Orbit feedback at the LHC

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Operation group

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Courtesy of Sergio Cittolin

***now at GSI**

Scales for feedbacks

	Synchrotron light sources	LHC
Size	m	km
Frequency scale	kHz	Hz
Position scale	nm	μm
Position scale [beam size]	σ	σ

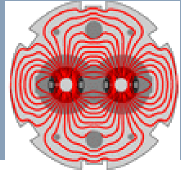
The LHC 'fast' orbit feedback is what for at light source one generally calls the Slow Orbit FB (SOFB)

Large Hadron Collider LHC

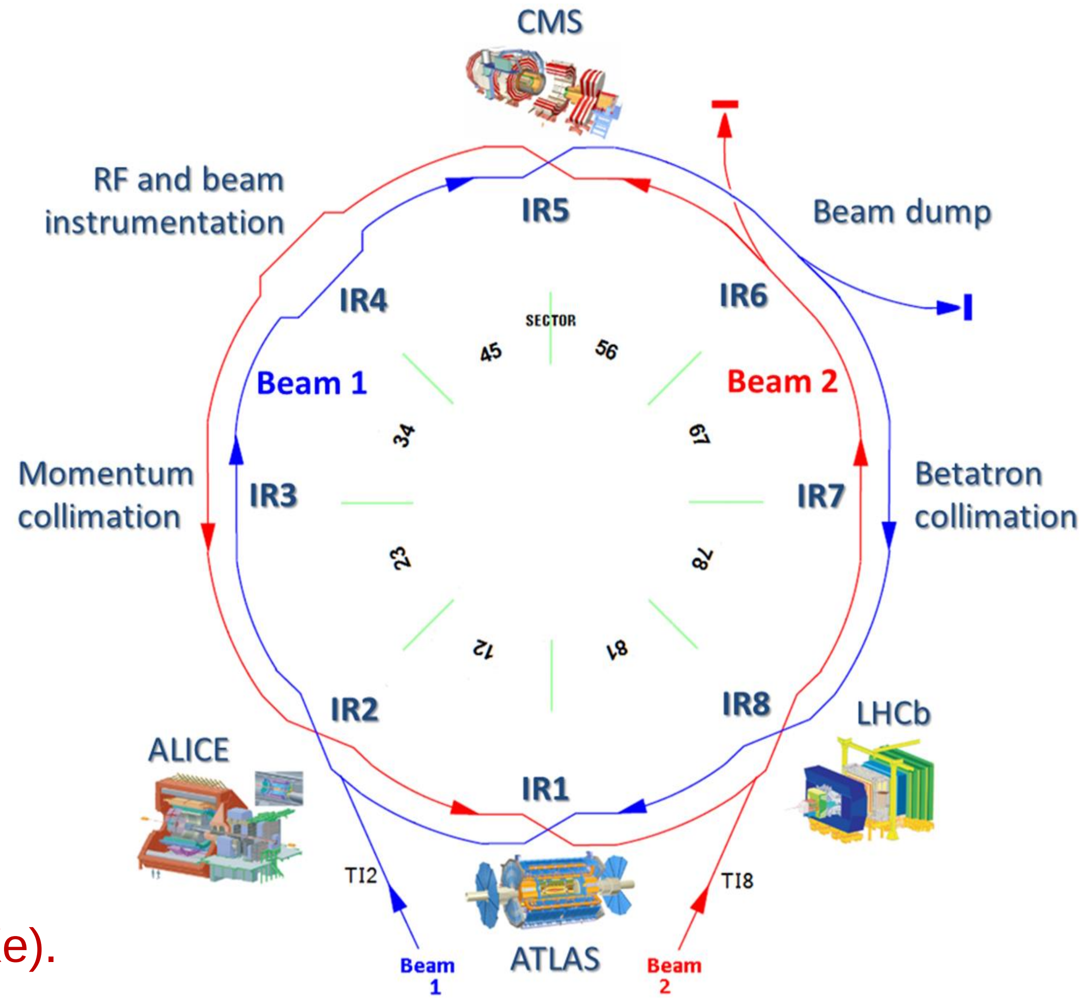
Installed in a 26.7 km tunnel

at a depth of 70-140 m

LHC Layout



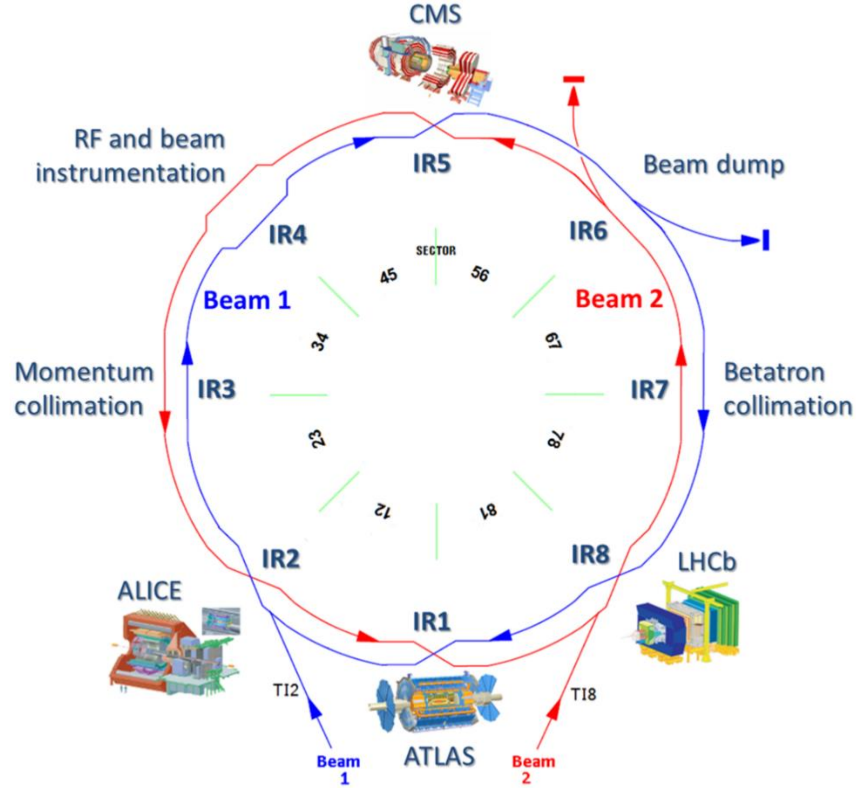
- Total length 26.66 km.
- 8 arcs (sectors), ~3 km each.
- 8 straight sections of 700 m.
- Beams cross in 4 points.
- Operating energy 6.5 TeV.
- Almost fully superconducting magnet system.
- 2-in-1 magnet design with separate vacuum chambers.
- **2 COUPLED rings**.



The LHC can be operated with protons and ions (so far Pb and Xe).

