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

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Abstract

During Run 1 and in 2015 LHC operation has not been perturbed by vibrations and higher frequency (>1 Hz) ground motion. The effects of some large earthquakes were observed on the beam orbits, but no beam was lost or spoiled by such events. In the coming years two new sources of perturbations could possibly impact LHC operation: civil engineering for HL-LHC in points 1 and 5 as well as enhanced seismic activity due to the development of a geothermal energy program Geothermie 2020 by the Canton of Geneva. The triplet area is particularly sensitive to vibrations due to large beta-functions and strength and resonances in the frequency range of 10-30 Hz. Depending on amplitude, frequency and wavelength vibrations may lead to loss of performance or in the worst cases to beam dumps. To evaluate the impact of both projects on the LHC performance, measurements of the effect of vibrations on the beam and of the transfer functions of vibrations through the ground and magnetic structure have been conducted. The results of these measurements will be summarized and possible mitigation methods in form of a fast orbit feedback and girder design will be discussed.

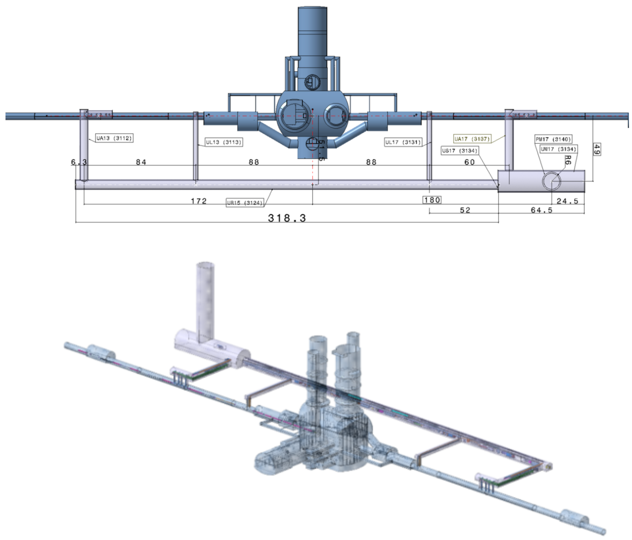

Figure 1: Civil engineering for HL-LHC.

INTRODUCTION

The HL-LHC civil engineering (CE) work is expected to last four to five years between 2018 and 2022. HL-LHC CE works include the construction of new access shafts, underground galleries and caverns in points 1 and 5, an example is shown in Fig. 1. The distance between the new underground areas parallel to the LHC tunnel and the tunnel itself is approximately 40 m. The vertical shafts are located roughly 90-95 m from the the closest triplet along the tunnel. The underground design was modified to place the shaft as far as possible from the triplets. Most of the CE work must be completed before LS3 for installation of HL-LHC equipment. The current schedule foresees to drill the vertical shafts in 2018 in parallel to LHC beam operation (last year of run 2), to excavate the underground structures (horizontal galleries and caverns) during LS2 and to finish the work (concrete etc) during the first years (2021-2022) of run 3.

Geothermie 2020 is a renewable energy production project by the Canton of Geneva. It aims to exploit geothermal energy for electricity production and heat generation. The project is managed by the SIG (Service Industriel de Genve). The project is currently in the prospection phase to identify suitable locations in the Canton of Geneva. Seismic studies were performed in 2015, some of them overlapping the LHC tunnel, to obtain a better map of the underground and to identify suitable locations for deep geothermal drillings (few kms). CERN has been associated to the project because it may 'suffer' from the seismic activity induced by the Geothermie 2020 project. In 2015 CERN could profit from the presence of a vibrating truck used for the seismic studies to perform vibration tests in point 1. The tests will be described later in this document.

Exploitation of geothermal energy may induce seismic activity due to the injection of high pressure water and the 'fraking' of the rocs due to the water pressure. Earthquakes of magnitude around 2 have to be expected, with maxima reaching magnitude 3. The expected duration of such events is around 1 second. The expected peak ground motion amplitude is in the range of 1-10 μm for earthquakes of magnitude 2, with an uncertainty of an order of magnitude. The simulations indicate that the peak ground motion increases by a factor 10 for every magnitude. The expected rate of earthquakes with magnitudes that could affect the LHC is difficult to predict, it may possibly range between 1/week and 1/month. The seismic activity is particularly high during the first months of exploitation: in Basel around 200 earthquakes with magnitude between 1 and 3 were observed over a period of a few months. For this reason the consultant on the geological aspects of Geothermie 2020, Résonance Ingénieurs-Conseil SA, strongly recommends to begin the exploitation phase during a long shutdown of the LHC (LS2, LS3 or beyond).

The impact on the LHC of the two projects is:

- HL-LHC civil engineering: performance degradation of the LHC due to beam offsets at IP, emittance growth from noise. Beam aborts if vibration induced orbit changes cause beam losses exceeding the beam loss monitor thresholds.
- Geothermie 2020: Beam aborts if vibration induced orbit changes cause beam losses exceeding the beam loss monitor thresholds.

