A short story around the beam orbits at LEP and LHC

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LEP overview

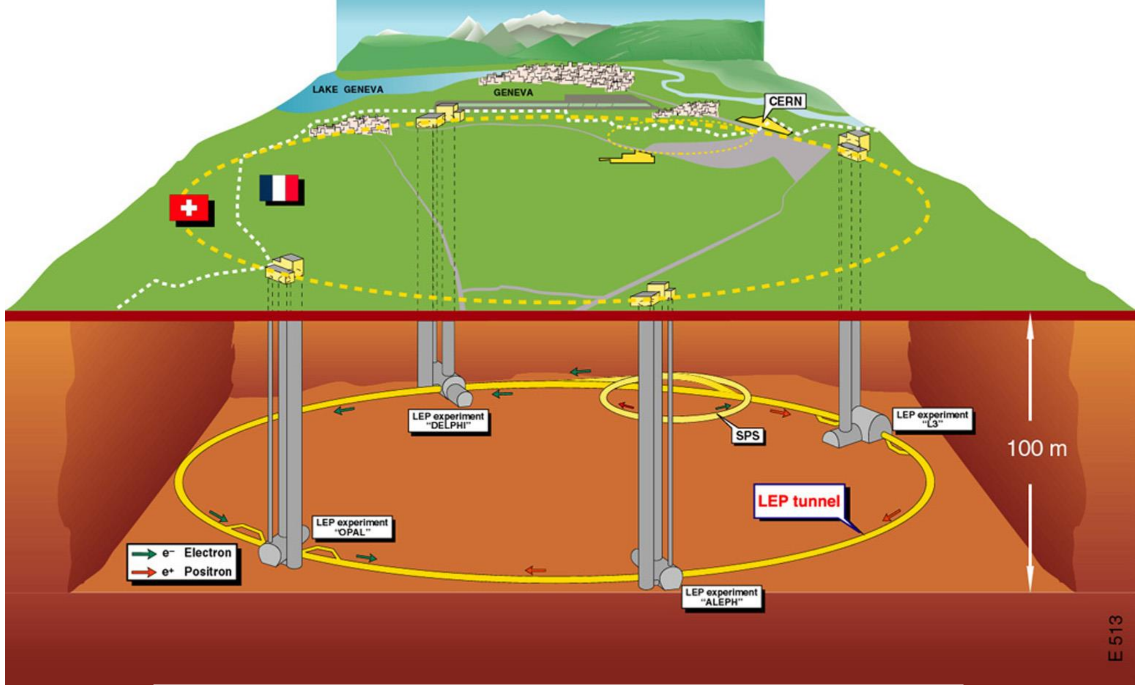
LEP was installed in what is now the LHC tunnel with a circumference of 26.7 km.

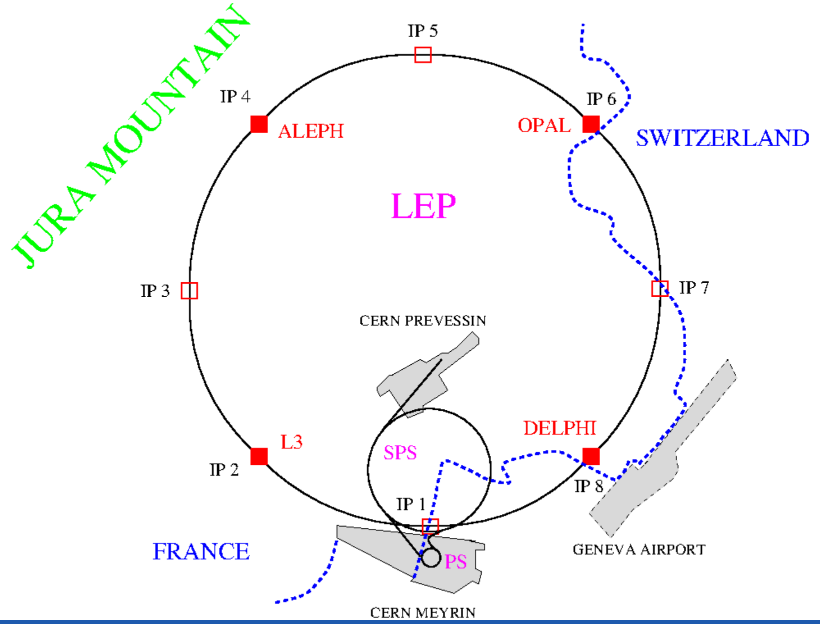
The tunnel had(s) 8 access points arranged symmetrically around the ring.

- 4 experiments installed at the even points.

LEP operated colliding beams over a beam energy range of ~43 GeV to 104.5 GeV.

- 4-12 bunches per beam.
- **e+ and e- beams shared a common vacuum chamber**.





LEP orbit measurement

System designed in the mid 1980s.

All but a few BPMs based on **signal normalization – no gain**.

- Possible due to the large separation of the bunches in most of the ring despite single vacuum chamber.
- This choice proved to be very reliable.

By 1992 it took **12-15 seconds** to acquire an orbit – remained like this until LEP switched off.

- Due to the slow system, **no ‘real-time’** controls was possible (LEP came a bit early for this).
- No possibility to control power converters during ramp / squeeze phase – only predefined function could be executed.

The LEP system provided **turn-by-turn data**: opened the window for first beta-beating / optics measurements with turn-by-turn data!

Orbit correction for highest luminosity

At LEP1 the machine was **beam-beam limited** at $\xi \sim 0.03$-0.04 depending on the configuration.

Performance very sensitive to details of the vertical orbit (through vertical emittance).

- **Random search for a "golden" orbit**, using MICADO based corrections – **not very deterministic**.
- Orbits could be re-used from fill to fill, with some re-tuning.

At LEP2 the **beam-beam limit was lifted** by the strong damping, $\xi \sim 0.08$ could be reached.

- Combined corrections with **dispersion free steering** (DFS, combined orbit+dispersion correction) using the SVD (or MICADO) algorithms led to orbits with good performance – **much more deterministic**.
- Final tuning of the performance again with random corrections on top of orbit obtained with DFS.

LEP low-beta quadrupoles

The last vertically focusing super-conducting **low-beta quadrupole** in front of the IP was on a **cantilever support**.

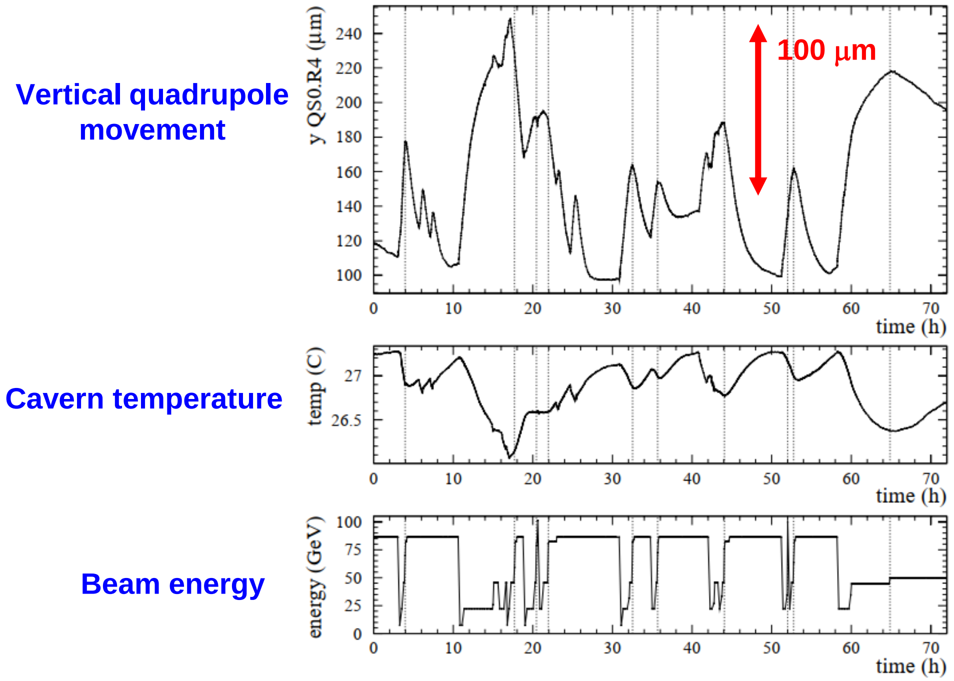
- Quad was inside the experiments.

