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Considerations on alignment and vibrations for FCCee

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BE-OP-LHC

Acknowledgements: F. Poirier, G. Roy, H. Mainaud Durand, M. Guinchard, F. Carra, A. Piccini, J. Keintzel

Outline

- Introduction
- Alignment
- Orbit response to vibrations and mitigations
- Special vibrations sources

Ground motion

R. Steinhagen, CERN thesis 2007-058

- The **LHC tunnel** at an average depth of **100m** is a “pretty quiet” place – at least when the machine technical noise is absent.
  - @ 1 Hz → vertical amplitude ~ 1 nm.
- The **much deeper FCC tunnel** should be at least equivalent.
- “Technical” noise can degrade conditions by ~1 order of magnitude from ~ 1Hz upwards.

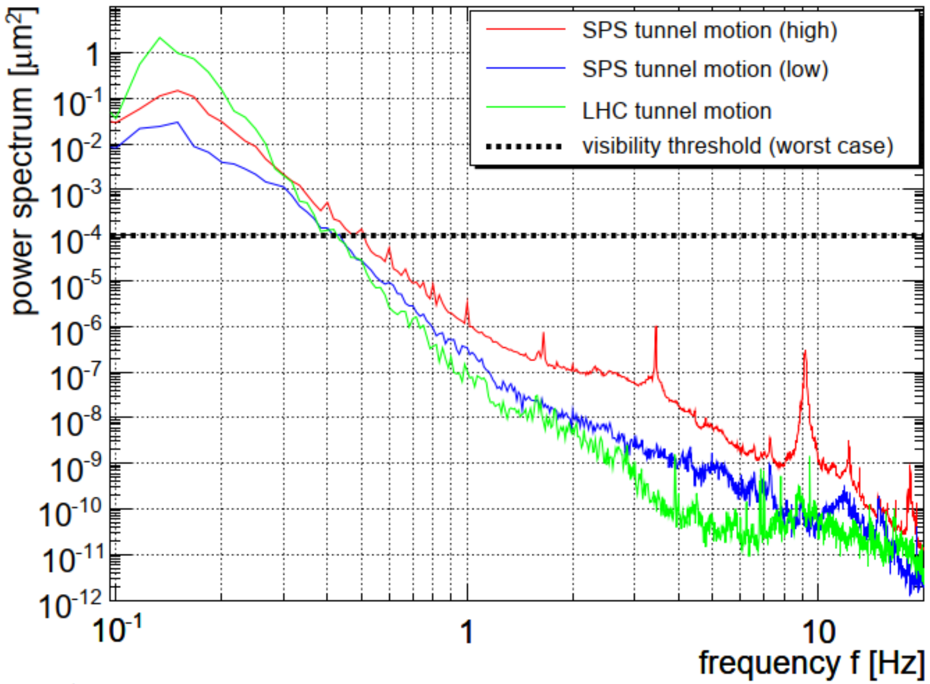

Figure 4.9: Averaged ground motion power spectra in the SPS and LHC tunnel. The ‘high’ SPS spectrum was recorded during a period of ongoing installation work. The data was taken using a sensitive geophone. The visibility threshold corresponds to the ground-motion level having a 1 μm effect detectable by the LHC beam position monitor, assuming a worst-case constant propagation factor $\kappa = 100$.

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- **Number to remember:** the **integrated** noise level is **~10 nm** for **f ≥ 1 Hz**.

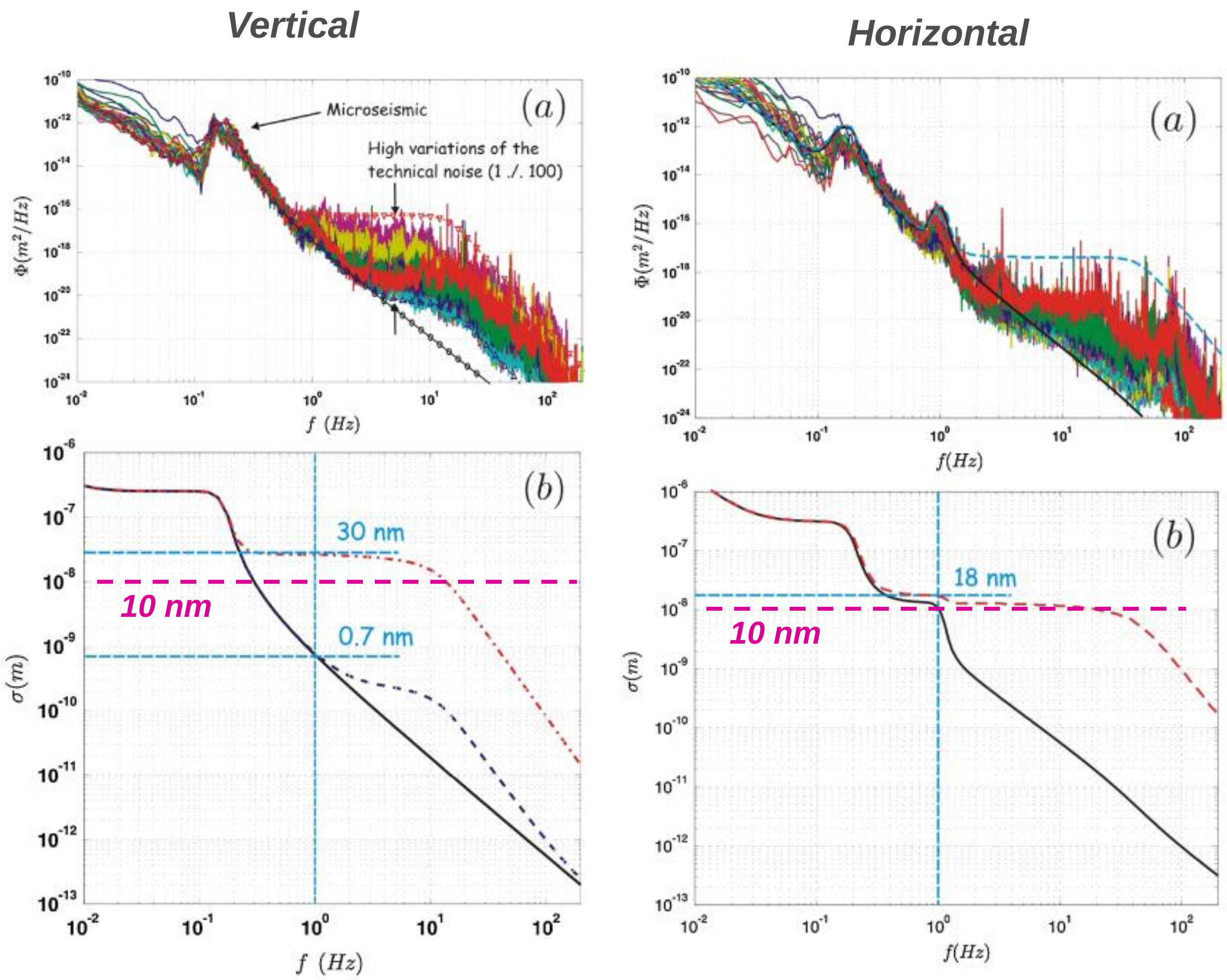

FIG. 5. (Color) (a) Power spectral densities of the measured vertical displacement in the LHC tunnel; model extracted from the measurements (solid circled line); lower and upper envelopes of the measured PSDs. (b) Integrated RMS displacements of the model (solid line) and the lower (dashed line) and upper (dash-dotted line) envelopes shown in (a).

FIG. 6. (Color) (a) Power spectral densities of the measured lateral displacement in the LHC tunnel; model extracted from the measurements (solid line) and upper envelope of the PSDs (dashed line). (b) Integrated RMS displacements for the model (solid line) and the upper envelope (dashed line) shown in (a).