VIBRATION MEASUREMENTS

To evaluate the impact of vibrations induced by CE, the transfer functions between a source of ground motion and the triplet cold mass have been determined in a number of test setups. Parasitic beam observations complemented the measurements whenever this was possible. The following transfer functions (TF) were determined (Fig. 2):

- the TF H0(ω) between ground and the triplet cold mass,
- the lateral TF H1(ω) of the ground,
- the vertical TF H2(ω) of the ground,

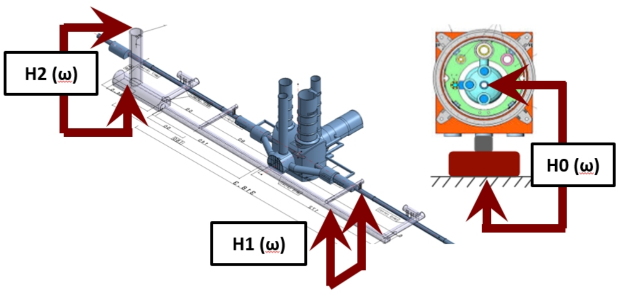

Figure 2: The three transfer functions that were determined during the measurement campaign.

Triplet transfer function

A spare Q1 magnet installed in SM18 was used to determine the transfer function H0(ω) from the ground to the triplet cold mass (CM). The measurement was performed with a drilling machine and with a simple impact hammer. The result of the measurements are presented in Fig. 3 for the case of the continuous noise spectrum induced by nearby drilling. Strong modes are visible at 21.5 Hz (vertical mode), 8.4 Hz and 12 Hz (lateral modes) with amplification factors of around 100. As will be shown later, those resonances appear in many other measurements and also on the beam. The gain measured during this test may be under-evaluated depending of the mode shapes since the measurements could only be done at the extremities of the cold mass. The yriplet interconnections should have a limited impact on the dynamic behaviour.

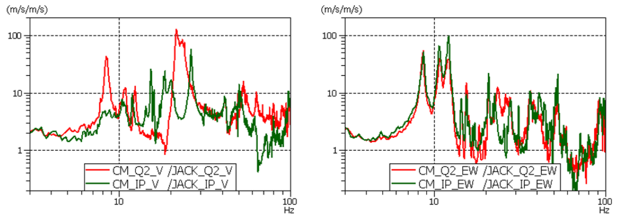

Figure 3: Response of the triplet to external ground motion noise. The TF H0(ω) between ground and CM is shown for the vertical (left) and lateral motion (right). The two curves refer to the IP side (green) and Q2 side (red) of the Q1. The difference of the TFs is due to the support of the CM inside the cryostat (two feet on the Q1 side, a single foot on the Q2 side).

Ground transfer functions

A measurement of the horizontal TF H1(ω) was performed between the TT41 transfer line and the TAG41 tunnel. The two tunnels are separated by 40 m of molasse rock. A shaker was installed in TAG41, the vibrations were measured with geophones installed next to the shaker and in the TT41 line at a distance between 40 and 80 m. The propagation speed of the waves was determined to be 950 m/s which is consistent with shear waves. A factor two in attenuation was gained by doubling the distance.

Figure 4: The vibrating truck used for the tests in SR1. The peak force is 17 kN.

The vertical transfer function H2(ω) was measured at Point 1 with a vibrating truck, see Fig. 4 and 5. The truck is able to generate vibrations at a defined frequency between 4 and 100 Hz and apply a force of 17 kN. Geophones installed on the surface next to the truck and in UJ16 were used to determine the vertical transfer function. Beam observations were made in parallel (distance truck-triplet $\simeq$89 m). For this vertical test the speed of the waves was determined to be 2200 m/s which is consistent with the expected speed of pressure waves in Molasse. The signals on the geophones in UJ16 were fully correlated over a length of 12 m up to frequencies of 25 Hz.

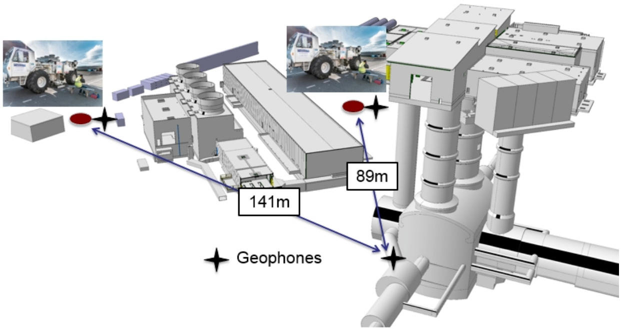

Figure 5: Configuration of the vibrating truck measurements in SR1. The distances between the truck and the triplet corresponded to 89 m and 141 m. Geophones were installed on the surface next to the truck and in UJ16.