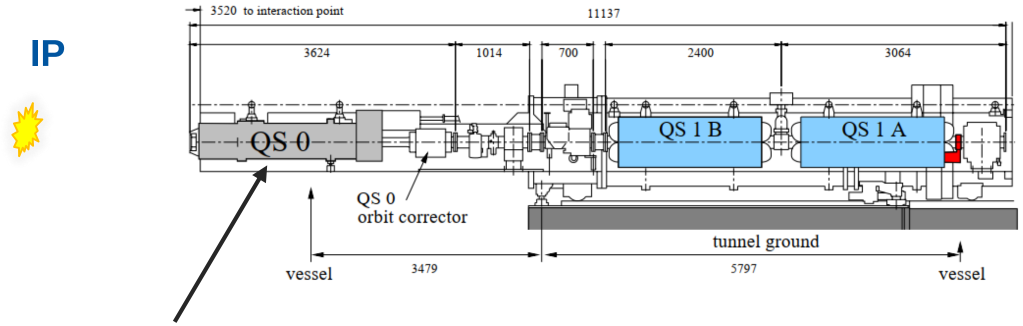
LEP suffered from **large temperature driven vertical movements** of those quadrupoles (8) due to support design.

The movements had a huge impact on availability:

- Large vertical orbit drifts over time.
- Coupled to the absence of real-time orbit control, **many beams were lost during the ramp or squeeze** due to excessive vertical orbit excursions (→ anti-damping due to V dispersion).
- Once in collision, a slow orbit feedback could stabilize the orbit.

LEP probably lost ~20-30% of integrated performance due to this effect (aborted cycles).





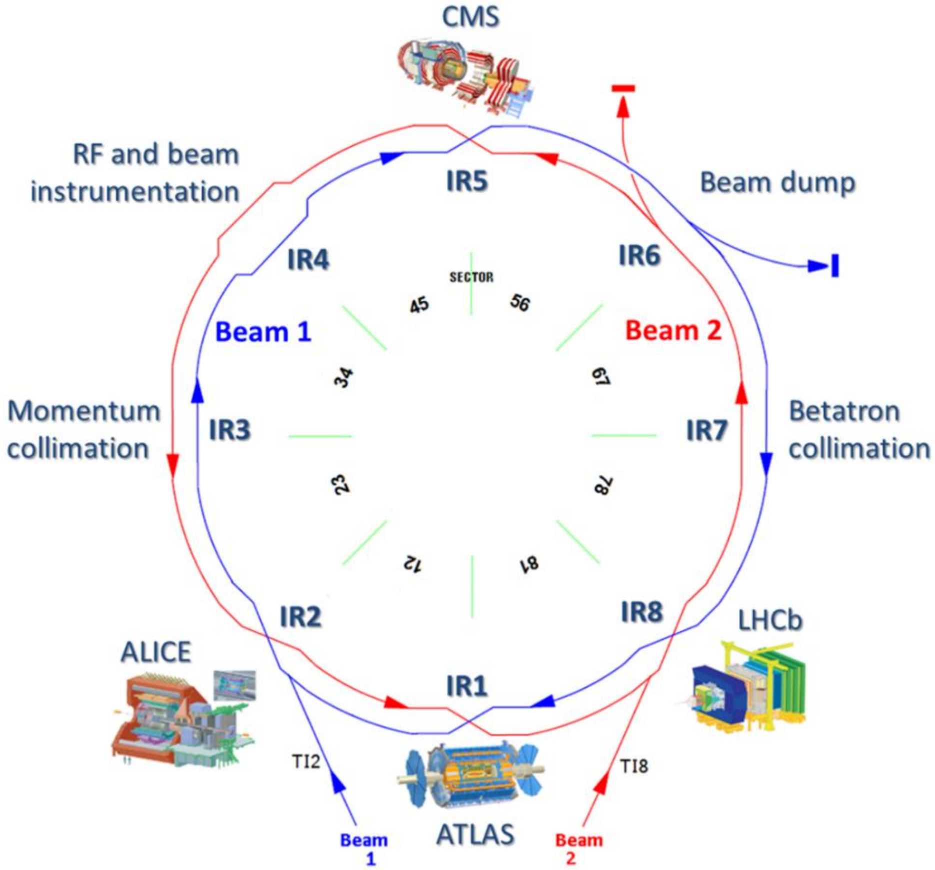
Final vertical low-beta quadrupole

LHC

ATLAS & **CMS** : high luminosity experiments, **$L \sim 2x10^{34}$ $cm^{-2}s^{-1}$**.

LHCb : medium luminosity experiment, **$L \sim 2\times10^{33}$ $cm^{-2}s^{-1}$**.

ALICE : low luminosity / ion experiment, **$L \sim 10^{31}$ $cm^{-2}s^{-1}$**.



2-in-1 magnet design with **separate vacuum chambers**.

Almost fully superconducting magnet system.

Operating energy 6.8 TeV.

The 2 rings are magnetically coupled.

The two beams cross in the 4 experiments.

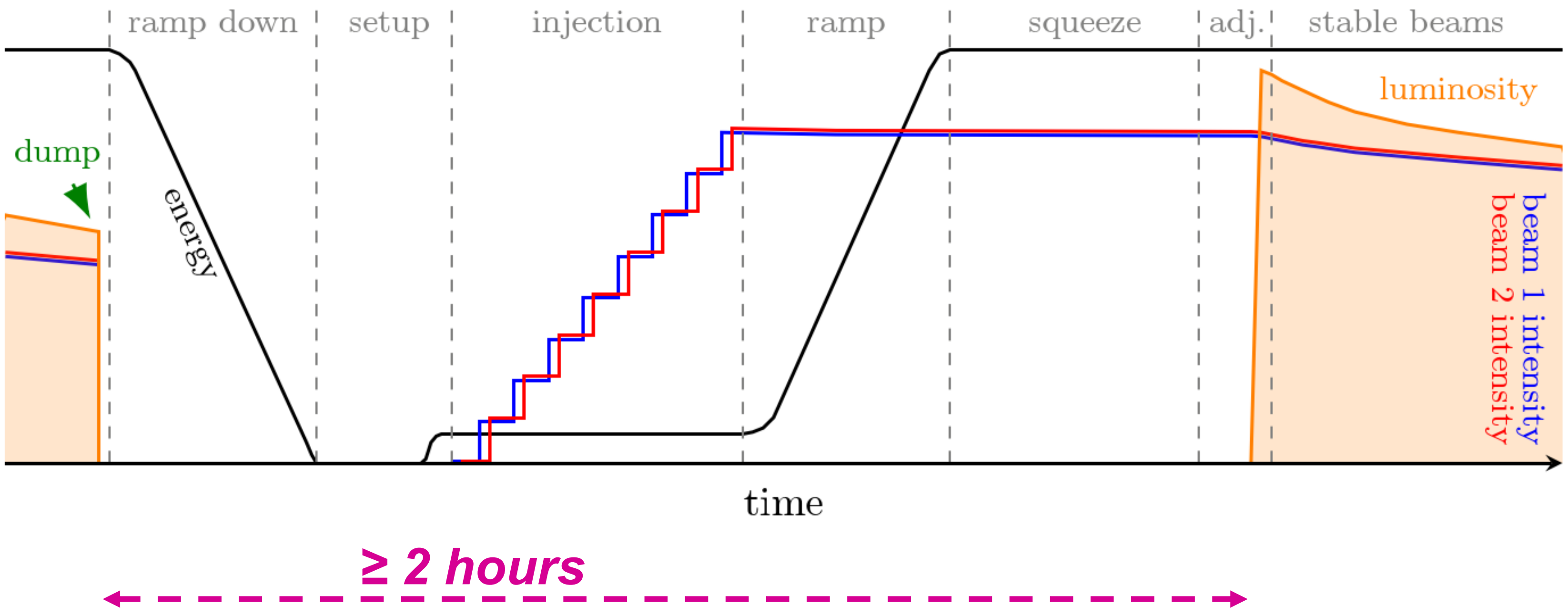
~200 m common vacuum chamber.

