ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB116

EFFECT OF GROUND MOTION INTRODUCED BY HL-LHC CE WORK ON LHC BEAM OPERATION*

M. Schaumann†, D. Gamba, M. Guinchard, L. Scislo[1], J. Wenninger,
CERN, Geneva 23, CH-1211 Switzerland
[1]also at Cracow University of Technology, 31-155 Cracow, Poland

Abstract

The official groundbreaking of the civil engineering (CE) work for the high luminosity upgrade of the LHC started on 15 June 2018 parallel to LHC beam operation. Compactor work and shaft excavation around the two low beta experiments, ATLAS and CMS, were expected to induce vibrations to the accelerator magnets and cause orbit disturbance, beam loss and potentially premature beam dumps. Ground motion sensors were installed on the surface and close to the triplets, where the CE works were expected to have the largest impact on the beams. This paper discusses the observations made on the LHC beams that could be correlated to CE work.

INTRODUCTION

Seismic activity from natural, such as earthquakes, or cultural (human-made) sources, including civil engineering works, excite ground vibrations that can be transmitted on to the circulating beam through the accelerator elements. The main effect is the change of the beam position (orbit) all along the circumference of the accelerator due to the displacement of the quadrupoles. If the orbit changes are too large and too fast, beam losses on the collimators will lead to a beam abort. Repeated beam aborts will affect the integrated luminosity performance. Smaller, but frequent excitation could affect luminosity production by the reduction of the beam overlap at the interaction points (IP) [1].

Earthquakes are rare events and their effect on the LHC beam depends on their magnitude and distance of the epicentre. Many such events were observed on the LHC beams, but so far no beam dump was caused [2].

HL-LHC Civil Engineering

CERN deployed a seismic network in the beginning of 2017 [3] in collaboration with the Swiss Seismological Service (SED) in view of future ground motion sensitive projects that are planned in parallel to the LHC beam operation, such as High Luminosity LHC (HL-LHC) civil engineering [4] and geothermal exploitation in the Geneva canton (Geothermie2020 [5, 6]).

The HL-LHC project requires new large infrastructures and services for powering and cooling of the new inner triplet quadrupoles and RF crab-cavities around the two main experiments ATLAS (IP1) and CMS (IP5). HL-LHC CE campaign started in April 2018 with different types of surface works, e.g. the construction of new infrastructure and buildings, before the official ground breaking on 15 June. The excavation of the shafts started mid of August.

The risk of vibrations generated by CE was evaluated carefully [4, 7] and seismic sensors were installed in critical locations on the surface and underground close to IP1 and IP5. The first year of data taking was used to collect reference measurements. Once CE works began, the seismic activity in the LHC tunnel was monitored constantly. In order to quantify the impact on LHC operation from an early stage, a warning system was setup to trigger when the vibration levels exceeded a threshold.

Beam Observables

Beam observables, such as orbit, luminosity, beam intensity and losses were analysed in comparison to ground motion activity especially when a warning was triggered. Particularly for this purpose the existing instrumentation of the transverse dampers (ADT) [8, 9] and the Beam Position Monitors (BPM) with DOROS readout [10] were extended to capture and log beam spectra, allowing to investigate the ground vibration frequencies amplified on the beam.

The logged ground motion spectra are calculated from the position data over the last minute and are logged three times per minute. The ADT spectra are calculated from position data of the first 10 seconds of each minute and therefore contain only a snapshots of every sixth 10 s window. This reduced resolution and only partial time coverage has to be kept in mind when comparing to ground motion spectra. Certain effects will be washed out and appear less evident.

OVERVIEW 2018

During the whole period from April to December 2018 several types of CE work have been performed, using a variety of tools inducing vibrations in different frequency ranges. Figure 1 shows the rms motion obtained from ground motion and ADT beam spectra measurements within four selected frequency bands during LHC luminosity production in 2018. Compressing the individual frequency information into the rms of a frequency band helps to quickly identify when ground motion activity is picked up by the beams. Once correlations are identified, the full spectra and beam evolution data are investigated in detail (the next section gives an example for LHC fill number 6757).

The presented analysis focuses on the vertical plane, since CE activity primarily excites vertical ground vibration [11] and thus this is the main direction in which the triplet quadrupoles will react and transmit the movement to the beam.

