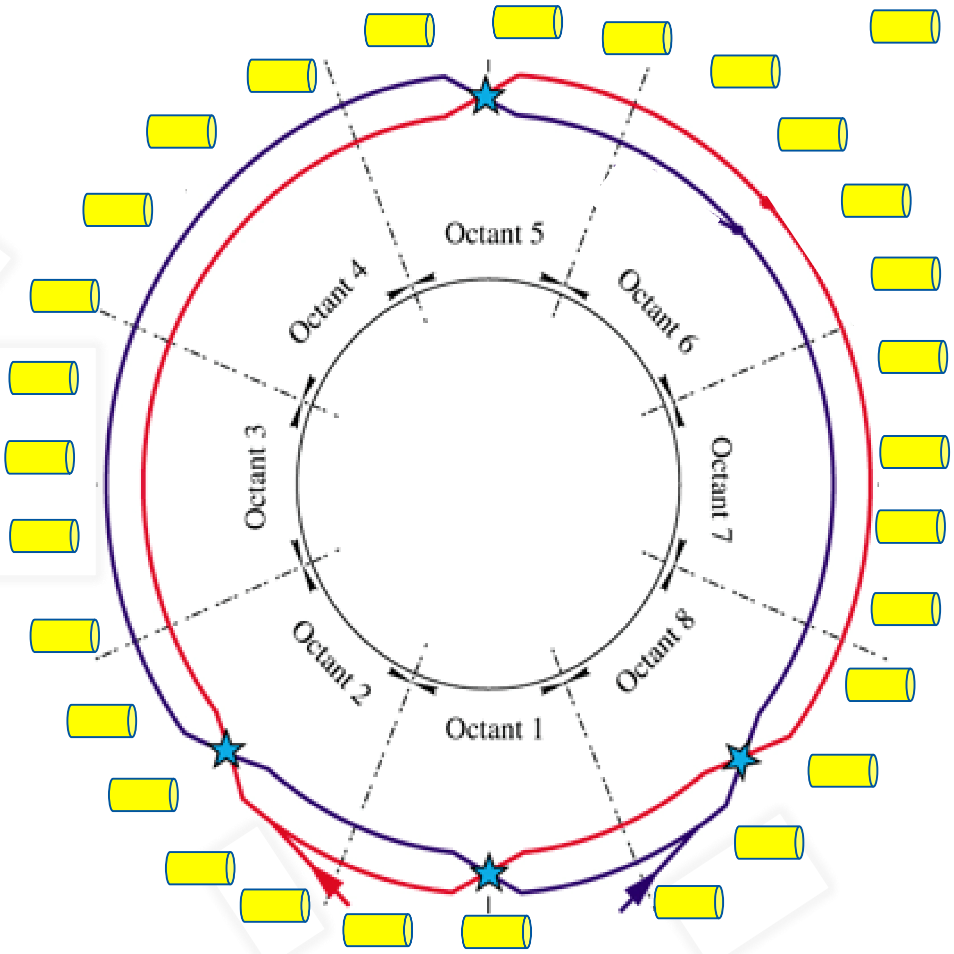


LHC Design Parameters

- 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 !

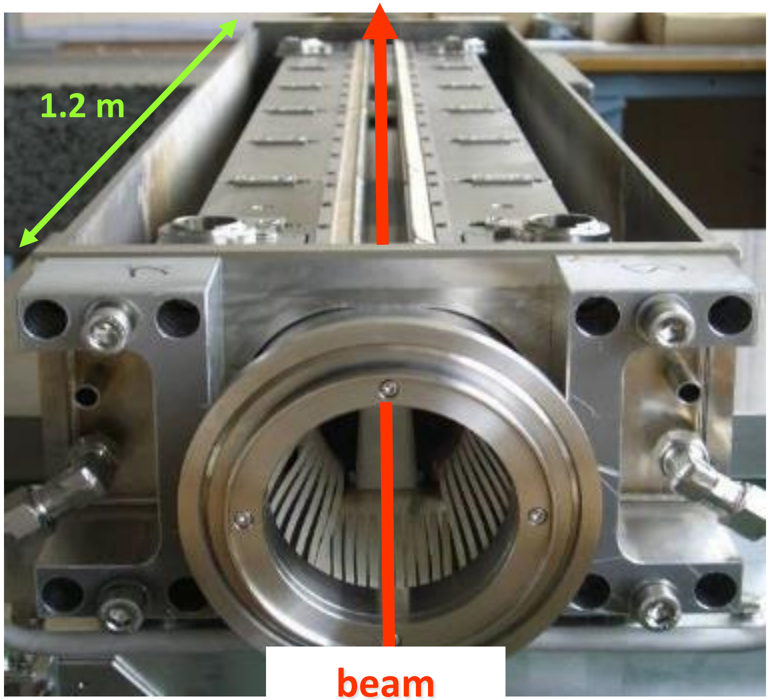


3600 x



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.*

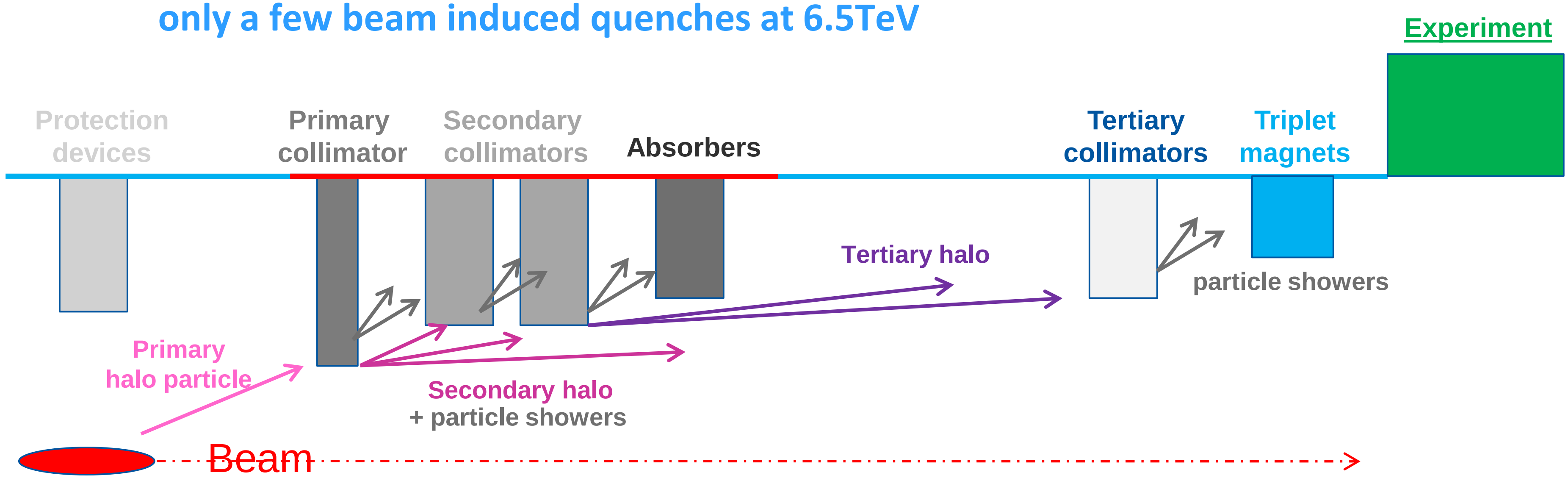


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

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

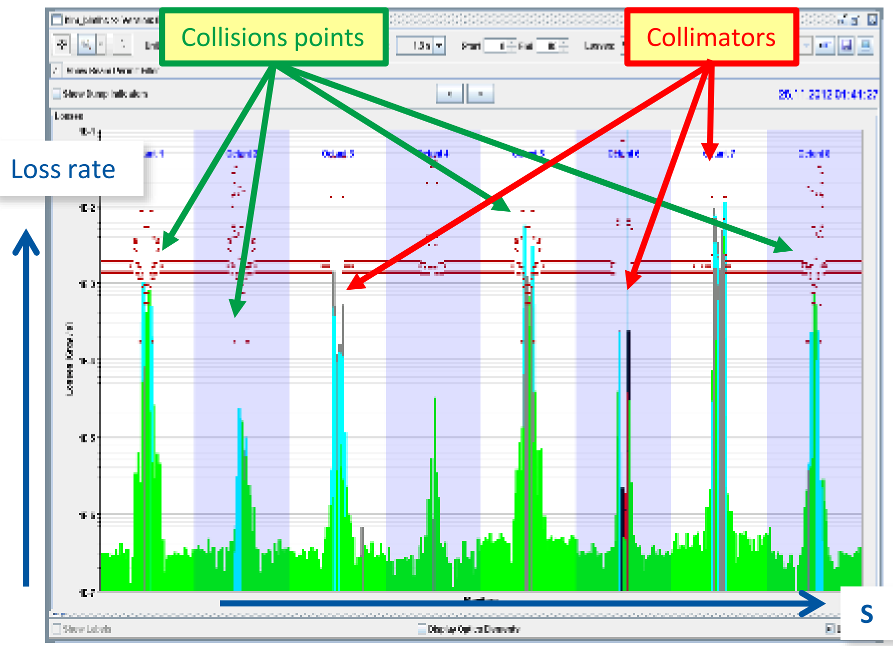
Collimation System

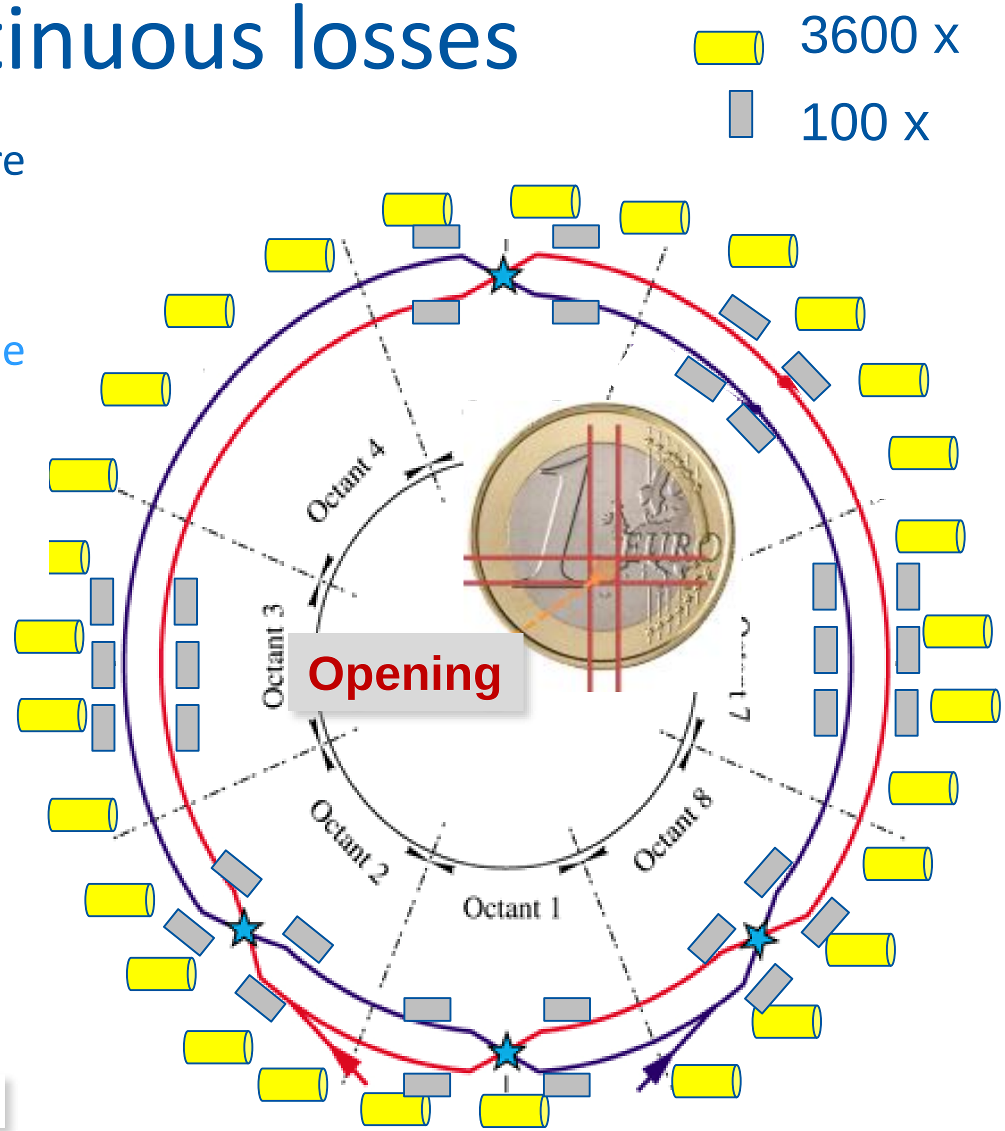
- To be able to absorb the energy of the (high energy) protons, the collimators are staged – primary, secondary, tertiary – multi-stage system.
- The system worked perfectly – also thanks to excellent beam stabilization and machine reproducibility – only one setup / year.
  - ~99.99% of the protons that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



