

Operational challenges of the LHC

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Part 2: LHC challenges

- Luminosity & interaction regions
- Injector chain
- Machine Protection
- Collimation

Luminosity and Interaction Regions

Luminosity & its limitations

The equation for luminosity reveals different parameters that can be tuned to maximize L:

$$L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*}$$

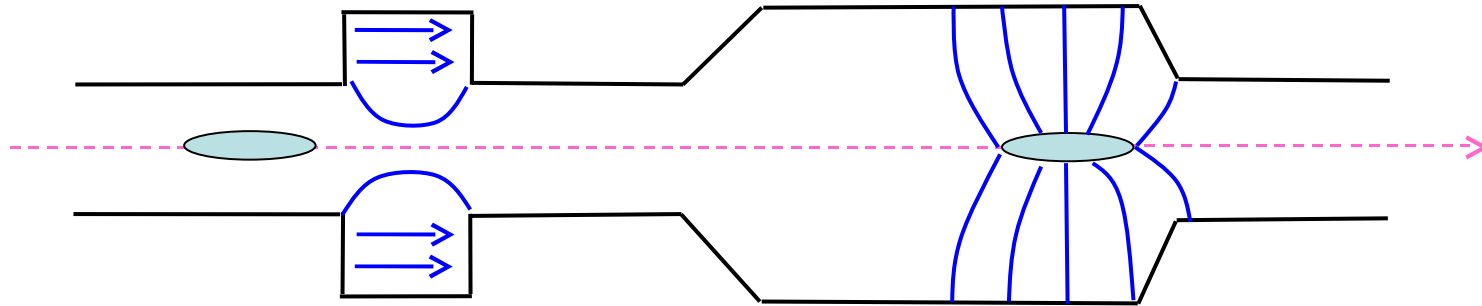
- f : the revolution frequency is given by the circumference, $f=11.246$ kHz.
- N : the bunch population - $N=1.15 \times 10^{11}$ protons
 - Injectors (brighter beams)
 - Collective interactions of the particles
 - Beam encounters
- k : the number of bunches - $k=2808$
 - Injectors (more beam)
 - Collective interactions of the particles
 - Interaction regions
 - Beam encounters
- σ^* : the size at the collision point - $\sigma_y^* = \sigma_x^* = 16 \mu\text{m}$
 - Injectors (brighter beams)
 - More focusing - stronger quadrupoles

For $k = 1$:

$$L = 3.5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$$

Collective (in-)stability

- The electromagnetic field of a bunch interacts with the chamber walls (finite resistivity!), cavities, discontinuities etc that it encounters:



- The fields act back on the bunch itself or on following bunches.
- Since the fields induced by of a bunch increase with bunch intensity, the bunches may become COLLECTIVELY unstable beyond a certain intensity, leading to poor lifetime or massive losses intensity loss.
- Such effects can be very strong in the LHC injectors, and they will affect the LHC: we have many carbon collimators that have a bad influence on beam stability!

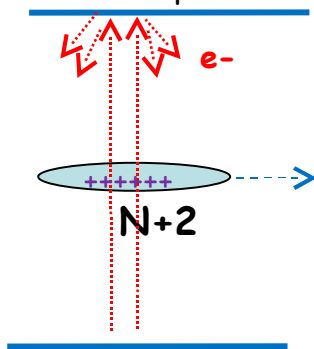
→ With the presently installed collimators, we cannot reach nominal performance because of beam (in)stability !!

Electron clouds...

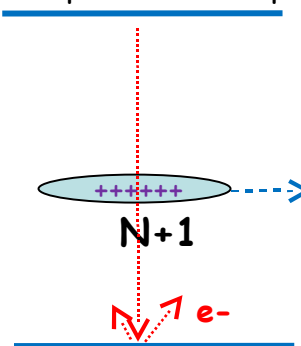
... affect intense beams with positive charge and closely spaced bunches.

- ❑ Electrons are generated at the vacuum chamber surface by beam impact, photons...
 - ❑ If the **probability to emit secondary e- is high enough**, more e- are produced and accelerated by the field of a following bunch(es) and multiplication start...
 - ❑ The cloud of e- that may build up can **drive the beam unstable**, and at the LHC, **overload the cryogenic system by the heat they deposit on the chamber walls !**
 - ❑ This effect depends strongly on surface conditions, simulations are tricky because they are very sensitive to very low energy (\sim eV) electrons. **The latest simulation indicate that the problem may be less severe than initially anticipated but ...**
- Fortunately the impact of all those electrons cleans the chamber surface, reduces the electron emission probability and eventually the cloud disappears !

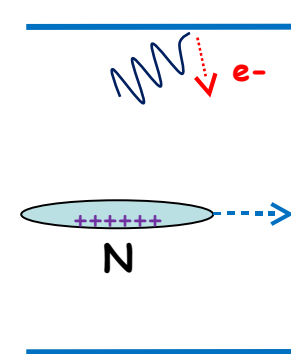
Bunch N+2 accelerates the e-, more multiplication...



Bunch N+1 accelerates the e-, multiplication at impact

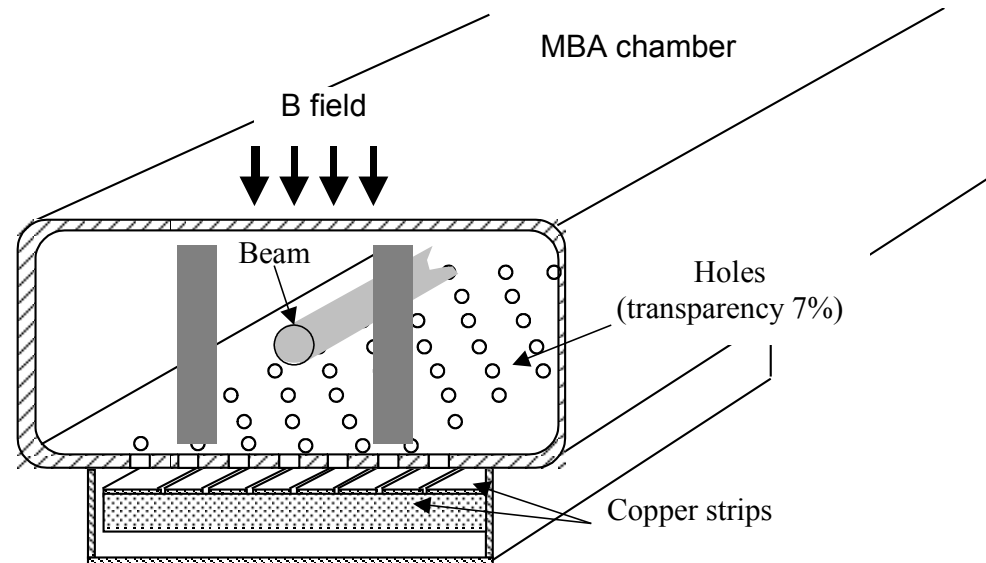
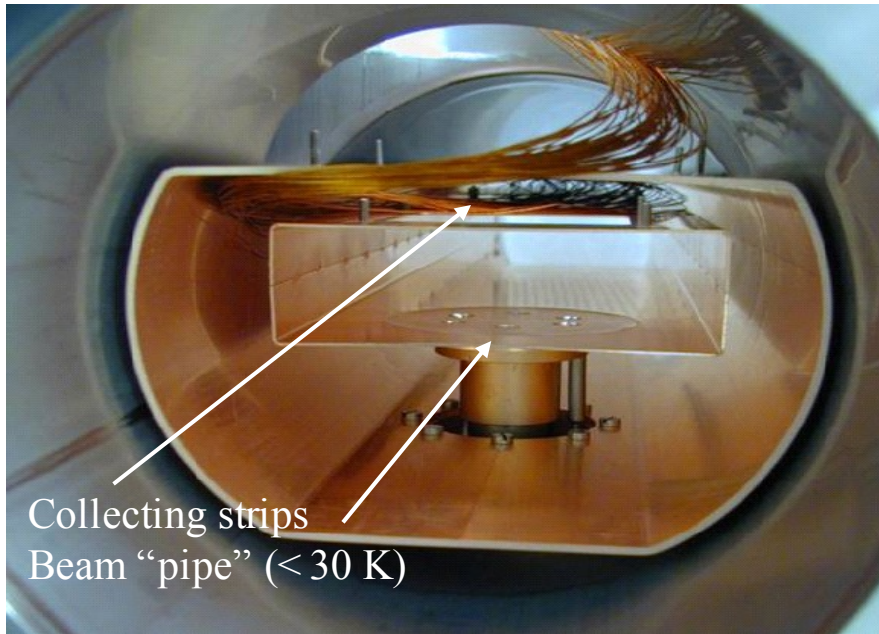


Bunch N liberates an e-



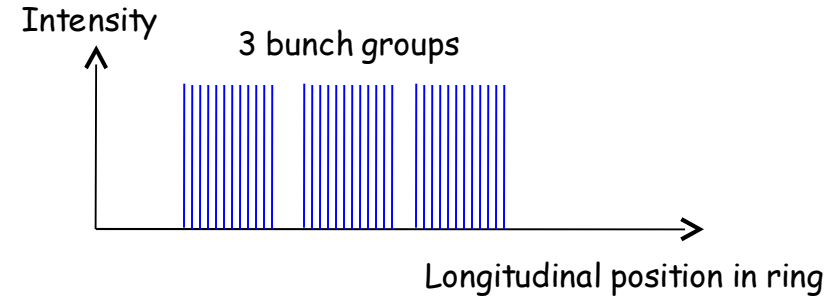
Electron Cloud Detectors

- When first beams with LHC structure and intensity were injected into the SPS, the beam was completely unstable and within seconds the vacuum valves closed due to high pressure !
- The origin of the problem was traced to electron clouds, and since then the SPS has become an electron cloud 'laboratory', in particular to study the surface cleaning by the cloud itself.
- The electron clouds have been studied using for example dedicated Si-strip detectors installed inside the vacuum chamber.

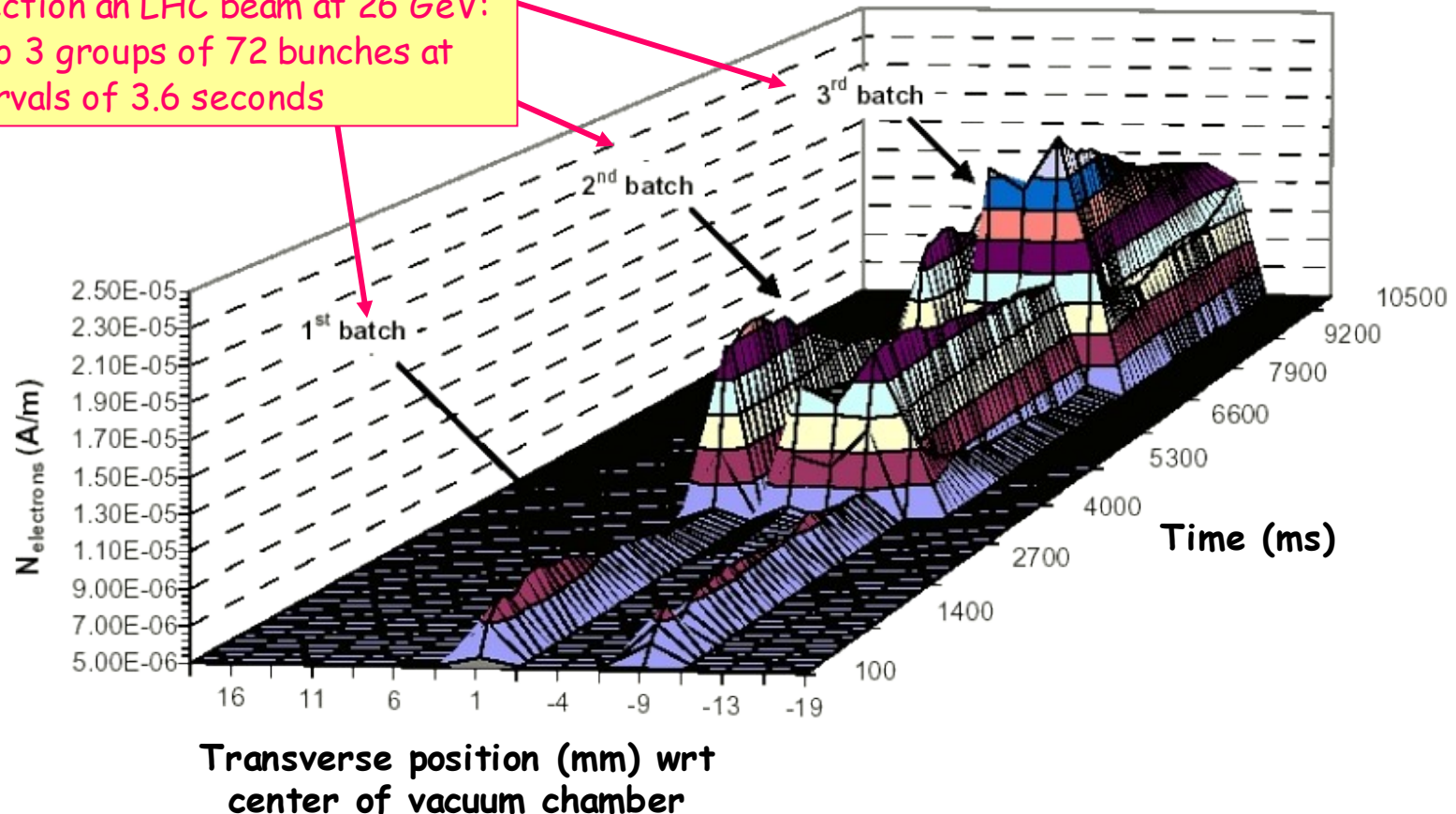


Electron Cloud Measurements at SPS

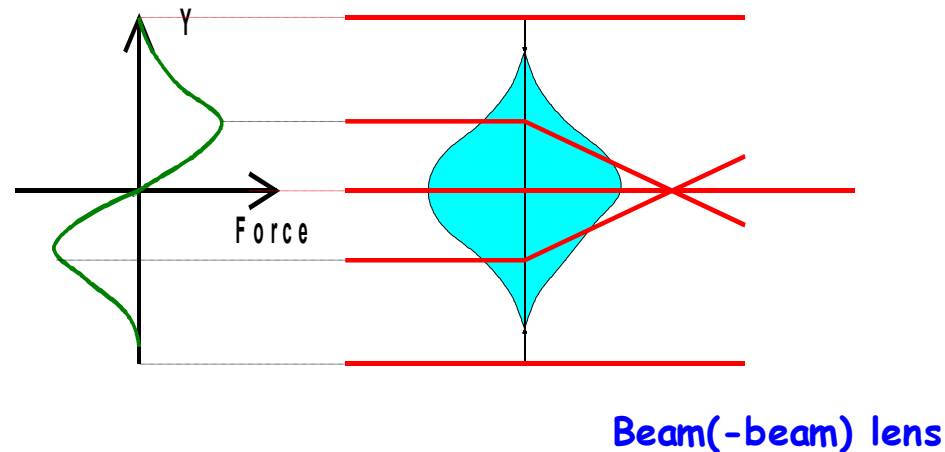
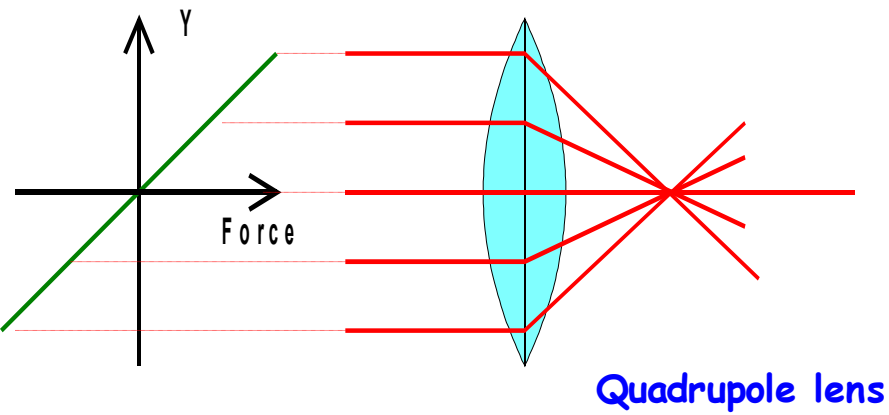
The cloud grows with the number of closely spaced bunches: each bunch amplifies the cloud (until it saturates)



