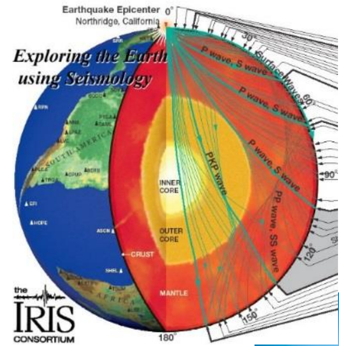
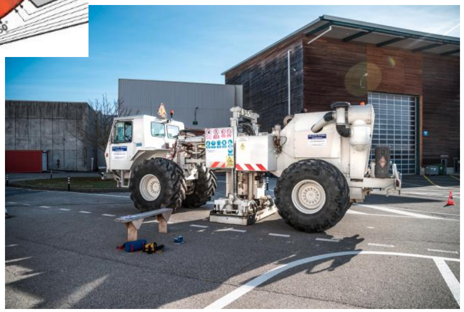
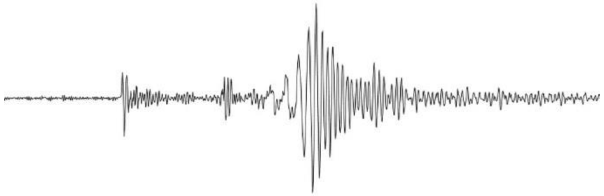




Lessons Learned from the Civil Engineering Test Drilling and Earthquakes on LHC Vibration Tolerances

N. Biancacci, L. Carver, P. Fessia, M. Gasior, M. Fitterer,
M. Guinchard, J. Osborne, M. Poehler, J. Wenninger



HL-LHC TC – Feb 2016

Outline

Introduction

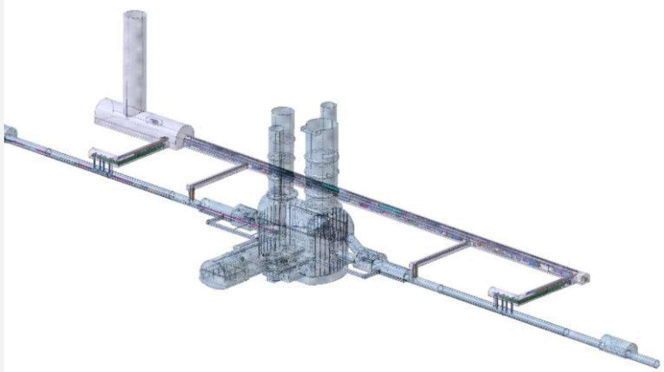
Vibration measurements

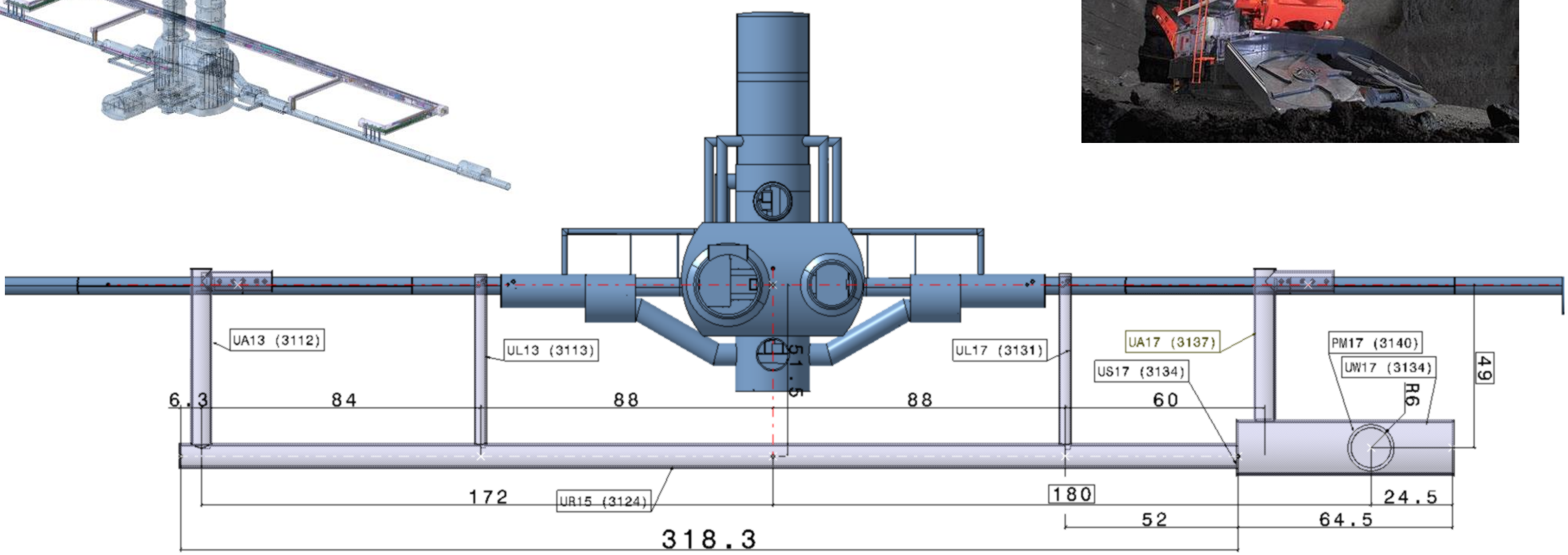
Geothermie 2020 and earthquakes

Conclusions

HL-LHC civil engineering

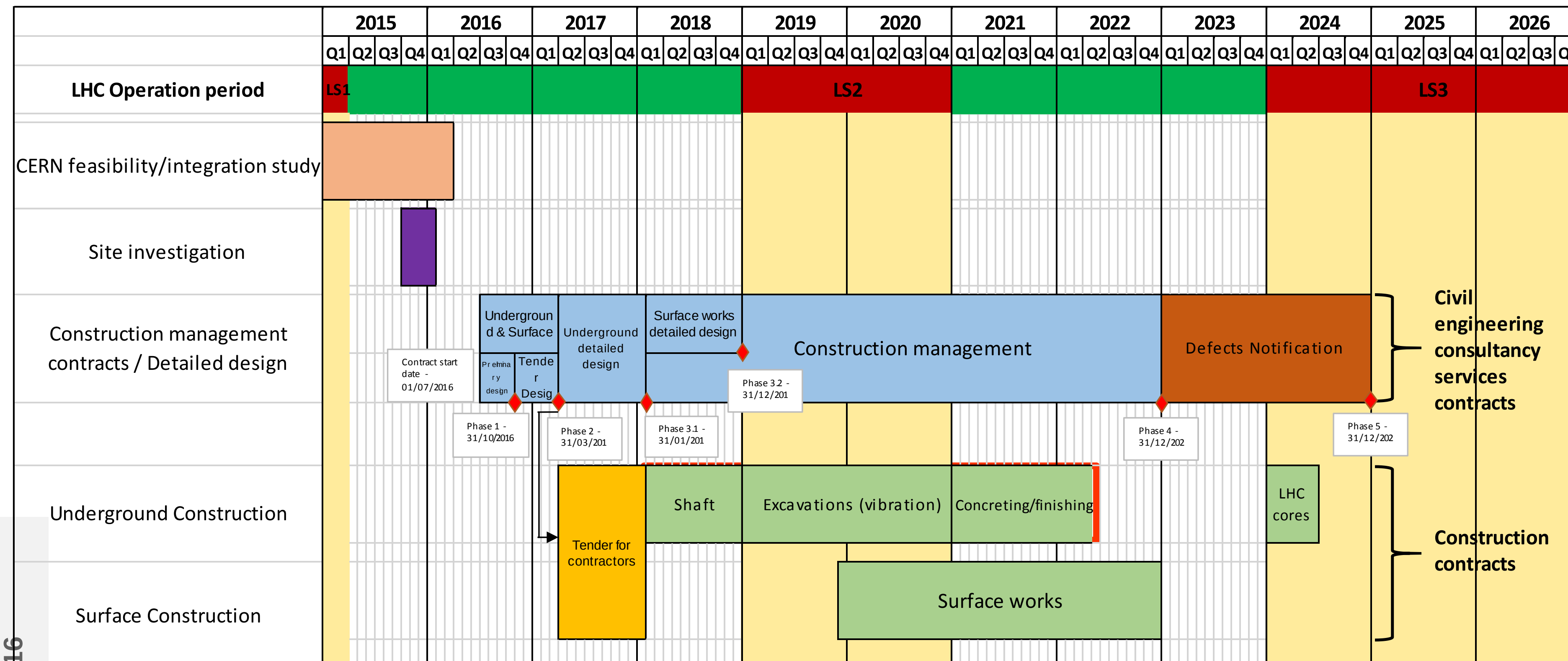
- The HL-LHC civil engineering work implies the construction of new access shafts, underground galleries and caverns in points 1 and 5.
  - *The distance between the new underground structures and the LHC tunnel is approximately 40 m.*
- Most of the work must be completed before LS3 for installation of HL-LHC equipment.





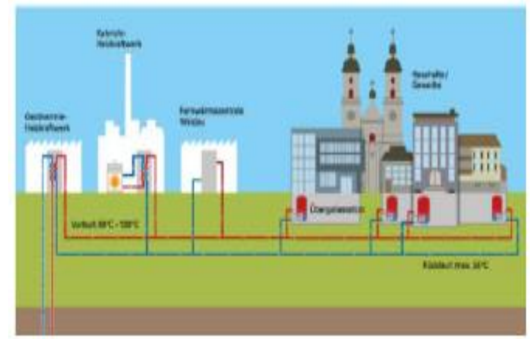
Civil engineering schedule

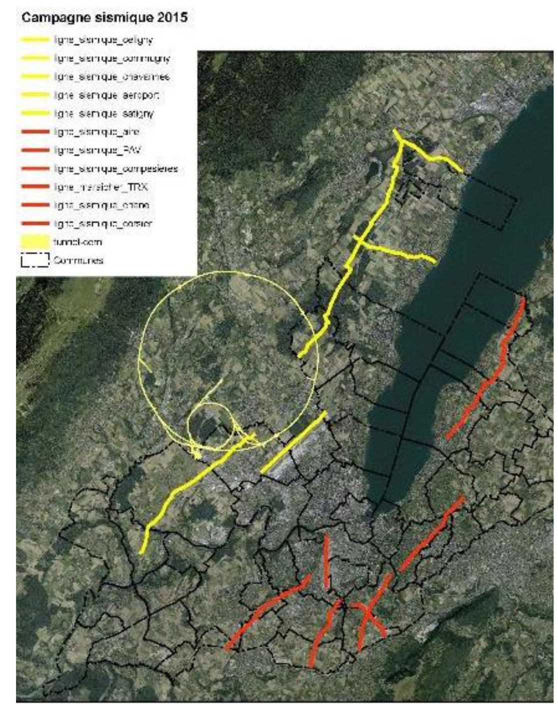
- The **vertical shaft excavation overlaps with the 2018 LHC run**, the distances to the triplet are 90-95m longitudinally + height. The underground design was modified to place the shaft as far as possible from the triplets.
- The horizontal galleries and cavern will be excavated during LS2.
- **Concreting / finishing work overlaps with LHC runs 2021 / 2022**.



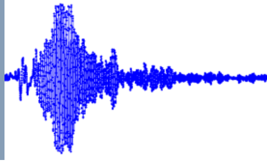
Geothermie 2020

- **Geothermie 2020** is a renewable energy production project by the Canton of Geneva to exploit geothermal energy for electricity production and heat generation. The project is managed by the SIG (Service Industriel de Genève).
- The project is currently in the prospection phase to identify suitable locations. Seismic studies were performed in 2015 – some of them overlapping the LHC tunnel.
  - *CERN could profit from the presence of a 'vibrating' truck to perform vibration tests in point 1.*
- Exploitation of geothermal energy may induce seismic activity (injection of high pressure water). **Earthquakes of magnitude ~2** have to be expected.
- CERN is associated to the study since the seismic activity may have detrimental effects on operation of the LHC.





Impact on LHC



- HL-LHC civil engineering:
  - *Performance degradation of the LHC due to beam offsets at IP, emittance growth from noise etc,*
  - *Beam aborts if vibrations exceed a critical threshold, leading to large orbit excursion and beam losses above BLM thresholds.*

- Geothermie 2020:
  - *Beam aborts if vibrations exceed a critical threshold, leading to large orbit excursion and beam losses above BLM thresholds.*

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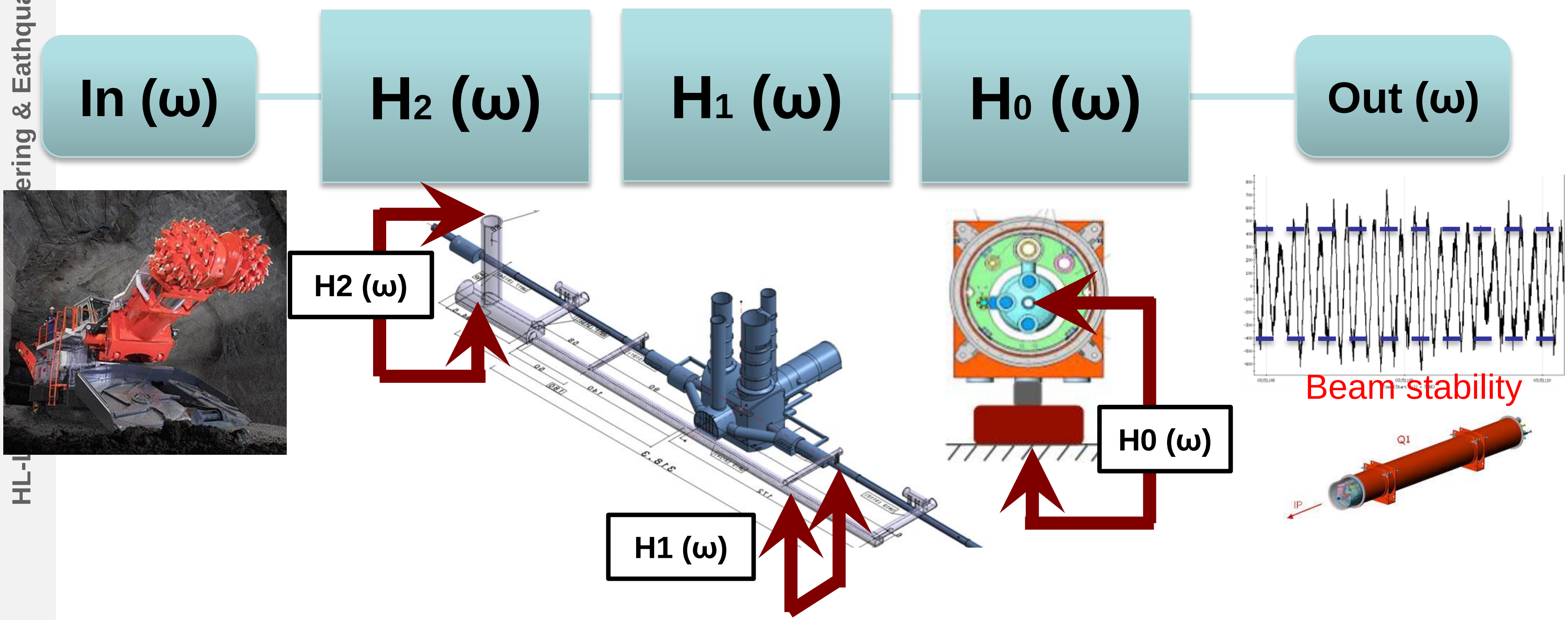
From noise to the beam

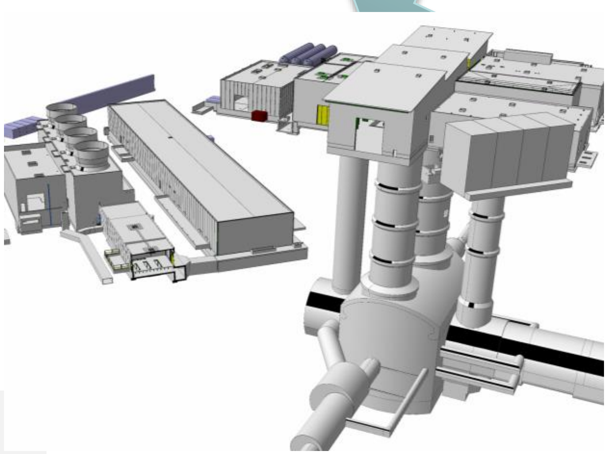
- To evaluate the impact of CE, the transfer functions of the ground (vertical H2, horizontal H1) and of the triplet support (ground to CM H0) have been determined in a number of test setups.
- Parasitic beam observations were made whenever this was possible.