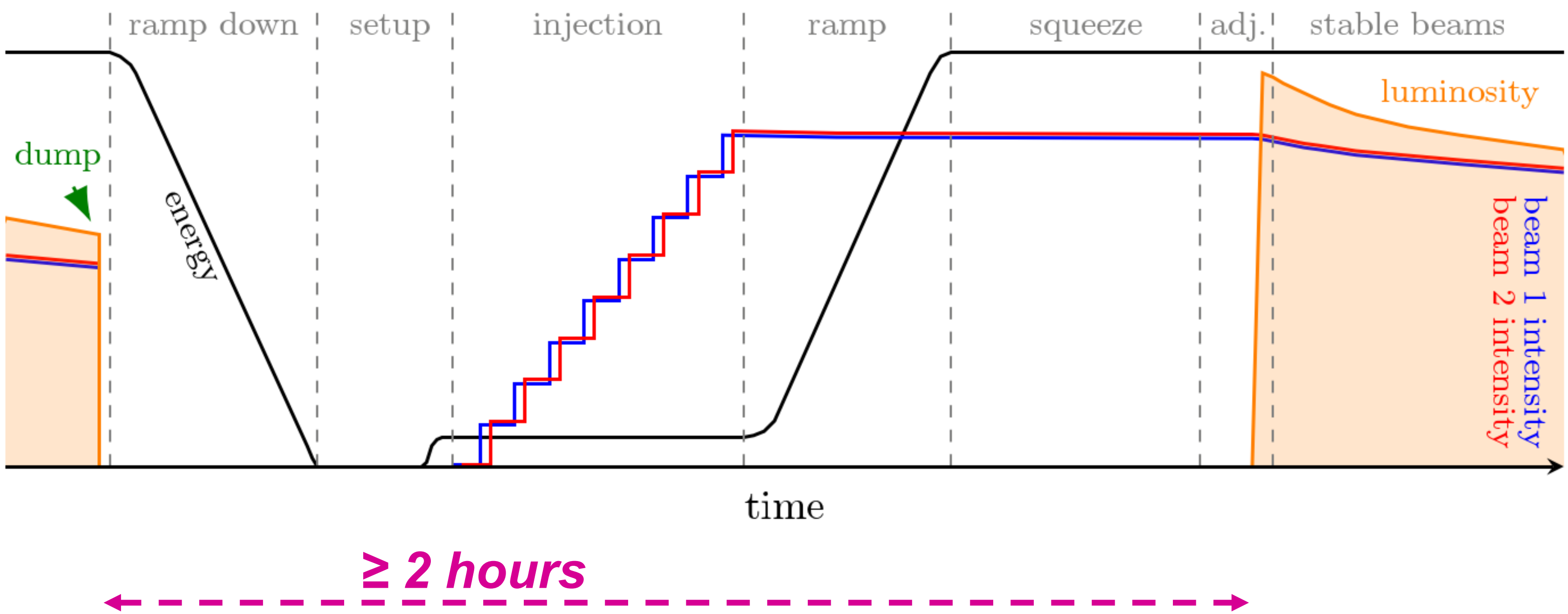
LHC Experiments (Users)

- **ATLAS** and **CMS** are the two high luminosity experiments, **L ~ 10^{34} cm^{-2}s^{-1}**.
- **LHCb** is a medium luminosity experiment, **L ~ 4×10^{32} cm^{-2}s^{-1}**.
- **ALICE** is a low luminosity / ion experiment, **L ~ 10^{31} cm^{-2}s^{-1}**.
- LHCb and ALICE are **luminosity levelled**.
  - The actual luminosity is << than the luminosity with head-on collisions.
- **TOTEM**, **ALFA** and **AFP** are small forward physics experiments.



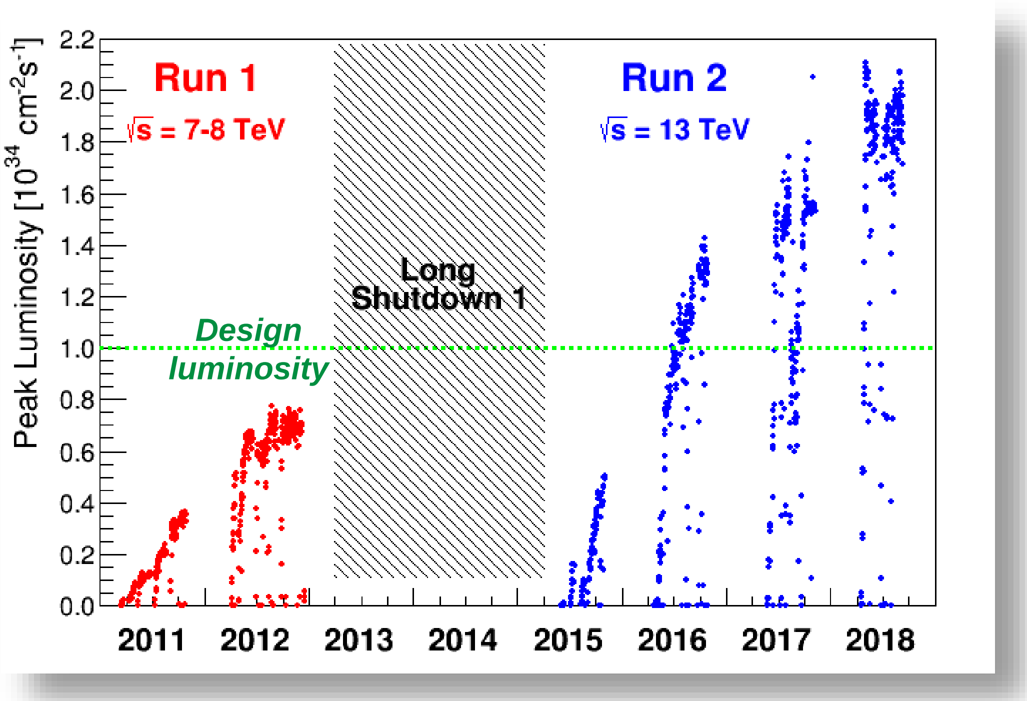
LHC machine cycle

- Beams are injected and accumulated at **450 GeV** (up to ~2800 bunches) with a detuned optics (large β at the interaction points (IP)).
- The beams are accelerated to **6.5 TeV** in a 20 minute ramp during which the optics is already partially squeezed (lower β at IPs).
- At higher energy the final beta squeeze is applied and the beam are brought into collision for ~ 12 hour long physics data taking.



LHC performance

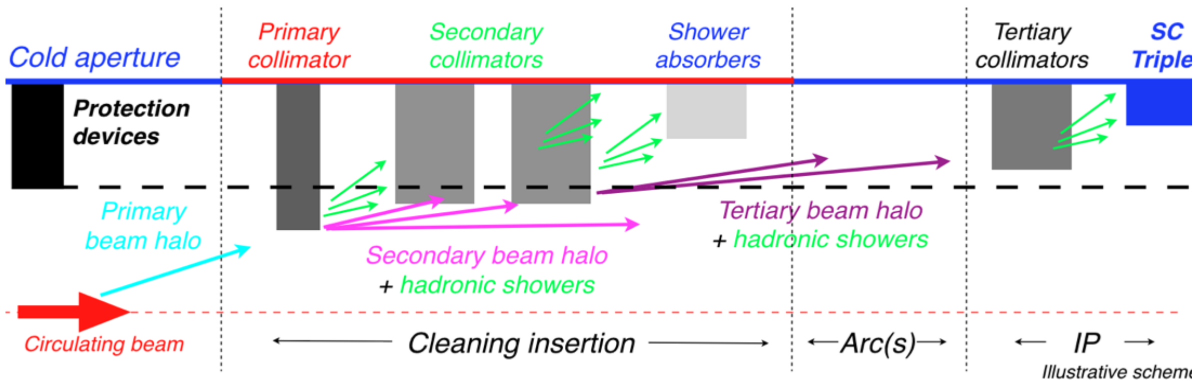
- The LHC performance currently reached **twice design luminosity** thanks to:
  - Excellent hardware performance and good availability,
  - A precise machine setup (orbit, optics),
  - An excellent reproducibility,
  - Very bright proton beams from the injector chain.



