Observations and measurements on the impact of earthquakes and cultural noise on the LHC operation and their extrapolation to HL-LHC parameters.

B. Di Girolamo, M. Guinchard, M. Schaumann, J. Wenninger

Acknowledgments:
N. Azaryan, J. Budagov, R. Corsini, P. Fessia, M. Fitterer, D. Gamba, A. Gorzawski, M. Lyablin, M. Poehler, R. Steinhagen

Review of the needs for a hollow e-lens for the HL-LHC
6th October 2016

Outline

- Summary of civil engineering studies for HL-LHC
- Ground motion and measurements at CERN
- Study of long-distance earthquakes
  - ✧ Correlation of ground motion with LHC data
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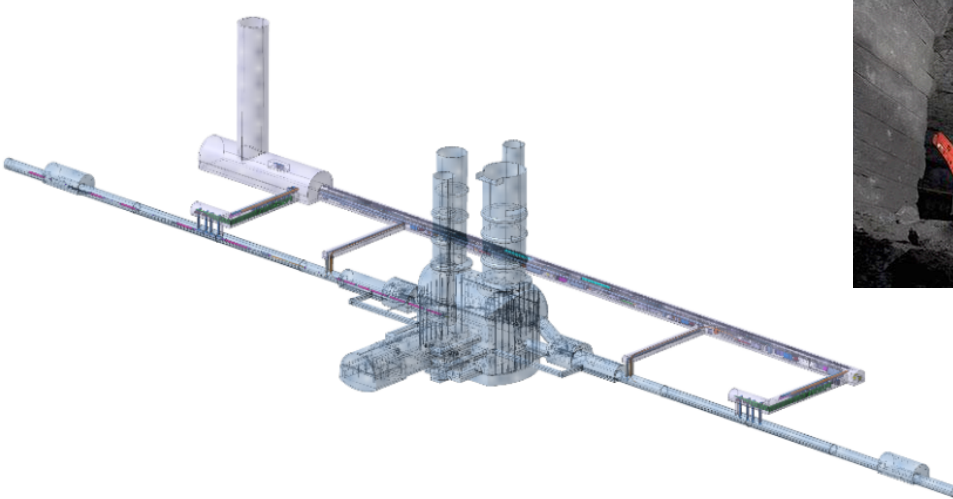
HL-LHC civil engineering

- The HL-LHC civil engineering work implies the construction of new access shafts, underground galleries and caverns in points 1 and 5.
  - The distance between the new underground structures and the LHC tunnel is approximately 40 m.
- Most of the work must be completed before LS3 for installation of HL-LHC equipment.
  - Some work **overlaps with LHC operation**, which could lead to **performance degradation** of the LHC due to beam offsets at IP, emittance growth from noise etc.

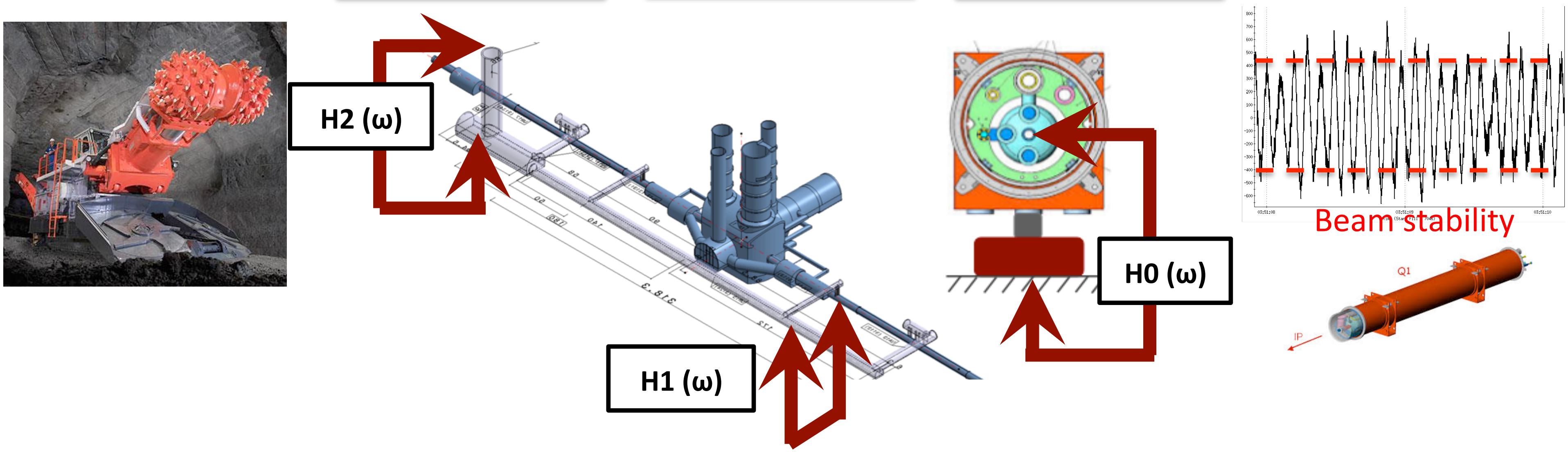


M. Guinchard & J. Wenninger

From noise to the beam

- To evaluate the impact of CE, the **transfer functions of the ground** (vertical H2, horizontal H1) **and of the triplet support** (ground to CM H0) have been determined in a number of test setups.
- Parasitic beam observations were made whenever this was possible.

In (ω) — **H_2 (ω)** — **H_1 (ω)** — **H_0 (ω)** — **Out (ω)**



M. Guinchard & J. Wenninger

Summary of Civil Engineering Studies

- Vibration tests reveal **strong mechanical resonances of the triplet** [8 - 20 Hz].
  - The resonances can boost ground vibrations to amplitudes that can be **problematic for the beams**.
  - *A feasibility study of a fast beam orbit feedback system could be considered.*

- The **excavation of** caverns and **underground structures** should be made **during LS2**.
- The convolution of measured transfer functions seems to indicate that the construction of the **HL-LHC CE vertical shafts should be compatible with beam operation (2018)**.

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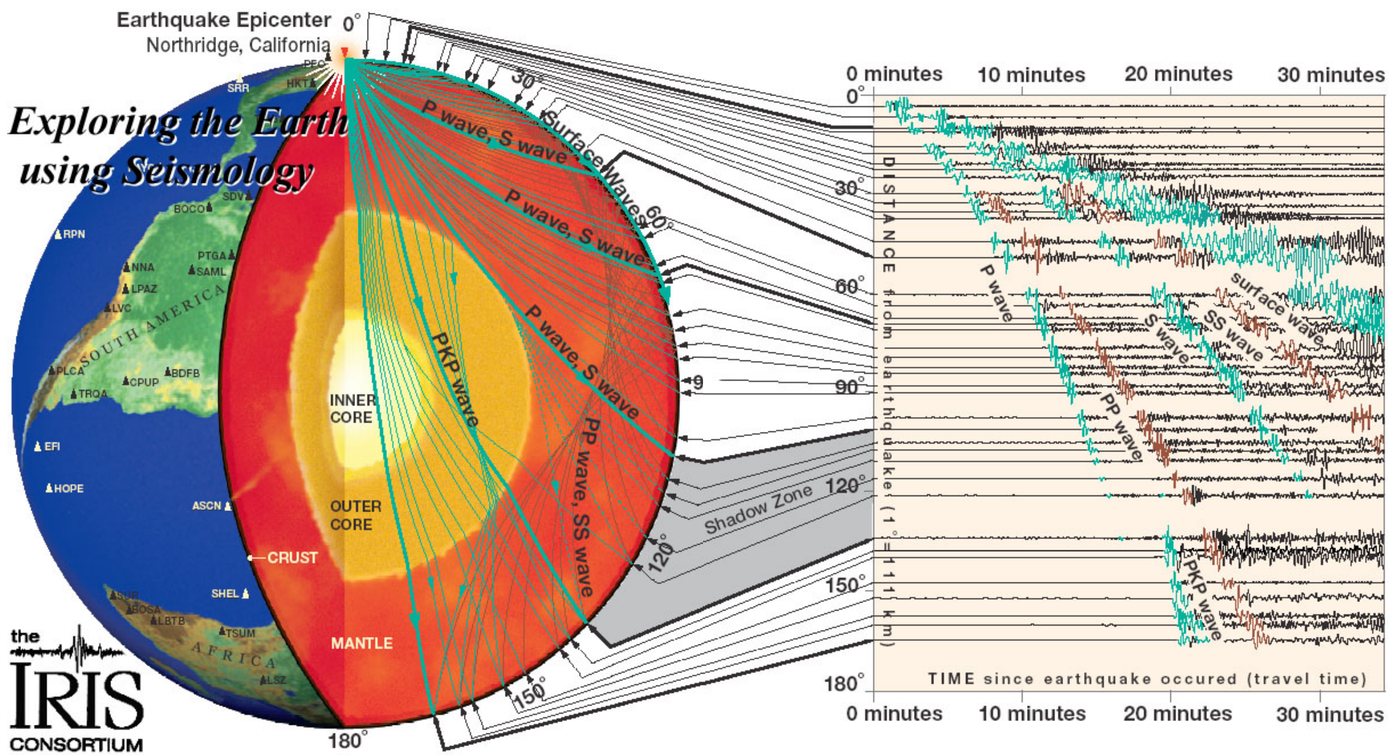
Waves from Earthquakes

The different types of body (Pressure, Shear) and surface (Rayleigh, Love) waves, the multiple paths and reflections of the wave produce a complex signature of earthquakes at seismic measurement stations – and also at the LHC.

Although the seismic activity in the Geneva area is very low, waves from far away earthquakes can affect the LHC.



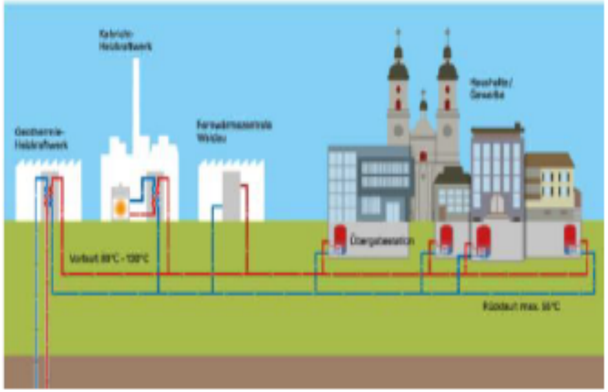
L. Braille (Purdue U.) / The IRIS (Incorporated Research Institutions for Seismology) consortium

Slide from J. Wenninger

Geothermie 2020

Geothermie 2020 is a renewable energy production project by the Canton of Geneva to ***exploit geothermal energy*** for electricity production and heat generation.

Principle of energy exploitation: water is pumped into a bore hole under high pressure to stimulate a geothermal reservoir.



This may induce seismic activity and **earthquakes of magnitude ~2** have to be expected.

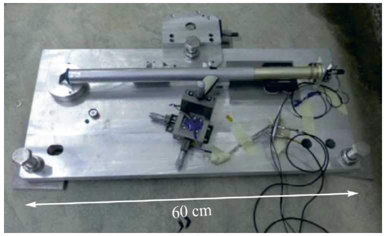
Duration: ~1 second, rate: 1/week – 1/month?

Amplitude ~1 μm (factor 10 uncertainty).

Earthquake Monitoring around CERN

- Monitoring of the regional seismic activity is poor (from the Swiss side).
- In the context of the Geothermie 2020 project (see below) a network is been build to monitor the natural seismic activity down to magnitude ~1.5 (Geneva Univ.).

- **Ground motion measurements at CERN:**
  - ***Network of geophones*** (EN-MME) will be installed in the LHC service areas of Point 1 and 5
    - Installation foreseen during EYETS 2016/2017.
    - Currently a prototype is installed in TT1, operating since Apr. 2016.
  - ***Precision Laser Inclinometers*** (**PLI**, collaboration between CERN, ATLAS, Dubna Institute)
    - Long term plan is to install devices in ATLAS cavern.
    - Currently a prototype is installed in TT1, operating since Mar. 2015.



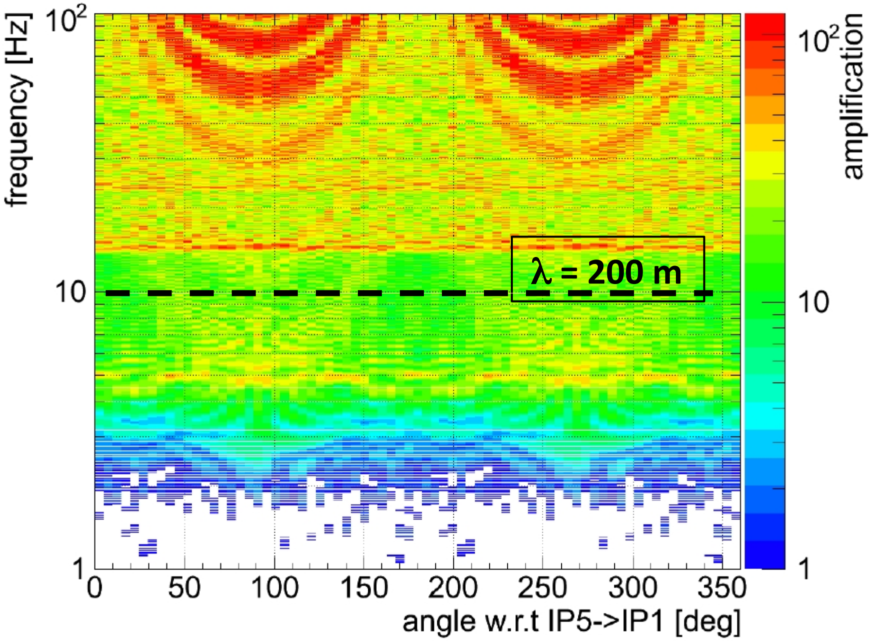
LHC Ring Response

Simulations of the amplification of the wave effect on orbit displacement due to the LHC lattice were carried out during the design of the orbit feedback (by R. Steinhagen).

The response of the LHC to ground motion waves depends on wavelength and direction, the **amplification can reach a factor ~100** for waves travelling along the LSS in IR1 and IR5 (direction NW →SE).

Large amplifications are associated to resonant response of (parts of) the LHC.

Transverse wave (S), vertical plane, v = 2000 m/s



R. Steinhagen, CERN Thesis 2007-058

Currently this study is been extended in order to obtain the response under HL-LHC conditions.

