Machine Protection

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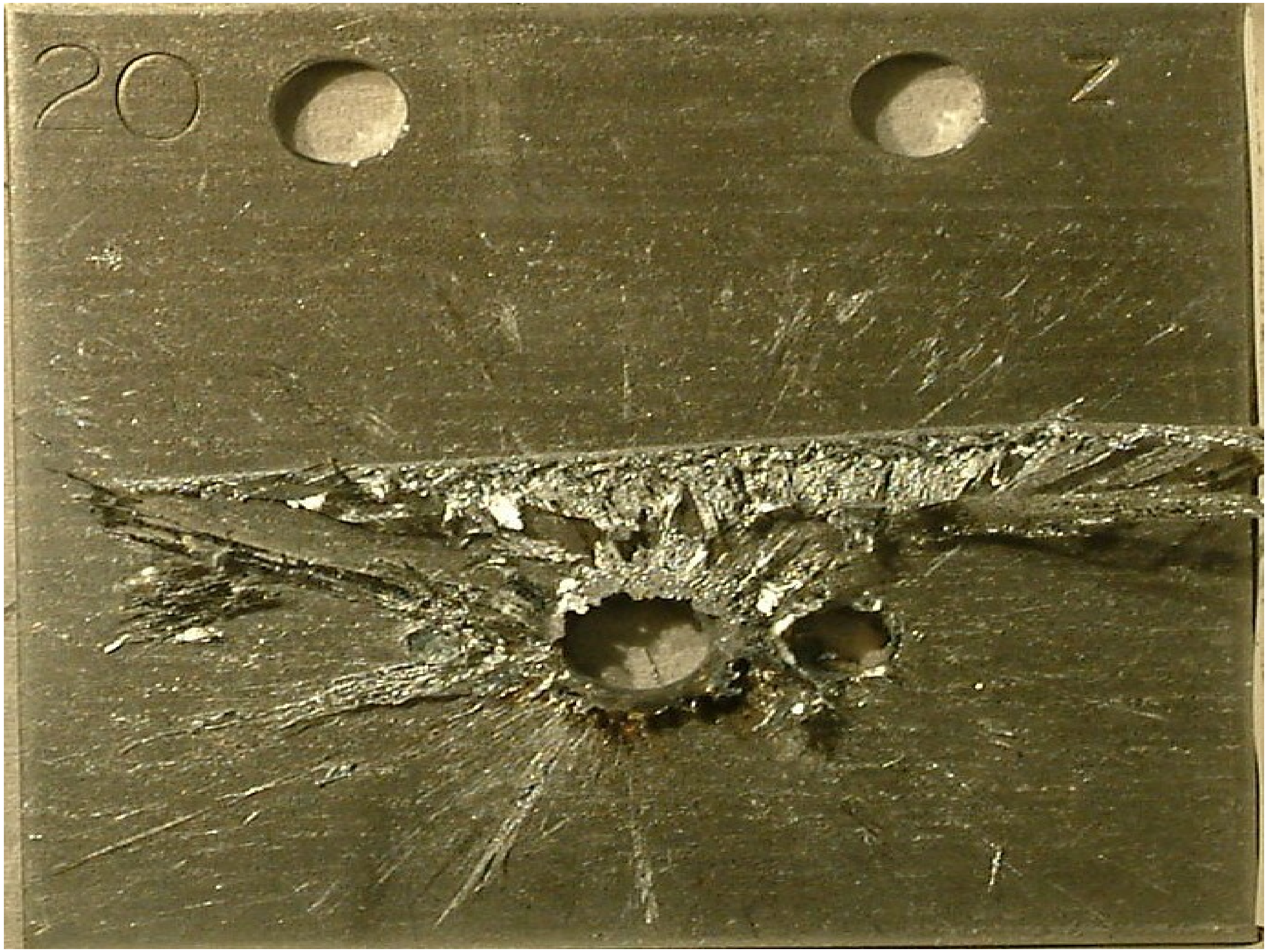


- Material and acknowledgements to: R. Schmidt and J. Wenninger

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.**

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).

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 !

Hazard and Risk for accelerators

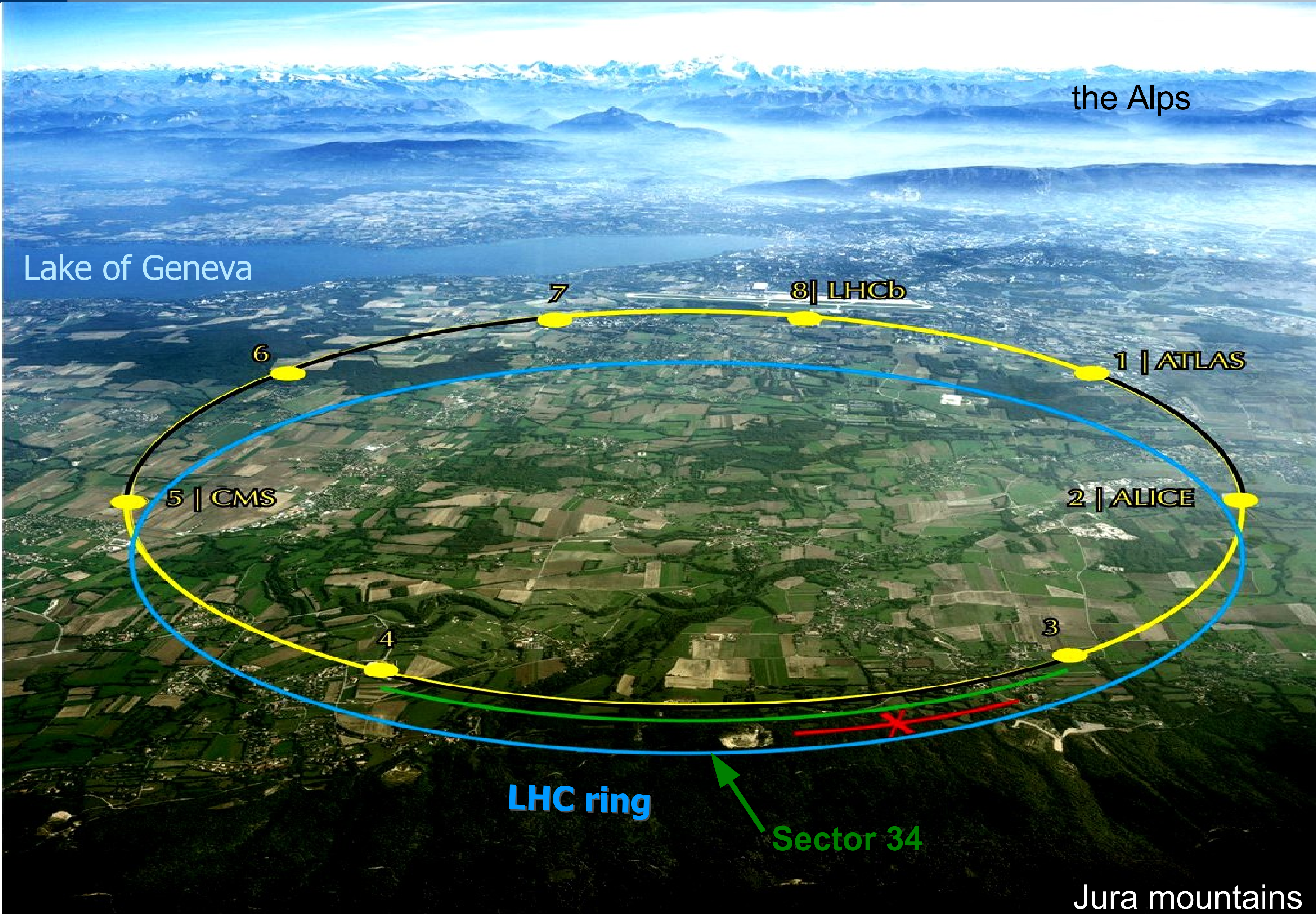
- **Hazard:** a situation that poses a level of threat to the accelerator. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes "active“: **incident / accident**. **Consequences** and **possibility** of an incident interact together to create **RISK**, can be quantified:

