Orbit Stabilization at the Large Hadron Collider (LHC)

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- Introduction to the LHC
- Stabilization issues and requirements
- Expected sources of perturbations
- Overview of the BPM-corrector system
- Conclusions

There will be a ‘follow-up’ talk by R. Steinhagen :
‘Large scale orbit correction for the LHC’

Orbit feedback at a hadron machine ?

Hadron machines are usually not ‘famous’ for their orbit stabilization systems.

This is explained by the fact that the main aim of orbit correction in hadron machines is….

… *to keep the beam in the pipe !*

The LHC is not really different in that respect, but the LHC ‘pipe’ and what is circulating inside are special :

- The LHC is a complex superconducting machine.
- The LHC magnets are very sensitive to beam loss.
- The LHC will explore new territory in terms of stored beam energy.

LHC overview

The LHC is a superconducting proton and ion collider with design luminosity of 10^{34} cm^{-2} s^{-1}

The LHC will be installed in the former 26.7 km long LEP tunnel.

The LHC consists of 2 rings that cross in 4 interaction reagions :

- 2 high lumi exp. (CMS / ATLAS)
- 2 low lumi exp. (ALICE / LHC-B)

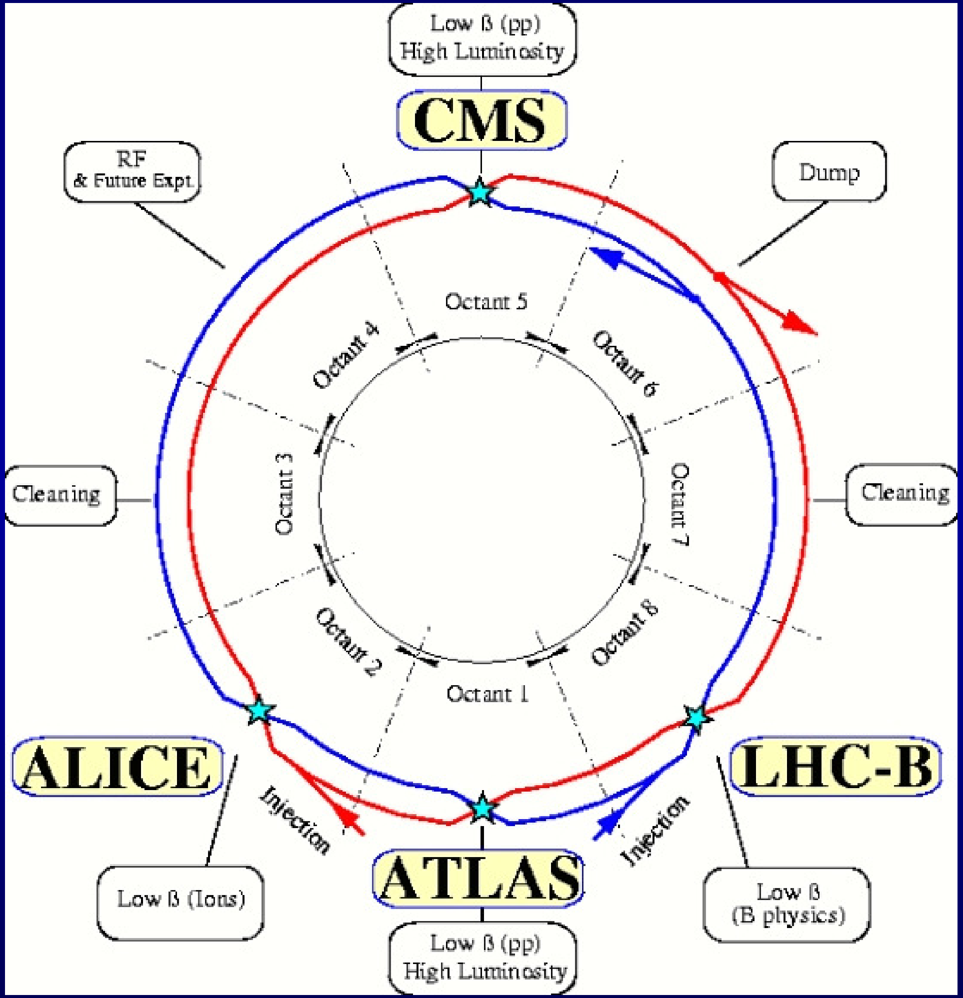
Each ring has 8 arcs and 8 long straight sections.

Energy range :

- Injection at 450 GeV/c
- Collisions at 7 TeV/c

BEAM 1 clockwise

BEAM 2 counter-clockwise

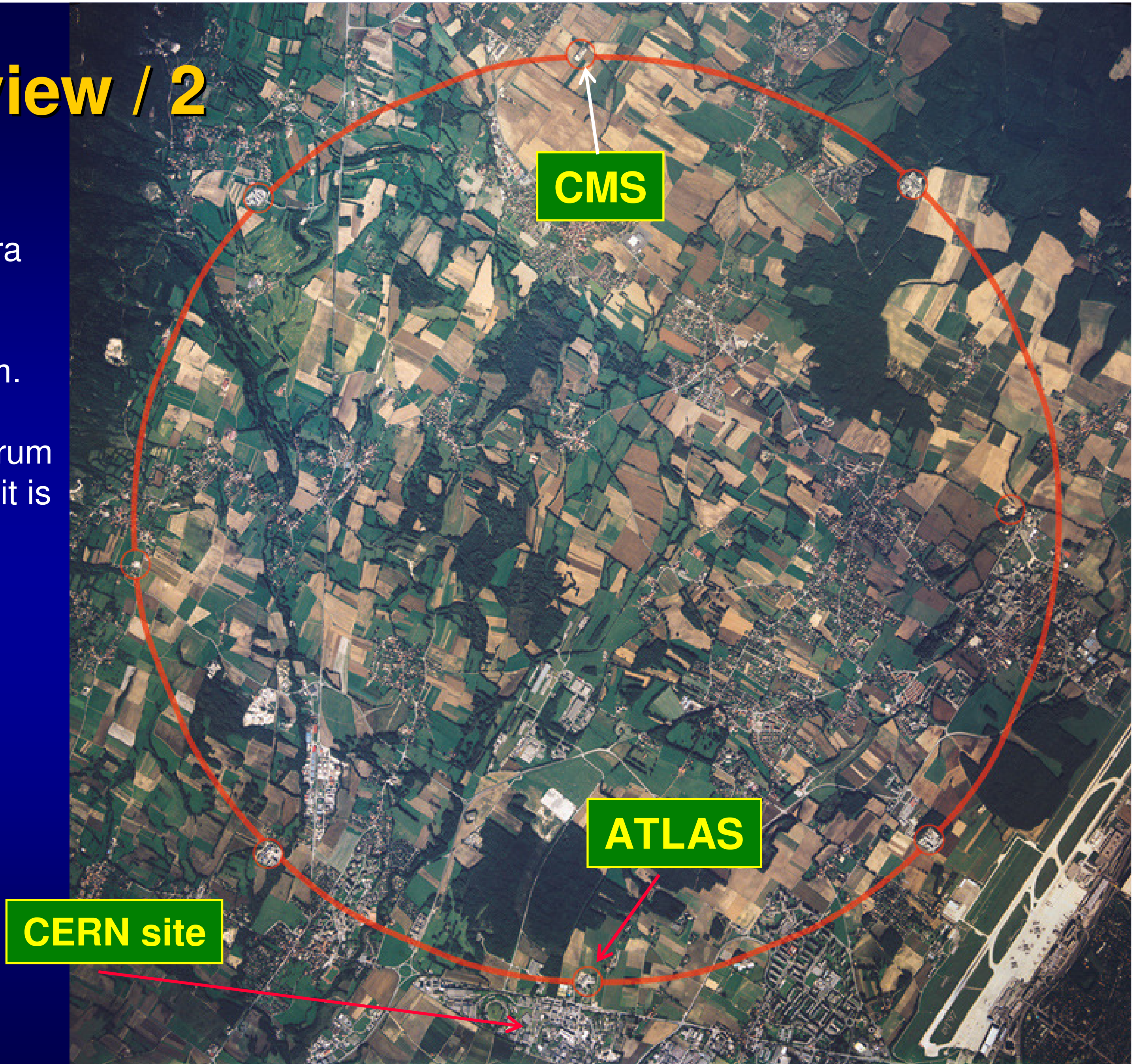


LHC overview / 2

The tunnel extends from Geneva airport to the Jura mountain.

Tunnel depth is 70-140 m.

The ‘natural’ noise spectrum in the tunnel is very low (it is adequate for a linear collider).