Injection an LHC beam at 26 GeV:
up to 3 groups of 72 bunches at
intervals of 3.6 seconds



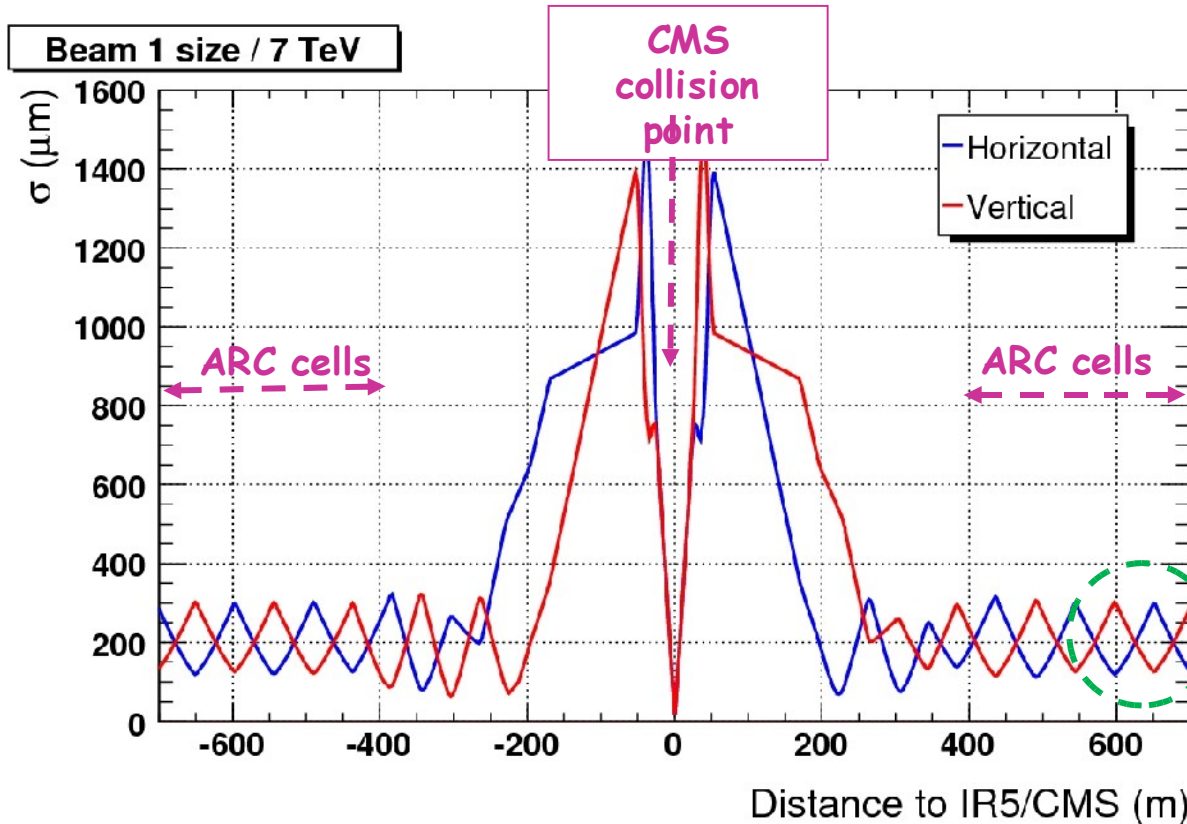
'Beam-beam' interaction



- When a particle of one beam encounters the opposing beam at the collision point, it senses the fields of the opposing beam.
- Due to the typically Gaussian shape of the beams in the transverse direction, the field (force) on this particle is non-linear, in particular at large amplitudes !
- The effect of the non-linear fields can become so strong (when the beams are intense) that large amplitude particles become unstable and are lost from the machine:
 - poor lifetime
 - background

THE INTERACTION OF THE BEAMS SETS A LIMIT ON THE BUNCH INTENSITY!

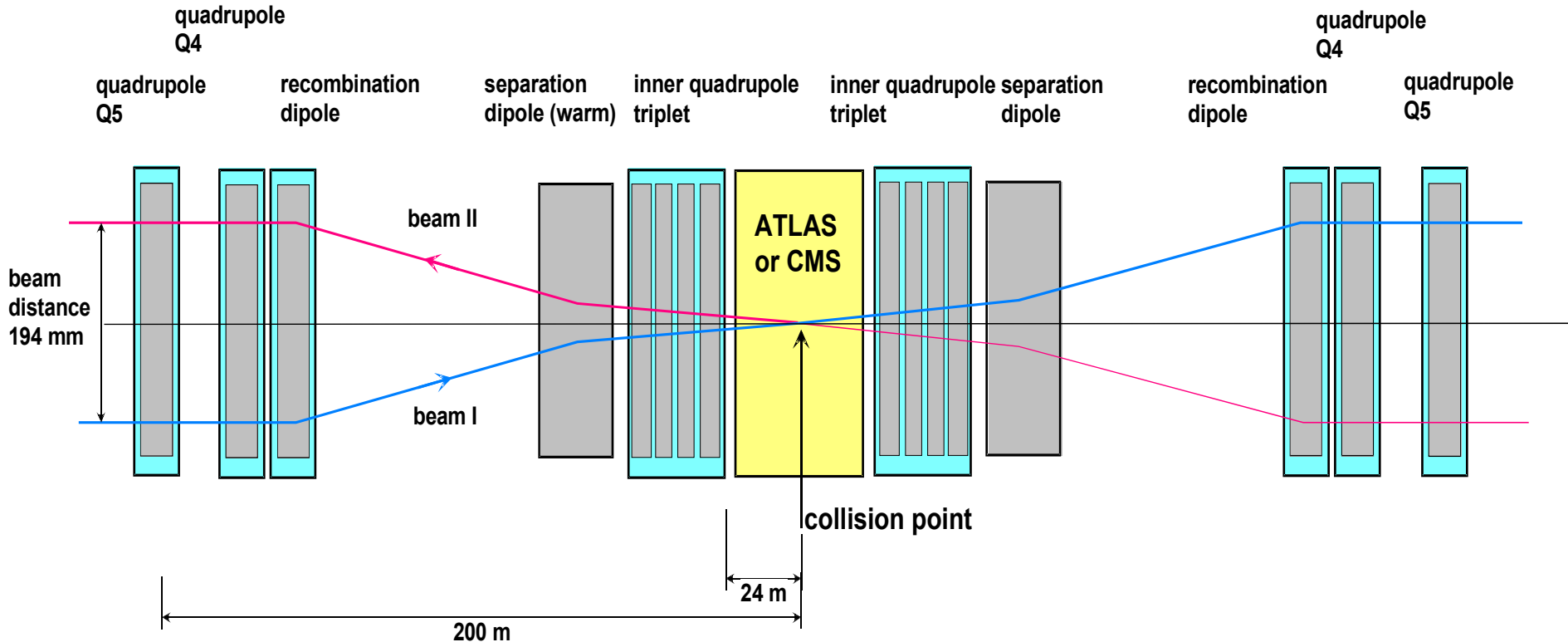
Beam envelope



Fits through the hole of a needle!

- The envelope of the size beam is given by the so-called ' β -function' (\Leftrightarrow optics):
 - In the arcs the optics follows a regular pattern.
 - In the long straight sections, the optics is matched to the 'telescope' that provides very strong focusing at the collision point.
- Collision point size (rms, defined by ' β^* '):
CMS & ATLAS : 16 μm LHCb : 22 - 160 μm ALICE : 16 μm (ions) / >160 μm (p)

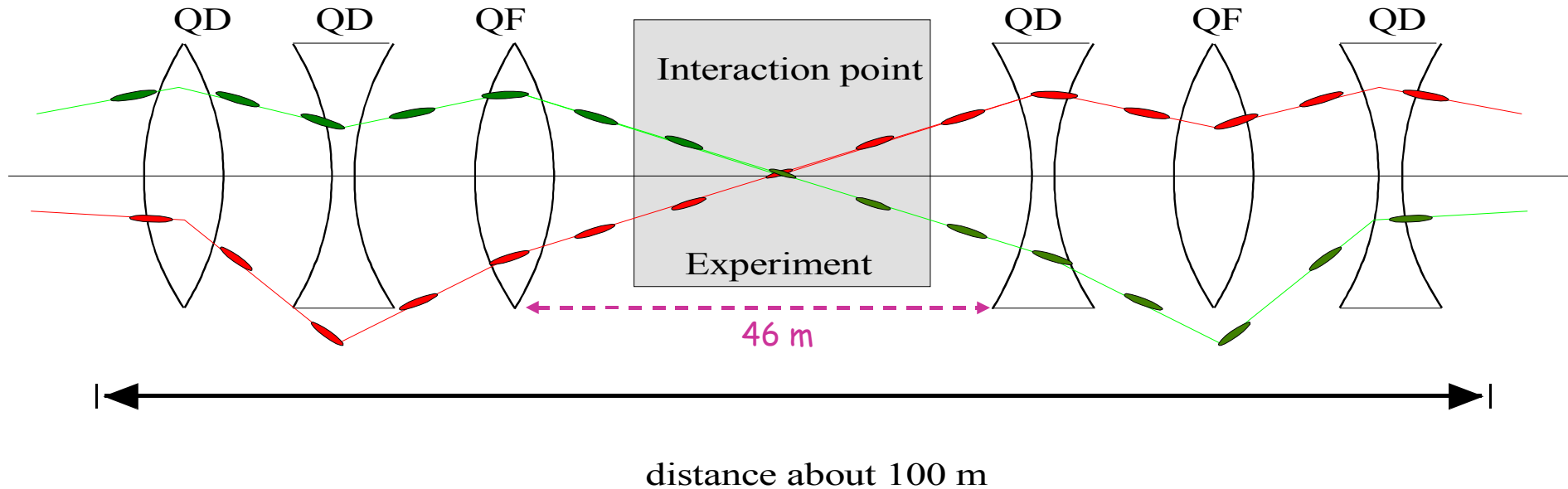
Combining the beams for collisions



Example for an LHC insertion with ATLAS or CMS

- The 2 LHC beams circulate in separate vacuum chambers in most of the ring, but they must be brought together to collide.
- Over a distance of about 260 m, the beams circulate in the same vacuum chamber and they are a total of ~ 120 encounters in ATLAS, CMS, ALICE and LHCb.

Interaction region layout



- The final focus is made with the high gradient and large aperture 'triplet' quadrupoles (US-JAPAN):
 - Large beam size $\sim 100 \times$ size at IP
 - Large beam separation from crossing angle ~ 12 mm
- Beam sizes :

- at IP (ATLAS, CMS)	$\sigma = 16 \mu\text{m}$	$\beta^* = 0.5 \text{ m}$	$\sigma \propto \sqrt{\beta}$
- in the triplets	$\sigma = \sim 1.6 \text{ mm} \beta$	$\sim 5'000 \text{ m}$	
- in the arcs	$\sigma = \sim 0.2 \text{ mm}$	$\beta = 200 \text{ m}$	

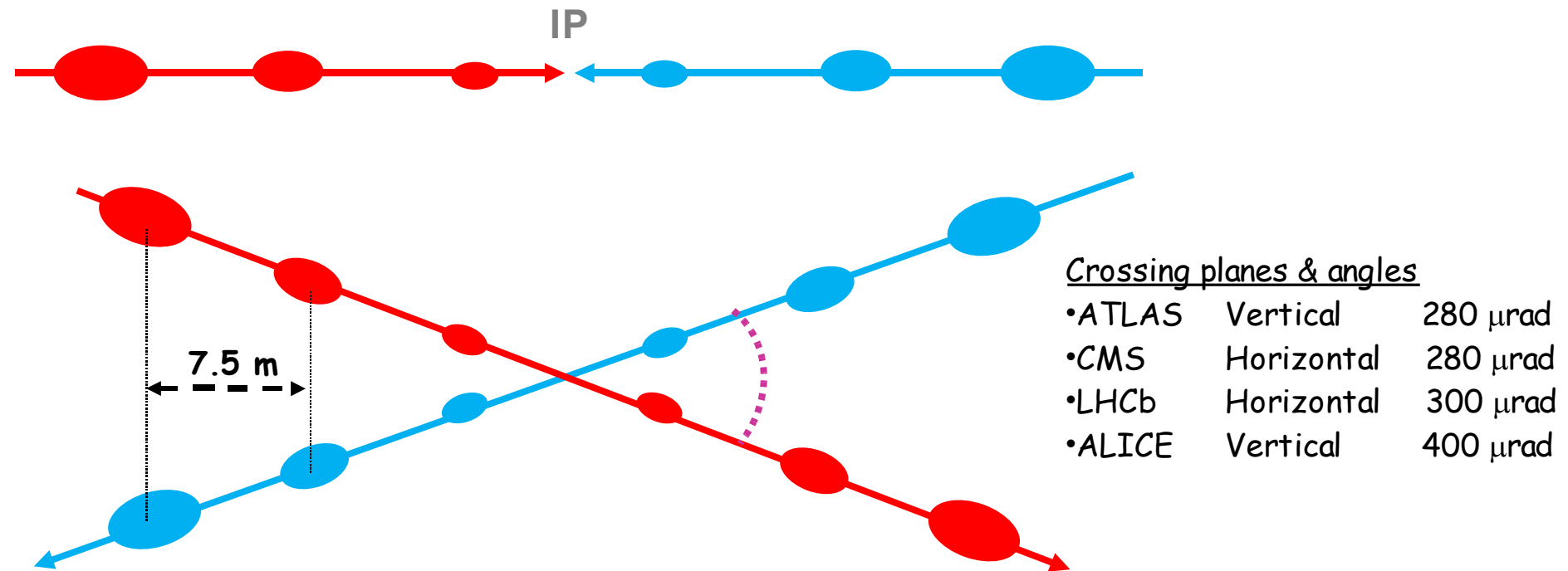
Crossing angles

- Since every collision adds to the 'Beam-beam budget' un-necessary direct beam encounters must be avoided wherever the beams share a common vacuum:

COLLIDE WITH A CROSSING ANGLE IN ONE PLANE!