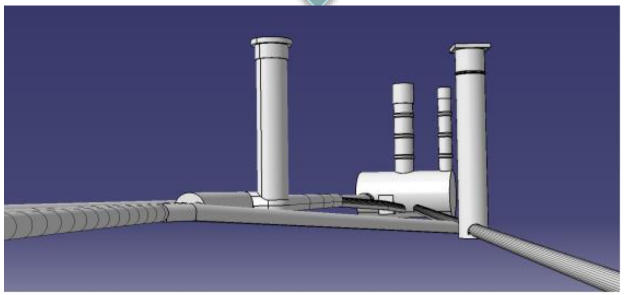


Measurements

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

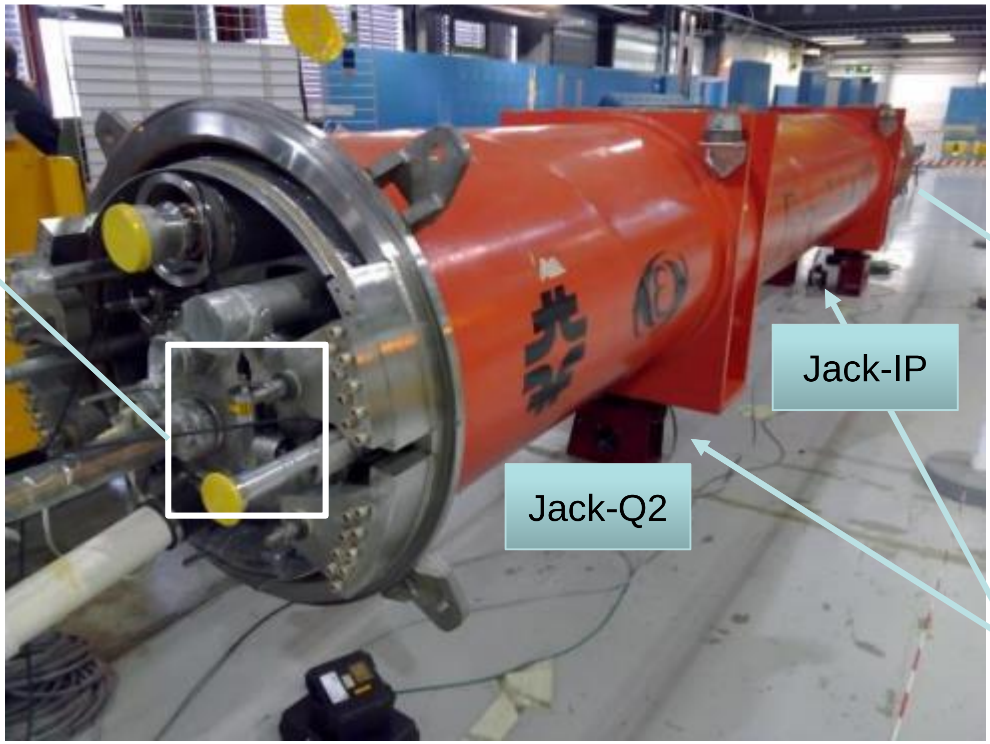
Measurements in ATLAS area (UL16/SR1)	Measurements in AWAKE area (TAG41/TT41)	Measurements at SM18 with Q1 triplet spare

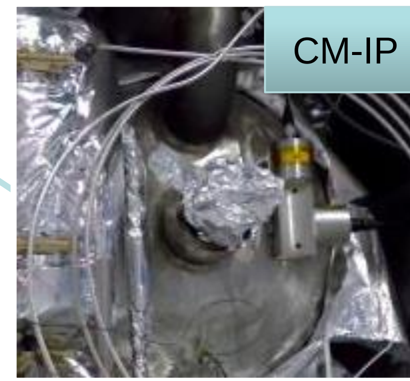


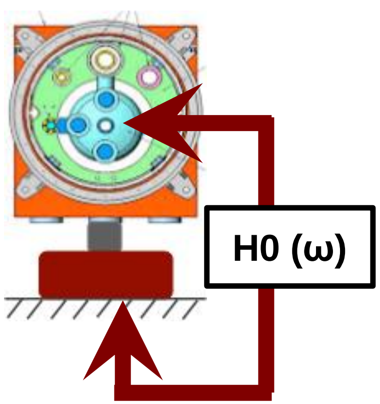


Q1 transfer function H0

- A spare Q1 magnet installed in stand alone at SM18 was used to determine the transfer function from the ground to the triplet CM.
- It was assumed that the interconnects have limited impact on the response.

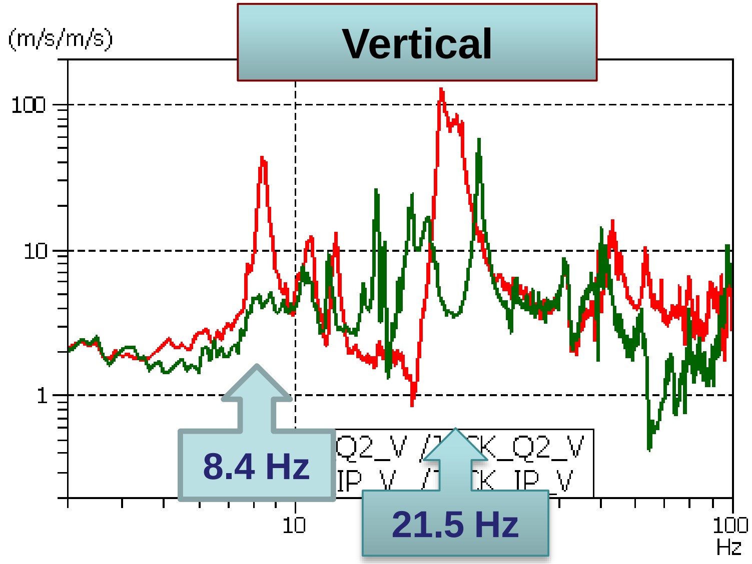


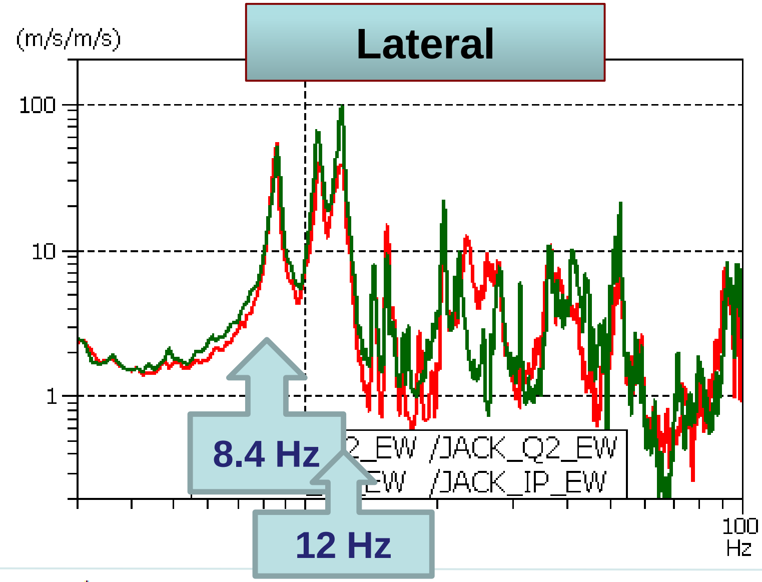


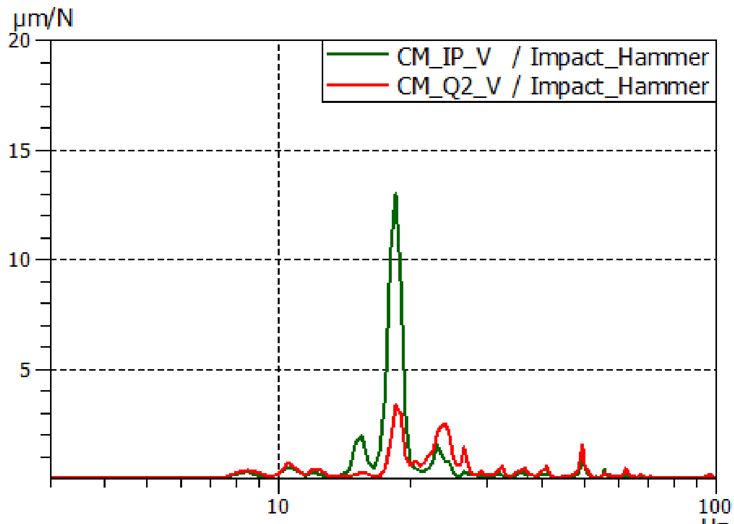


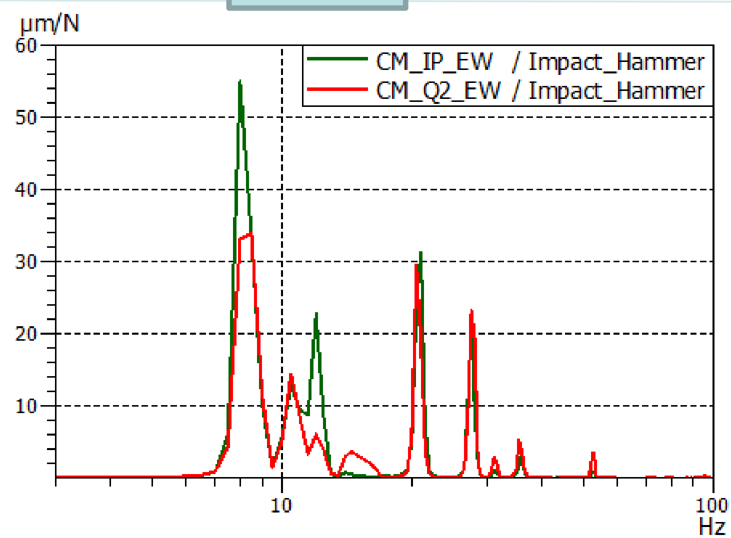
Q1 Transfer function H0

Strong **modes** (x100) at **21.5 Hz** (vertical), **8.4 Hz and 12 Hz** (lateral).



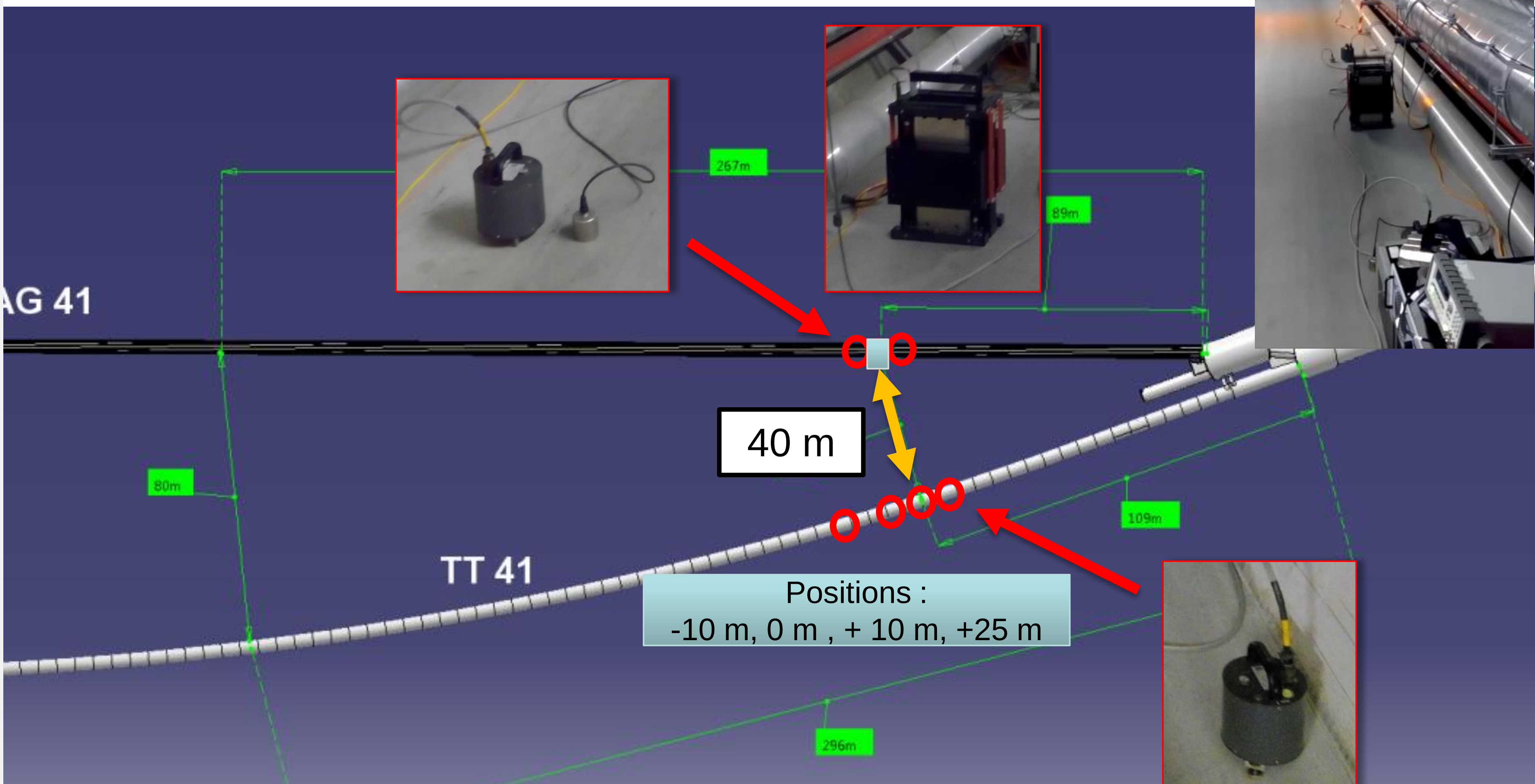






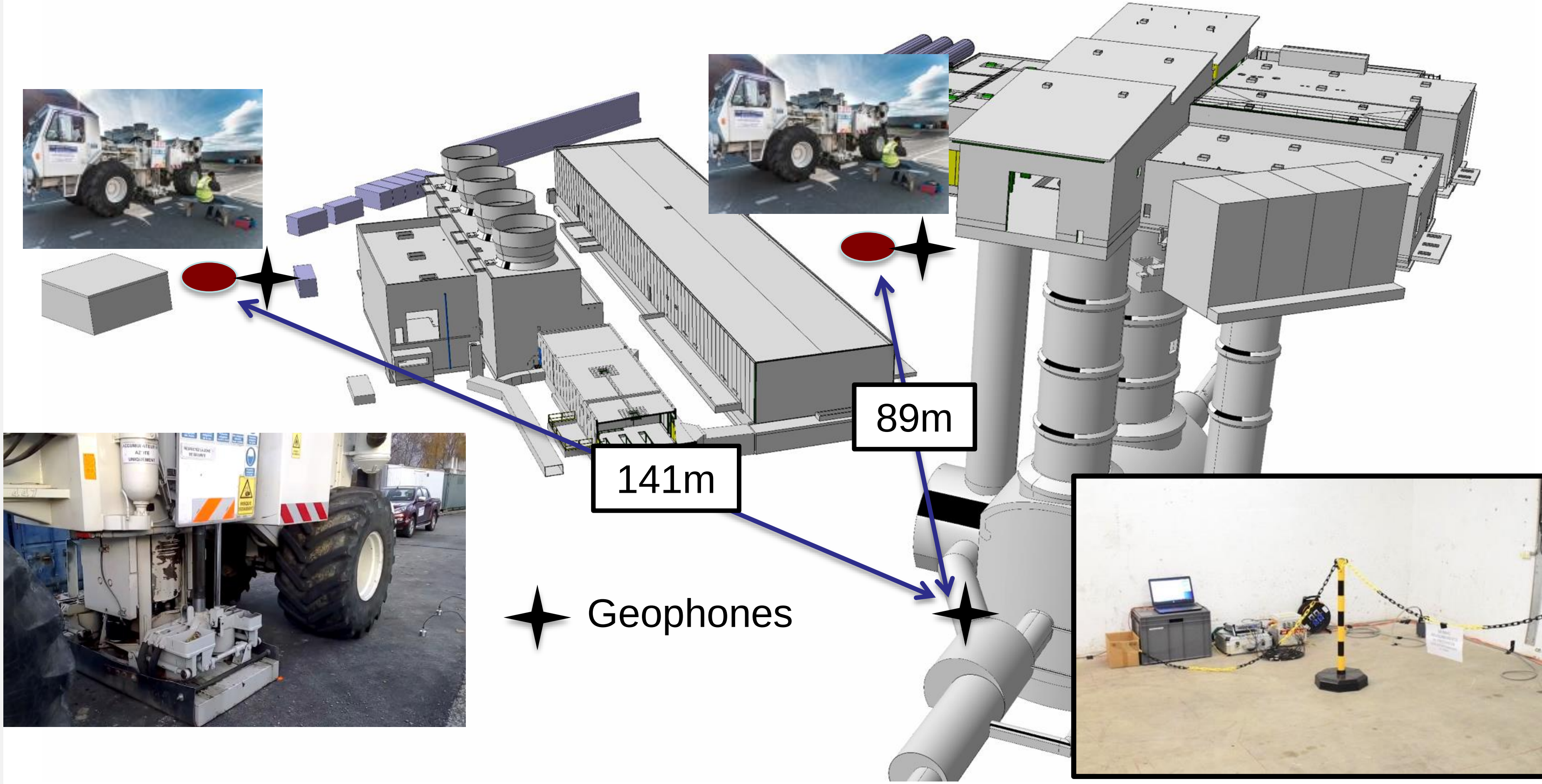
Setup for H1 (ω)

- Test (TT41/CNGS) with shaker - lateral distance of 40 m.