Superconducting magnets

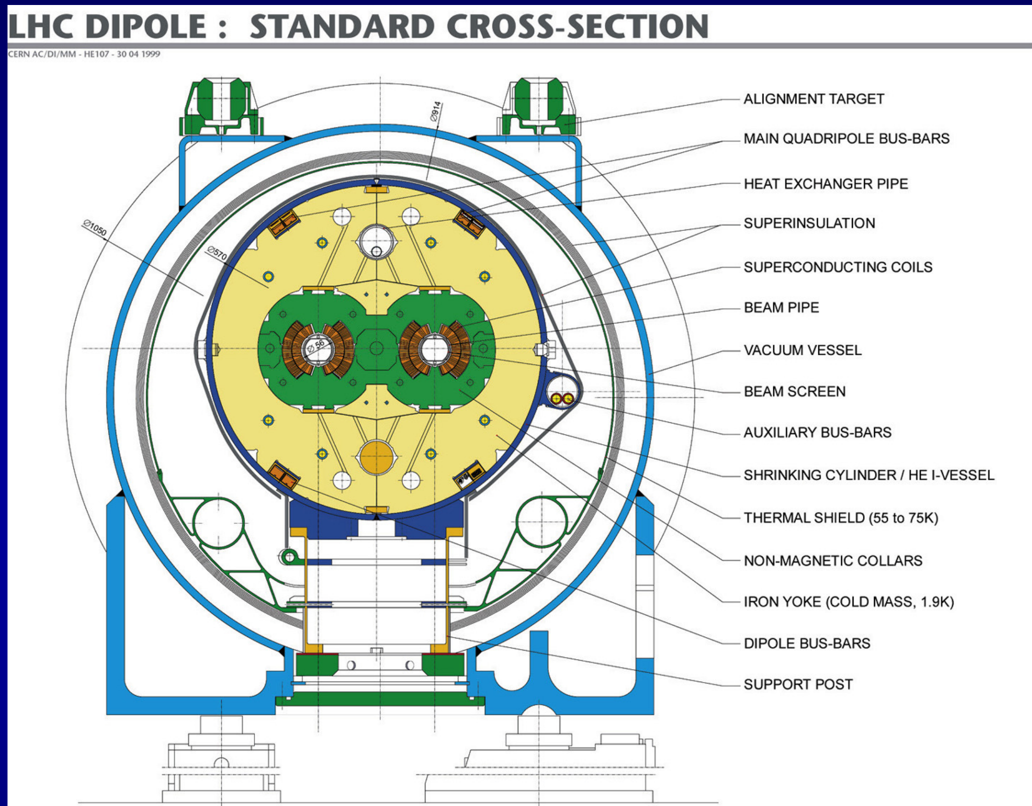
Special 2-in-1 design :
One magnet for the 2 beams.

To reach the nominal field of 8.33 T, the Nb-Ti dipoles magnets are operated at 1.9 K (super-fluid He) with a current of 12 kA.

The magnet aperture is 56 mm.

A consequence of the ‘extreme’ design:

- At 7 TeV the magnets are operated very close to the quench limit.
- A fast beam loss of less than one part per 10^7 of the beam may quench a magnet.



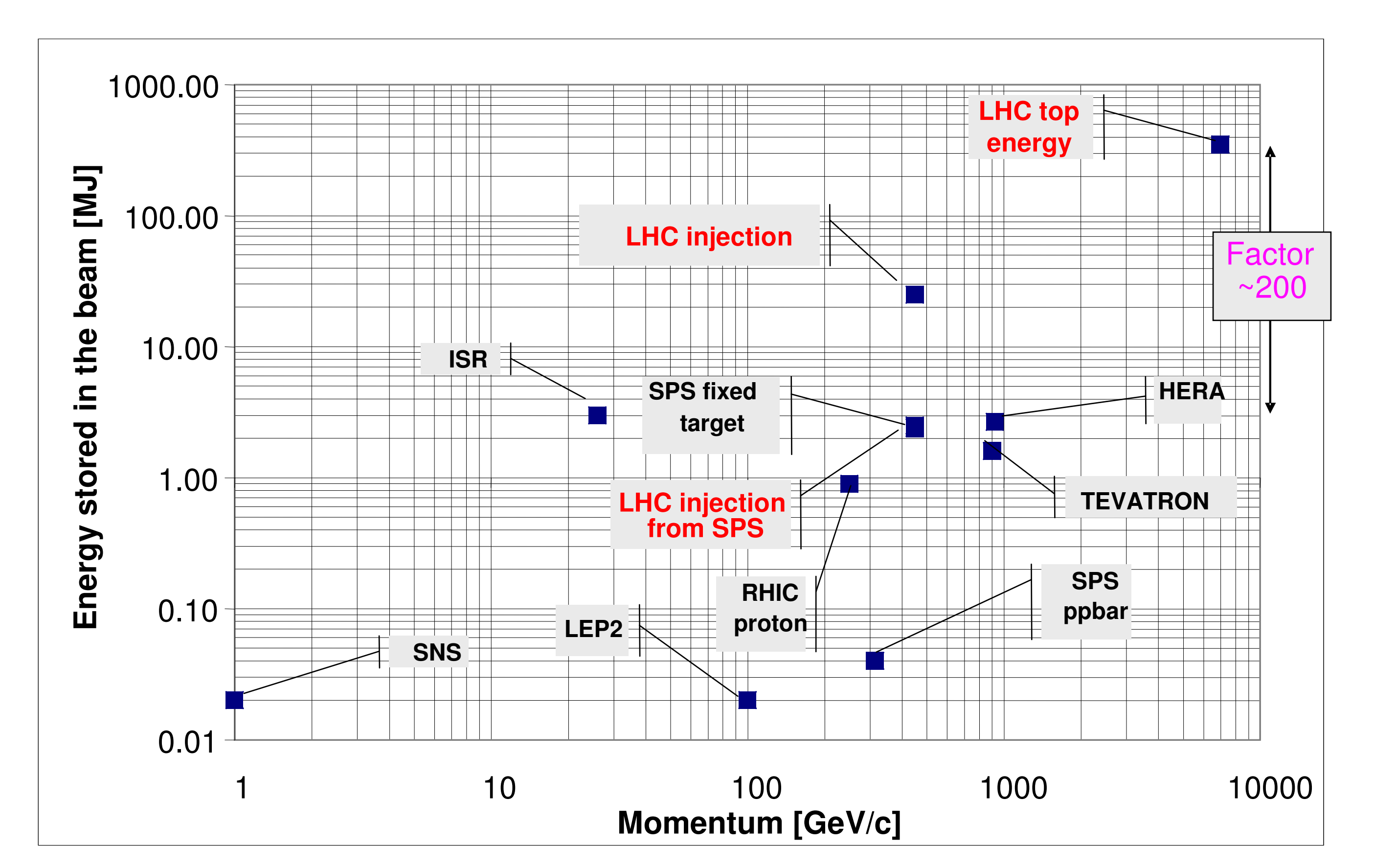
The recovery time from a quench at 7 TeV is ~ 6 hours.

LHC beam parameters

Beam structure (protons) :		
• Bunch separation	25 ns (or multiples)	
• Bunch intensity	5×10^{9} to 1.1×10^{11} protons	
• Number of bunches	1 – 2808	
β function :		
• Arcs (max)	180 m	
• Insertions (max)	~ 5000 m	
• Interaction region β^*	18 m (injection)	0.5 m (collisions)
Emittance (round beam) :		
• 450 GeV	7.7 nm	
• 7 TeV	0.5 nm	
Beam size at 7 TeV (rms) :		
• Arcs	300 µm	
• Interaction region	15 µm	
Bunch length at 7 TeV (rms) :	8 cm	

Energy stored in the LHC beams

- The energy stored in each LHC beam exceeds by more than 2 orders of magnitude that of any existing machine : 350 MJ stored / each beam.
- The transverse energy density / brightness is even a factor 1000 higher.



Sufficient to melt 500 kg of Cu

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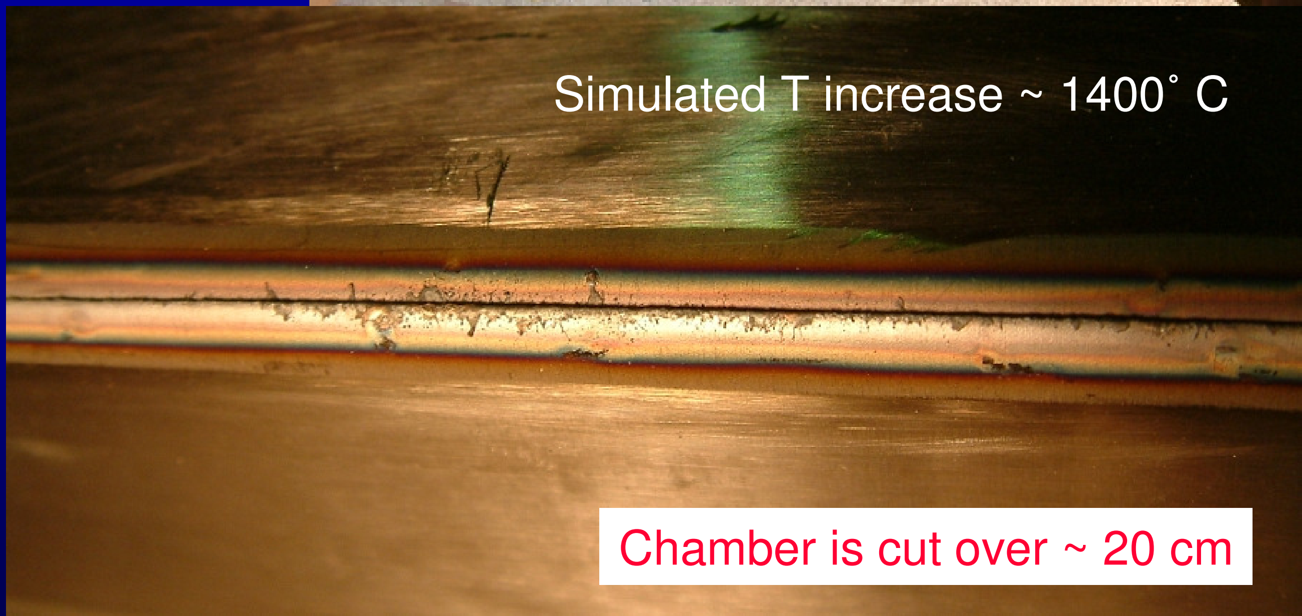
Equivalent of :