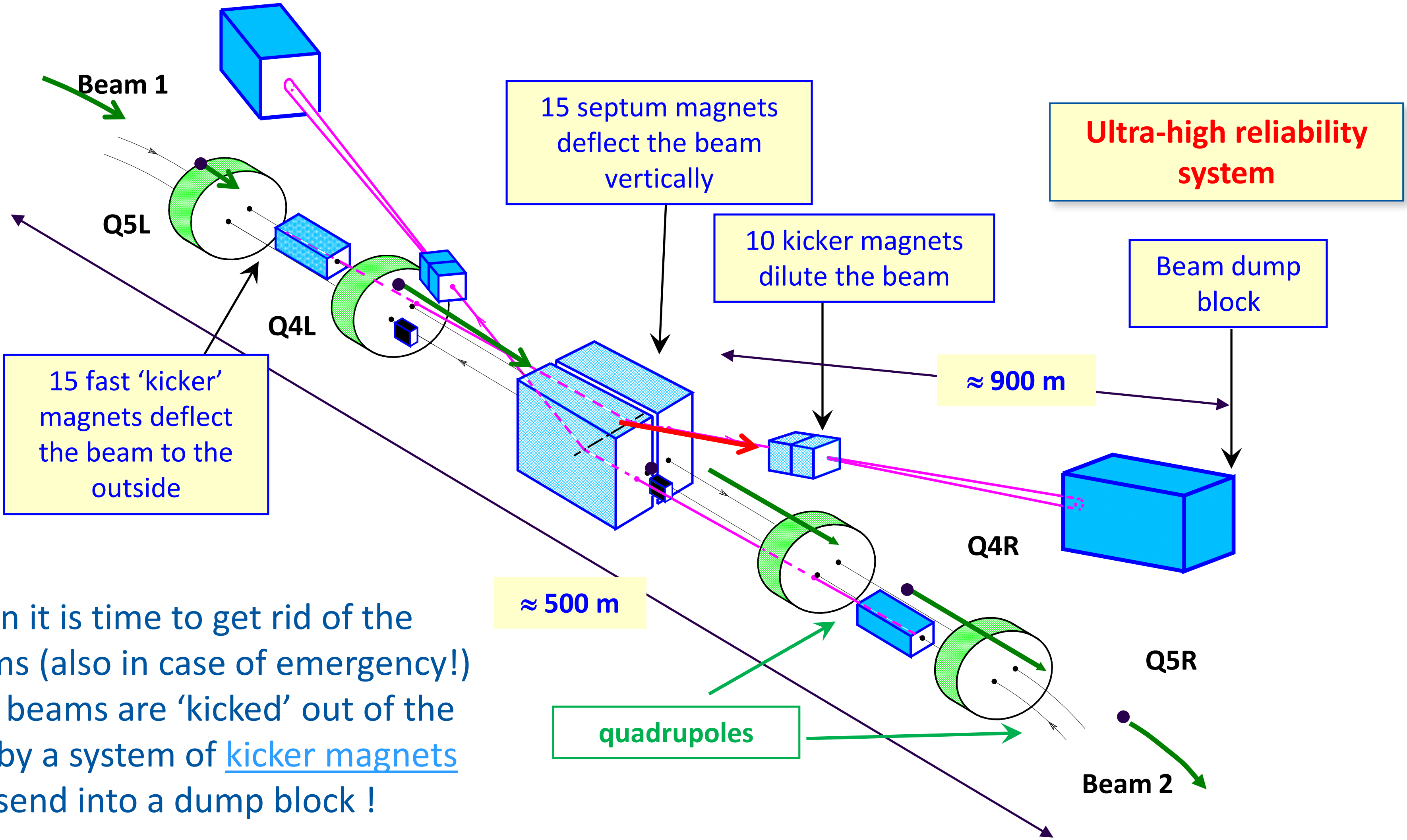
Collimators and continuous losses

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





LHC beam dumping system

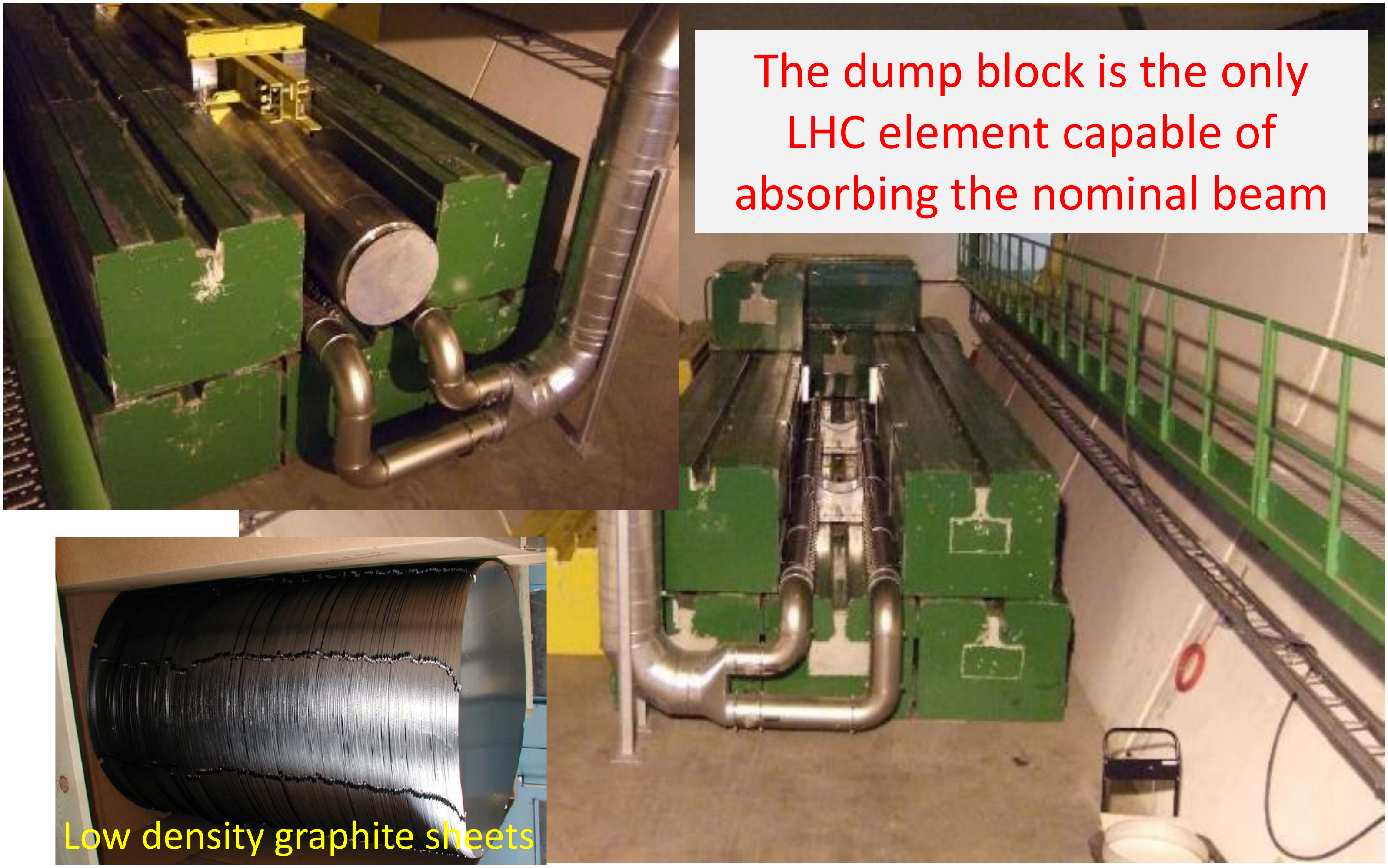


When it is time to get rid of the beams (also in case of emergency!) , the beams are 'kicked' out of the ring by a system of kicker magnets and send into a dump block !

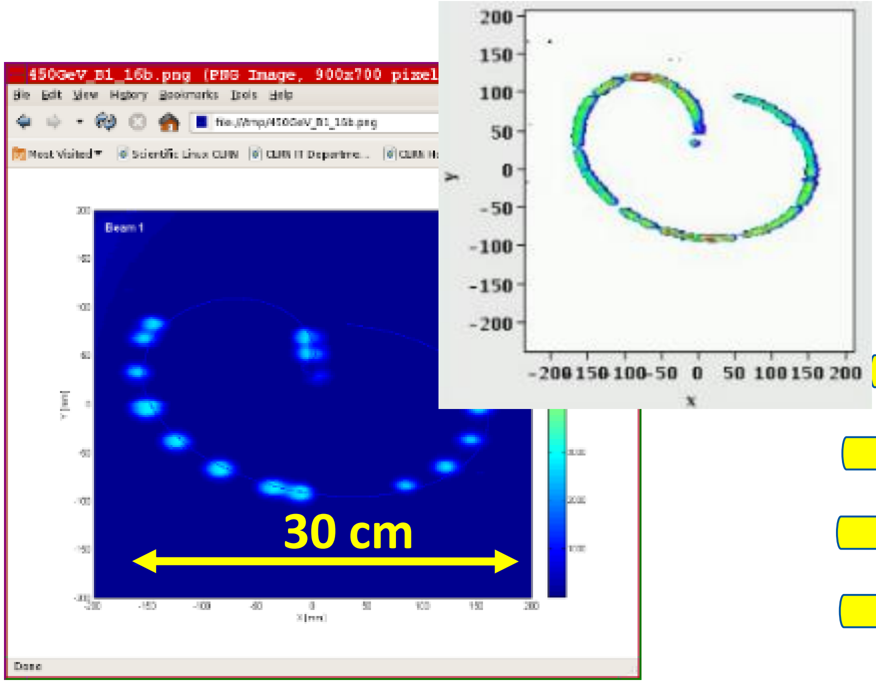
LHC dump line

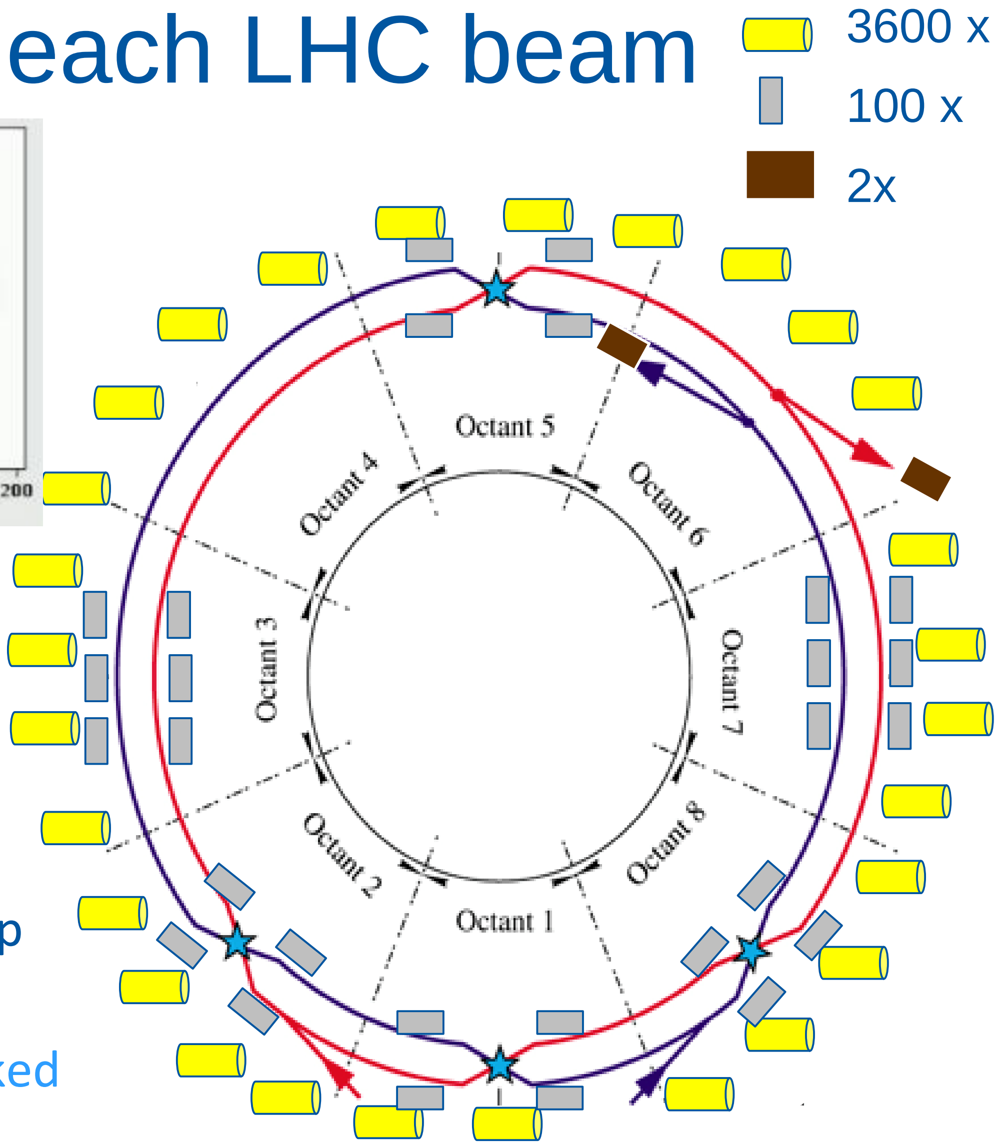
LHC dump block

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 !

Failure analysis process – step 1

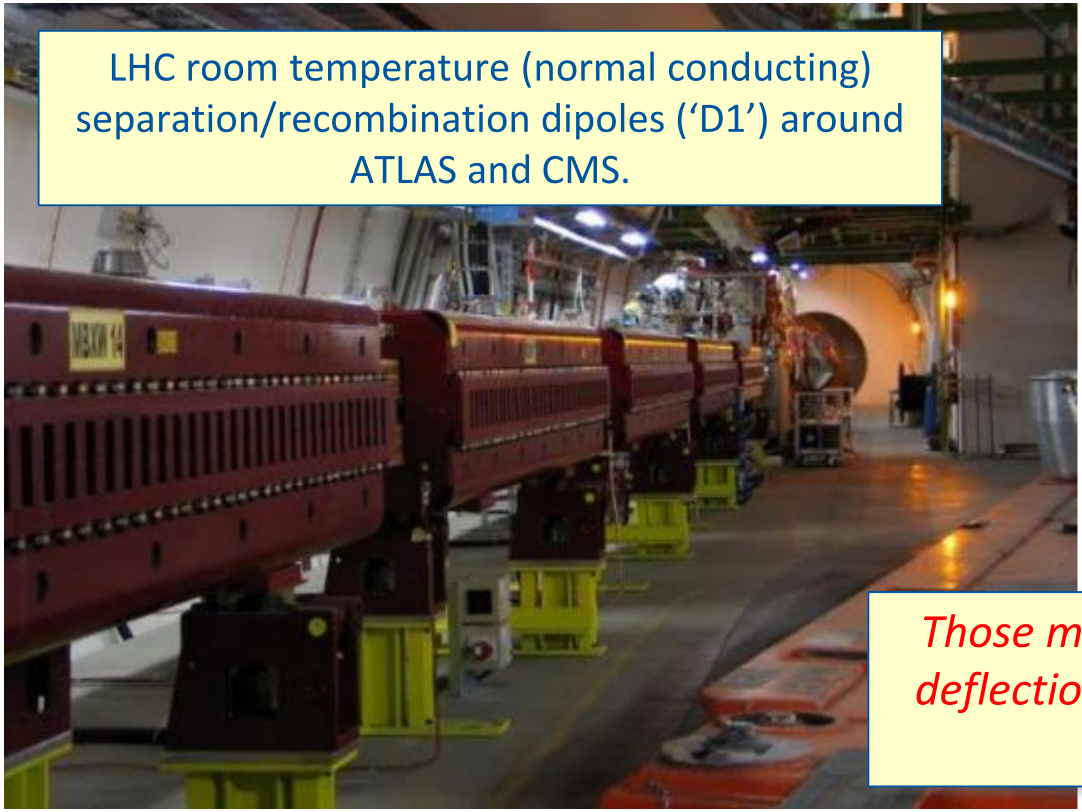
Let us pick an example for the LHC

- 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

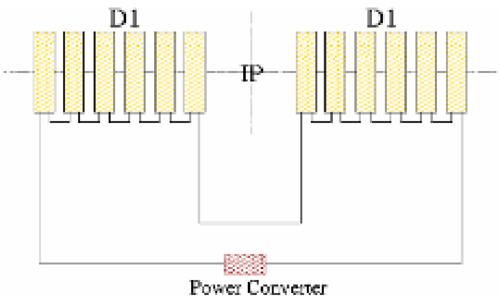
- Step 2: Identify a critical element – the D1's (separation/re-combination dipoles around the high luminosity experiments)

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



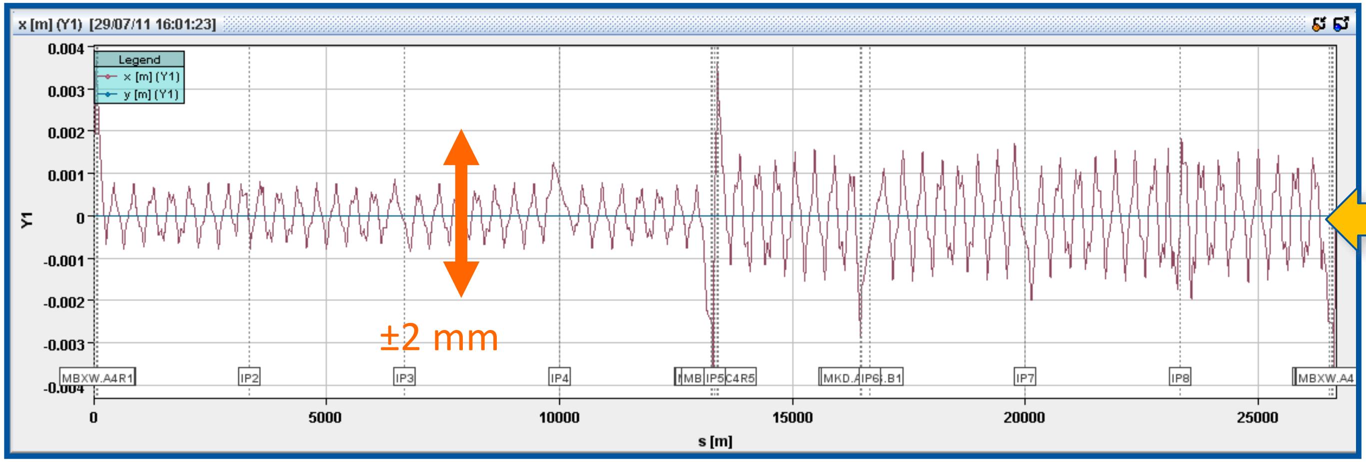
Those magnets are very strong (large deflections) and they are fast –> good candidates