The transfer functions H1(ω) and H2(ω) obtained from the TT41 and SR1 tests are presented in Fig. 6. Above 10 Hz the attenuation factors are larger than 20. The attenuation results of the vertical measurement are possibly biased by surface waves.

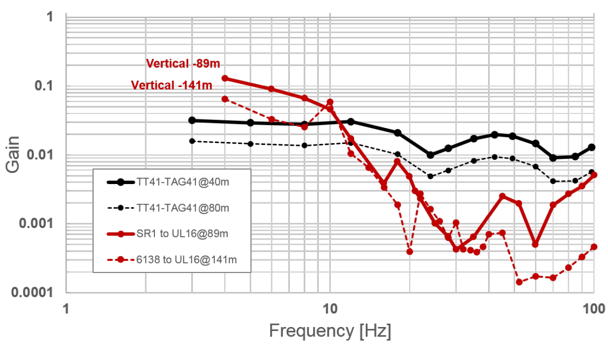

Figure 6: Measured attenuation factors (TFs) for ground motion as a function of the frequency for the vertical measurements in SR1 (red, H2(ω)) and the horizontal measurements in TT41 (black, H1(ω)). In the frequency range above 10 Hz the attenuation is ≥ 20.

Beam response

The combined effect of the triplet magnets on the beams depends strongly on the coherence and wavelength of the ground motion. The effect of other nearby LSS quadrupoles (for example Q4) is expected to be lower because of the reduced betatron function as compared to the triplet. The orbit shifts induced by a 1 μm movement of the triplet magnets ranges between no effect and orbit shifts larger than 100 μm peak in the ring and IR shifts of up to 1/2 beam size. Depending on the pattern of the triplet shifts, either the IR beam position and/or the orbit in the ring are affected [1].

Beam measurements performed parasitically during operation in 2015 using the ADT and the high resolution DOROS BPM electronics at the Q1 indicate the presence of activity in the frequency range of the triplet resonances [2]. Figure 7 presents the noise spectra determined by the ADT and DOROS data for a β^* of 40 cm where the impact of triplet vibrations is expected to be highest. Activity around 20 Hz in vertical and around 12 Hz in horizontal is clearly visible. The amplitude of the beam oscillations is on the micrometer scale and not (yet) a problem for beam operation. The data confirms that natural ground motion is exciting small amplitude vibrations of the triplet magnets.

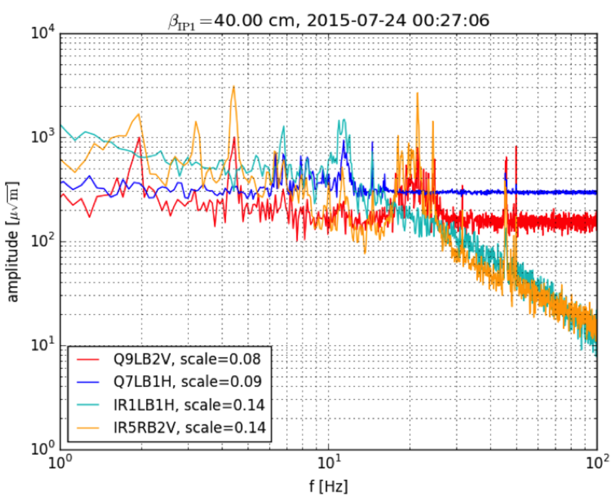

Figure 7: Beam spectrum on the frequency range 1-100 Hz as measured by the ADT (Q7 and Q9 traces) and the DOROS systems (IR1 and IR5 traces). The rolling off visible in the frequency spectrum recorded by the DOROS system is due to low-pass filter around 100 Hz in the DOROS electronics.

Beam measurements were performed with the vibrating truck at the distance of 89 m for the squeezed optics ($\beta*$ 80 cm) at 6.5 TeV and at injection. Beam oscillations were recorded with multi-turn data (all BPMs) and ADT data. Some results of the measurements:

- Beam oscillations were only observed in the vertical plane. This is consistent with the truck location and the generation of pressure waves travelling from the surface to the tunnel. Figure 8 presents the beam position data (turn-by-turn) in quiet conditions and with the truck vibrating at 22 Hz.
- Beam oscillations were only observed for vibration frequencies of $18-22$ Hz, consistent with the triplet resonances. Outside the triplet resonances no activity

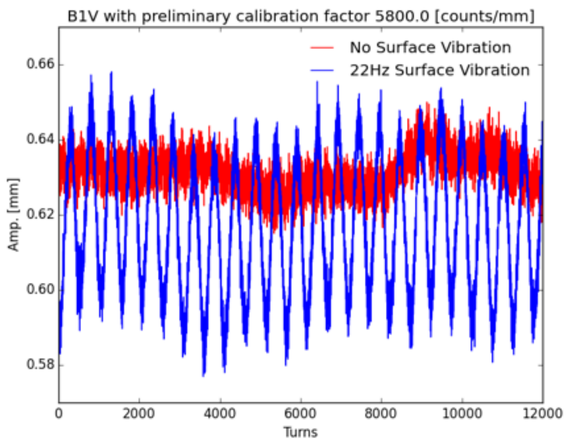

Figure 8: Beam oscillations in the vertical plane as measured with the B1 ADT BPM in quiet conditions (red trace) and with the vibrating truck oscillating at 22 Hz (blue trace). With truck the peak-to-peak amplitude is $\simeq 50\mu$m.