C. Collette et al, PRAB 13, 072801

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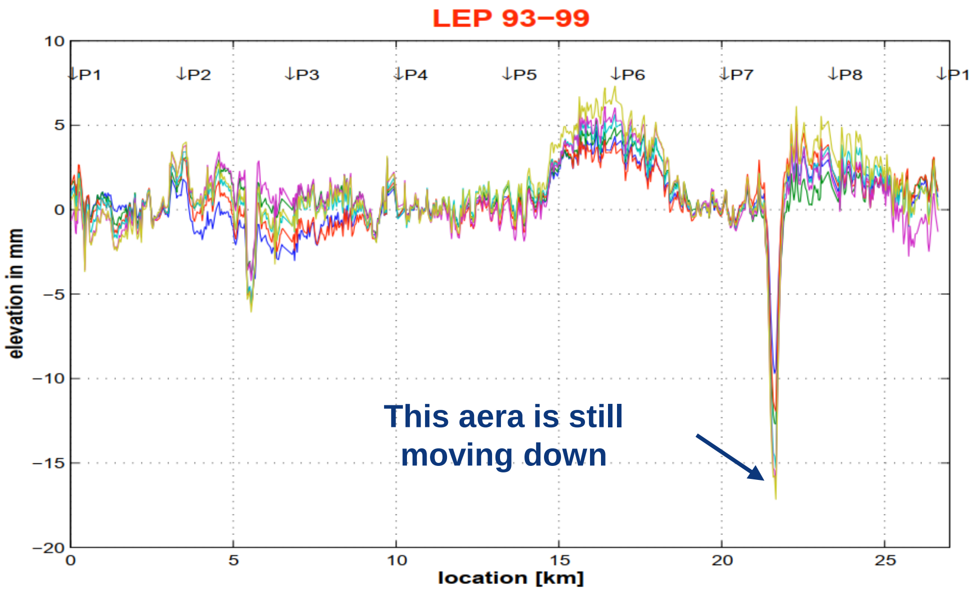
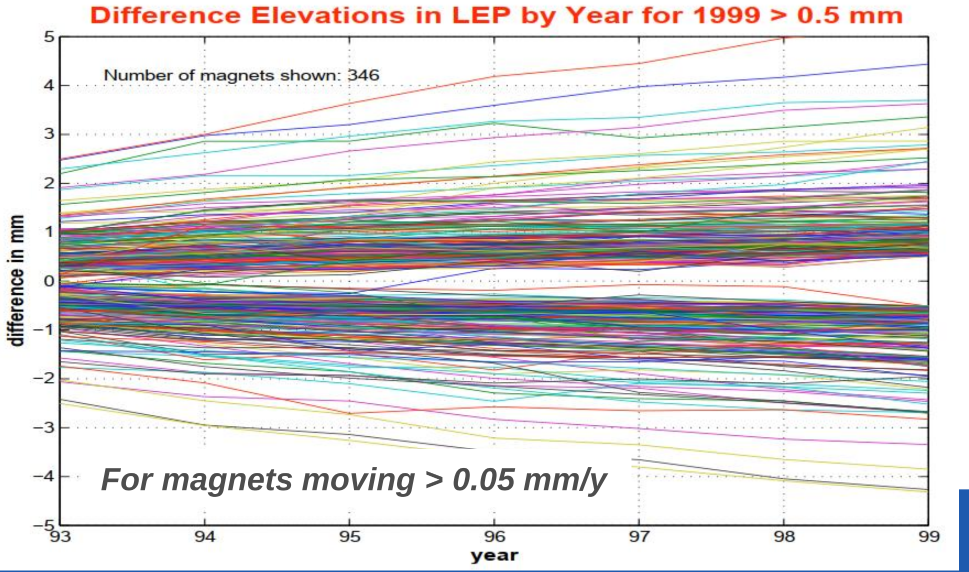
Slow ground motion - LEP

- A lot of experience on LHC tunnel movements from **LEP times**.
  - **Complete LEP vertical re-alignment each winter** (1993-1999).
    - Nice data summary: R. Pitthan, CLIC Note 422.
  - Complete **LHC** re-alignment only **every ~4-5 years** during long shutdowns.
- No ATL-law-like random movements observed in LEP data over almost 10 years.
- Typical movements of ~**0.07 mm / year**.
  - With peaks close to **0.3 - 1 mm / year** in some areas, in particular around **new underground structures** (LHC and HL-LHC).

R. Pitthan, CLIC Note 422





Alignment tolerances

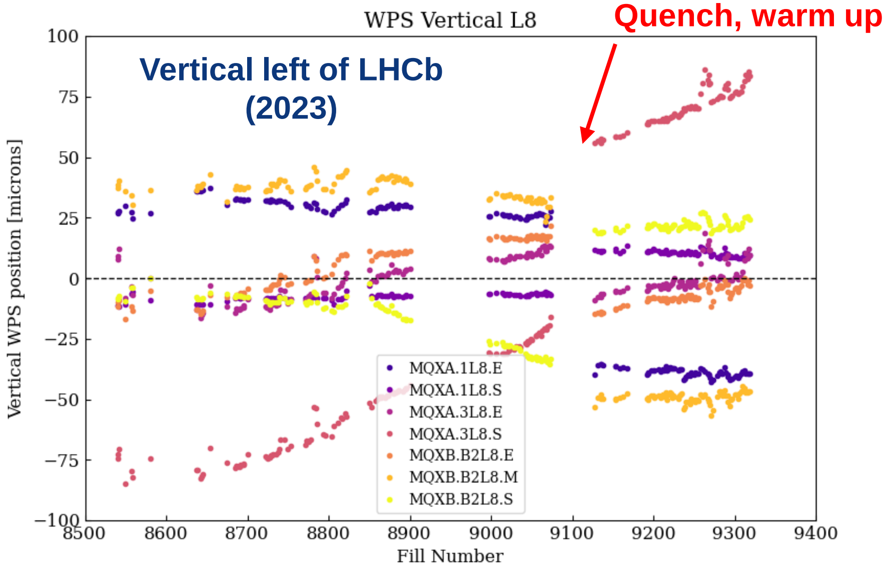
- Based on experience, to avoid more than ~1 major realignment / year, FCCee should **tolerate movements** of at least **~0.1 mm/y** + **initial alignment tolerance.**
  - **Aim for ≥ ~0.15 mm tolerance for the arcs and the less critical long straights.**
  - **Low-beta insertions will require "special treatment"**, but the number of magnets and the length of beam lines are limited.

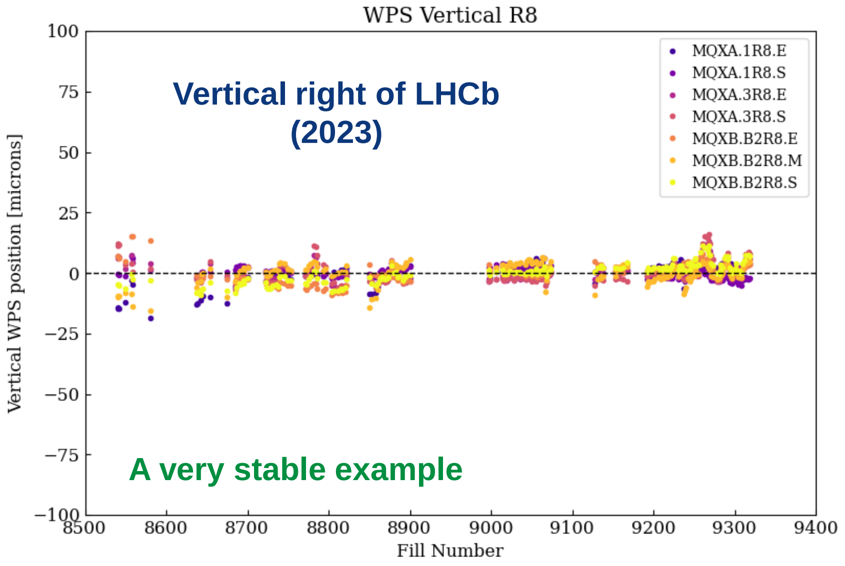
- FCCee strategy for initial alignment, monitoring and regular re-alignment must still be defined – not in today's scope !
  - See presentation by H. Mainaud Durand at the ATDC#2 (https://indico.cern.ch/event/1404867/).