- There is a price to pay :

A reduction of the luminosity due to the finite bunch length of 7.6 cm and the non-head on collisions → L reduction of ~ 17%.



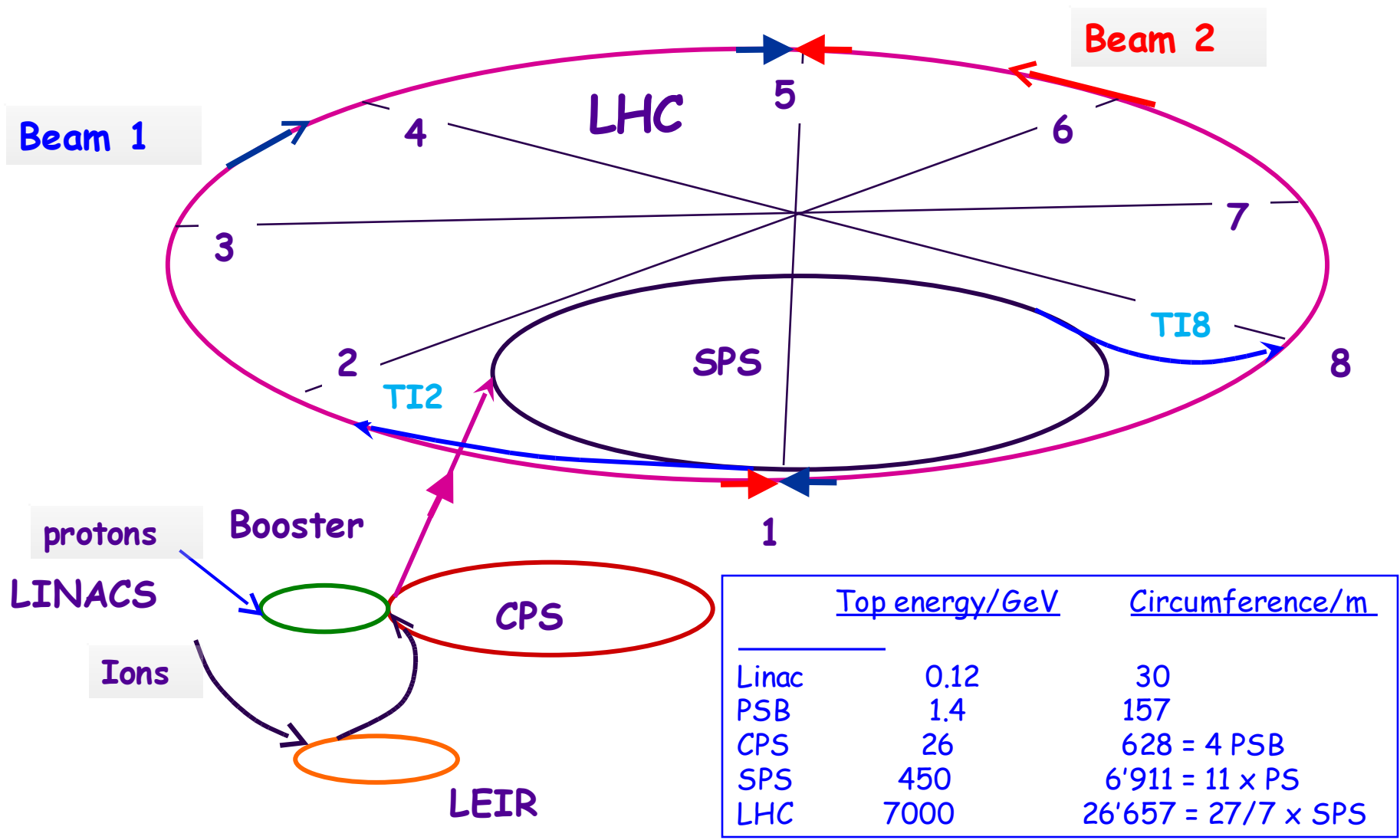
The LHC Injectors

The LHC injector complex

- The CERN Proton Injectors:
 - Linac 2 (1979)
 - Proton Synchrotron Booster (4 superposed rings !) - PSB (1972)
 - Proton Synchrotron - PS (1959)
 - Super Proton Synchrotron - SPS (1976)

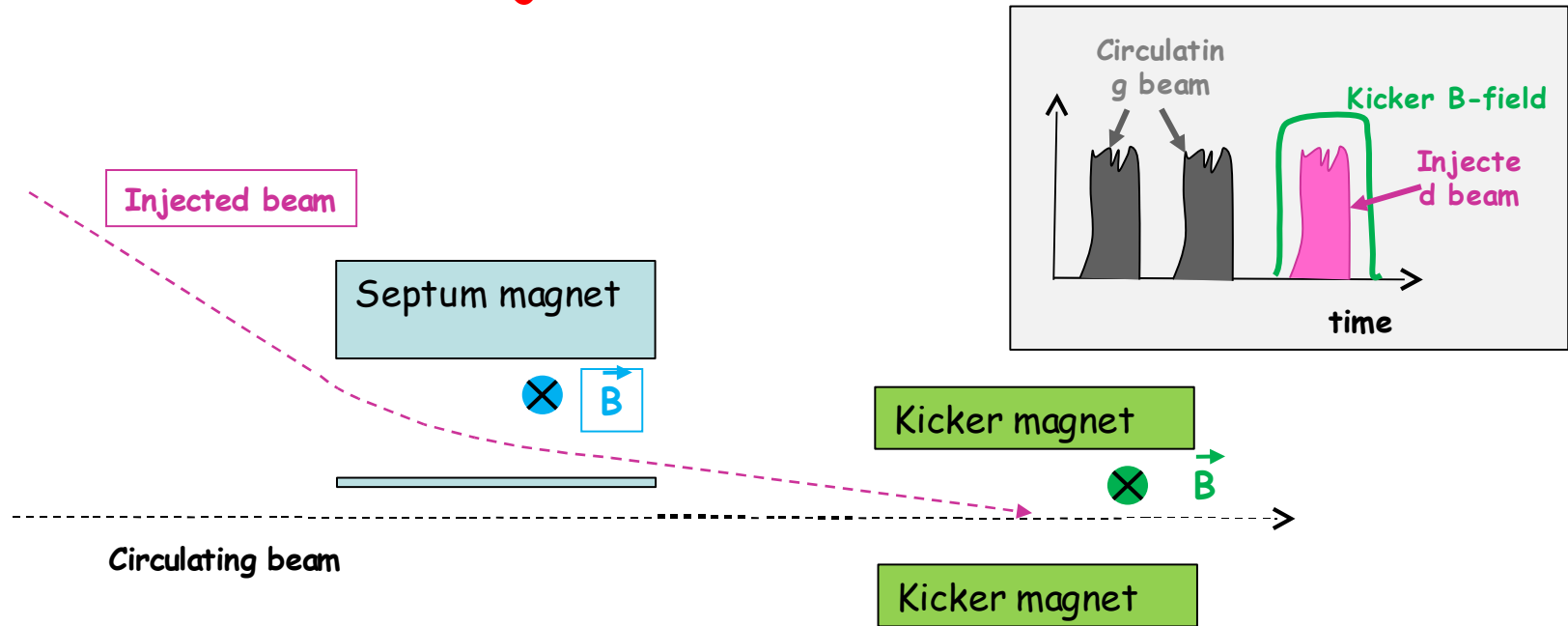
- The PSB-PS-SPS Complex had to be upgraded in order to provide the beams with the appropriate intensity, pattern (25 ns spacing) and size for the LHC !
- Two 3 km long new transfer lines had to be build to transfer the 450 GeV SPS beam to the LHC.
- Latest items that have been commissioned, both October/November 2007 :
 - The transfer line for the injection into ring 1 (injected in IR2/ALICE).
 - The lead ion beam in the SPS: accelerated to 450 GeV and extracted into the transfer line to the LHC.

The injectors have a delicate task, because protons (and ions) 'remember' everything you do to them - in particular the harmful things that increase the beam size !



Note the energy gain/machine of 10 to 20 - and not more !
 The gain is typical for the useful range of magnets !!!

LHC beam injection (and extraction)



- A **septum dipole magnet** (with thin coil) is used to bring the injected beam close to the circulating beam.
- A **fast pulsing dipole magnet ('kicker')** is fired synchronously with the arrival of the injected beam: deflects the injected beam onto the circulating beam path.
→ 'Stack' the injected beams one behind the other.
- At the LHC the septum deflects in the horizontal plane, the kicker in the vertical plane (to fit to the geometry of the tunnels).
- Extraction is identical, but the process is reversed !

Bunch patterns

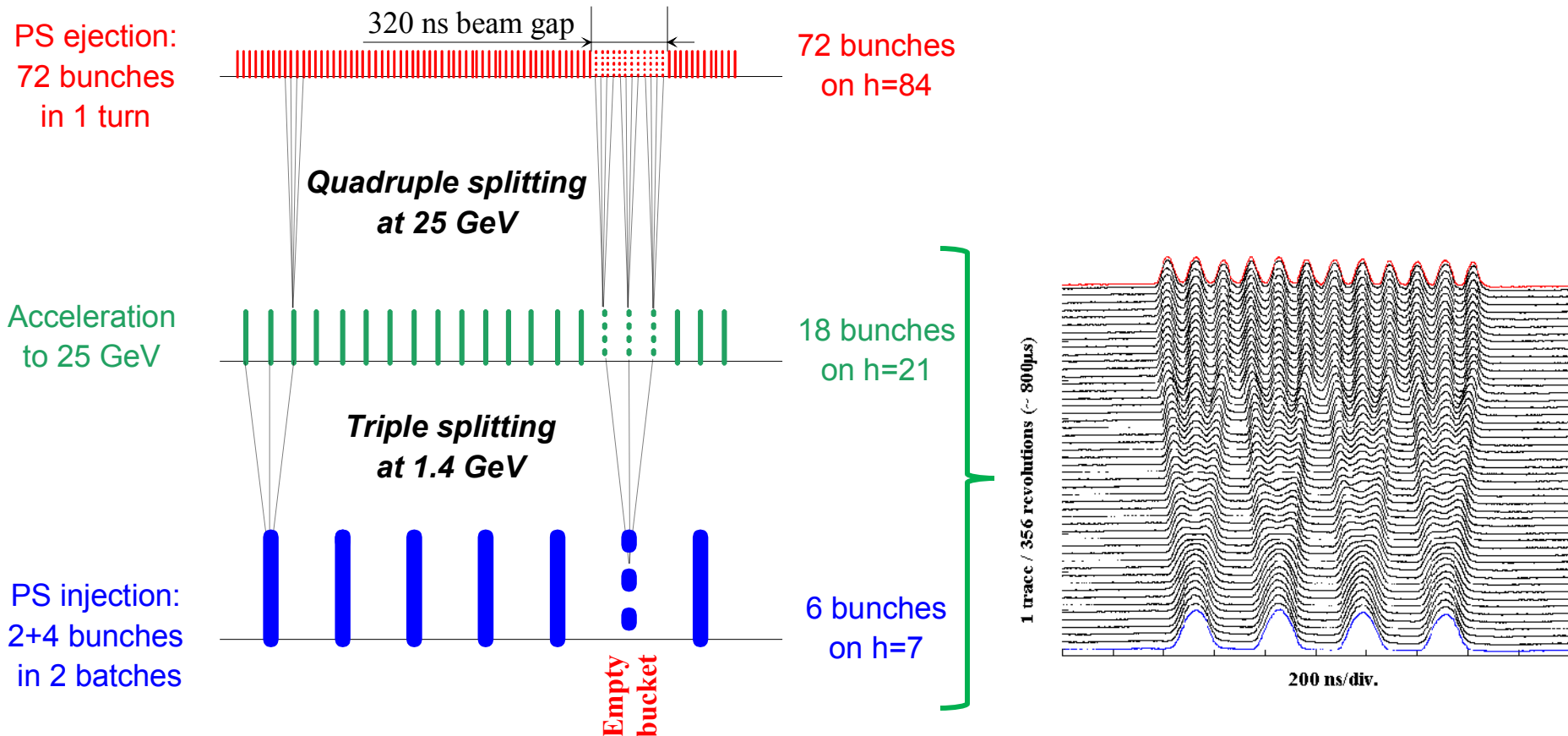
The nominal bunch pattern of the LHC is created by combining and splitting of bunches in the injector chain :

2. 6 booster bunches are injected into the PS.
3. Each of the 6 bunches are split into 12 smaller bunches in the PS, yielding a total of 72 bunches at extraction from the PS.
4. Between 2 and 4 batches of 72 bunches are injected into the SPS, yielding between 144 and 288 bunches at extraction from the SPS.
5. A sequence of 12 extraction of 144 to 288 bunches from the SPS are injected into the LHC.