RISK = Consequences · Probability

Related to accelerators

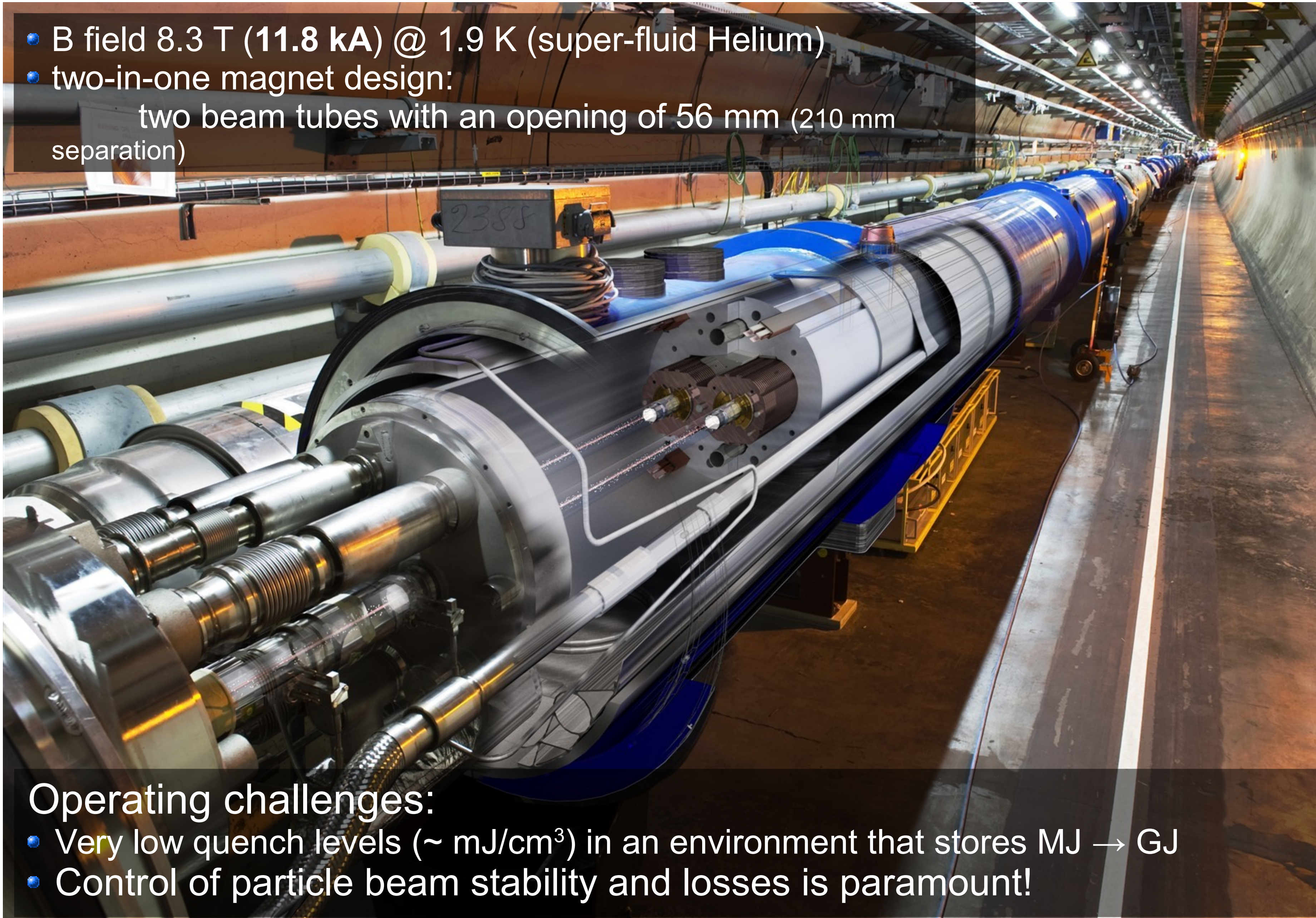
- Consequences of an uncontrolled beam loss
- Probability of an uncontrolled beam loss
- The higher the **RISK**, the more **Protection** is required

The Large Hadron Collider LHC
Installed in the LEP tunnel, 27 km, Depth of 70-140 m



27 km Circumference – 1232 LHC dipole magnet

- B field 8.3 T (**11.8 kA**) @ 1.9 K (super-fluid Helium)
- two-in-one magnet design:
  two beam tubes with an opening of 56 mm (210 mm separation)



Operating challenges:

- Very low quench levels (~ mJ/cm^3) in an environment that stores MJ → GJ
- Control of particle beam stability and losses is paramount!

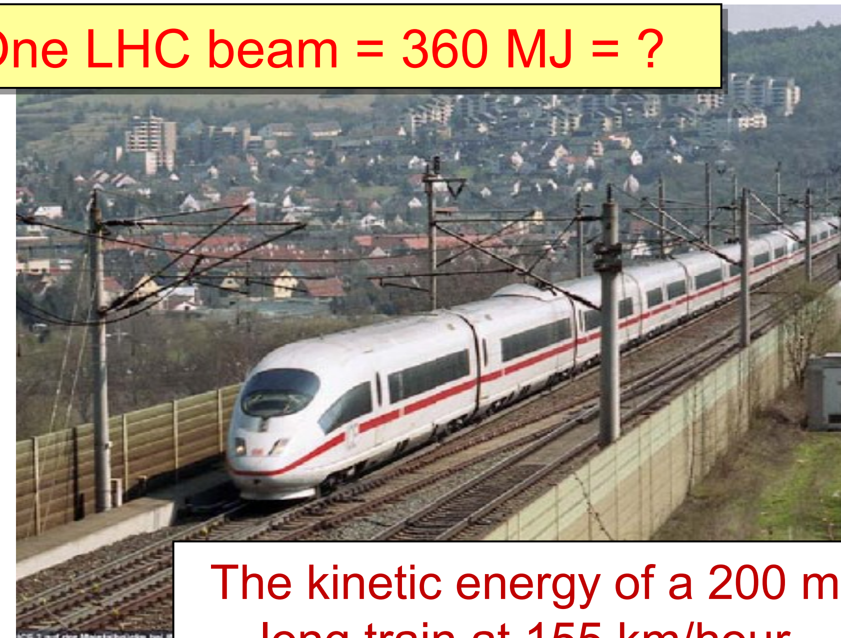
Relevant parameters for MPS

- ❑ Momentum of the particle
- ❑ Particle type

  Activation is mainly an issue for hadron accelerators.
- ❑ Energy stored in the beam

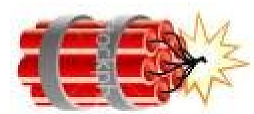
  1 MJ can heat and melt 1.5 kg of copper.
- ❑ Beam power
- ❑ Beam size
- ❑ Power or energy density
- ❑ Time structure of beam

One LHC beam = 360 MJ = ?