Peak luminosity is limited to ***≈2.2×10^{34} cm^{-2}s^{-1}*** *by the cryogenic cooling capacity of the low-beta quadrupoles*

Stability tolerances

- In 2018 LHC operated with stored beam energies of **~340 MJ** compared to **tolerable loss rates** in SC magnets of ~ **mW/cm^{-3}**.
  - 3×10^{14} protons per beam for a tolerable transient loss (<< seconds) of ~ 10^{8}-10^{9} p.
- The SC magnets are protected from transient losses by a complex 4 stage collimation system with ~100 mostly Carbon based double-jaw collimators that are positioned following a strict hierarchy.
  - Relative retraction tolerances of **~0.25-0.5σ** (O(25-100 μm)).



- To ensure that the beams collide reproducibly at the IPs every cycle, the tolerance on the beam position at the IPs is **~0.5-1σ** (O(5-10 μm)).

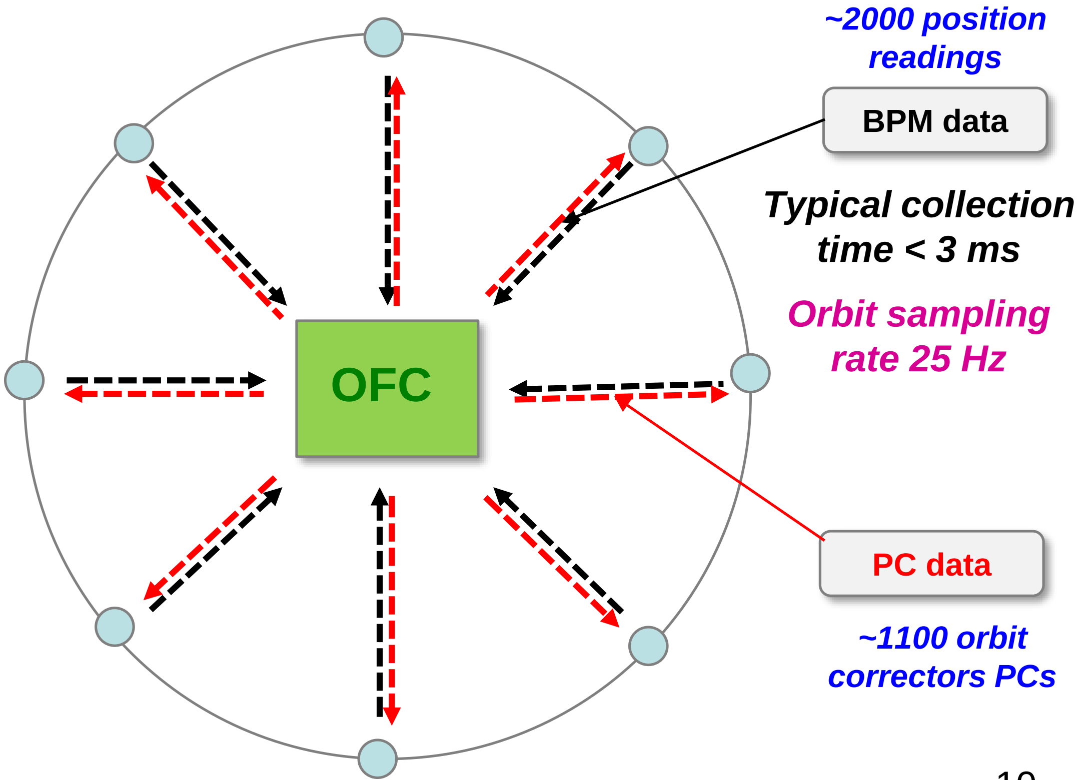
σ = rms beam size

Orbit perturbations

- With its high inductance SC circuits the LHC is intrinsically a '**slow**' machine.
  - Perturbation time scales ~ O(seconds).
  - Actuators are slow (respectively [too] weak on fast time scales).
    - No dedicated 'fast' correctors.
  - A dynamic phase with faster transients appears in the first ~30 seconds of the ramp due to the 'snapback' effect of persistent currents in the SCs.
    - Affects tune and chromaticity more than orbit. Q' transients of ± 30 units !
- Natural ground motion levels in the deep LHC tunnel are low and are generally not an issue.
  - Main 'issue' are slower cycle to cycle changes of the orbit (~ hours).
- An orbit feedback with **closed loop BW ~ 0.1-1 Hz** seemed sufficient for the needs of the LHC.
  - The orbit feedback is complemented by a tune feedback.
  - Both orbit and tune FBs are active in every machine cycle.
  - Settings feed-forward of the FB trims is used to minimize the FB load (be more resilient against FB outages).

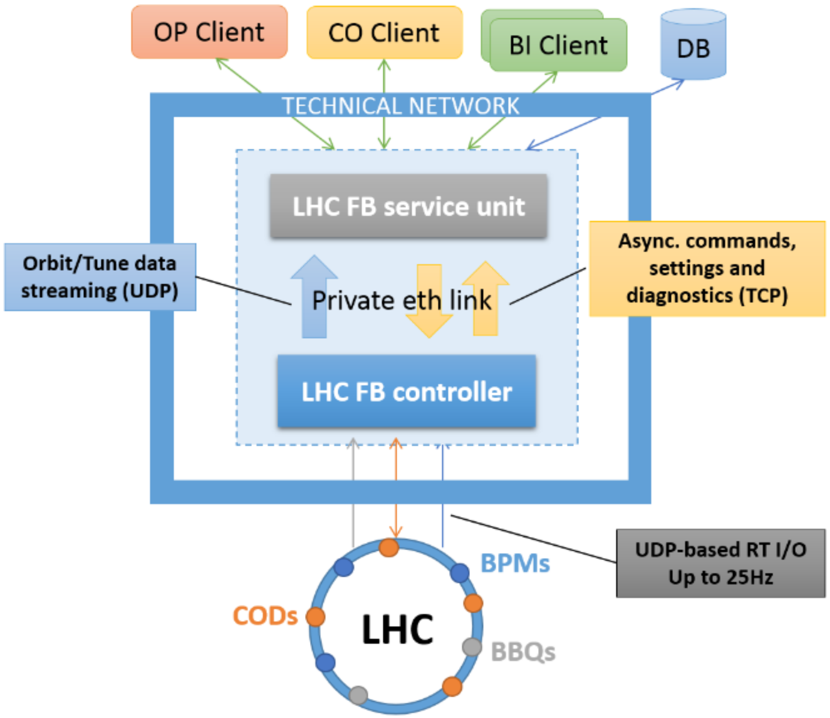
Architecture design

- A central **FB Controller** (**OFC**) is running in the control room where all data is concentrated, processed and corrections dispatched.
- The beam position monitors and the power converters (PC) that feed the magnets are distributed around the LHC ring.
  - The sensor data is obtained from 70 Front End Computers (FECs) installed in 8 LHC points.
  - The actuators data is dispatched to ~40 FECs installed in 8 LHC points.
- The data is transmitted over the accelerator technical network as standard (UDP) data packets.
  - Option of QA on FB packets (priority at switch level) is available, but it was never used.