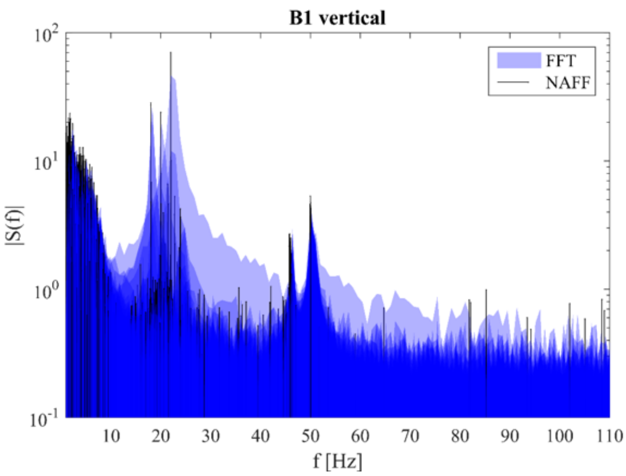

Figure 9: Beam oscillation spectra in the vertical plane as measured with the B1 ADT BPM (raw data example in Fig. 8). The spectra of all measurements (4 to 100 Hz) have been superposed. The dark blue area corresponds to the background (no truck) conditions. The light blue area corresponds to measurements with the truck active, and one notices the enhancement of the peaks near 20 Hz in those conditions. This peak coincides with the first vertical IT eigen-frequency.

was measurable on the beam spectrum. The FFT of the beam position data is shown in Fig. 9 where all the spectra have been superposed: the dark blue area corresponds to the background (quiet) conditions. The effective amplitudes of the triplet quadrupoles were in the few μm range for a ground motion amplitudes of 50 nm in the tunnel.

- The observed B2/B1 amplitude ratio of 2.5 implies that the three triplet quadrupoles oscillated with different amplitudes. The amplitude ratio would be consisted with a larger oscillation amplitude of the Q2 magnet as this leads to asymmetries between B1 and B2. A coherent oscillation of all 3 triplet quadrupoles would generate almost equals amplitudes for both beams.

The observations are consistent with the triplet resonances that enhance the vibrations by a factor significantly larger than 10.

The expected motion of the triplet magnetic center during truck tests is presented in Fig. 10. The motion is only significant between 18 and 22 Hz, in agreement with the beam observations. The exact triplet motion is difficult to deduce from the beams since the effect of the individual magnets would have to be unfolded, but the approximate amplitudes agree well with the expectations.

Vertical drilling tests down to the depth of the LHC tunnel around SR1 could also be monitored with the same setup (but not with beam). Figure 11 presents the predicted triplet movement at the 22 Hz resonant frequency as a function of depth. For a depth of less than 30 m no ground motion is detected (signal within the background). Only below that depth there is some enhancement, but the predicted triplet movement remains at the level of 0.1 to 0.2 μm which should be acceptable for beam operation.

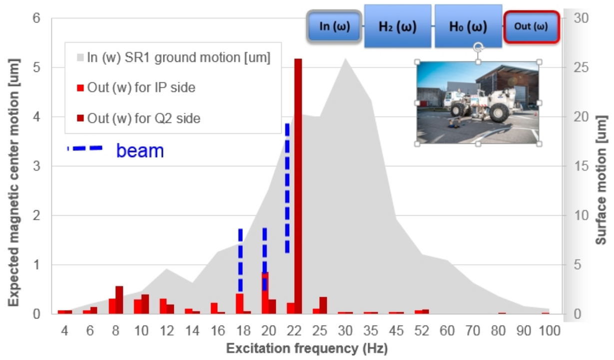

Figure 10: Predicted triplet oscillation amplitudes due to the vibrating truck as a function of the truck frequency. The vertical dashed blue lines are the triplet amplitudes estimates from the beam oscillation data.

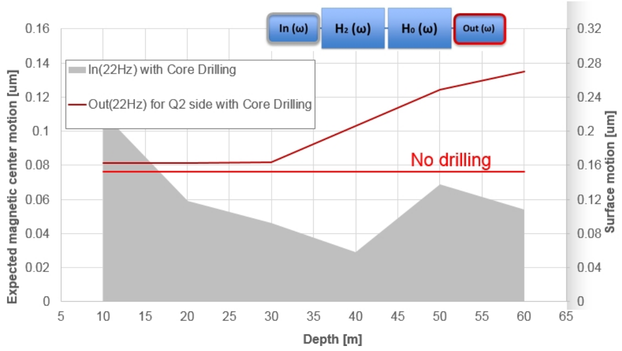

Figure 11: Predicted triplet oscillation at the 22 Hz resonance due to the vertical shaft drilling as a function of the depth. The background noise is indicated as flat line.