Slide from J. Wenninger

Simulation of Ring Response

Simulation tool under development

Input

1) Measured ground motion (in mm)
2) Travel direction of the wave w.r.t LHC

"snapshots" of the wave's passage

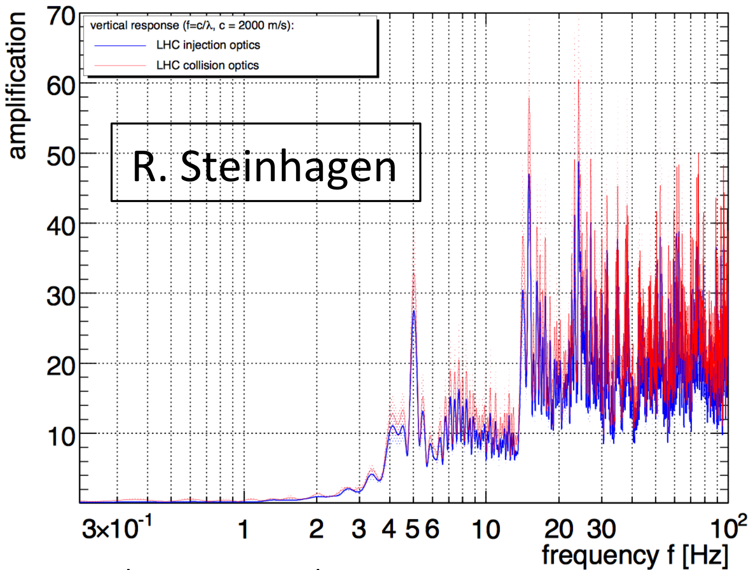
- quadrupole offsets
- closed orbit change due to offsets

Output

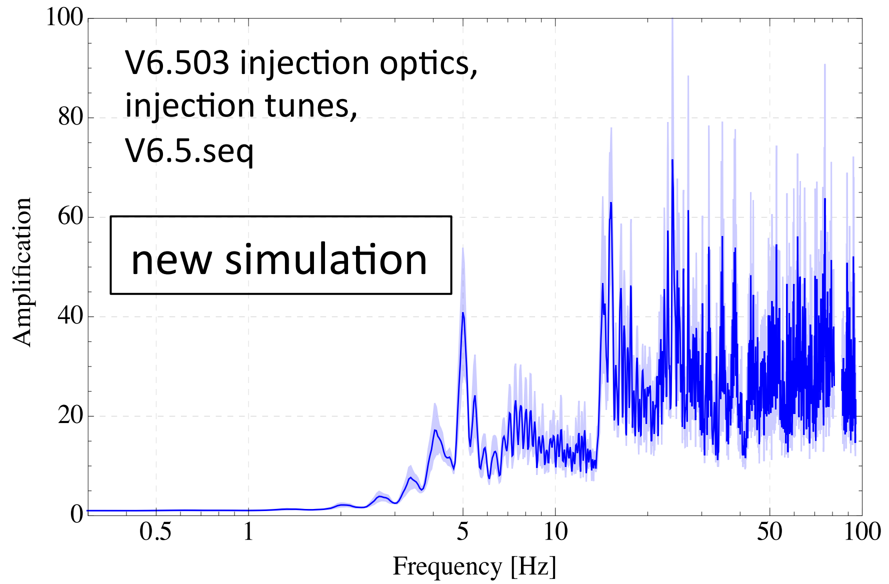
Time evolution of the ring response in terms of RMS and mean orbit.

Benchmarking Simulations

Vertical plane response to transverse wave excitation, v = 2000 m/s



R. Steinhagen, CERN Thesis 2007-058



- *Results for vertical responds from new simulation tool are in good agreement with the old study.*
  - All important resonances appear at the same frequencies and with approximately the same ratios to each other.
- *In the horizontal plane larger discrepancies are observed.*
- *The simulation code is still under development and being reviewed.*

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Observed Earthquakes at the LHC

Presented at Charmonix 2016

Location	Date	Mag	LHC	DR (mm)	Int (10^{13} p/ beam)
Italy	20-05-12	6	4 TeV collisions	±60	14
Costa-Rica	05-09-12	7.6	4 TeV collisions	±80	19
Chile	16-09-15	8.3	Injection	±200	5
Chile	17-09-15	6.5	6.5 TeV collisions	±15	10
Italy	24-08-16	6.2	Injection (MD)	±60	0.3
Ascension Islands	29-08-16	7.1	6.5 TeV collisions	±20	20

New events with available ground motion measurements in TT1.

Qualitative estimate of RMS orbit distortion impact (LHC):

50µm (≈0.25σ@TCP) beam dumps unlikely
>~100µm (≈0.5σ@TCP) beam dumps probable
>~200µm (≈1σ@TCP) beam dumps definitive

If beams would be dumped for a certain orbit movement, strongly depends on tail population, wave properties …

Scaling the loss pattern at TCP, the first Italy event could have dumped under HL-LHC conditions.

Italy Earthquake, 24th Aug. 2016

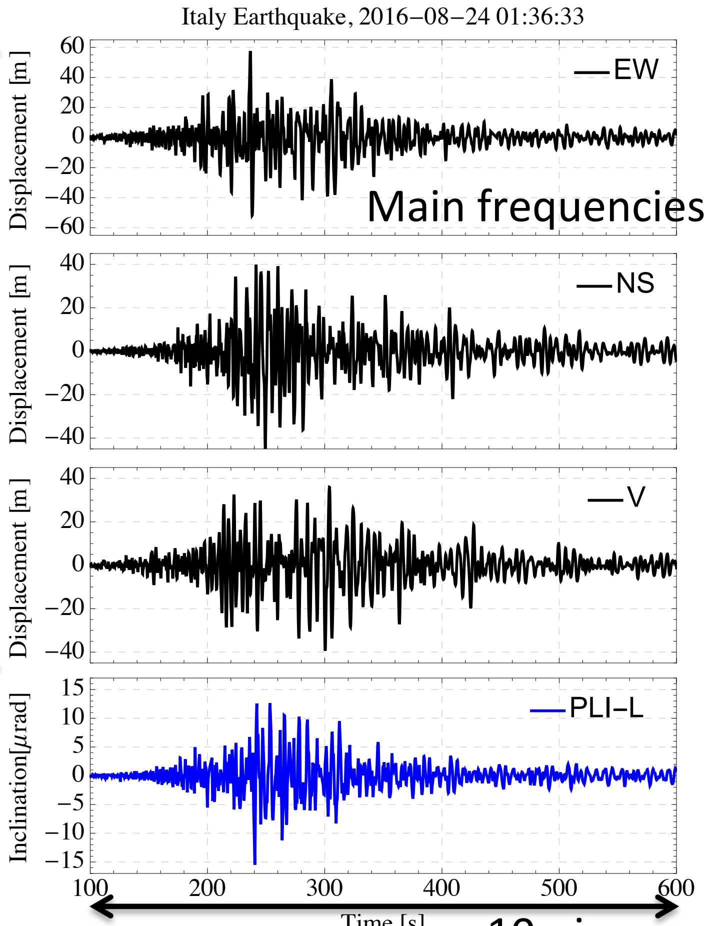
Magnitude 6.2 in ITALY
Wednesday, August 24, 2016 at 01:36:33 UTC

The prototype ground motion devices in TT1 recorded the event.

Main frequencies: 0.1-0.3 Hz (8-3s)

Geophone measurement TT1

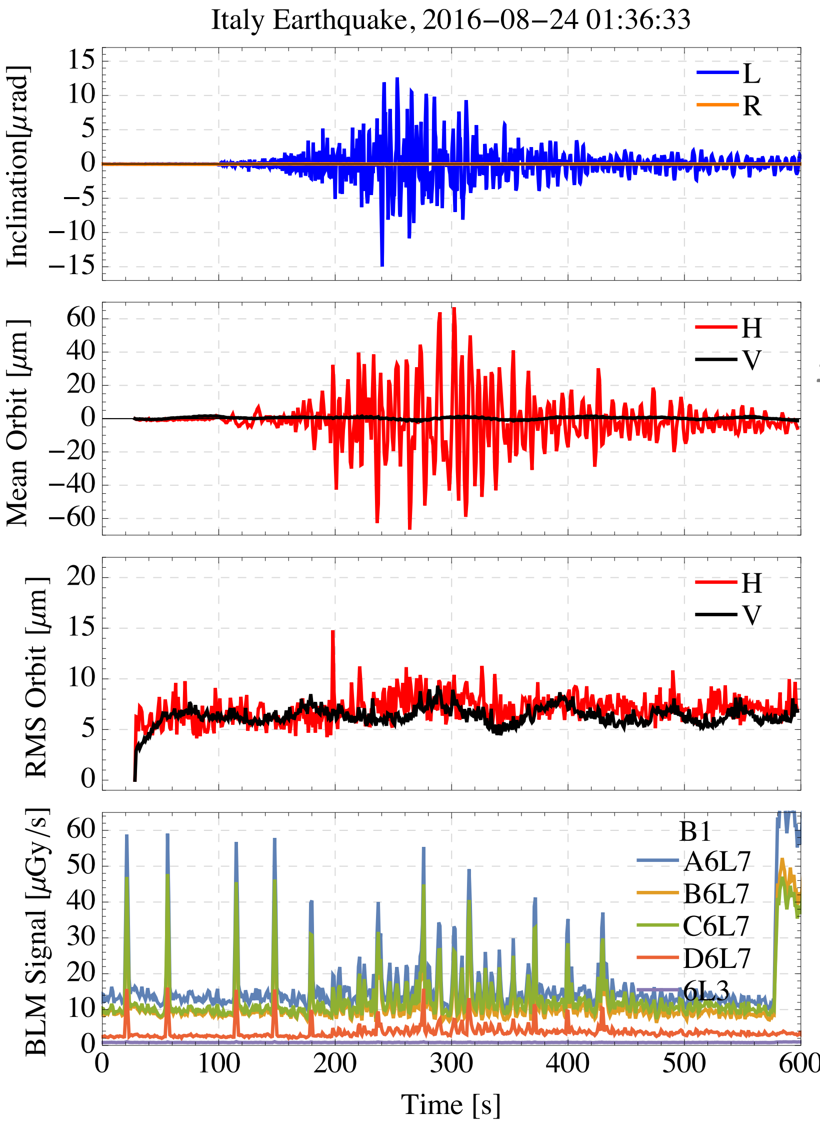
Inclinometer data TT1



Amatrice after the earthquake

Italy Earthquake: LHC Observations

The LHC was performing MDs and only Beam 1 was present at the time of the earthquake.



Inclinometer signal

±10mrad

Meas. mean orbit

±60μm

Meas. RMS orbit

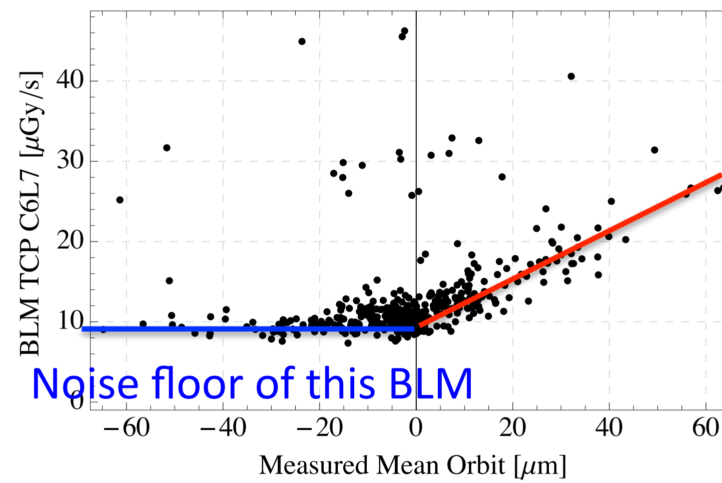
no signal visible

TCP BLMs in IR7

nicely correlate with orbit

Timing and overall shape of ground motion measurement and orbit signal fit.