Low-beta triplets @ LHC

- The low-beta triplets @ LHC are equipped with Hydrostatic (HLS) and **Wire positioning (WPS) systems**.

- In general **cryostat movements over one year are in the range 0.05-0.1 mm**. Exceptions are generally due to **magnet quenches**: the cold mass/cryostat do not return to the same position (but improving over time with no. of quenches !).
  - Note that in the past years all quenches where actually triggered by… the quench protection system (faults, electrical perturbations…).





Alignment @ CEPC (1)

A look at the chapter on alignment of the CEPC TDR.

- **Target for initial alignment: 0.1 mm** (total error, includes fiducials).

- **Step 1**: **pre-alignment** of components on the **girders** with proper fiducialisation.
  - **16 teams**, integrated time for all components is estimated to be ~6 years.
- **Step 2**: **initial alignment** of the components in the tunnel during installation.
  - **16 teams** for the collider, 16 teams for the booster, total time allocated is ~2 years (// to installation).
- **Step 3**: **iterative survey & re-alignment around smoothed line**.
  - **64 teams**, 2-3 iterations. No time estimate is provided.

- Beam commissioning begins only after step 3 is completed.

Alignment @ CEPC (2)

- **No permanent monitoring of the component alignment**. HLS or WPS are discussed as options, but they are not considered. **Reason: cost**.

- A yearly re-alignment is foreseen during 3-4 month of shutdown.
  - No estimate of the required resources → they will need their 64 teams !
  - Aim to rely on BPMs (should use corrector strengths !) to estimate local ground movements.

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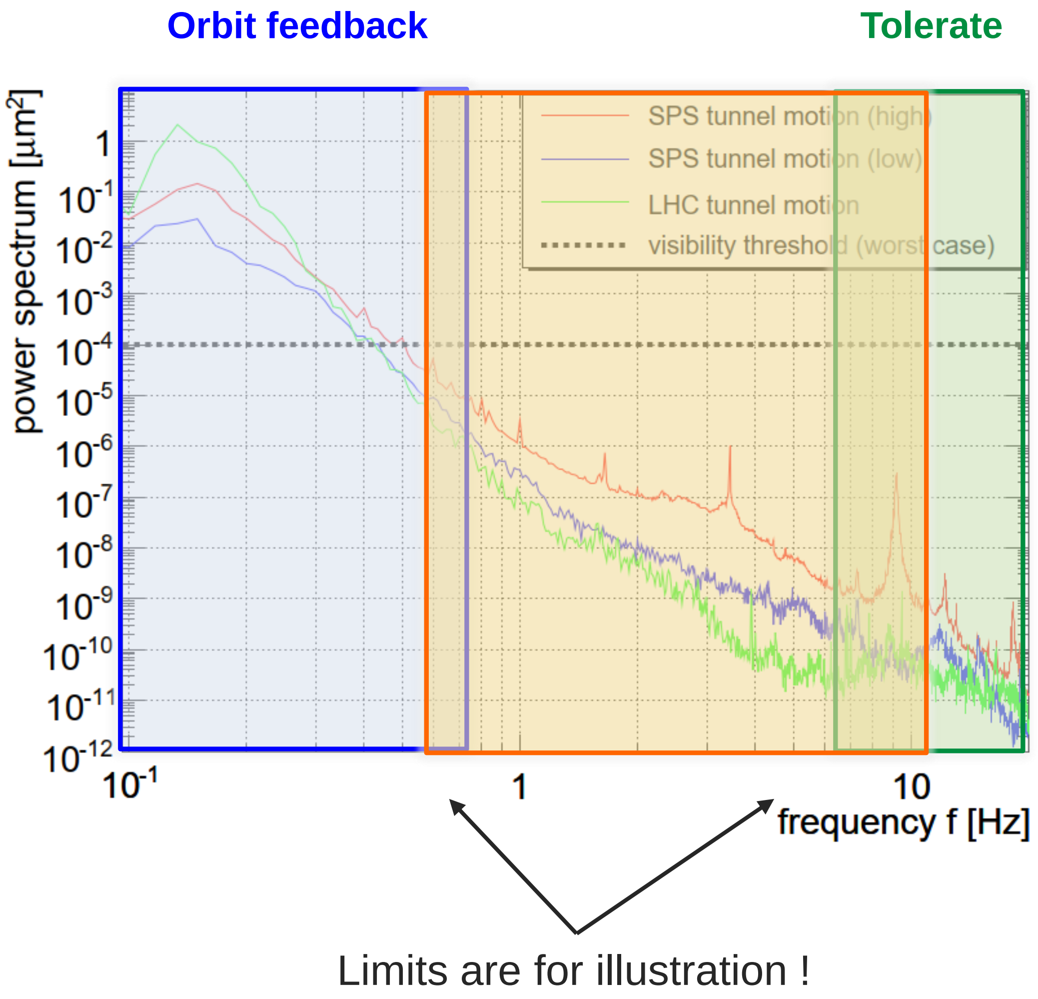
Impact of vibrations

- **Impact** of GM on beam and performance:
  - Low(er) frequencies: movements can be efficiently damped by a beam orbit feedback.
  - Medium frequencies: may be too high frequency for feedback, yet too large amplitude to ignore. Impacted by girder design (damping, mechanical resonances).
  - High(er) frequencies: movements can be tolerated.

- Important to **split requirements** for low-beta quadrupole region from main arc and other points.
- **Focus** from now on is on **arc + non-IR points**.