Machine	Bunches IN	Bunches OUT	Comment
Booster PSB	2-4	2-4	
PS	6	72	2 injections, splitting
SPS	(2-4)x72	144-288	2 to 4 injections
LHC	12x(144-288)	2808	12 injections

Bunch Splitting at the PS

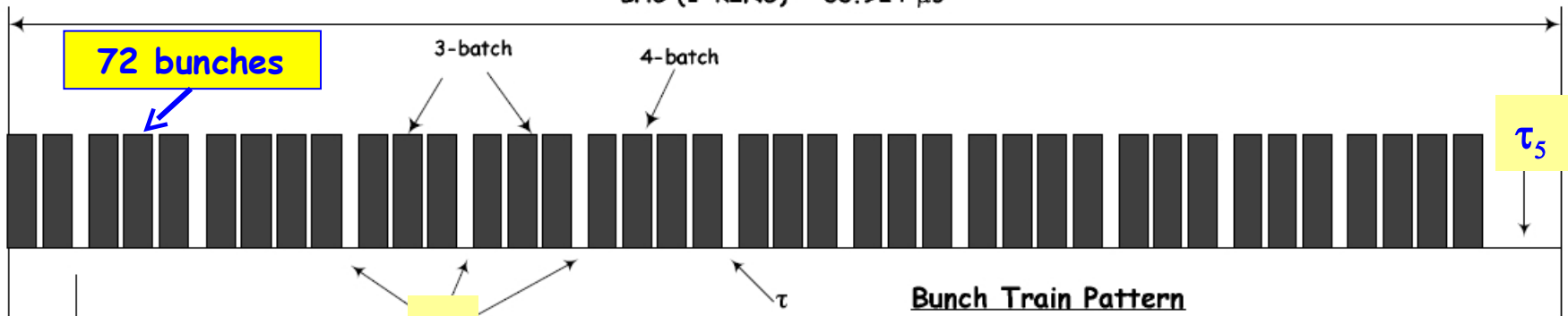
- The bunch splitting in the PS machine is the most delicate operation that is performed in the injector chain.
- The quality of the splitting is critical for the LHC (uniform intensity in all bunches...).



Bunch pattern details

- The nominal LHC pattern consists of 39 groups of 72 bunches (spaced by 25 ns), with variable spacing between the groups to accommodate the rise times of the fast injection and extraction magnets ('kickers').
- There is a long 3 μs hole (τ_5) for the LHC dump kicker (see later).

LHC (1-RING) = 88.924 μs



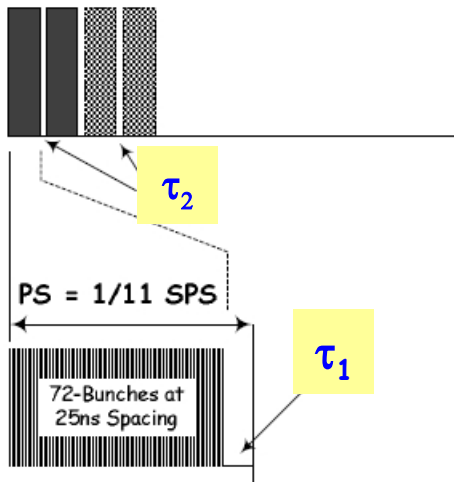
234 334 334 334

Filling Scheme

$$3564 = 2x(72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x(72b + 8e) + 31e + 3x\{2x[3x(72b + 8e) + 30e] + 4x(72b + 8e) + 31e\} + 80e$$

Beam Gaps

- τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
- τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
- τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975 μs)
- τ_4 = 39 missing bunches (" " 1.0 μs)
- τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3 μs)



Machine Protection

The price of high fields & high luminosity...

When the LHC is operated at 7 TeV with its design luminosity & intensity,

- the LHC magnets store a huge amount of energy in their magnetic fields:

per dipole magnet

$$E_{\text{stored}} = 7 \text{ MJ}$$

all magnets

$$E_{\text{stored}} = 10.4 \text{ GJ}$$

- the 2808 LHC bunches store a large amount of kinetic energy:

$$E_{\text{bunch}} = N \times E = 1.15 \times 10^{11} \times 7 \text{ TeV} = 129 \text{ kJ}$$

$$E_{\text{beam}} = k \times E_{\text{bunch}} = 2808 \times E_{\text{bunch}} = 362 \text{ MJ}$$

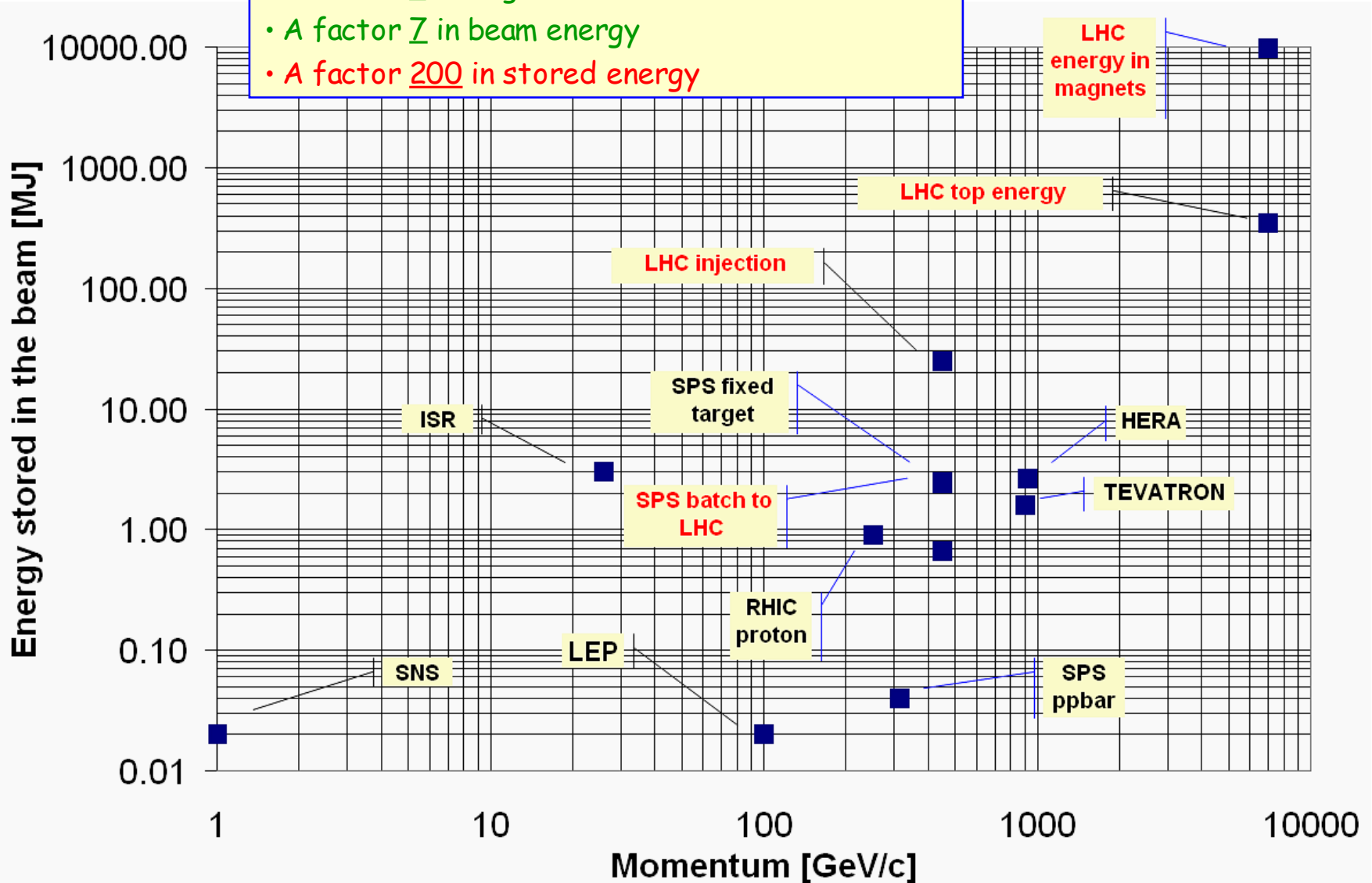
To ensure safe operation (i.e. without damage) we must be able to dispose of all that energy safely !

This is the role of Machine Protection !

Stored Energy

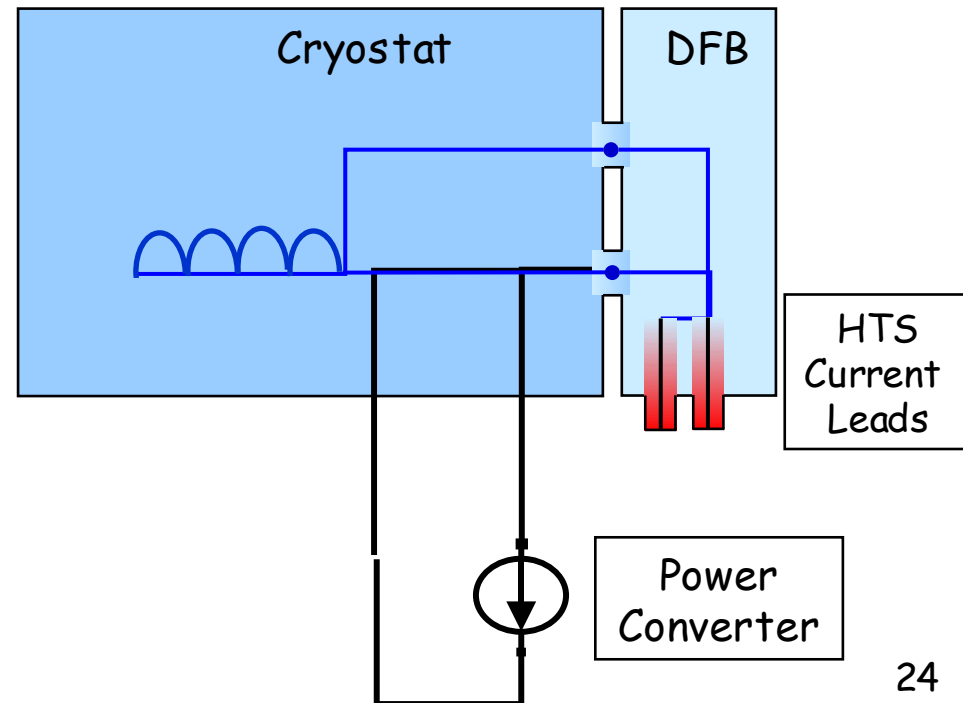
Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy

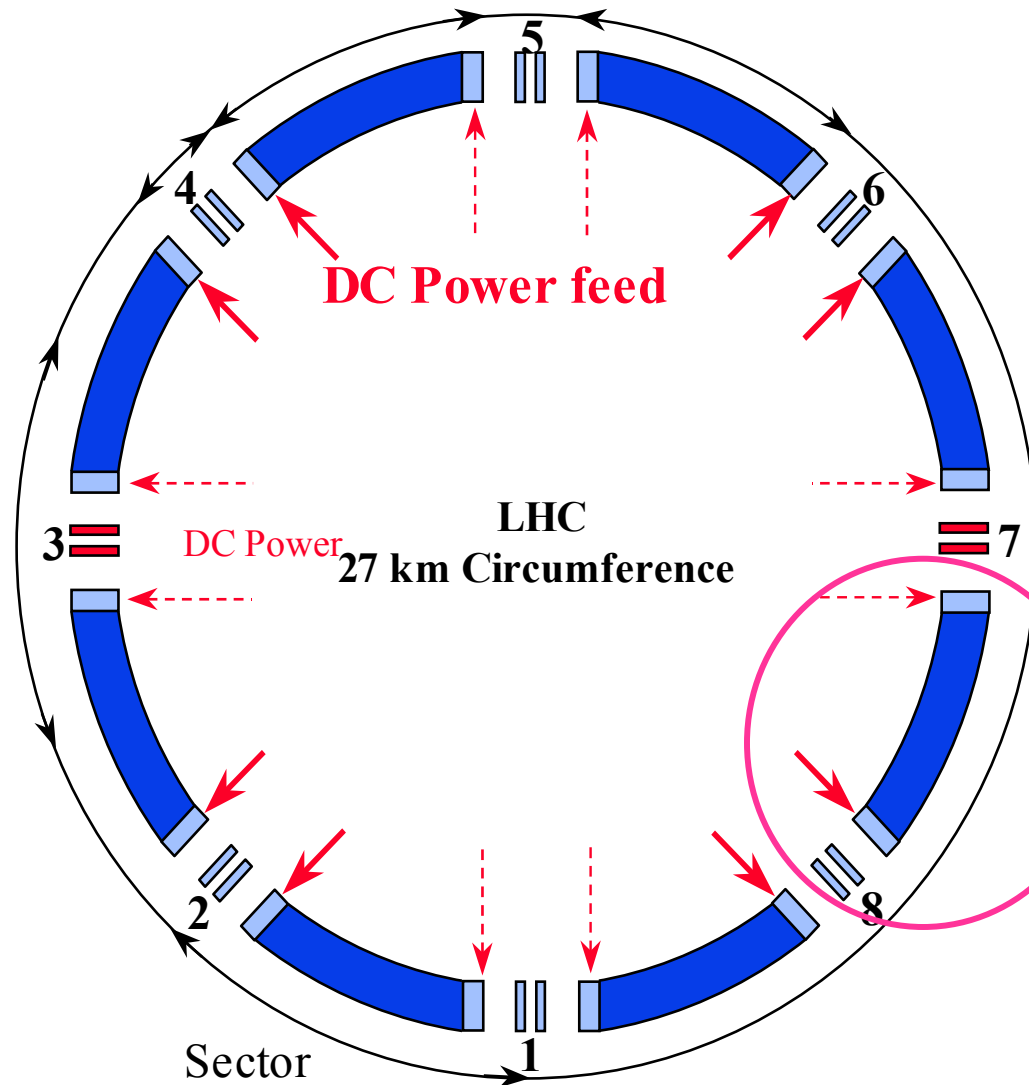


Powering superconducting magnets

- The magnet is cooled down to 1.9K or 4.5K
 - Installed in a cryostat.
- The magnet must be powered
 - Room temperature power converters supply the current.
- The magnet must be connected
 - By superconducting cables inside the cryostat.
 - By normal conducting cables outside the cryostat.
- The superconducting cables must be connected to normal conducting cables
 - Connection via current leads inside special cryostat (DFB)



LHC powering in sectors



- To limit the stored energy within one electrical circuit, the LHC is powered by sectors.
- The main dipole circuits are split into 8 sectors to bring down the stored energy to ~ 1 GJ/sector.
- Each main sector (~ 2.9 km) includes 154 dipole magnets (powered by a single power converter) and ~ 50 quadrupoles.

→ This also facilitates the commissioning that can be done sector by sector !