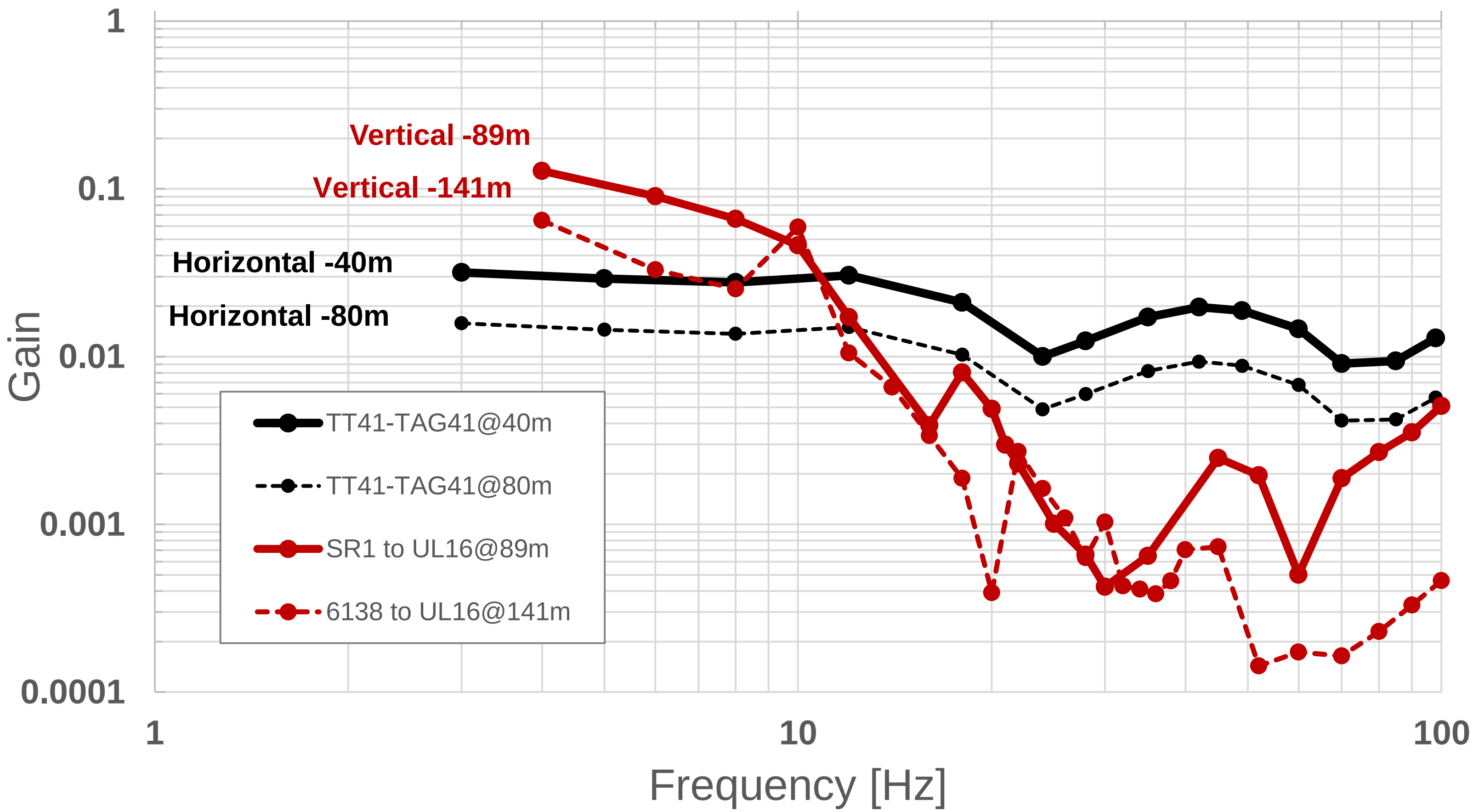
Setup for H2 (ω)

- Vertical transfer functions were measured at point 1 with a vibrating truck (**frequency range 4-100 Hz**). **Beam observations** were made in parallel (for 89m distance).



Transfer function results

- TT41 measurement dominated by shear waves, SR1 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**.



Triplet to beam

- The combined effect of the triplet magnets on the beams depends strongly on the coherence / wavelength of the vibration.
  - *The effect of other nearby LSS quadrupoles (Q4) is expected to be lower (β).*

For a displacement of +/-1 μm in horizontal plane (β* = 40 cm):

1. same displacement for all IT magnets in IR5:
   - IP: x(IP5,b1) = x(IP5,b2) = 1.17 μm
   - collimators: x_{max}(TCP,b1) = 3 μm

-> no separation of the beams
-> small residual orbit at collimators

2. alternated displacement of IT magnets in IR5:
   - IP: x(IP5,b1)= - x(IP5,b2) = -7.2 μm
   - collimators: x_{max}(TCP,b1) = 138 μm

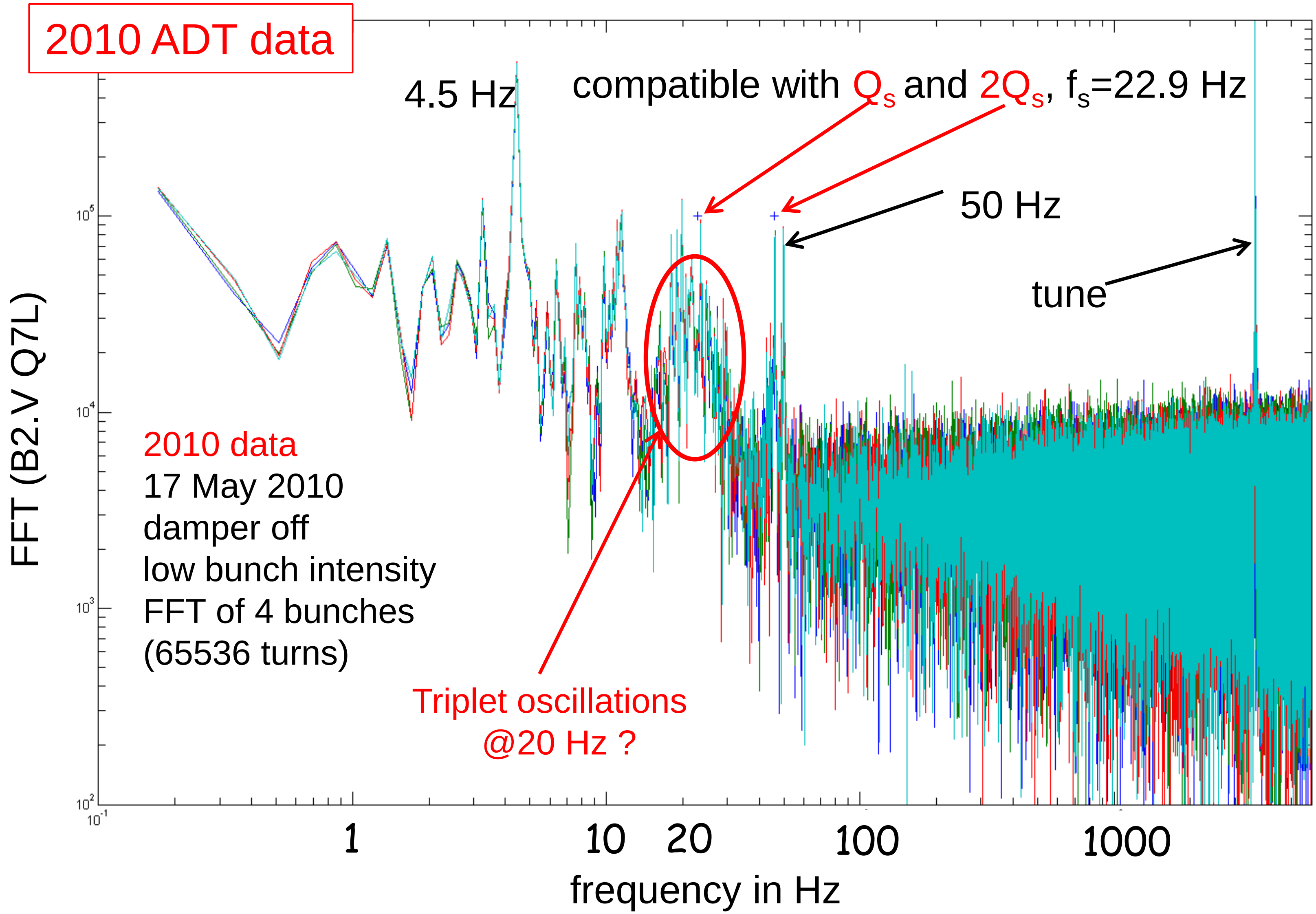
-> maximum = 14 μm separation at IP
-> residual orbit at collimators

3. "side-alternated" displacement of IT magnets in IR5:
   - IP: x(IP5,b1)= - x(IP5,b2) = -0.81 μm
   - collimators: x_{max}(TCP,b1) = 170 μm

-> small = 1.6 μm separation at IP
-> maximum residual orbit at collimators

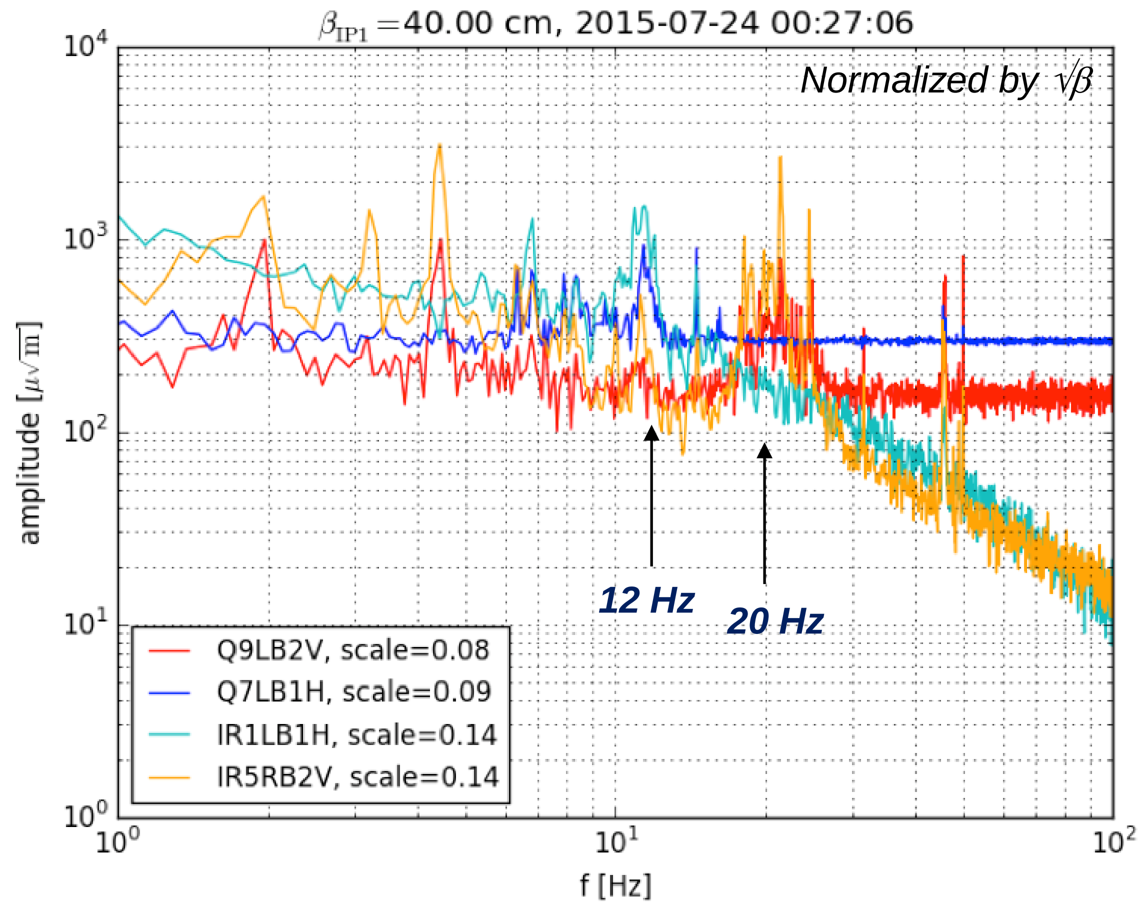
- Orbit shifts of > 100 μm at the TCPs can induce beam aborts.

Natural beam spectrum



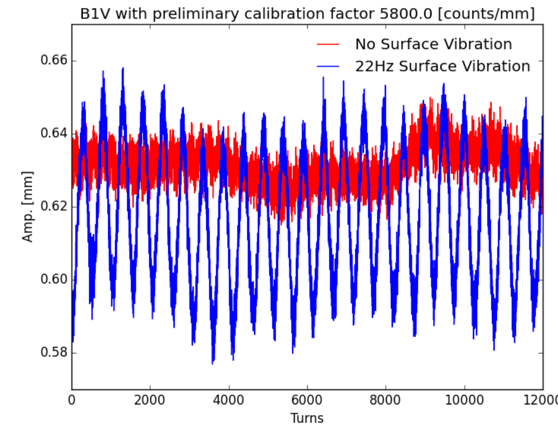
Natural beam spectrum

- Measurements performed in 2015 using the ADT and the high resolution DOROS BPM electronics at the Q1's confirm the presence of activity in the frequency range of the triplet resonances.
  - *Amplitudes at on the scale of ~μm.*

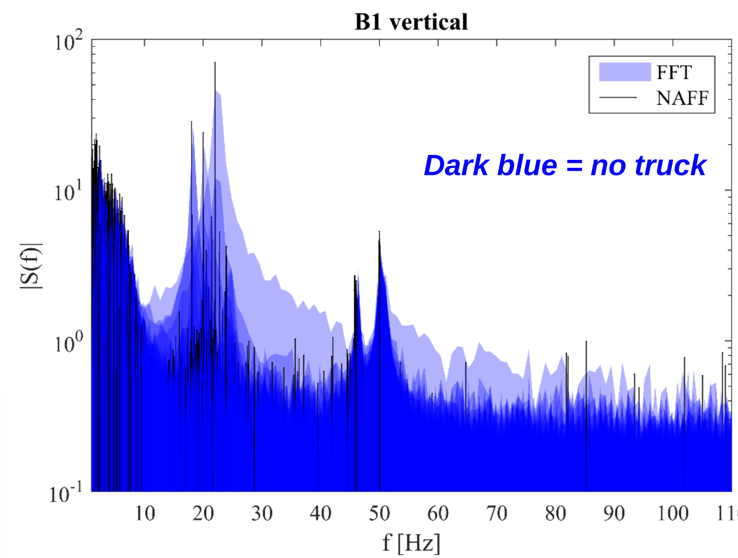


Vibrating truck impact

- 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.*



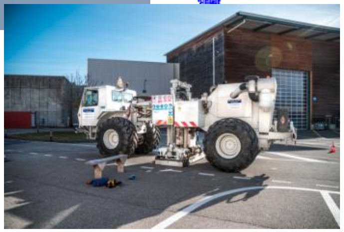
- Measurements results:
  - *Beam oscillations were only observed in the vertical plane ⇔ truck location.*
  - *Beam oscillations were only observed for* ***vibration frequencies of 18-22 Hz*** *– consistent with the triplet resonances.*
  - *Observed B1/B2 amplitude ratio of ~2.5 implies that the different 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.*

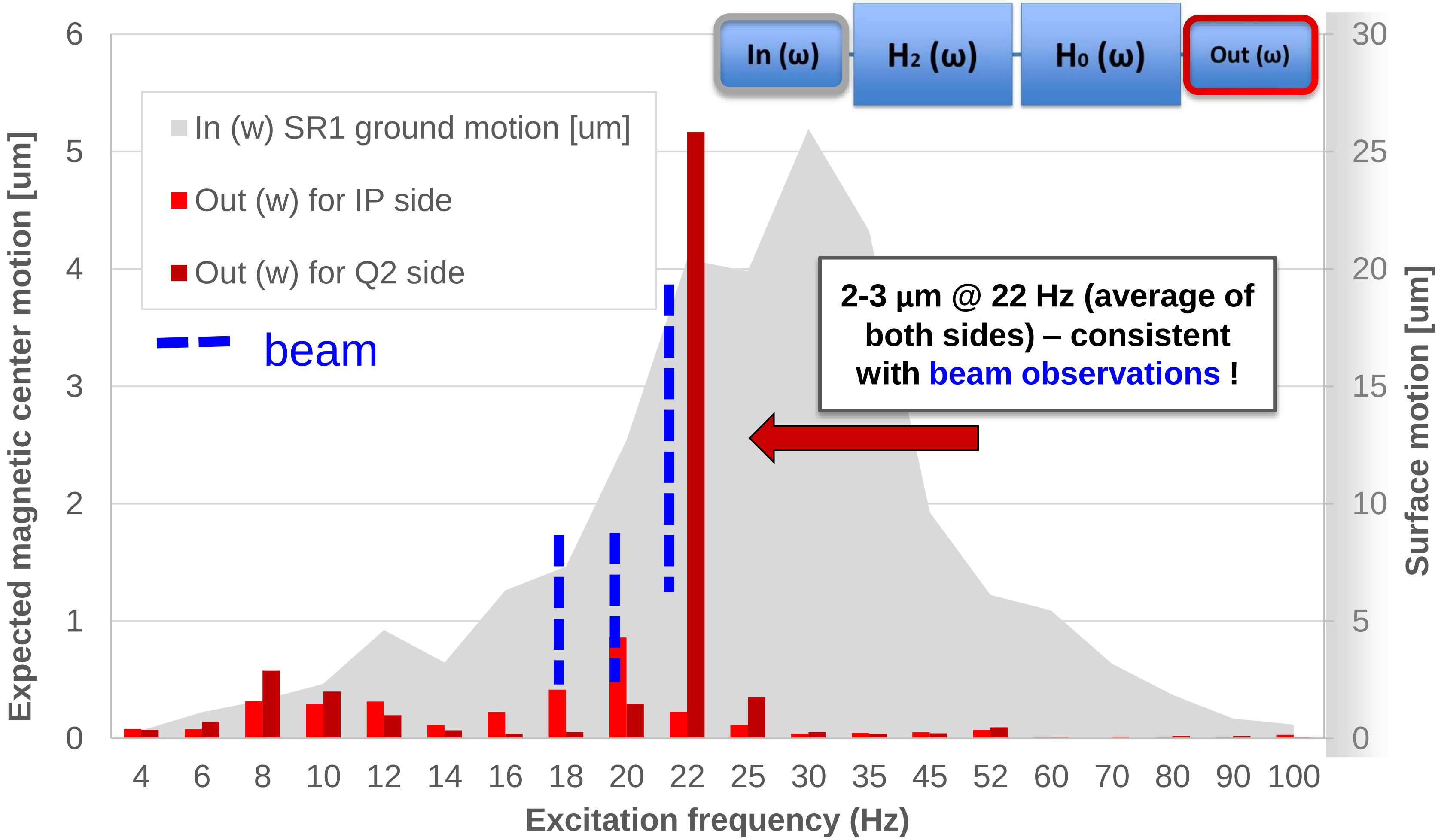


The observations are consistent with the triplet resonances that enhance the vibrations by a factor >> 10