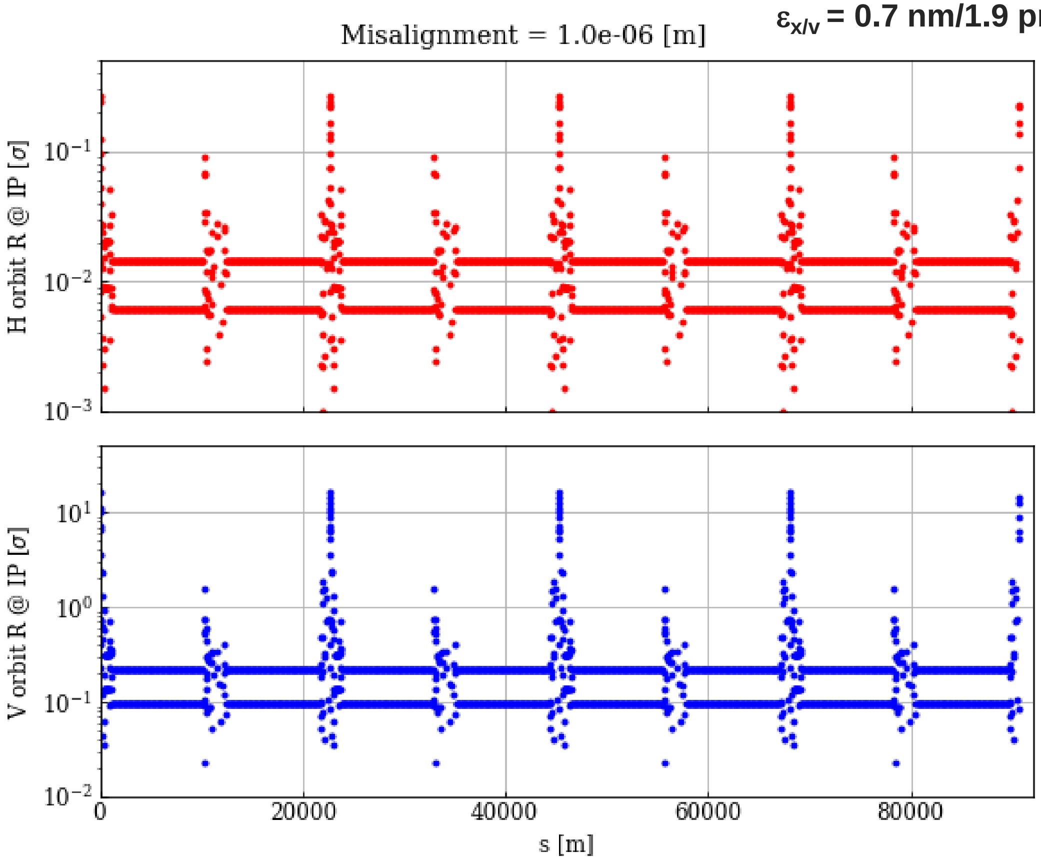
Orbit response → IP

- The arcs have many cells, but individually the impact is small compared quadrupoles near the exp. IRs (K1, β).
- Impact of **low-beta region** quads ~2 orders of magnitude larger than arc quads.
- **The horizontal plane is not critical** due to the much large emittance (size).

Orbit response at IP in units of IP size for quadrupole misalignment (phase factor set to 1) – GCC V23 Z.

$$R_u = \frac{|K1L_Q|\sqrt{\beta_{u,Q}}}{\sqrt{\epsilon}\ 2sin(\pi Q)}\ \delta_u$$

$\varepsilon_{x/y}$ **= 0.7 nm/1.9 pm**



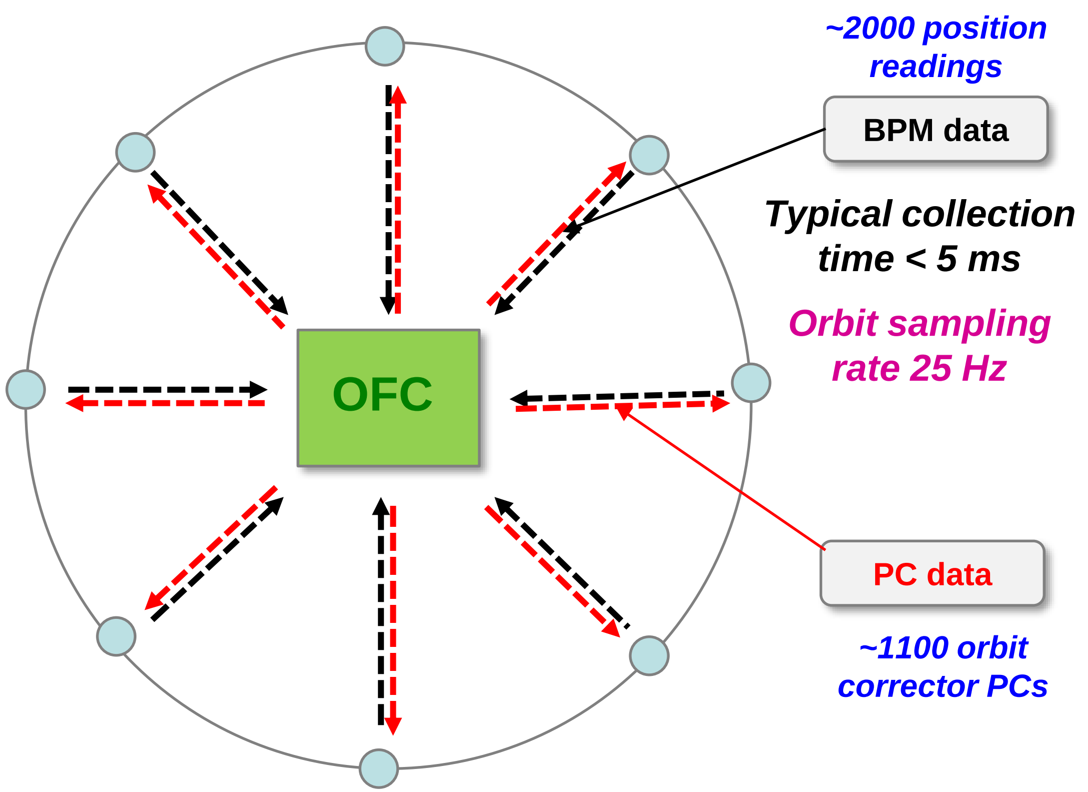
Low frequency – stabilization by orbit feedback

- **Orbit feedbacks (OFB)** are standard tools in modern light sources, also **essential at LHC**.
- Light sources achieve OFB bandwidths > ~100 Hz – but with revolution periods ~MHz.
- **Rule-of-thumb**: to **stabilize** up to a frequency $\mathbf{f_{BW}}$, the digital feedback system must operate at sampling frequency $\mathbf{f_s}$ = **100-1000 x** $\mathbf{f_{BW}}$ (and data processing delays << BW period).

- **LHC** as large machine: **centralized orbit feedback** on powerful server.
  - $\mathbf{f_s}$ **= 25 Hz**, limited (among other things) by PC control rate of 50 Hz (field-bus).
  - Data collection in ~4-5 ms, processing in ~20 ms → data to PCs, applied at next field bus cycle.
  - **Super-conducting orbit correctors** have **large inductances** and **long circuit time-constants** → cannot move currents very "quickly" (only very small kicks).
  - LHC OFB achieves excellent **perturbation damping below 0.2 Hz** – adequate also for ramp and beta squeeze.
  - With colliding beams the **closed orbit is stabilized to ~micron** (but with **spikes** – see later), limited over long fills by intensity & (rack) temperature dependence of the processing electronics.

LHC orbit feedback layout

- **Central architecture** with data exchange over normal IT network (quite revolutionary at the time of design in 2004).
- All BPM data is sent to a central server (OFC) handling the corrections, orbit references, optics responses etc, the correction are distributed to the power-converter gateways.
- Central architecture seems also best suited for FCCee, but data collection, central server and data distribution require careful design.



Low frequency – orbit feedback @ FCCee

- For FCCee we may want to aim for an **OFB bandwidth ≥ 1-few Hz.**
- Needed: **orbit acquisition > 100 Hz** for revolution frequency of **3 kHz**.
  - **Small number of turns for a close orbit**. Ok for Z with many bunches, potential issue at HZ at tt with few bunches ? To be checked with BI.
- Requires fast data collection and propagation to power converters.
  - One should be able to improve the 4-5 ms at LHC → 1-2 ms.
- **Requirements for kick change rates** to be established → impacts the **design of PCs and of magnets** (for example inductance of correctors).

Vibration impact, f ≥ 1 Hz

- For a **random** (uncorrelated) movement of the quadrupoles (girders), estimate impact on orbit movements at the IP.

RMS movement at IP, for uncorrelated GM amplitude of 10 nm:

Case (GCC V23 Z)	Horizontal [σ]	Vertical [σ]
Analytic estimate (arc)	0.002	0.03
Simulation F. Poirier (arc) (**)	---	~0.045
Simulation (arc)	0.0032	0.047
Simulation (all Q excluding low-beta area)	0.004	0.07
Simulation (all Q)	0.005	0.25

Analytic estimate (N cell arc cells) (*):

$$\frac{\Delta u^*}{\sigma_u^*} \simeq \sqrt{N_{cell}} \frac{|K1|L\sqrt{\beta_{eff}}}{\sqrt{\epsilon}4sin(\pi Q)} \delta_u$$

based on analytic linear orbit response

- **No issue for the horizontal plane**, for the **vertical plane** the movements approach **~σ/20** (excluding low-beta regions). No major difference expected for LCC lattice.