* Research supported by the HL-LHC project
† michaela.schaumann@cern.ch

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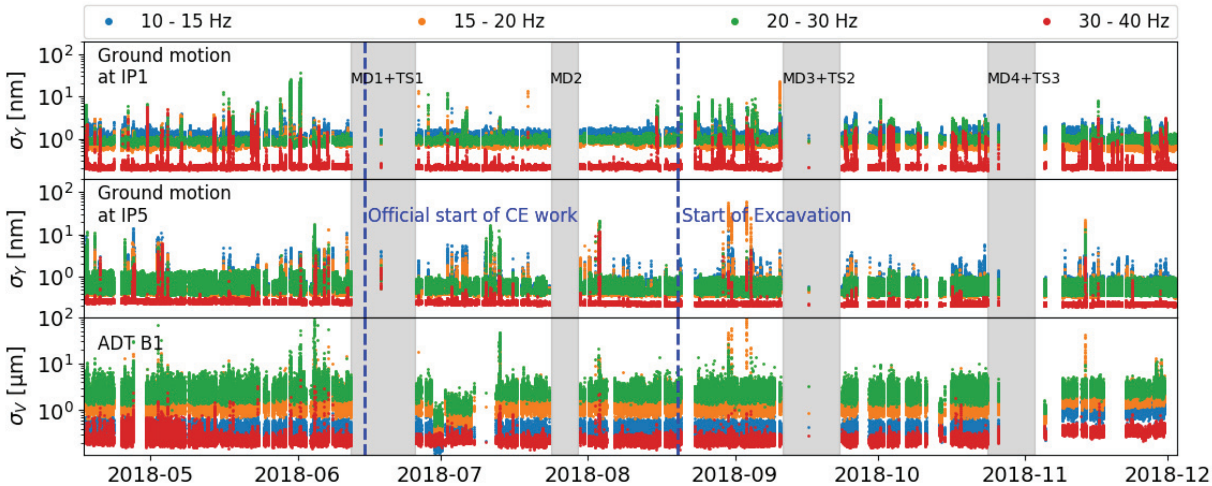

Figure 1: Ground (top: IP1, middle: IP5) and beam motion (bottom from ADT located in IP4) rms obtained from integration of spectra over selected frequency bands. Only data with colliding beams (*Stable Beams*) in 2018 is shown. Longer data gaps are due to machine development (MD) experiment periods and technical stops (TS). The official HL-LHC ground breaking and the start of shaft excavation are indicated by blue dashed vertical lines.

Only frequency ranges between 10 – 40 Hz are shown. This is a critical frequency range for two reasons. Firstly, the amplification from ground to cold mass vibrations of a triplet quadrupoles has strong vertical modes around 21 Hz [7]. Horizontal amplification is stronger at lower frequencies around 10 Hz. Secondly, CE machinery, e.g. ground compactors, operate close to these triplet eigenmodes [7] and can therefore lead to resonant excitation.

From the beginning of June, ground and beam excitation is observed in all four frequency bands displayed in Fig. 1. However, only a few ground motion events are highly amplified on the beams. Some events show activity over all bands, others clearly excite only distinct frequencies. The strongest and clearest events seen on the beams were generated in IP5 in the frequency range between 15 – 30 Hz (green and orange). These excitations lasted a few to several minutes. On top of this, clear repetitive time patterns, mainly in the 20 – 30 Hz band, lasting several hours, were generated in IP5 and transmitted to the beam[1]. Some of these oscillatory patterns as well appear during nights and are not present in IP1, which indicates that the source might not be CE related.

In general and neglecting these repetitive patterns, in IP5 frequencies between 10 – 20 Hz seem to be most commonly excited, while in IP1 activity at higher frequencies between 20 – 40 Hz are more often observed. This can be explained by the different equipment that has been used on the two sites.

The ground movement observed in the frequency range 1 – 10 Hz[2] is correlated in all three data sets (ground motion in both IPs and ADT). HL-LHC CE work in IP1 and IP5 will lead to ground motion signals limited to their source location. Only stronger or more global, e.g. natural, sources will lead to correlated signals in both IPs, which is not the concern of the presented analysis. Ground activity in the range 40 – 100 Hz[3] was recorded with high amplitudes especially in IP1 since mid August. The effect on the beam was however mild to negligible. Both outer frequency ranges have a low amplification from ground to cold mass (see Fig. 2 in Ref. [7]) and are therefore less critical.

EXAMPLE: FILL 6757

During the first period of the CE campaign, when surface work using compactors were performed in P5, some of the strongest reactions of the circulating beams were observed. Compactors compress the ground by vibrating in a variable frequency range around 20 – 30 Hz. The triplet is very sensitive to these frequencies because of the proximity to its eigenmodes.

Figure 2 shows the time evolution of several key observables on the example of Fill 6757 (4 June 2018). The seismic activity measured underground close to the IP5 triplet quadrupoles (top row) shows several clearly excited periods that were transmitted with varying impact to the LHC beams (bottom three rows). The CMS luminosity dips down by up to a few percent and the beam losses on the primary collimators and the rms of the vertical beam position around the ring increase on both beams. Even though the beams considerably reacted on the CE work, the highest loss spike reached only about 5% of the beam abort threshold.

The ground vibrations are of similar amplitude for the first five excited periods, while at $t = 1$ h, 3 h, 5 h and 6 h luminosity dips and beam losses are much stronger compared to $t = 5.6$ h. This varying reactions of the beam to excitation

[1] Because of the figure scale this feature appears only as an increased (green) line width for the IP5 ground motion and ADT data in Fig.1.