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

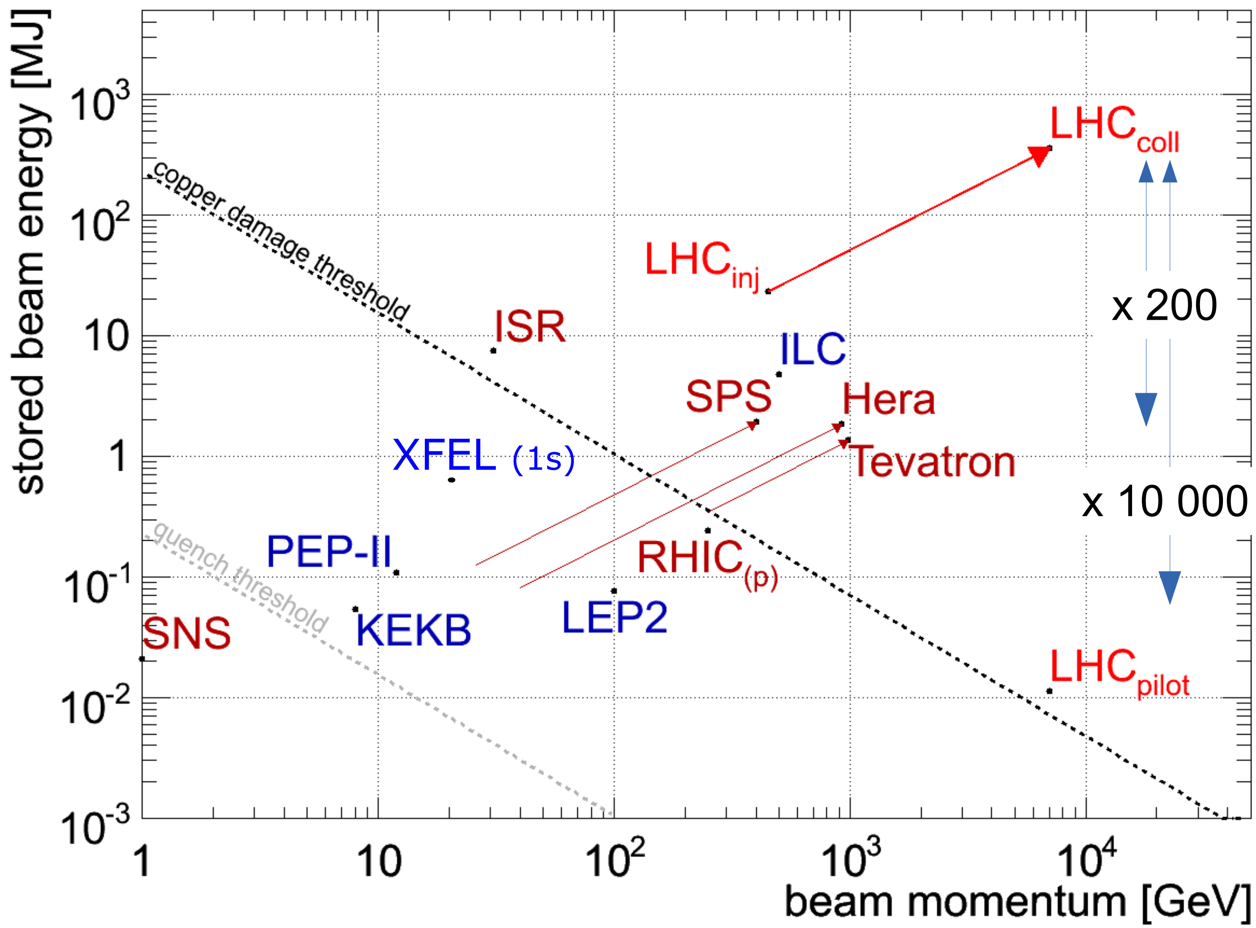
90 kg of TNT



15 kg of chocolate

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

Stored Beam Energies

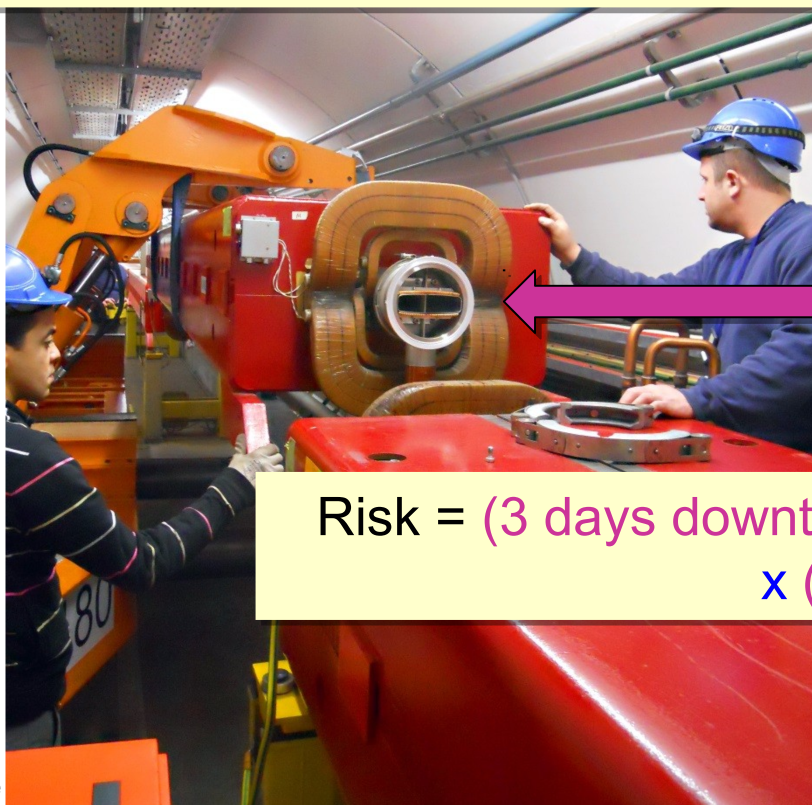


Quench Levels	Units	*Tevatron*	*RHIC*	*HERA*	*LHC*
Instant loss **(0.01 - 10 ms)**	[mJ/cm³]	4.5	18	2.1 - 6.6	87
Steady loss **(> 100 s)**	[mW/cm³]	75	75		5.3

From uncontrolled damage tests…

A real case from the 2008 SPS run !

- Impact on the vacuum chamber of a 400 GeV beam of $3x10^{13}$ 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)

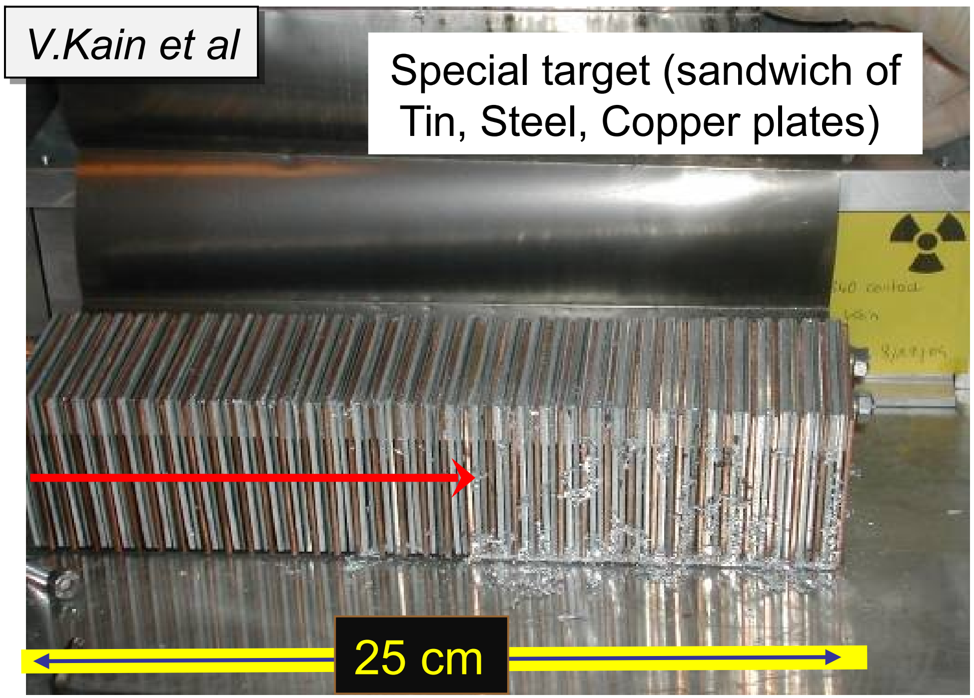
…to controlled damage tests

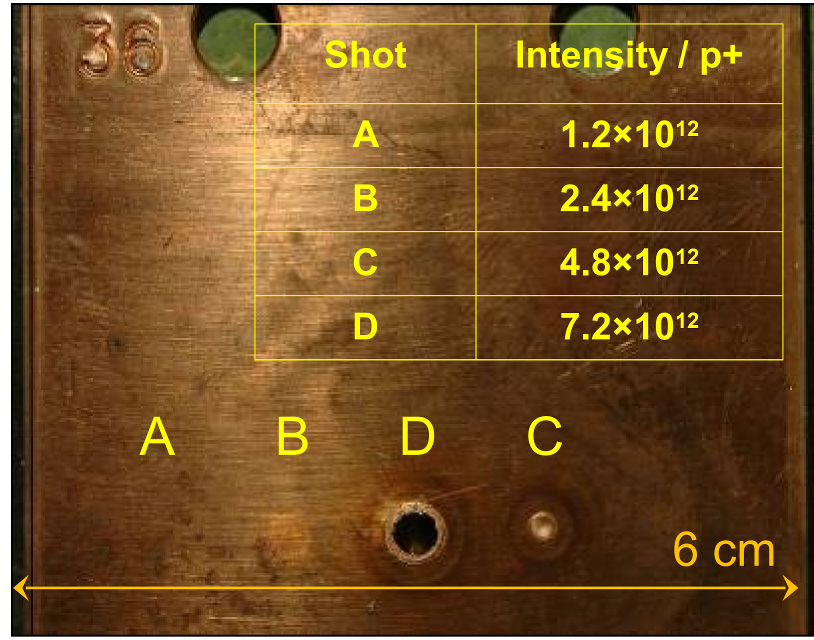
- In the past decade a lot of effort was invested to better understand the interaction of high energy / high density beams with matter.
- Experiments:
  - *Ad-hoc experiments for the LHC,*
  - *Construction of a dedicated test facility at CERN (HiRadMat @ SPS).*
- Modeling and comparison with tests.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



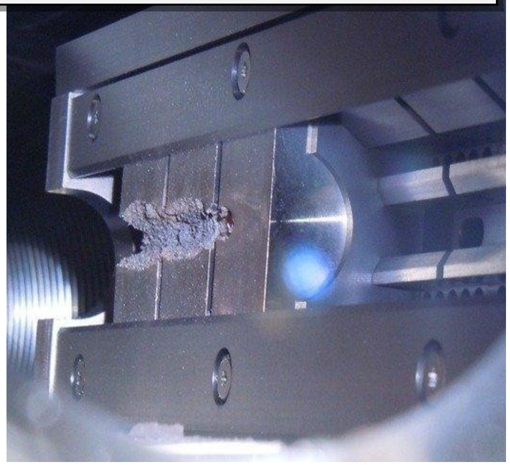


Shot	Intensity / p+
A	1.2×10^{12}
B	2.4×10^{12}
C	4.8×10^{12}
D	7.2×10^{12}

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

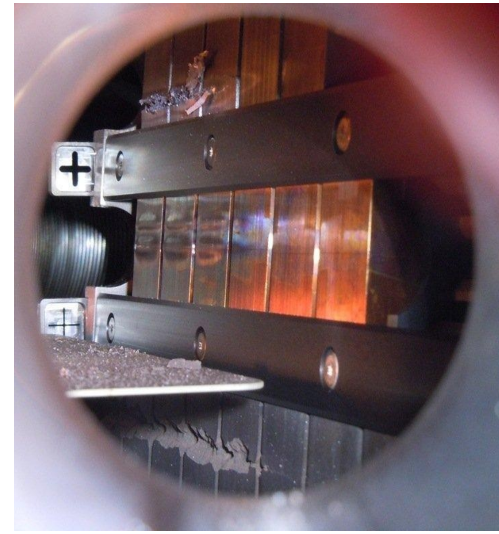
HiRadMat Tests – New Materials

Courtesy A. Bertarelli (EN)