Feedback architecture

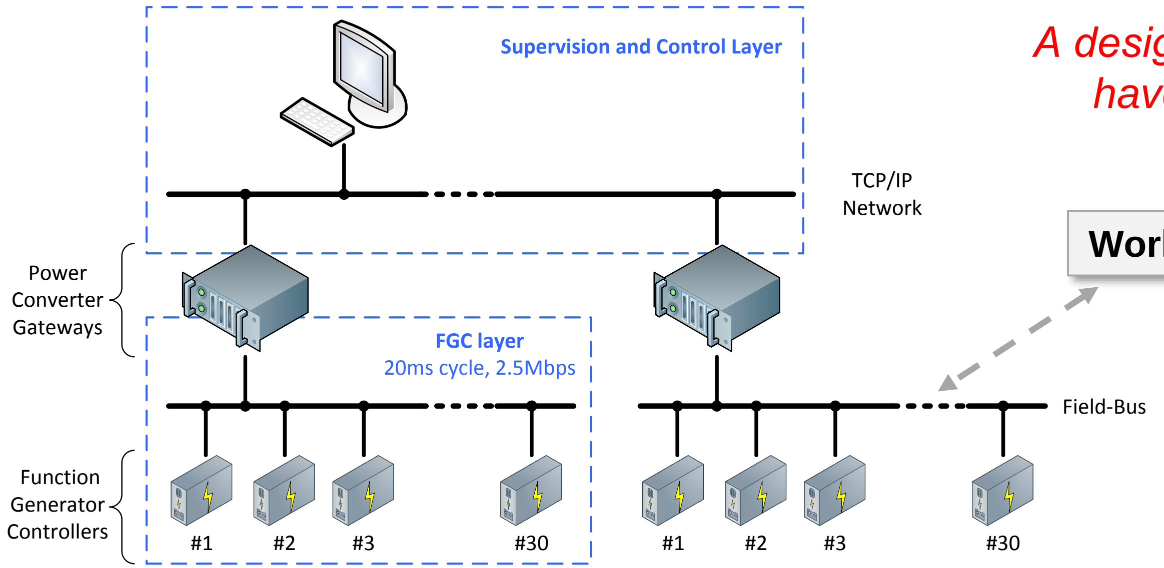
- The feedback is implemented in two C++ servers for data collection and control loop ('controller' → critical for operation) and for interfacing to the accelerator control system ('service unit').
  - The service Unit is implemented with the standard CERN front end computer design framework ('FESA') and looks like a standard control system device.
  - The controller is a custom build C++ server using the root framework.
- Each server is running on a HP ProLiant (2 x Intel Xeon CPU, 12 cores, 32 Gb RAM) with a private Ethernet Gb connection between to the servers.
  - ScientificLinux OS.



Actuation – power converter control layer

- The LHC PCs have fully digital control system, in some location with radiation optimized design.
- Local gateways (by LHC point) receive control inputs (functions, state commands, **RT inputs**) through the accelerator technical network.
- Data is exchanged between gateways and PC units by a RT **Worldfip** field bus operated at **50 Hz**.
- For orbit correctors the PC digital loop period is **80 milliseconds**.

A design 'error' – should have been 20 ms!

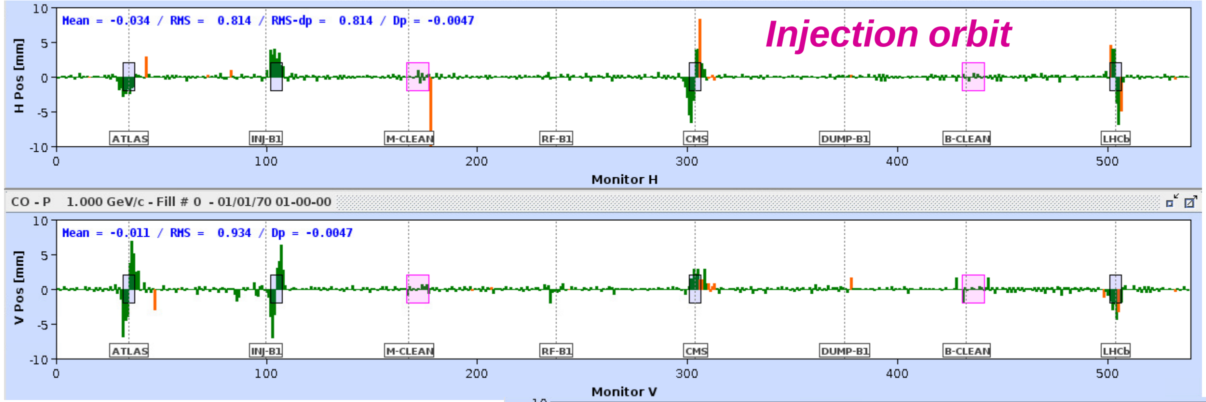


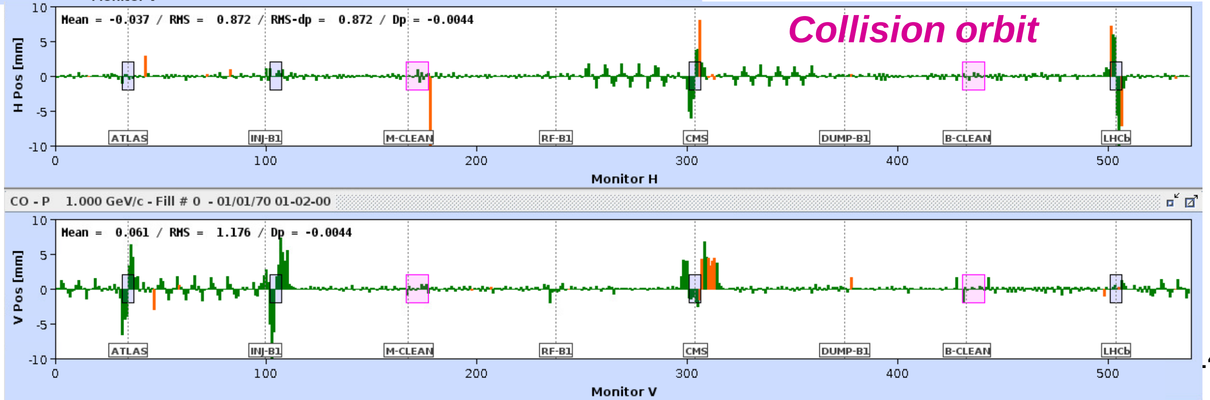
BPM performance

- The LHC BPM system consists of button BPM and couplers.
  - Some directional couplers see both beams in a common vacuum chamber.
- In a typical year the LHC operates with filling patterns ranging from 1 single bunch to ~2800 bunches.
  - Bunch spacing of 25 ns, 50 ns, 75 ns, 100 ns,
  - Bunch intensity range 4×10^9 to ~2×10^{11} charges.
- The orbit measurement resolution (one sample) is generally < 1 μm.
- The **performance** of orbit correction at the LHC is partly limited by residual **bunch pattern** dependent systematic errors at the level of ~20-50 μm rms.
  - Residual after BPM calibration.
- A second systematic limitation is **temperature effects of the electronics** (despite T stabilized rack): ~20-50 μm rms.
- The long term stability seems to be in the shadow if those two effect.

Dynamic orbit references

- The target orbit for the LHC OFB evolves along the LHC cycle.
  - Crossing angles and beam separation at the IPs, bumps to shift collision points, to compensate dispersion etc.
- Tracking of the orbit requires synchronization of the OFB with the machine cycle. Each BPM reference position is a time varying function along the cycle.
  - For the arc sections, the reference are in most cases constant,
  - Changing references concern mainly the 4 straight sections of the experiments.