[2] not shown in Fig. 1

[3] not shown in Fig. 1

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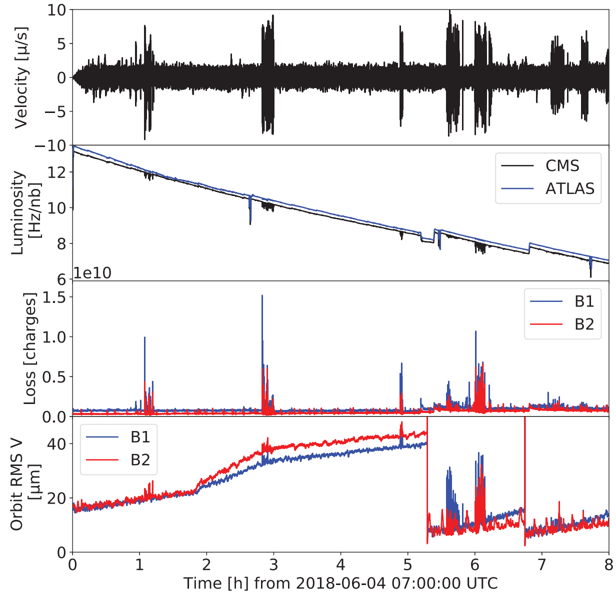

Figure 2: Seismic activity in IP5 (top row) and beam evolution during Fill 6757 (4 June 2018). 2nd to 4th row: ATLAS and CMS online luminosity, calibrated losses on primary collimator, vertical rms orbit. Several ground excitation periods are clearly visible on each data set. The orbit rms is calculated with respect to the operational orbit feedback reference, defining the rms to zero when taken in the beginning of collisions at $t = -3.6$ h. At $t = 5.3$ h and $t = 6.7$ h a β^*-levelling step was performed in IP1 and IP5, before which the orbit reference was updated, resulting in the rms going back to zero. The short luminosity dips at $t = 2.6$ h, 5.5 h and 7.7 h are induced by luminosity optimisations.

of similar strength can be explained by the frequency content of the received ground movement as illustrated in Fig. 3. This figure selects individual spectra out of the mentioned periods in Fig. 2. The black line shows a reference spectrum during a calm moment without CE work. The red spectrum, recorded at $t = 5.6$ h, excited around 25 Hz and had only very little impact on the beam. The orange, green and purple lines, recorded at $t = 2.8$ h, 4.9 h and 6 h exiting around 21 – 22 Hz, had the largest effect on the beam, because those almost exactly hit the triplet resonance at 21 Hz. The two periods around $t = 7 - 8$ h feature about half the seismic amplitude and excite around 30 Hz, leading to an effect on the beam hardly above the noise level.

CONCLUSION AND OUTLOOK

The HL-LHC civil engineering work was clearly visible on the LHC beams. From June 2018, ground motion linked to CE surface activity exceeded the predefined warning threshold on multiple occasions. These events caused orbit disturbances, beam losses and (mainly CMS) luminosity dips of the order of a few percent. The effects were however hardly noticeable during daily LHC operation. No premature beam dumps were induced. The reaction of the

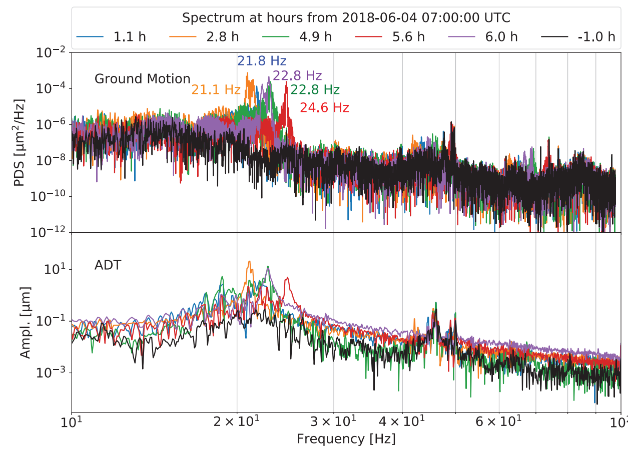

Figure 3: Ground motion (top) and beam (from ADT, bottom) spectra during five CE working periods, showing the changing ground excitation frequency and its presence on the beam. Black: reference measurement without CE excitation.

beams strongly depends on the frequency content of the exciting ground vibrations. The surface work with ground compactors around IP5 had the most significant impact around the triplet eigenfrequency of 21 Hz.

The combination of ground motion sensor recordings, triplet transfer function measurements and optics simulation qualitatively reproduce the effects observed on the LHC beams [12]. The LHC is very close to HL-LHC in terms of optics sensitivity. The IP1/5 triplets are the most critical elements and cause the largest orbit disturbance when vibrating. Preliminary HL-LHC triplet transfer function estimates suggest to be a bit more forgiving than the present triplet [13]. The next important step during the current LHC long shutdown (LS2) is to verify these transfer function estimates on actual hardware and by that confirm the assumed scaling between LHC and HL-LHC.

ACKNOWLEDGEMENT

We would like to thank G. Baud, M. Gasior, J. Olexa, M. Soderen and D. Valuch for setting up the new data streams and interfaces to collect and log beam spectra with the ADT and DOROS BPMs of the LHC. Our gratitude goes to M. Fernandes Morais and Z. Arenas for providing details of the executed CE activities.

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