(**) F. Poirier, Tuning WG meeting, https://indico.cern.ch/event/1410645/

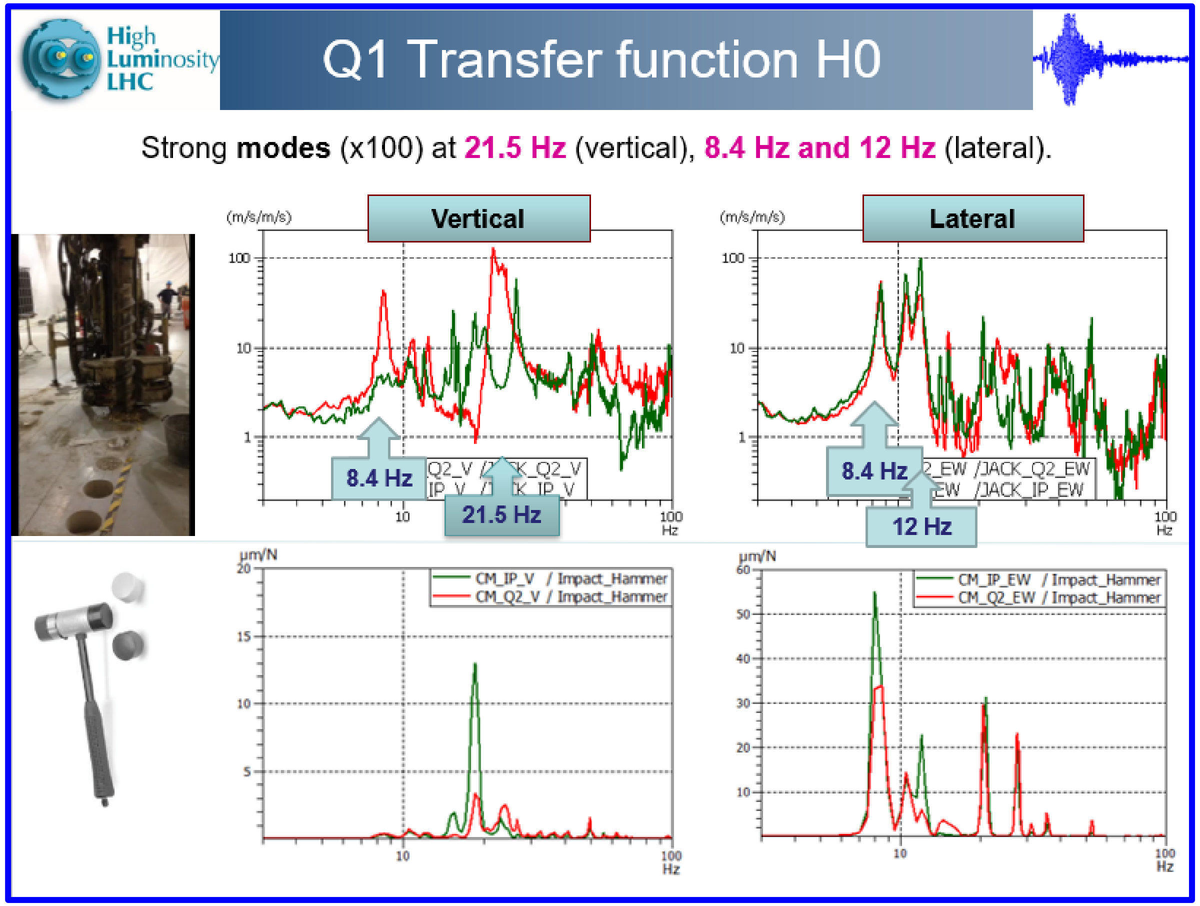
(*) R. Steinhagen, CERN thesis 2007-058

Girders

- **Resonances of transfer function ground → beam for quadrupoles need attention** they can **enhance GM** by ~2 orders of magnitude and inject this on the beam.

- For example: LHC quadrupole assembly modes are in the range 8 – 25 Hz.

LHC low-beta triplet quadrupole transfer functions
(Lessons Learned from the Civil Engineering Test Drilling, LHC performance workshop, Chamonix 2016)

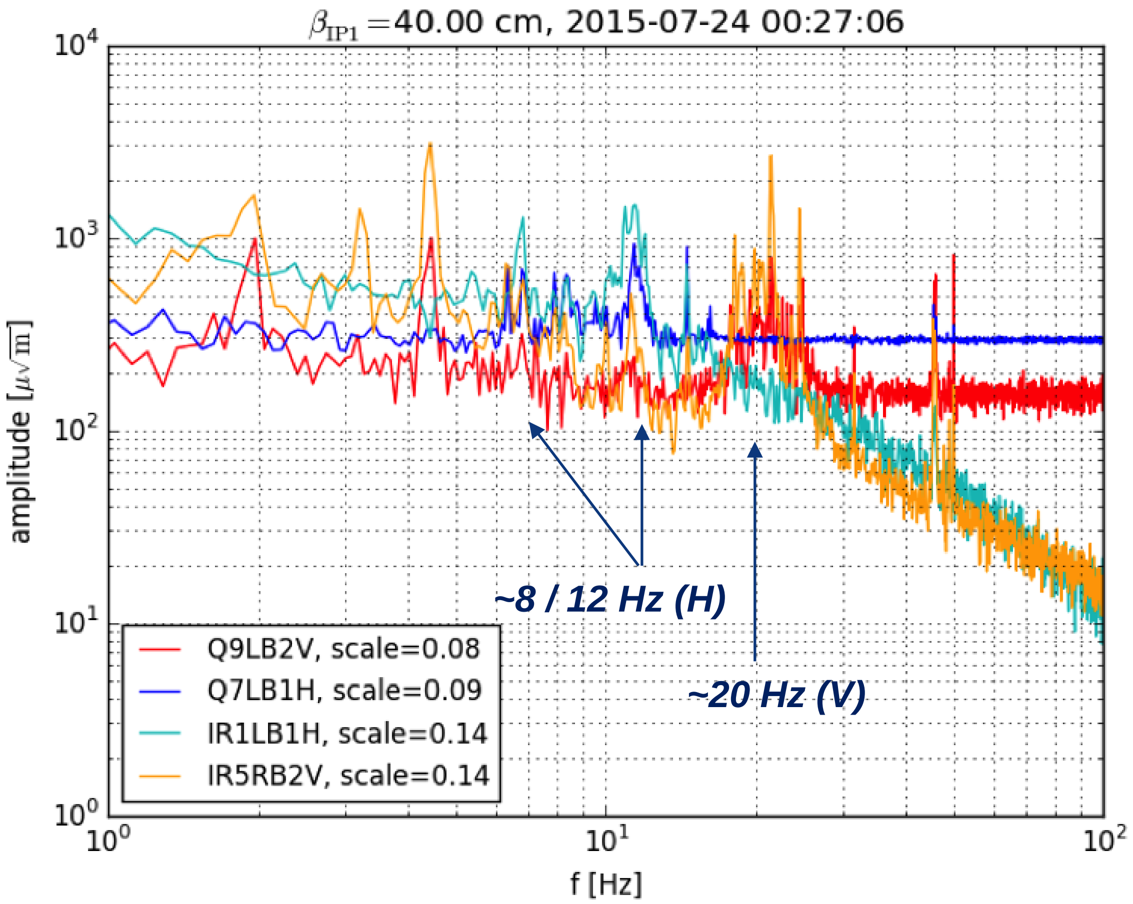


LHC beam spectra

- **Modes of the LHC quadrupole assemblies** in the **range 8 – 25 Hz** are clearly visible on the beam spectra.
  - Peaks are 5-10 x above ‘background’.
  - Not a performance issue at LHC (so far).