Losses increase with increased mean orbit

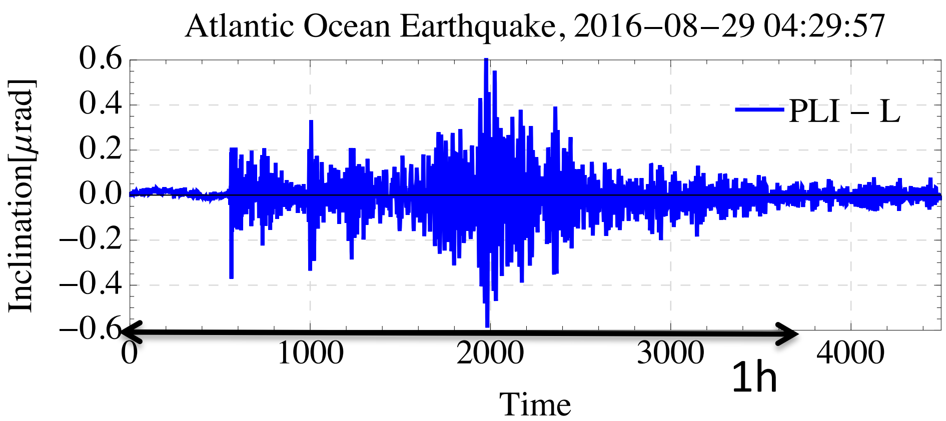


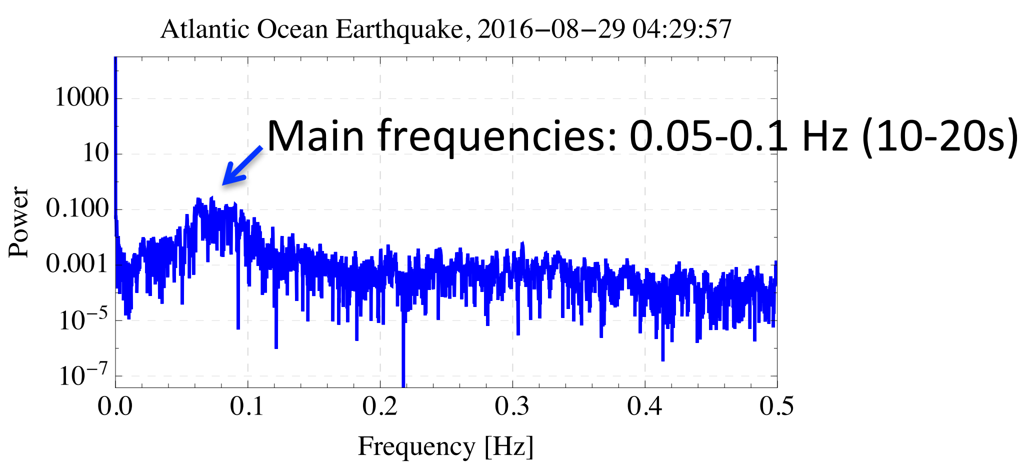
Noise floor of this BLM

Ascension Islands Earthquake, 29th Aug. 2016

Magnitude 7.1 in Ascension Islands
Monday, August 29, 2016 at 04:29:57 UTC

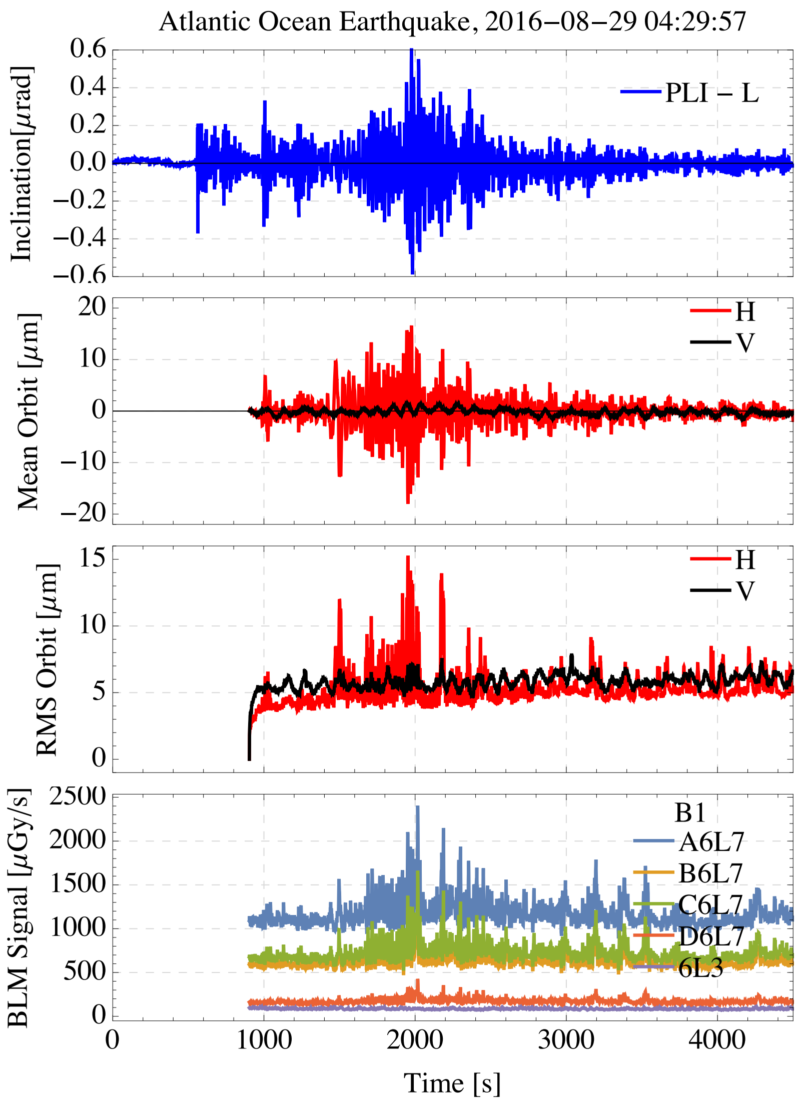
LHC was in stable collisions

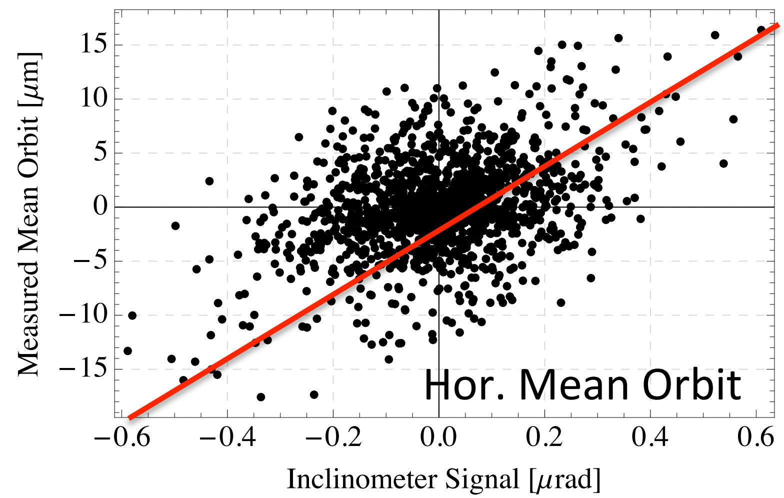


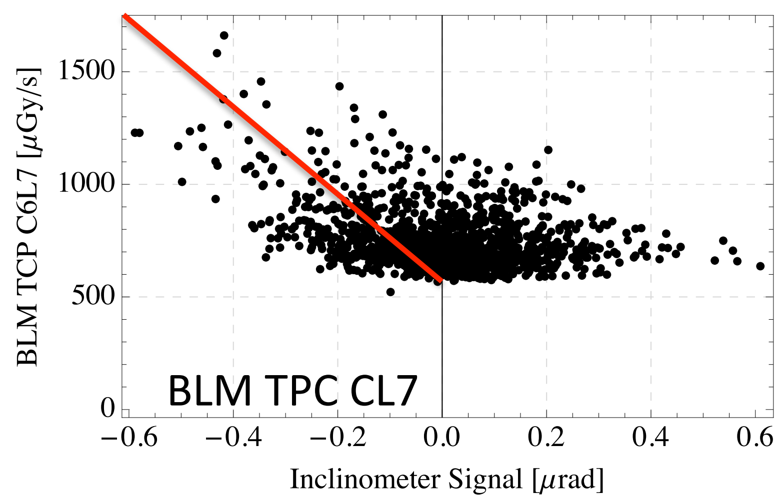


Observations on the LHC Beam

Clear correlations between ground motion in TT1, orbit and losses in IP7.



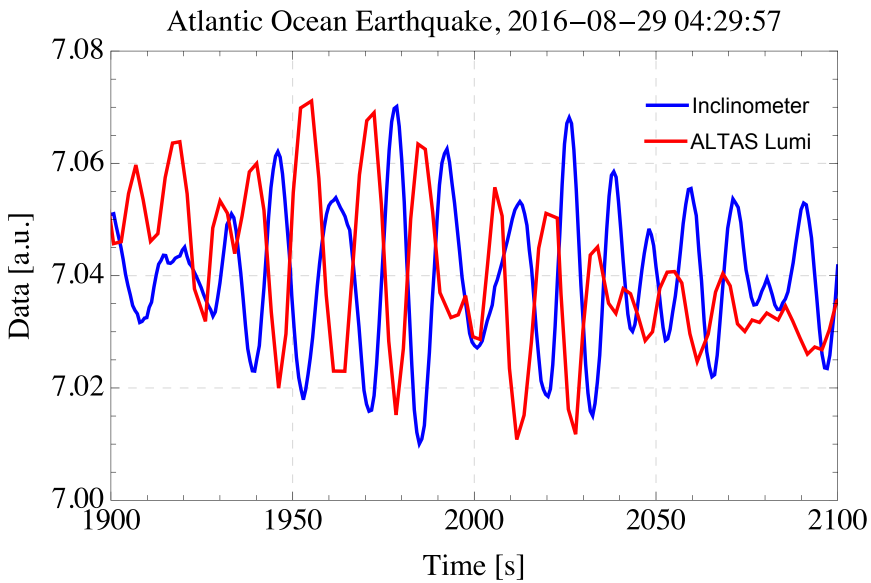


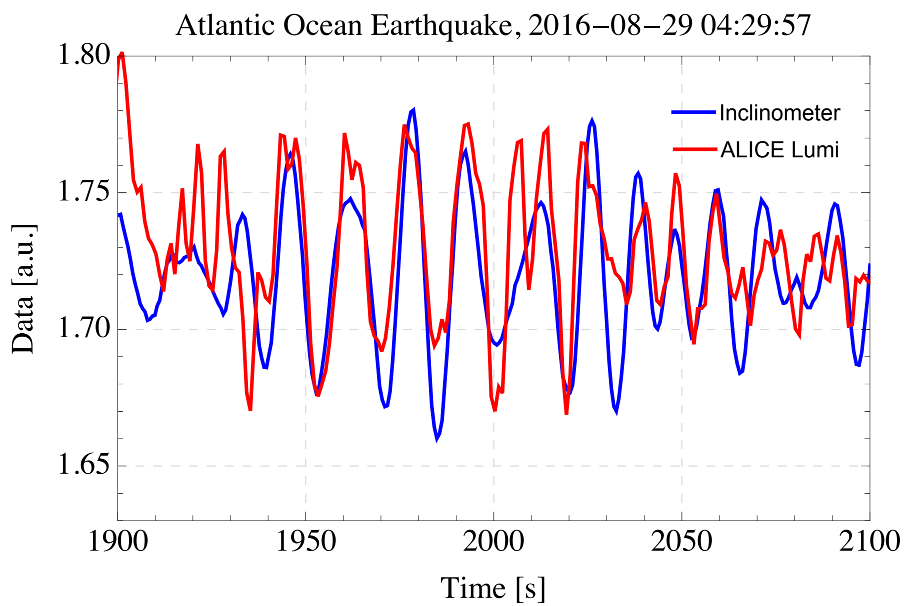


Correlations of Ground Motion with Luminosity

Luminosity shows good correlation with ground motion in TT1.

- ALICE/LHCb oscillate in phase with the ground motion.
- ATLAS/CMS oscillate with π/2 phase difference.

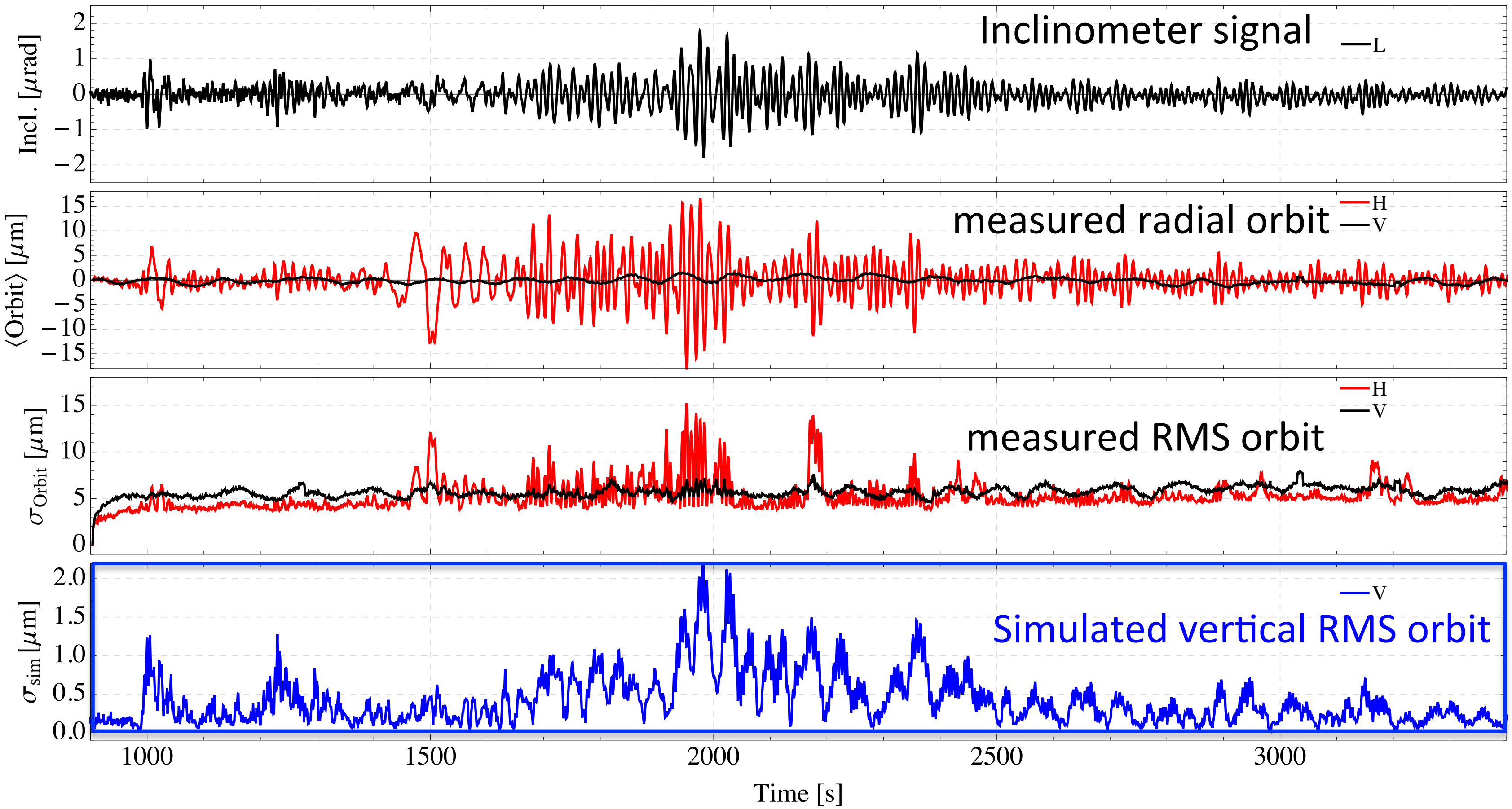




Simulation of Orbit Responds

Simulation with Inclinometer data

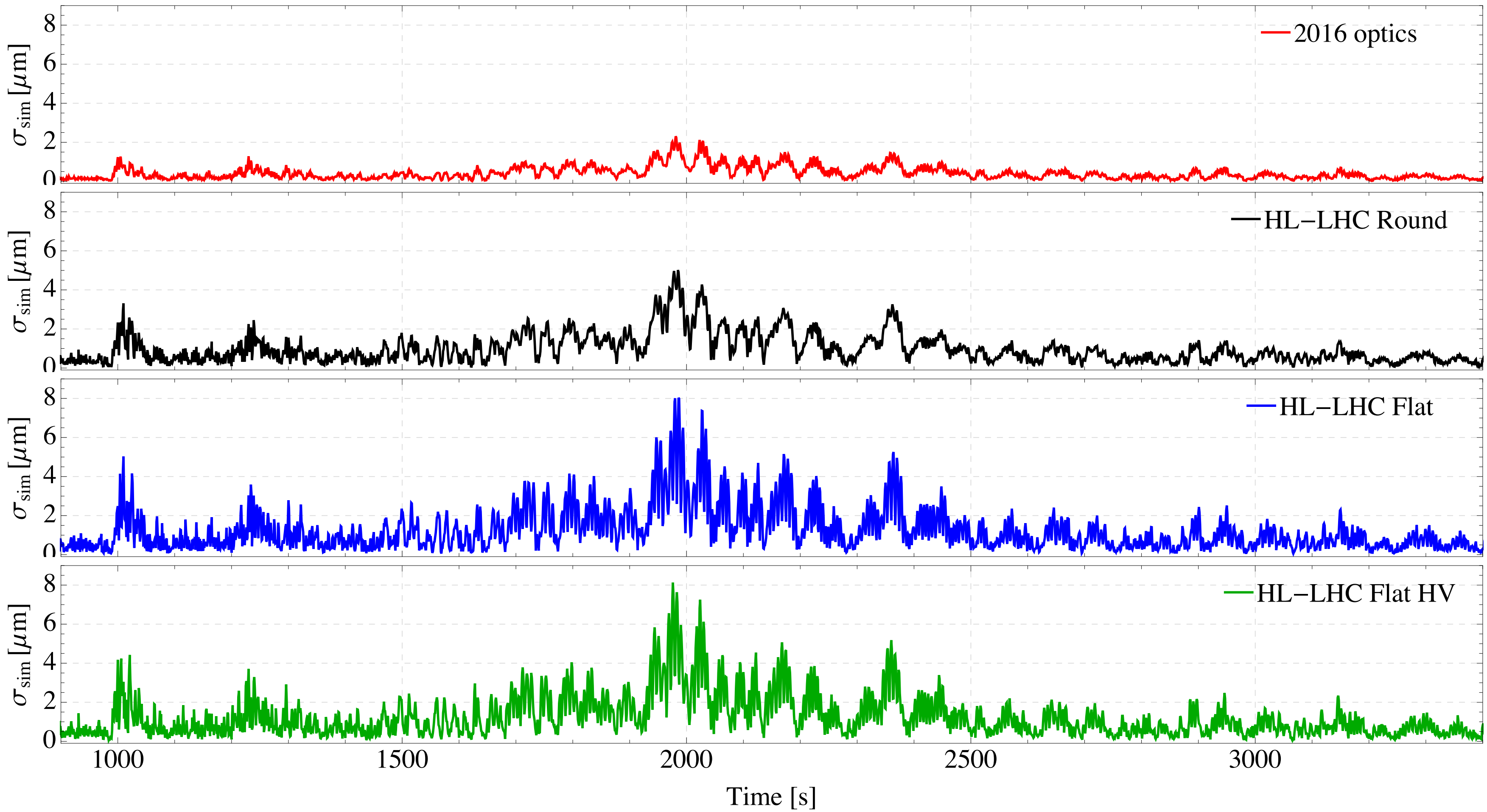
- No proper calibration to units of meter (as required for the simulation).
  → ***Amplitude of simulated RMS orbit distortion not reliable.***
- Assumed same signal for longitudinal and vertical offsets.
  → ***Some frequencies and amplitudes may not be covered in simulation.***
  → ***Where orbit and inclinometer show equivalent peaks the simulation follows.***