Fast Orbit Feedback

While for the new HL-LHC triplets the design of the support feet or girders may be optimized to optimize the transfer functions from the ground to the CM [1], such an option seems excluded for the existing triplets. This leaves an active beam orbit feedback as only option to counteract vibration effects until LS3 in case the vibration levels would exceed the tolerances in LHC run 2 or run 3.

The current LHC orbit feedback system is based on a Linux RT server that operates effectively at 12.5 Hz [3]. The system could be pushed to 50 Hz, but not beyond. The system closed loop bandwidth is around 0.2 Hz, and the system cannot be scaled to a bandwidth of 20 to 30 Hz.

To actively fight triplet induced beam oscillations around 20 Hz, a fast digital orbit feedback operating at a sampling frequency of at least 1 kHz would be required. The system requires a number of new components or modifications:

- A number of new high accuracy (μm resolution) local BPMs would be required in LSS1 and LSS5. The DOROS electronics seems to be suitable and could probably be used in parallel to the standard BPM electronics, as is already done on the Q1.
- Normal conducting (NC) orbit correctors (COD) must be installed between triplets and Q5. Two magnets are required per plane. The associated power converter (PC) must be abe to drive the NC COD at least 100 times faster than all currently installed LHC CODs. The integrated magnetic field depends on the magnet location and on the assumed maximum oscillation application. An integrated field of 0.2 Tm seems adequate for triplet amplitudes of 5-10 μm.
- The access to the PC cannot transit over the WorldFip bus since it is limited to 50 Hz. A new link operating at or above 1 kHz would have to be developed.
- The control logic must be moved from a RT line server to a FGPA-like system.
- A dedicated network for data exchange will have to be installed. The network must link LSS1 and LSS5 because a global correction including both LSS should be performed to avoid issues of cross-talk between two feedback loops.

Such a fast orbit FB system could be feasible, but a detailed study is required (if desired) to assess its performance and feasibility.

EARTHQUAKES AT LHC

The seismic activity in the Geneva area is very low, and monitoring of the regional seismic activity is poor (from the Swiss side). In the context of the Geothermie 2020 project Geneva University was mandated to build a network of instruments to monitor the natural seismic activity down to magnitudes around 1.5. The aim is to be ready as soon as possible in order to understand the natural seismic background.

On the CERN site a network of geophones will be installed by EN-MME in the LHC service areas of all points during the summer 2016. This will provide continuous monitoring of ground noise and earthquake activity. Data from earthquakes will be transmitted to the central Swiss seismic institute located at EPF Zurich to correlate the CERN data with other instruments (network of Geneva Univ. and other Swiss monitors).

Operational usage of the DOROS (Q1 and collimator BPMs) in synchronized turn-by-turn mode and of the ADT observation box data will provide better monitoring of the beam oscillations for the coming run. It will be possible to monitor the beam noise with high resolution over the duration of the run.

Precision Laser Inclinometers installed in the ATLAS cavern also provide high resolution information on earthquakes.

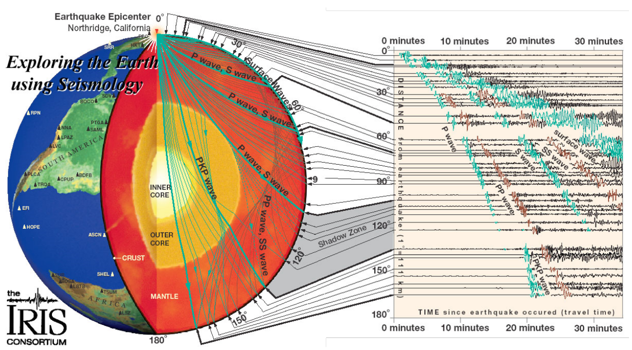

Figure 12: Propagation of seismic waves and arrival times as a function of the angular separation between source and detector (courtesy IRIS consortium).

Seismic waves

The different types of body waves (Pressure [P] waves, Shear [S] waves) and surface waves (Raleigh waves, Love waves), the multiple paths and reflections of the waves produce a complex signature of earthquakes at seismic measurement stations, and this also applies to the LHC. Figure 12 presents the propagation and arrival of waves as a function of the angular distance between the earthquake and the monitoring station.

The frequency spectrum of waves induced by earthquakes ranges from the mHz (earth oscillations and surface waves) to around 100 Hz for local seismic events. The signatures of large and distant earthquakes ('teleseismic') are dominated by low frequencies, typically below 1 Hz. Ground motion from local earthquakes (for example Geothermie 2020) extends to higher frequencies.