- Girder design for FCCee is very important !

Amplitude spectrum from beam position monitors
(Lessons Learned from the Civil Engineering Test Drilling, LHC performance workshop, Chamonix 2016)



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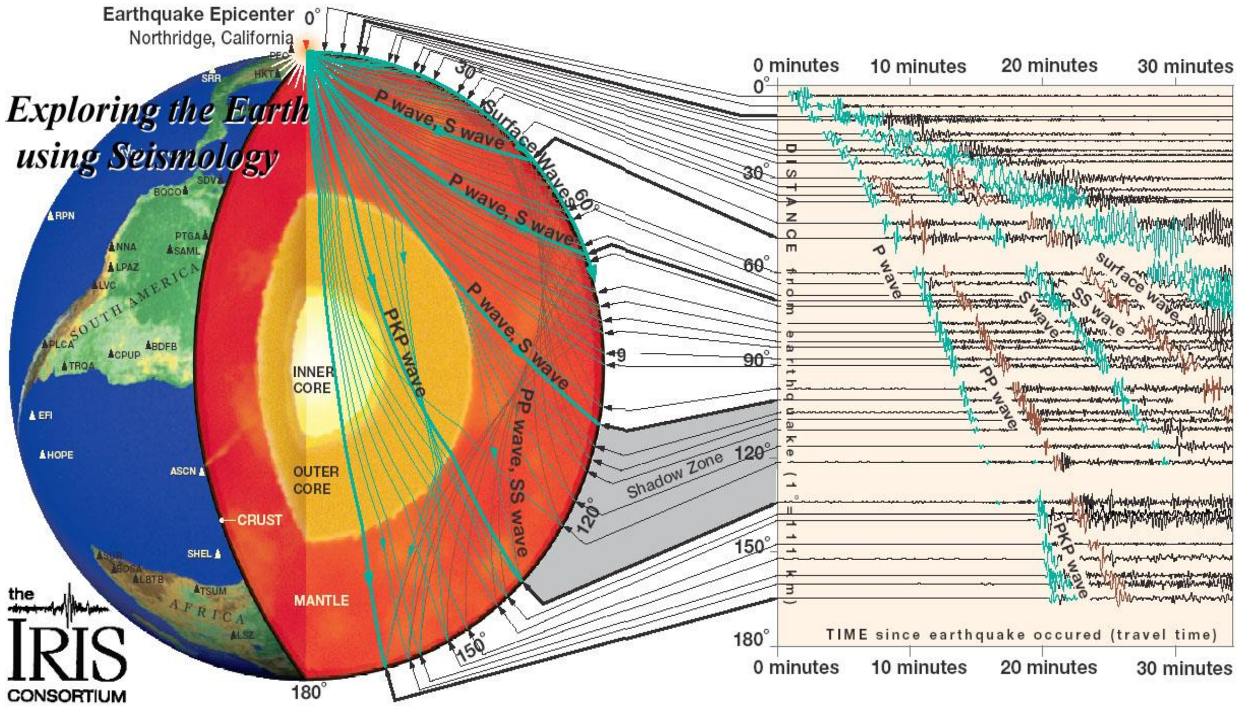
Earthquakes

- Large accelerators are a good **earthquake "detectors"** or **"amplifiers"**, although not as sensitive as specialized devices.
  - Limited by ~micrometer BPM resolution for the case of LHC.

- Many earthquakes were **observed at the LHC**, **no beam abort**, despite **significant impact** → next slides.

- Whether FCCee will be equally tolerant will have to be evaluated. For example, work by F. Poirier et al → impact check.

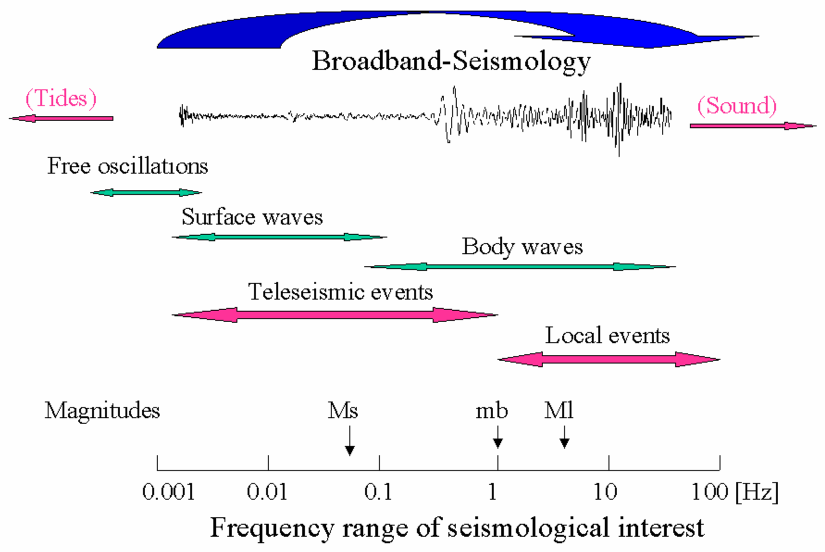
*Different types of body (**P**ressure, **S**hear) and surface waves (**R**aleigh, **L**ove), multiple paths and reflections produce a complex signature at seismic stations.*



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

Earthquake frequency spectrum

- The frequency spectrum of waves induced by earthquakes ranges from **~ mHz** (earth oscillations and surface waves) to **~100 Hz** for **local seismic events**.
- The signature of **large and distant earthquakes** (teleseismic) is dominated by **low frequencies < 1 Hz**.
- Ground motion from **local earthquakes** extends to **higher frequencies**.

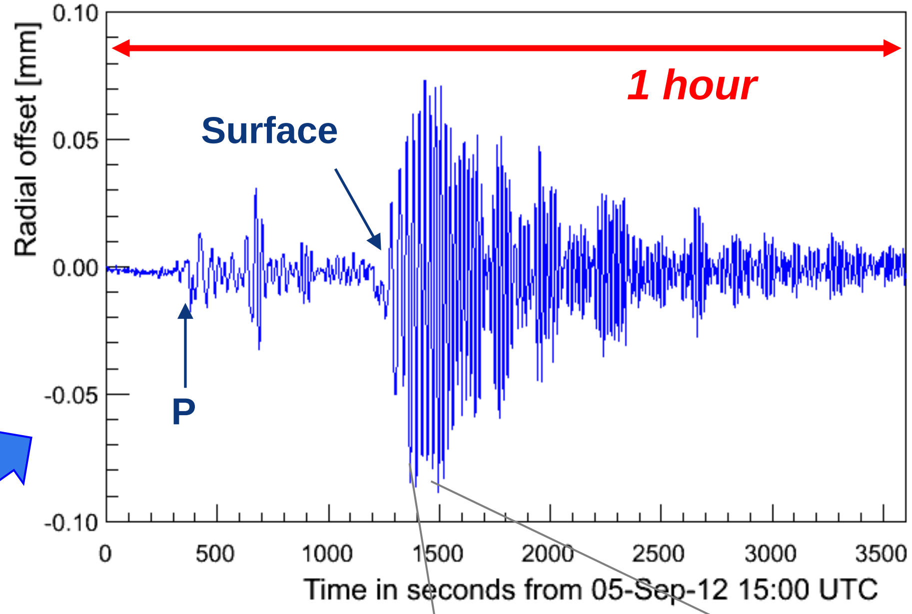


Distant earthquake example

- **Earthquakes of magnitude ≥ ~7 anywhere on our planet** are visible mainly through **RADIAL** oscillations on the rings due to pressure waves.
  - Transverse effects are small / not always detectable.
- Peak-to-peak **dp/p ~10^{-4} @ LHC** → **>10^{-3} @ FCCee**

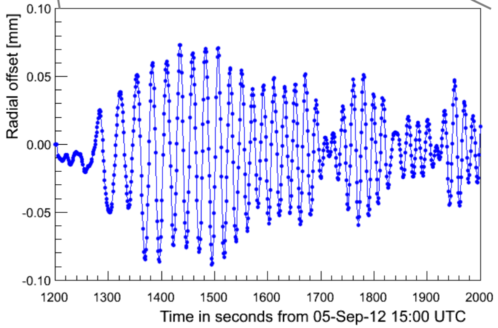
A **magnitude 7.6** earthquake in Costa Rica (05/09/2012 @ 14:42:10 UTC) struck the LHC with **stable colliding beams**.