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

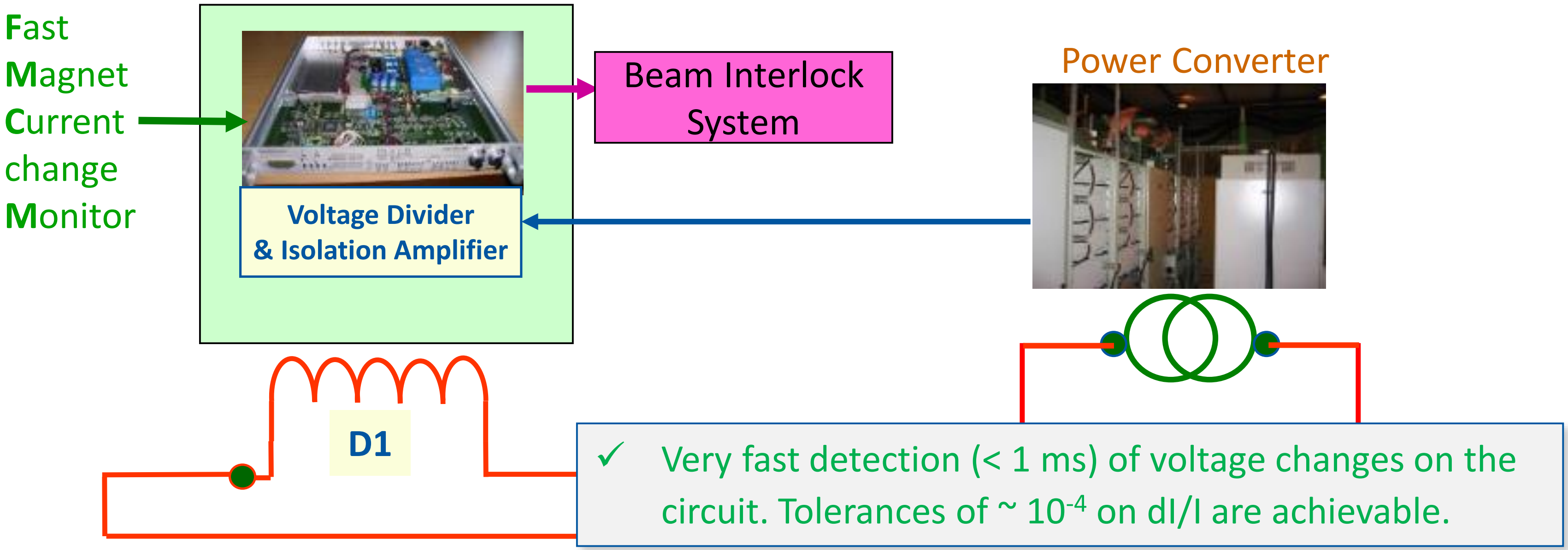
Simulated orbit change along the LHC ring a few **milliseconds** after failure.



It does not fit !

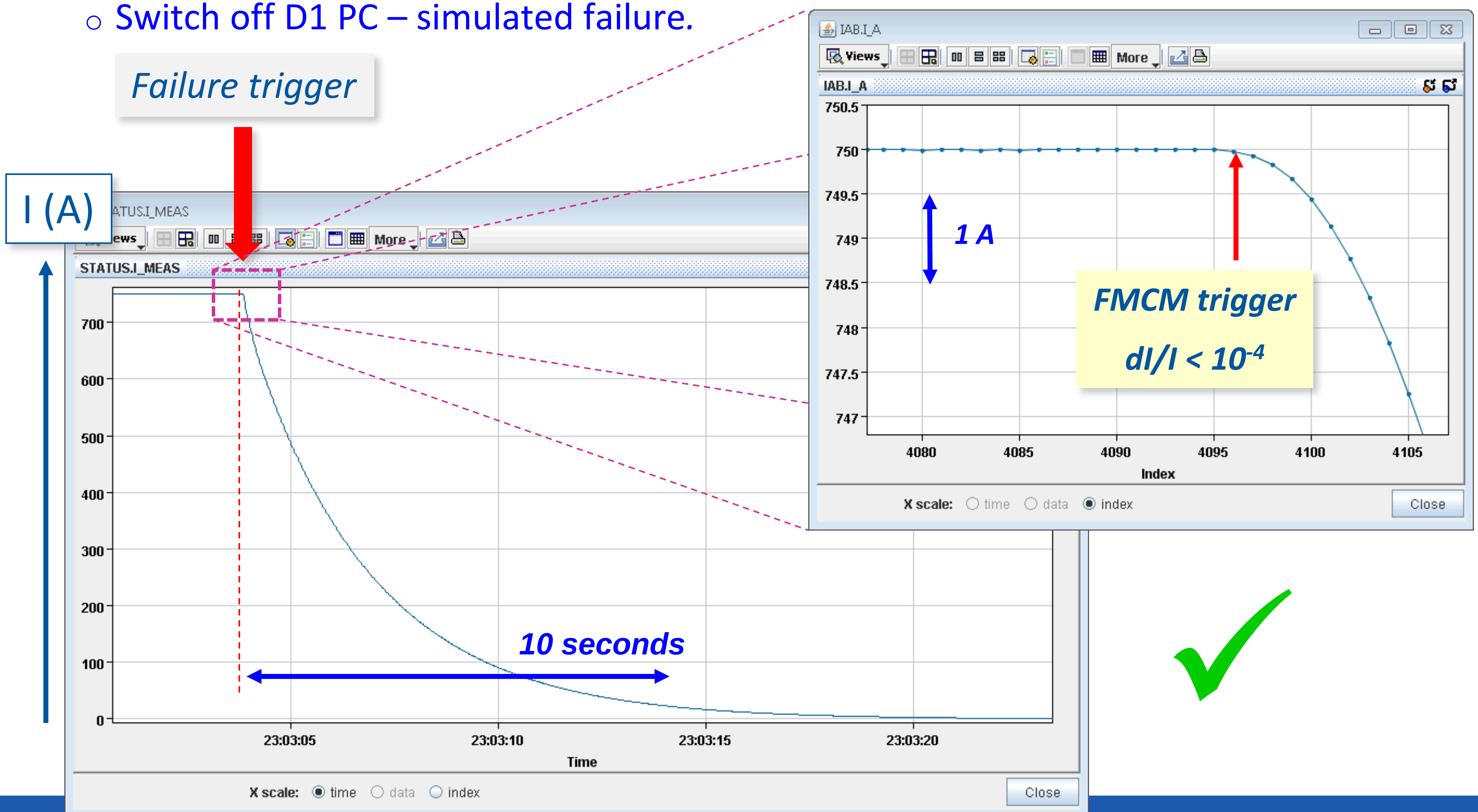
Failure analysis process – step 4

- *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.



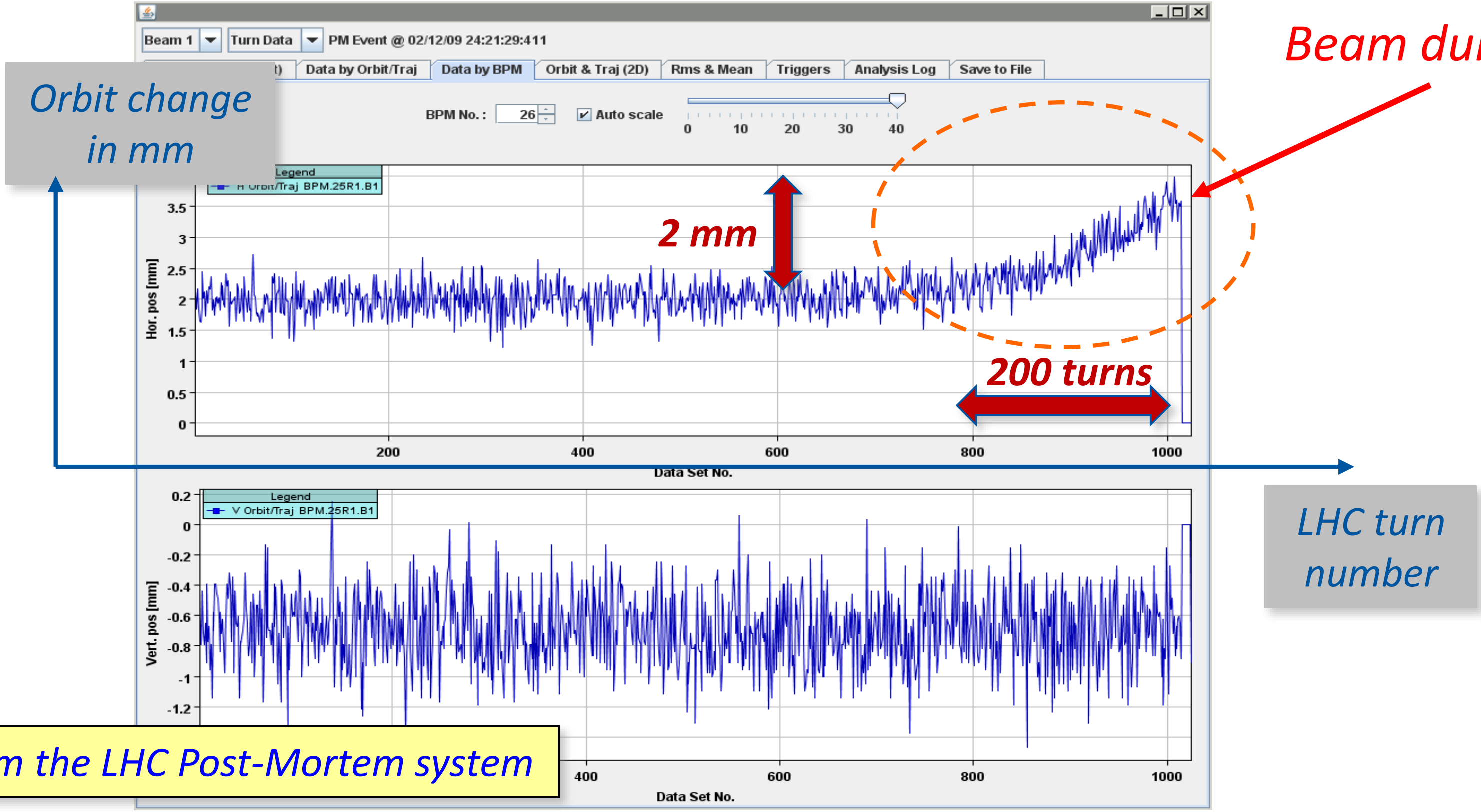
Failure analysis process – step 5

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



Failure analysis process – step 6

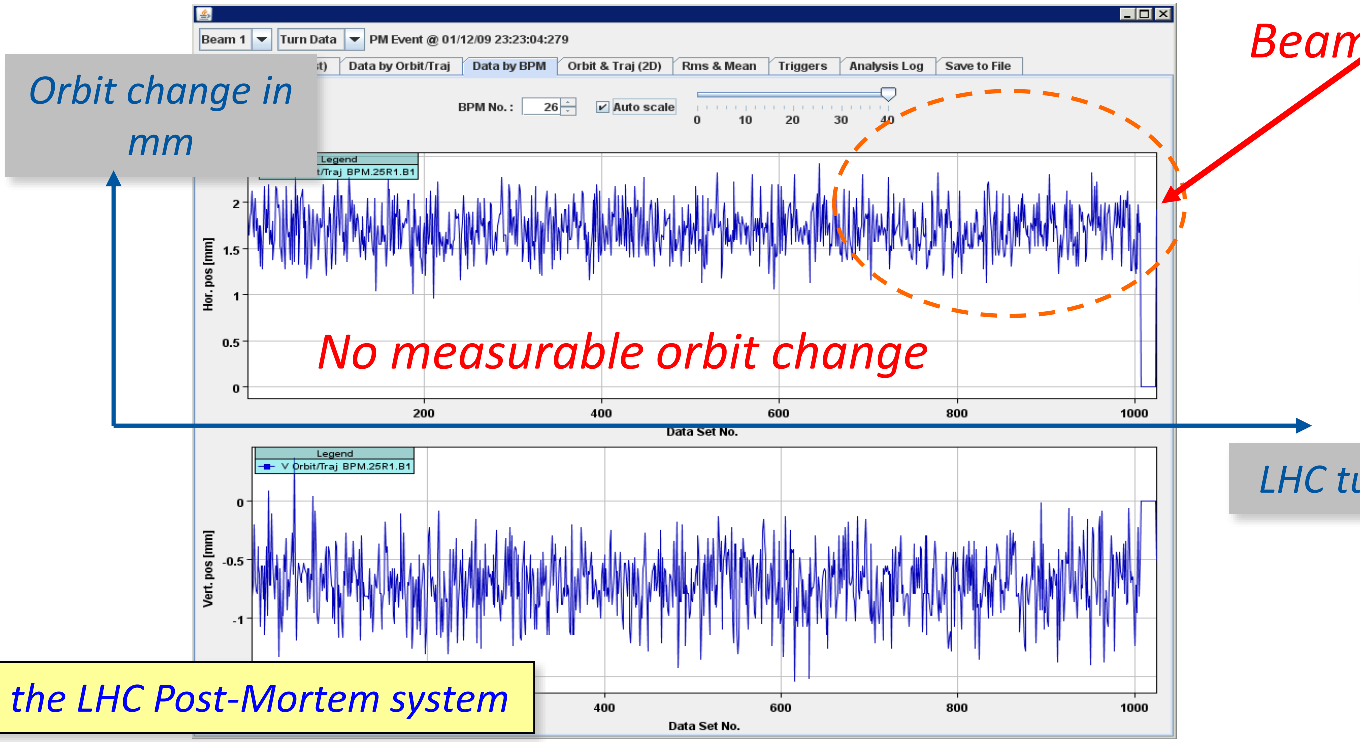
- Step 6: Real test with beam – no FMCM
  - Low intensity ('safe') test beam.
  - Switch off D1 PC – simulated failure.
  - Beams dumped by the LHC BLMs when beams hit the collimators