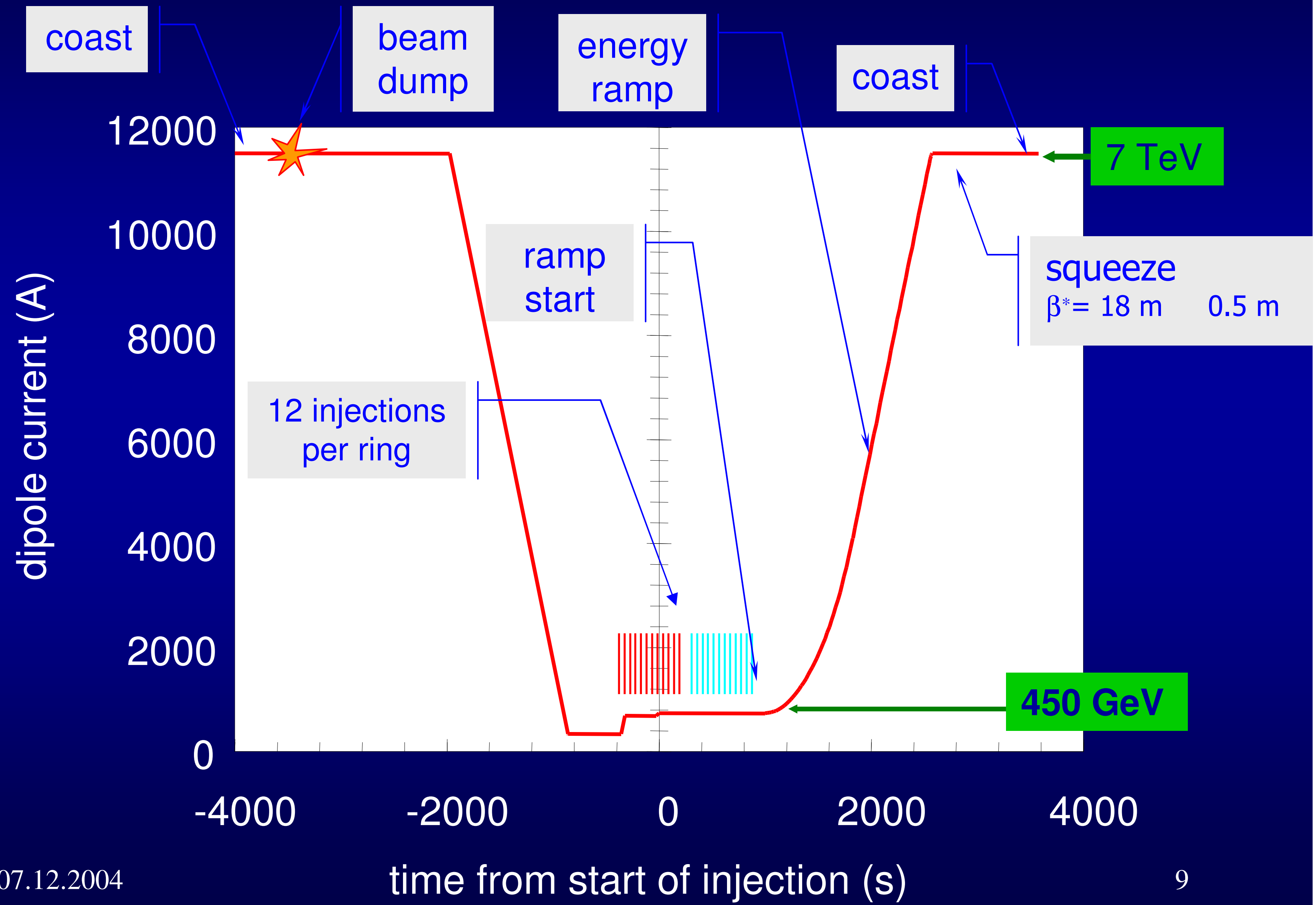
- 90 kg of TNT
- 25 kg of sugar

What you can do with 1% of the energy stored in the LHC beam…

Impact of a 450 GeV/c proton beam corresponding to ~ 2 MJ into a quadrupole chamber



Operation cycle



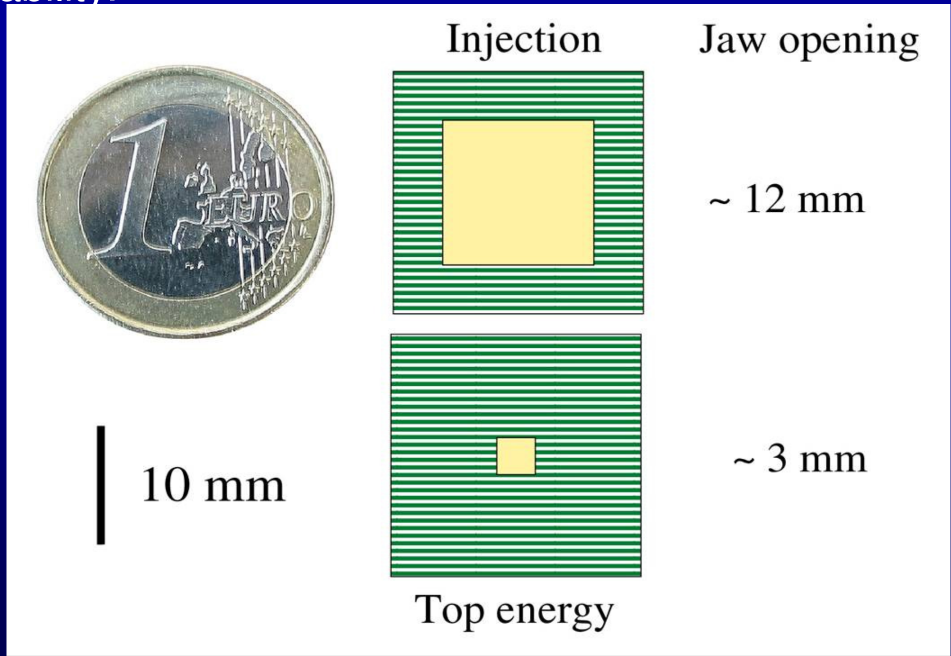
Beam collimation

Due to head-on and long range beam-beam as well as non-linearities, particles will drift to large amplitudes.

To prevent quenches of the SC magnets, the collimation system has to catch ≈99.99% of all particles that drift out of the machine. This is orders of magnitude better than what is required at existing proton machines.

Due to limited apertures near the interaction regions, the primary collimators must be closed to ≈5-7σ constraints on orbit stability.

The primary collimator aperture at injection and top energy.



There will be ~ 120 collimators jaws at the LHC

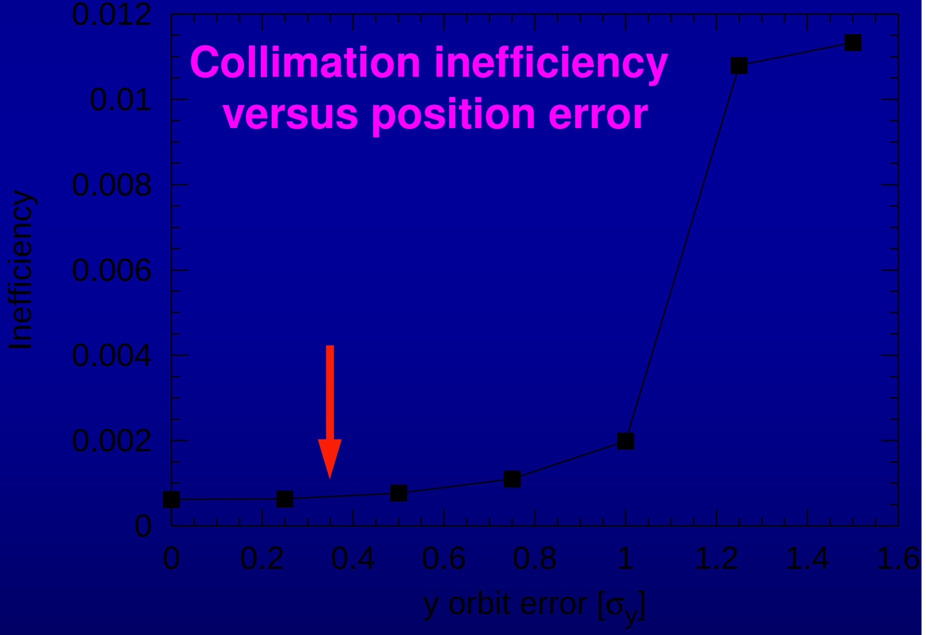
Collimation & protection requirements

The very high demands on collimation and the need for protection of the machine against uncontrolled beam loss sets the hardest constraints on stabilization.

In particular we must maintain the alignement of the beam wrt collimator jaws and absorbers / protection devices that are separated by many kms.