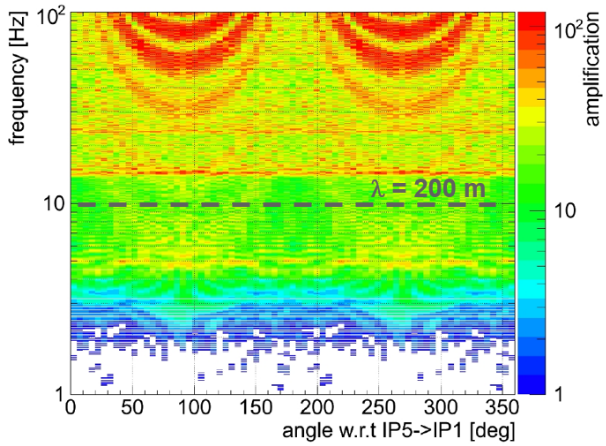

Figure 13: Amplification of ground motion shear waves (vertical direction) as a function of the frequency and of the wave orientation with respect to the LHC ring.

Simulations of the amplification of the wave motion by the LHC magnetic lattice on orbit displacement were carried out during the design phase of the orbit feedback. The response of the LHC to ground motion waves depends on wavelength and direction, the amplification can reach a factor around 100 for waves travelling along the LSS in IR1 and IR5 as shown in Fig. 13. Large amplifications are associated to resonant response of (parts of) the LHC.

Earthquakes at the LHC

In the few years of operation a number of earthquakes had some impact on the LHC. Most of them went unnoticed because their effect was moderate and because they occurred during a dynamic phase (like ramp or squeeze) where the intrinsic beam movements shadow the earthquake effects and when the orbit feedback could counteract all or part of their impact. The cleanest signatures are obtained when the LHC is in stable beams or at injection. A distinct signature of the earthquakes are the radial and transverse orbit changes that will be shown in the figures below. Other signatures include luminosity loss and beam loss at the primary collimators (TCPs). The list of main events is given in Table 1. The impact of some of them is presented below.

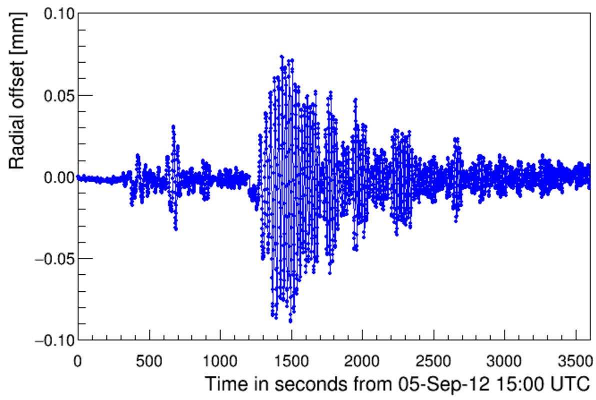

Figure 14: Radial beam movement due to the Costa Rica earthquake on 05/09/2012. The first perturbation is due to the P-wave (Pressure), followed by a S-wave (shear) of PP-wave (reflected P wave). The main perturbation occurs when the slower surface waves reach the ring (around 1250 seconds).

Table 1: Earthquakes that affected the LHC during beam operation. All events struck the LHC during stable beams except the first Chile event that occured at injection. ΔR is the peak radial orbit change during the event, see Fig. 14, 15 and 19.

Location	Date	Mag	ΔR (μm)	I/beam (10^{13} p)
Modena (It)	20/05/2012	6	$\pm$60	14
Costa Rica	05/09/2012	7.6	$\pm$80	19
Chile	16/09/2015	8.3	$\pm$200	5
Chile	17/09/2015	6.5	$\pm$15	10

A magnitude 7.6 earthquake in Costa Rica (05/09/2012 at 14:42:10 UTC) struck the LHC during stable beams in fill 3032. The first waves arrived at CERN around 15:06 UTC. The arrival of the different waves can be observed on the radial beam position in Fig. 14. A first perturbation of the radius corresponds to the arrival of the P-wave, followed somewhat later by a PP (reflected P) wave or S-wave. The largest perturbation occur when the surface waves hit the LHC. The peak amplitude is equivalent to largest tides. The period of the oscillations is around 20 seconds. The impact of this earthquake on luminosity is barely visible for this high luminosity fill (L $\simeq 6 \times 10^{33}$ cm^{-2}s^{-1}). Loss spikes at the primary collimators are visible, but they are smaller than many other loss spikes in that fill.