Simulations with HL-LHC Optics

Compared to the 2016 LHC optics the sim. RMS orbit response increases by a factor

- **~2 for round HL-LHC optics**
- **~3 for flat HL-LHC optics**



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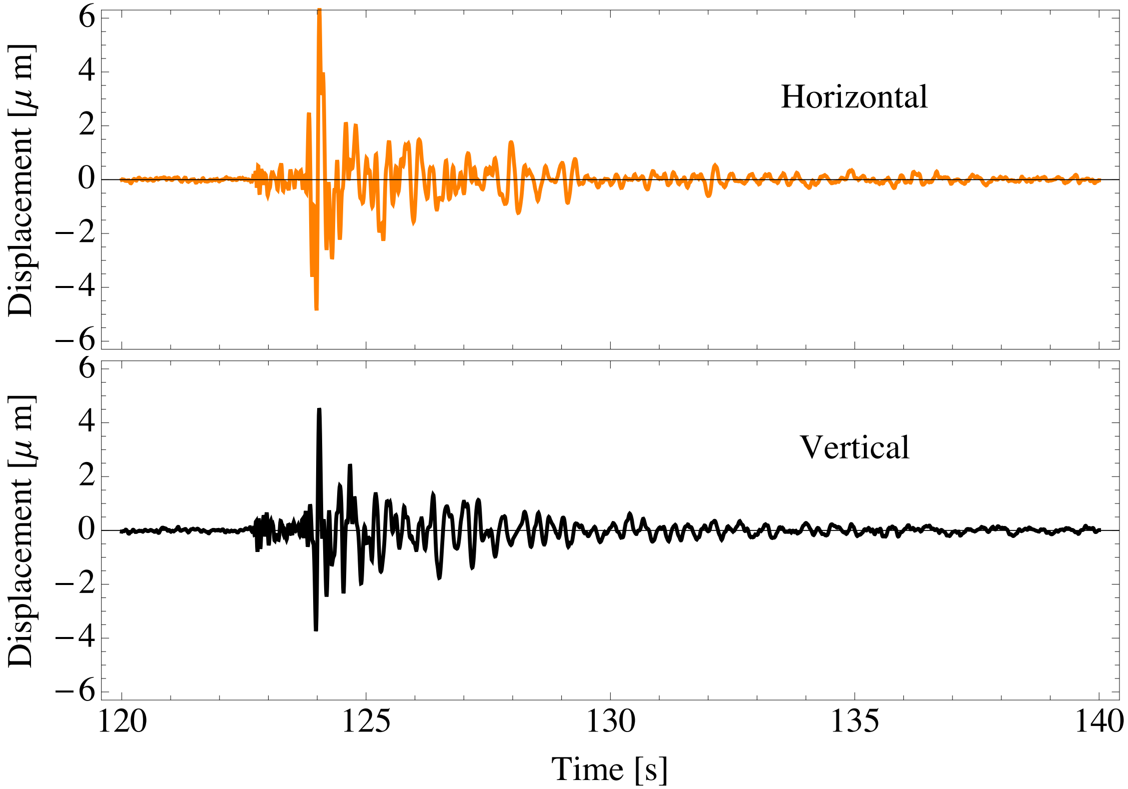
Seismic activity from *Geothermie 2020*



Seismic signal (magnitude ~1.8)

measured during a test injection of high pressure water

Amplitude ~**4-6µm**
Duration **<10s**

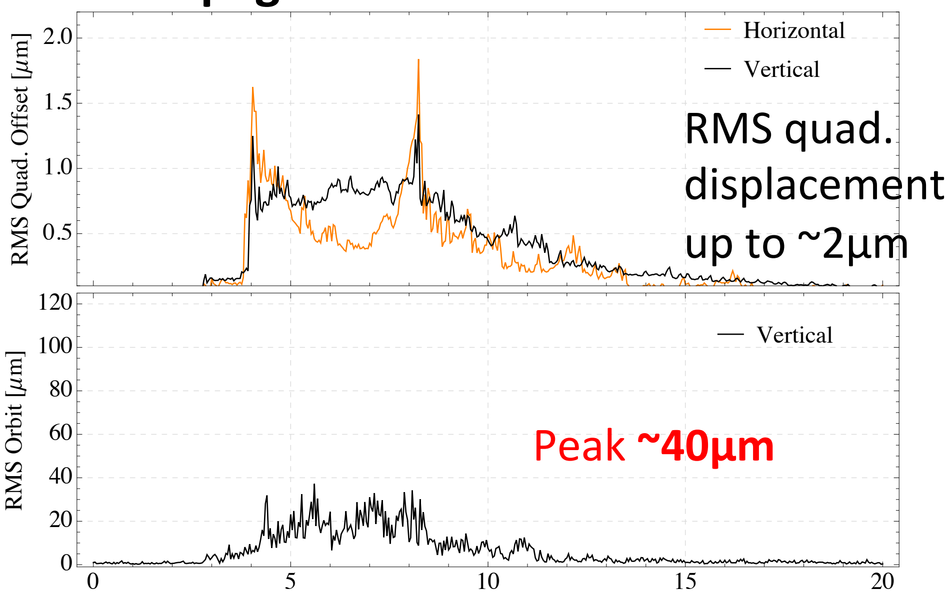
Report of RESONANCE Ingenieurs-Conseils SA, RT-424.02-1/MK/CB/ST/CL, data provided by Martin Koller, data set used SMZW_093

Simulation Results for 2016 Conditions

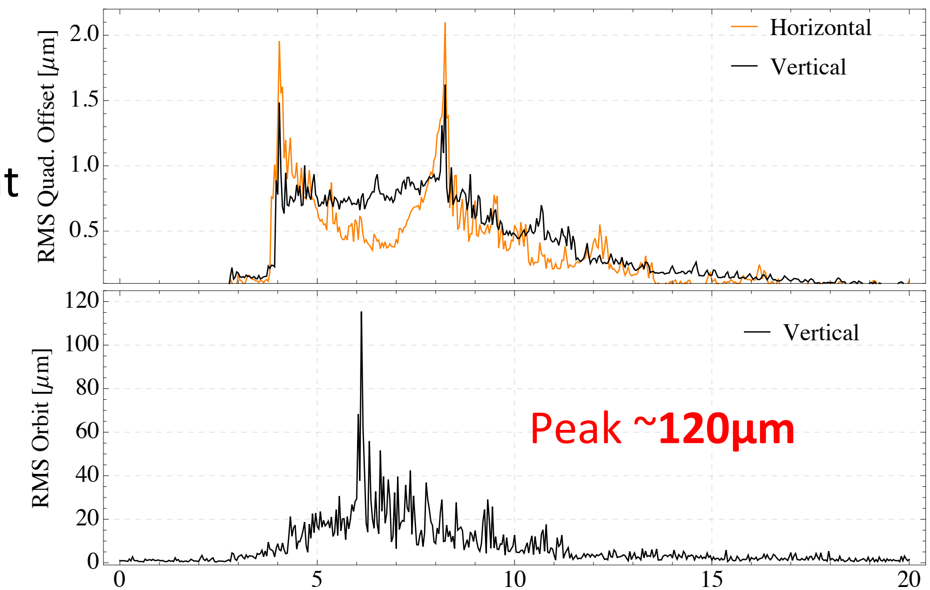
2016 Optics

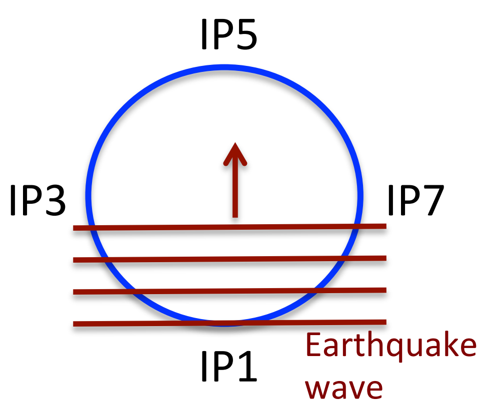
For the simulation it was assumed that plane wave fronts travel parallel to the LHC plane.

Propagation direction: IP1->IP5

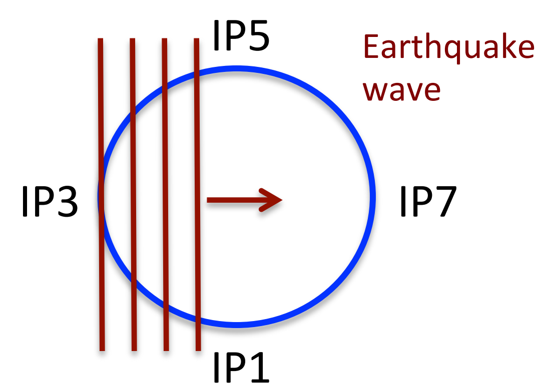


Propagation direction: IP3->IP7





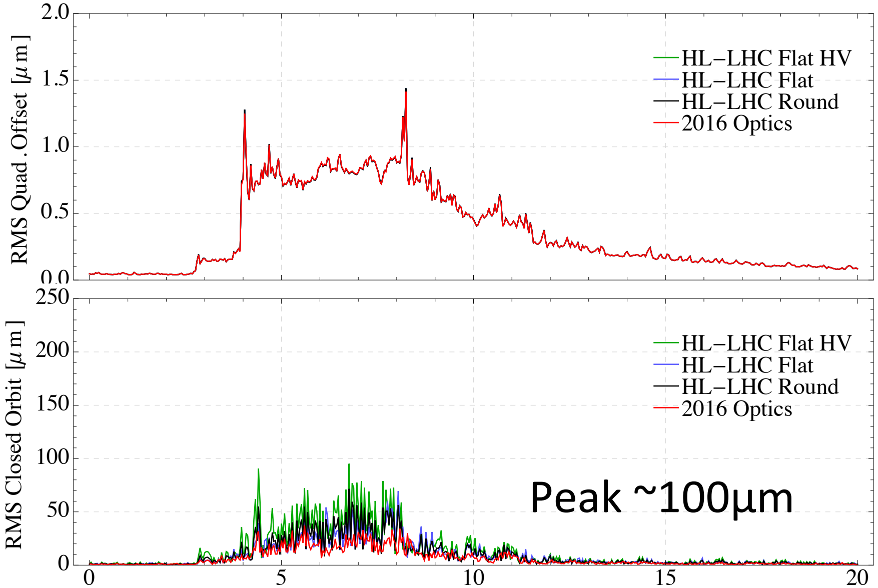
RMS orbit strongly dependent on direction of the wave → **factor 3**



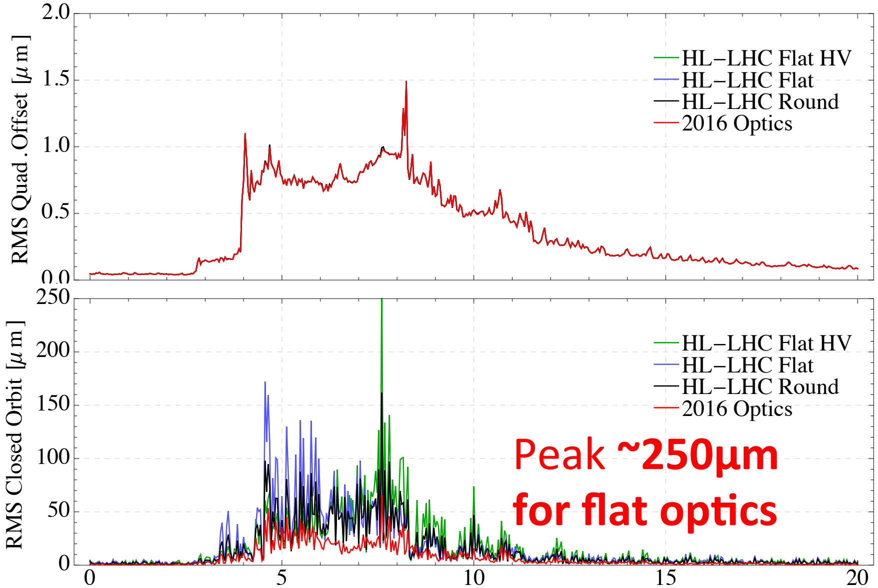
HL-LHC Optics Cases

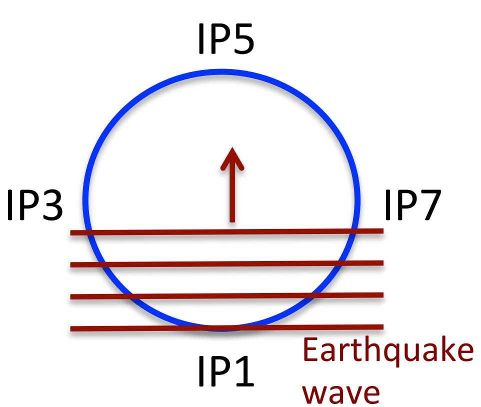
Vertical Response

Propagation Direction: IP1-> IP5

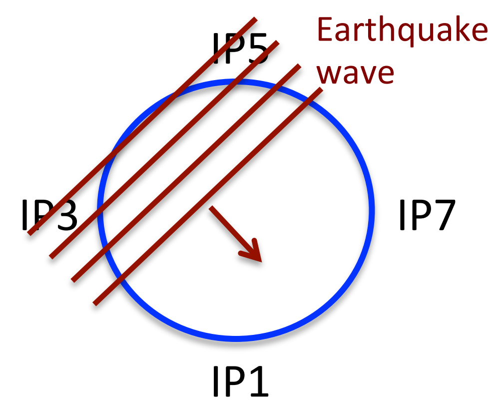


Propagation Direction: IP4-> IP8





RMS orbit increases by a **factor 2-3 for HL-LHC optics, with resonant spikes up to a factor 5 for flat optics.**