From the LHC Post-Mortem system

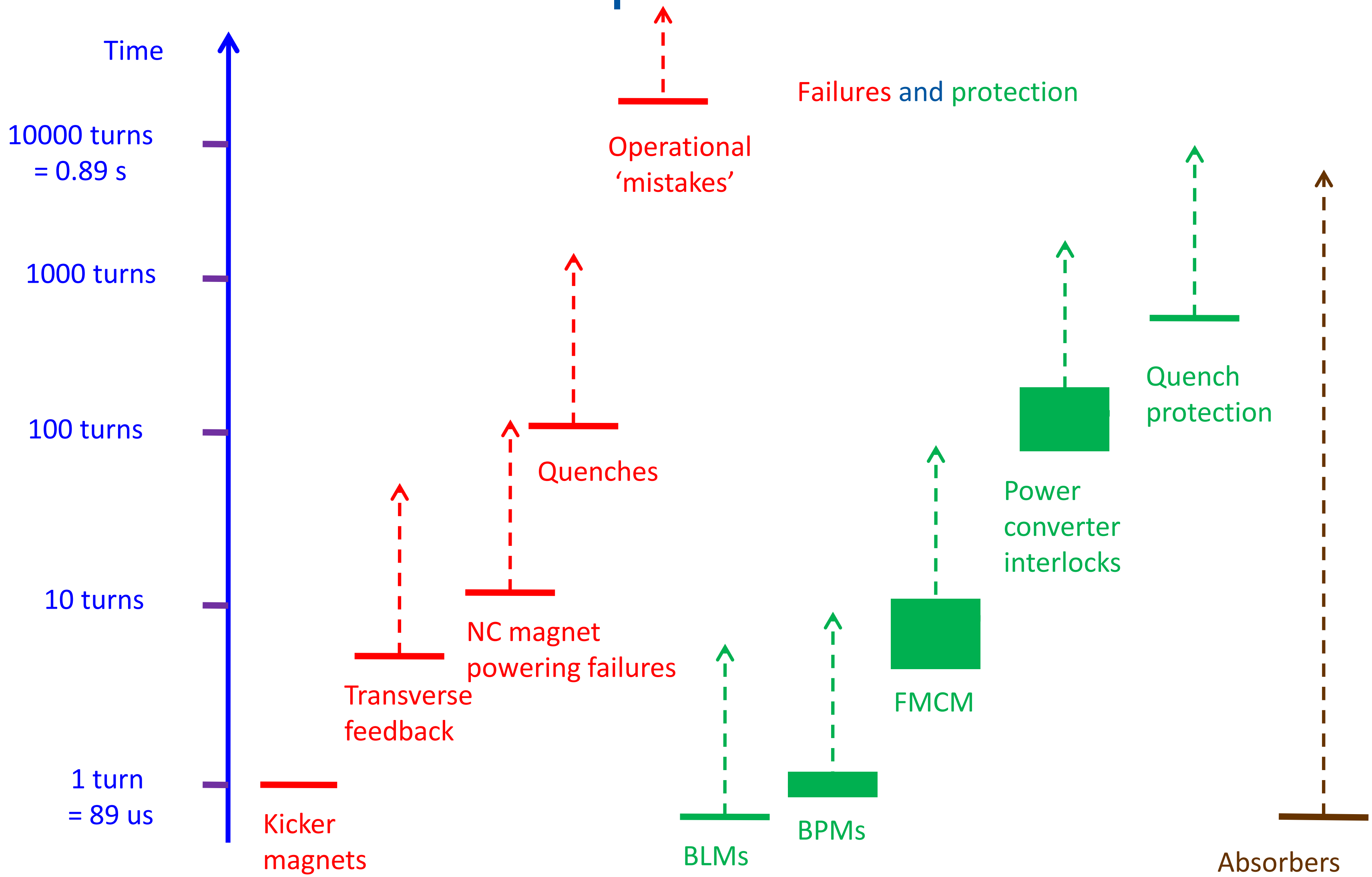
Failure analysis process – step 7

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



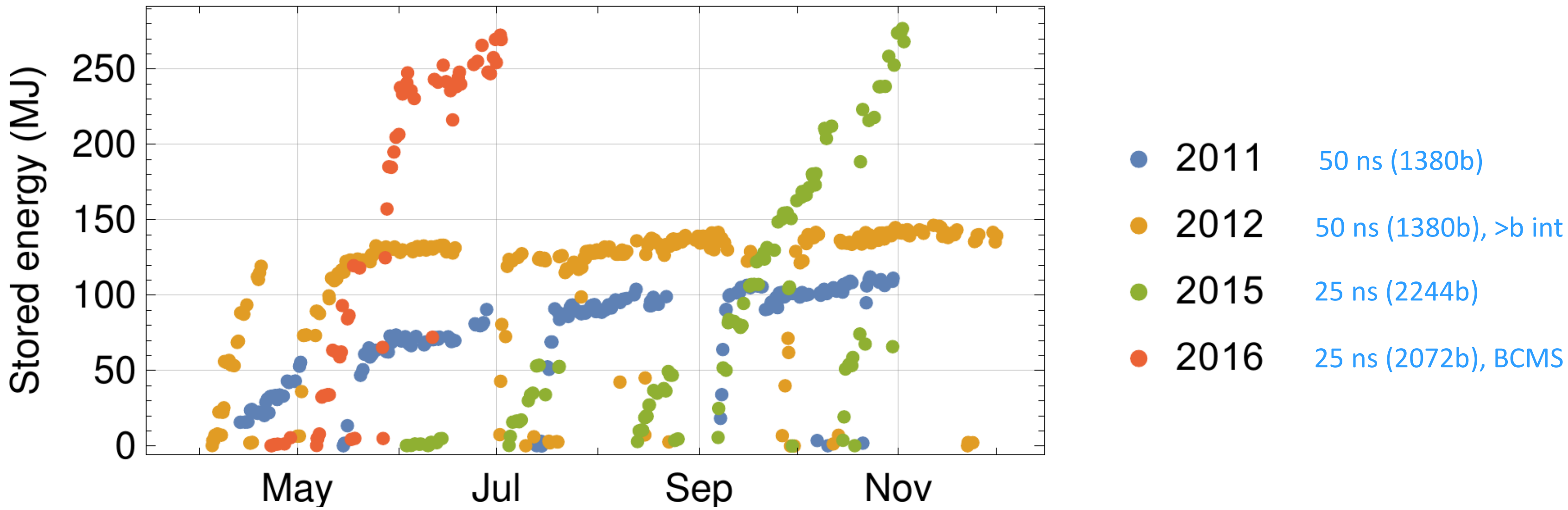
From the LHC Post-Mortem system

Failure timescales + protection at the LHC

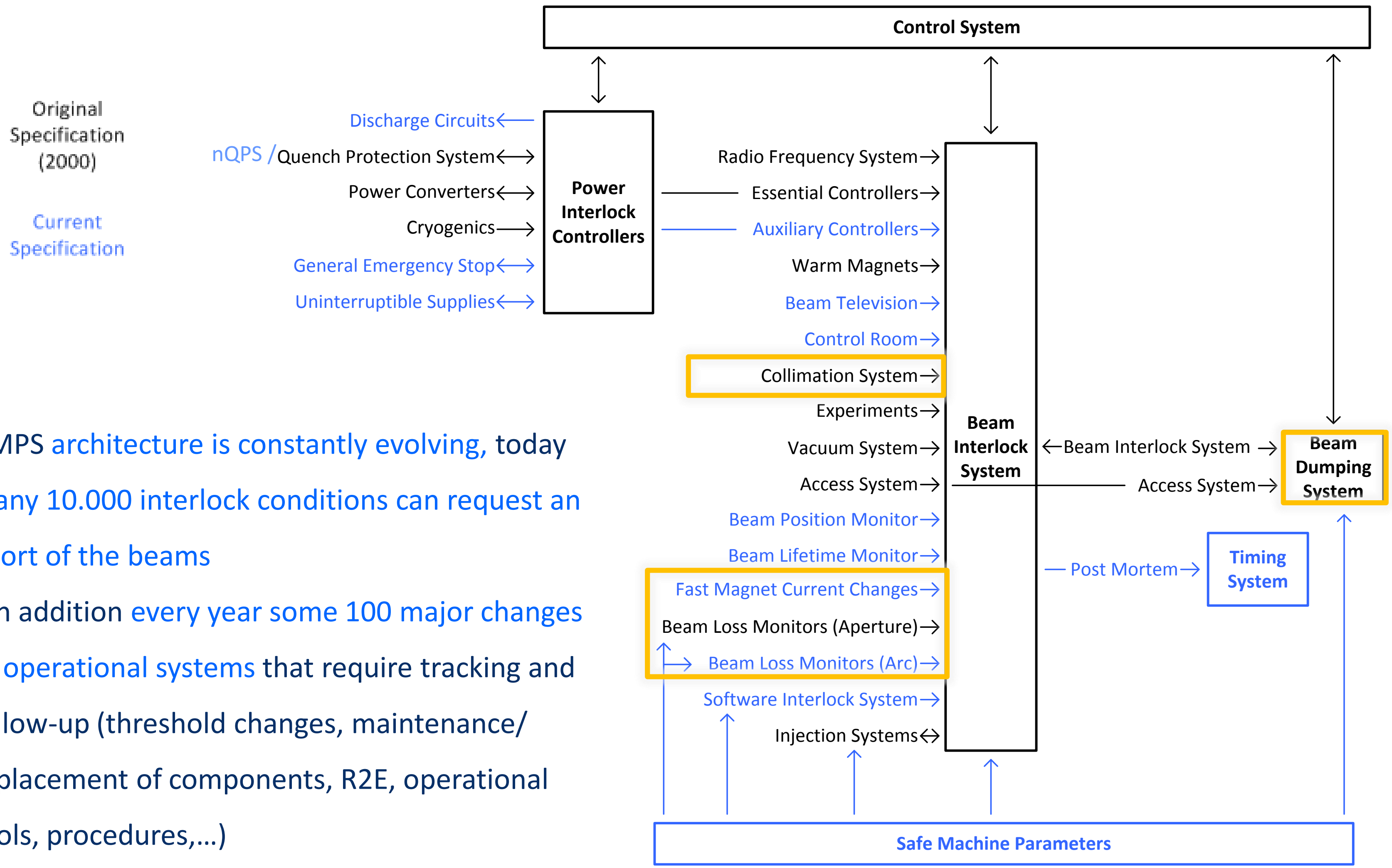


Learning curve

- It took more than a year of commissioning and tuning (e.g. BLM thresholds) to reach the maximum intensity at 3.5/4 TeV /6.5TeV
- 'Only' in the second half of 2015 and after the splice consolidation during the first long shut-down we approached design energies
- Design luminosity of 1E34 cm-2s-2 exceeded during 2016 operation



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,…)

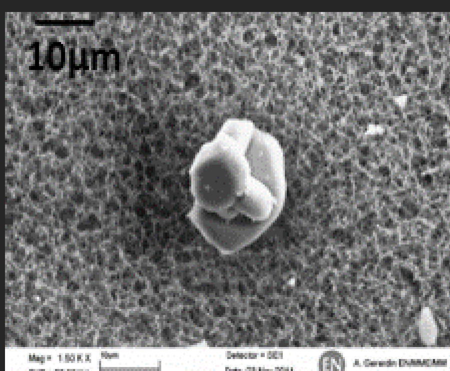
Outline

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

The less expected… 1/4

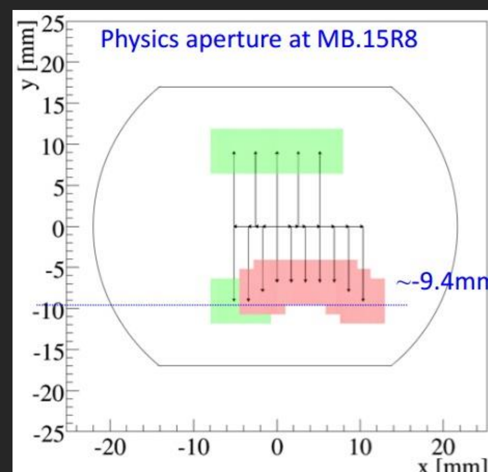
UFO

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



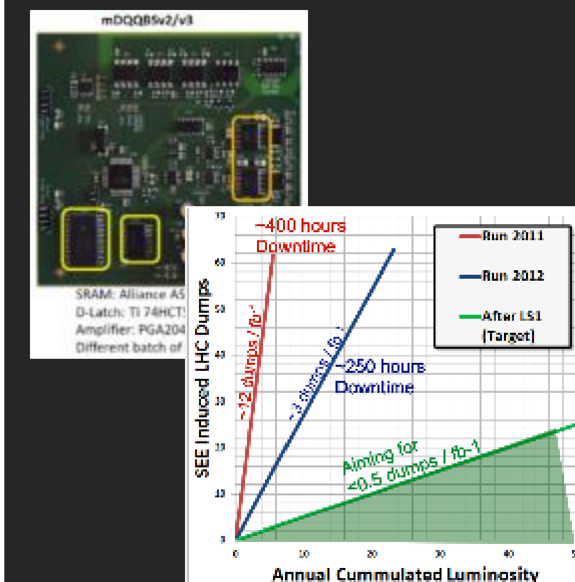
ULO (Unidentified Lying Object)

- 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… 2/4

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

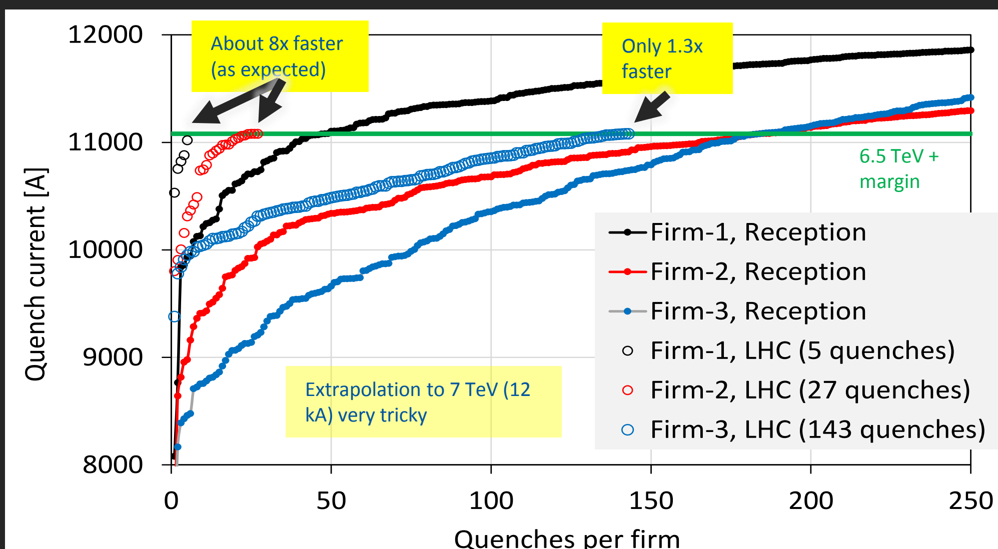
SPS BEAM DUMP

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

The less expected… 3/4

Magnet Training to 7TeV

- Magnets from firm 3 are very slow (re-)trainers / small preservation of memory
- Compatible with scenario where at each warm-up we have to re-start as for previous training
- Strategy to limit mechanical and electrical stresses during quench training campaigns



Best estimate for 7 TeV (first q. only)

sector	1000	2000	3000	total
12	3	19	7	28
23	3	12	30	44
34	2	16	22	40
45	2	9	62	73
56	1	8	63	73
67	3	7	46	56
78	3	24	46	72
81	3	5	50	58
LHC	20	100	325	445

Done	to do
7	21
17	27
15	25
49	24
16	57
20	36
21	51
28	30
173	272

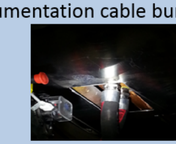
The less expected… 4/4

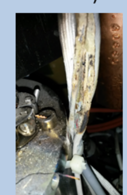
Magnet Circuits and earth faults

- Several earth faults to ground (cold and warm part) during commissioning and operation
- 1 week of downtime due to short in dipole circuit of sector 34
- August 2016 spent 2 days investigating
- and mitigating potential inter-turn short

Commissioning

- RB.A56
  - 2 intermittent earth faults during CSCM – disappeared
  - 1 intermittent earth fault after training – disappeared
- RB.A34
  - Active water coupling nut vs. grounded surface on surrounding infrastructure
- RQF.A12
  - Active water coupling nut vs. grounded surface on surrounding infrastructure
- RB.A34
  - Diode pot saga ("to burn or not to burn")
- RQX.L1
  - Instrumentation cable burnt





Beam operation

- RB.A78
  - 8 h LHC downtime on 8/7/2015
  - 5 h LHC downtime on 10/8/2015
  - 19 h LHC downtime on 11/8/2015
  - Water coupling nut/ 2x earth detection card
- RQF.A78
  - 5 h LHC downtime on 13/10/2015
  - Water leak
- RCS.A78B2
  - 9 h LHC downtime on 18/7/2015
  - 10 min LHC downtime on 13/8/2015 (not incl. pre-cycle)
  - Under investigation