LHC cycle

Beams are injected and accumulated at 450 GeV (up to ~2750 bunches) with a detuned optics.

The beams are accelerated to 6.8 TeV in 20 minutes combined with partially squeezed (lower β^*).

At higher energy the final beta squeeze is applied and the beam are brought into collision for ~ 12-15 hour long physics data taking.



LHC orbit measurement

The start was much better than for LEP: **specification of the BPM system performance,** written by members of accelerator physics, beam operation and beam instrumentation groups.

Specified the system performance:

- Resolution, accuracy, alignment,
- Modes: closed orbit, turn-by-turn, bunch-by-bunch,
- Orbit feedback,
- Beam parameter ranges,
- Etc…

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the **Large Hadron Collider** project

LHC Project Document No.
LHC-BPM-ES-0004 rev 2.0

CERN Div./Group or Supplier/Contractor Document No.
SL/BI

EDMS Document No.
327557

Date: 2002-02-11

Functional Specification

MEASUREMENT OF THE BEAM POSITION IN THE LHC MAIN RINGS

Abstract

This Functional Specification covers the Beam Position Measurement System (BPM System) distributed along the LHC rings. The observables provided by the BPM System are the beam trajectories, the closed orbits, the beam oscillations measured at one azimuth in the machine and optionally the bunch currents. The beam parameters that can be calculated from these observables are identified. The requirements arising from LHC beam dynamics are used to set tolerances on the beam parameters. Given typical LHC operations scenarios, these requirements and tolerances are translated into specifications for the BPM System.

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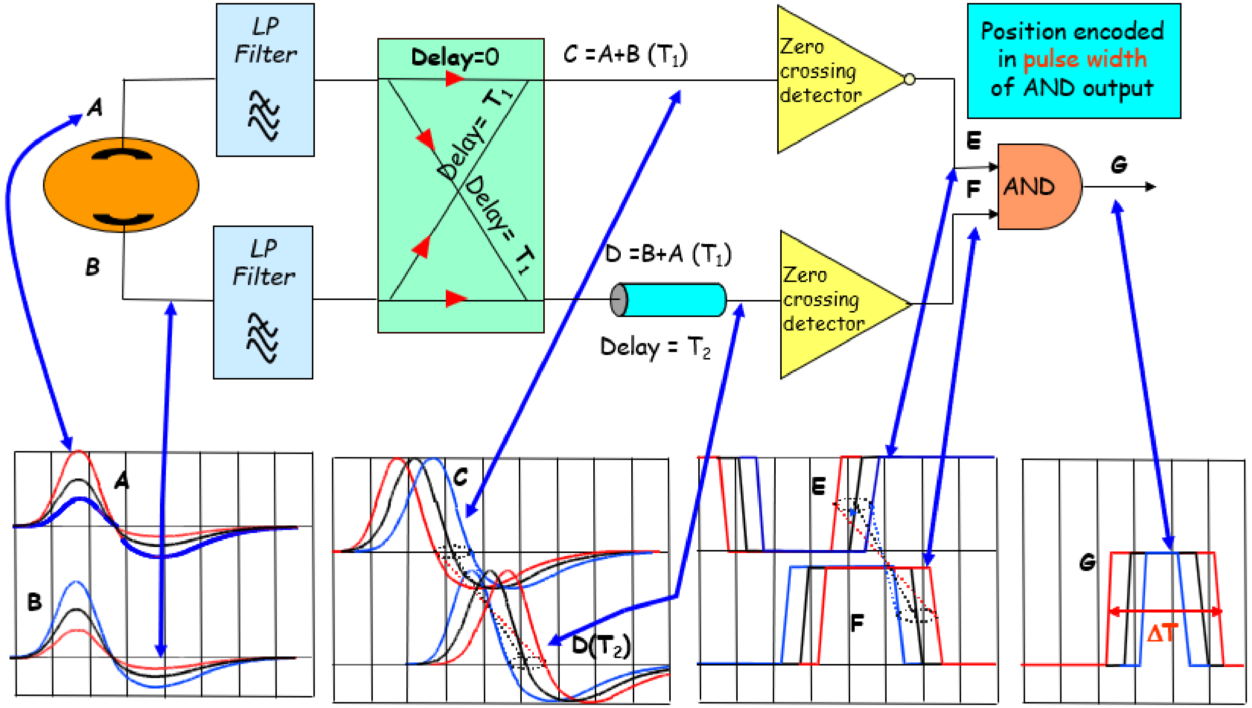
BPM electronics design

Following the LEP example, the BPM electronics has **no gain**, the intensity is normalized out (**Wide Band Time Normalization – WBTN**) and the system is **intrinsically bunch-by-bunch** (25 ns min spacing).

- Turn-by-turn and bunch-by-bunch data come for free, closed orbit is just the average of selected bunches over a given time interval.

Extra complication for experimental IRs:

- In the low beta sections both beams travel in the **same vacuum chamber over** ~200 m, directional couplers are used to separate the beam signals – some **residual cross-talk**.



Residual **beam pattern systematics** (single bunch versus trains of different structures) after BPM calibration:

- ~50 μm rms residual systematics when switching beam type.
- Sort of OK, but not very nice.

LHC orbit system architecture

The **advent of powerful gigabit ethernet links** around 2005 opened the possibility to use a standard communication network for data transmission.

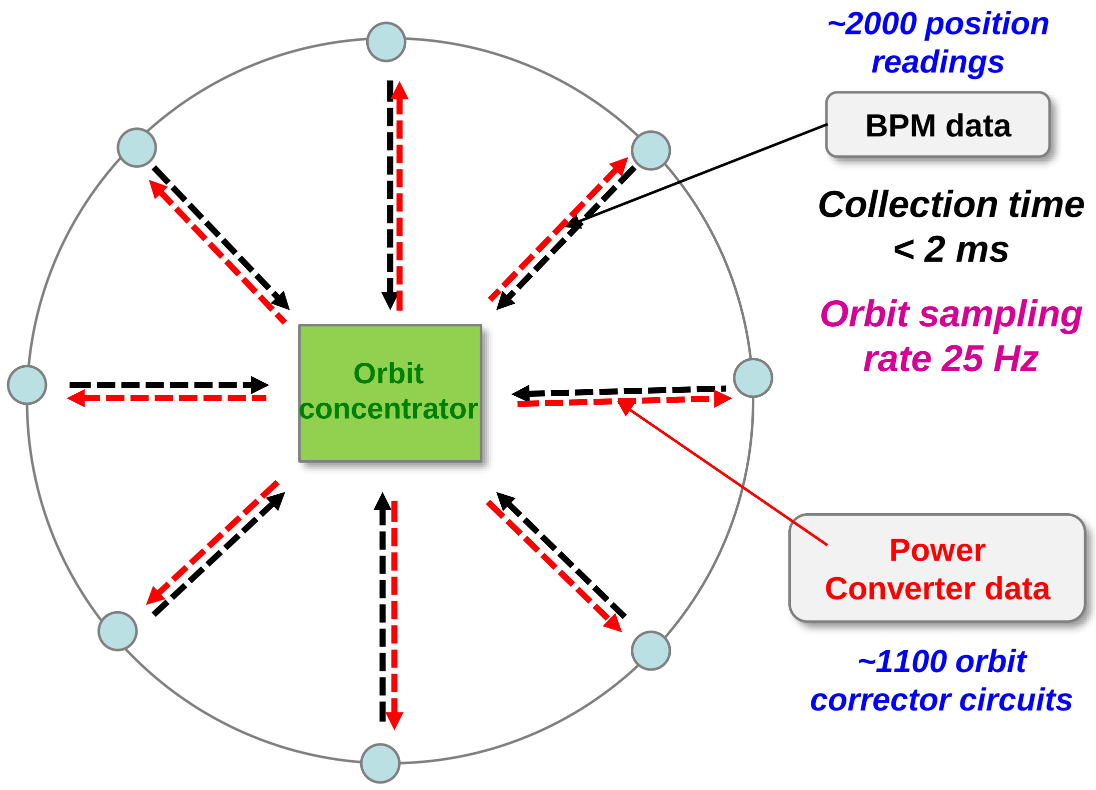
Centralized architecture with **data concentration** of the complete 2-ring orbits – data exchange over accelerator controls gigabit ethernet.