Truck → triplet predictions

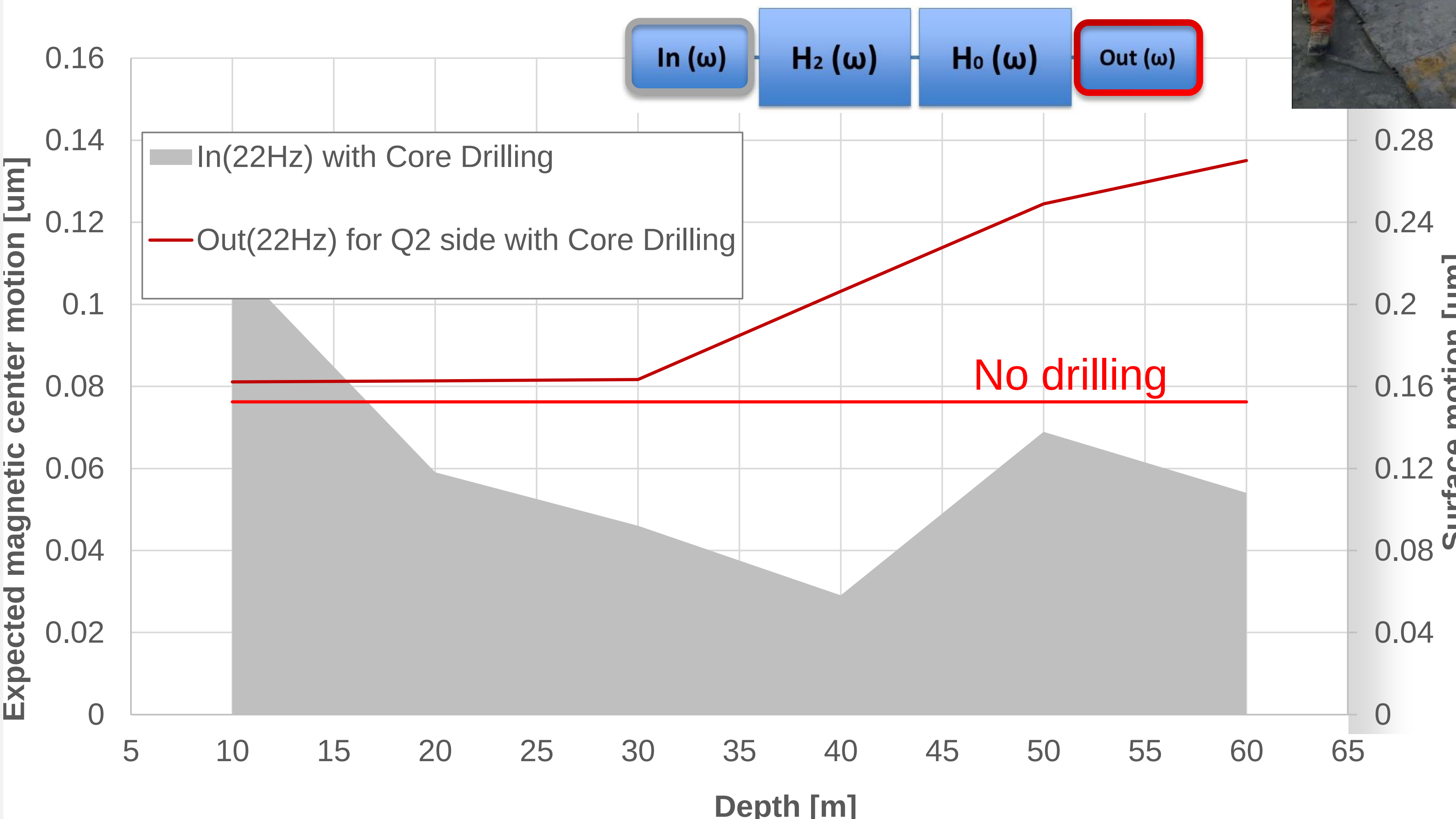
- Expected motion of the triplet magnetic center during truck tests.





Core drilling → triplet predictions

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



Active beam feedback

- The current LHC orbit feedback is based on a Linux RT server that operates effectively at 12.5 Hz (up to 50 Hz possible).
  - *Closed loop bandwidth ~0.2 Hz.*
  - *Cannot be scaled to a bandwidth of 20-30 Hz.*
- To actively fight triplet induced beam oscillations at ~20 Hz, a fast orbit feedback operating $\geq$ 1 kHz would be required:
  - *High accuracy local BPMs in LSS1+5 $\rightarrow$ DOROS ~ Ok,*
  - *Normal conducting COD between triplets & Q5 & associated PC – must be > 100 times faster than other LHC CODs, BL $\leq$ ~0.2 Tm (5-10 μm triplet CM amplitudes).*
  - *PC access cannot go via WorldFip (50 Hz) $\rightarrow$ $\geq$ 1 kHz link,*
  - *Controls logic in FPGA-style,*
  - *Dedicated network for data exchange (BPM-controller-PC).*
- Such a system could be feasible, but a detailed study is required (if desired) to assess its performance.

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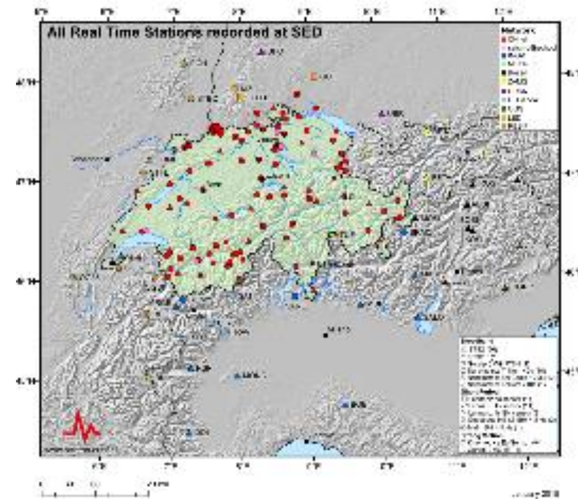
Earthquake monitoring

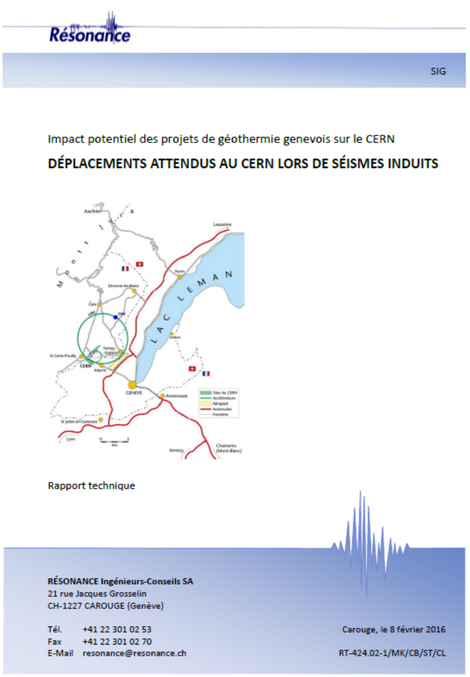
- The Geneva area has a very low seismic activity, **monitoring of the regional seismic activity is poor** (from the Swiss side).
- In the context of the Geothermie 2020 project Geneva Univ. has been mandated to build a network to monitor the natural seismic activity down to magnitudes ~1.5.
  - *Understand the natural seismic background.*



- On the CERN site a **network of geophones** (EN-MME) will be installed in the LHC **service areas** of all points **~ summer 2016**.
  - *Continuous monitoring of ground noise and earthquake activity.*
  - *Data from earthquakes will be transmitted to the Swiss central seismic institute at located at EPF Zurich to correlate with other instruments.*
- Operational usage of the **DOROS** (Q1 & coll BPMs) turn-by-turn data (synchronized !) and of the **ADT observation** box data will provide better monitoring of the beam oscillations for the coming run.
- **Precision Laser Inclinometers** installed in the ATLAS cavern also provide high resolution information on earthquakes.

Geothermie 2020

- A report on the possible impact of earthquakes was recently published by the engineering company Resonance SA (mandated by SIG).
- The expected earthquake magnitudes may reach up to ~3, but most earthquakes are expected to be limited to magnitude ~2.
- The **CM movements are predicted to reach ~1-10 μm for magnitude 2 earthquakes** (a factor 10 more for magnitude 3).
    - *Triplet CM resonances were taken into account.*


Résonance

SIG

Impact potentiel des projets de géothermie genevois sur le CERN

DÉPLACEMENTS ATTENDUS AU CERN LORS DE SÉISMES INDUITS

Rapport technique

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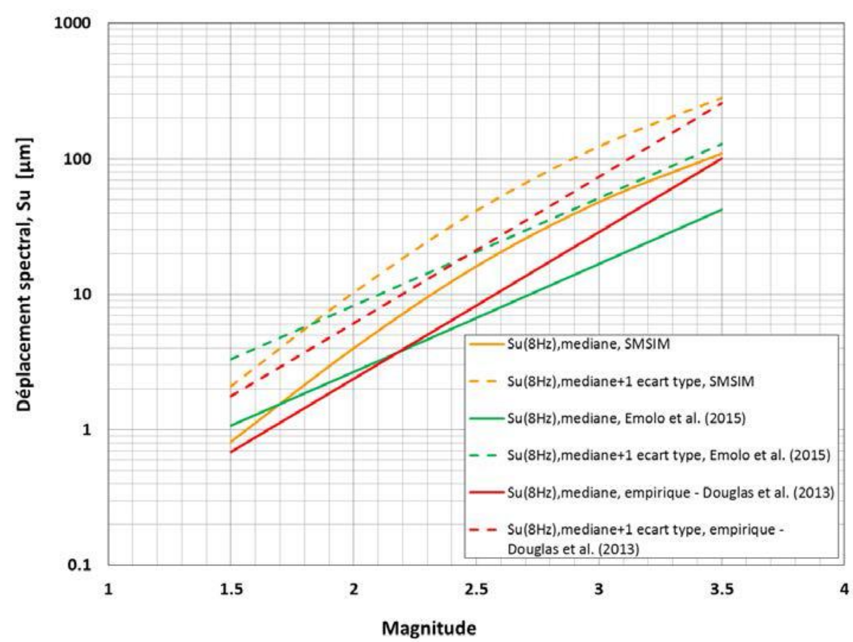
Carouge, le 8 février 2016

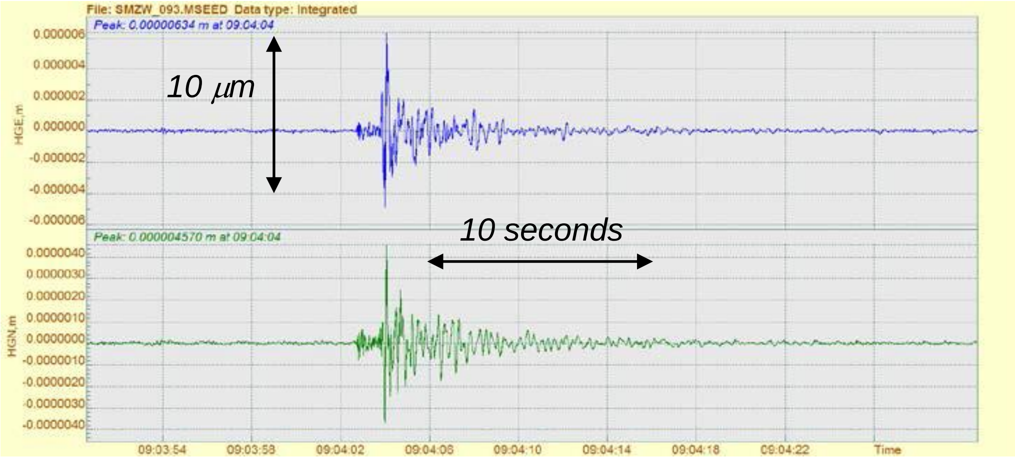
RT-424.02-1/MK/CB/ST/CL



Geothermie 2020

- The earthquakes are expected to be very short (~ second), so the triplet CM will not have time to enter in full resonance.
- The earthquake rates are difficult to predict, but in the initial phase of exploitation **hundreds of earthquakes** may be generated over few months !
  - *Experience from other geothermal projects in Switzerland (Basel).*

Example of an earthquake recorded during geothermal exploitation tests in Basel In a geological setting similar to the LHC tunnel

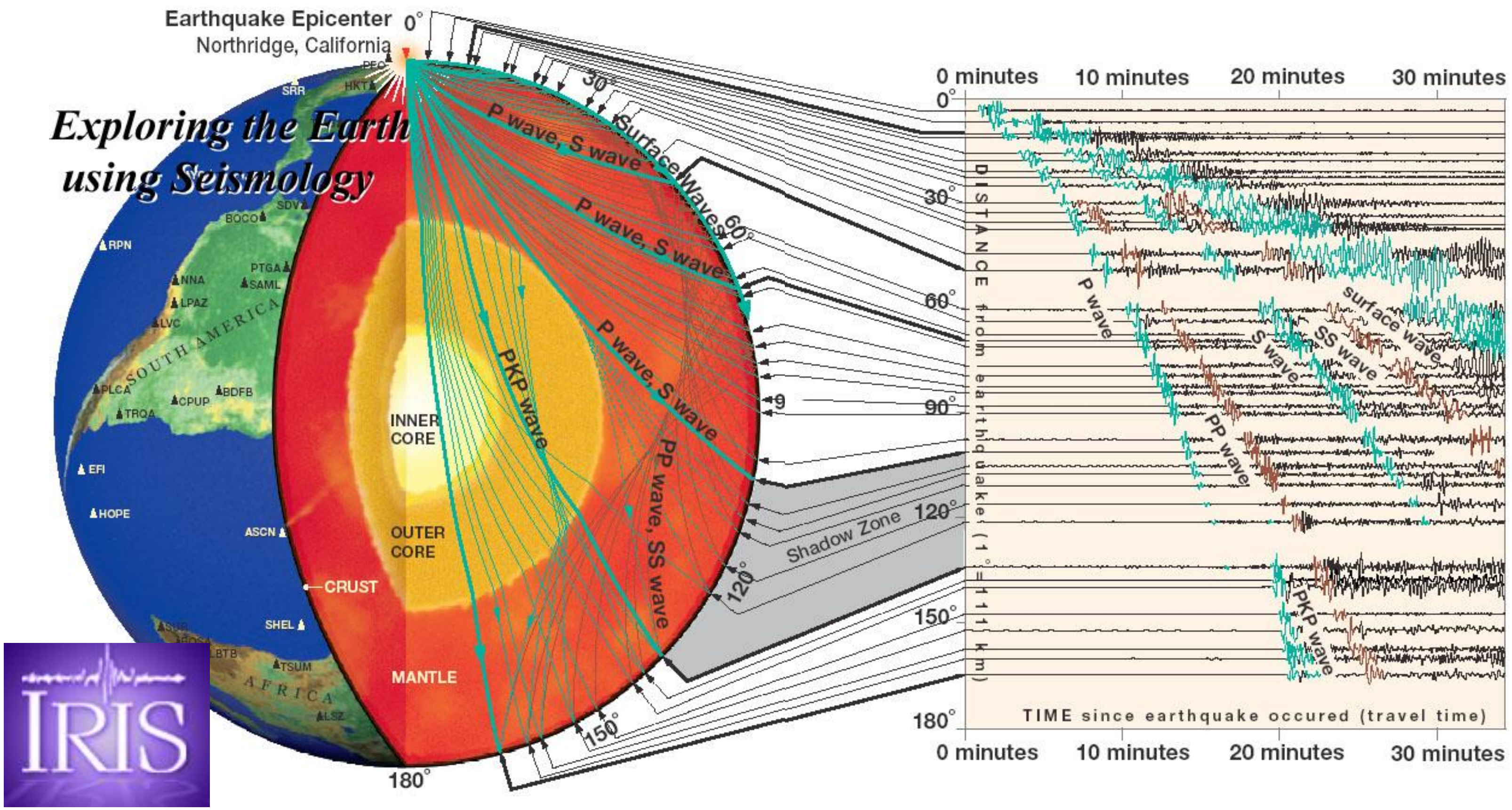


- An important recommendation of the report by Resonance SA:

The beginning of exploitation should coincide with a Long Shutdown of the LHC !

Waves from earthquakes

Different 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 – also at the LHC.