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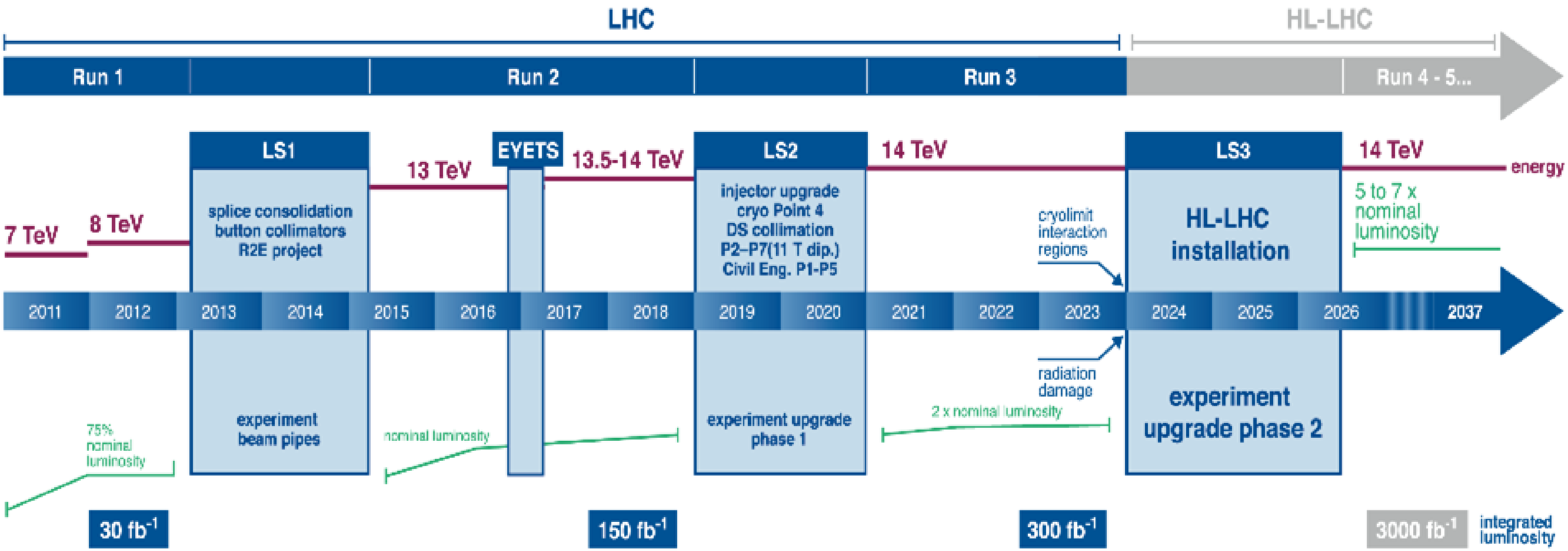
Summary

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

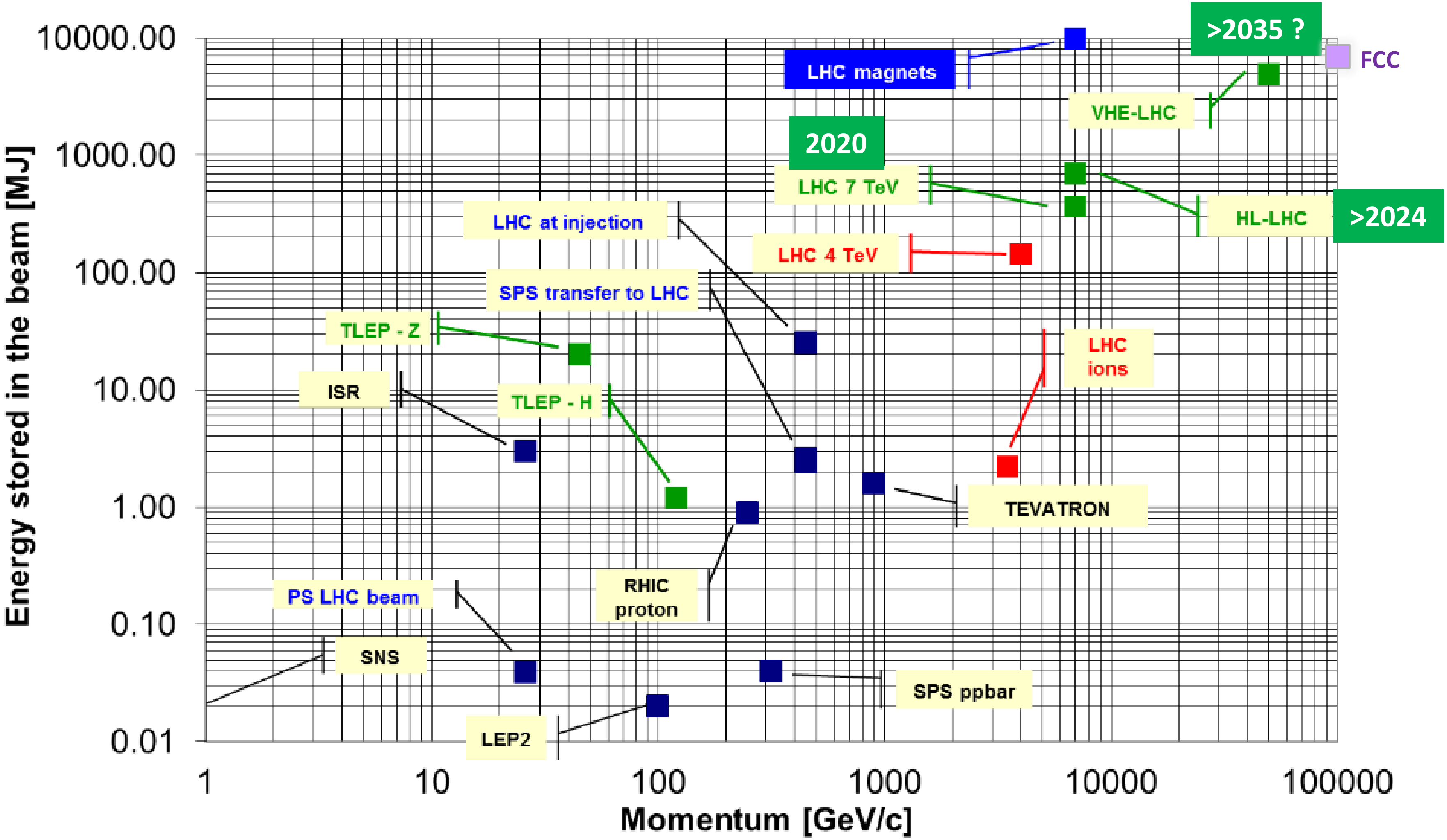


75ns / 50ns
1.5m -> 1m->0.6m

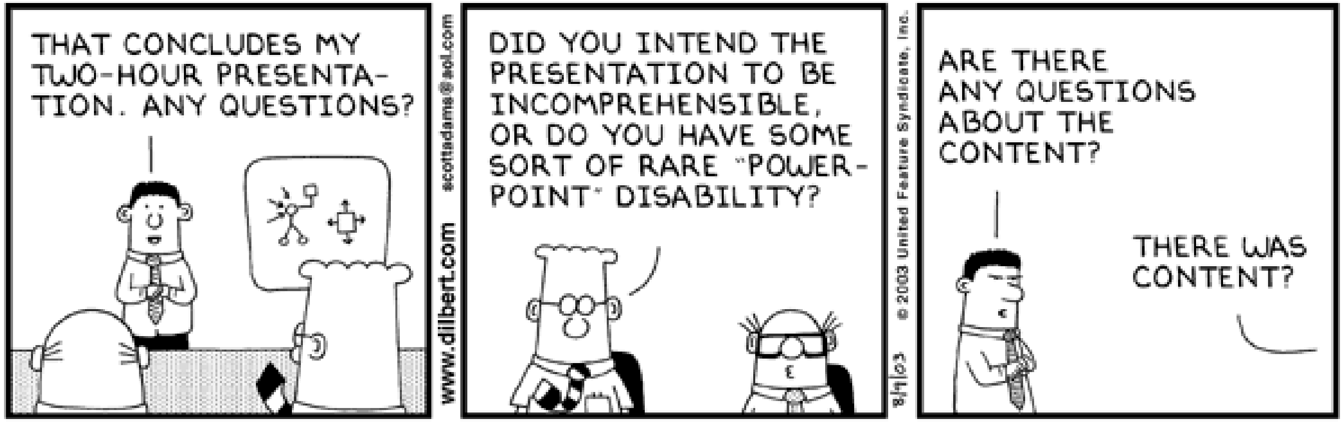
50ns / 25ns
0.8m -> 0.4m

- Excellent performance of LHC and its machine protection systems during first 5 years of commissioning and exploitation, allowing to exceed design luminosity (despite limitations)
- Injector upgrade and HL-LHC projects will imply as well new MP challenges

Stored energies- the future



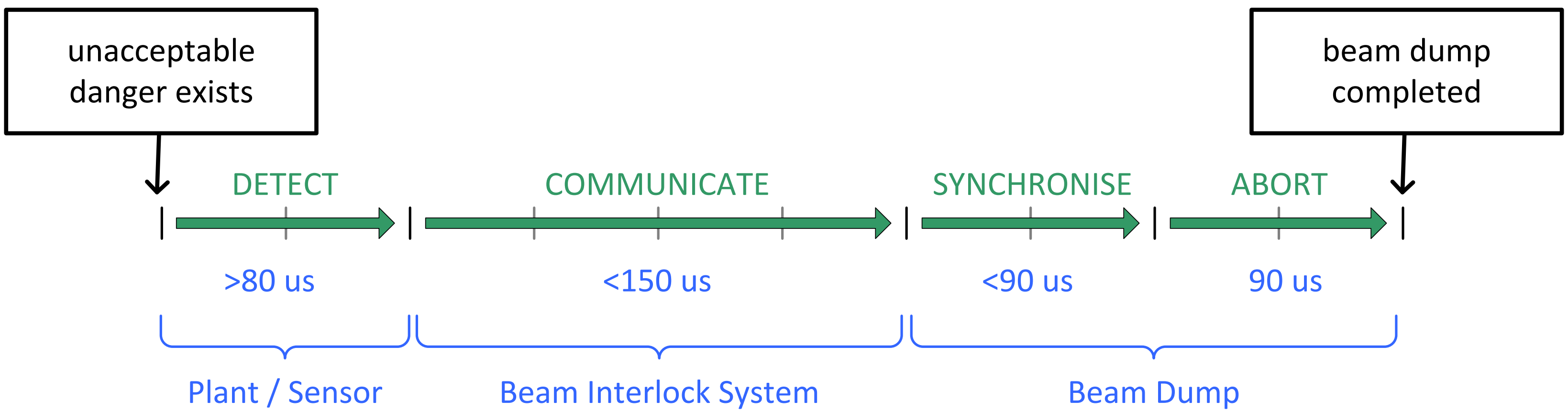
Thank you for your attention!
Questions ?



SPARE SLIDES

The beam is 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 !

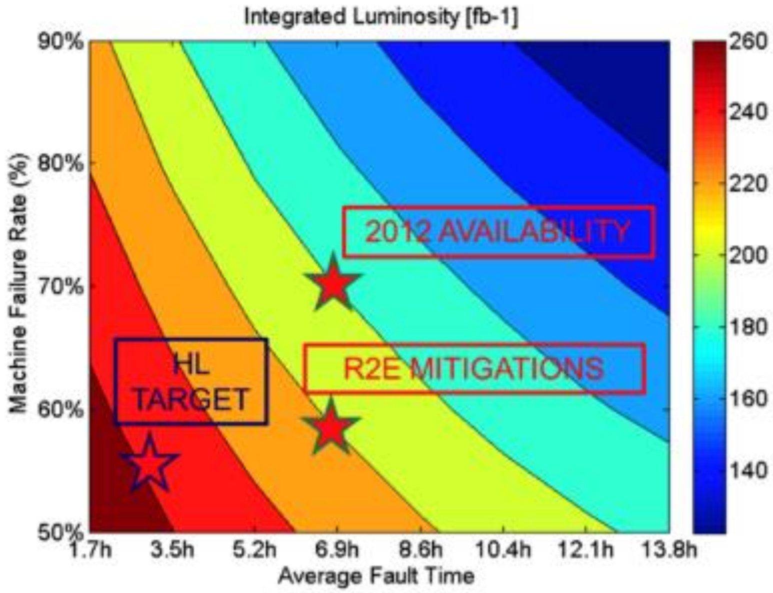


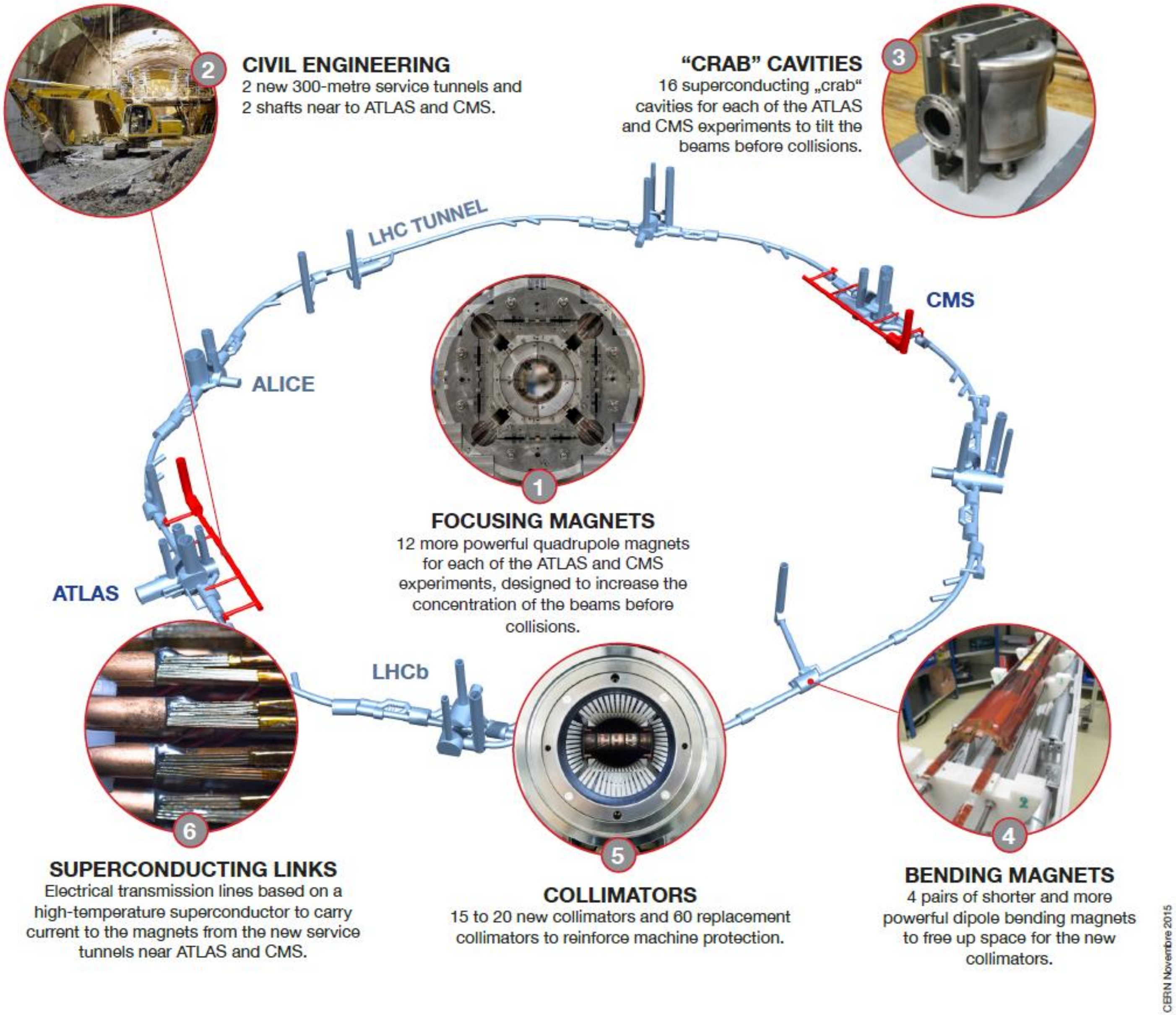
At the LHC the delay can be as much as ~3 turns – ~300 us

A few other challenges

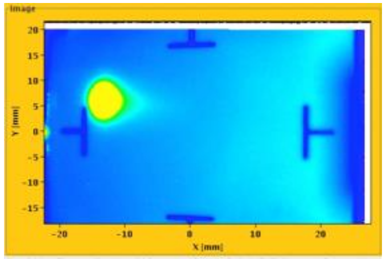
Very bright beams, very high bunch population, very high beam current

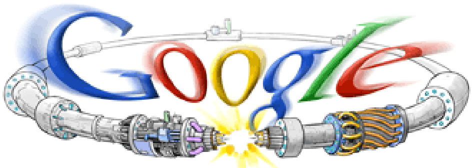
- Beam stability
  - New low impedance collimators
- Beam lifetime & loss spikes
  - Magnet quenches
- Machine protection
  - Failure scenarios - local beam impact - equipment damage
  - Quench protection
- Machine availability
  - Radiation to electronics (SEUs etc.)…




CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.
"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.
LHC TUNNEL
CMS
ALICE
FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.
ATLAS
LHCb
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.
COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.
BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.
1
2
3
4
5
6
CERN Novembre 2015
CERN

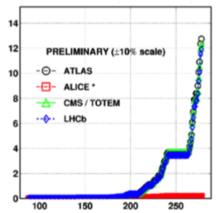
August 2008
First injection test



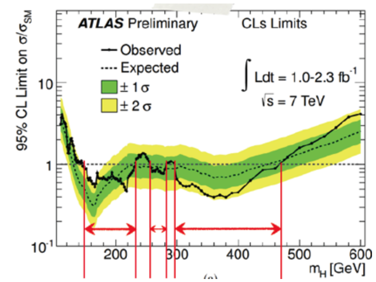


Sept. 10, 2008
First beams around

November 29, 2009
Beam back



October 14, 2010
L= $1x10^{+32}$
248 bunches

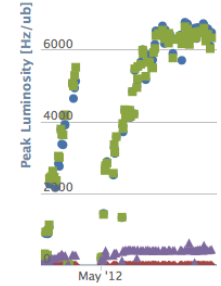


October, 2011
$3.5x10^{+33}$, 5.7 fb^{-1}

First Hints!!