Closed orbit data at 25 Hz for orbit feedback.

- 200 Hz acquisition rate could be achievable.
- **Fb closed loop period limited to 12.5 Hz** by field bus link to orbit corrector power converters. Adequate for a SC machine like LHC.
  - Super-conducting orbit correctors with large inductance – intrinsically “slow” actuators.

Turn-by-turn data is triggered and concentrated following on-demand requests.

- Injection steering, optics measurements etc.



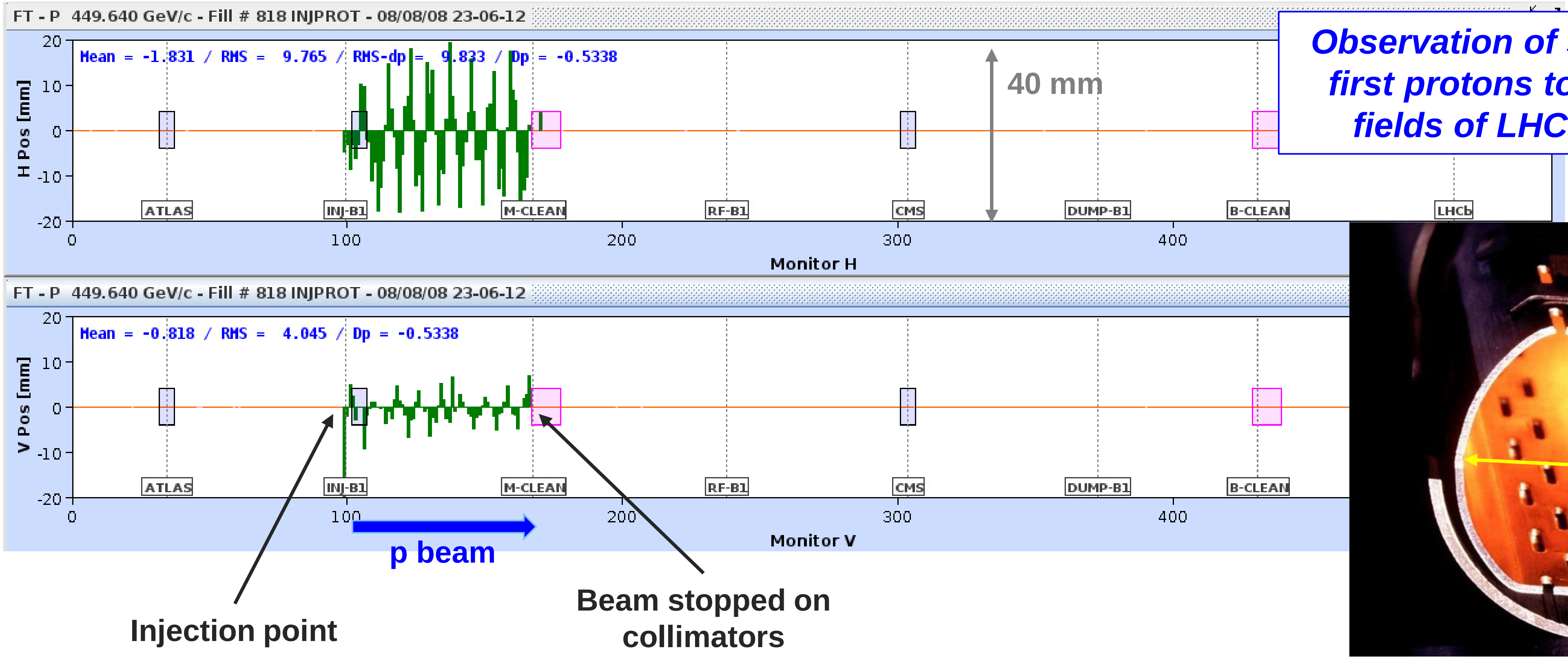
data transfer over standard gigabit ethernet

And it worked !

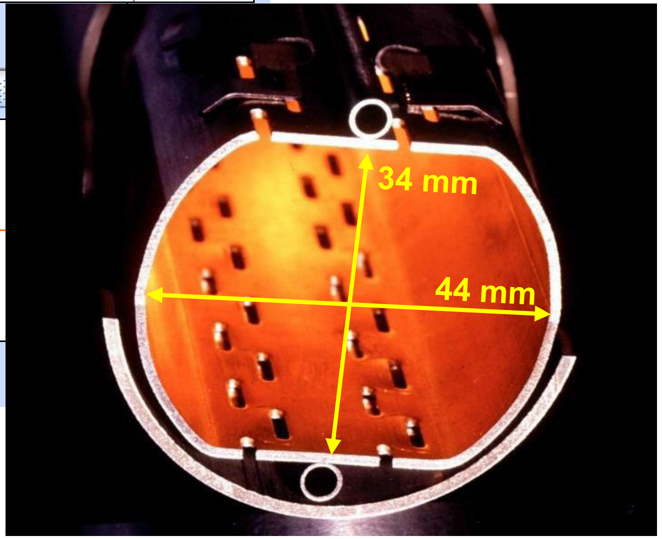
BPM system work on day 1 – hour 1 – min 1 – second 1.

One of **the first trajectory measurements in LHC** during the first sector test – **August 8th 2008** !

Self-triggered acquisition mode – no external clock required !



Observation of some of the first protons to probe the fields of LHC magnets

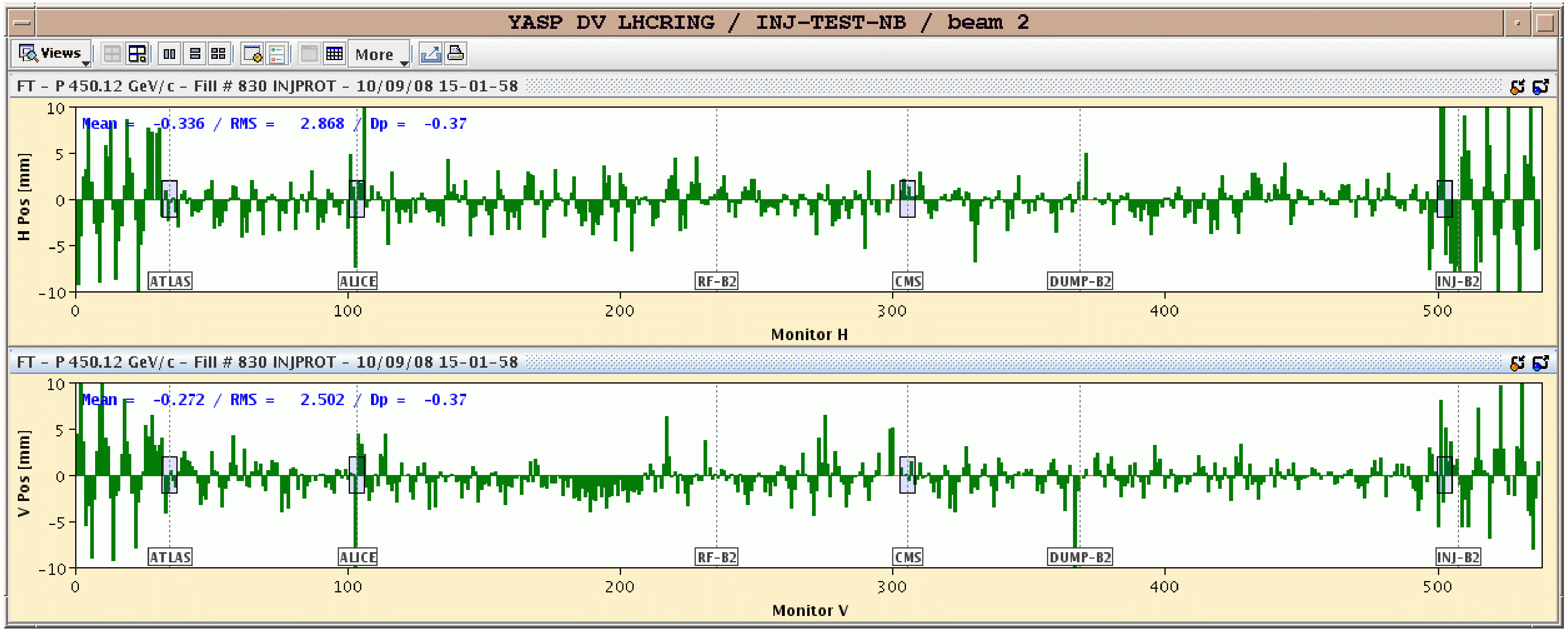


First turn of beam 2…

On the 27 km path, the beam accumulates **too many kicks** to make it around without corrections – ‘thread’ the beam sector by sector (stop on collimators)