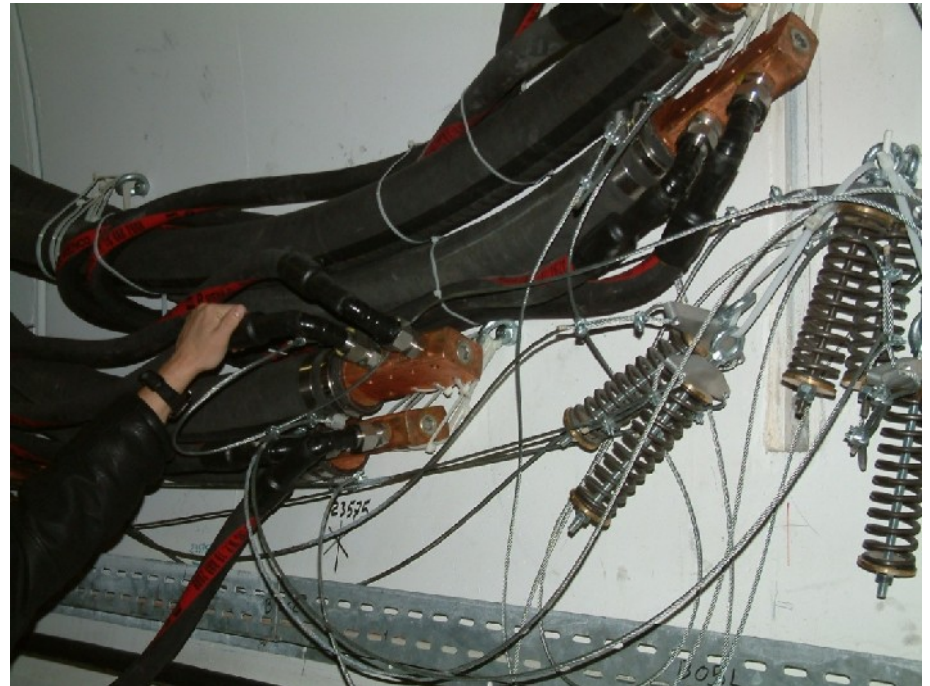
Powering Sector

Powering from room temperature source...

6 kA power converter



Water cooled 13 kA Copper cables
! Not superconducting !



...to the cryostat

Feedboxes ('DFB') : transition from Copper cable to super-conductor

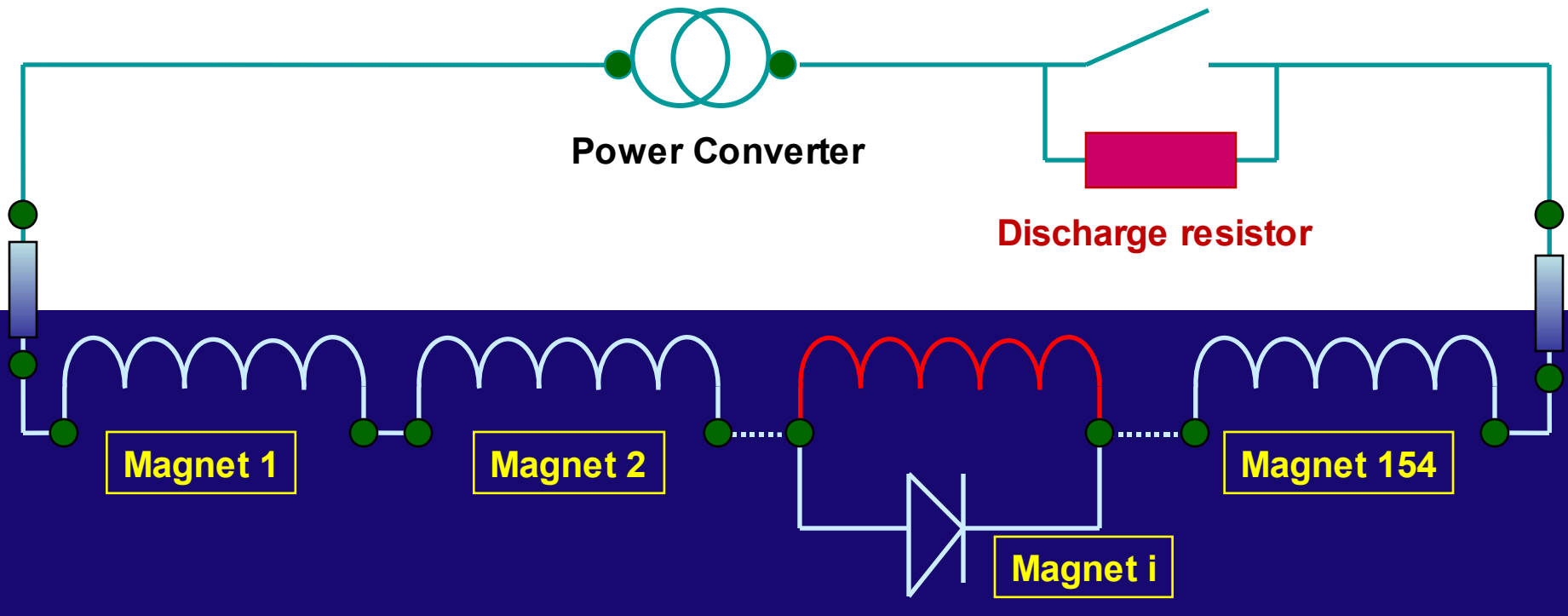
Cooled Cu cables



Quench

- A quench is the phase transition from the super-conducting to a normal conducting state.
- Quenches are initiated by an energy in the order of few mJ
 - Movement of the superconductor by several μm (friction and heat dissipation).
 - Beam losses.
 - Cooling failures.
 - ...
- When part of a magnet quenches, **the conductor becomes resistive**, which can lead to excessive local energy deposition (temperature rise !!) due to the appearance of Ohmic losses. To protect the magnet:
 - The quench must be detected: a voltage appears over the coil ($R \sim 0$ to $R > 0$).
 - The energy release is distributed over the entire magnet by force-quenching the coils using quench heaters (such that the entire magnet quenches !).
 - The magnet current has to be switched off within $\ll 1$ second.

Quench - discharge of the energy



Protection of the magnet after a quench:

- The quench is detected by measuring the voltage increase over coil.
- The energy is distributed in the magnet by force-quenching using quench heaters.
- The current in the quenched magnet decays in < 200 ms.
- The current of all other magnets flows through the bypass diode (triggered by the voltage increase over the magnet) that can stand the current for 100-200 s.
- The current of all other magnets is discharged into the dump resistors.

Dump resistors

Those large air-cooled resistors can absorb the 1 GJ stored in the dipole magnets (they heat up to few hundred degrees Celsius).



If it does not work...



During magnet testing the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

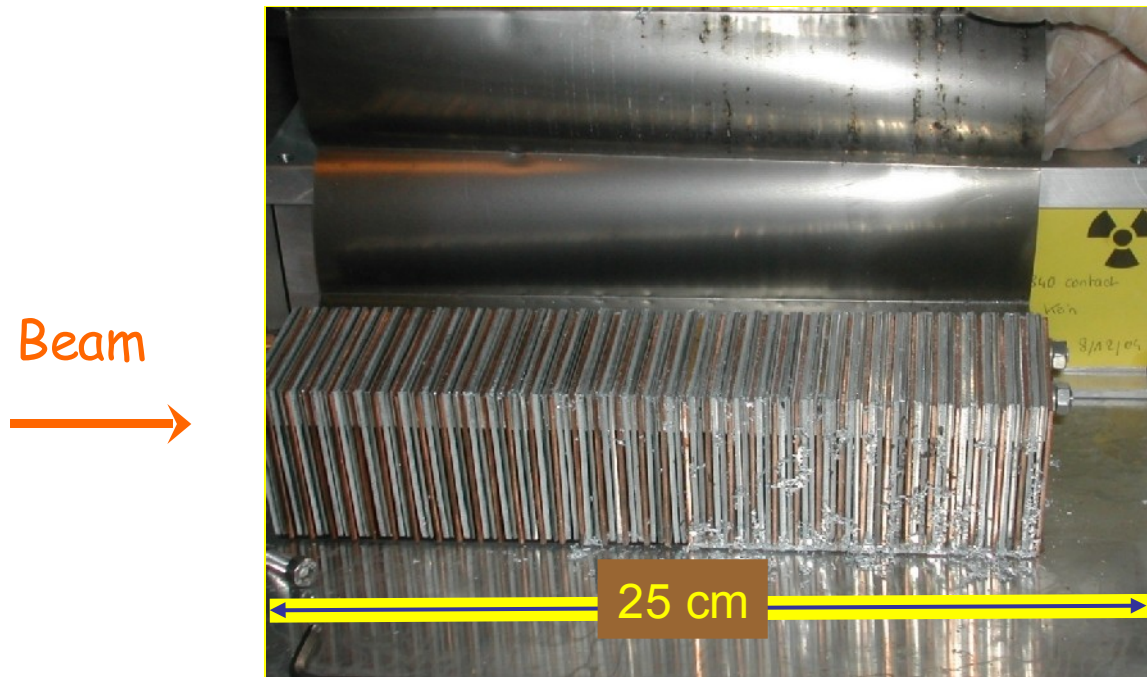
Beam induced damage test

The effect of a high intensity beam impacting on equipment is not so easy to evaluate, in particular when you are looking for damage :

heating, melting, vaporization ...

→ Controlled experiment:

- Special target (sandwich of Tin, Steel, Copper plates) installed in an SPS transfer line.
- Impact of 450 GeV LHC beam (beam size $\sigma_{xy} \sim 1$ mm)

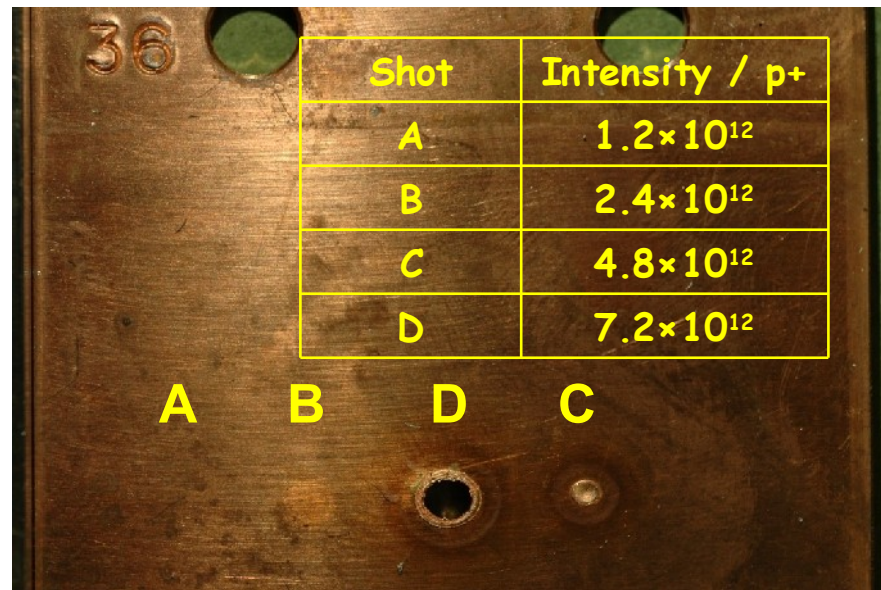


Damage potential of high energy beams

Controlled experiment with 450 GeV beam to benchmark simulations:

- Melting point of Copper is reached for an impact of $\approx 2.5 \times 10^{12}$ p, damage at $\approx 5 \times 10^{12}$ p.
- Stainless steel is not damaged with 7×10^{12} p.
- Results agree with simulation.

Effect of beam impact depends strongly on impact angles, beam size...



Based on those results LHC has a limit for safe beam at 450 GeV of

10^{12} protons \sim 0.3% of the total intensity

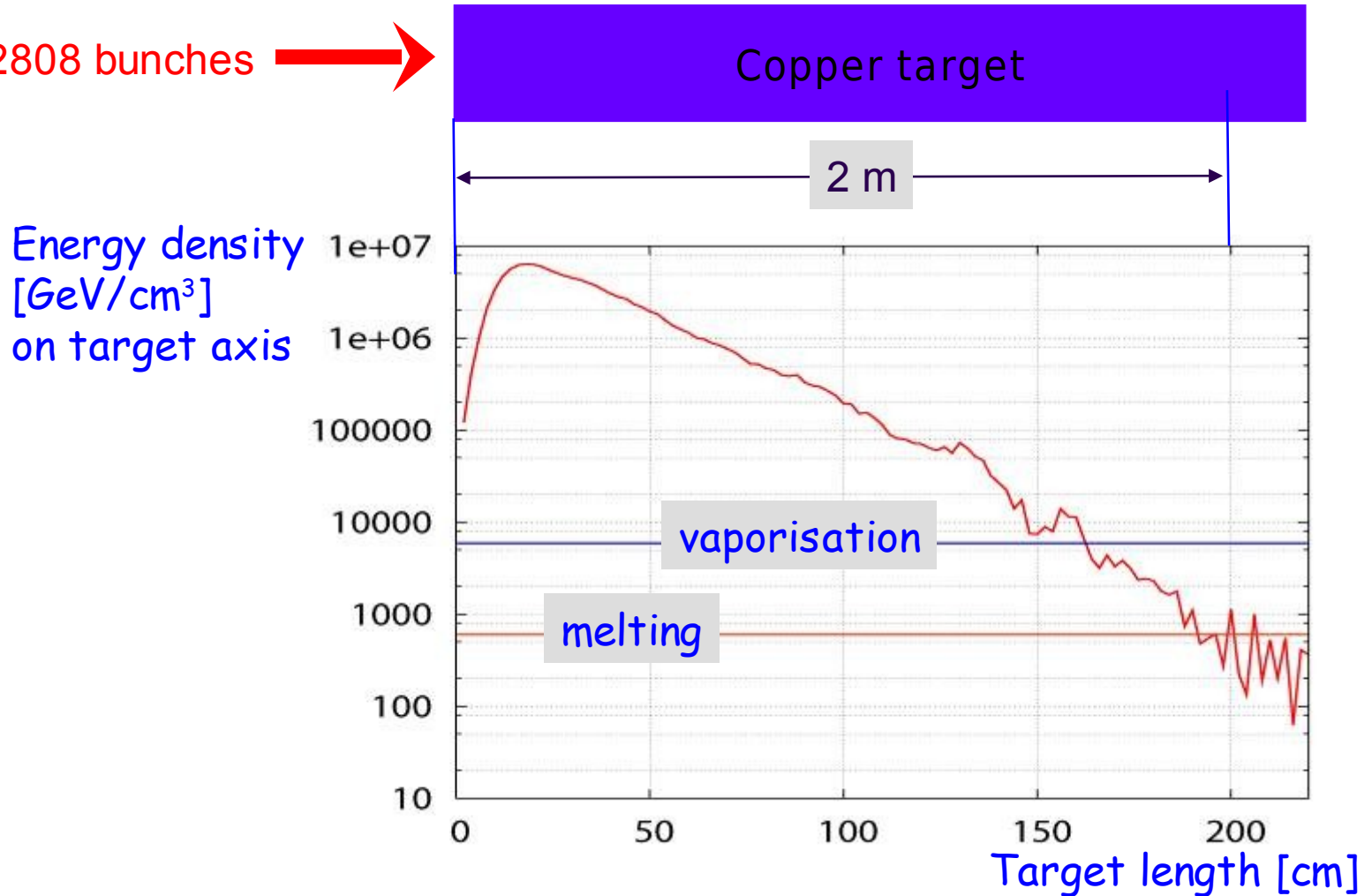
Scaling the results yields a limit @ 7 TeV of

10^{10} protons \sim 0.003% of the total intensity

Safe beam
=
No damage !