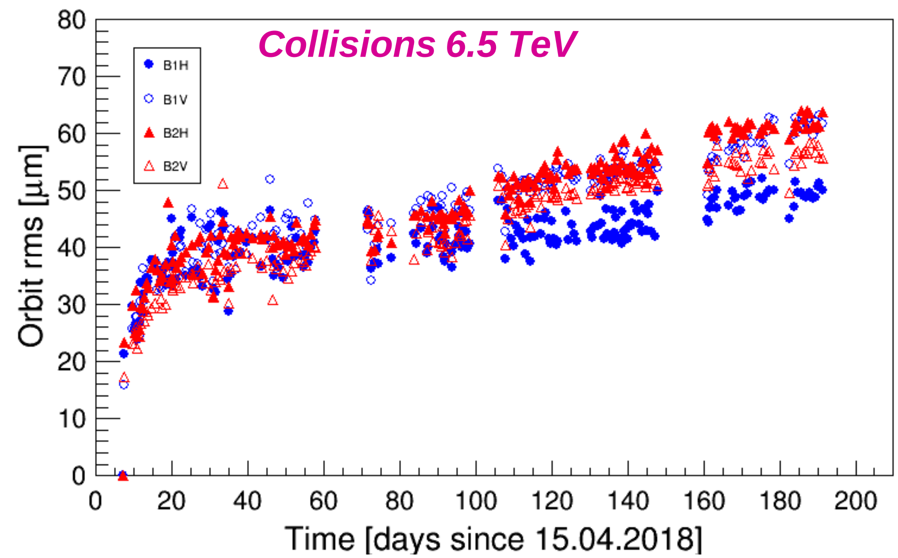


Correction strategies

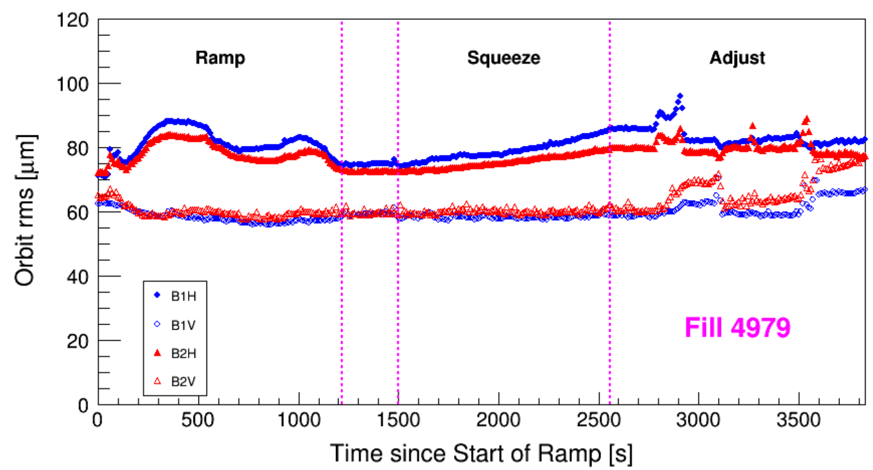
- The optics at LHC is corrected using **BPM multi-turn techniques** (kick with AC-dipole) complemented by **k-modulation** for the betatron functions and waist location at the IPs.
  - Beta-beating in the range of 2-10%.
  - Limited number of individually powered quadrupole circuits.
- The OFB can rely on the **model response matrix** that is switched along the cycle to follow the machine optics.
  - Pre-calculation of the matrices (SVD) for up to ~ 20 optics.
- Classical SVD correction provides very good performance.
  - Typically ~400 out of 520 eigenvalues are used for injection, ramp and squeeze phases with a BW of ~0.1 Hz.
    - High eigenvalues removed to avoid noise propagation unto IP orbits.
  - For stable collisions only 40 out of 520 eigenvalues are used with a reduced BW of ~0.01 HZ; as the orbit drifts very slowly, emphasis is set on soft corrections that are insensitive to BPM systematic errors.
    - Minimizes impact of electronics temperature.

Orbit stability in operation

- **Long term reproducibility** of the orbit (yearly run) is **~50 μm**.
  - Limited by uncorrectable ground motion and/or long term BPM stability.
  - Short term stability ~ 20-30 μm over ~10 days.
- For the duration of a collision period (~12 hours) the stability is **~10-20 μm**, *dominated by BPM systematic errors*.

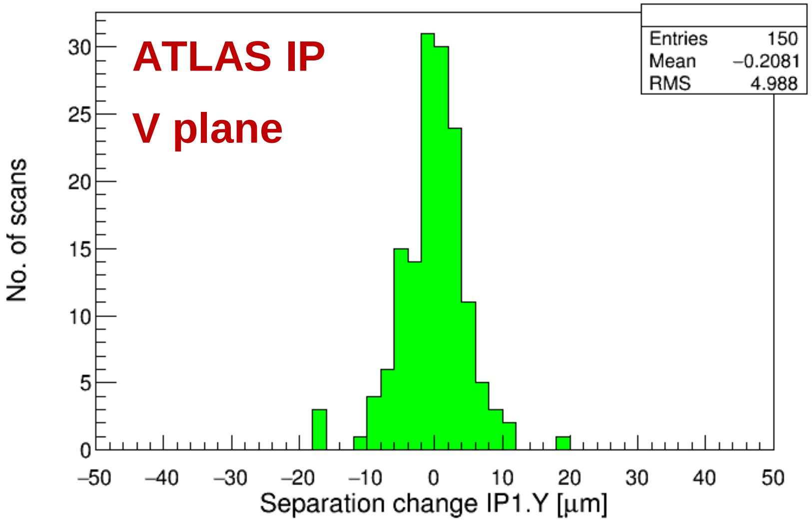


- The stability within the machine cycle is at a similar level.
  - Limitation of eigenvalues explain some structures.

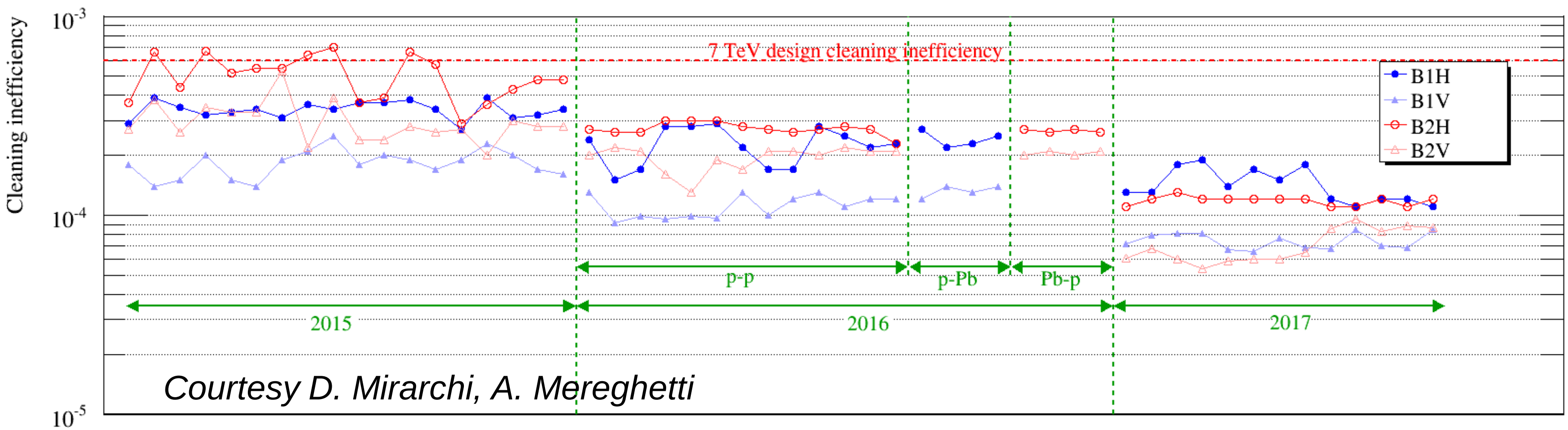


Orbit stability in operation (2)

- Fill to fill **reproducibility of the collision point** is ~ $\sigma/2$.
  - Excellent performance given the complexity of the low beta section around the IPs.