Radial excursion close to ±0.1 mm ~ large tide



zoom

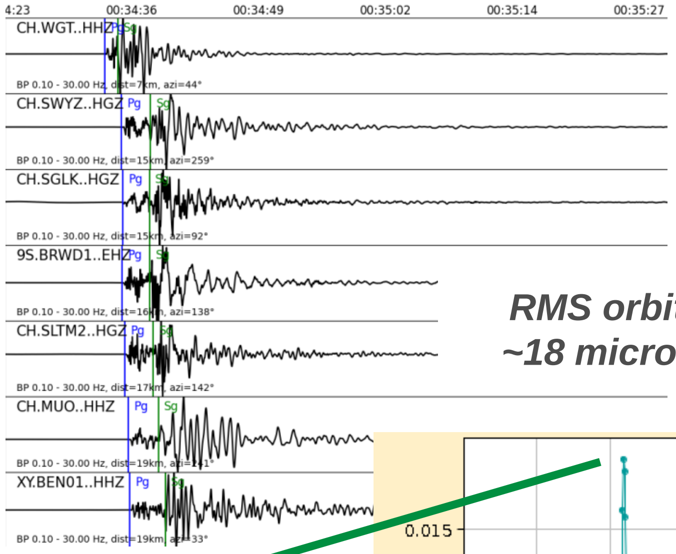
Period ~20 s



Local earthquakes

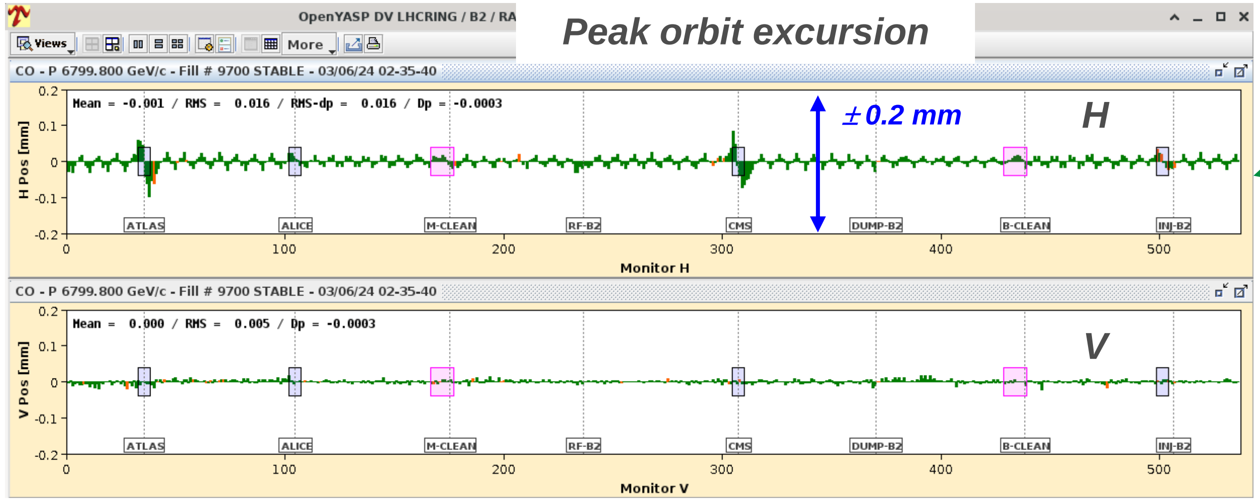
A **magnitude 4** earthquake in North-East Switzerland (**03/06/2024** @ 00:34:32 UTC, ~220 km from CERN) reached the LHC with **stable colliding beams**.

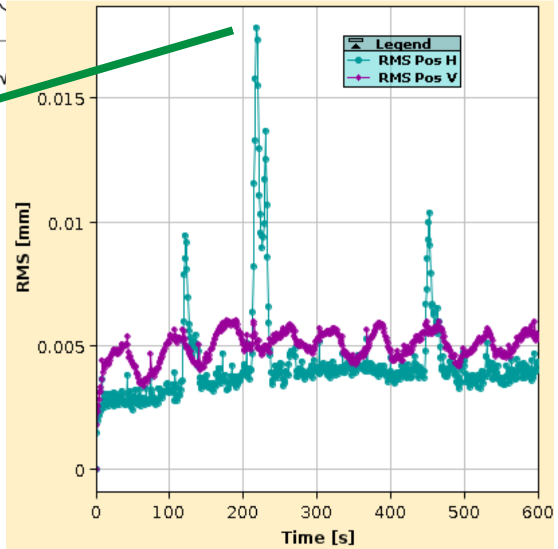
- **Local earthquakes of magnitude ≥ 4** are visible on the LHC BPM system (sometimes on the luminosity).
- Contrary to distant earthquakes, there is no radial modulation, some transverse oscillations of the closed orbit.