Stabilization requirements

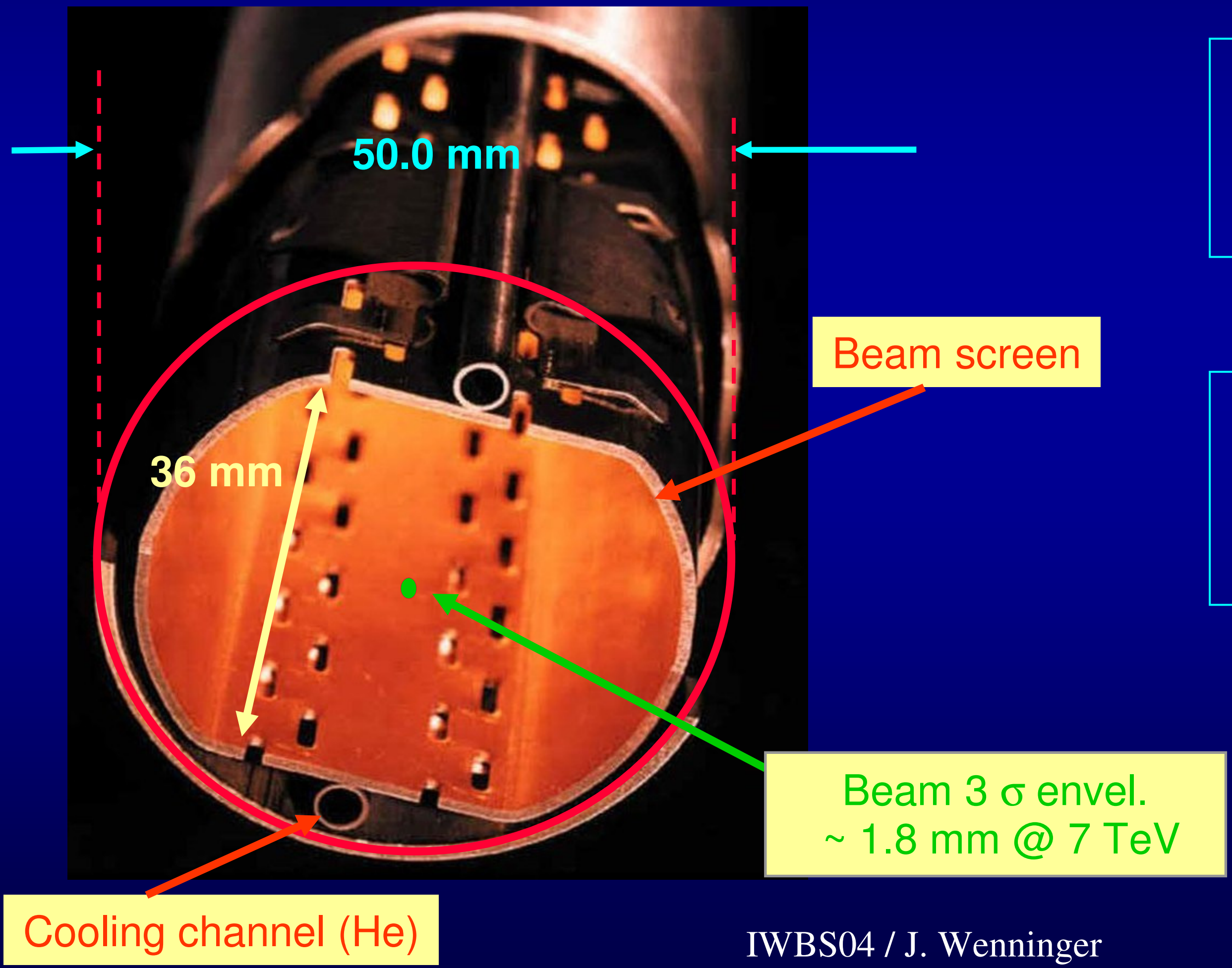
- In the 2 collimation sections (over a distance of few 100 meters) :
  $< \pm 0.3\ \sigma \qquad \approx 70\ \mu\text{m}$
- At protection devices installed in 6 long straight sections :
  $< \pm 0.5\ \sigma \qquad \approx 100\text{-}400\ \mu\text{m}$



Vacuum chamber

The vacuum chamber is protected by a beam screen operated at T = 4-20 K :

- intercepts synchrotron radiation (total power 3.6 kW, enery loss per turn 7 keV)
- carries image currents.



Vac. Ch. aperture

450 GeV	~ 10 σ
7 TeV	~ 40 σ

Machine aperture for collisions

~ 10-12 σ

Electron clouds

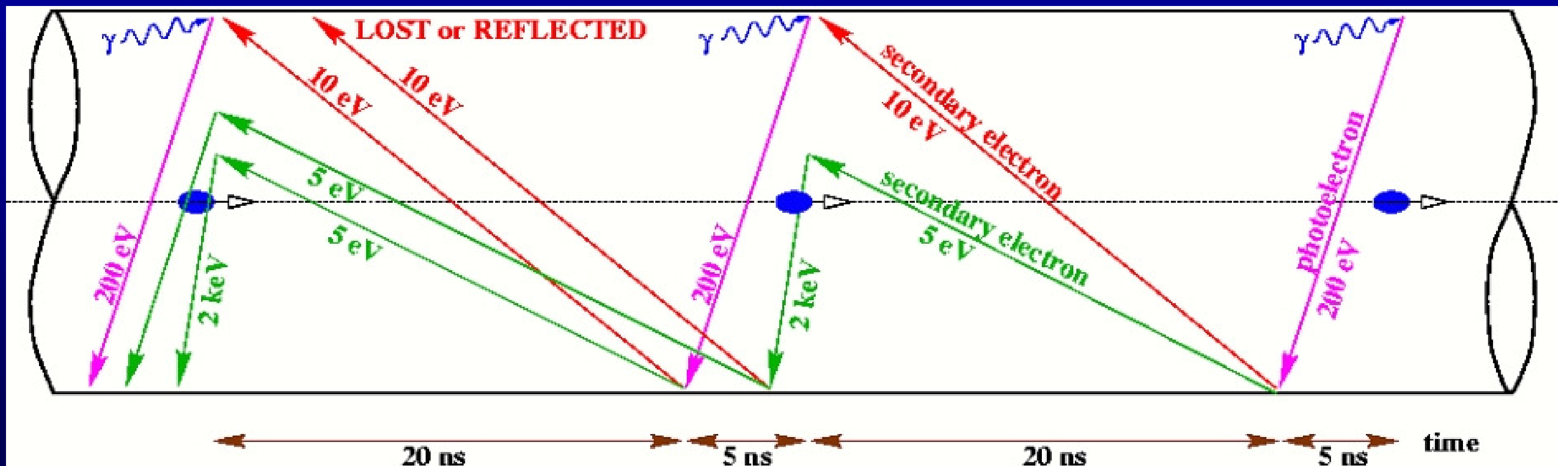
Affect beams with positive charge, high intensity and short bunch spacing :

- Vacuum pressure increase.
- Energy deposition : at the LHC the deposited power may exceed the 1 W/m (at 4 K) cooling capacity of the vacuum chamber.
- Beam stability : head-tail and coupled bunch.

'Electron clouds' are due to multipacting inside the vacuum chamber and depend on the surface properties (secondary emission yield).

Multipacting can be cured by 'cleaning' of the chamber with the beam – run with high multipacting for a sufficient amount of time.

But the chamber cleaning is 'local' (around the orbit) stabilization to ~ 0.5 mm rms to operate within the 'cleaned' areas.



Requirement overview

Stabilization requirements :

- Excellent (for the proton world) global control during all operational phases :
  - RMS change < 0.5 mm.
- Tight constraints around collimators and absorbers :
  - RMS change < ≈ 50-70 μm for nominal performance.
- The only demanding requirement from 2 special experiments :
  - Stability of ~ 5-10 μm over 12 hours around their IR – feasability must be demonstrated (BPM performance).

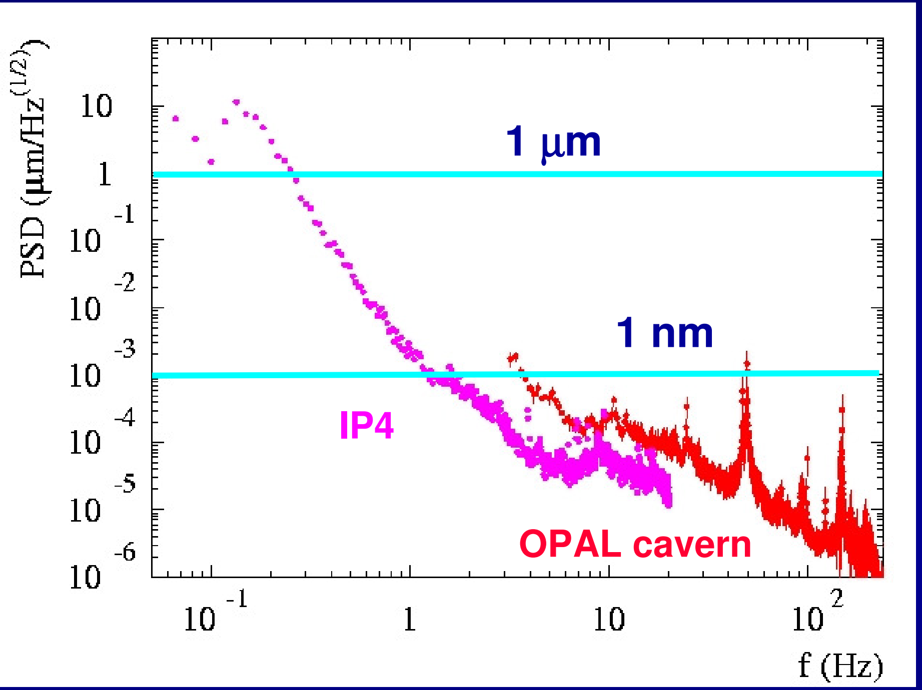
Dominant sources of orbit perturbations :

- Ground motion.
- Dynamic effects from superconducting magnets.
- Beta squeeze.

Ground motion

The LEP/LHC tunnel is a fortunately a quiet place…

LEP/LHC tunnel noise spectrum



Assuming that :

orbit rms ≈ κ × ground movement

Uncorrelated motion : κ ≈ 35
Ground waves :
f < 5 Hz κ ≈ 1
f > 5 Hz 1 < κ < 100

CO movements at f > 0.1 Hz
are expected to be ≤ 20 µm !