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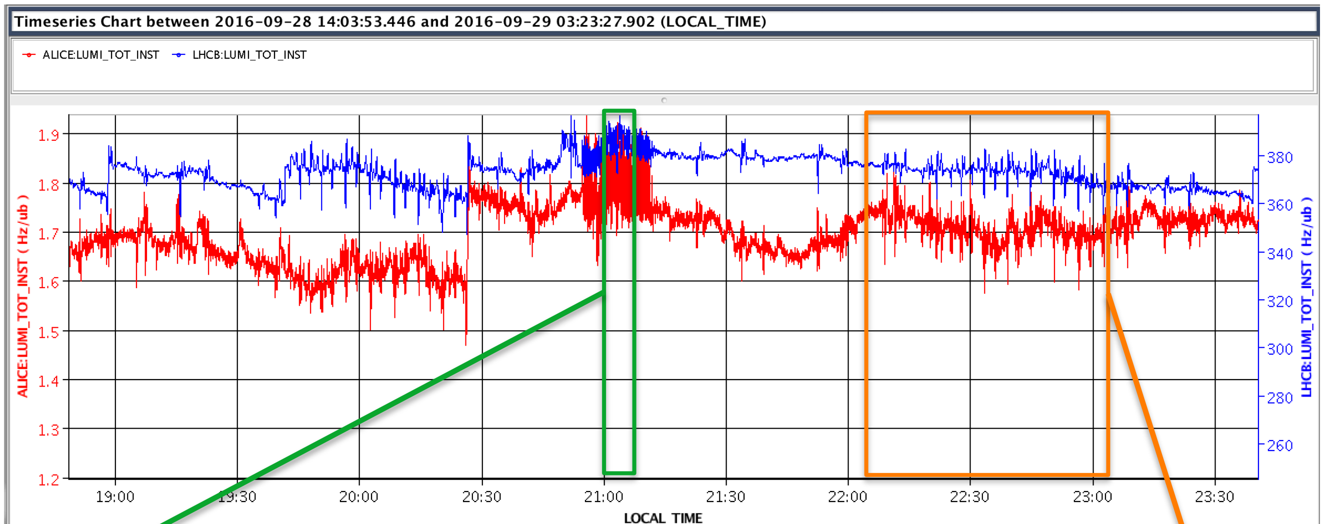
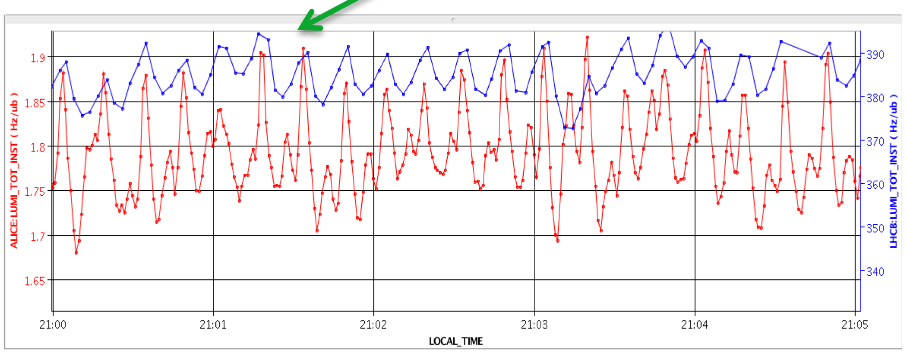
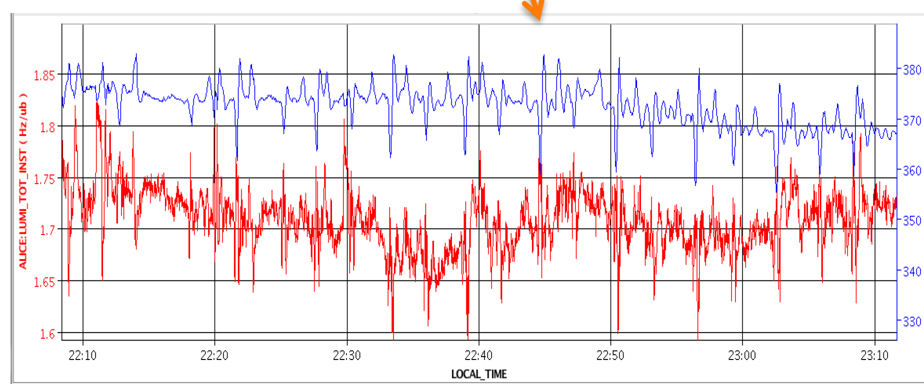
Luminosity Oscillations of Levelled Experiments

- **Luminosity oscillations of levelled experiments are frequently observed.**
  1. Period ~15 seconds
  2. Period ~2.5 minutes



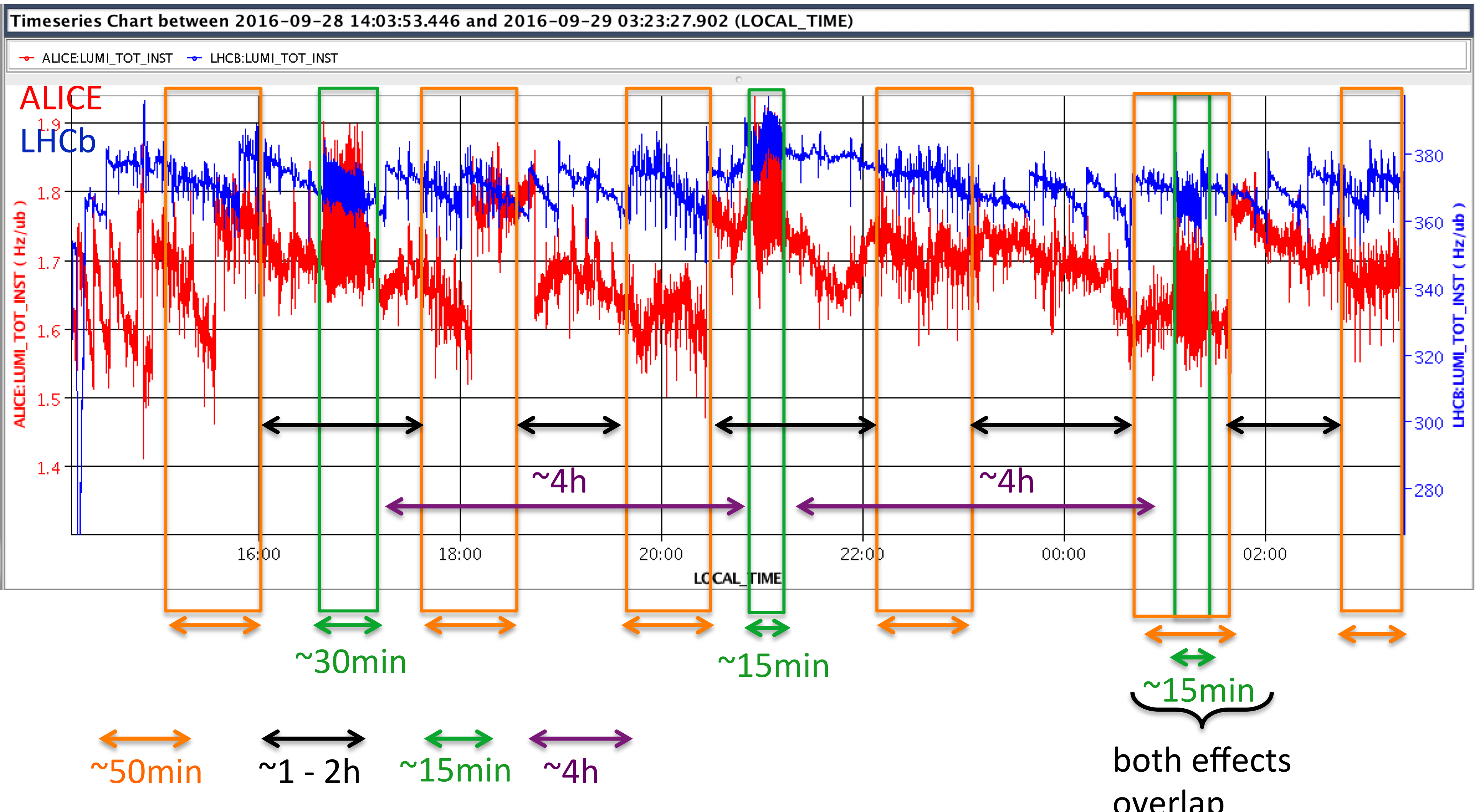
Example
Fill 5345





Luminosity Oscillations: Fill 5345

Effects have often a similar duration (~minutes) and re-appearing intervals (~hours).
→ Seems to be caused by a technological source.



Effect with ~15s Period

Oscillation of amplitude ~±4 μm in **vertical** at Q1 BPM in **IR1** (β = 1200 m)

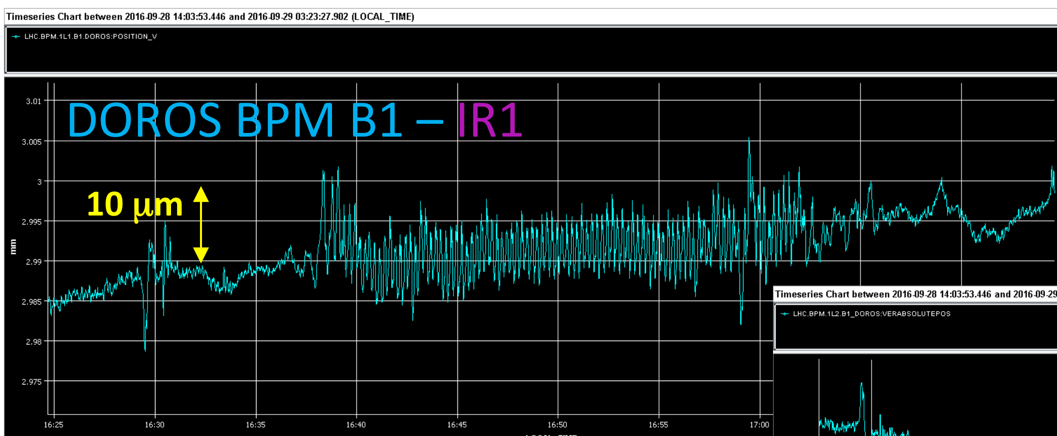
- amplitude in arcs is ~ 2 μm

Oscillation of amplitude ~±1 μm in **vertical** at Q1 BPM in **IR2** (β = 60 m)

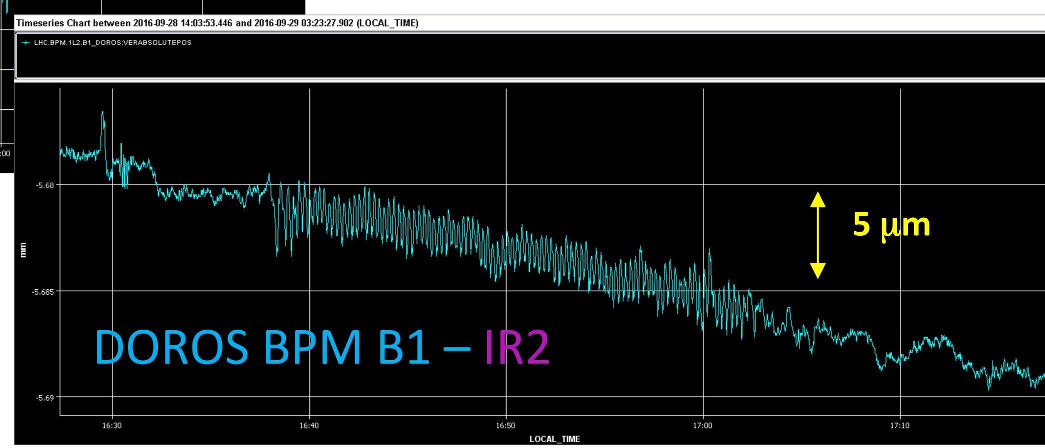
- amplitude in arcs is a little larger

→ The oscillations of the orbit may be a bit too small to explain the luminosity fluctuations unless the source is a quadrupole.

- *The orbit oscillations are due to the beam offset w.r.t. quadrupole axis,*
- *The luminosity fluctuation due to the β-function modulation. The levelled experiments are much more sensitive !*



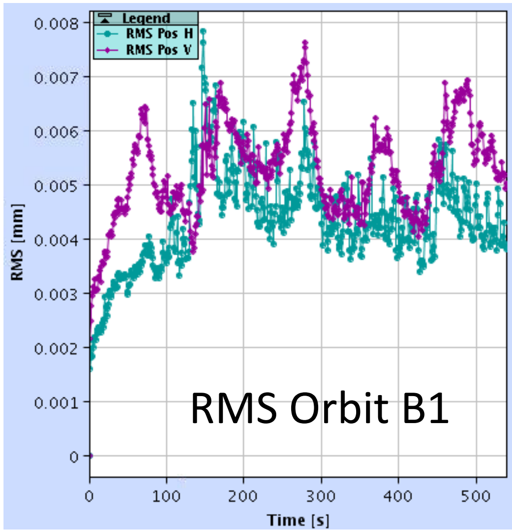
B2 shows similar amplitude in both cases

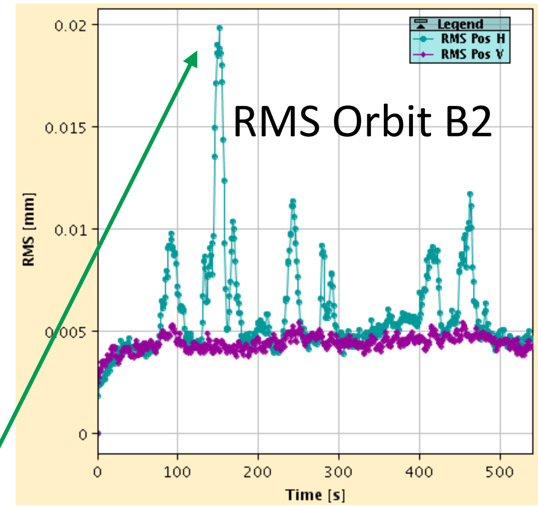


Effect with ~2.5min Period

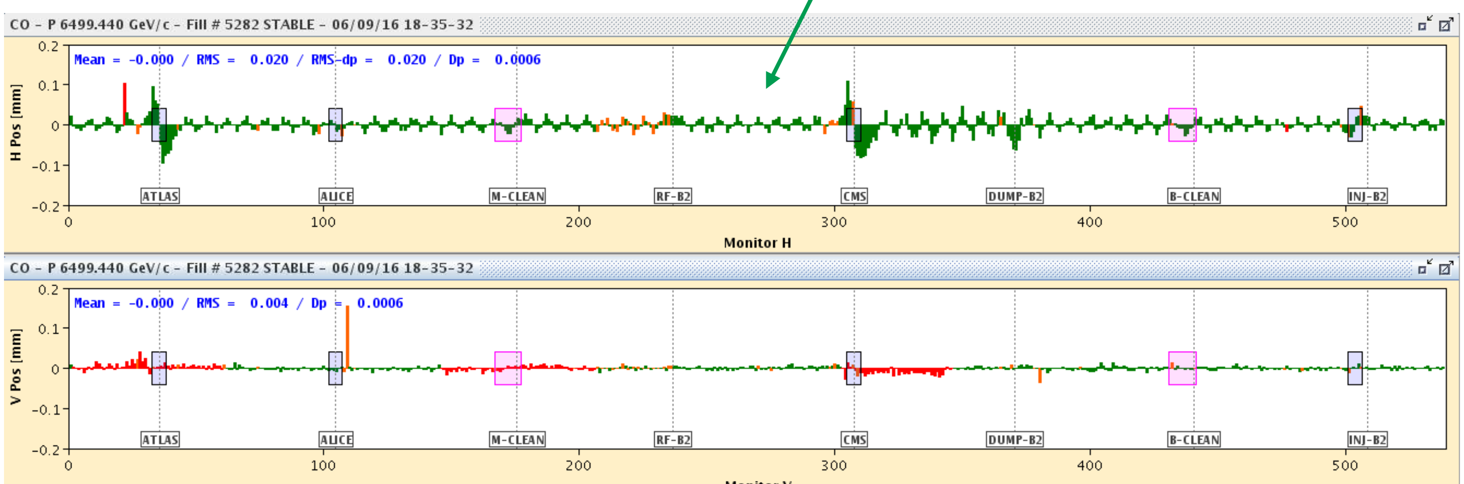
A second effect with a different frequency causes:

- **Orbit oscillations** mostly observed in **B2-Hor with amplitudes of ~20 μm**.
- Periodic 'spikes' are observed in the RMS orbit of B2.