Two consecutive earthquakes with magnitude 6 struck Northern Italy (Modena) on 20/05/12 at 02:01(03) UTC

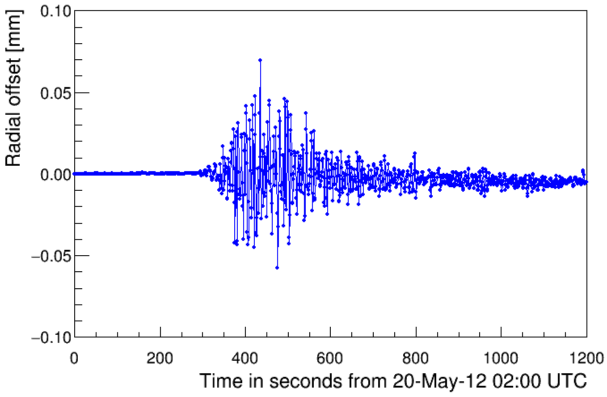

Figure 15: Radial beam movement due to the Modena earthquake on 20/05/2012.

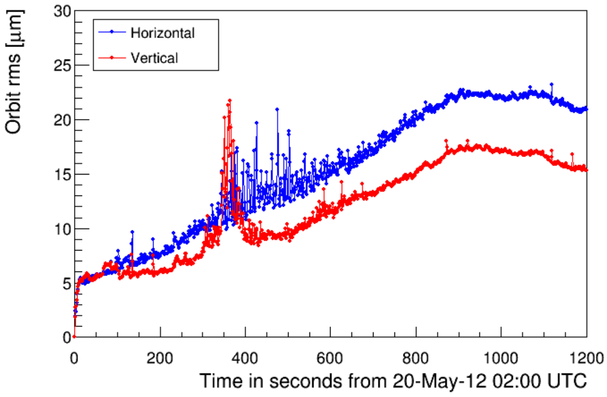

Figure 16: Transverse beam movement due to the Modena earthquake on 20/05/2012. The vertical is the r.m.s. change of the horizontal and vertical orbits. For the horizontal orbits the radial movement has been subtracted.

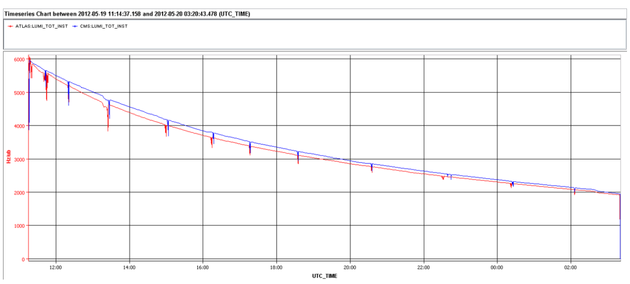

Figure 17: Luminosity evolution in fill 2646. The luminosity drops are all due to IR optimization, with the exception of the last one that is due to the earthquake in Modena.

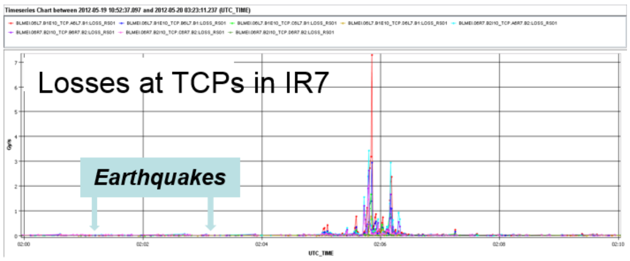

Figure 18: Losses at the primary collimators in fill 2646 due to the earthquake in Modena.

while fill 2646 was in stable beams. The impact of the earthquake was clearly visible on losses, luminosity and orbit, but it was not noticed at the time (4 AM local time). The radial and transverse beam movements are presented in Fig 15 and 16. The frequency spectrum of this earthquake extends to much higher frequencies than the Costa-Rica earthquake. Radial activity is visible a long time after the main perturbation, while the duration of the transverse activity (vertical plane) is much shorter. There is a visible drop in luminosity (around 7%, Fig. 17), while the beam losses at the TCP reached around 10% of the 4 TeV dump threshold, see Fig. 18. The intensity loss per beam corresponds to 0.4% of the total intensity, or 5×10^{12} protons per beam.

The largest impact that was observed at the LHC was due to the M8 Chile earthquake that struck the LHC while it was at injection in September 2015 , see Fig. 19. The radial amplitude reached ± 200 μm when the surface waves hit the ring, which is more than twice as large than the strongest tides. At the maximum of the amplitude the ring swings back and forth with a period of 20 seconds which is visible on the radial beam movement and on the transverse r.m.s. as shown in Fig. 20 and 21.

A comparative frequency spectrum of the main events is presented in Fig. 22. The dominant low frequency waves of the distant earthquakes are clearly visible. To be noted that the sampling frequency of the orbits (all figures) is 1 Hz.