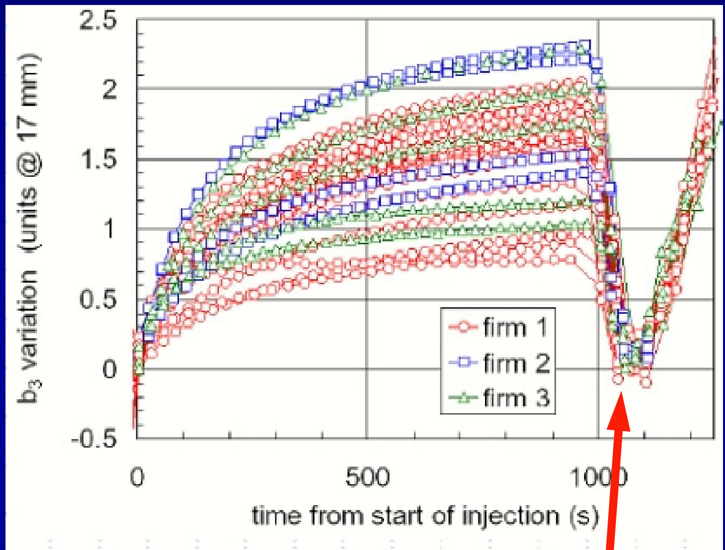
Long term orbit drifts (LEP) : ~ 200-500 µm rms over a few hours
~ 20-50 µm rms over ~ minute(s)

a priori we expect similar figures for the LHC !

‘Snapback and decay’ in superconducting magnets

Start of ramp

Example of the b3 / sextupole error



~ 900 sec decay @ injection

~ 50 sec Snapback

- Long lasting inter-strand eddy currents due to field ramps (persistent currents) have a strong effect on the field quality of the magnets – issue at injection.
- Affect orbit, tune, chromaticity (~ 90 units)….
- Time dependence :
  - § Decay on the injection plateau.
  - § ‘Snapback’ at ramp start.
- At injection the magnetic machine is not stable for the first ~ 30 minutes.

The orbit is affected by random dipole (b1, a1) and quadrupole (b2) errors :

≈1-4 mm rms change in the both planes

Other perturbations

During the energy ramp from 0.45 to 7 TeV :

- From "experience" at other CERN machine we expect drifts of few mm rms.

The beta-squeeze at the IRs is the most delicate part of the LHC cycle !

- Due to the expected alignment / static CO errors (±0.5 mm) the optics change can generate large orbit changes – up to 20 mm rms.
- The optics changes continously response matrix must be kept updated.
- Effects are very sensitive to the input conditions :

  orbit offset, optics and strength change in IR quads.

Collisions :

- (Parasitic) beam-beam kicks – negligible in the first year(s).

More complications

The 2 ring design of the LHC adds other complications :

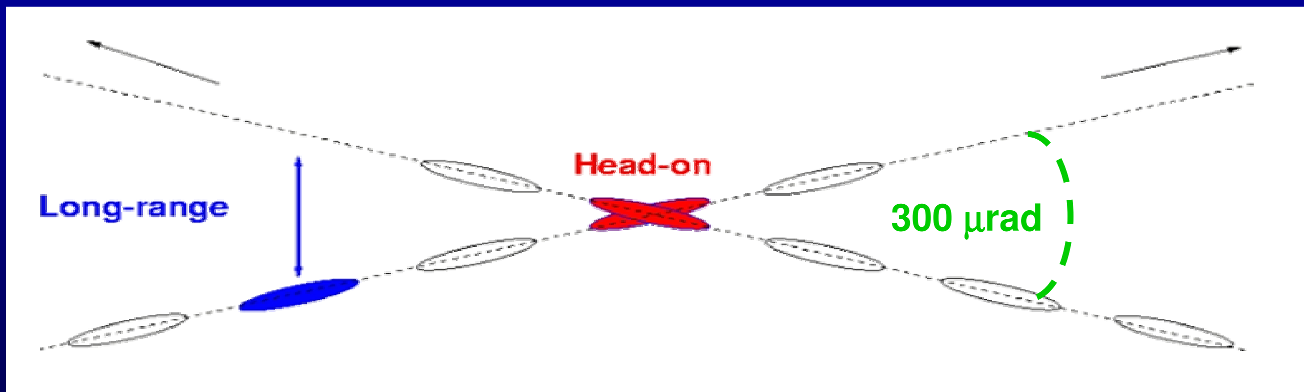
- Every orbit change moves the beams one wrt other at the interaction points.

  Orbit drifts (and corrections !) can reduce the beam overlap & the luminosity.

- Correctors installed in the common vacuum chambers near the experiments affect the beams with the opposite sign.

  Orbit correction using these correctors must handle both beams simultaneously.

- To minimize the effects of long-range beam-beam collision around the collision points (~30 encounters around each collision point), the beams collide with a crossing angle of 300 μrad.



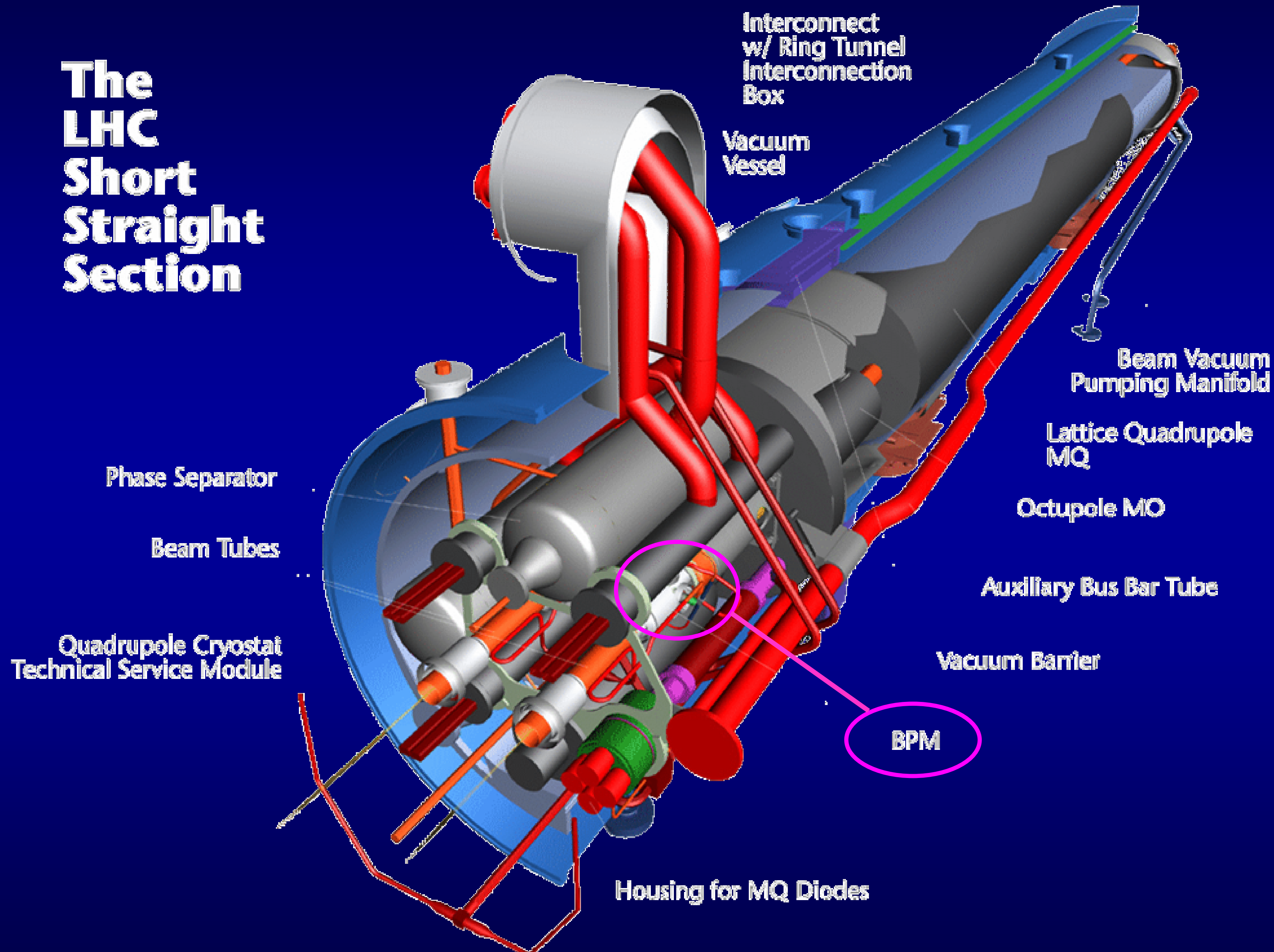
Beam position measurements

- 528 BPMs (Horizontal + Vertical) per ring.
- There is one BPM at each quadupole, except in the collimation sections where there is one BPM on both sides of each quadrupole.
- In the arcs the phase advance between BPMs is 45˚ - sampling is OK.