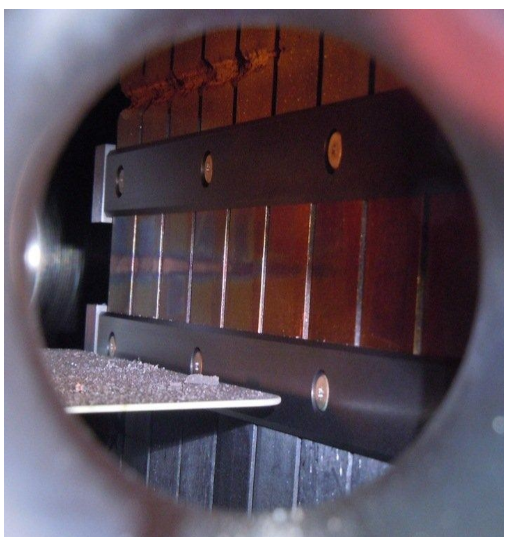


Inermet 180, 72 bunches

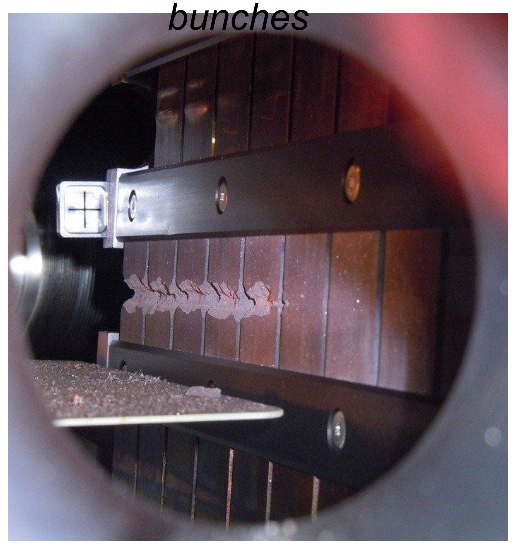
Molybdenum, 72 & 144 bunches



Glidcop, 72 bunches (2 x)



Copper-Diamond 144 bunches



Molybdenum-Copper-Diamond 144 bunches

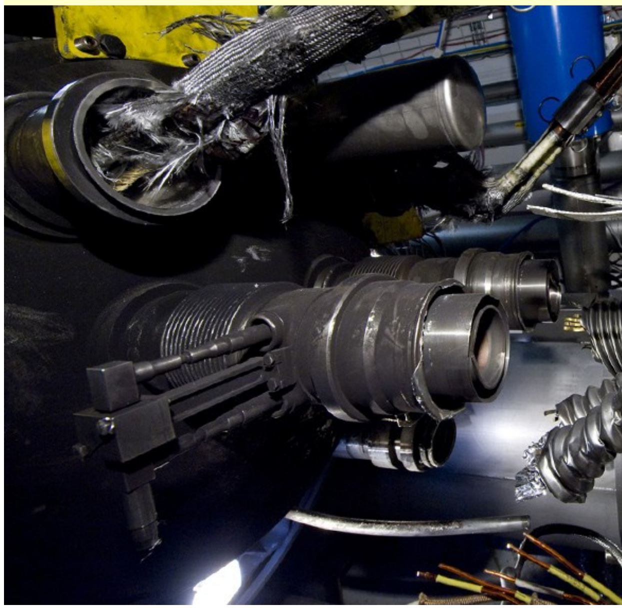
Molybdenum-Graphite (3 grades) 144 bunches

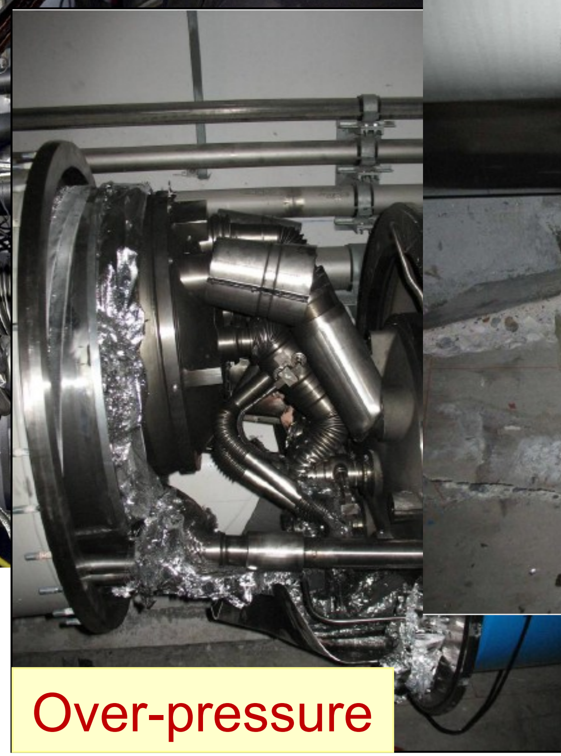
Release of 600 MJ at LHC

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.

Arcing in the interconnection





Over-pressure

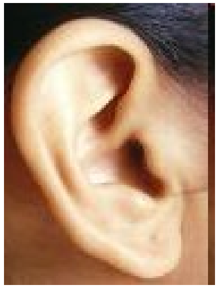
Magnet displacement

53 magnets had to be repaired

Machine Protection

Example for Active Protection - Traffic

- A monitor detects a dangerous situation



- An action is triggered

- The energy stored in the system is safely dissipated

Example for Passive Protection

- The monitor fails to detect a dangerous situation

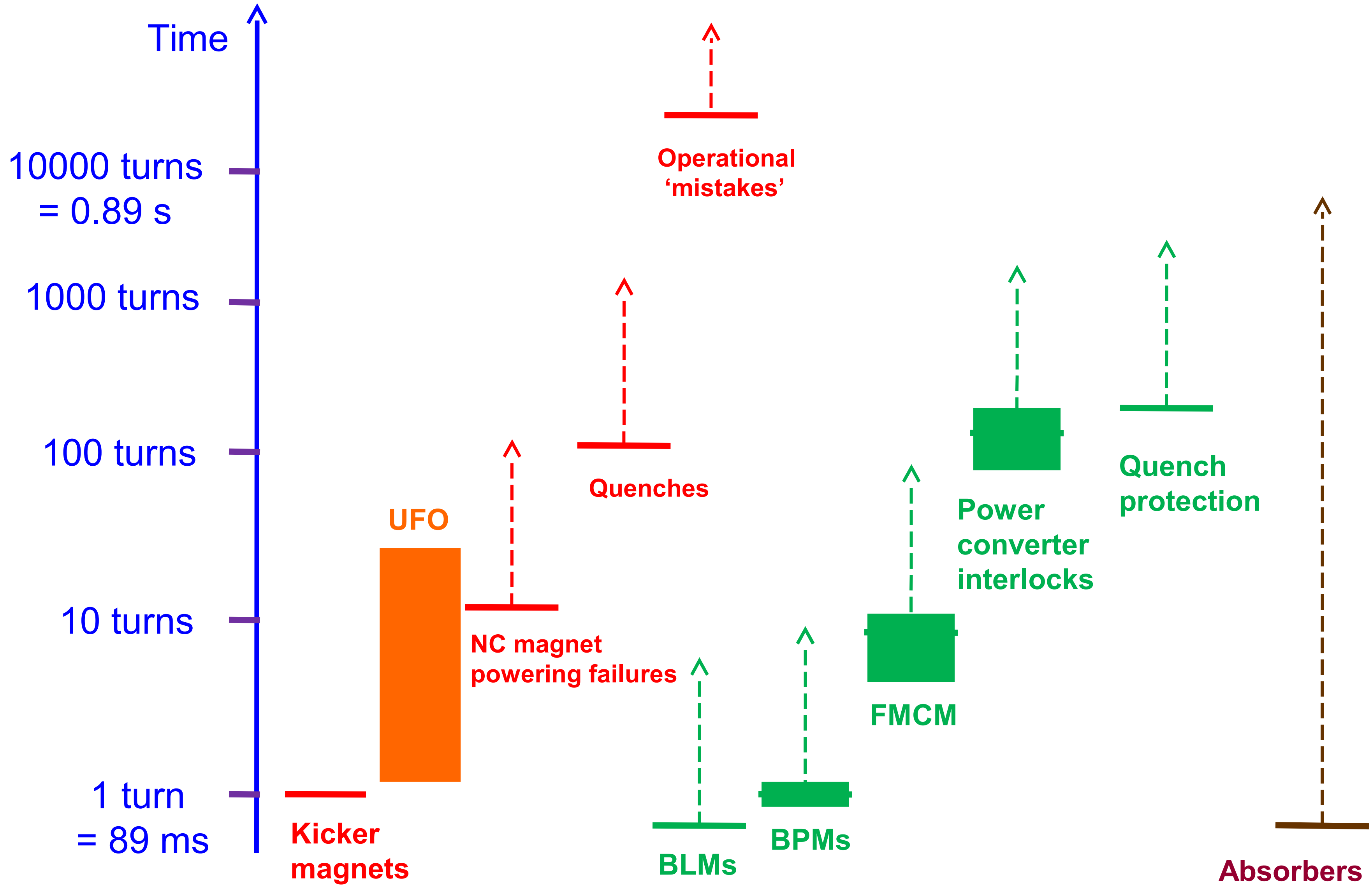
- The reaction time is too short

- Active protection not possible – passive protection by bumper, air bag, safety belts