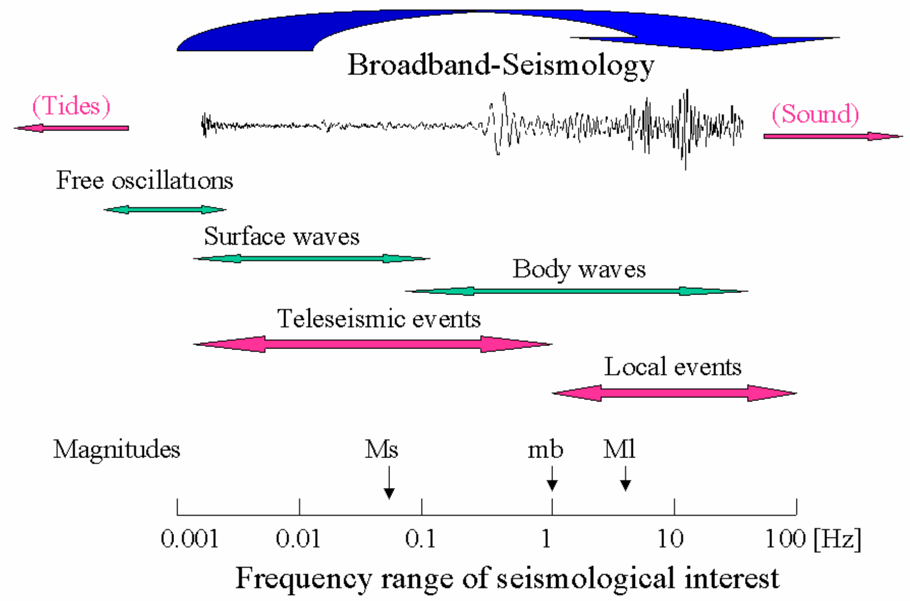
L. Braille (Purdue U.) / The IRIS (Incorporated Research Institutions for Seismology) consortium

Earthquakes & LHC

- 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.

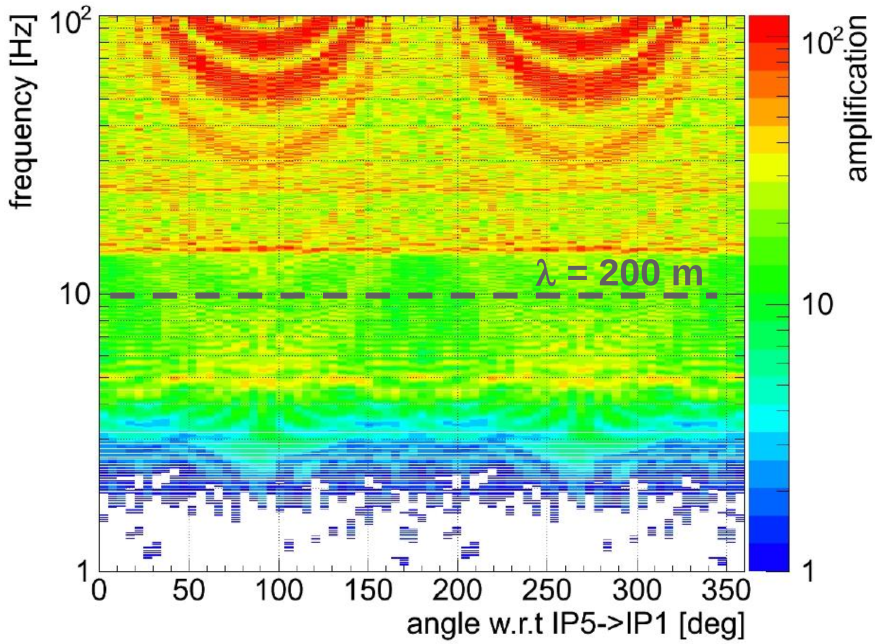


LHC ring response

- 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.

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

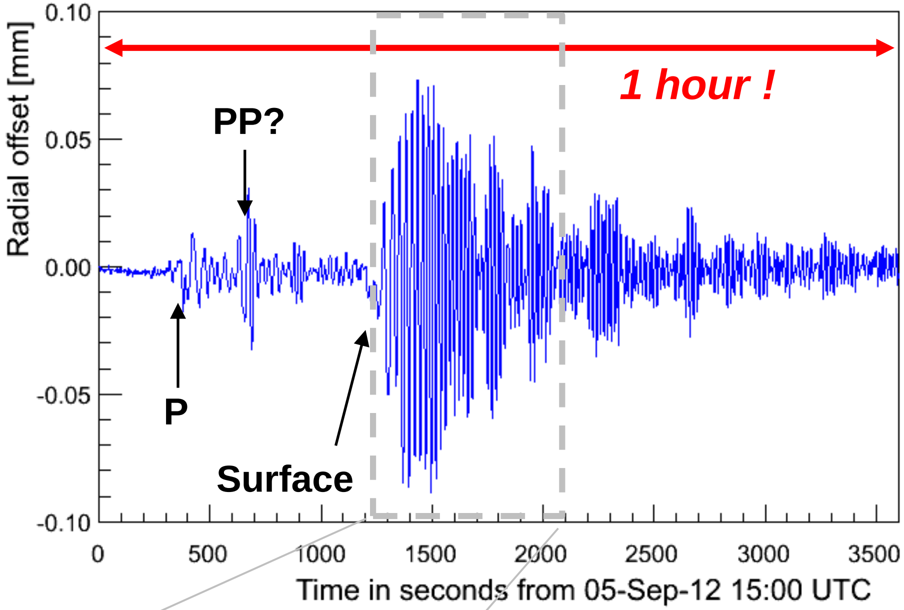
- The response of the LHC to ground motion waves depends on wavelength and direction, the **amplification can reach a factor ~100** for waves travelling along the LSS in IR1 and IR5 (direction NW →SE).
    - *Large amplifications are associated to resonant response of (parts of) the LHC.*

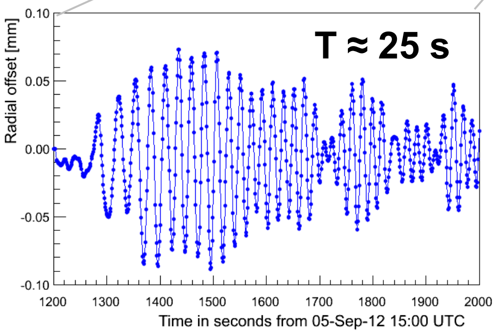


R. Steinhagen, CERN Thesis 2007-058

Costa Rica earthquake - 2012

- A **magnitude 7.6** earthquake in Costa Rica (05/09/2012 @ 14:42:10 UTC) 'struck' the LHC in **fill 3032** during stable colliding beams.
  - *Arrival of the first waves at CERN ~15:06 UTC.*

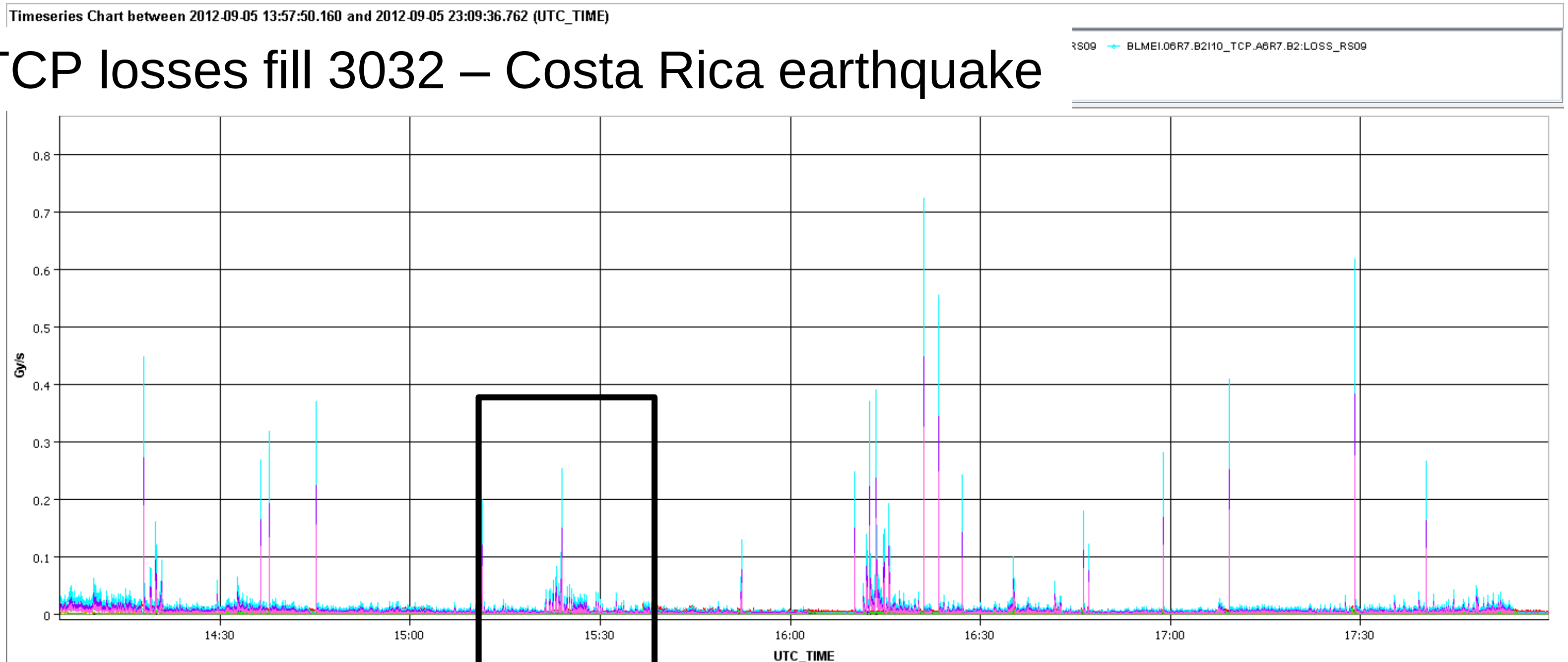


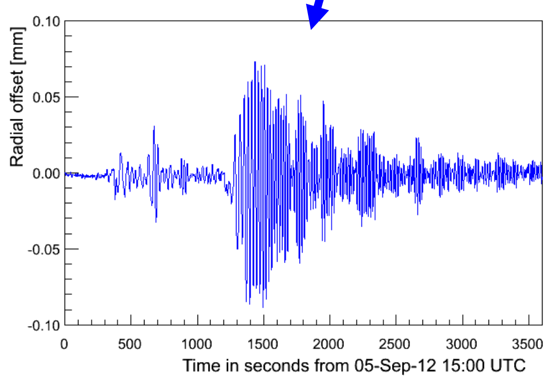


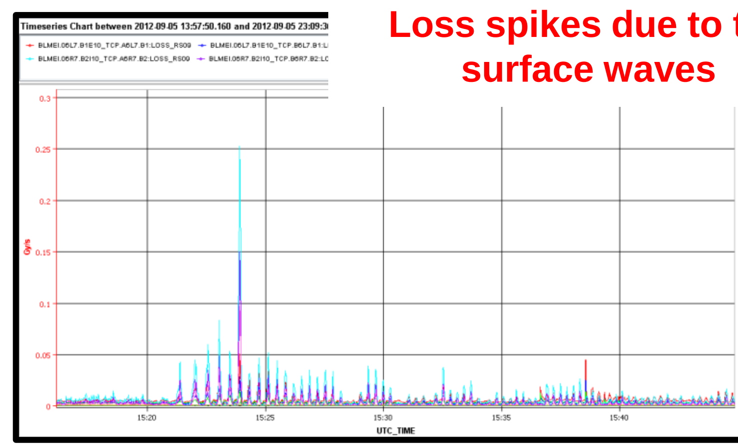
- The arrival of the different waves can be observed on the radial beam position – equivalent to largest tides.
  - ***Barely visible impact on luminosity*** *(6×10^{33} $cm^{-2}s^{-1}$) - high luminosity / intensity fill !*
  - *Loss spikes, but smaller than many others in that fill !*

Costa Rica earthquake - losses

TCP losses fill 3032 – Costa Rica earthquake



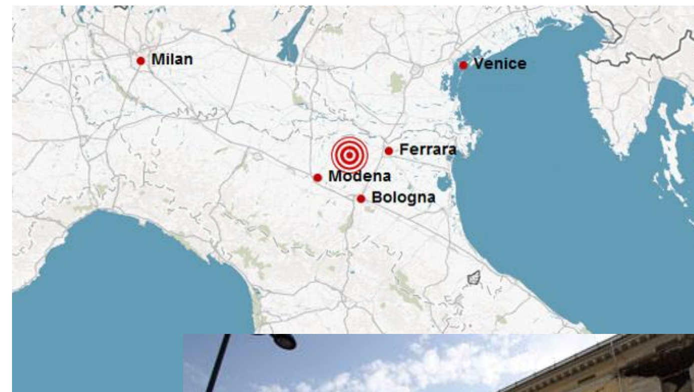


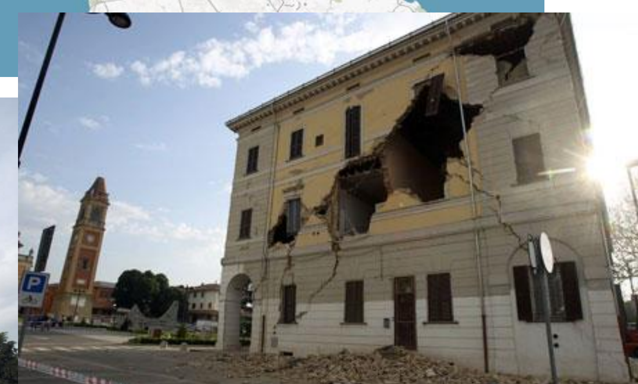


Loss spikes due to the surface waves

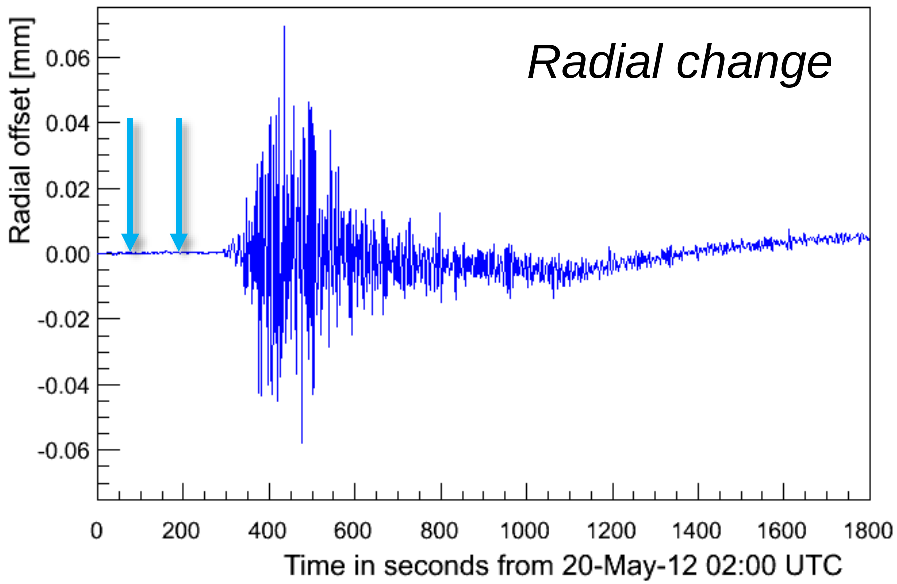
Italy earthquake – May 2015

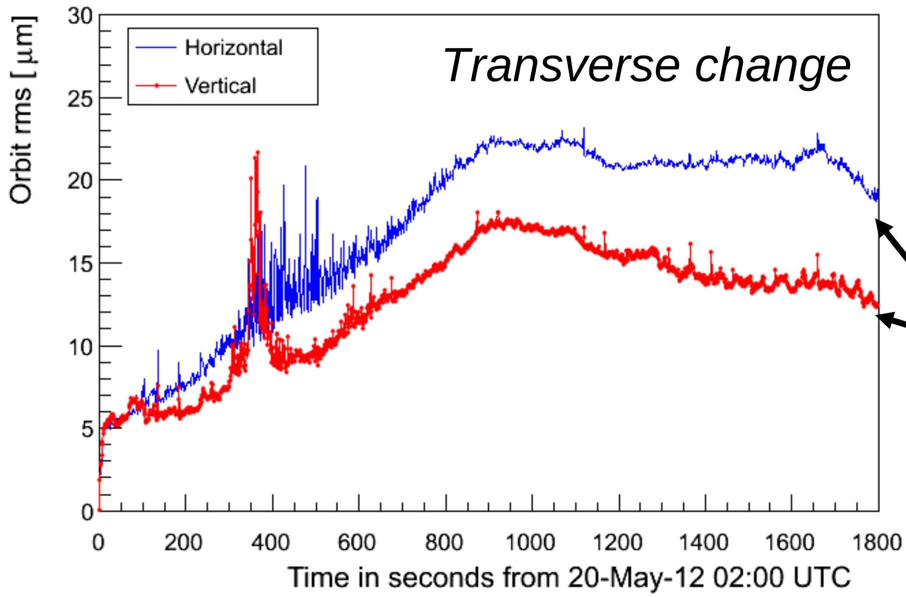
- Two consecutive earthquakes with **magnitude 6** struck Northern Italy on 20/05/12 at 02:01(03) UTC while fill **2646** was in stable beams.
- The impact of the earthquake was clearly visible on **losses, luminosity and orbit**, but not noticed at the time (4 AM local time).