Beam 2 threading

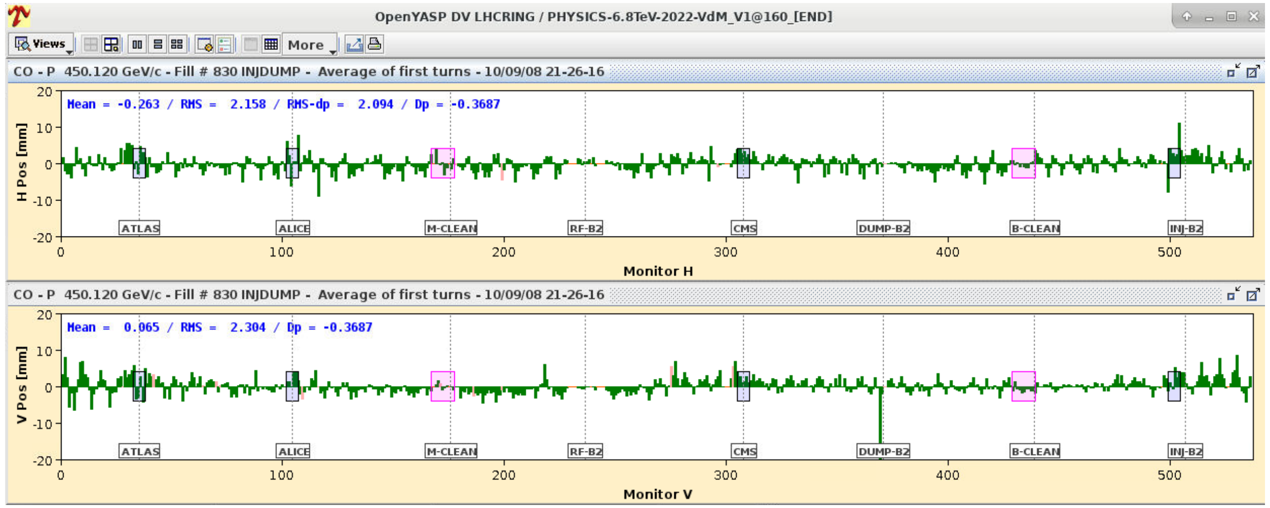
BPM availability ~ 99%



… in a control room full of bystanders !

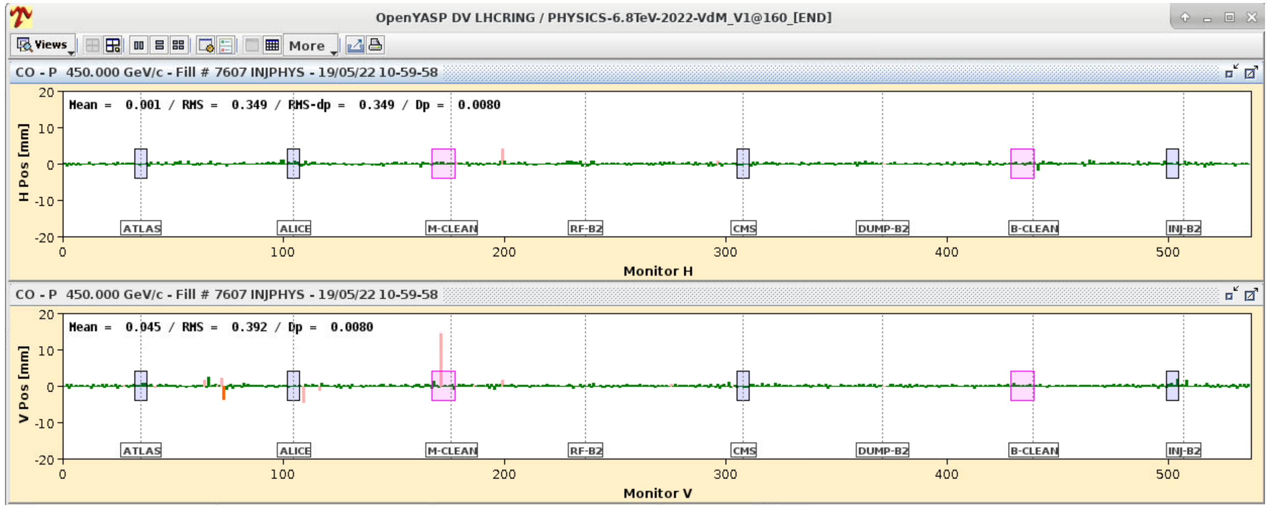
First LHC circulating beam

In the early evening first day both beams were captured by the RF system and circulating !



September 10th 2008

May 2022



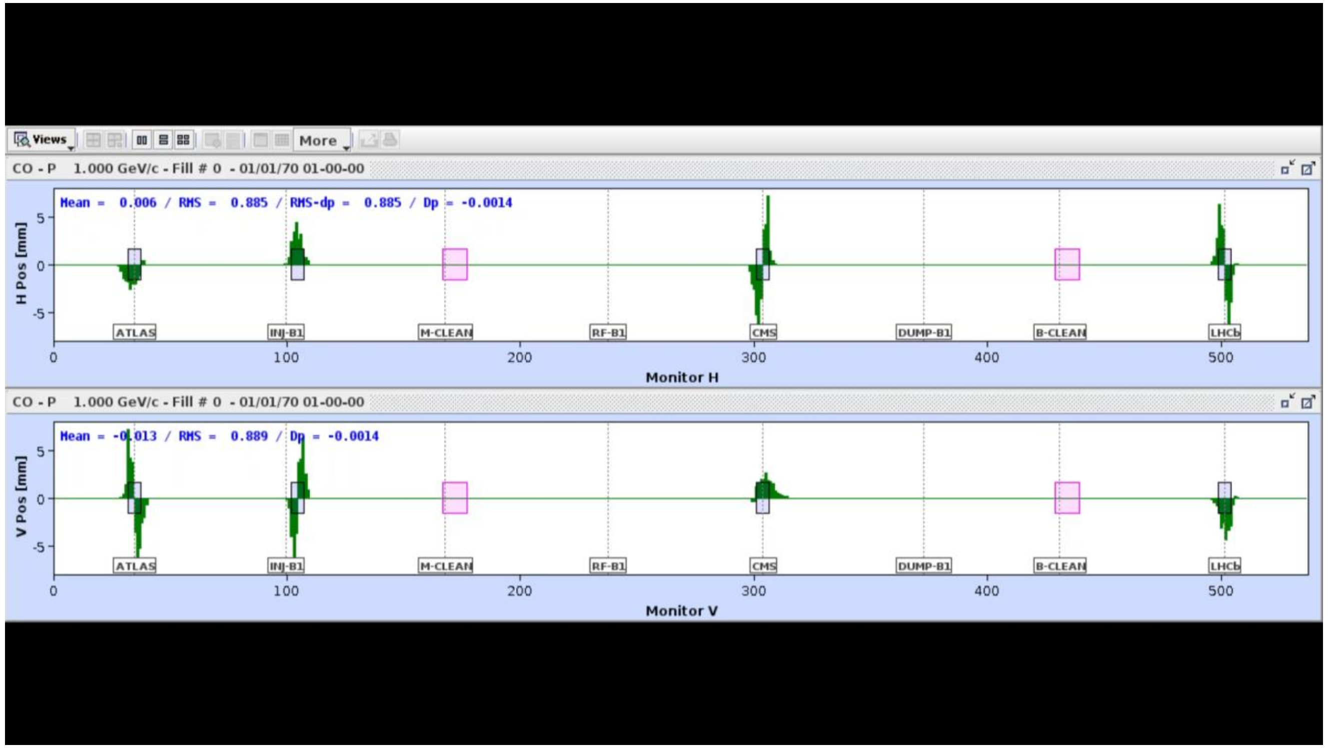
Best orbit correction at LHC with **rms of ~300-350 μm**.