MPS Design Strategy

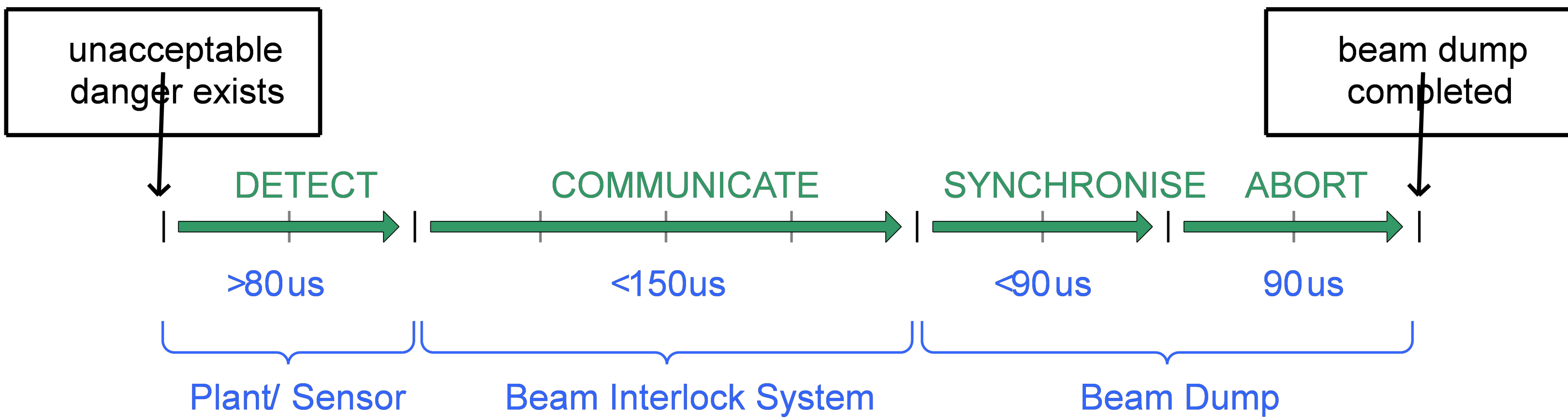
- Avoid a failure by design – if you can.
- Detect a failure at the hardware (equipment) level and stop operation – first protection layer.
- Detect the consequences of the failure on beam parameters (orbit, tune, losses etc) and stop operation – second protection layer.
- Stop beam operation.
  - *Inhibit injection, send beam to a dump,*
  - *Stop the beam by collimators / absorbers.*
- *Demonstrate safety / availability / reliability*
  - *use established methods to analyse critical systems and to predict failure rate*
- *Managing interlocks*
  - *disabling of interlocks is common practice (keep track !)*
  - *LHC: masking of some interlocks possible for low intensity/low energy beams*
- Elements of protection – third protection layer
  - ✓ Equipment and beam monitoring,
  - ✓ Collimators and absorbers, beam dumps,
  - ✓ Interlock system linking different systems.

Timescales @ LHC



The beam's gone immediately isn't it?

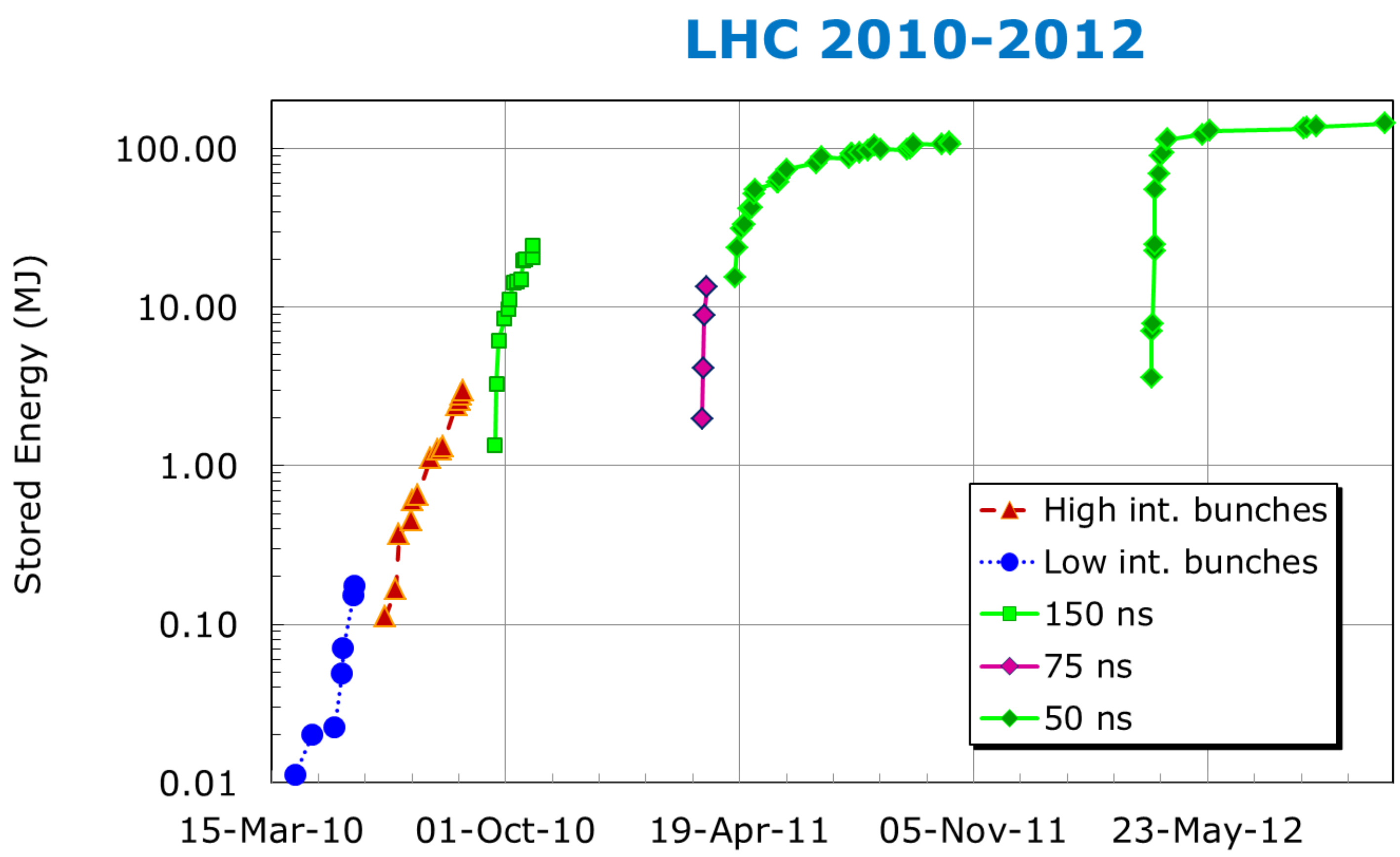
- Unfortunately even the best failure detection takes some time, the signal must be propagated to the dumping system, the dumping system must synchronize to the beam.
  - Unavoidable delay to fire the dump !



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

LHC Machine Protection 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



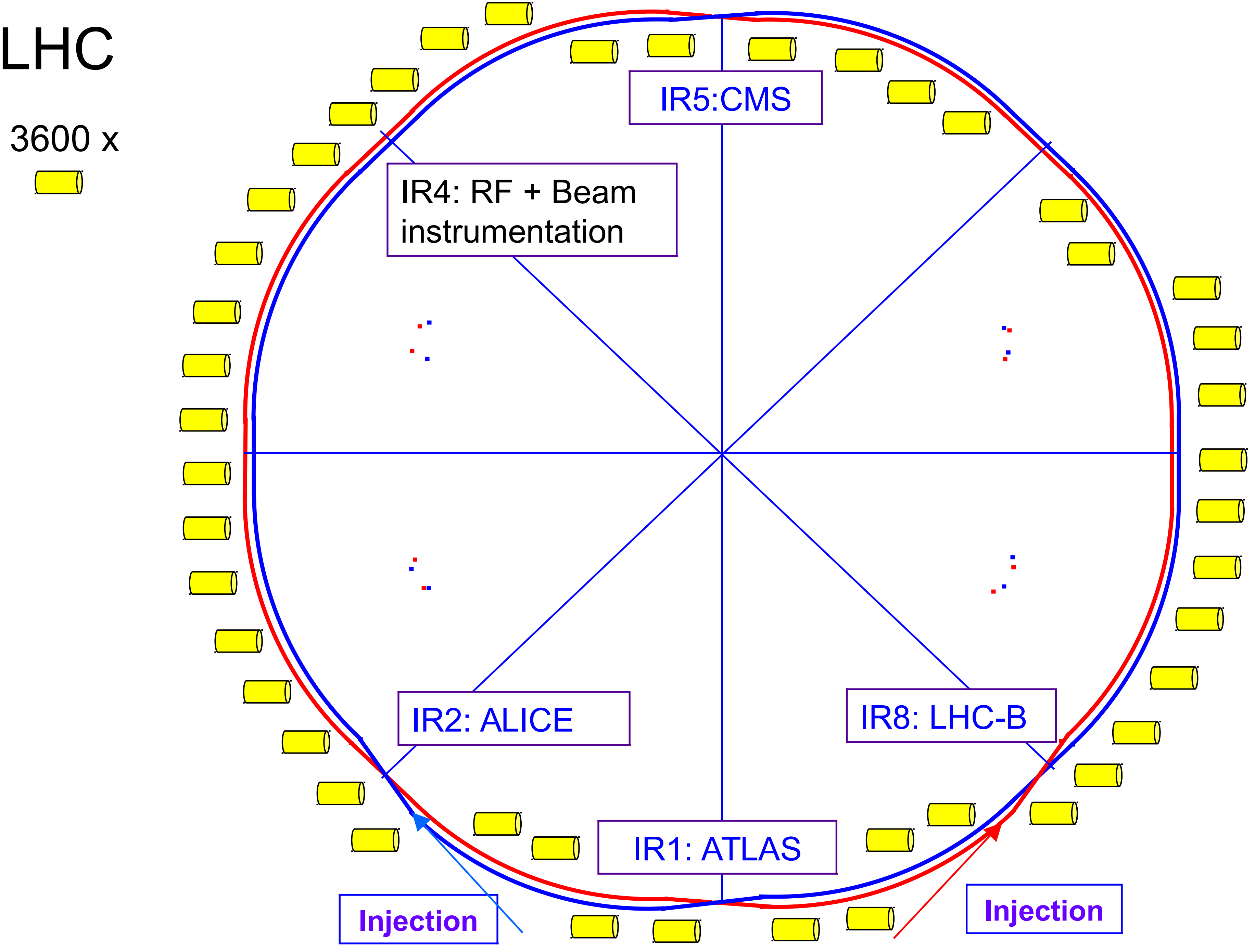
Beam Instrumentation for Machine Protection