Italy earthquake – orbit response

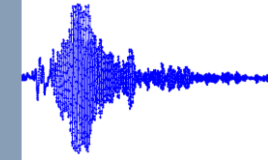




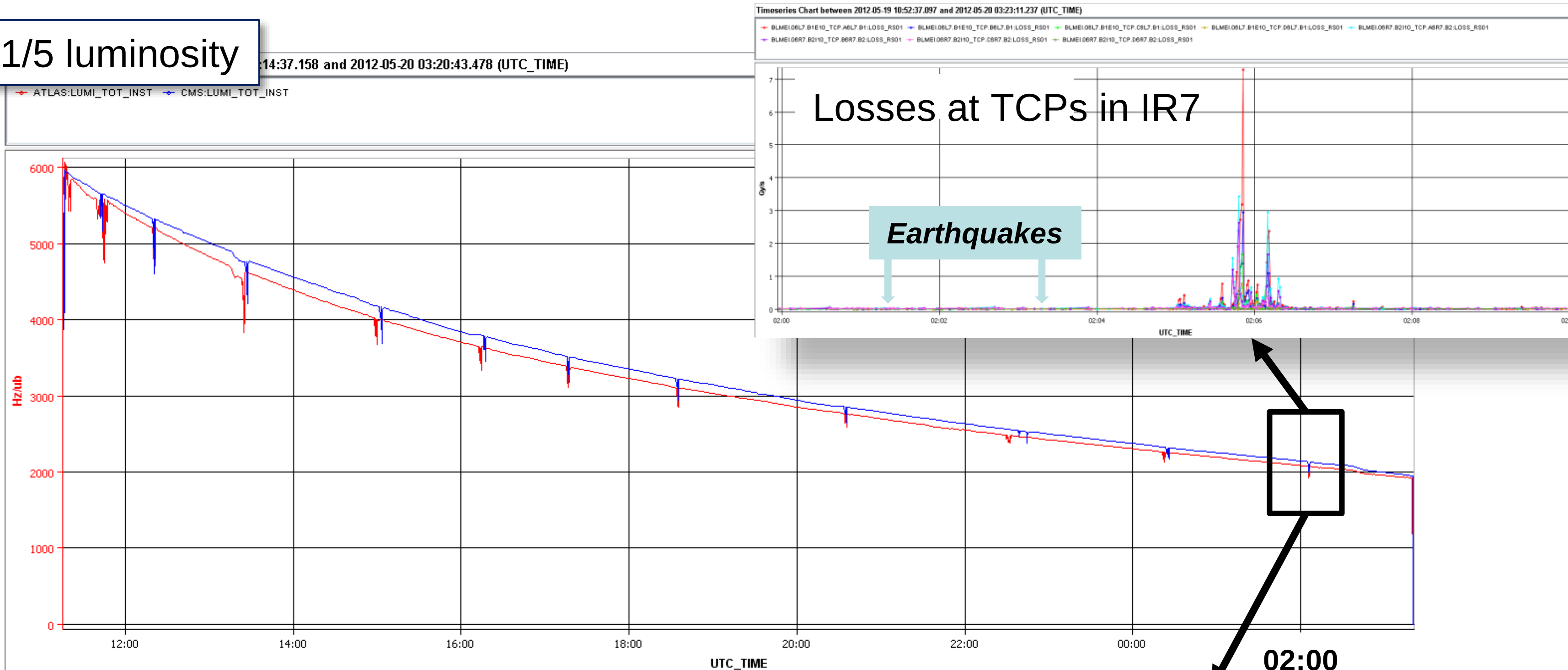
- The spectrum of this ‘nearby’ earthquake extends to much higher frequencies.
- There is a strong radial and a significant transverse response.
- Radial activity is visible a long time after the main perturbation, while the duration of the transverse activity (v plane) is much shorter !

RMS drift due to the BPM electronics(temperature), ground motion, BPM noise…

Italy earthquake – luminosity



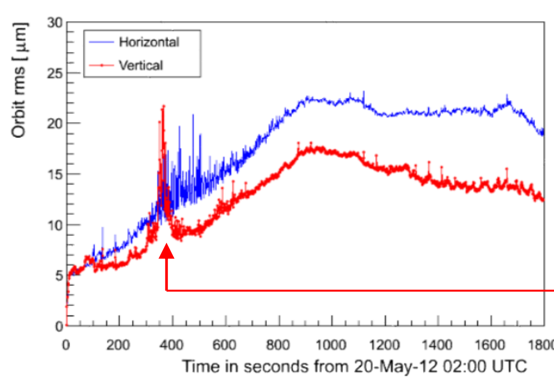
IR1/5 luminosity

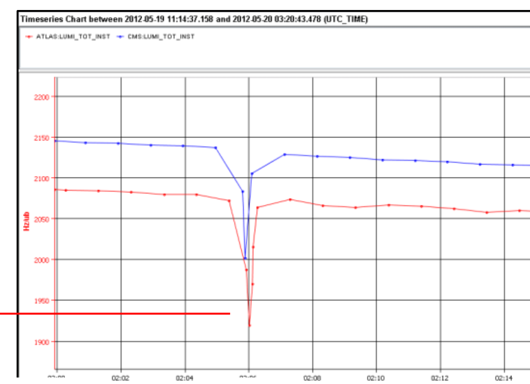


Visible drop in luminosity (7%)

TCP losses reached **~10% of dump threshold** (4 TeV).

~5x10^{12} protons lost per beam, ~0.4% of the total intensity.





Introduction

Vibration measurements

Geothermie 2020 and earthquakes

Conclusions

Earthquake - summary

- **Large earthquakes** (M ~6-8) have a **clear impact on LHC** even at a large distance from the LHC ring. **We have survived all events** (maybe with some luck !).

Location	Date	Mag	LHC	ΔR (μm)	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

- **Nearby small earthquakes** (M ~3 in Valais) **have not been observed**.
- A **network of geophones and improved beam measurements** will be used to monitor ground motion and low magnitude natural earthquake activity. This should help us assess better the possible impact of earthquakes induced by geothermal energy production.
- **Tail cleaning** (with e-lenses etc) could mitigate the impact of Earthquakes.

Vibrations - summary

- Both SM18 and in situ (pt 1) 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.
  - *We could consider a feasibility study of a fast beam orbit feedback system.*
- **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). **The source spectra will be measured to improve the predictions**:
  - *The rotating header machine (excavations),*
  - *The hammer and excavator to be used for the shaft,*
  - *The concrete pump to be used to concrete the tunnel during Run III.*
- The mechanical design of the CM for the HL-LHC triplet should try to take into account the observations made on the existing triplets.

- LHC ground motion spectrum (a) and integral (b).

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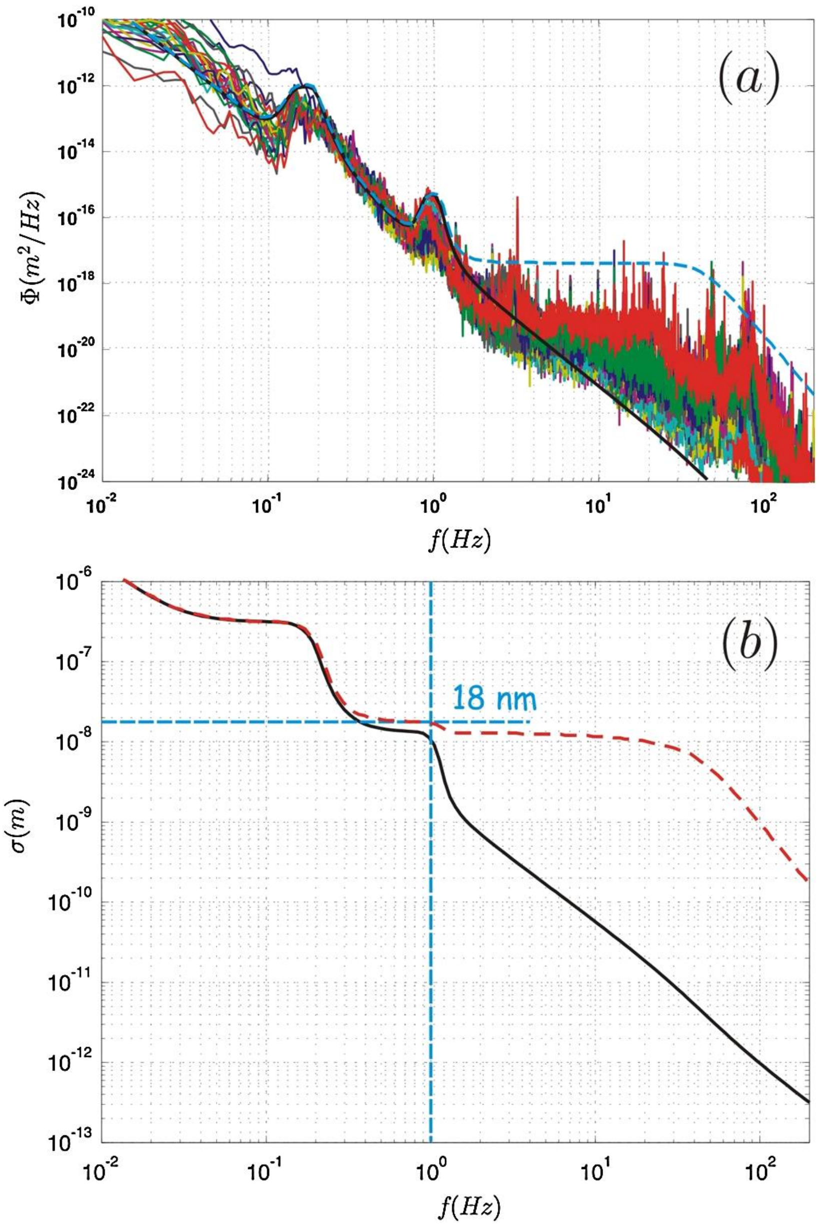

Equipment

- Heavy seismic vibrator truck used like known excitation source

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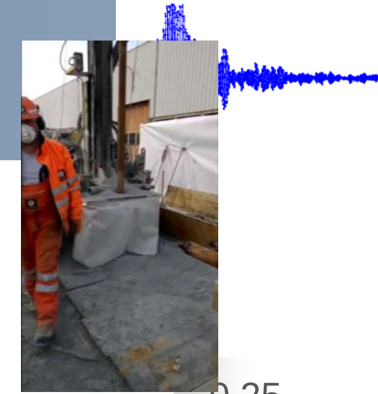
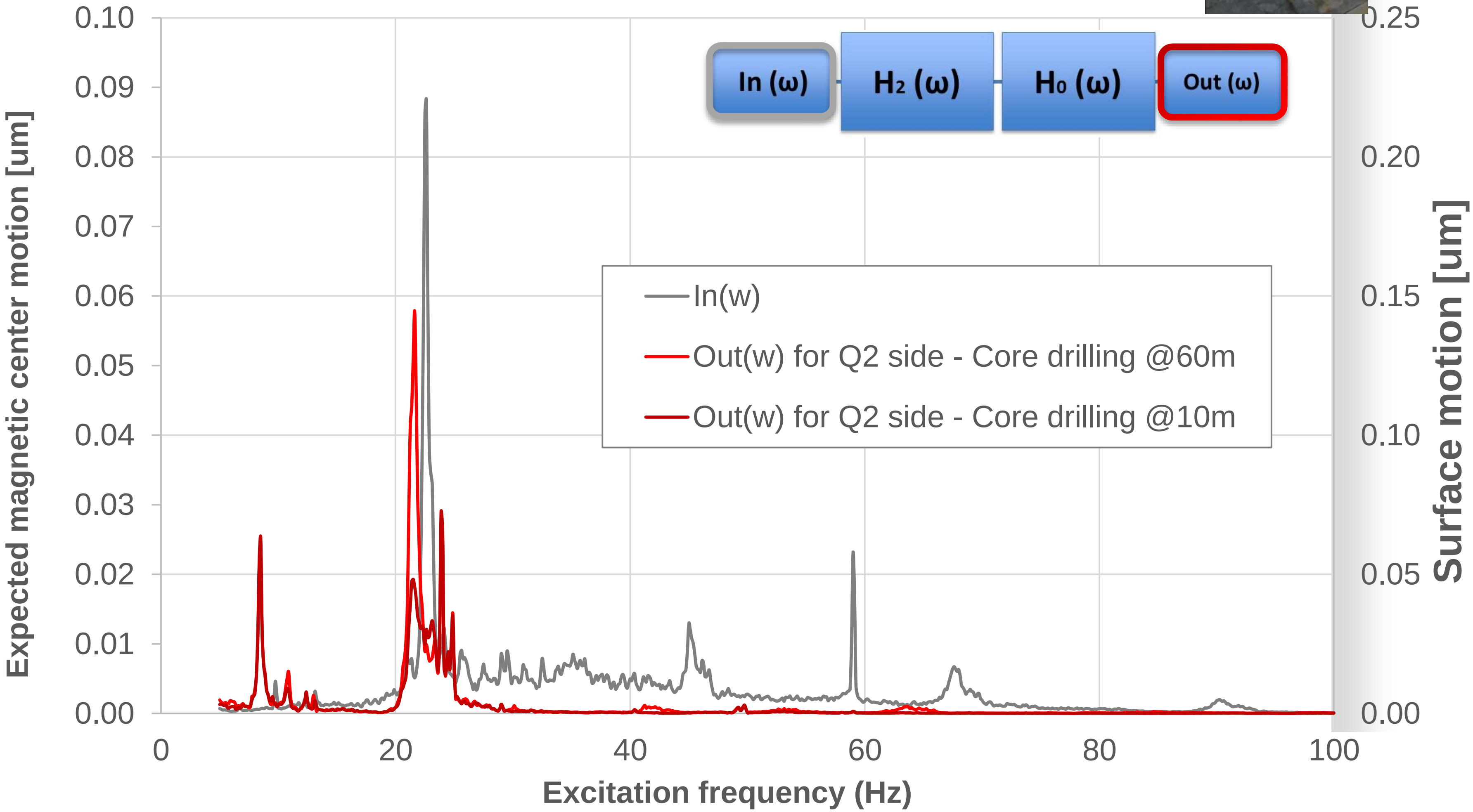
SIG

Vibrator IVI MARK 4	
Truck weight	20 tons
Excited frequency	4 up to 100 Hz
Excitation type	Fixed and sweep sine
Force injected	17 kN peak

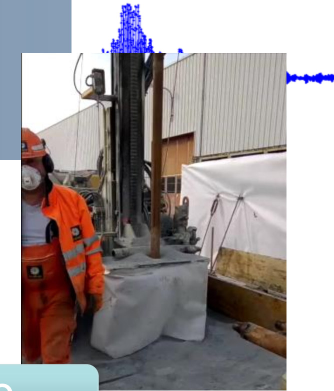
Core drilling → triplet predictions



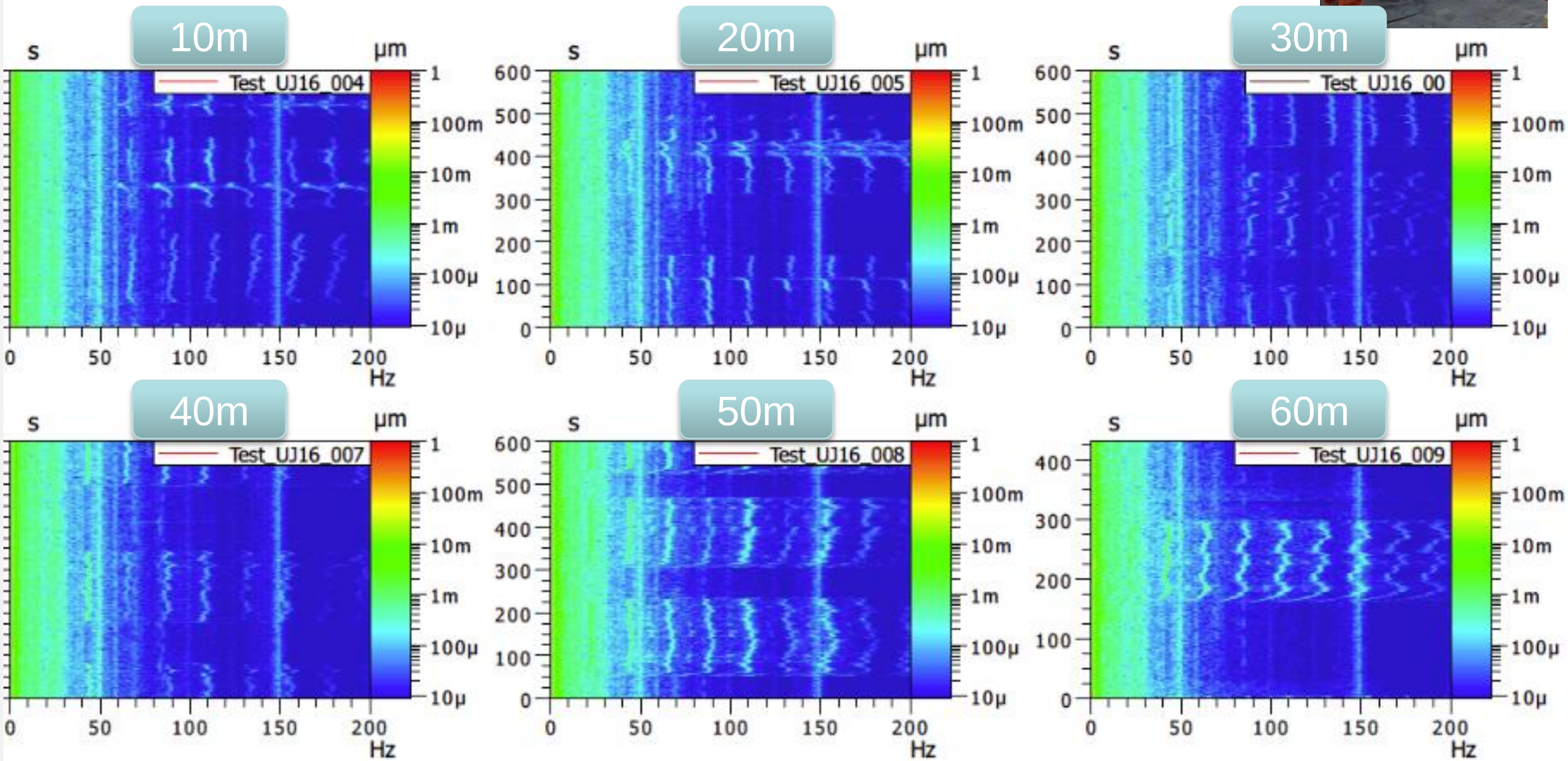
- Expected motion of the triplet magnetic center : < 0.1 μm