Hadron collider orbit control

Like in most hadron machine, the main aim of orbit correction is to **keep the beam within the aperture**. No concern about dispersion if it does not impact the beam size too much.

The orbit is **flattened with SVD algorithms**, and a unique flat reference is used for an entire operation year.

- Year to year changes are small.



Bumps to separate the beams, crossing angles and other orbit bump features are added as overlays on the flat reference.

- Bump amplitude and composition vary along the cycle. Flat orbit + overlay bumps are used by the feedback as **dynamicc target orbits** through ramp, squeezes etc.
- Orbit feedback essential to ensure **~50 μm rms orbit stability** from injection to collisions.

Alignment

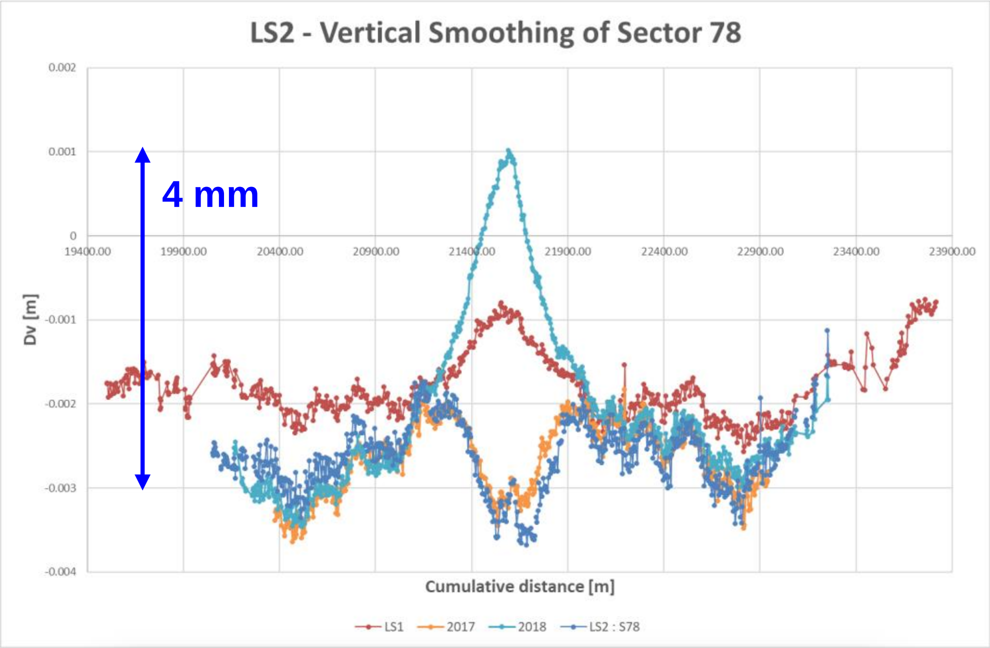
Large rings like LEP/LHC pass through different geological layers – including **active fault lines**.

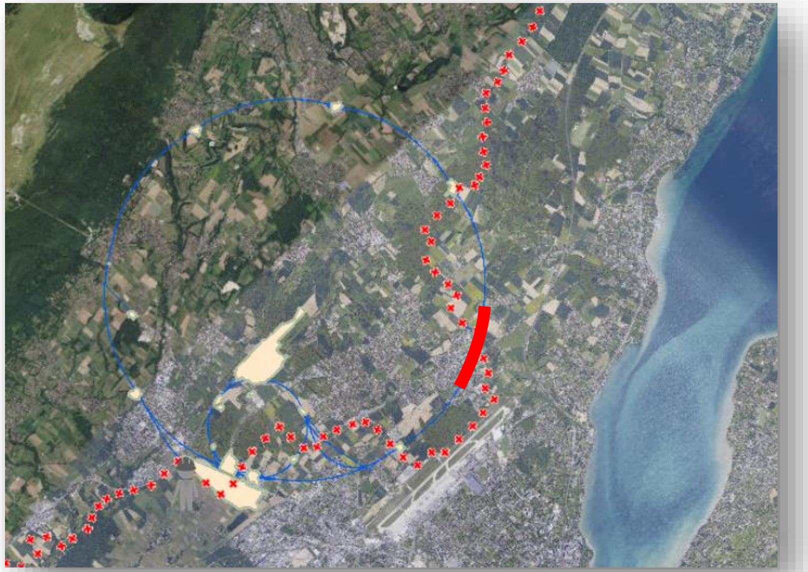
While LEP was **re-aligned to ~0.1 mm vertically** every year, at LHC only **the straight sections** are **realigned** every year.

- (most of) the arcs are left to drift over the 3-4 year long runs, which is not an issue.

A very **active fault line** – already causing trouble to LEP – is crossed by one arc, with **vertical movements of 1-3 mm per year**.

- Preventive mis-alignment to obtain on average a reasonable alignment over one year.





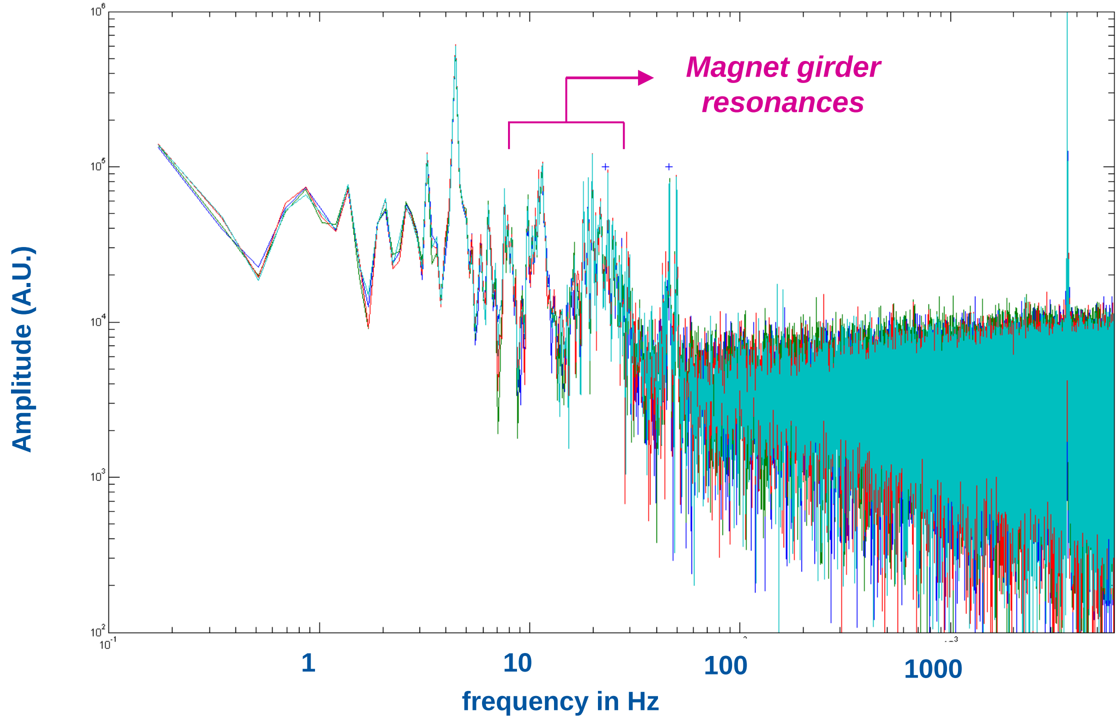
Vibrations

Despite its installation in a deep (50-140 m) tunnel, the beam oscillation spectrum exhibits residual **cultural noise**.

The LHC **magnet assemblies** have **mechanical resonances** in the frequency range of **5-35 Hz**. The girder resonance lines are clearly visible in the beam spectra.

- Orbit feedback (and magnet system) too slow to counter-act.

Some lines of unknown origin (for ex 4 Hz in vertical plane).