- Beam Loss Monitors
  - stop beam operation in case of too high beam losses
  - monitor beam losses around the accelerator (full coverage?)
  - could be fast and/or slow (LHC down to 40 μs)
- Beam Position Monitors
  - ensuring that the beam has the correct position
  - in general, the beam should be centred in the aperture
- Beam Current Transformers
  - if the transmission between two locations of the accelerator is too low (=beam lost somewhere): stop beam operation
  - if the beam lifetime is too short: dump beam
- Beam Size Monitors
  - if beam size is too small could be dangerous for windows, targets, …

Beam Loss Monitors

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are ~3600 chambers distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !

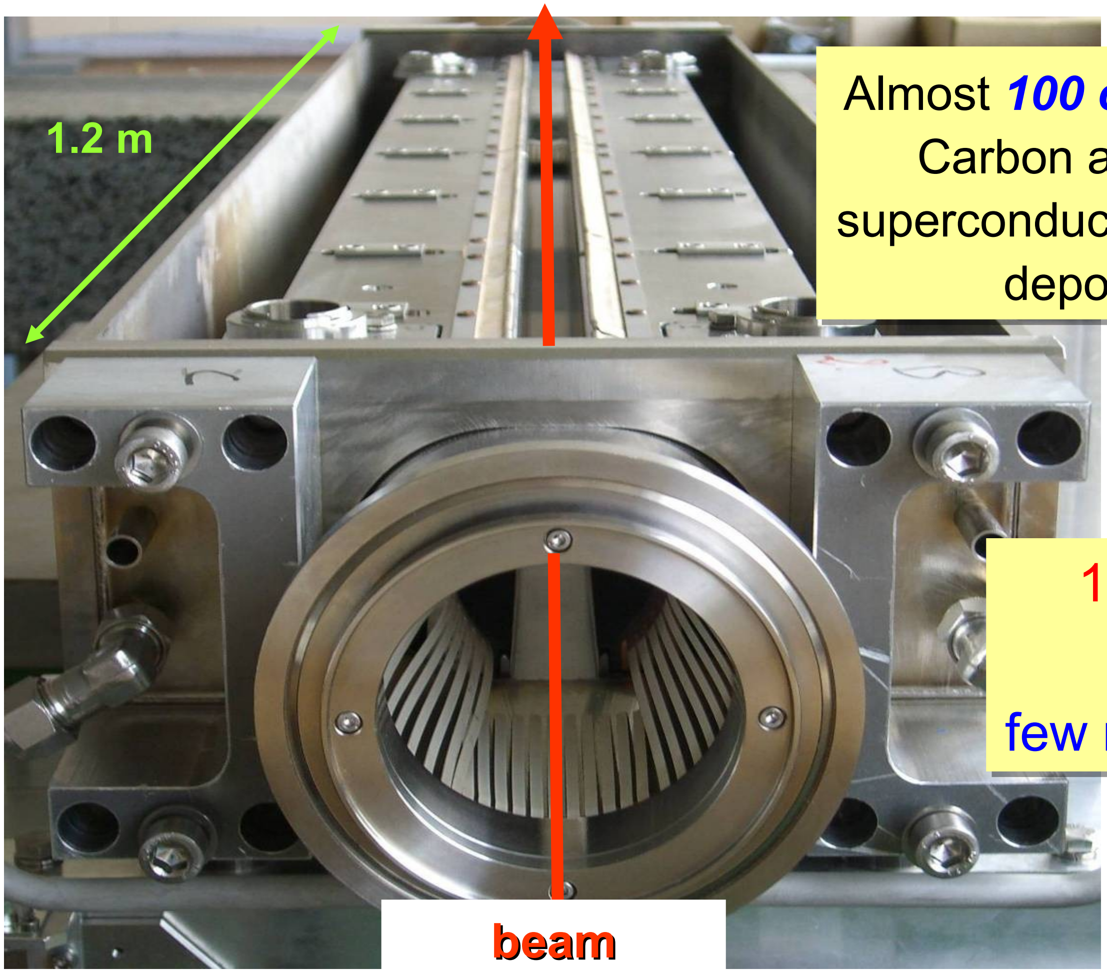
LHC



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.*

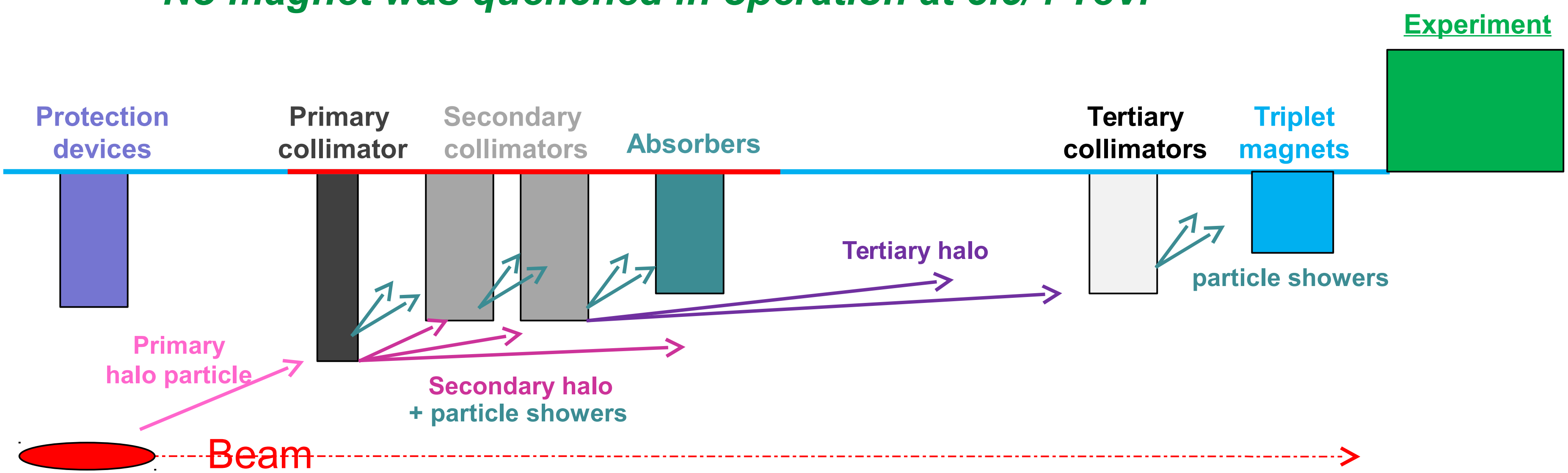


Almost ***100 collimators***, mostly made of Carbon and Tungsten, protect the superconducting magnets against energy deposition from the beam