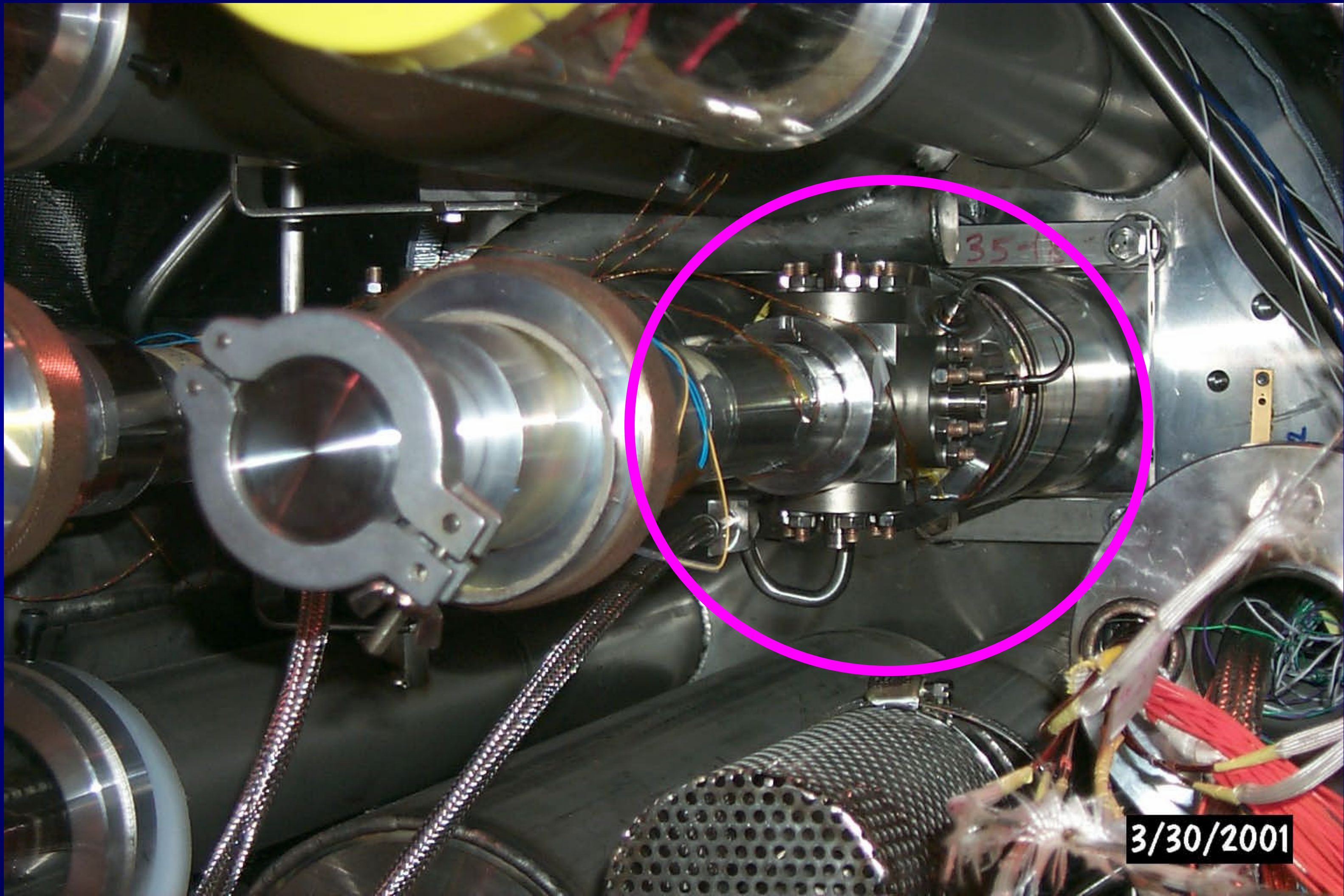
- Acquisition based on 'Wideband Time Normalizer' principle (CERN design) :
  - § Full bunch-by-bunch acquisition (40 MHz system).
  - § RT orbit sampling at up to 50 Hz – averaged over one 50 Hz period (225 turns).
  - § Orbit resolution < 1 µm for nominal intensity.
  - § Multiturn acquisitions of up to 100k turns / BPM.

- BPM system issues :
  - § Residual intensity / bunch length dependence of measurements may reach ~ 100 µm.
  - § Influence of hadronic showers on the signal of BPMs near collimators.
  - § Interference RT / multiturn acquitions.
  - § Reliability ?

The ARC BPMs


The LHC Short Straight Section
Interconnect w/ Ring Tunnel Interconnection Box
Vacuum Vessel
Beam Vacuum Pumping Manifold
Lattice Quadrupole MQ
Octupole MO
Auxiliary Bus Bar Tube
Vacuum Barrier
BPM
Housing for MQ Diodes
Phase Separator
Beam Tubes
Quadrupole Cryostat Technical Service Module

The ARC BPMs / 2



Steering magnets

There are 280 orbit corrector magnets per ring and per plane.

Most (> 90%) of the orbit correctors are superconducting magnets :

- Circuit time constants τ = L/R ≅ 10 to 200 s slow !!!
- EVEN for SMALL signals, the PC bandwidth is ~1 Hz.
  At 7 TeV : ~ 20 μm oscillation / corrector @ 1 Hz.

The PCs are connected over a real-time fieldbus (WoldFip) to the gateways that control them – the bus operation is limited to 50 Hz.

Consequence :

The LHC orbit FB will operate at up to 50 Hz - more likely at 25 Hz.

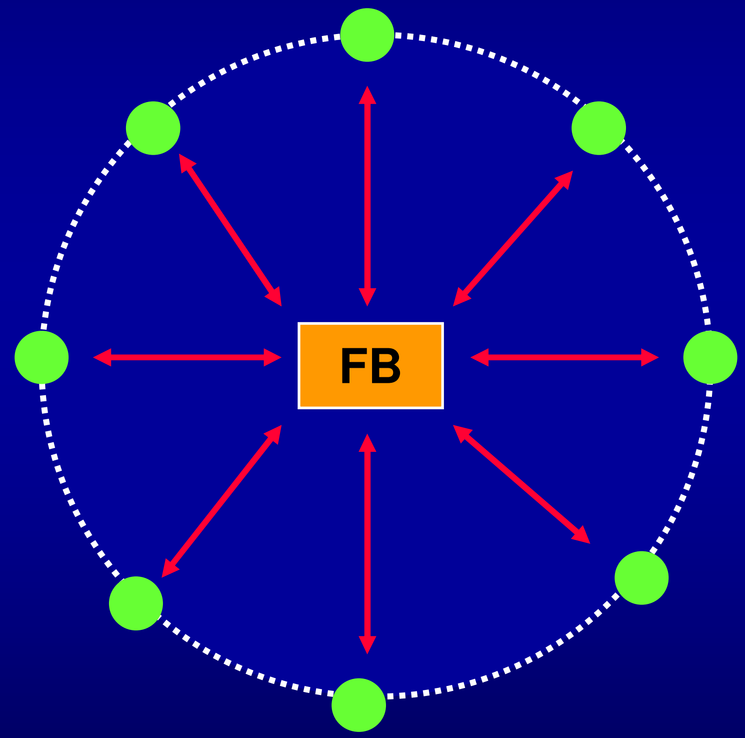
But this sampling rate is adequate given the expected perturbations !

Feedback layout

The monitors, correctors and their electronics are installed at the 8 LHC access points – spread over 27 km data transport is an issue.

To achieve the best flexibility, we have opted for a centralized FB design :

- Corrections will be performed in one central location – global & local corrections.
- The data is transported over Gigabit Ethernet.
- Note : for a combined (2 ring) global correction the matrix size is up to ~ 1050 x 560.



Details will be described in
R. Steinhagen's presentation :
'Large scale orbit correction for the LHC'

Summary

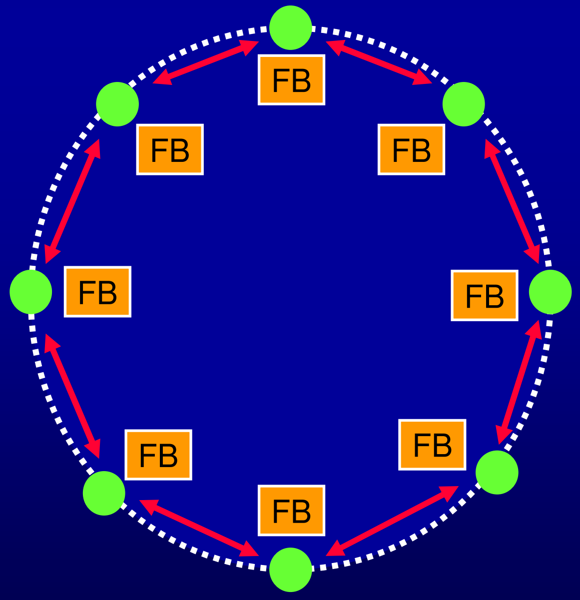
- The LHC is the first hadron collider that requires a real-time orbit feedback.
- The main reasons for a feedback are the collimation requirements of the high intensity beams inside a superconducting machine.
- The difficulty at the LHC arises from the large geographical distribution of equipment and the complexity of the 2 rings.
- The FB system will be operated at up to 25-50 Hz – for initial operation with low intensity a frequency of 0.1-1 Hz will be sufficient.
- The reliability of the orbit FB must be high – a quench of a magnet at 7 TeV ‘costs’ around 6 hours of recovery time.
- More details on the design will be given by R. Steinhagen.

Architecture

Local

reduced # of network connections.
numerical processing simpler.
…

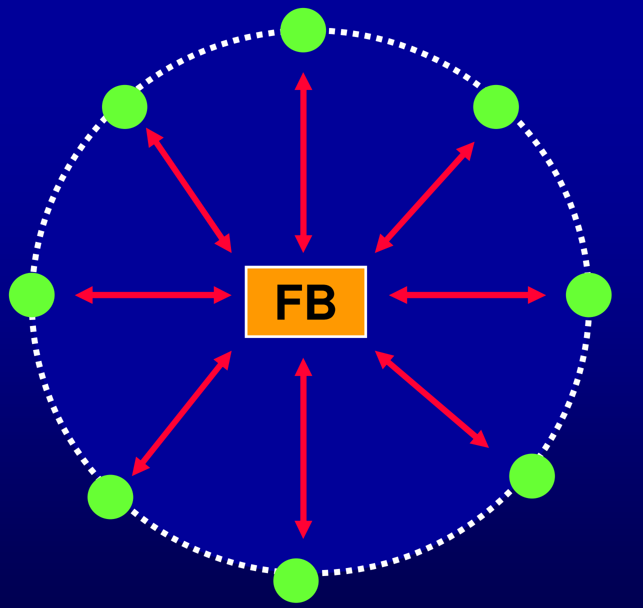
- × less flexibility.
- × not ideal for global corrections.
- × coupling between loops is an issue.
- × problem with boundary areas to ensure closure.
- × ..