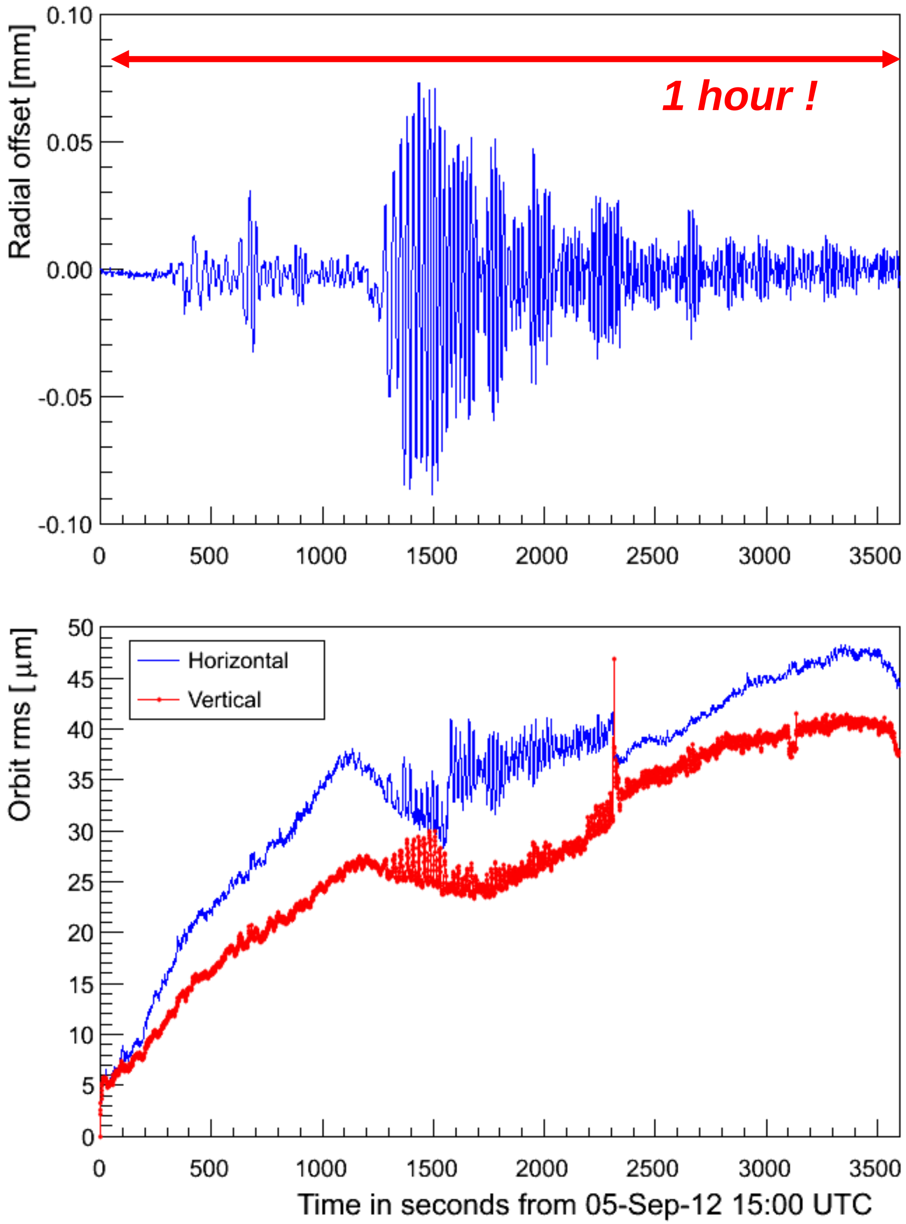
Core drilling



- LHC ground motion as a function of the core-drilling depth (point 1).

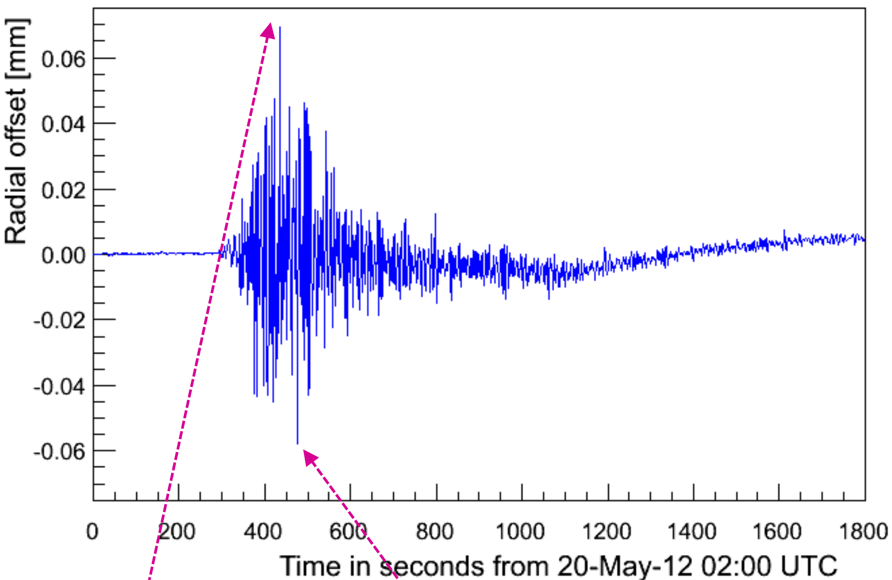


Costa Rica earthquake – orbit response

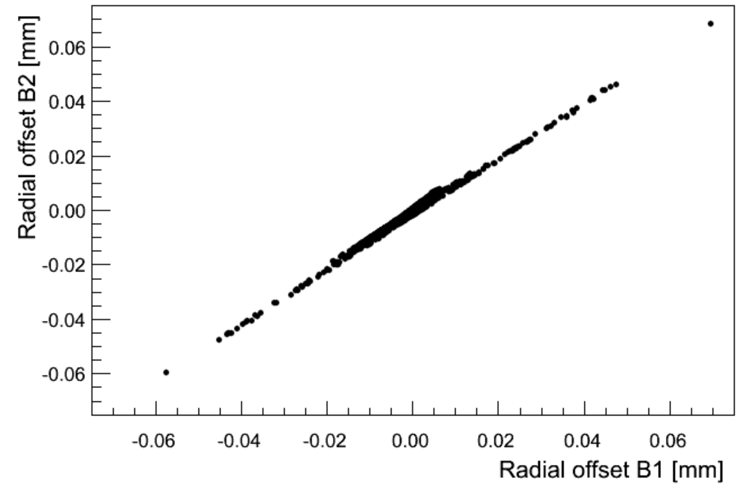


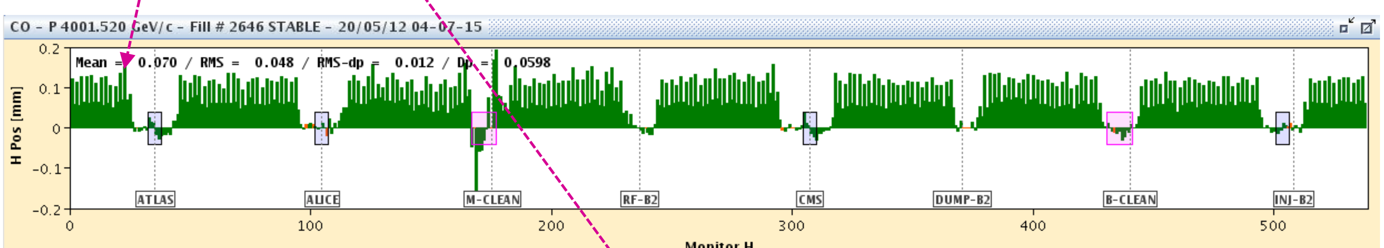
- Earthquake visible on the ring radius for over 1 hour.
- The first P waves (6 km/s) seemed to affect the LHC mainly radially – but there are also weaker.
- The surface waves (4 km/s) are visible in radial and transverse.
  - *Radial amplitude is larger than for Italy Earthquake, **equivalent to strongest tides**.*

Italy earthquake – radial response

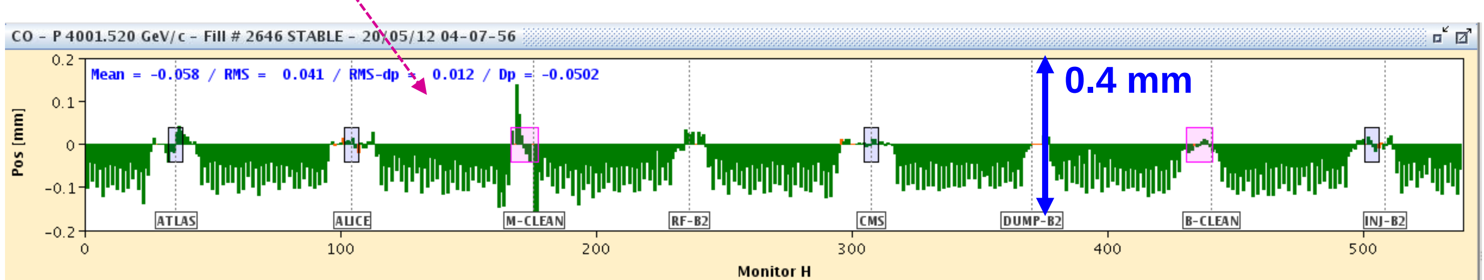


B1 and B2 are fully correlated – as expected

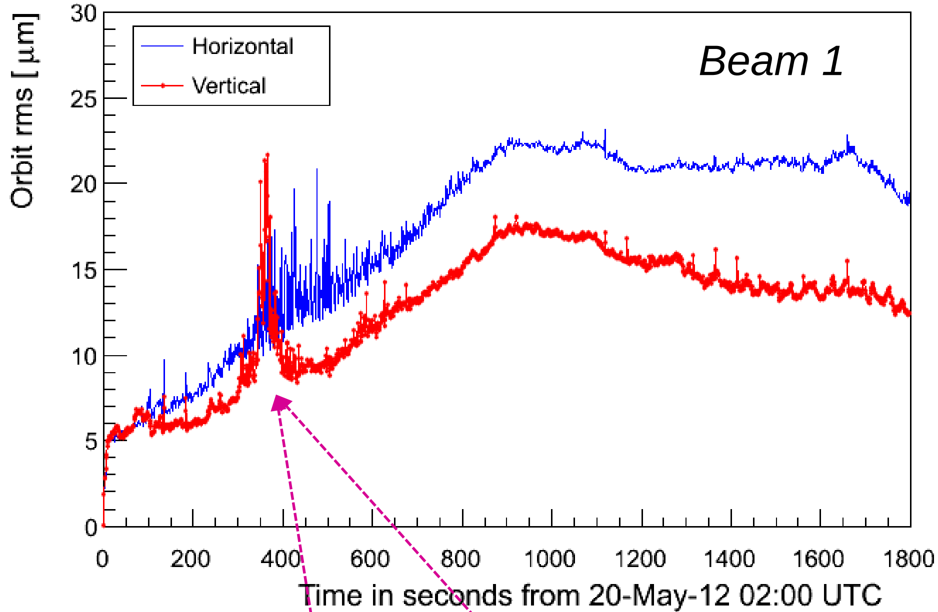




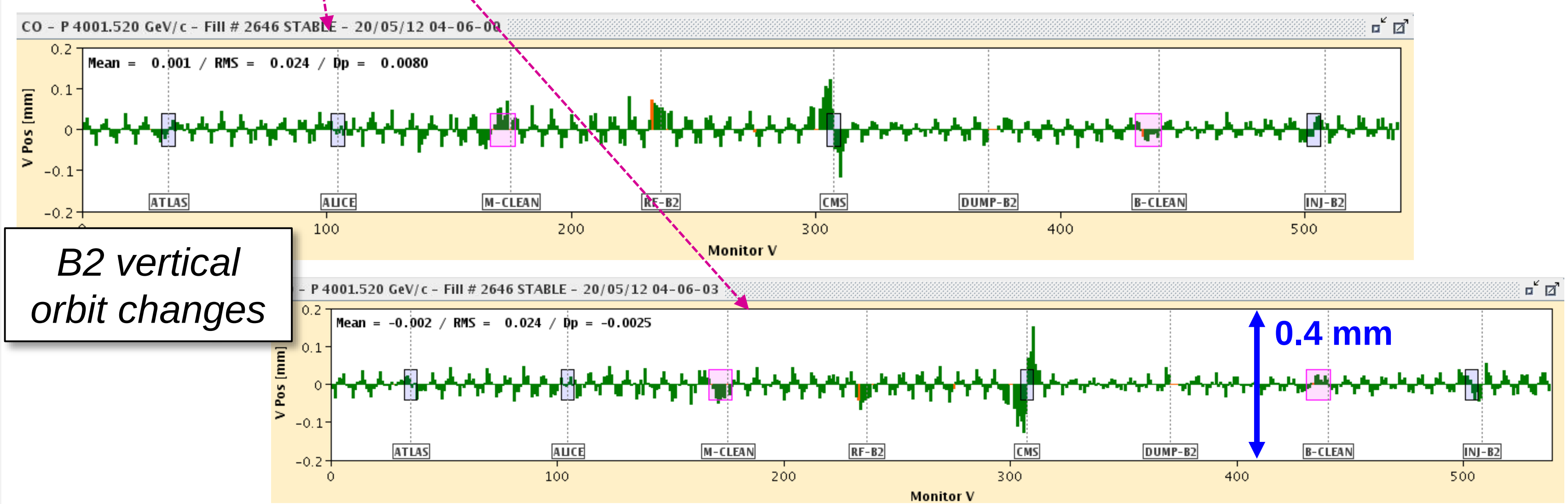
B2 horizontal orbit change



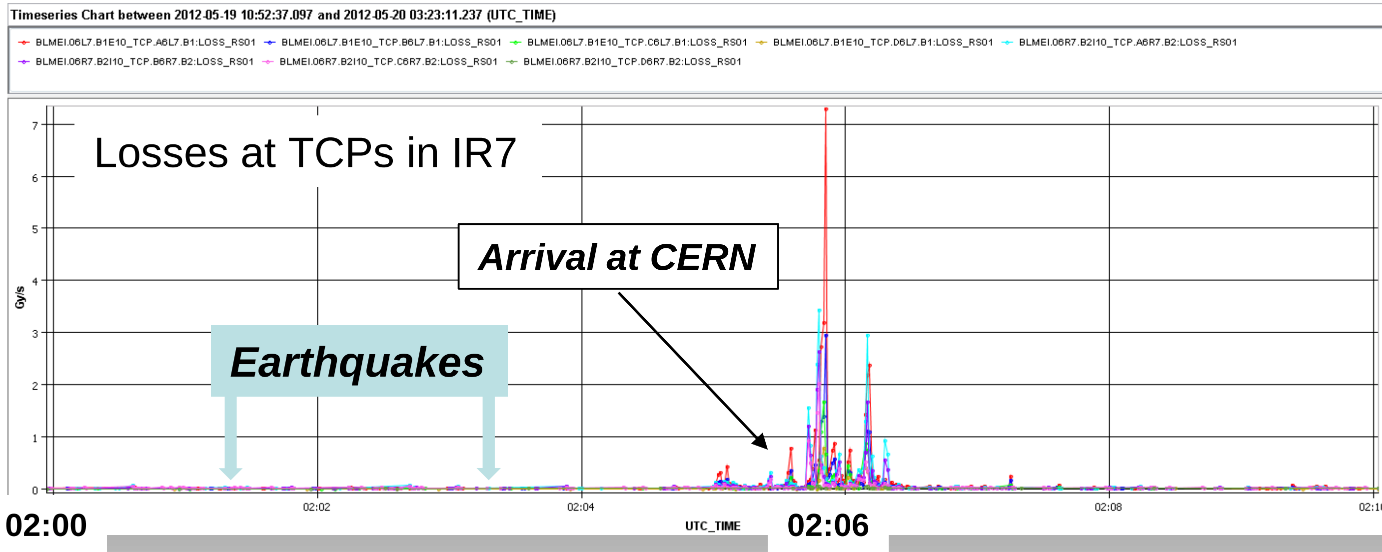
Italy earthquake – transverse response



- For the horizontal plane the rms is calculated after subtraction of the dispersive / radial change.
- Peak amplitude in arcs ~50 µm for σ ~350 µm (ε ~ 2.5 µm).
- Beam offsets reconstructed by interpolation to the IP are within the noise of ~±5 µm.