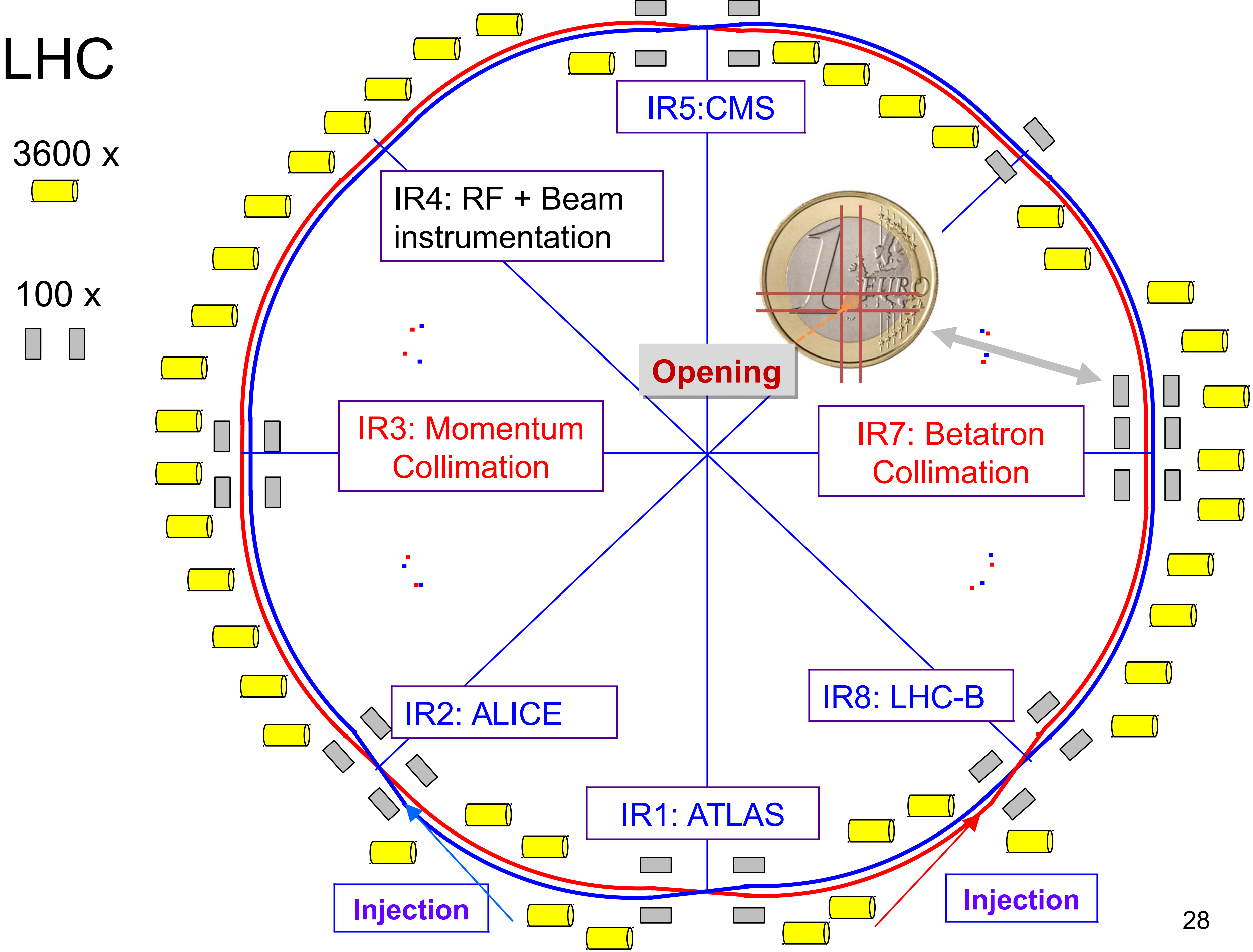
140 MJ in each beam
versus
few mJ to quench a magnet

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.***

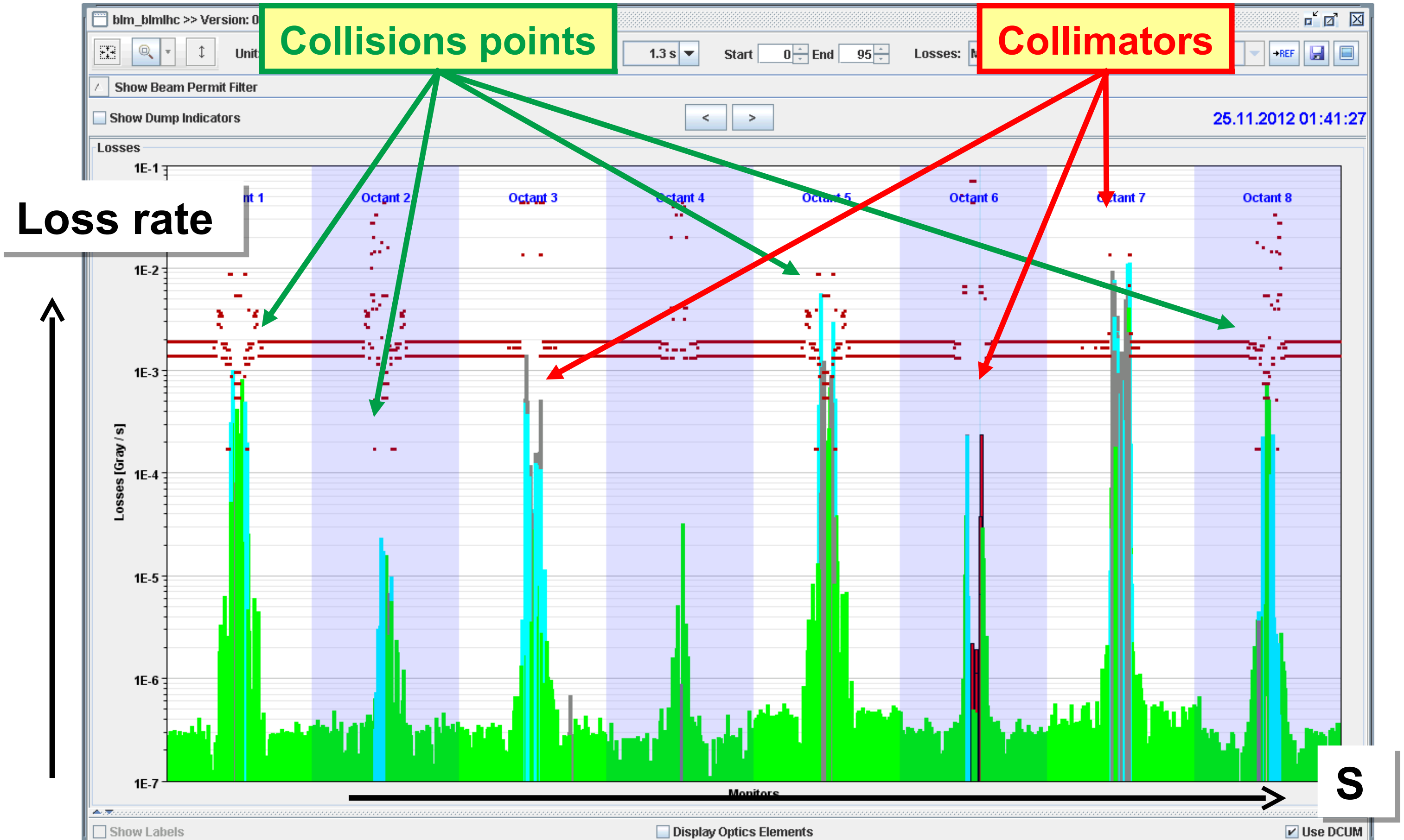


LHC


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

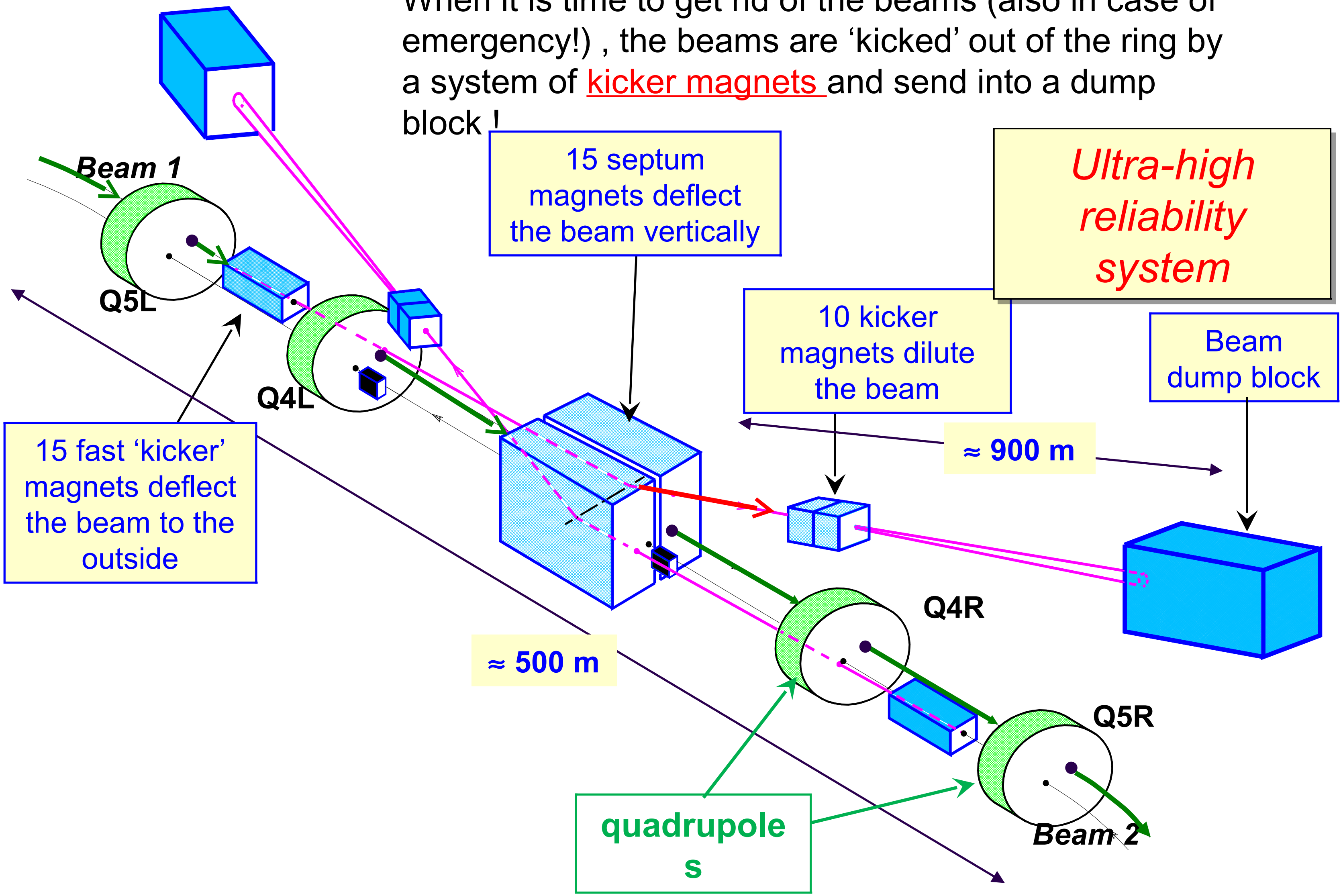
Continuous beam losses at LHC

- 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 !