Full LHC beam deflected into copper target

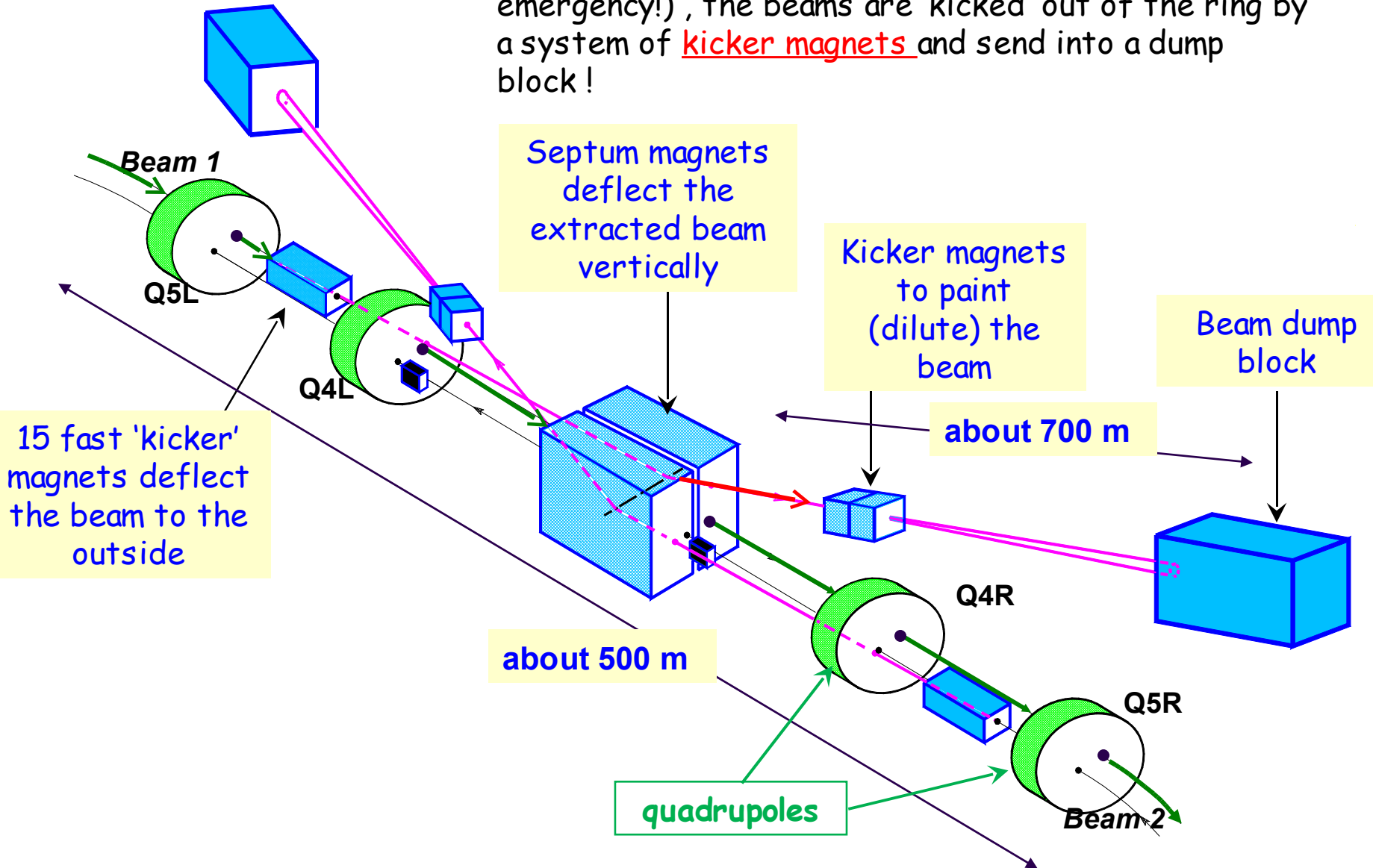
2808 bunches 



The beam will drill a hole along the target axis !!

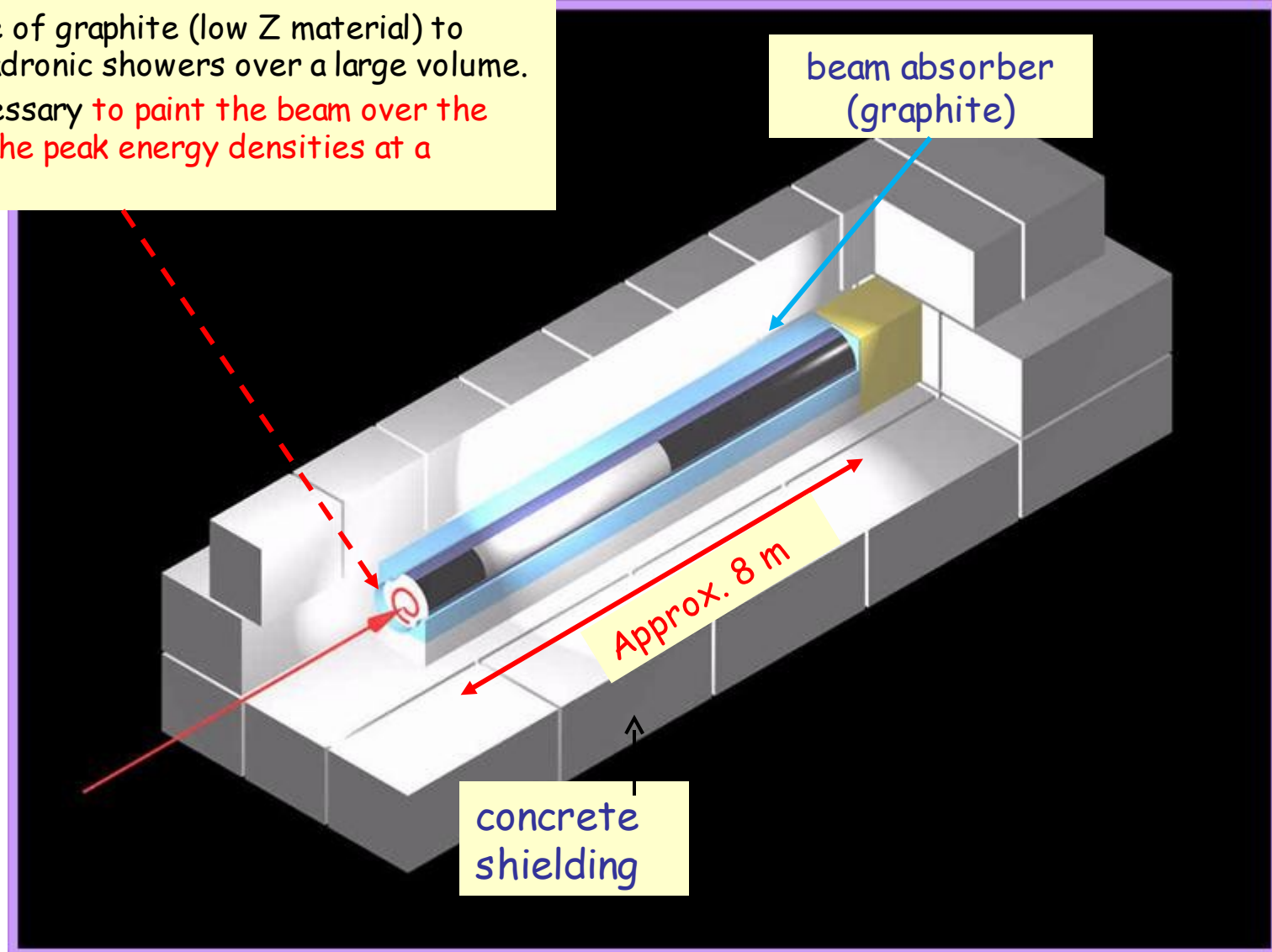
Schematic layout of beam dump system in IR6

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!



The dump block

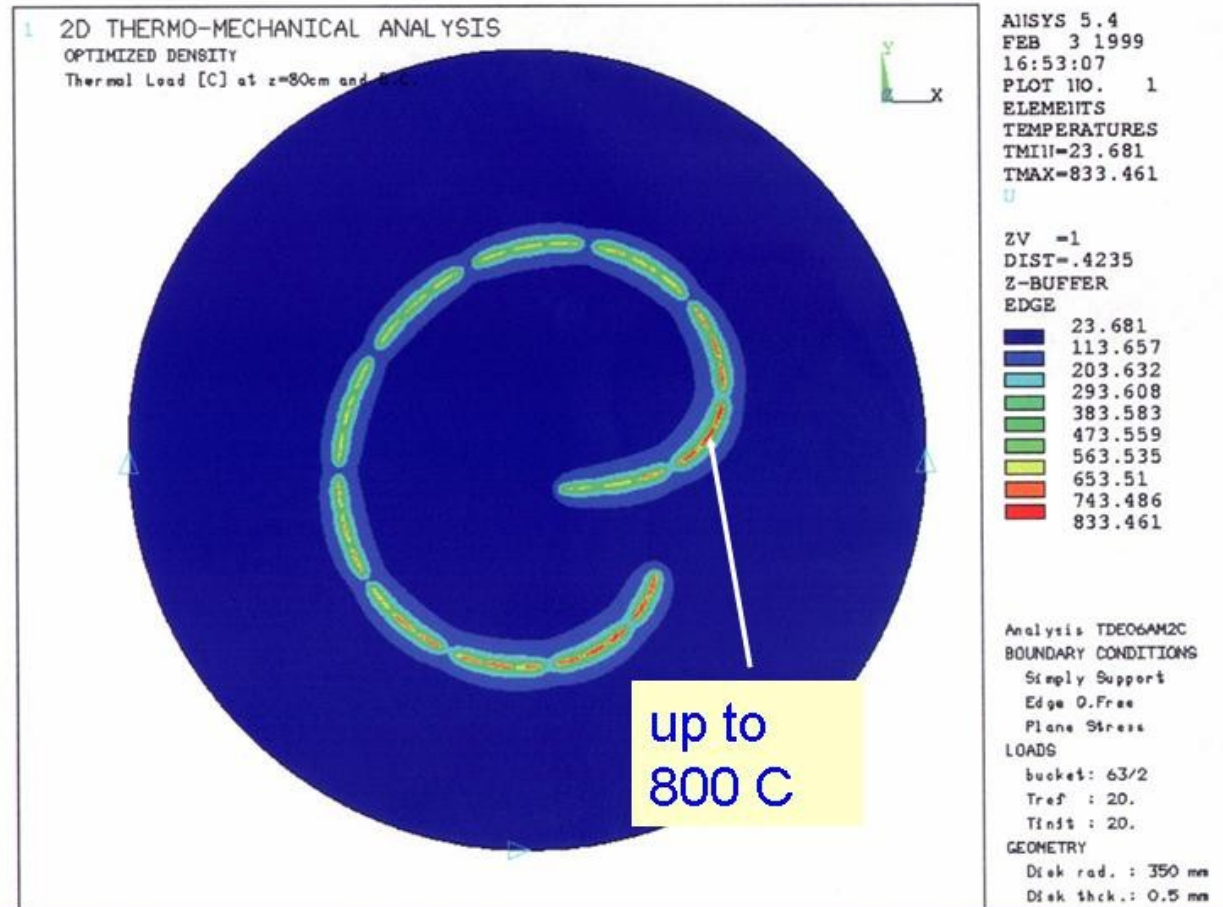
- This is the **ONLY** element in the LHC that can withstand the impact of the full beam!
- The block is made of graphite (low Z material) to spread out the hadronic showers over a large volume.
- It is actually necessary to paint the beam over the surface to keep the peak energy densities at a tolerable level!



Beam on dump block

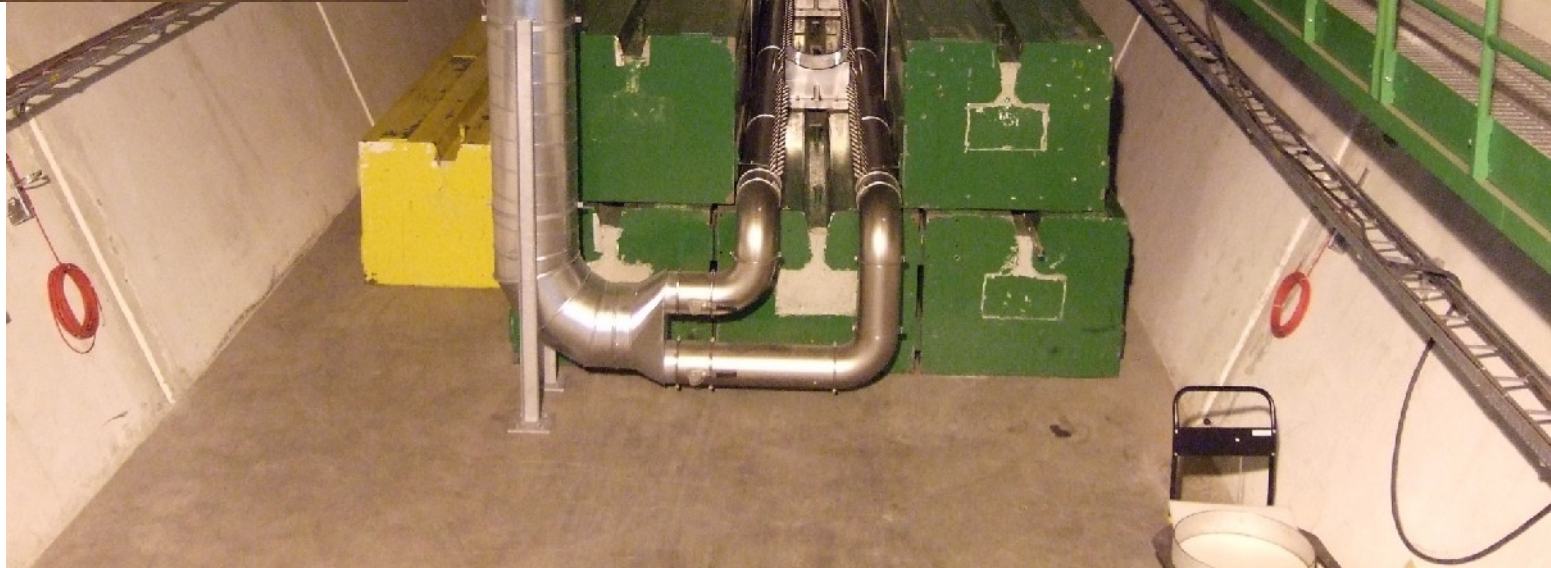
To reduce the peak energy density in the dump block :

- Beam size is increased to ~1 mm due to long distance from ring to the dump block.
- Additional blow up due to dilution kickers: painting of beam on beam dump block.
- Note : the beam impacts over less than 0.1 ms.