- Collimation system beam cleaning performance remains stable over a run.
  - One unique collimator setup at the beginning of each year.
  - Orbit reproducibility well with specification.

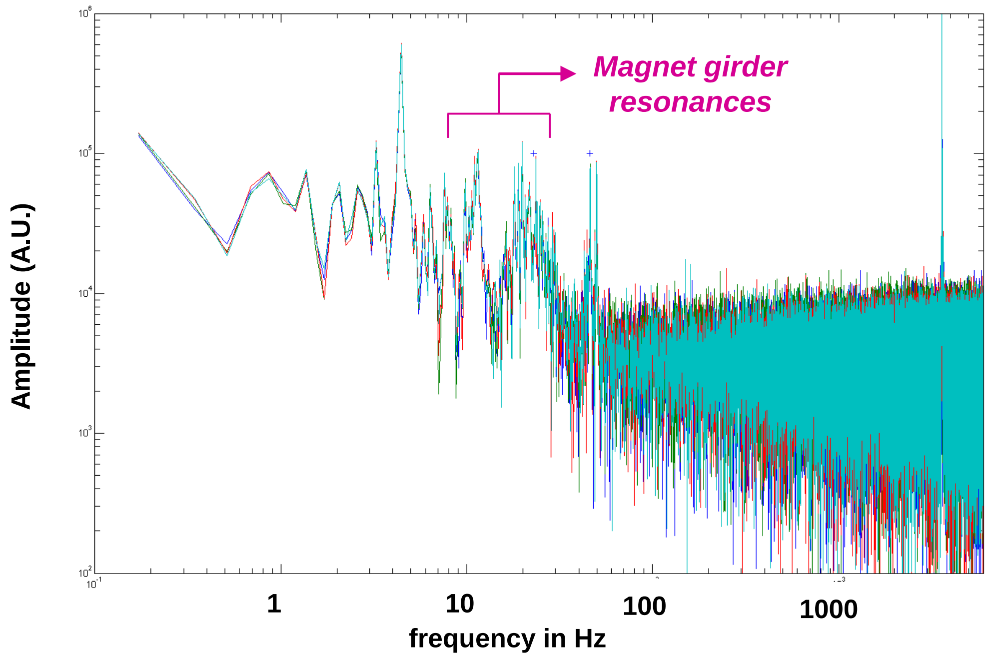


Courtesy D. Mirarchi, A. Mereghetti

Vibrations

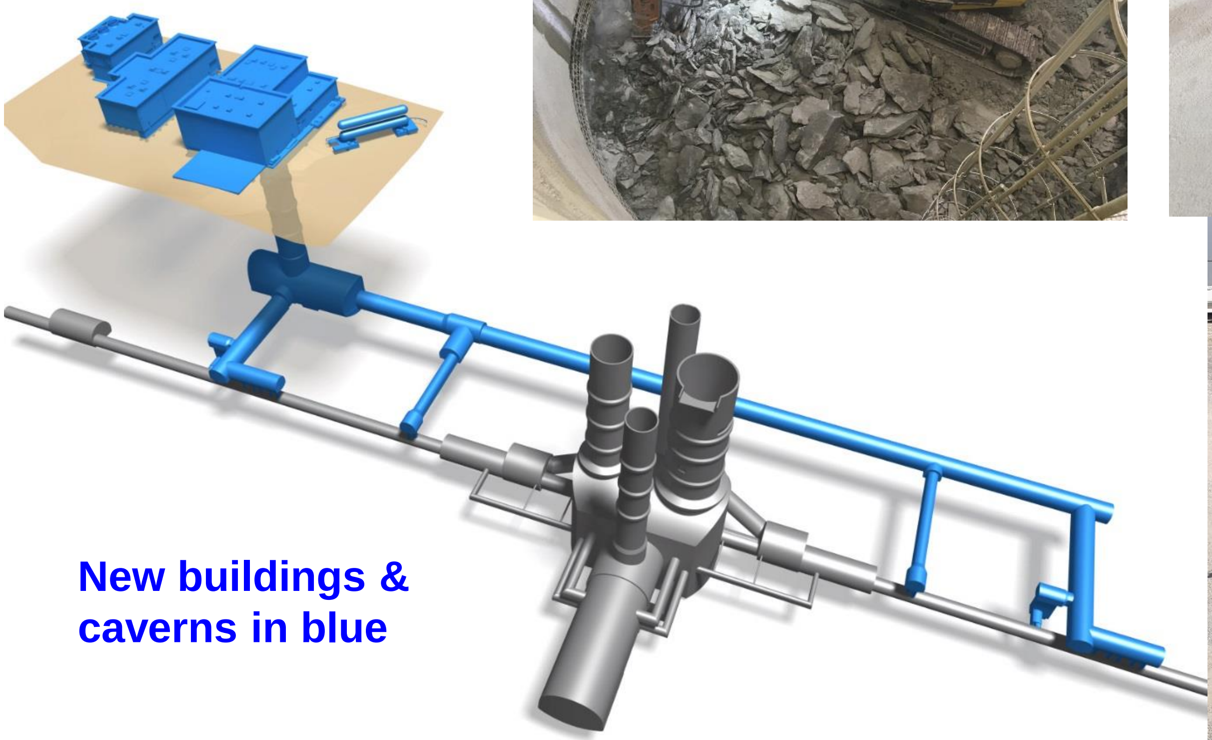
- The LHC OFB is evidently not capable of counteracting high frequency orbit changes (above ~ Hz scale).
- While in normal operation the performance is of the OFB is well adapted to the machine perturbations, ut in some cases the OFB reaches its limits:
  - Vibrations of low beta-section quadrupoles (girder resonances) amplified **by civil engineering** works for the LHC high luminosity (HL-LHC) upgrade,
  - **Earthquakes**, possibly generated by geothermal energy exploitation.
    - Micro-seismic activity.
  - (Semi-) periodic fast perturbation (~1-2 seconds) of (yet) unknown origin.

Typical LHC proton beam oscillation spectrum



Civil engineering for upgrade

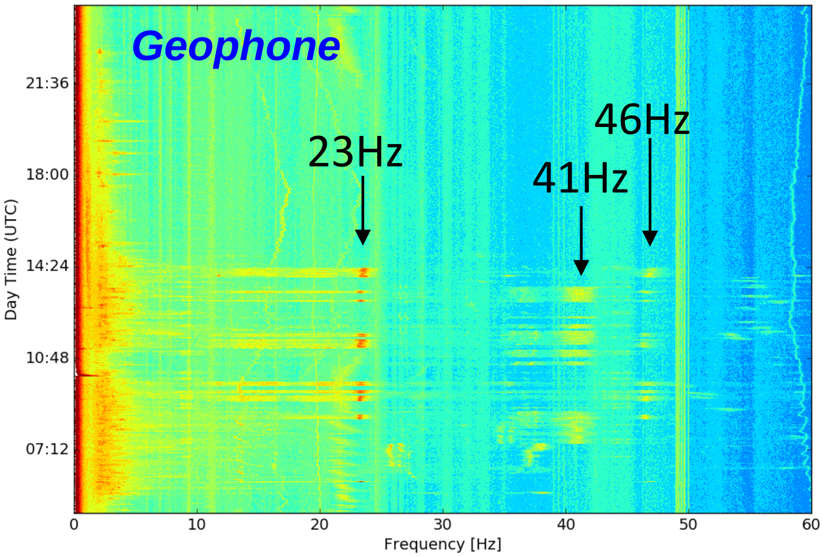
- Major CE activity at two LHC points: new surface buildings, shafts and underground caverns.
  - Shaft excavation has started (from the surface).