Typical LHC proton beam oscillation spectrum

Civil engineering for LHC upgrade

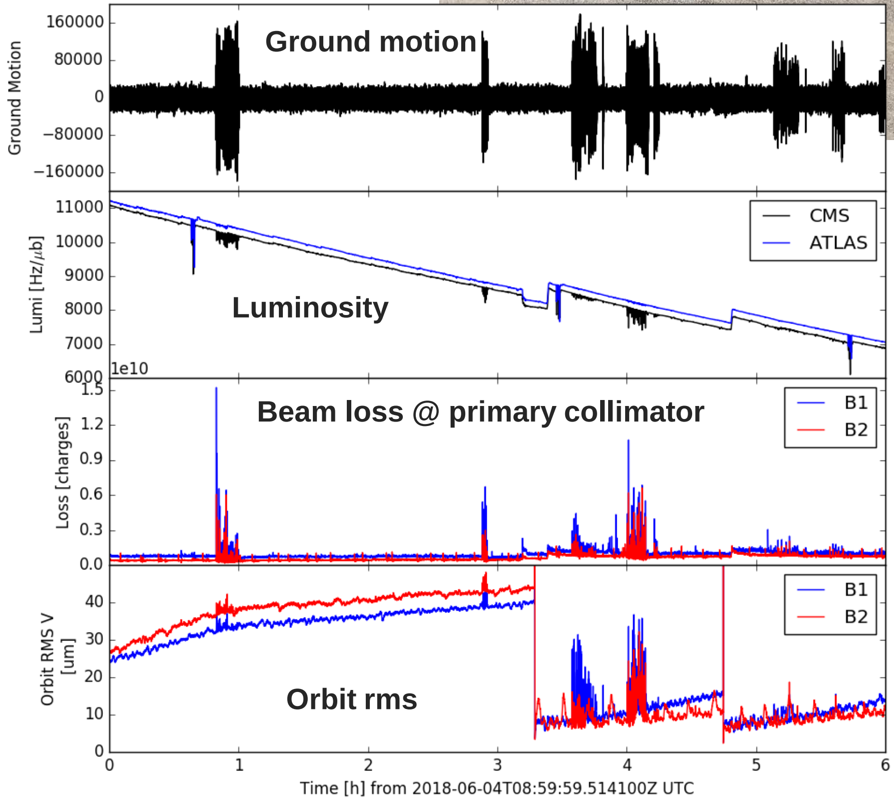
In the early part of the CE work, an important volume of soil was moved around and compacted during LHC operation.

Ground compactors compact soil by **vibrating**, they managed to **shake beams colliding at the IP ~100 m underground**.

- Vibrations with **frequencies ~20 Hz** were transmitted through 100 m of rock to the tunnel magnets and their supports that resonate in the frequency range 8-22 Hz.
- Low-beta quadrupoles, very large betatron function.

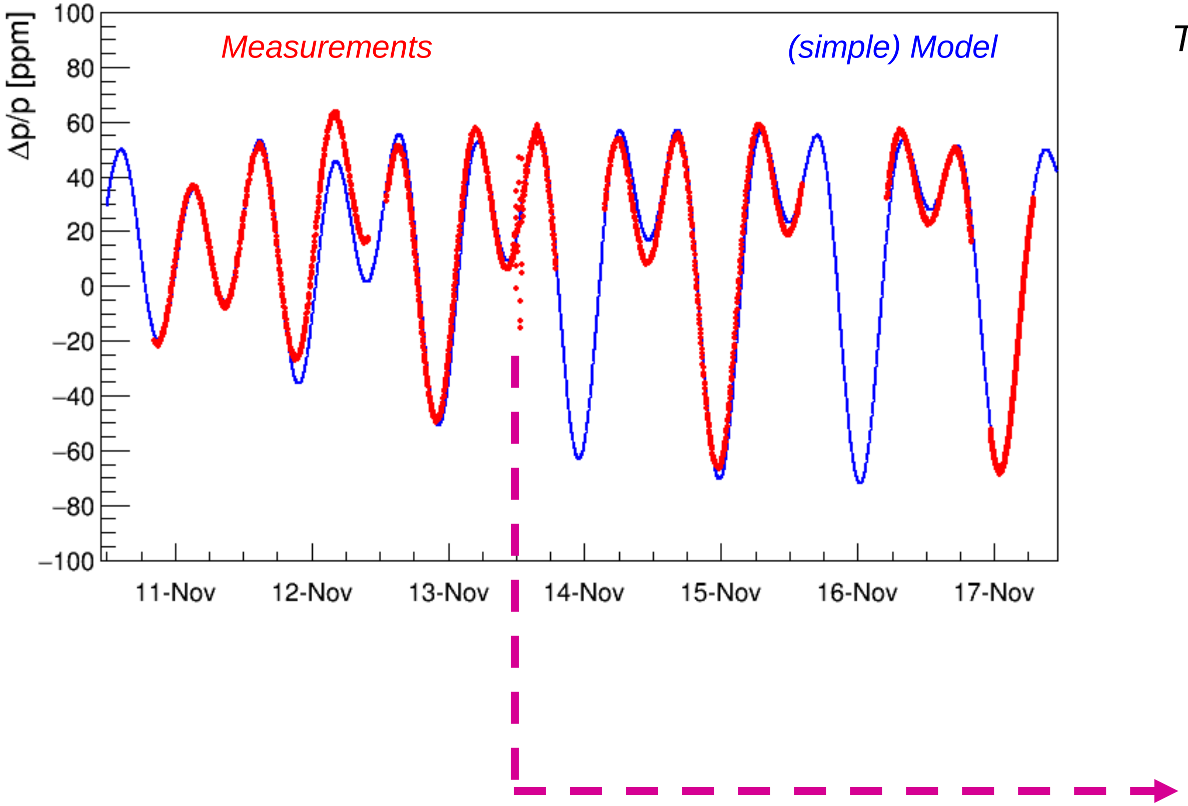
The resonant excitation generated **micrometer amplitude beam movements** that were clearly visible on the CMS experiment luminosity.

~100 m below



Tides – not just @ LEP

LHC feels the tides like LEP. A long stable period with long fill thanks to low luminosity provided one of the nicest and cleanest tide measurements @ LEP/LHC (measured with BPMs).

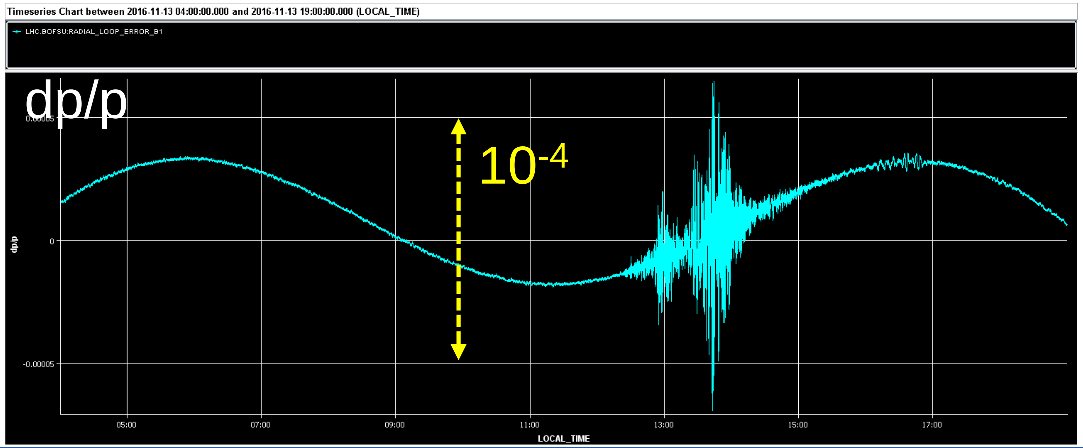


Tide observations (from orbit changes) over one week at 4 TeV in 2016

(expressed in energy change $\Delta p/p$)