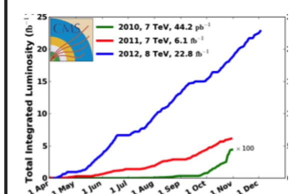
June 28 2011
1380 bunches

1380

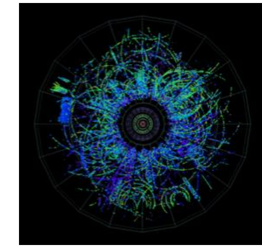


May 2012
Ramping
Performance

March 14th 2012
Restart
with Beam



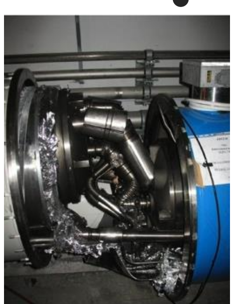
Nov. 2012
End of p^+ Run 1



Feb. 2013
p-Pb^{82+}
New Operation
Mode

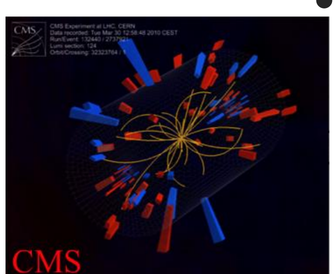
Repair and Consolidation

2008	2009	2010	2011	2012	2013

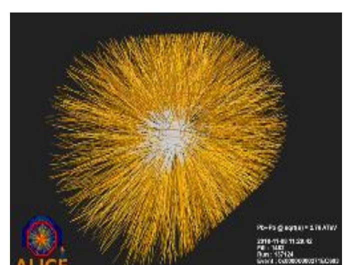


Sept. 19, 2008
Disaster

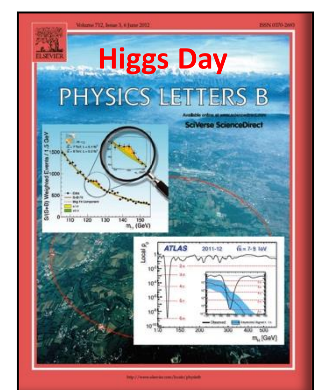
March 30, 2010
First collisions at 3.5 TeV



November 2010
Pb^{82+} Ions

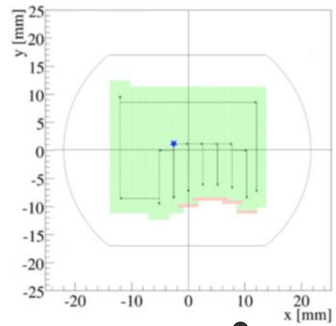


November 2011
Second Ion Run

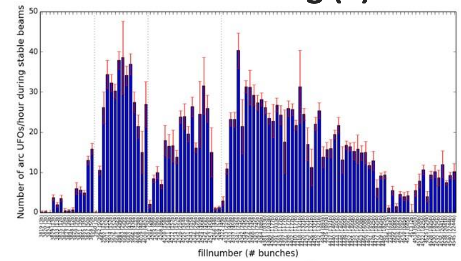


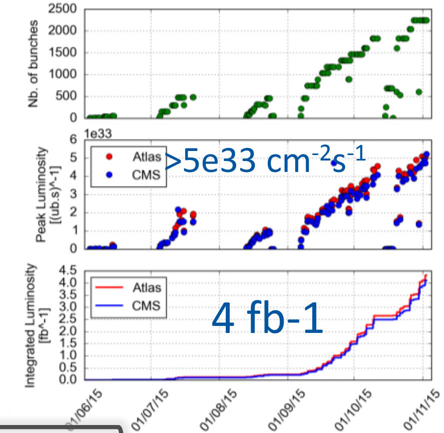
LS1

ULO in May



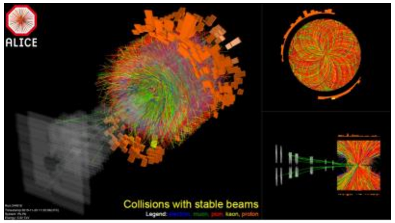
UFO conditioning (?)





3[rd] June – First SB

28[th] Oct.- SB with record N_b



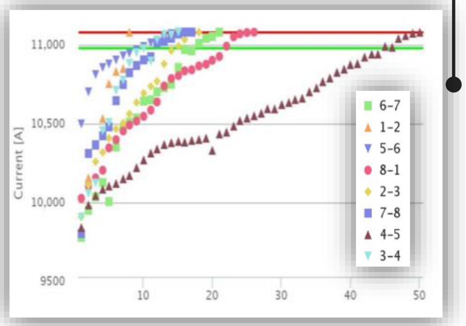
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

IONS at the end

5[th] April

Q3/2014-Apr2015	2015	2016

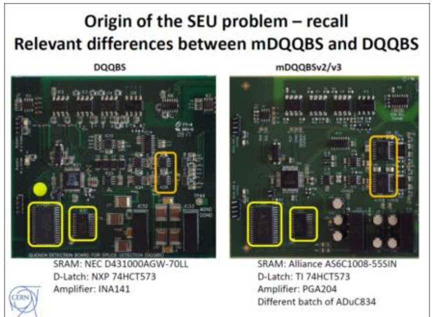
Dipole training campaign



10[th] April

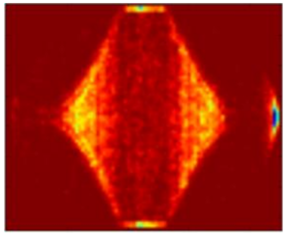
Beam at 6.5 TeV

July-August SEU on QPS



YETS

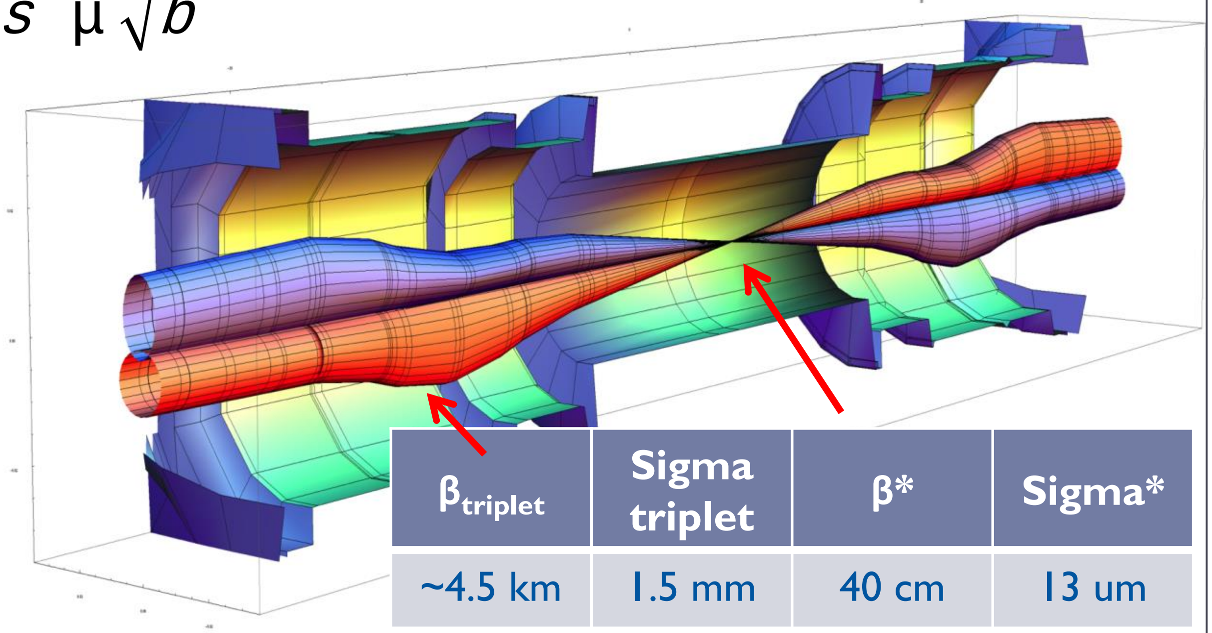
E- cloud



Squeeze in ATLAS/CMS

- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution – experience counts

$s^{*} \mu \sqrt{b^{*}}$

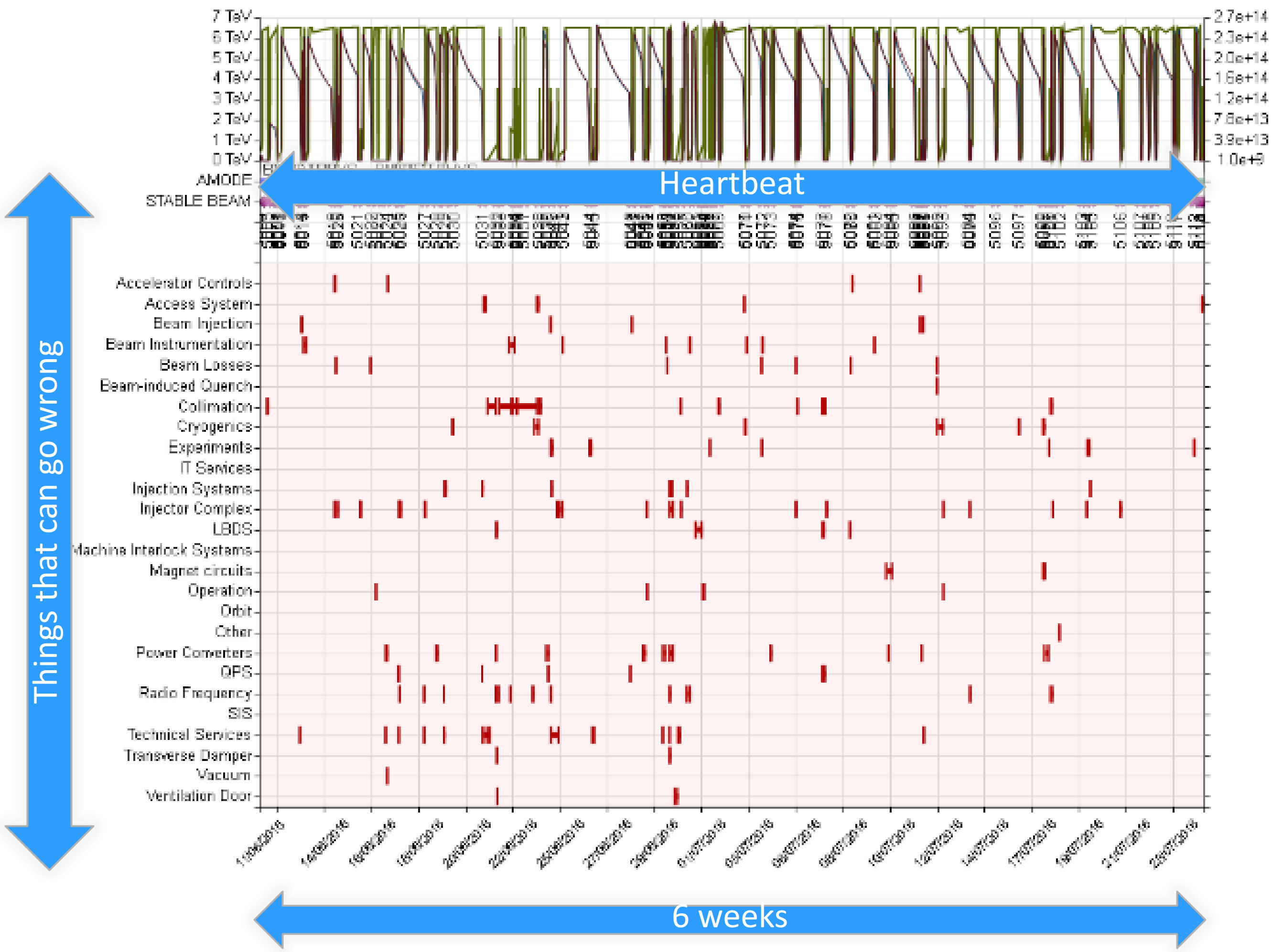


$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	40 cm	13 um

Beam envelope vs mechanical aperture in triplet and EXP

Image courtesy John Jowett

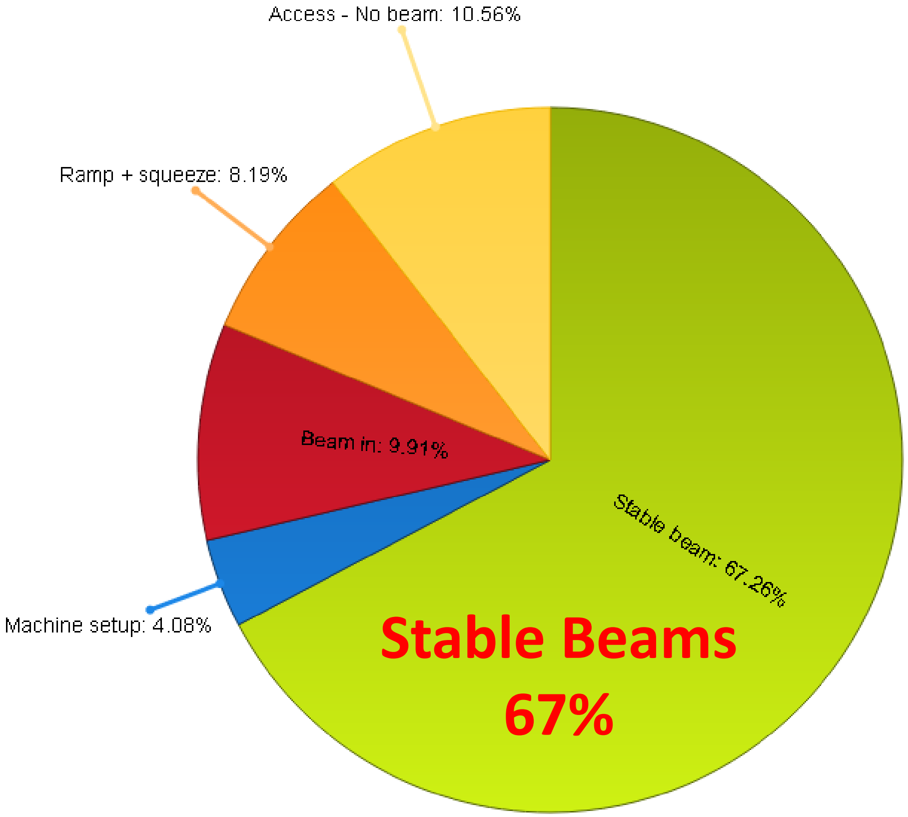
Then enjoy some remarkable availability

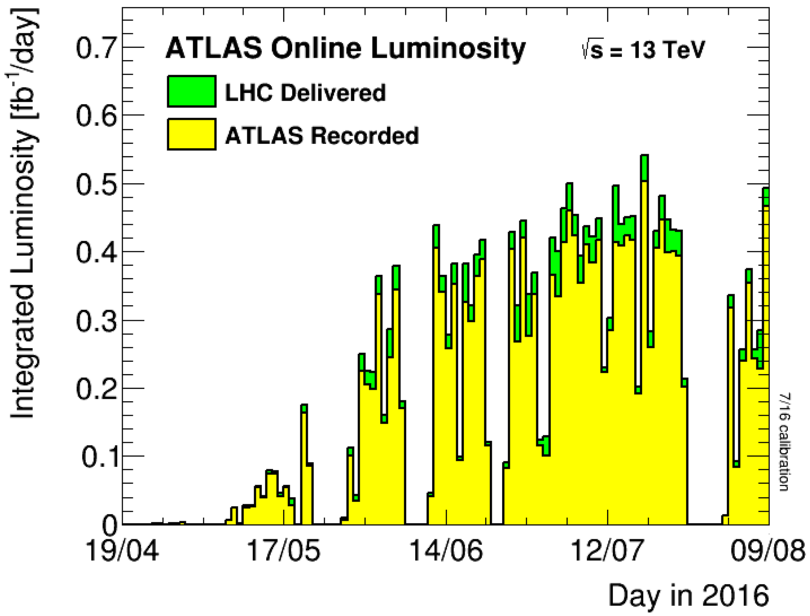


Introduced in Run2 a common metrics and tracking of LHC downtime and root causes
-> cern.ch/aft