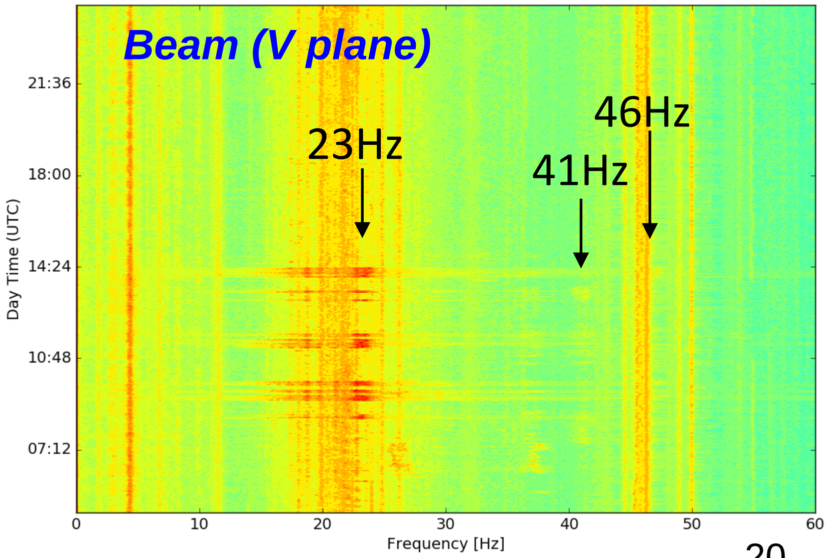


New buildings & caverns in blue

Civil engineering vibrations

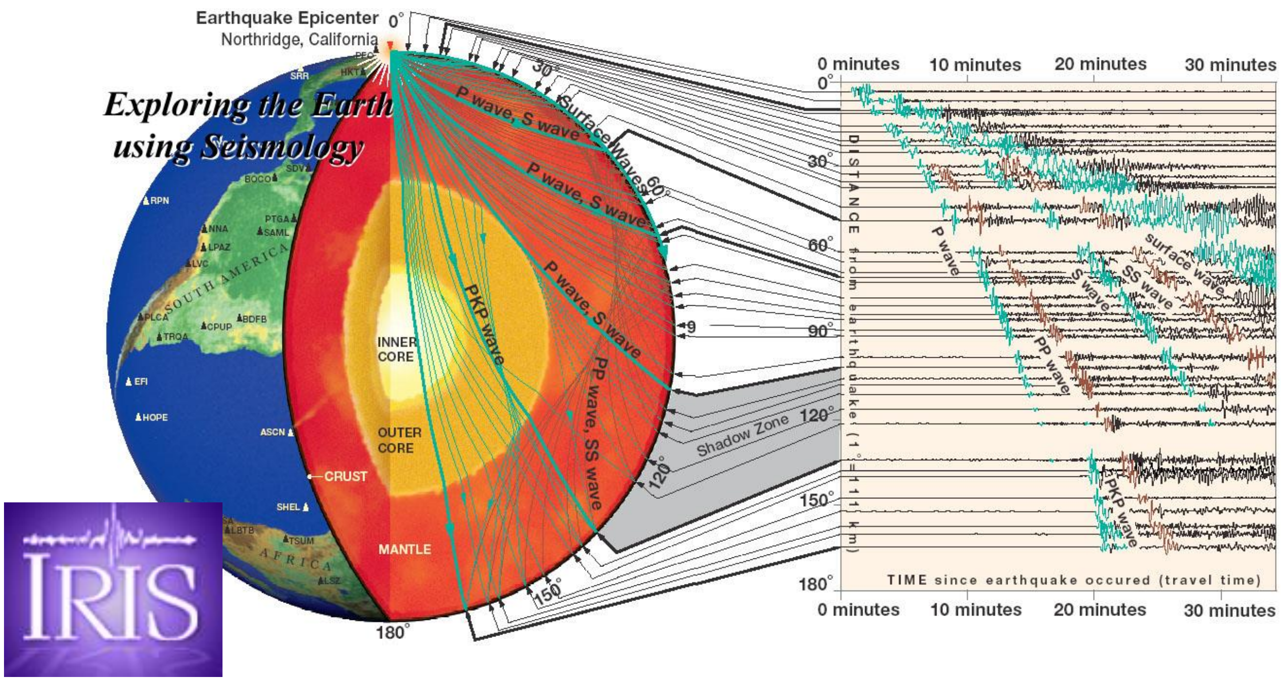
- Vibrations due to CE can be clearly observed on geophones installed near critical magnets and on the beams.
  - Main girder resonances are in the range of 8 - 22 Hz.
- The main impact so far was due to **ground compactors** operating on the surface (~100 m above tunnel).
  - Compaction by vibration,
  - Frequency range covers the magnet girder resonances.
- Fortunately those activities provoked only minor perturbations, the CE of the shaft excavation is still > 50 m above tunnel level and no impact was observed so far…