Example Fill 5282



Conclusions

- Civil engineering:
  - **Strong mechanical resonances of the triplet** at [8, 20 Hz].
  - Excavation of HL-LHC vertical shafts should be **compatible with 2018 LHC operation**.

- **Large earthquakes (M>6) have a clear impact on the LHC.**
  - So far NO event cased a beam dump.

- (Prototype) ground motion measurements at CERN are under commissioning.
  - IP1 and 5 are planned to be equipped with geophones in the EYETS 2016.

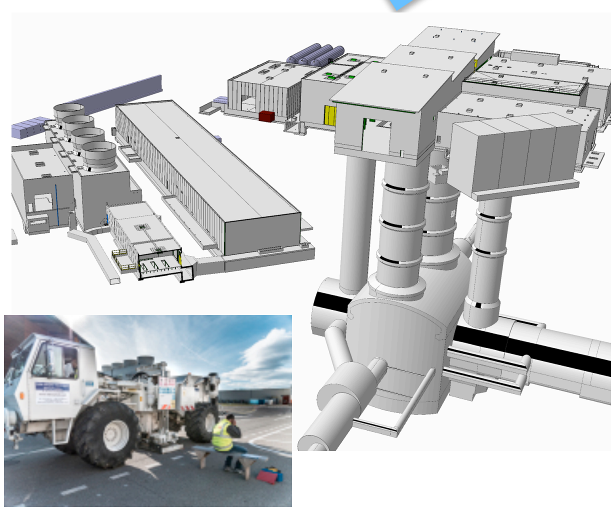
- Simulations to predict the ring orbit response are being renewed and extended to as well make estimates for HL-LHC.
  - Simulations are still in the development phase.

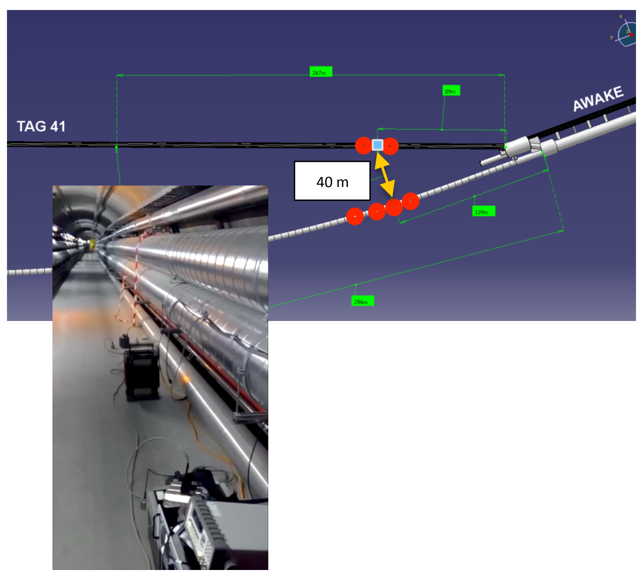
Backup

Transfer Function Measurements

In (ω) — H_2 (ω) — H_1 (ω) — H_0 (ω) — Out (ω)

Measurements in ATLAS area (UL16/SR1) with a **vibration truck**	Measurements in AWAKE area (TAG41/TT41) with a **shaker**	Measurements at SM18 with **Q1 triplet spare**





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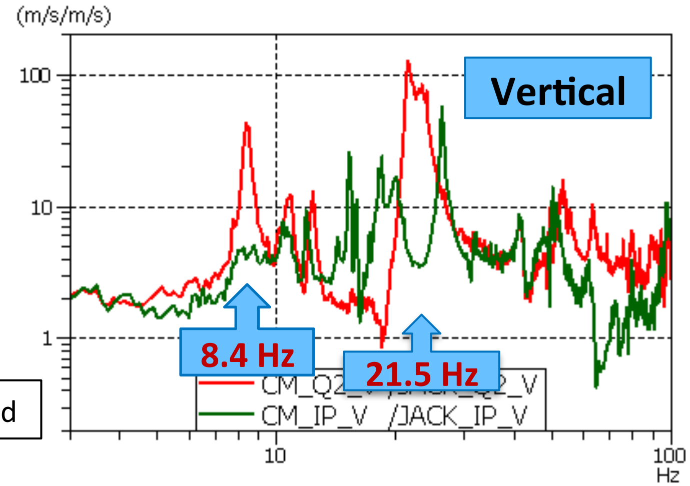
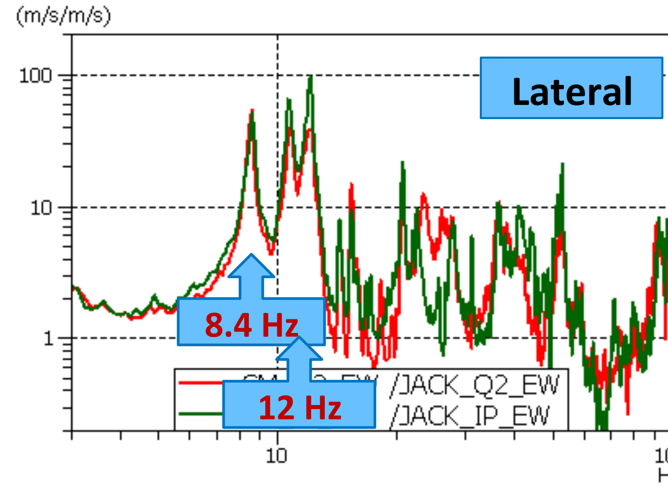
Transfer Function Results for H0(ω)

Measurement of Q1 transfer function H0 shows strong **modes** at **21.5 Hz, 8.4 Hz and 12 Hz**.

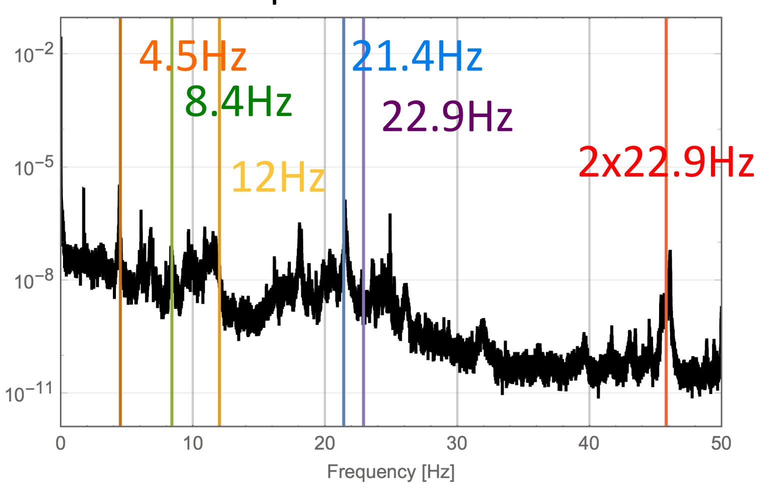


M. Guinchard

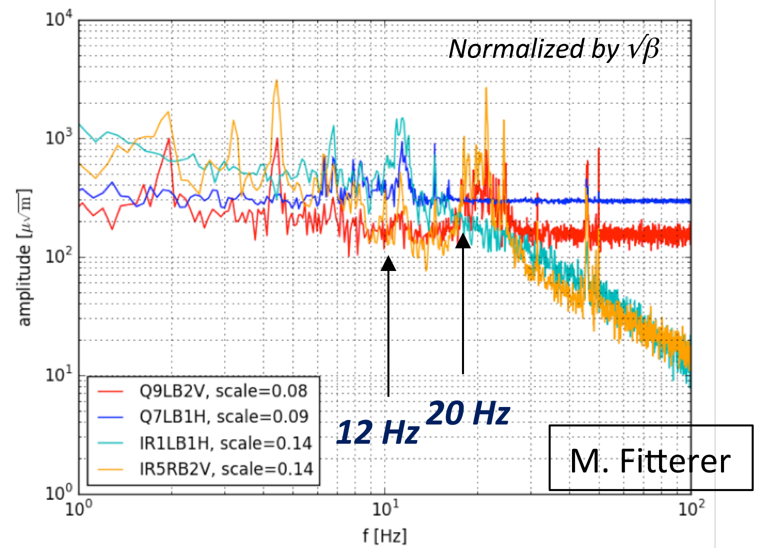


Measurements performed using the **ADT** and the **DOROS BPMs** at the Q1's and the **100Hz BLM data** confirm the presence of activity in the frequency range of the triplet resonances.

FFT of a sample of the BLM 100Hz data

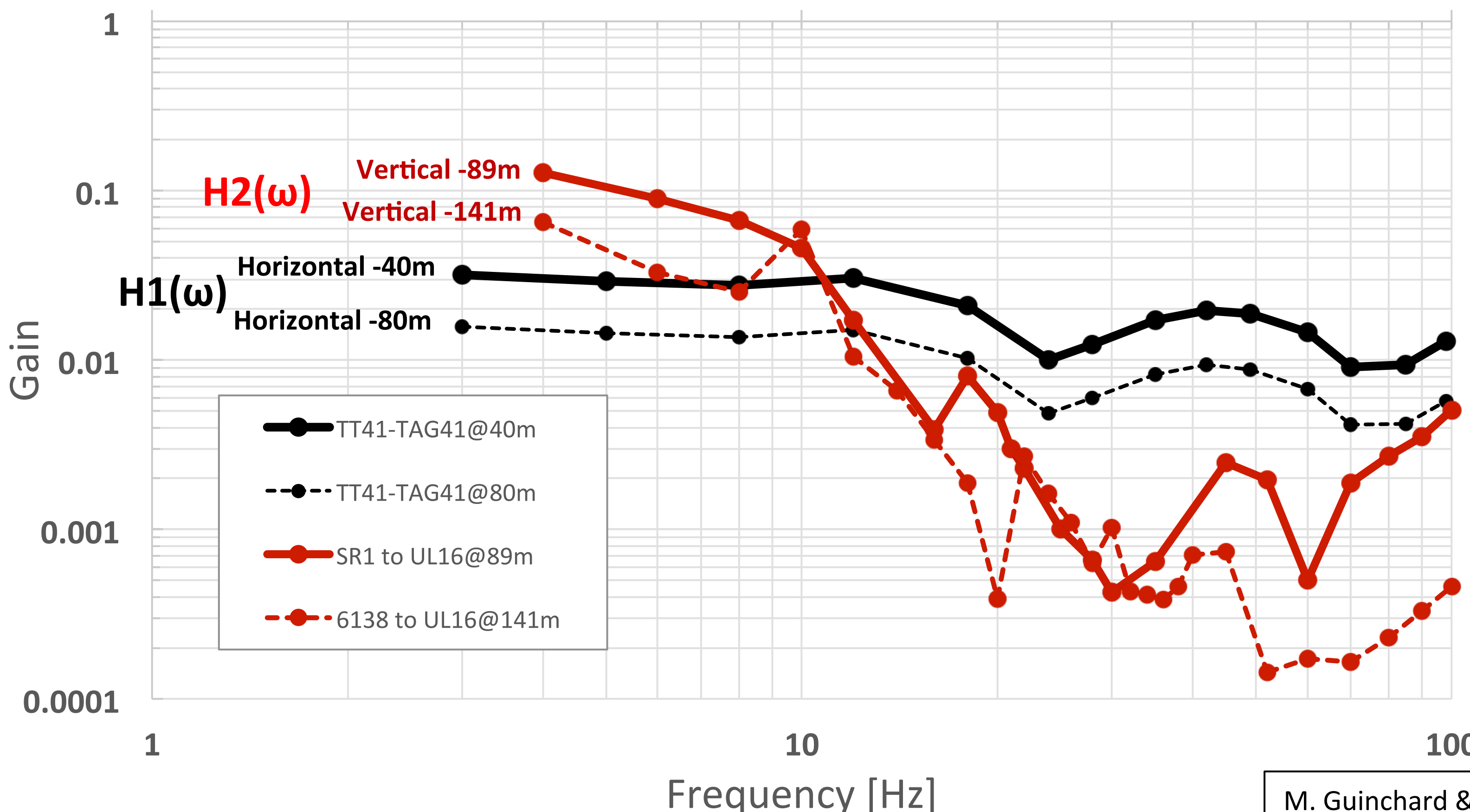


2015 ADT and DOROS BPM data



Transfer Function Results for H1(ω) and H2(ω)

- TT41 (H1(ω)) measurement dominated by shear waves, SR1 (H2(ω)) measurement by pressure waves – confirmed by wave propagation speed.
- Gain for vertical measurement is possibly biased by surface waves.
- The **source distance is together with planning decoupling the main ally that we have to minimize / avoid impact on beams.**



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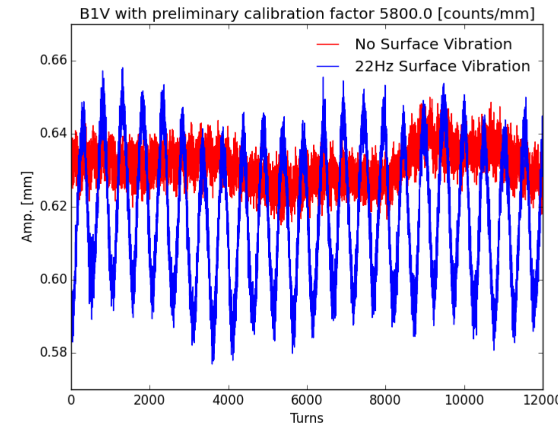
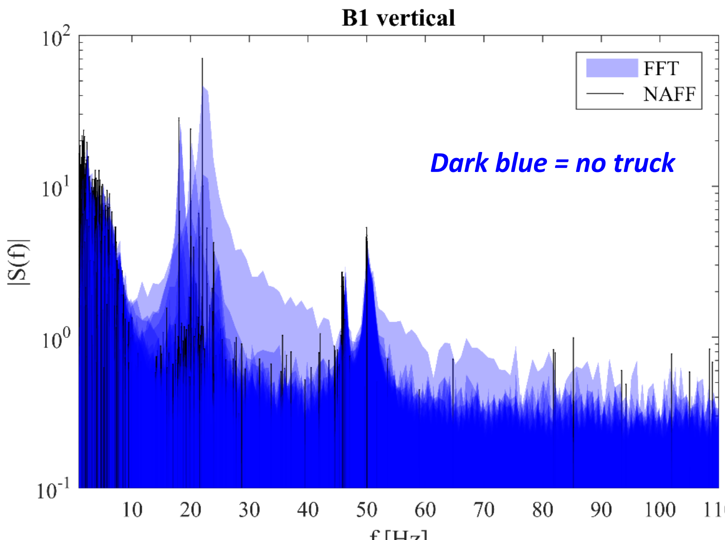
Vibrating truck impact on LHC beam

- Beam measurements with the vibrating truck were performed for the squeezed optics (80 cm) at 6.5 TeV and at injection.
  - Multi-turn data (all BPMs) & ADT data.