Central

entire information available.
all options possible.
can be easily configured and adapted.
…

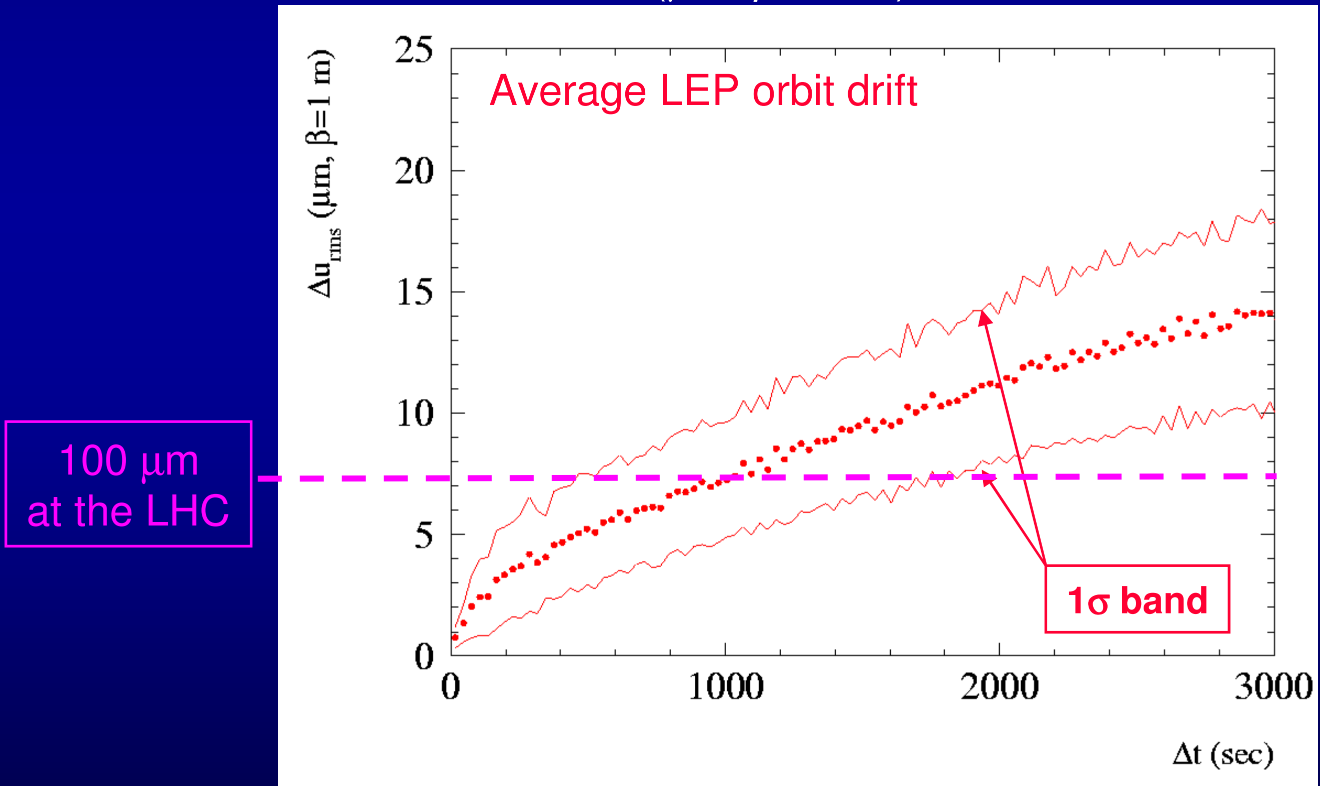
- ×network more critical – DELAYS !
- × large amount of network connections.
- ×…



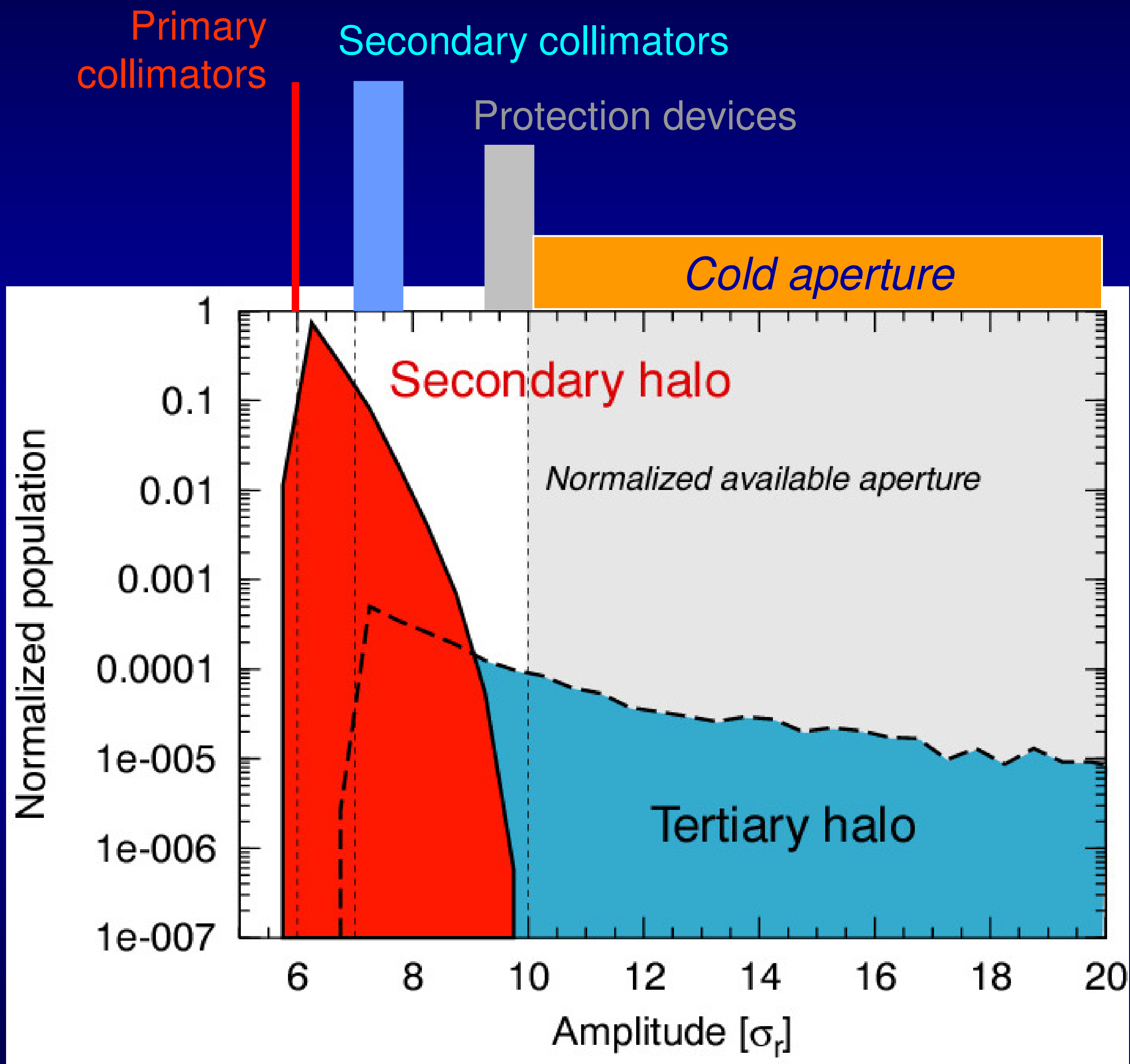
LEP slow orbit drifts

The measured slow LEP orbit drifts give a good indication of what to expected at the LHC
no problem for a FB running at 0.5 Hz or more.

RMS drift (μm, β = 1 m) versus time



3-stage collimation



Strategy:

Primary collimators are closest.

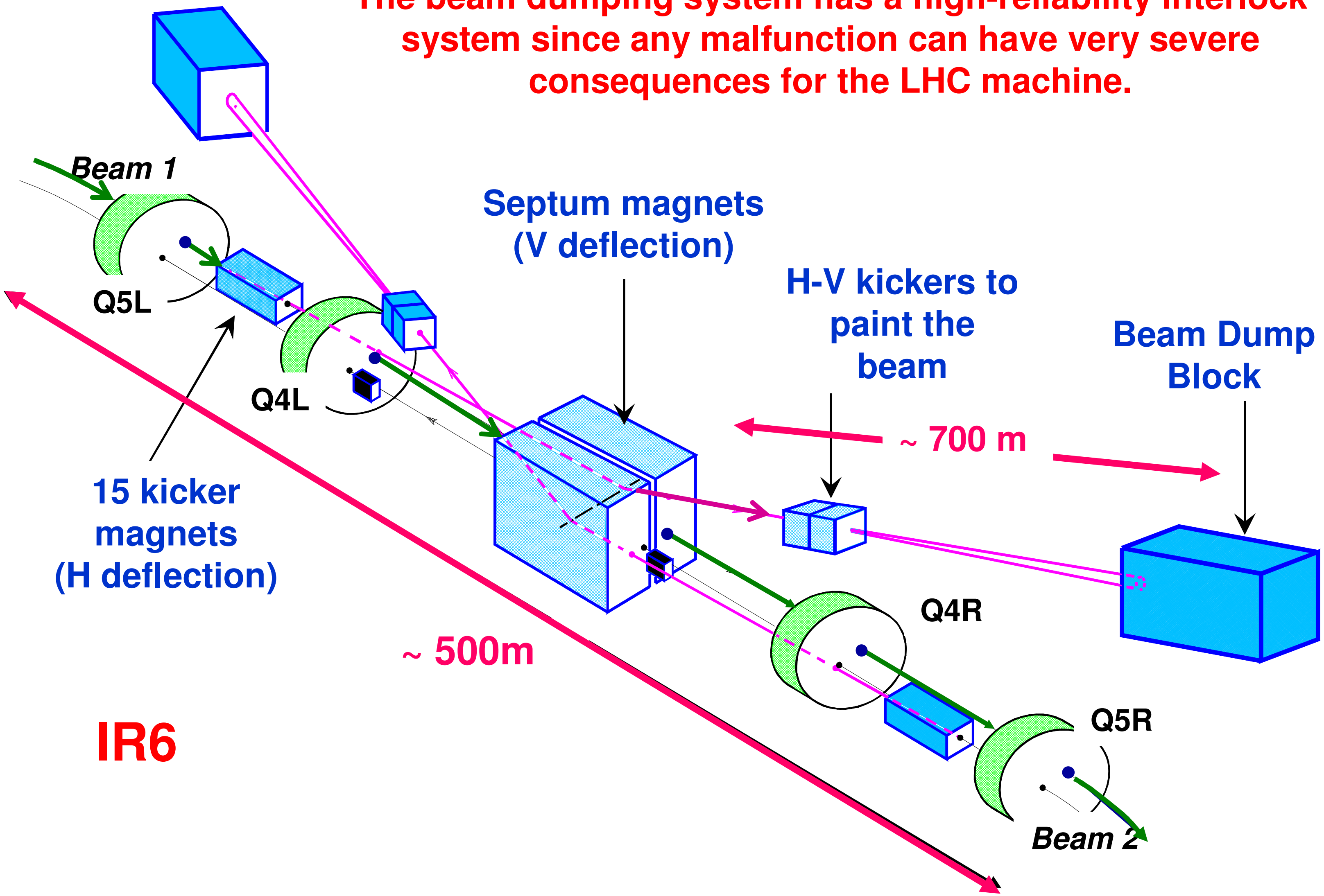
Secondary collima-tors are next.