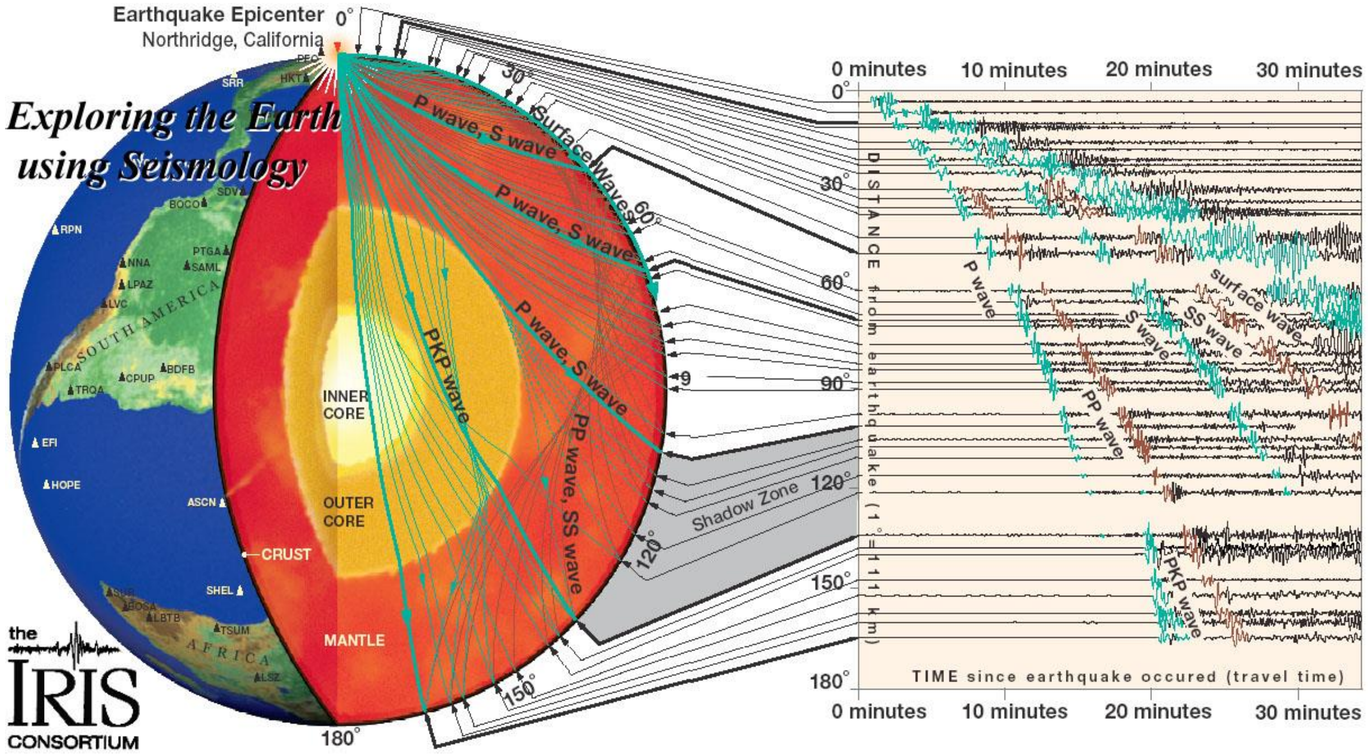
Earthquake in New Zealand

The pressure waves induce a modulation of the circumference similar to tides



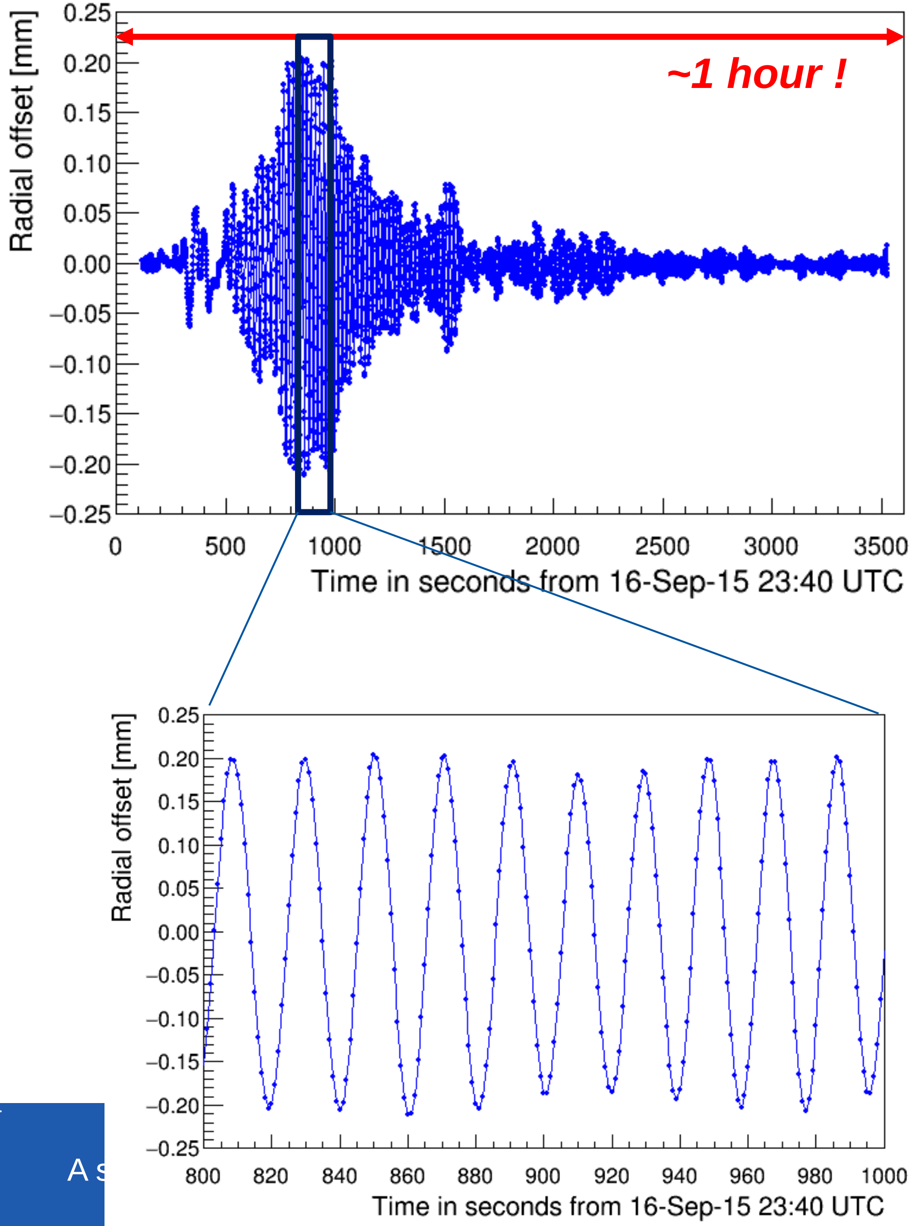
Earthquakes

Various types of body (**P**ressure, **S**hear) and surface waves (**R**aleigh, **L**ove), multiple paths and reflections between core and mantle produce a complex signature of earthquakes at seismic measurement stations – also at the LHC.



L. Braille (Purdue U.) / The IRIS (Incorporated Research Institutions for Seismology) consortium

Record earthquake



The main impact of large earthquakes is a **radial oscillation** due to **surface pressure waves** – like tides.

At the peak of the wave, a **stable period of 20 seconds** : corresponds to a **wavelength of ~80 km** (v = 4 km/s).

- Observed in all strong & far distance earthquakes (M >= 7).

This example shows the earthquake with the strongest signal at LHC so far: **twice the amplitude of the strongest tides**.

- None of the earthquakes observed so far led to a beam abort.

For FCC-ee @ Z such an earthquake amplitude would correspond to an **energy modulation of ~ ±300 MeV**.

8.3 magnitude earthquake near Illapel (Chile) 16 Sept 2015 22:54 UTC.

Distance to LHC ~ 12’000 km (on Earth surface)

Summary

There was a generation change in the performance of the orbit systems from LEP to LHC.

The LHC BPM system is adequate for a hadron collider, orbit reproducibility is limited by systematic effects due to bunch pattern dependance. Complex orbit manipulations can be performed thanks to a flexible control system and orbit feedback.

- But it is not a sub-micron BPM system required for FCCee – was not designed like that !

Due to their size large machine are more affected by the geology, alignment is an issue at large scales (resources and time) – see presentation by H. Mainaud last week.

Cycled machine like LEP and LHC clearly encounter different issues than a steady state machine like FCC-ee, but the experience will be relevant for the booster.

- The magnetic cross-talk booster – collider could have a significant impact for FCCee.

FCCee will be a mix between a synchrotron light source (constant energy operation, top up, emittances etc) and LEP/LHC (size) – some of the LHC experience is relevant, others is not !