Rigorous analysis and exploitation of data for availability optimization of individual subsystems

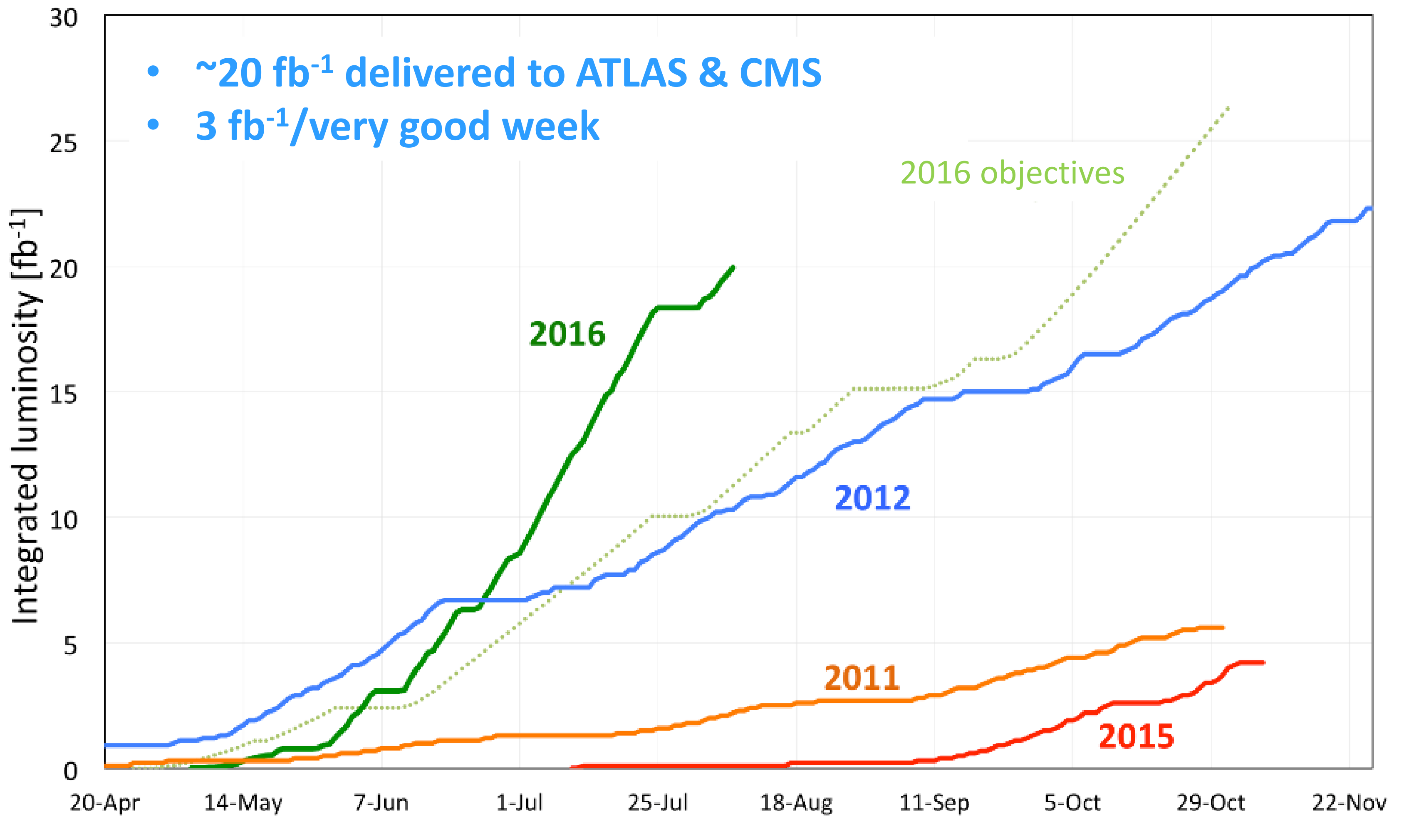
Availability: 11th June – 23rd July





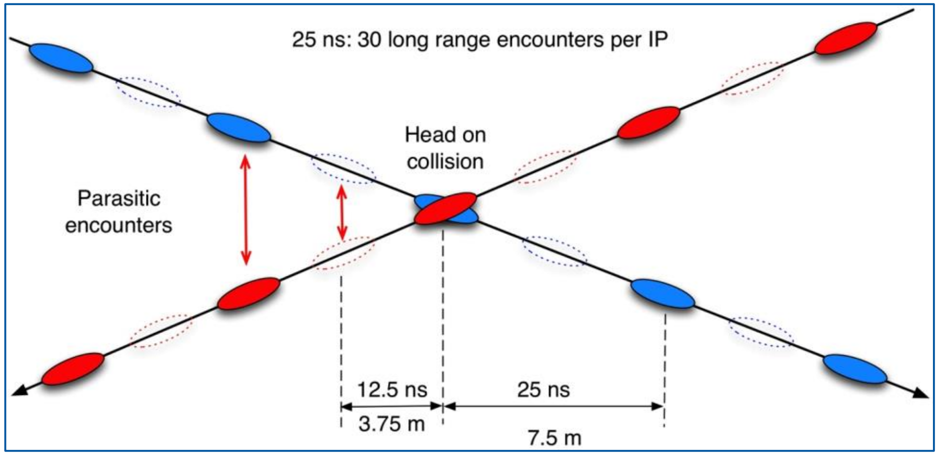
Many nice, long fills, collecting up to 0.5fb^{-1} in a single fill

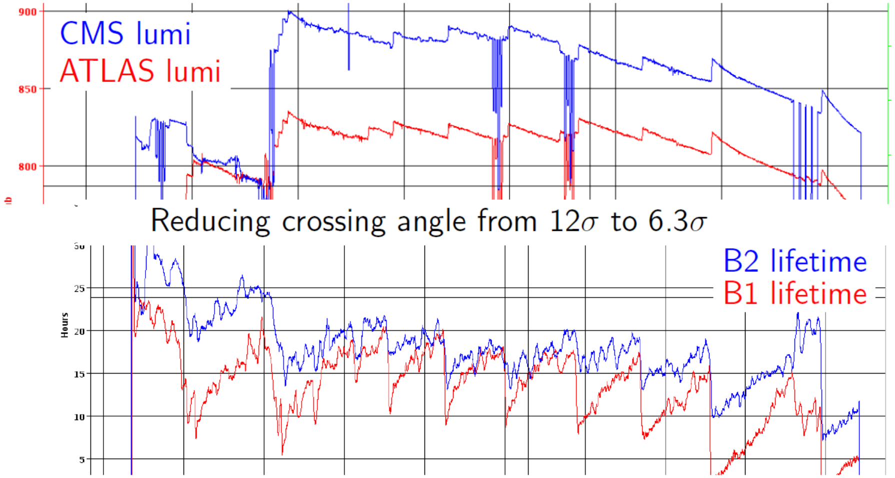
Integrated luminosity



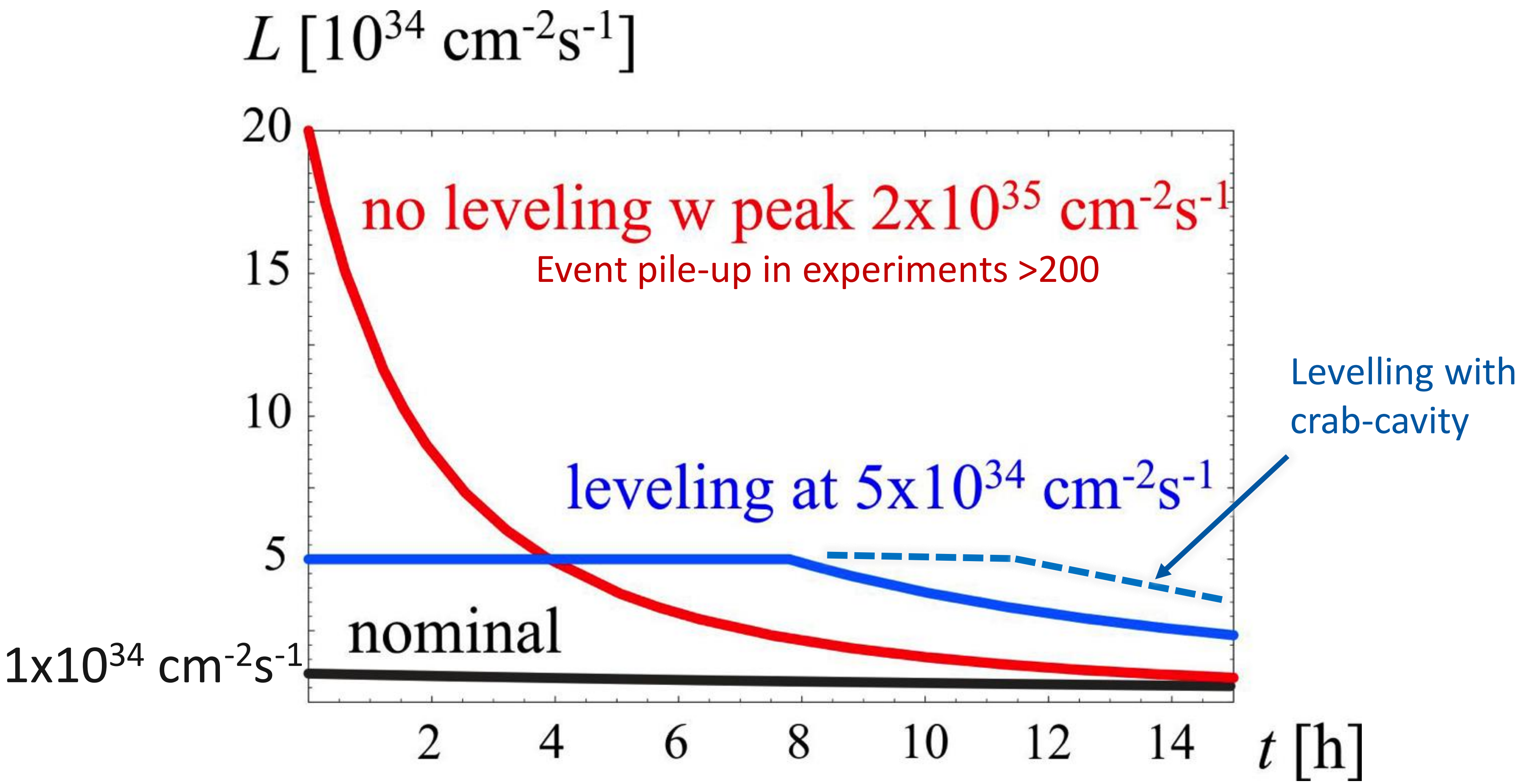
The expected…

- Head-on beam-beam effect not a major limitation
- Long range beam-beam to be taken seriously
  - Crossing angle for sufficient separation in order of 10 -12 σ (otherwise bad lifetime & beam loss)
    - Reduces long-range beam-beam interactions
    - Reduces beam-beam tune spread and resonances
    - Reduction of mechanical aperture
    - Reduction of luminous region
    - Reduction of overlap and instantaneous luminosity