L. Bruno: Thermo-Mechanical Analysis with ANSYS

...takes shape !



'Unscheduled' beam loss due to failures

In the event **a failure** or **unacceptable beam lifetime**, the beam must be **dumped immediately and safely** into the **beam dump block**

Two main classes for failures (with more subtle sub-classes):

Beam loss over a single turn

during injection, beam dump or any other fast 'kick'.

Passive protection

- Failure prevention (high reliability systems).
 - Intercept beam with collimators and absorber blocks.
- Active protection systems have no time to react !

Beam loss over multiple turns

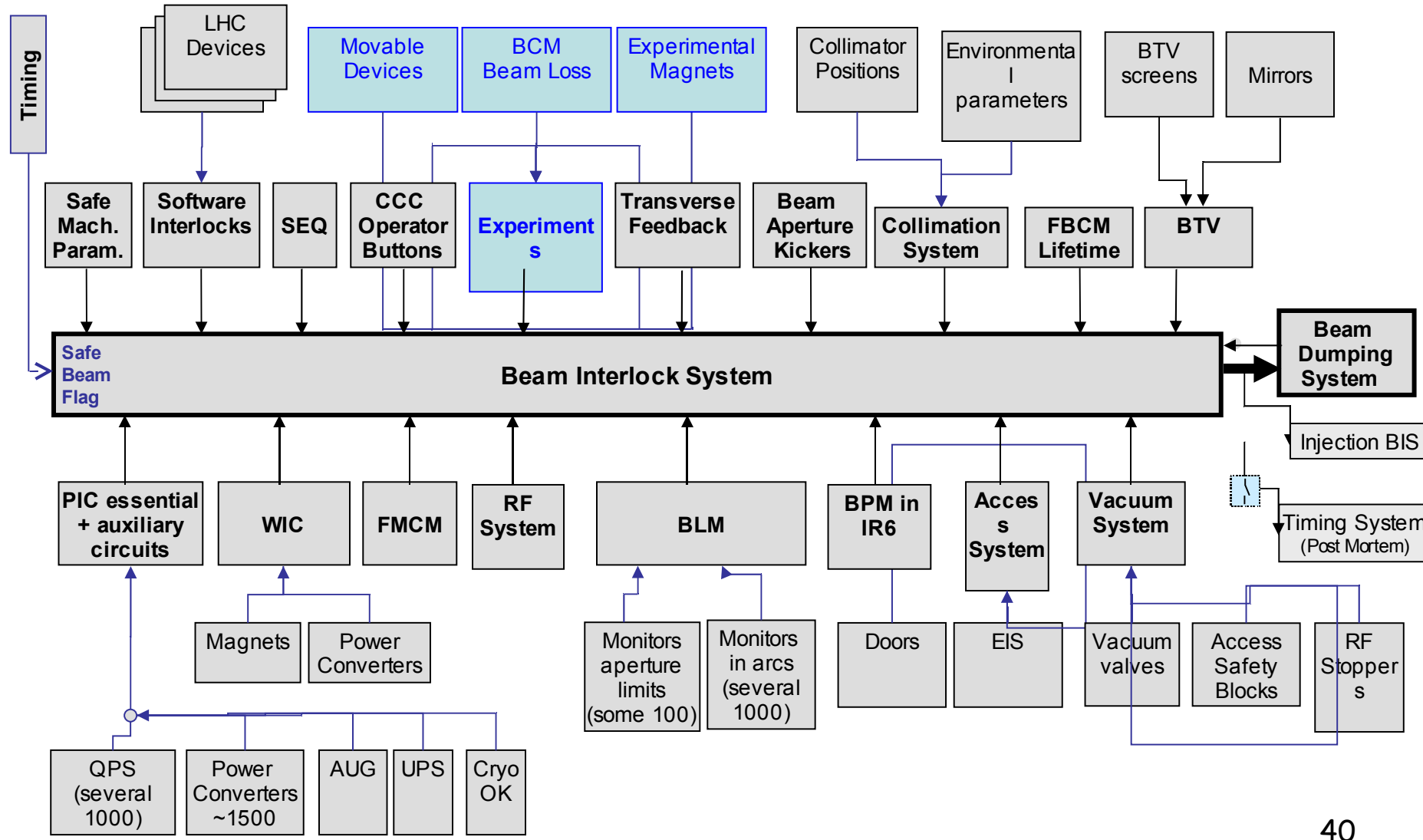
due to many types of failures.

Active Protection

- Failure detection (by beam and/or equipment monitoring) with fast reaction time (< 1 ms).
- Fire beam dumping system

Interlock system

Over 10'000 signals enter the interlock system of the LHC !!



Example : beam loss monitors

- Ionization chambers to detect beam losses:
 - N_2 gas filling at 100 mbar over-pressure, voltage 1.5 kV
 - Sensitive volume 1.5 l
 - Reaction time $\sim \frac{1}{2}$ turn ($40 \mu s$)
 - 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 !



Collimation

Operational margin of SC magnet

Applied Field [T]

B_c critical field

The LHC is ~1000 times more critical than TEVATRON, HERA, RHIC

quench with fast loss of $\sim 10^{6-7}$ protons

8.3 T / 7 TeV

Normal state

Superconducting state

QUENCH

0.54 T / 450 GeV

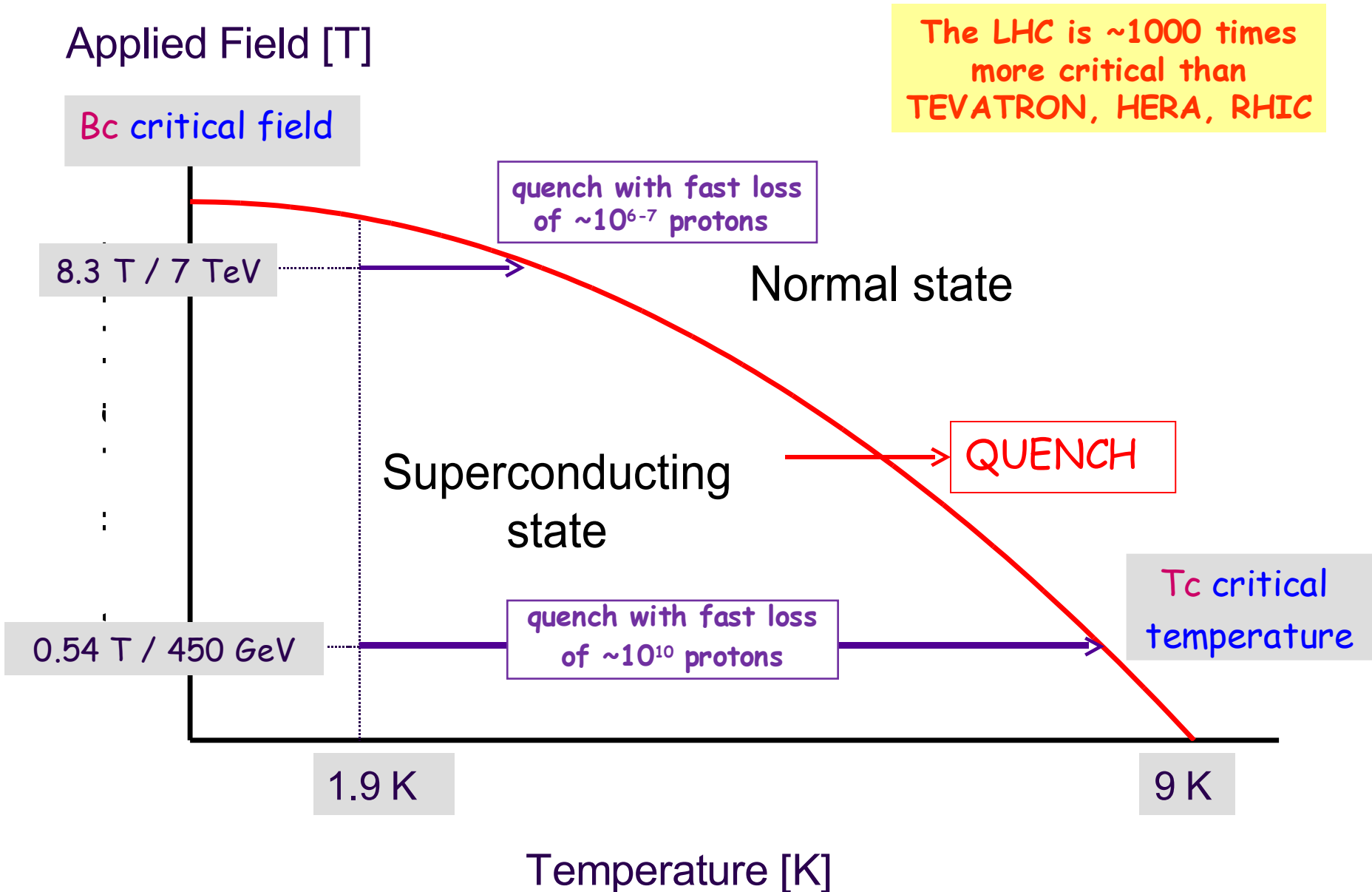
quench with fast loss of $\sim 10^{10}$ protons

T_c critical temperature

1.9 K

9 K

Temperature [K]



Beam lifetime

Consider a beam with a lifetime τ :

$$N(t) = N_0 e^{-t/\tau} \Rightarrow \frac{dN(t)}{dt} = -N(t)/\tau$$

Number of protons lost per second for different lifetimes (nominal intensity):

$$\tau = 100 \text{ hours} \quad \sim 10^9 \text{ p/s}$$

$$\tau = 25 \text{ hours} \quad \sim 4 \times 10^9 \text{ p/s}$$

$$\tau = 1 \text{ hour} \quad \sim 10^{11} \text{ p/s}$$

Quench level $\sim 10^{6-7}$ p

While 'normal' lifetimes will be in the range of 10-100 hours (in collisions most of the protons are actually lost in the experiments !!), one has to anticipate short periods of low lifetimes.

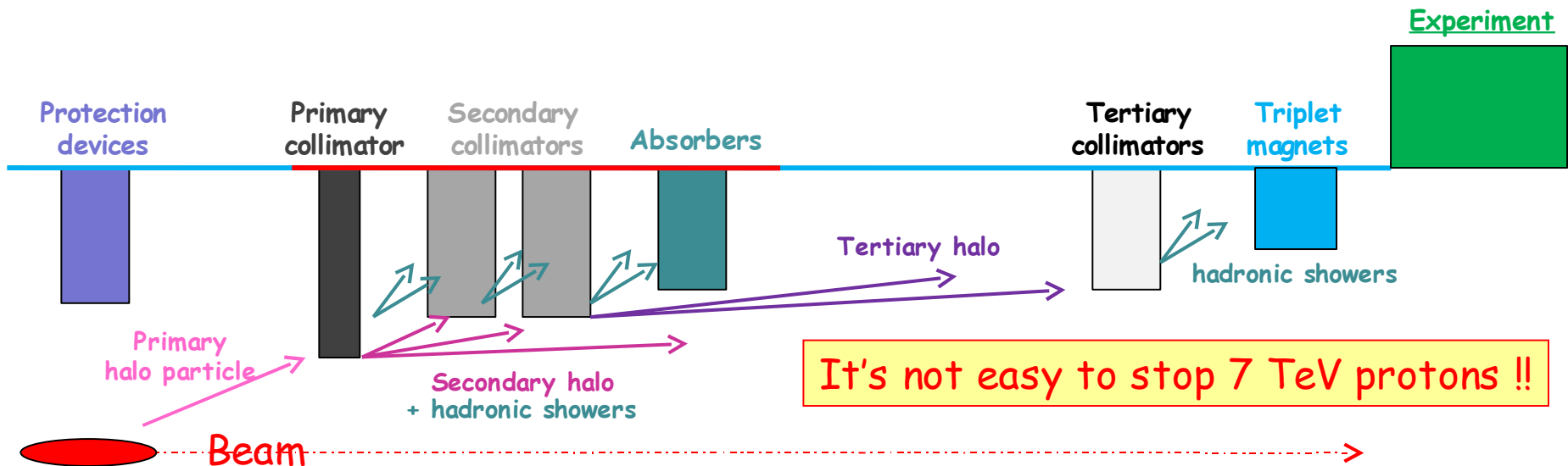
→ To survive periods of low lifetime (down to 0.2 hours) we must intercept the protons that are lost with very very high efficiency before they can quench a superconducting magnet : collimation!