- Measurements results:
  - *Beam oscillations were only observed in the vertical plane ⇔ truck location.*
  - *Beam oscillations were only observed for* ***vibration frequencies of 18-22 Hz*** *– consistent with the triplet resonances.*
  - *Observed B1/B2 amplitude ratio of ~2.5 implies that the different triplet quads oscillated with different amplitudes.*
  - *The oscillation amplitudes of the triplet CMs were in the* ***few μm range for a ground motion amplitudes of ~50 nm*** *in the tunnel.*



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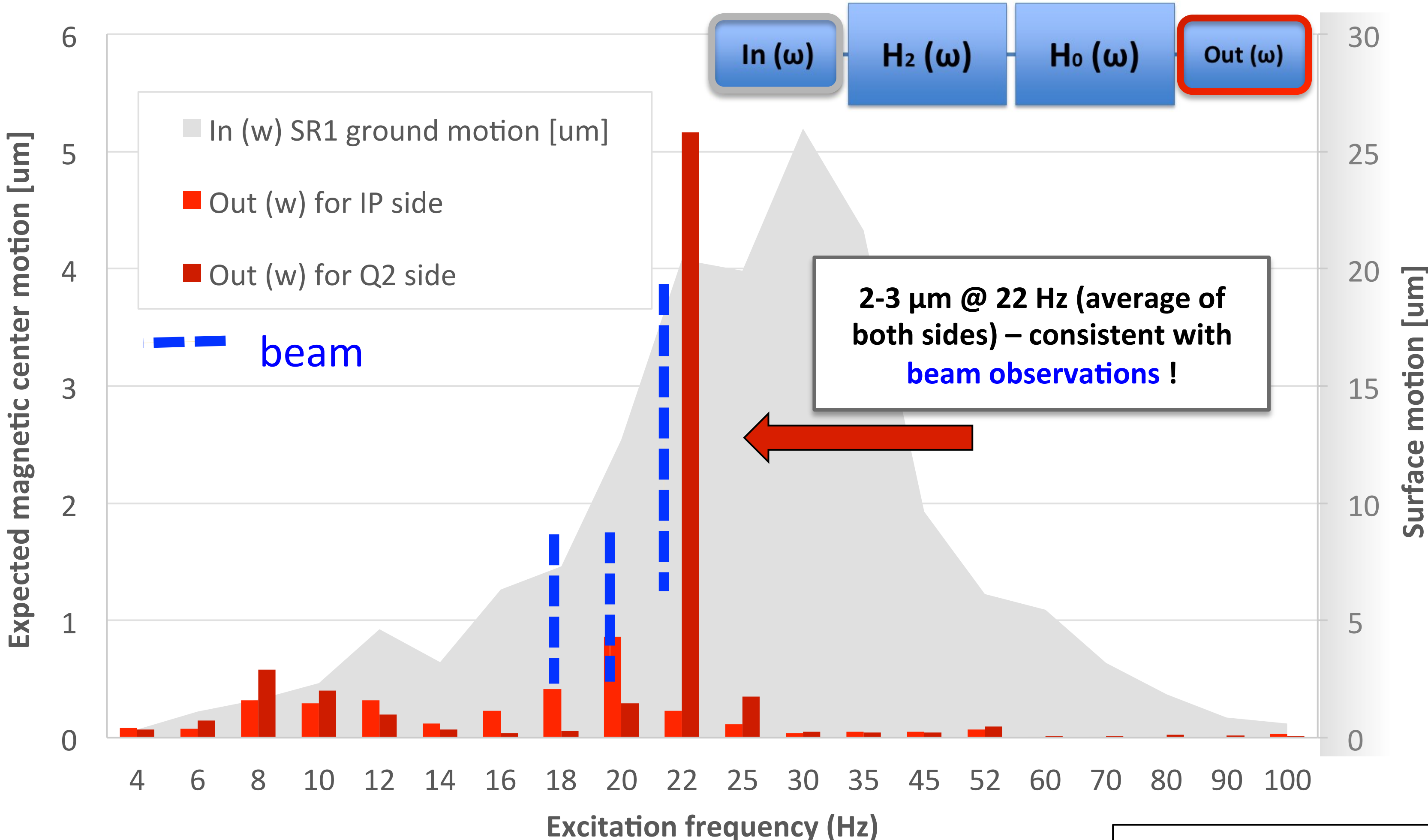
The observations are consistent with the triplet resonances that enhance the vibrations by a factor >> 10

Truck → triplet predictions

- Expected motion of the triplet magnetic center during truck tests.



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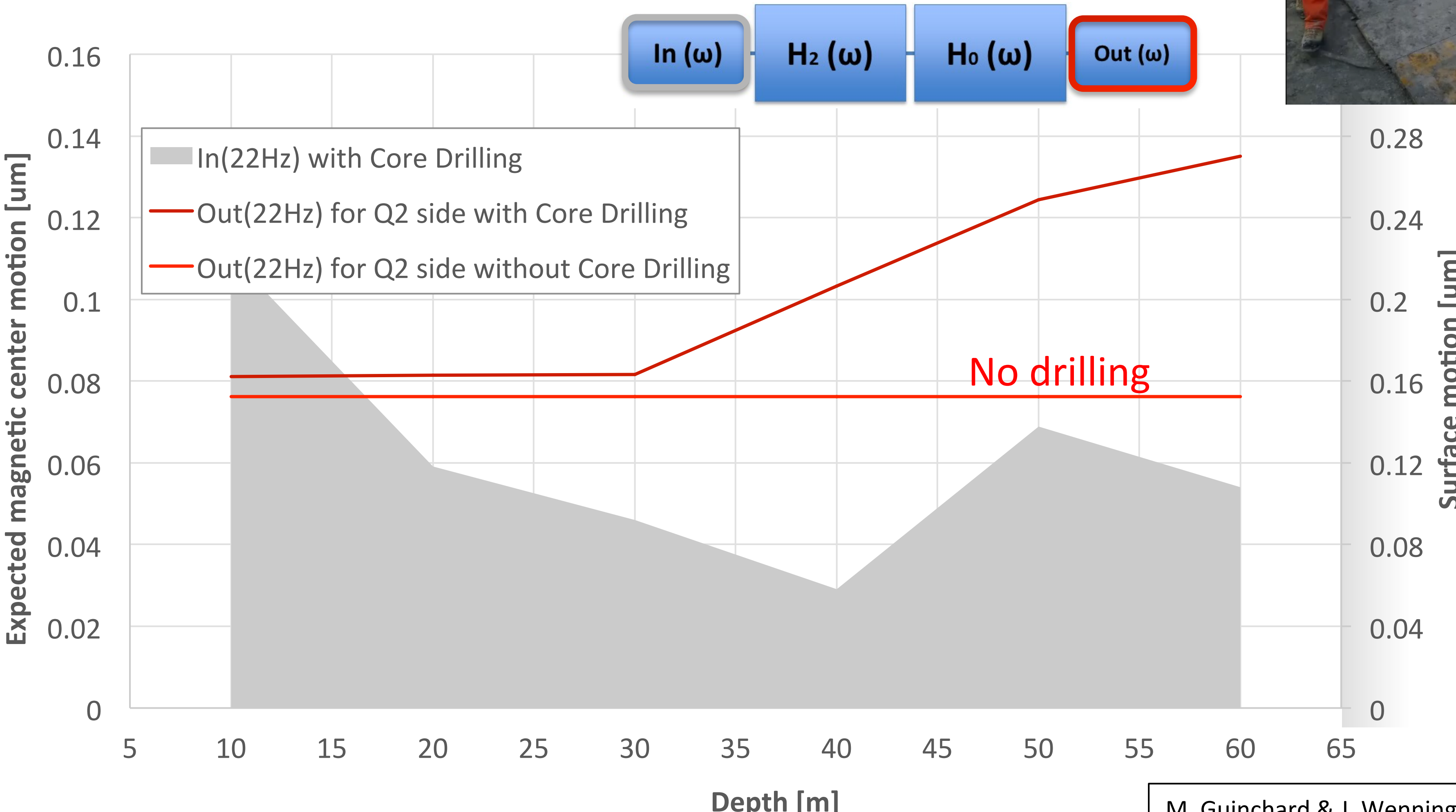
Core drilling → triplet predictions

- The expected motion of the triplet magnetic center vs depth remains at level of ≈ 0.1-0.2 μm – acceptable.



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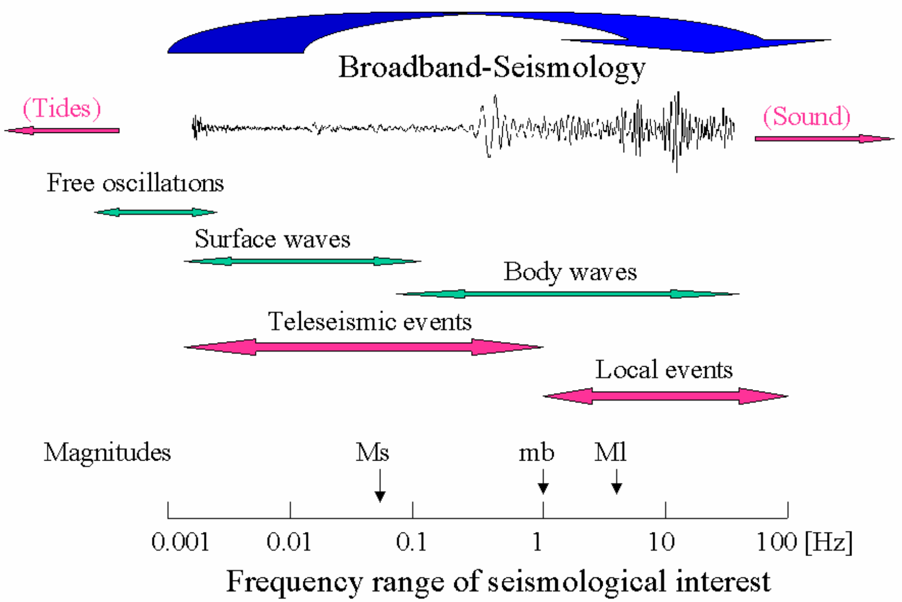
Frequencies of Earthquakes

- Frequency spectrum of waves induced by earthquakes ranges from **~ mHz** (earth oscillations and surface waves) to **~100 Hz** for local seismic events.

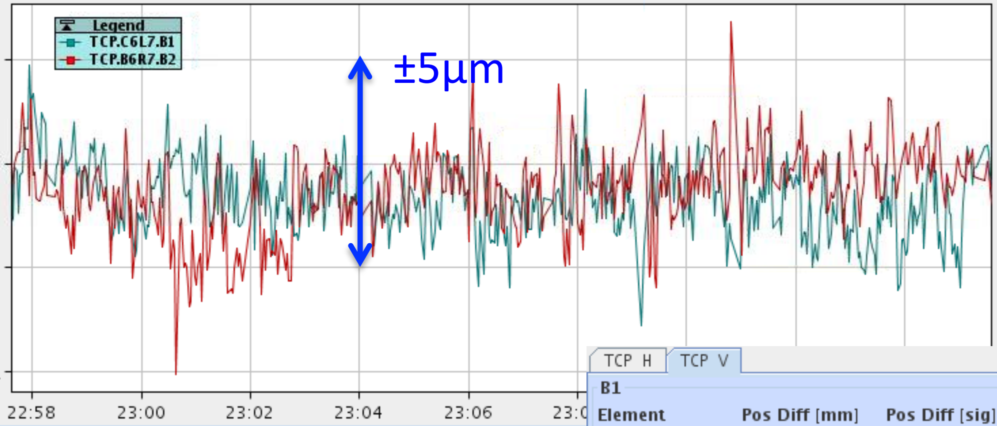
➢ The signatures of large and distant earthquakes (teleseismic) are dominated by low frequencies < 1 Hz.

➢ Ground motion from local earthquakes (Geothermie 2020) extends to higher frequencies.



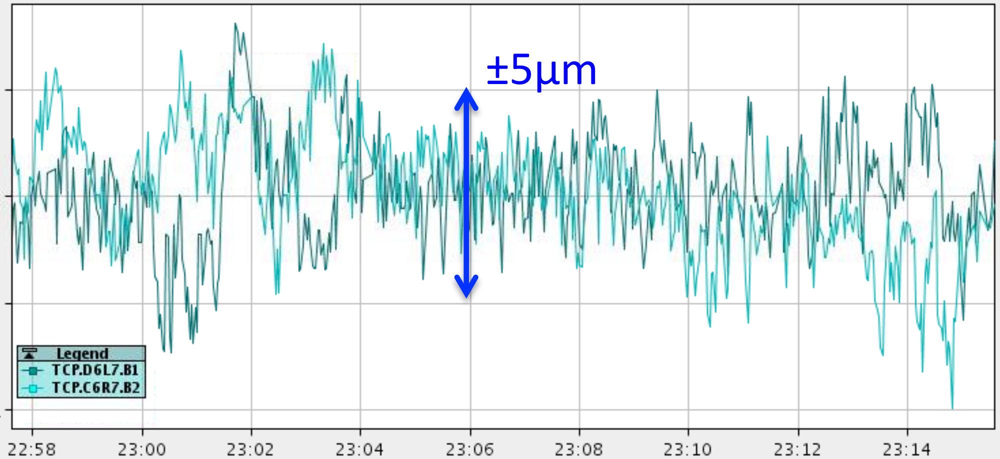
Slide from J. Wenninger

Orbit Stability at TCP



Element	Pos Diff [mm]	Pos Diff [sig]	Display
TCP.C6L7.B1	-0.001	-0.005	☑
TCP.B6L7.B1	-0.001	-0.006	☐
TCP.6L3.B1	0.008	0.032	☐

Element	Pos Diff [mm]	Pos Diff [sig]	Display
TCP.B6R7.B2	-0.002	-0.007	☑
TCP.C6R7.B2	-0.002	-0.006	☐
TCP.6R3.B2	0.006	0.024	☐



Element	Pos Diff [mm]	Pos Diff [sig]	Display
TCP.D6L7.B1	0.003	0.013	☑
TCP.C6L7.B1	0.003	0.012	☐

Element	Pos Diff [mm]	Pos Diff [sig]	Display
TCP.C6R7.B2	-0.000	-0.002	☑
TCP.D6R7.B2	-0.001	-0.003	☐

The orbit at the TCP during stable collisions is controlled to ±5µm.