Absorbers for protec-tion just outside se-condary halo before cold aperture.

Relies on good knowledge and control of the orbit around the ring!

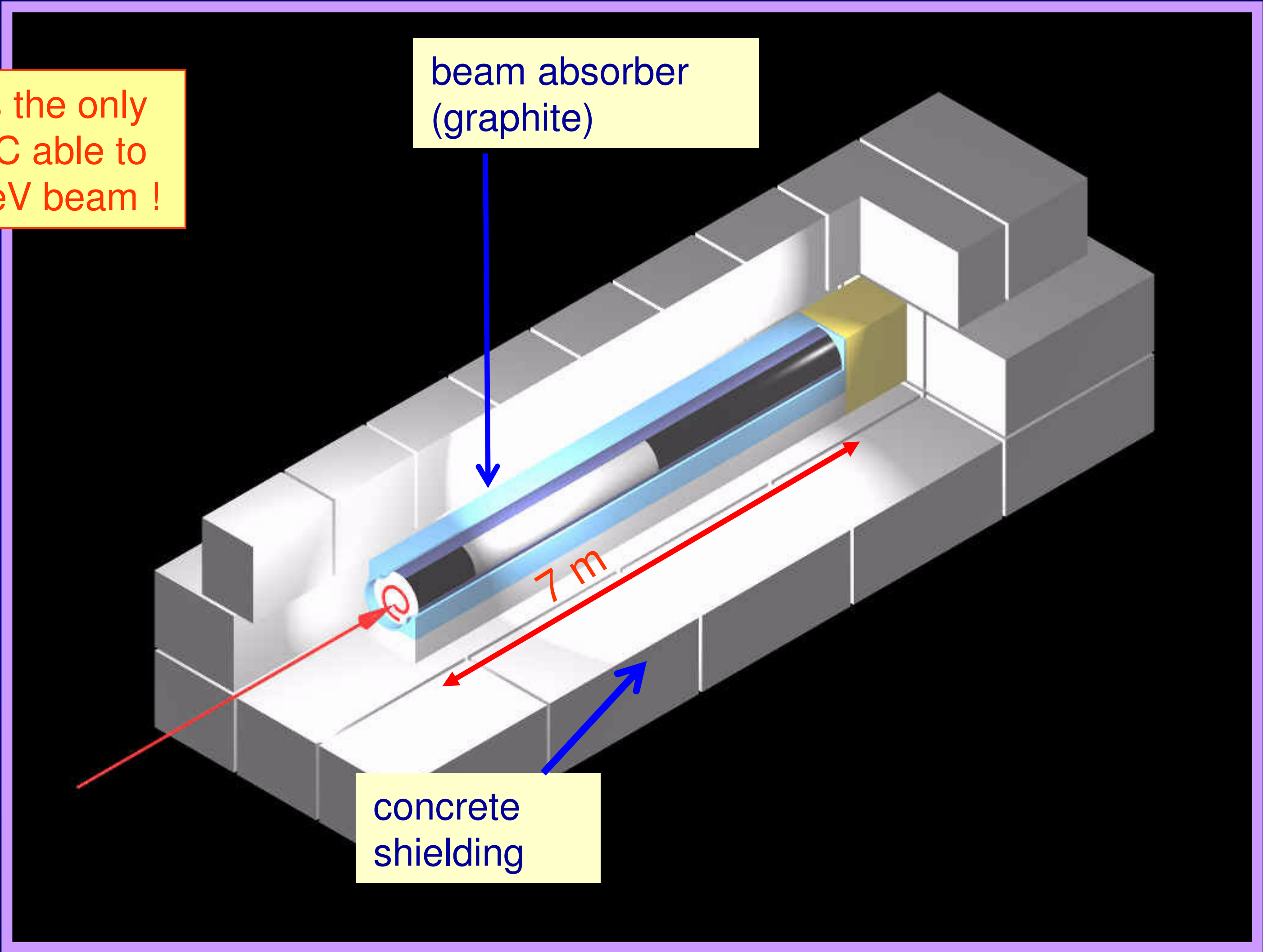
LHC beam dumping system

The beam dumping system has a high-reliability interlock system since any malfunction can have very severe consequences for the LHC machine.

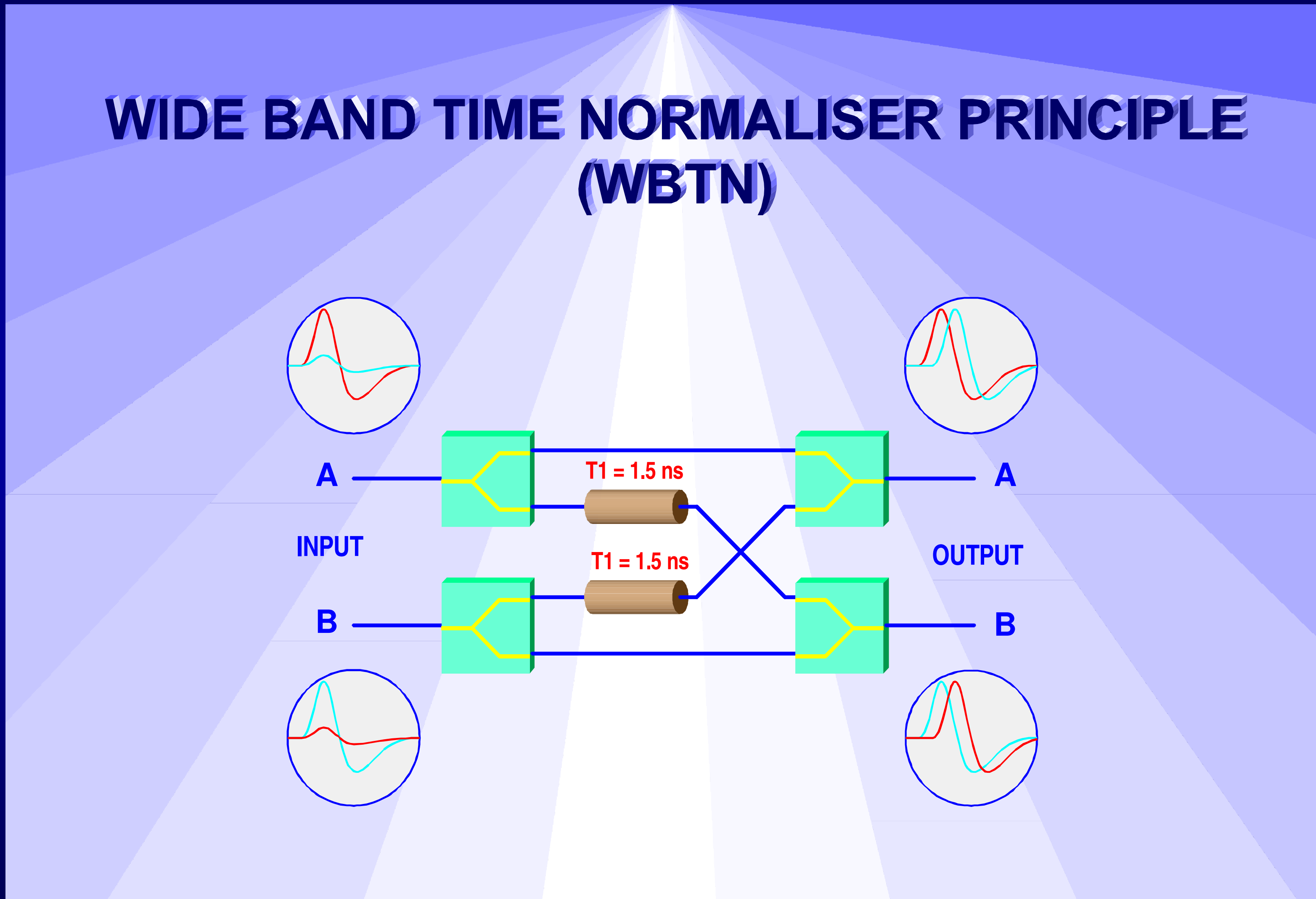


Beam dump block

The dump block is the only element of the LHC able to absorb the full 7 TeV beam !



LHC Amplitude to Time Normaliser Schematics



Wide Band Time Normalizer