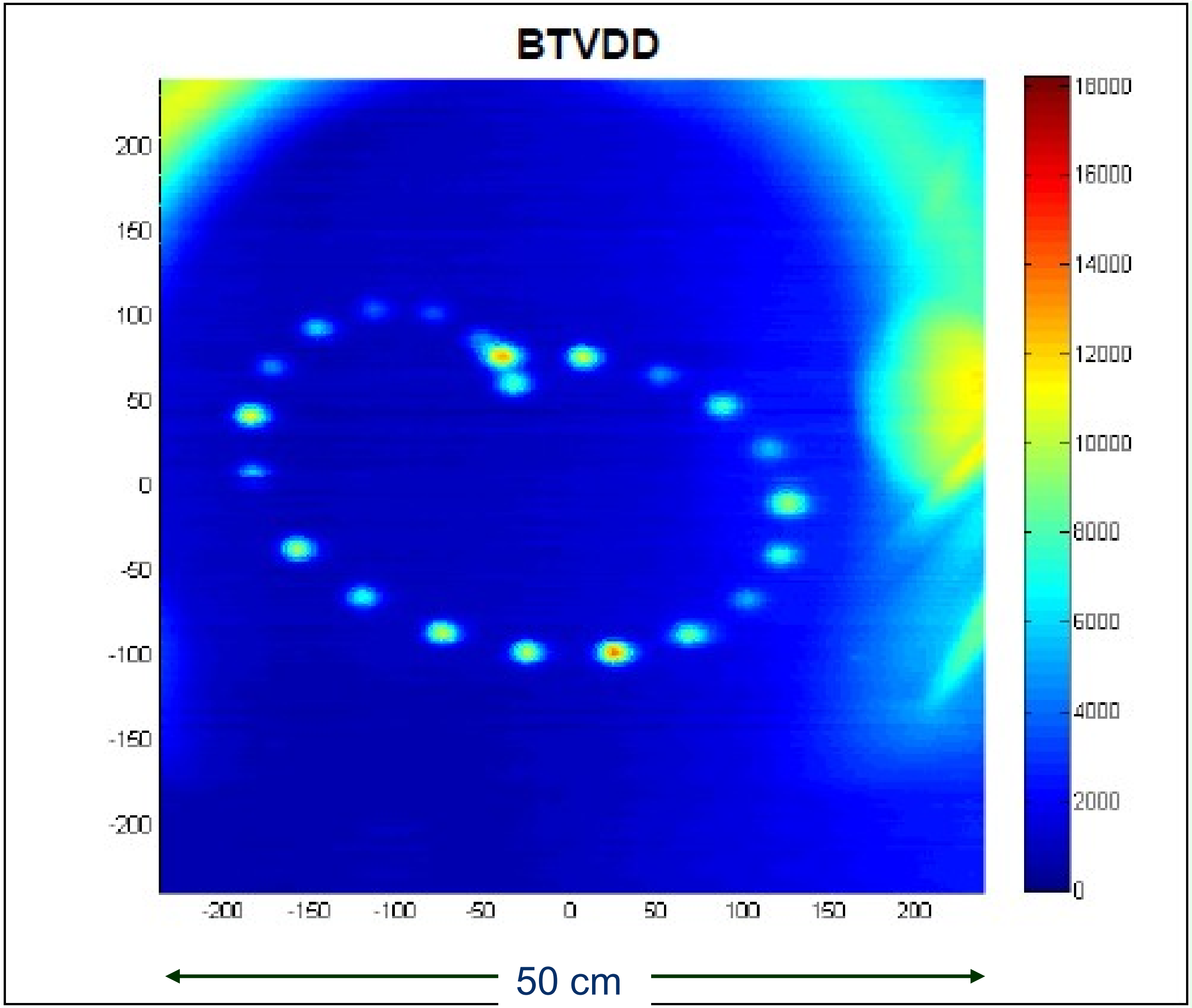


LHC Dump Line

The LHC dump block

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

Beam Dump

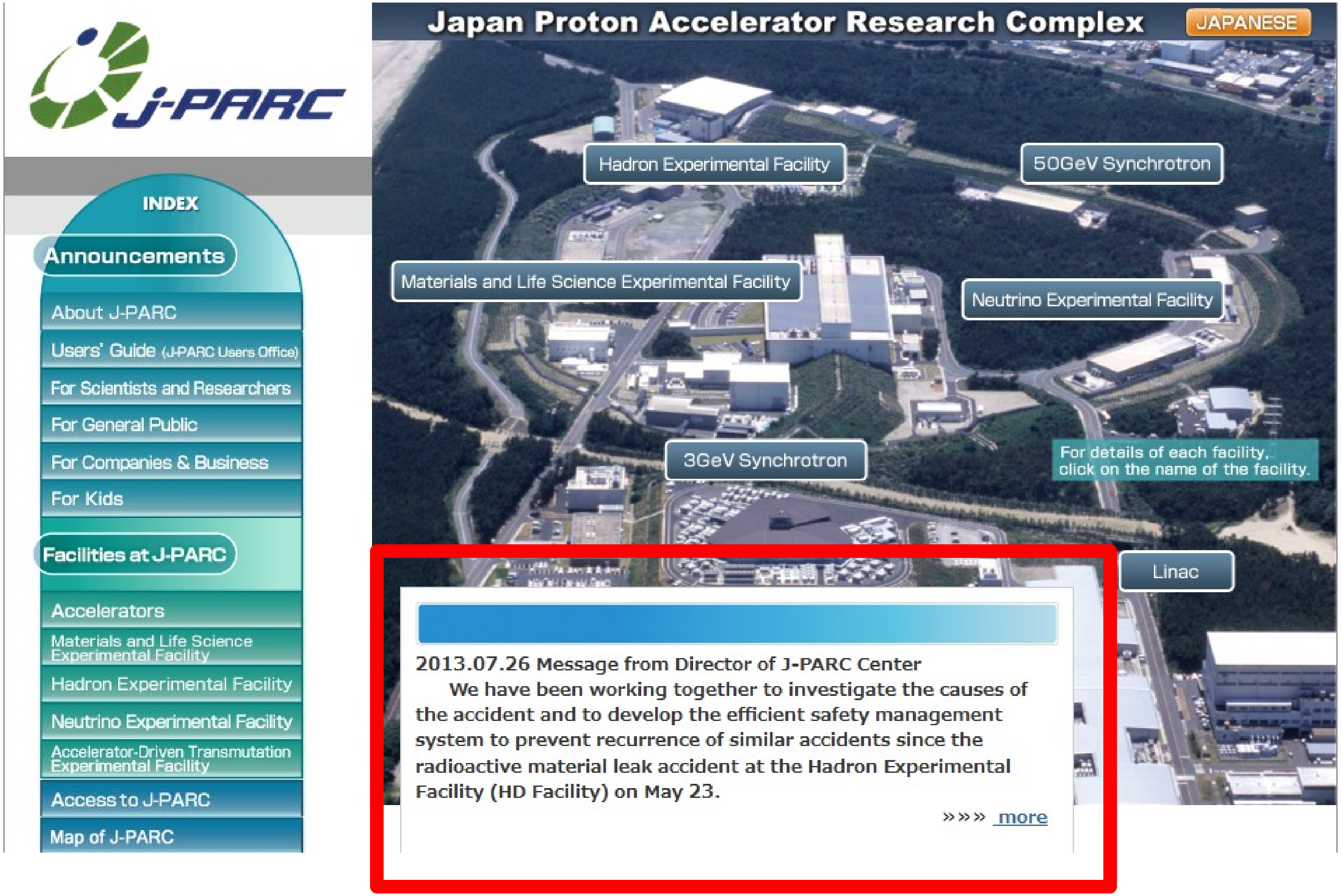


- Screen in front of the beam dump block
- Each light dot shows the passage of one proton bunch traversing the screen
- Each proton bunch has a different trajectory, to better distribute the energy across a large volume

The Unexpected

Incidents happen

JPARC home page – October 2013



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 are ongoing to allow JPAC to restart.

One insufficiently covered failure case had major consequences !

Summary

Machine protection:

- manages risk = 'failure probability' * 'failure consequences'

- 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,
- 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.

Acknowledgements to many colleagues from CERN and to the authors of the listed papers

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