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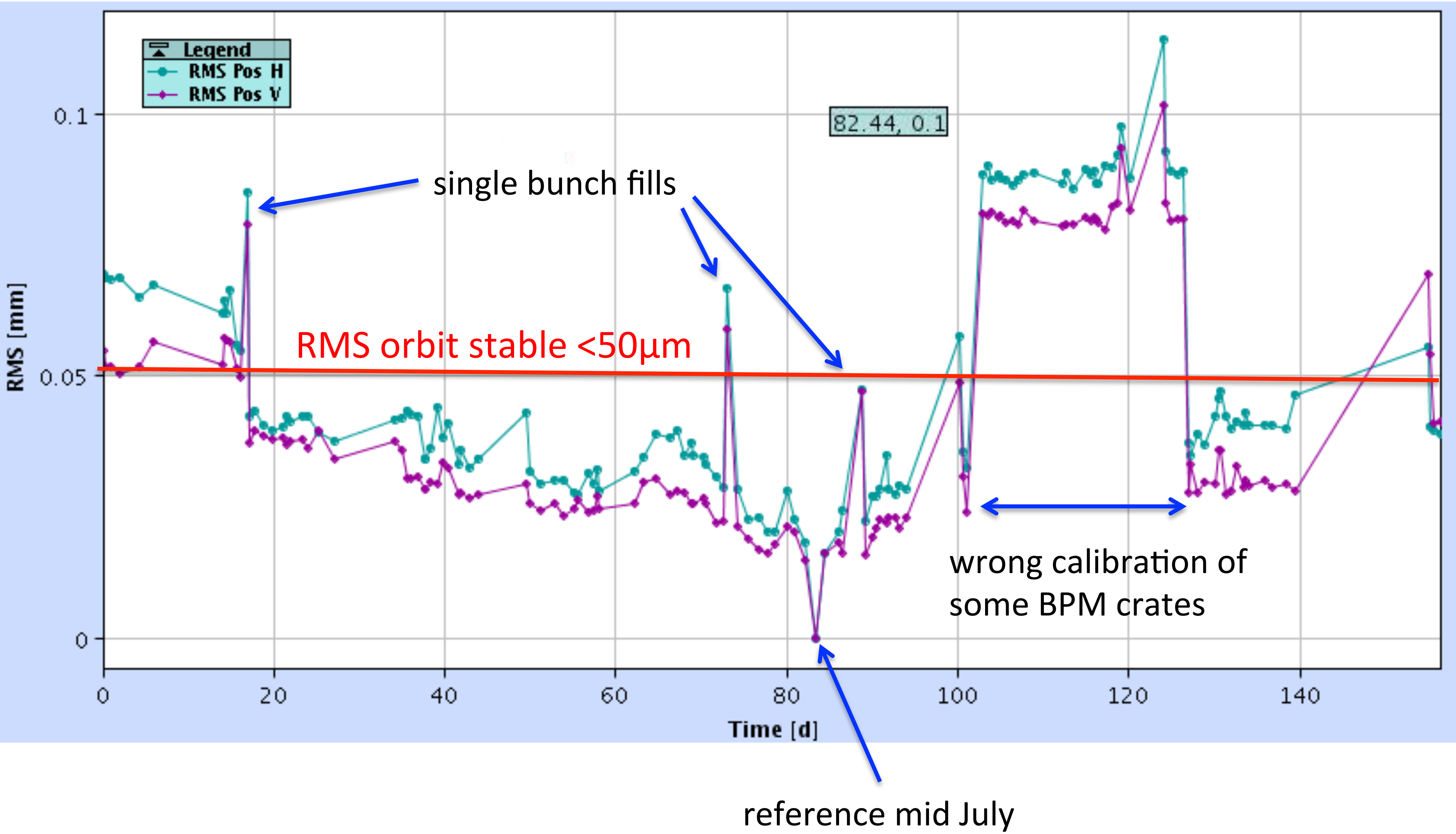
RMS Orbit over the year



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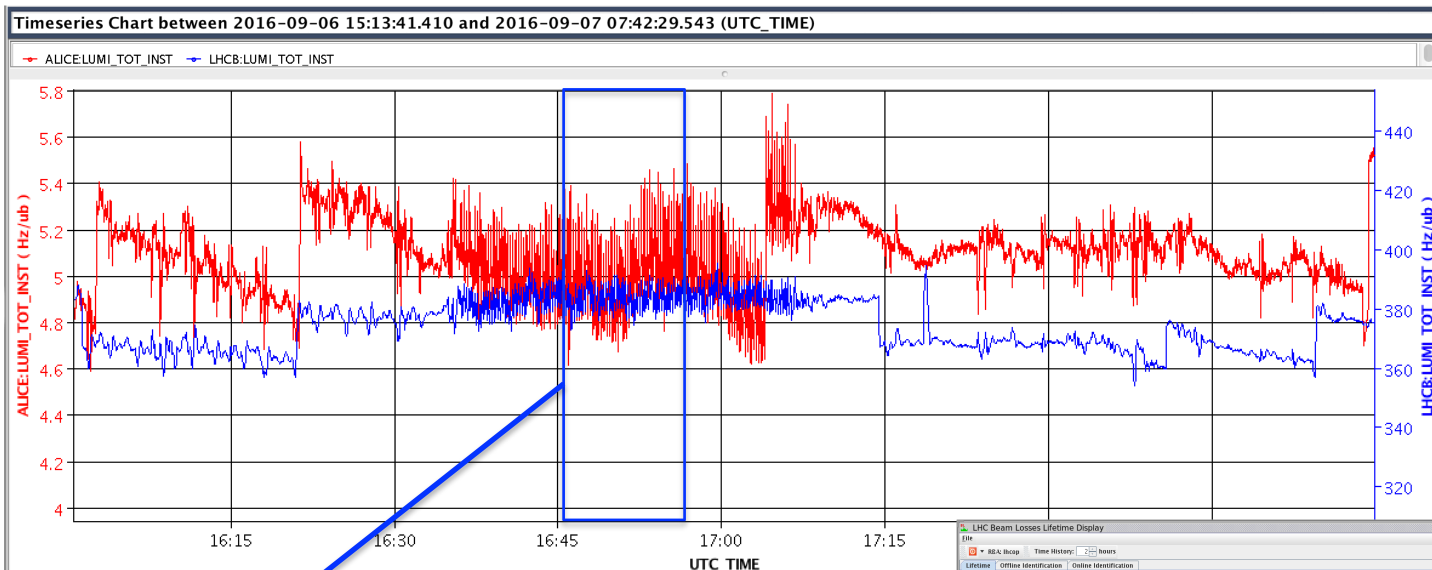
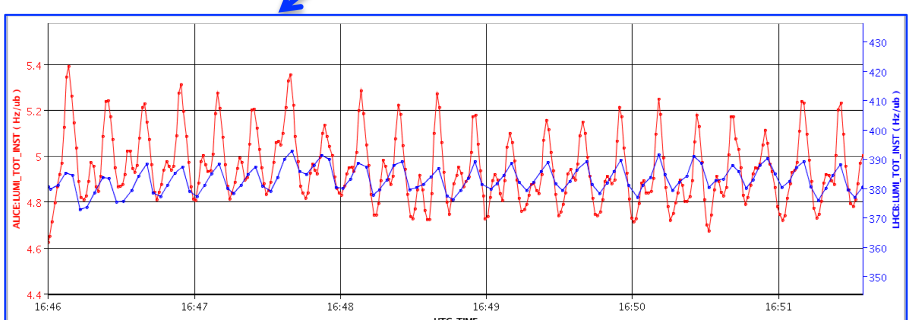
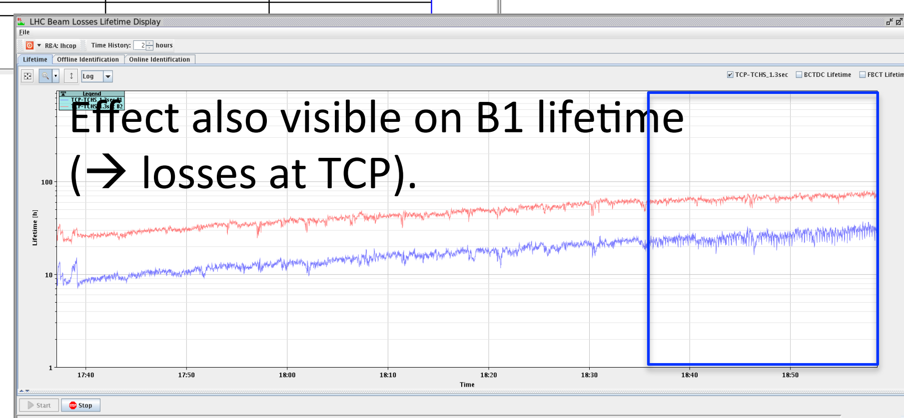
Luminosity Oscillations of Levelled Experiments

- **Luminosity oscillations of levelled experiments are frequently observed.**
- These oscillations correspond to ~2-4 μm of vertical beam separation at the IPs (@ β*= 3 and 10m).
- Period ~15 seconds



Example
Fill 5282

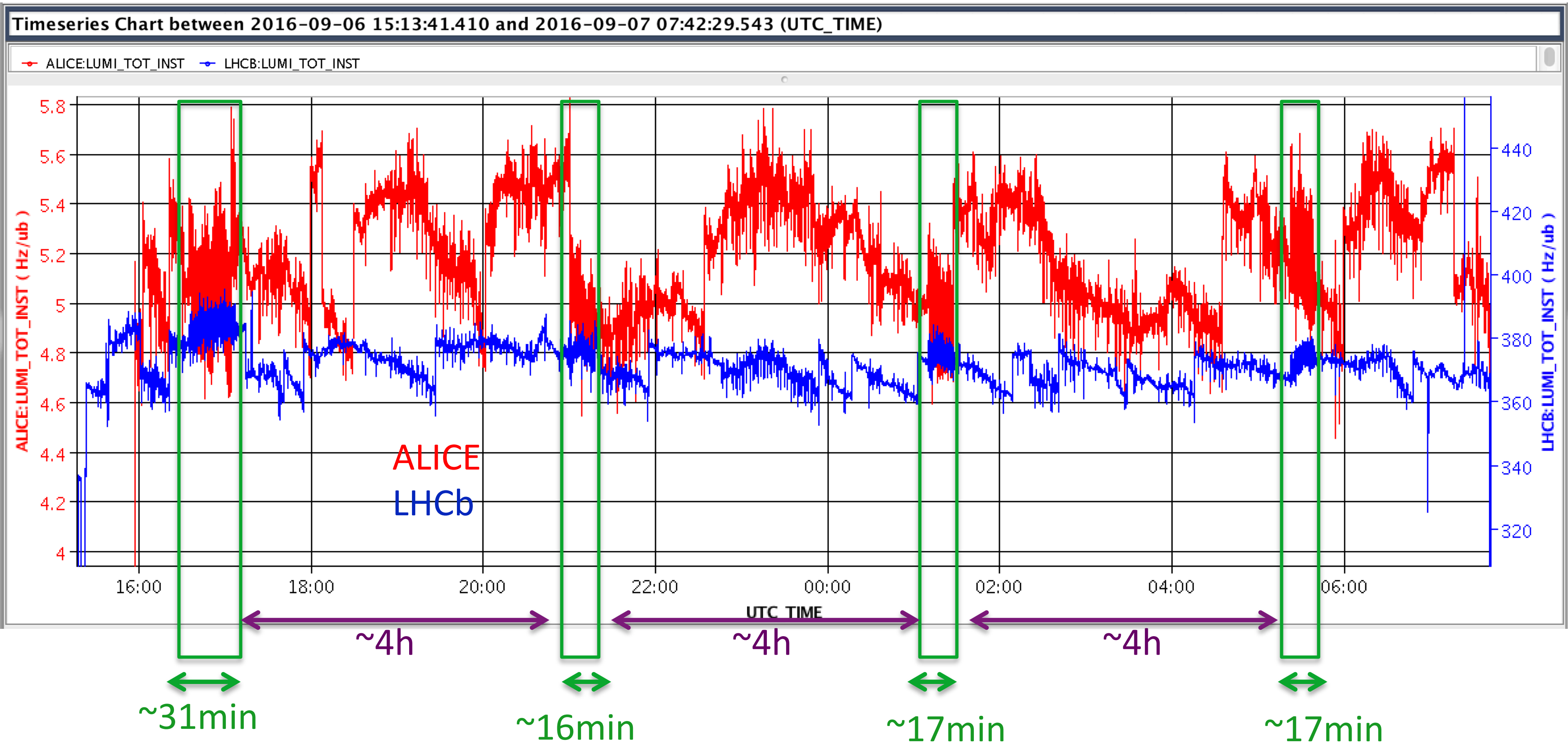




Effect also visible on B1 lifetime
(→ losses at TCP).

Luminosity Oscillations: Fill 5282

Effect has often a similar duration and re-appearing intervals.
→ Seems to be caused by a technological source, which is so far unknown.



Luminosity change due to beta-beat

- Luminosity change due to beta-beating with offset levelling:

$$L \sim \frac{1}{\sqrt{\beta}} \exp\left(-\frac{x^2}{4\beta\varepsilon} \right)$$

$$\frac{dL}{d\beta} = L\,\frac{1}{\beta}\left(-\frac{1}{2} + \frac{x^2}{4\beta\varepsilon} \right) = L\,\frac{1}{\beta}\left(-\frac{1}{2} + \frac{x^2}{4\sigma^2} \right)$$

$$\Delta L = \frac{dL}{d\beta}\Delta\beta = L\,\frac{\Delta\beta}{\beta}\left(-\frac{1}{2} + \frac{x^2}{4\beta\varepsilon} \right) = L\,\frac{\Delta\beta}{\beta}\left(-\frac{1}{2} + \frac{x^2}{4\sigma^2} \right)$$

$$\frac{\Delta L}{L} = \frac{\Delta\beta}{\beta}\left(-\frac{1}{2} + \frac{x^2}{4\sigma^2} \right)$$

Summary of Ground Motion Studies (1)

- **Large earthquakes** (M>6) **have a clear impact on the LHC**, even if originating at long distance.
  - **So far NO event cased a beam dump.**
  - **Potentially only one event would have dumped under HL-LHC conditions.**
  - Nearby small earthquakes have not been observed.

- **Prototypes** of geophones and high precision laser inclinometers are under commissioning and **recording ground motions in TT1**.
  - Since the ground motion backgrounds in TT1 and the LHC tunnel are quite different, any **correlation to LHC beam data** can only be **meaningful for long-distance earthquakes**.
  - For systematic correlation studies of the effect of ground motion on LHC operation, ground motion measurement devices are required in the LHC tunnel.

    → **Geophones will be installed in Point 1 and 5 in the EYETS** and the data will be logged to the database from next year on.

Summary of Ground Motion Studies (2)

- Simulations to predict the ring orbit response are being renewed and extended.
  - **The simulation code is still under development and all new simulation results presented here are very preliminary.**
  - *Long-distance strong earthquakes:*
    - Clearly observed on orbit, BLM and luminosity.
    - Simulation show already a qualitative reasonable agreement.
    - Simulation indicate that for HL-LHC optics orbit oscillations are increased by a factor 2-3 w.r.t. the current LHC.
  - *Potential seismic activity from Geothermie 2020 project:*
    - No comparison with beam data possible.
    - Simulations with current LHC collision optics show **rms orbit distortions > 120µm,** which could probably be survived.
    - For **HL-LHC optics** the simulation suggests (depending on the direction of the wave) an **enhancement** of a **factor ~2-3,**
      → which would most probably cause beam dumps.