CONCLUSION

Large earthquakes (with magnitude ≥ 6) have a clear impact on the LHC even when the source is at a large distance from the LHC ring. For large distance events the frequency spectrum is < 0.1 Hz, and so far we have survived all major events, maybe with a bit of luck. Nearby small earthquakes (magnitude 3 in the Valais) have not been observed on any beam observable. A network of geophones and better beam measurements will be used to improve the monitoring of ground motion and of low magnitude natural earthquake activity in the future. This should help us assess better the possible impact of earthquakes induced by geothermal energy production. An important point to note is the strong recommendation by the consultants geological aspects of the Geothermie 2020 to begin the exploitation phase of the

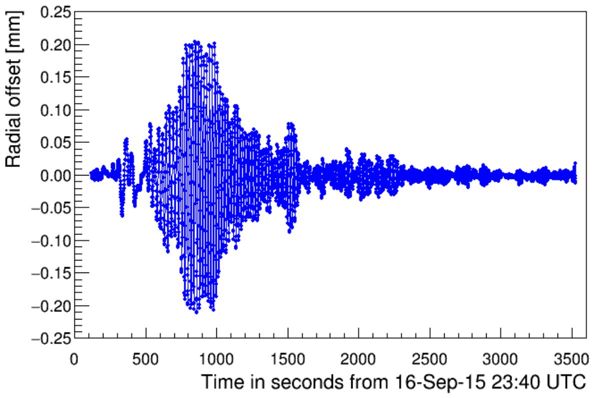

Figure 19: Radial beam movement due to the Chile earthquake on 16/09/2015.

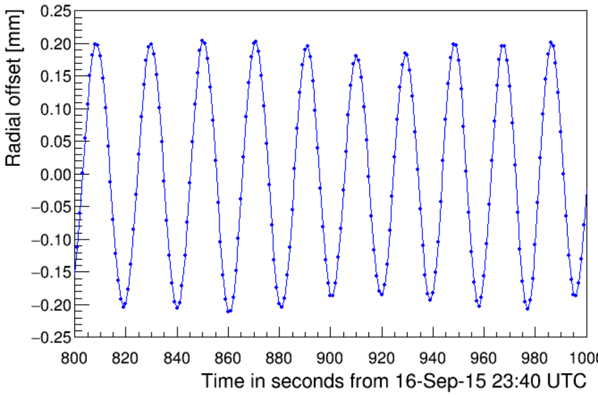

Figure 20: Radial beam movement due to the Chile earthquake on 16/09/2015 with a zoom on the time interval with stable amplitude.

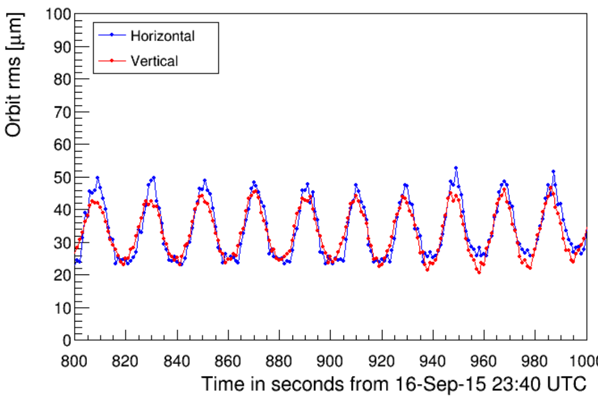

Figure 21: R.m.s. orbit change due to the Chile earthquake on 16/09/2015 with a zoom on the time interval with stable amplitude.

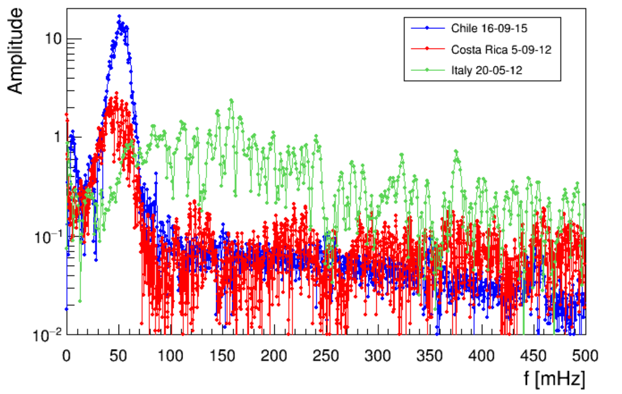

Figure 22: FFT of the radial beam movement for the Costa Rica, Chile and Modena earthquakes. The teleseismic events are characterized by low frequencies.

project during a long shutdown of the LHC due to the large seismic activity expected in the first months of the exploitation phase.

Both SM18 and in situ vibration tests reveal strong mechanical resonances of the triplet between 8 and 20 Hz. The resonances can boost ground vibrations to amplitudes that can be problematic for the beams. 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 in 2018. The excavation of caverns and underground structures should be made during LS2.

In the near future it is planed to measure the source spectra of the following devices to improve the predictions for vibrations:

- the rotating header machine (UR excavation),
- the hammer and excavator to be used for the shaft,
- the concrete pump to be used to concrete the tunnel during Run 3.

Those studies also highlight the need to carefully study the mechanical design of the cold-mass and the support (feet) for the HL-LHC triplets.

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