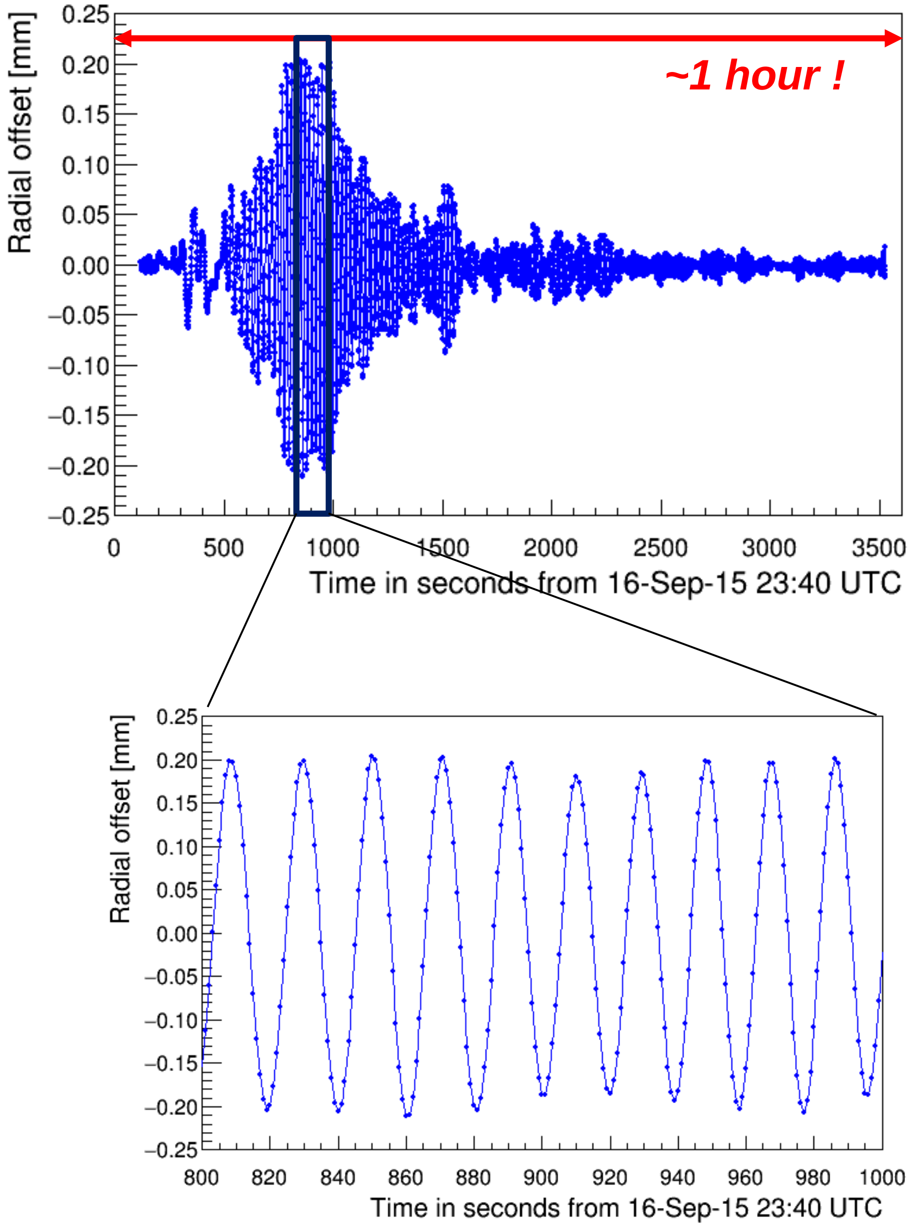
Earthquakes

- Various types of body (**P**ressure, **S**hear) and surface waves (**R**aleigh, **L**ove), multiple paths and reflections produce a complex signature of earthquakes at seismic measurement stations – like the LHC.
- Waves from earthquakes of **magnitude ≥ 7** are generally visible at the LHC as radial oscillations even for events occurring on other continents.
  - Beam losses observed sometimes, no beam dump so far.



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

Earthquake example (Chile)



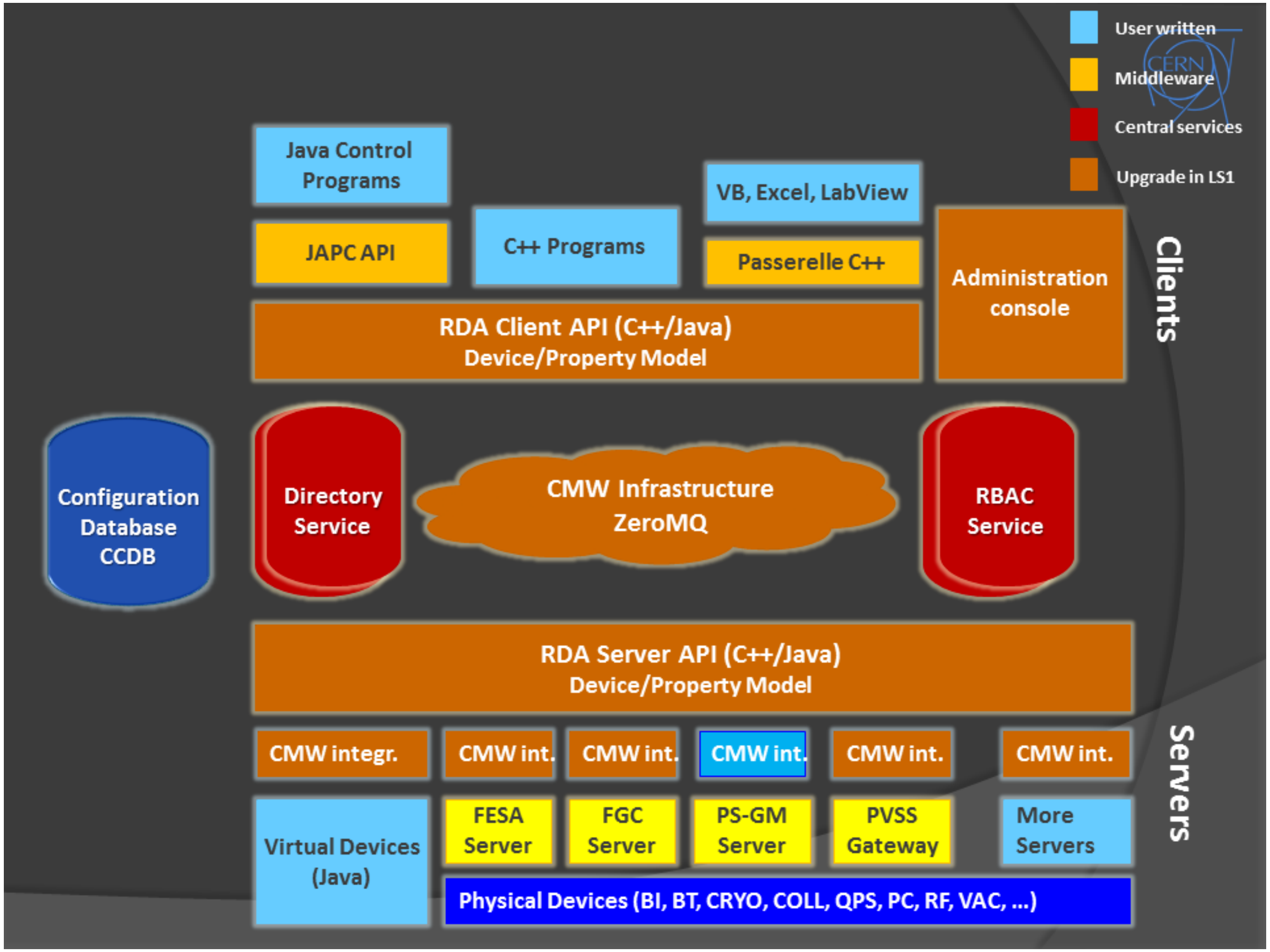
- The main impact on the ring is a radial oscillation of the ring due to surface waves.
- A zoom reveals a stable period of 20 seconds at the peak of the perturbation. This corresponds to a wavelength of ~80 km (v = 4 km/s).

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

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

Conclusions

- The LHC operated efficiently and reliably, reaching twice design luminosity, greatly helped by stable orbits and tunes during the cycle.
  - So far the design of the feedback was well matched to the needs.
- At the end of 2018 the LHC enters a two year long shutdown which will also be used to renovate the feedback control software after 10 years of operation.
  - Move the custom made controller to the CERN FEC framework,
  - Concentrate service unit and controller in one new & more powerful server,
  - Clean up functionality based on 10 years of experience and history.
- Based on the experience with human activity induced vibrations, some discussion on designing a faster orbit FB (up to ~30 Hz BW) have been triggered.
  - No decision at this stage (do we really need it?),
  - The design will be challenging due to high energy (actuators) and large ring size.


User written
Middleware
Central services
Upgrade in LS1
Java Control Programs
VB, Excel, LabView
JAPC API
C++ Programs
Passerelle C++
Administration console
Clients
RDA Client API (C++/Java)
Device/Property Model
Configuration Database CCDB
Directory Service
CMW Infrastructure ZeroMQ
RBAC Service
RDA Server API (C++/Java)
Device/Property Model
CMW integr.
CMW int.
CMW int.
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CMW int.
CMW int.
Servers
Virtual Devices (Java)
FESA Server
FGC Server
PS-GM Server
PVSS Gateway
More Servers
Physical Devices (BI, BT, CRYO, COLL, QPS, PC, RF, VAC, …)