RMS orbit change ~18 microns on B2

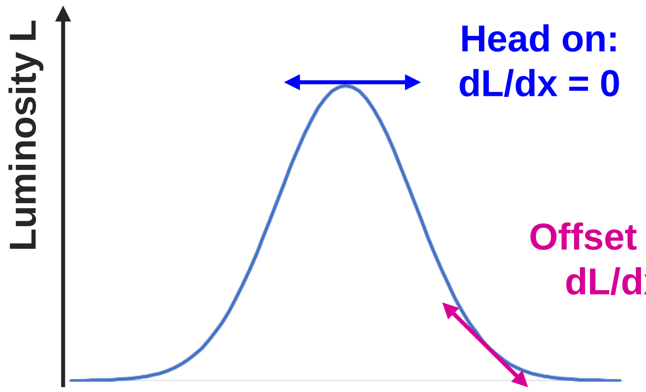
Peak orbit excursion



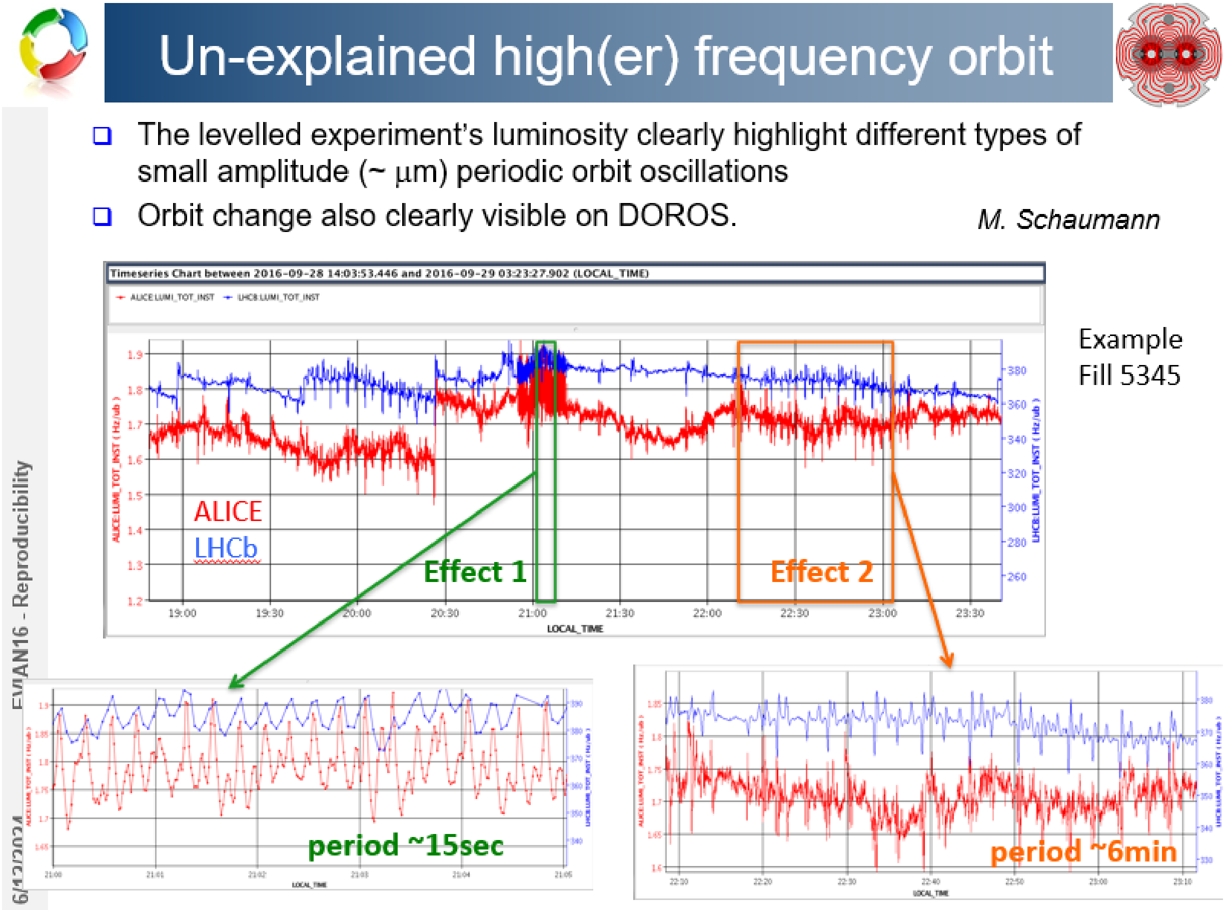


Technical noise – LHC "unknowns"

- When LHC beams are colliding for data taking, **micron-amplitude orbit perturbations** are frequently observed.
  - Time structures and amplitudes vary.
- Two experiments with **luminosity levelled** by **transverse offsets** at the IP (ALICE & LHCb) are particularly sensitive "oscillation detectors".

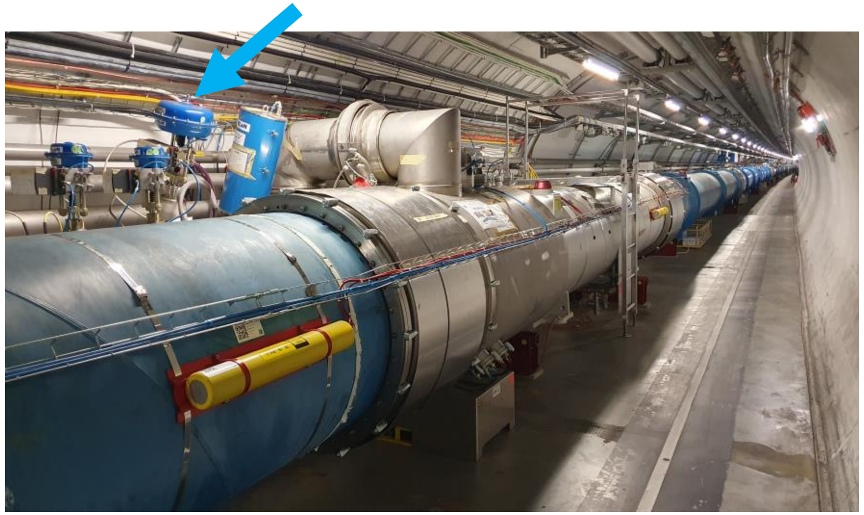


Evian workshop on LHC performance, Dec 2016



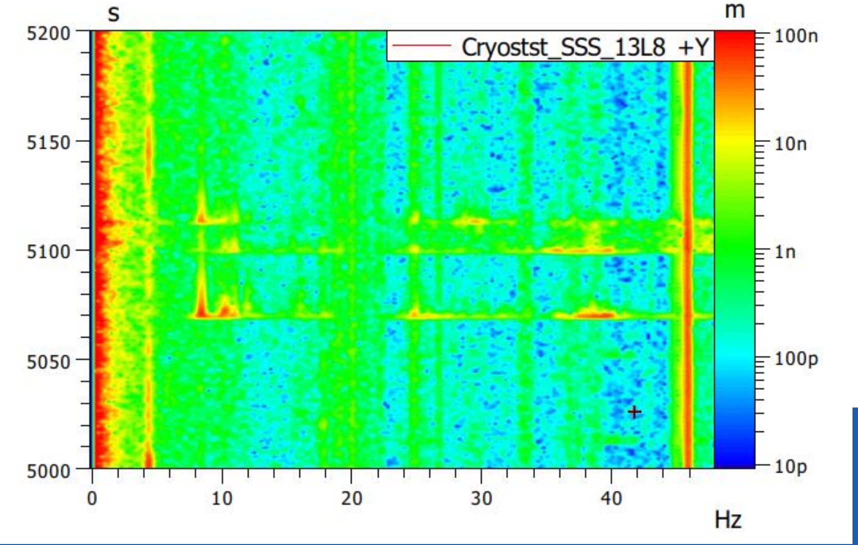
Technical noise – LHC cryogenics

- Recurrent orbit oscillations leading to beam aborts with ions: **~10 μm Q movements**, **~100 μm orbit excursions** (arc) → **source location identified,** consistent with Q movement.
- The offline analysis eventually pointed towards a **cryogenic valve** used to re-pressurize the cold magnets with liquid Helium at 3.5 bar. Refill frequency depends on … leaks.
- One location was equipped with **vibrations sensors** in 2024, observations…



Vibration of the cryostat at 8 and 10 Hz !

(measurements by EN-MME)



Summary (1)

- Given the experience from the LEP/LHC tunnel, we should aim to **tolerate ≥ 0.15 mm misalignments** in the **arcs** to avoid having to realign components too frequently.

- We have no strategy yet for alignment, the strategy outlined in the CEPC TDR is a **scaled up LEP-like approach**: get many surveyors and realign every year.

- Based on LHC data, assumption for integrated GM noise of **~10 nm for f ≥ 1 Hz** (1-30 nm).
- Vibrations for **f ≤ 0.2 Hz** can be damped efficiently with an orbit feedback.
- Above **f ≥ 30-50 Hz**, the amplitudes should be acceptable.
- The intermediate frequency range is more critical:
  - Push the orbit feedback bandwidth to higher frequency.
  - Careful girder design (transfer functions).
  - …

Summary (2)

- While the **LHC is “earthquake-tolerant”**, it is not clear if FCC beams will survive… Fortunately there are only a few important earthquakes per year. Impact of more frequent magnitude ~3 local earthquakes to be checked.

- For large and sensitive machines, technical noise can represent a challenge.
  - Not clear that all LHC noise is due to the cryogenic system !

FCCee versus LHC

- Comparison of some key numbers LHC-FCCee.
  - Typically, LHC emittance spread: -10% / +20%
- GCC Z arc lattice is very similar to the LHC arc (K1L, β, …).
- **LHC and FCCee horizontal plane are ~ similar**.

	ε_x (nm)	ε_y (pm)	β^*_x (m)	β^*_y (m)
LHC	~0.28	~280	0.3	0.3
FCC-ee @ Z	0.7	1.9	0.11	0.007