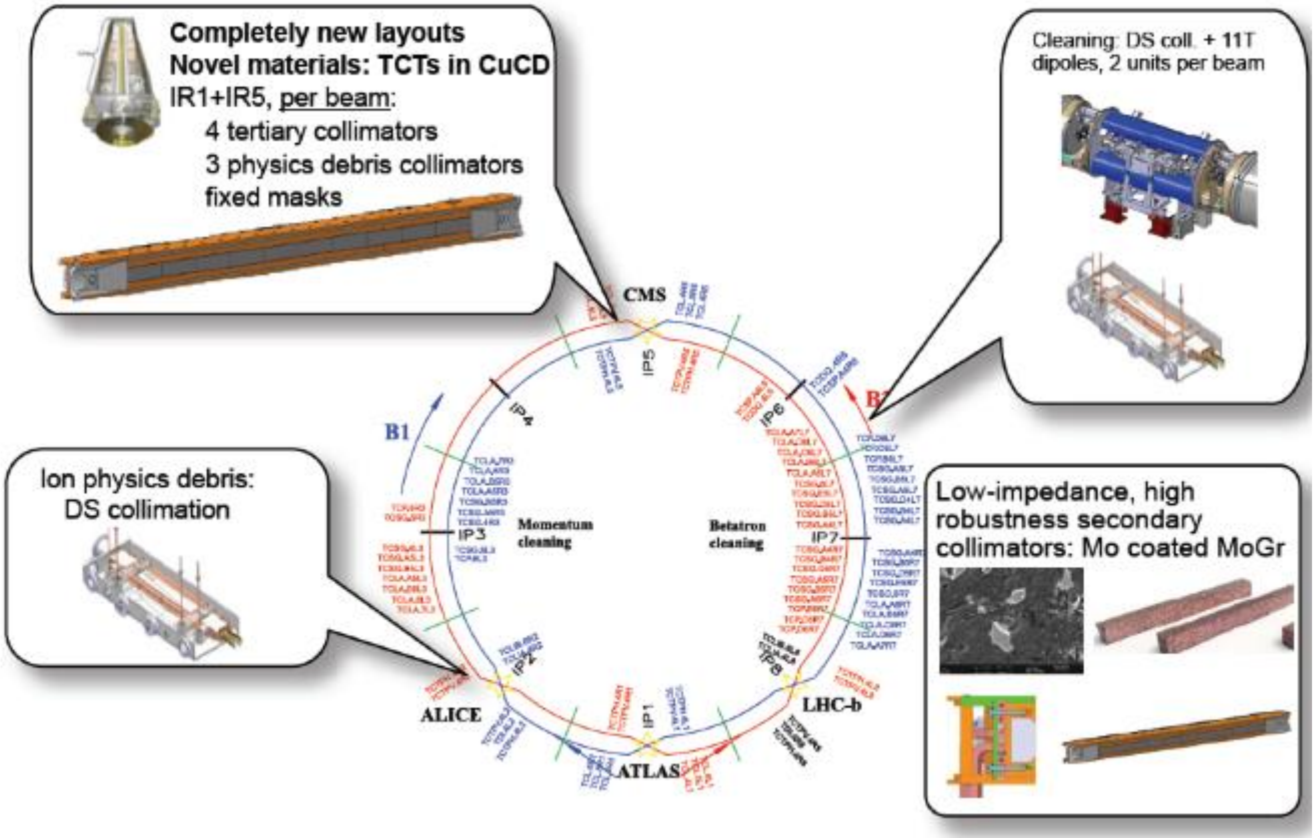


Operational Scenario for HL-LHC

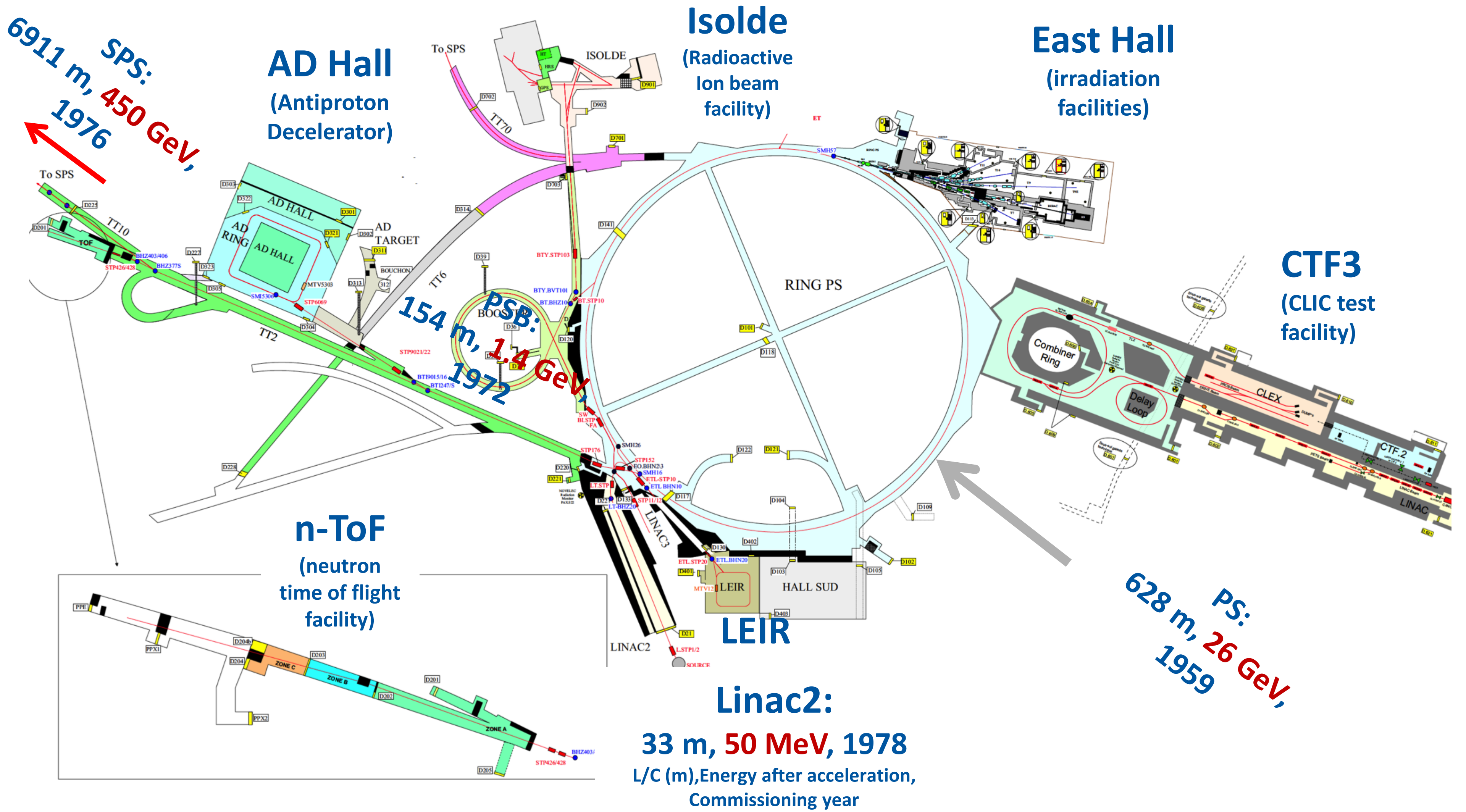


HL-LHC Collimation upgrades

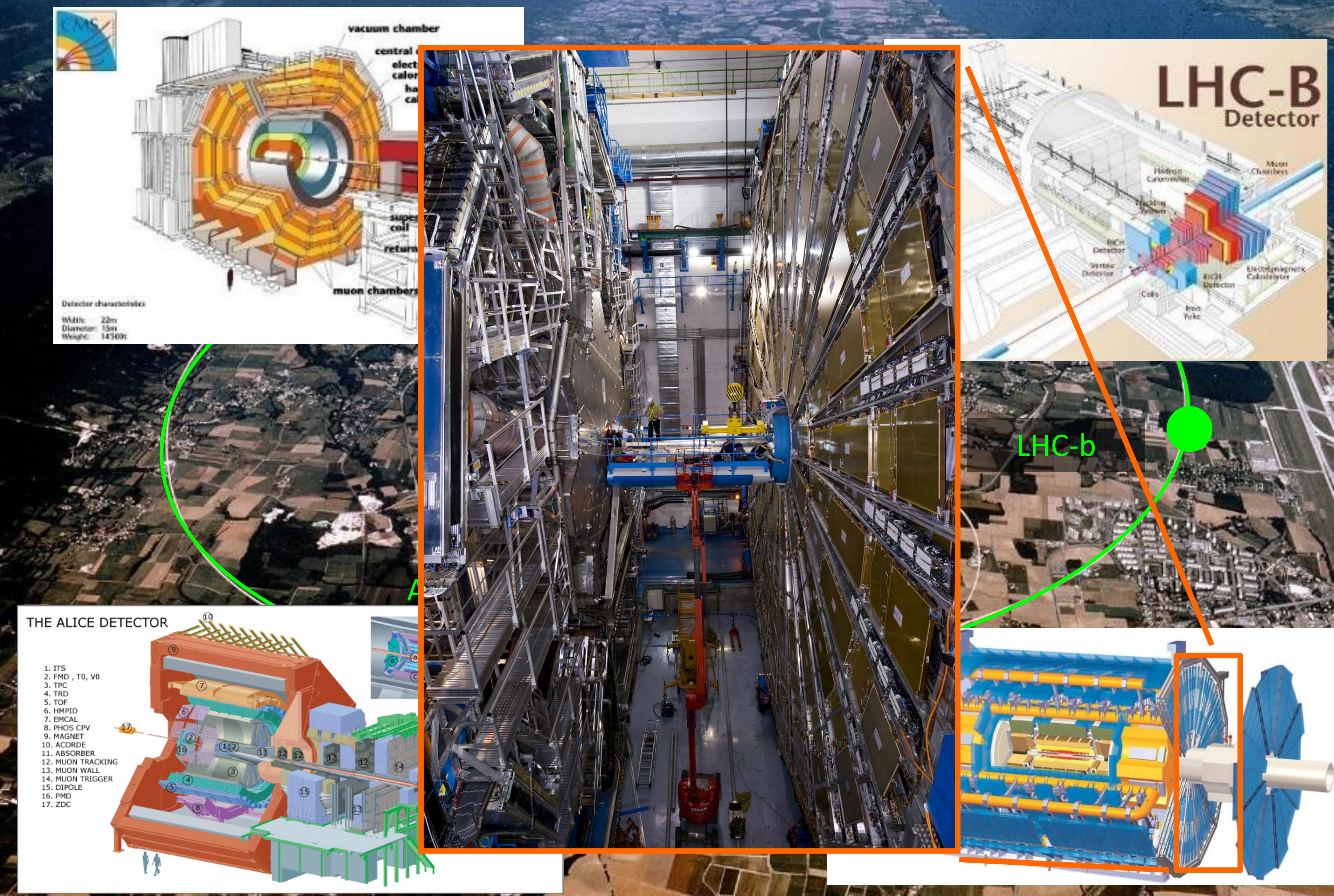
HL-LHC will bring higher bunch intensity, higher luminosity, higher radiation and potentially higher losses -> Collimation upgrades required



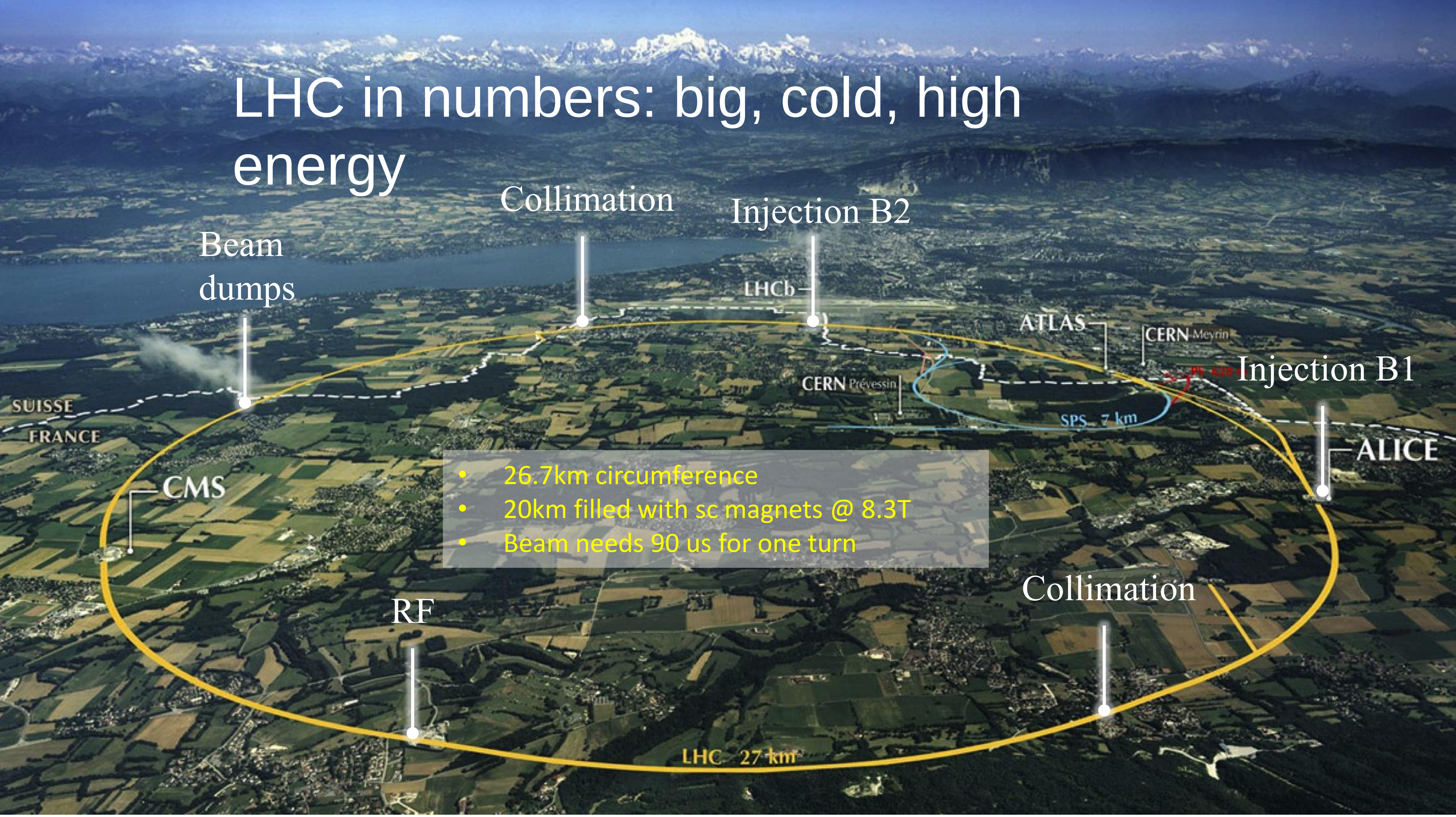
(Complete) PS Accelerator complex



CERN Accelerator Complex



LHC in numbers: big, cold, high energy



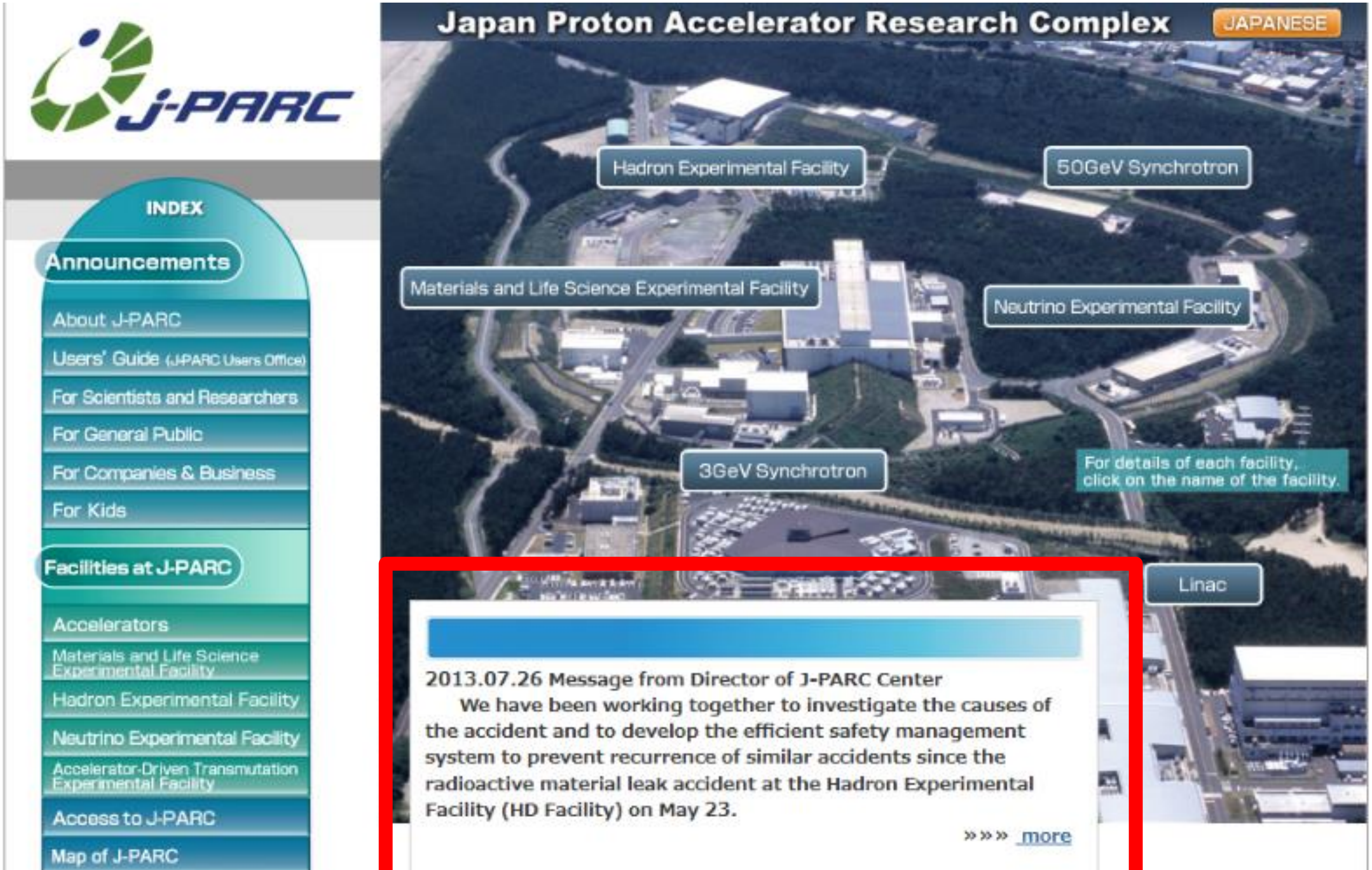
- 26.7km circumference
- 20km filled with sc magnets @ 8.3T
- Beam needs 90 us for one turn

1720 Power converters
> 10000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes helium, ~90 tonnes at 1.9 K
350 MJ stored beam energy in 2015
1.2 GJ magnetic energy per sector at 6.5 TeV

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 !