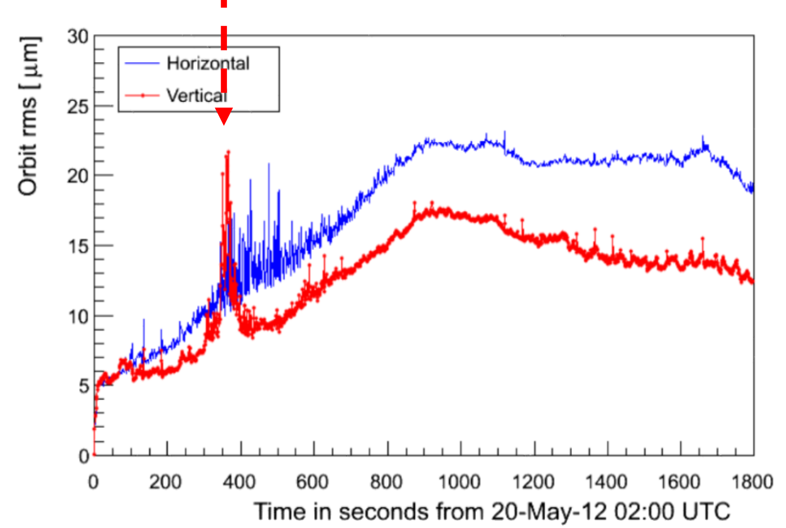


Italy earthquake – losses

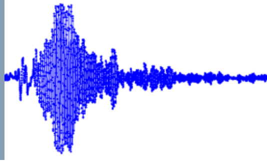


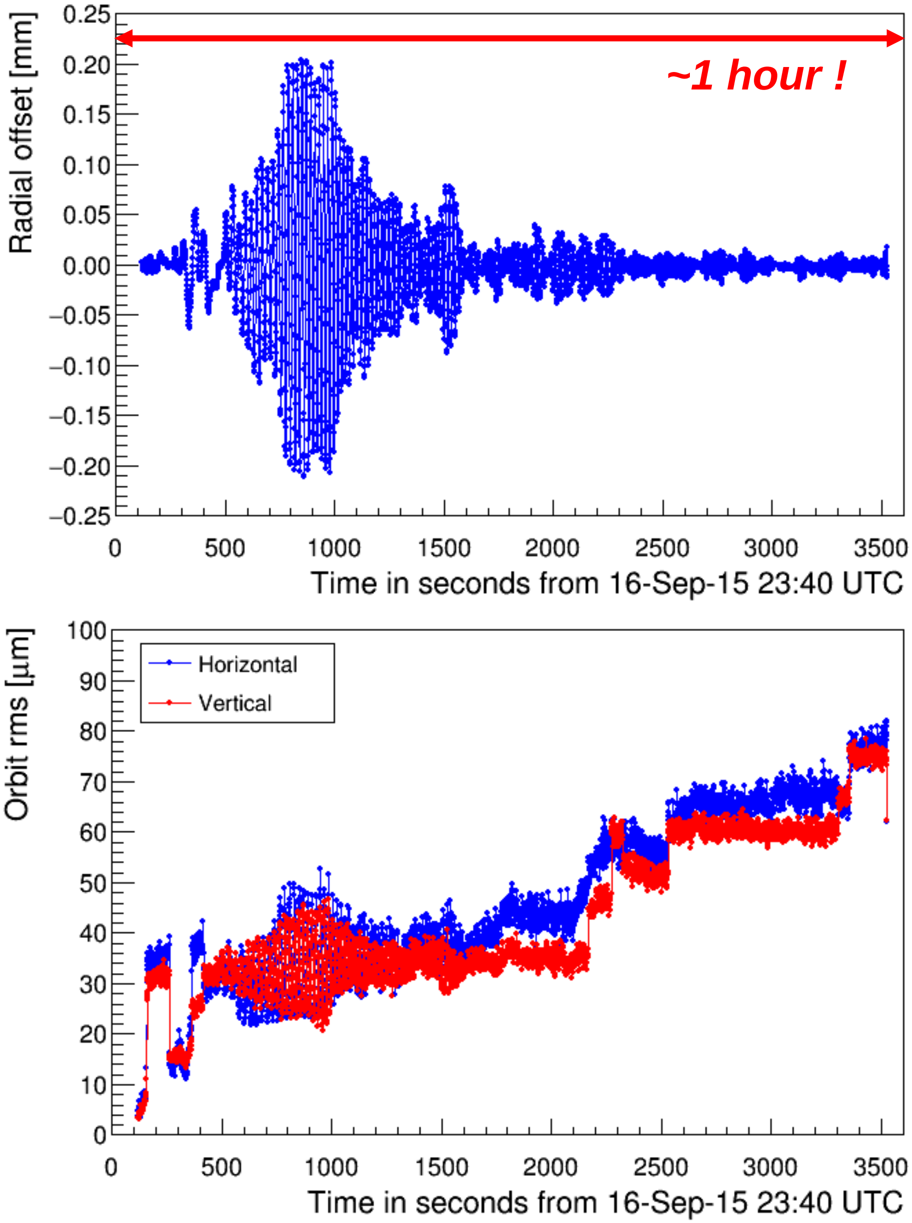
Beam losses at TCP reached ~ 10% of dump threshold (4 TeV).

Loss of **~5x10[12] protons per beam, ~0.4%** of the total beam intensity.



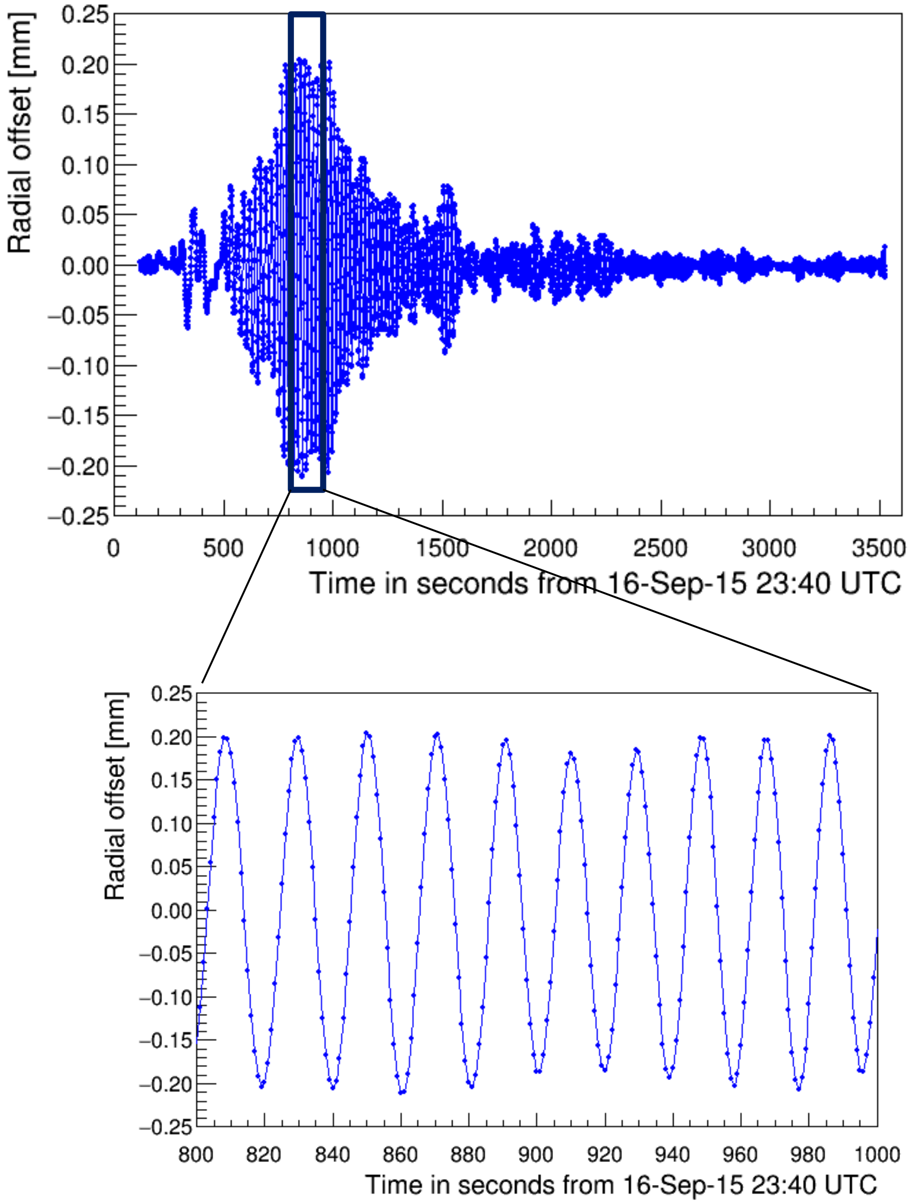
First Chile earthquake – orbit response





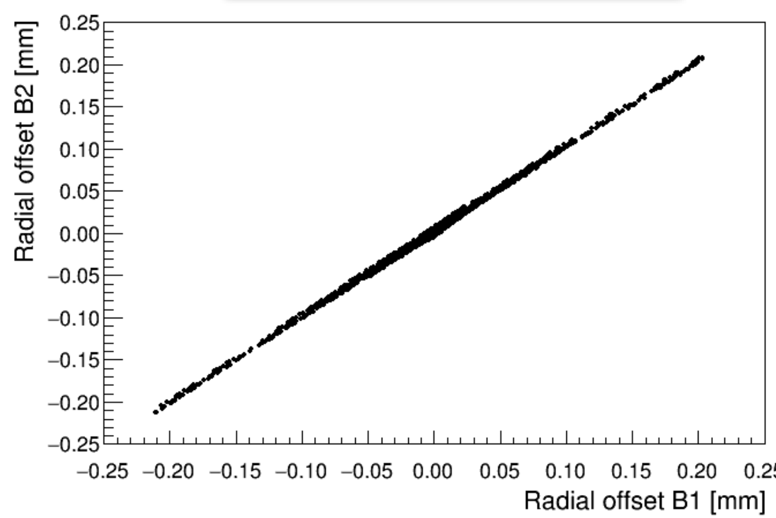
- Earthquake visible on the ring radius for ~1 hour.
- The time delay of roughly 1hour is consistent with 4 km/s propagation speed.
  - *Radial amplitude is twice as large as the **to strongest tides**.*
  - *Roughly ½ Q' measurement amplitude.*
  - *Period ~20 seconds.*
- Note: LHC at injection.

First Chile earthquake – radial response

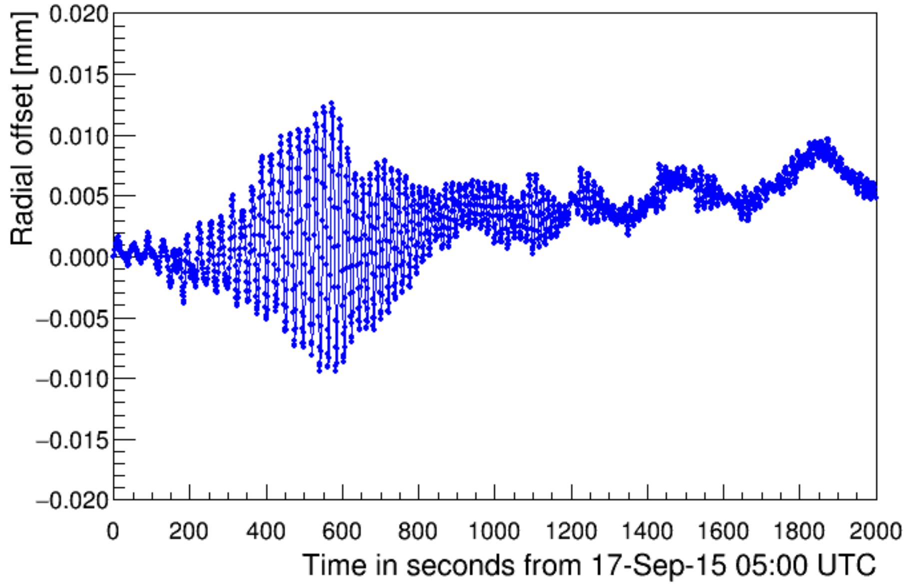


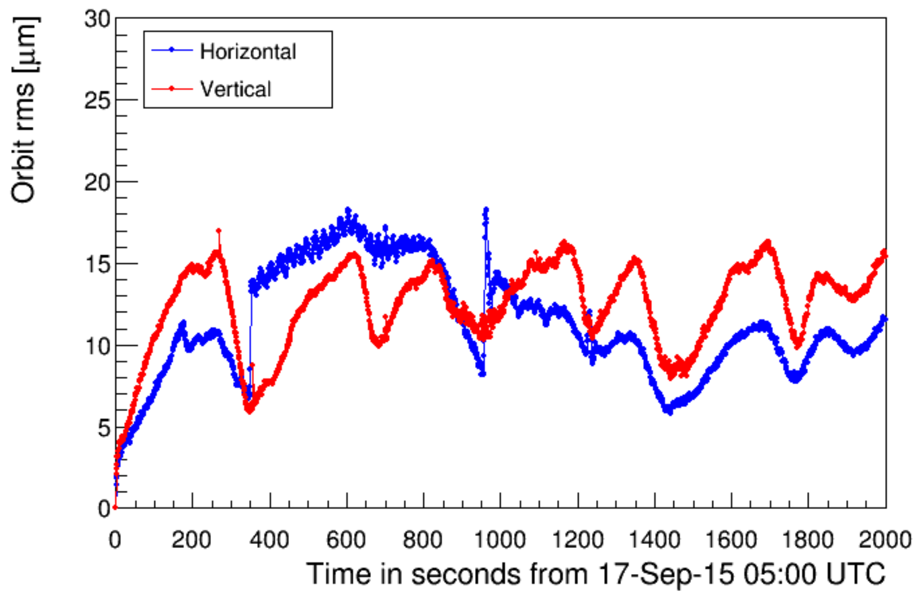
- A zoom reveals a stable period of 20 seconds at the peak. This corresponds to a wavelength of ~80 km (v = 4 km/s).
- Like for the Costa Rica event, the waves with long wavelength seems to propagate to LHC.
- Period of 20 seconds.

B1 and B2 are again fully correlated



Second Chile earthquake – orbit response

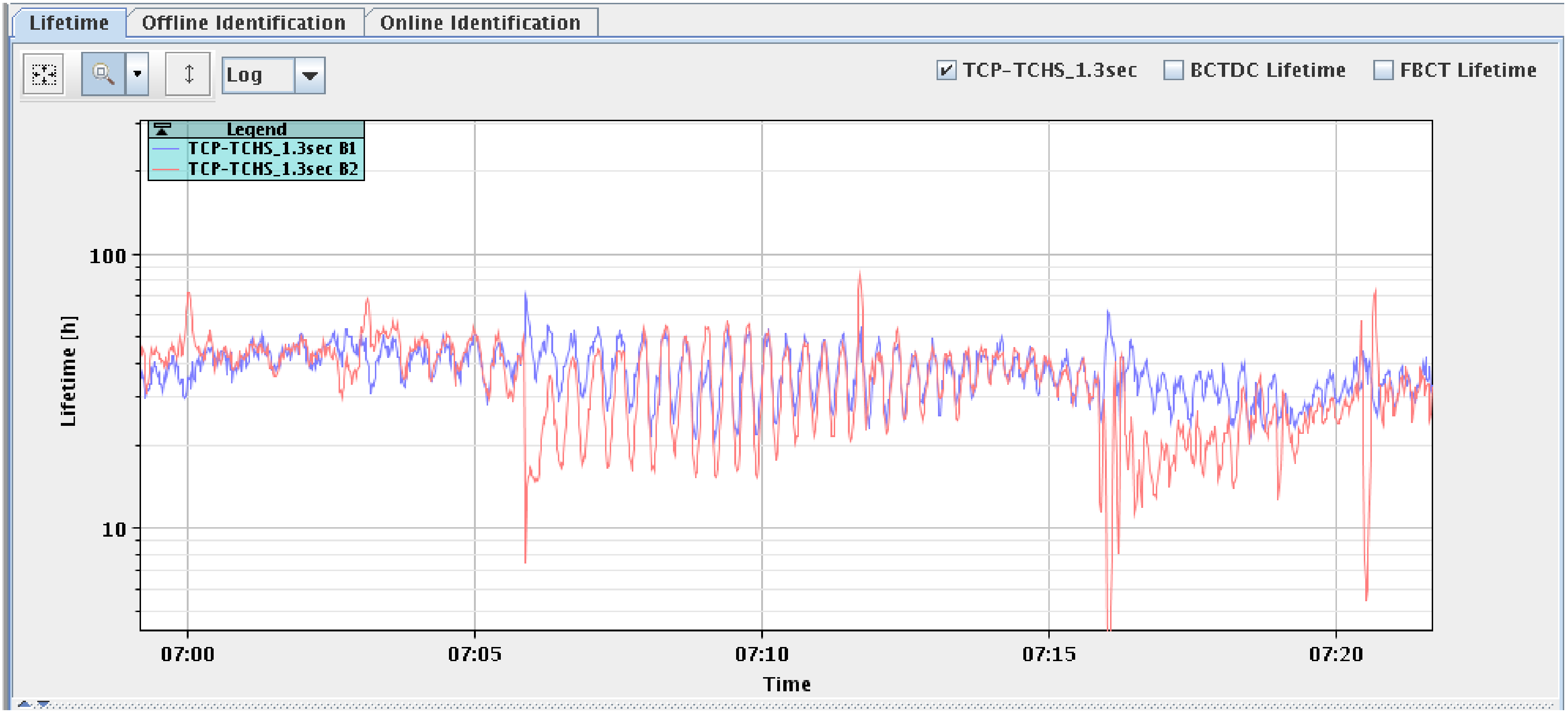




- Very small amplitude (10 times less than first event). Pure chance that it was observed.
- Period of ~25 seconds.
- LHC in stable beams.
- Time delay is the same than for first event.

Second Chile earthquake – lifetime !

- Beam lifetime due to the second earthquake – only 15 micron peak-to-peak orbit change !



Earthquake frequency spectra

- The spectra or the radial orbit oscialltions differ significantly between far earthquakes (Chile, Costa Rica) and the nearby earthquake.