Beam collimation

A multi-stage halo cleaning (collimation) system has been designed to protect the sensitive LHC magnets from beam induced quenches :

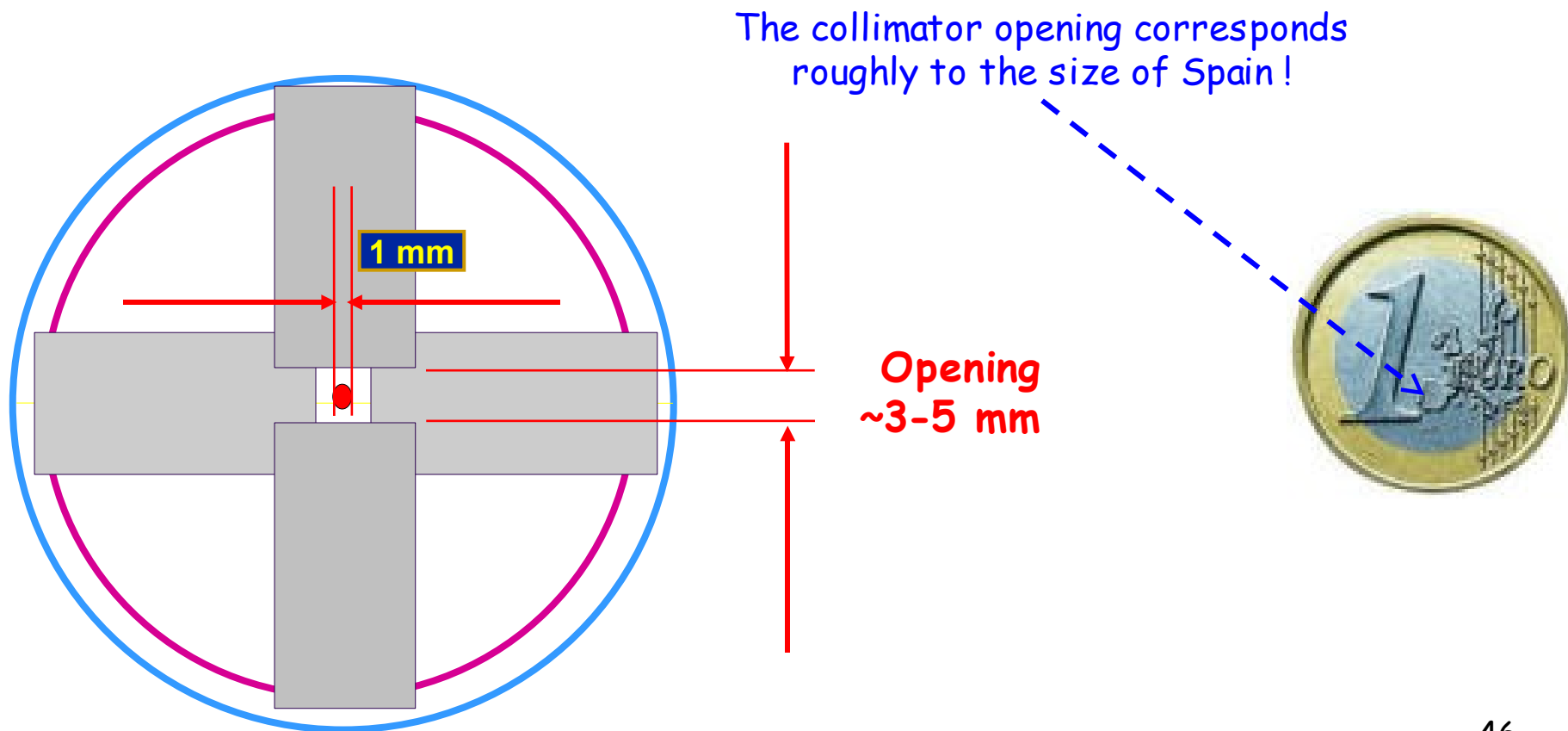
- ❑ Halo particles are first scattered by the primary collimator (closest to the beam).
- ❑ The scattered particles (forming the secondary halo) are absorbed by the secondary collimators, or scattered to form the tertiary halo.
- ❑ More than 100 collimators jaws are needed for the nominal LHC beam.
- ❑ Primary and secondary collimators are made of Carbon to survive severe beam impacts !
- ❑ The collimators must be very precisely aligned (< 0.1 mm) to guarantee a high efficiency above 99.9% at nominal intensities.

→ the collimators will have a strong influence on detector backgrounds !!



Collimator settings at 7 TeV

- For colliders like HERA, TEVATRON, RHIC, LEP collimators are/were used to reduce backgrounds in the experiments ! But the machines can/could actually operate without collimators !
- At the LHC collimators are essential for machine operation as soon as we have more than a few % of the nominal beam intensity !





'Phase 1 Collimator'

Designed for highest robustness.

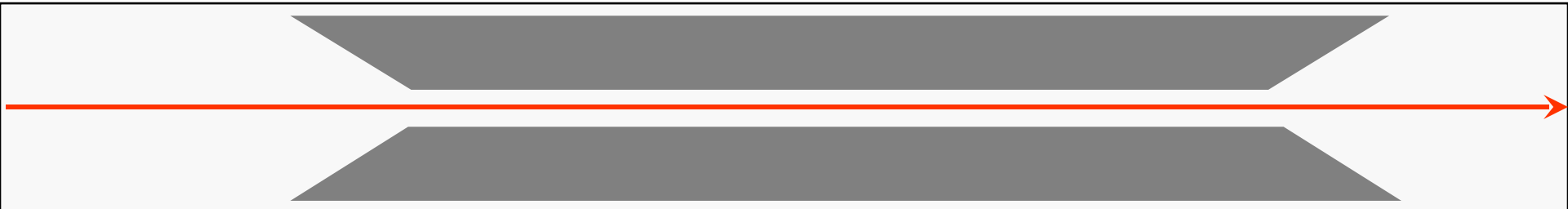
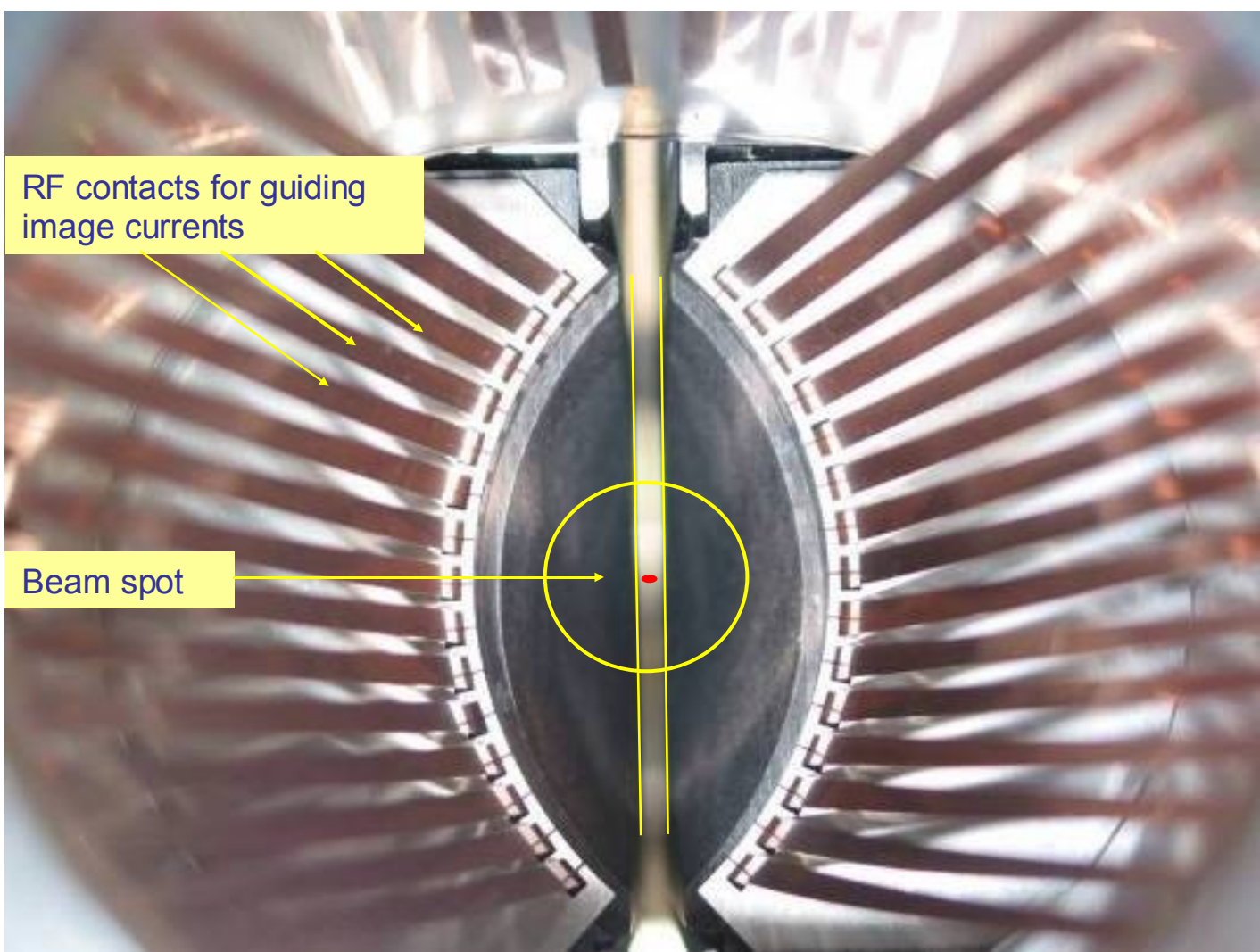
Carbon Composite material for the jaws that are with water cooled.

Drawback : not 'ideal' for beam stability !

>> Second generation collimator with metal coated surfaces..

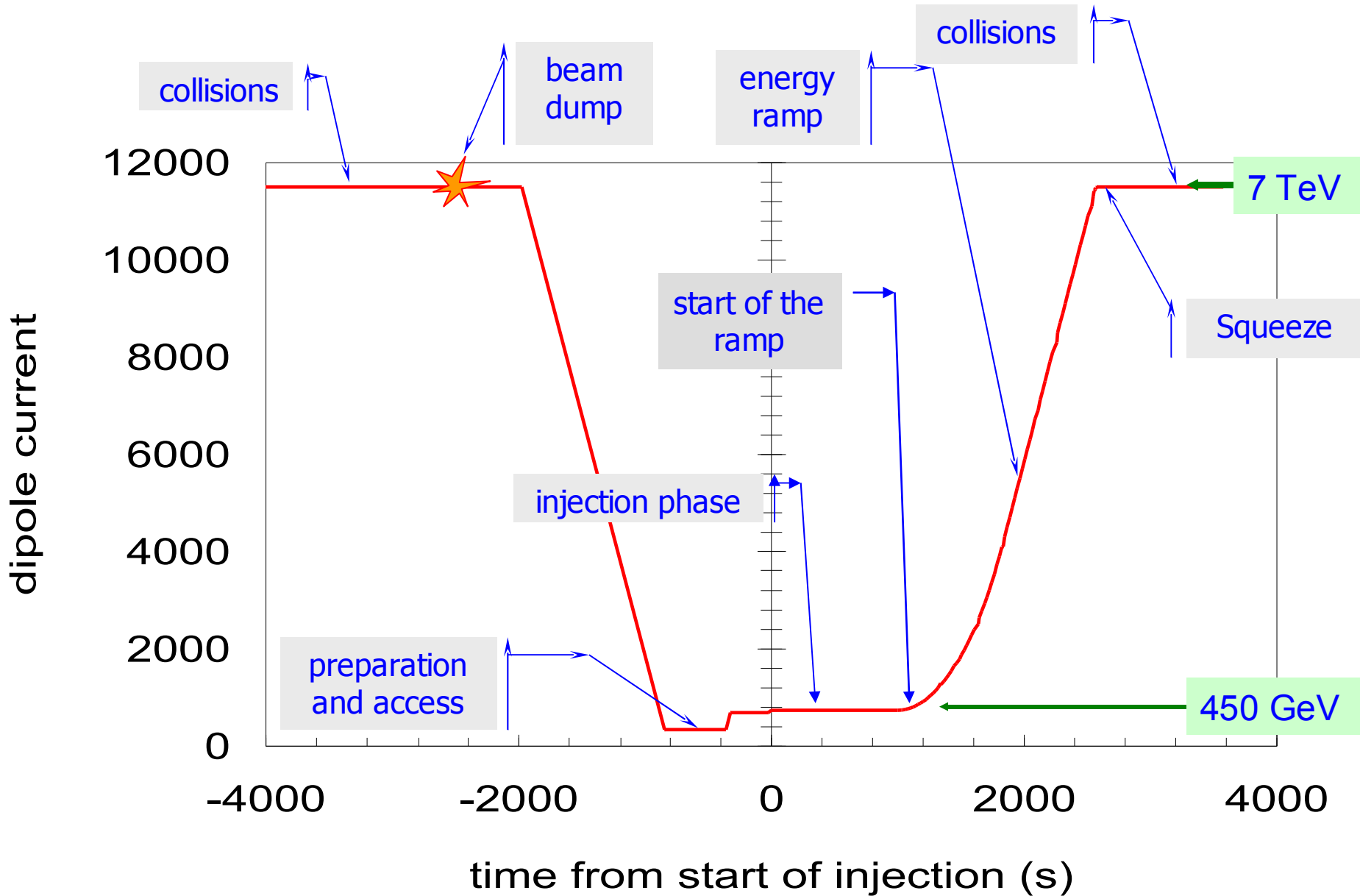
RF contacts for guiding image currents

Beam spot



LHC Operation

The LHC machine cycle



LHC operation : injection

The 'normal' injection sequence into a ring is expected to be:

3. Inject a single bunch into the empty machine:

Check parameters etc... and ensure that it circulates with reasonable lifetime.

5. Inject an intermediate beam of ~ 12 bunches:

Once the low intensity circulates, inject this higher intensity to fine tune parameters, adjust/check collimators and protection devices etc.

7. Once the machine is in good shape, switch to nominal injections:

Each ring requires 12 injections from the SPS, with a repetition rate of 1 every ~25 seconds. This last phase will last ~ 10 minutes.

Once it is 'tuned' the injection phase should take ~ 20 minutes.

...

Ramp and squeeze

- One both beam are injected, they will be ramped to 7 TeV in 20 minutes.

- At 7 TeV :
 - the beams are 'squeezed': the optics in IR1 and IR5 is changed to bring down the β^* (beam size at the collision point) from 10-18 m to the nominal β^* of 0.5 m (or whatever value is desired). The machine becomes much more sensitive to perturbations as β^* is reduced, that is why it is done at 7 TeV.
 - the beams are brought into collision: the magnets that kept the beams separated at the collision points are switched off. First collisions...
 - collimator settings are re-tuned, beam parameters are adjusted to optimize lifetime, reduce backgrounds etc (if needed).
 - all this is probably going to take $\sim \frac{1}{2}$ hour...

- Finally collisions for N hours : probably between 10 and 24 hours.
 - The duration results from an optimization of the overall machine efficiency...
 - The faster the turn-around time, the shorter the runs (higher luminosity !).

Summary

- The design luminosity calls for an amount of stored beam energy that is 2 orders of magnitude above what exists to date...
- .. and this energy must be circulated in superconducting accelerator magnets that are much more sensitive than in other existing machines (Tevatron, RHIC, HERA).
- Operating this collider will have to be very 'clean' and will require some changes in habits: protection and quench prevention are likely issues that will dominate / drive the machine commissioning and operation.

Operating the LHC will be a great challenge !!!