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ESTIMATED IMPACT OF GROUND MOTION ON HL-LHC BEAM ORBIT*

D. Gamba†, R. Corsini, M. Guinchard, M. Schaumann, J. Wenninger
CERN, Geneva 1217, Switzerland

Abstract

The High Luminosity LHC (HL-LHC) will require unprecedented orbit stability at the low beta collision points (IP1 and IP5), and the effect of seismic noise might become a relevant source of luminosity loss. Many studies have been conducted in the past to characterise the actual ground motion in the LHC tunnel, and recently a few geo-phones have been installed to permanently monitor the ground stability at IP1 and IP5. An estimate of the impact of the main machine element vibration on orbit at the IPs and collimators is presented, together with a first look at the data collected by the installed geo-phones.

INTRODUCTION

The impact of ground motion on LHC was studied (e.g. in [1,2]) on the basis of the LEP and SPS experience in order to assess the expected orbit drift along a fill and from fill to fill. Those studies resulted in the necessity of an orbit feedback able to cope only with low frequency drifts of the machine. This was confirmed by the LHC operation experience [3]. More recently, new studies have been necessary in view of the tunnel excavation works in preparation of HL-LHC and in view of the Geothermie2020 project [3–6]. In this framework it is also worth verifying that the present ground motion levels are compatible with HL-LHC operation, and eventually review the cold mass support design and/or foresee an upgrade of present orbit feedback.

The aim of this paper is to give a first comparison between HL-LHC and LHC in terms of sensitivity to ground motion.

ASSUMPTIONS

The impact of ground motion on the accelerator performance depends on its frequency f:

- $f < \approx 1$ Hz: slow orbit drifts; reduction of available orbit corrector strength; frequent machine re-alignments;
- $\approx 1 < f <$ a few 100 Hz: closed orbit jitter; beam intensity and luminosity losses;
- $f >$ a few 100 Hz: emittance growth; increase in tail's population; beam lifetime reduction.

Strong vibrations could also induce large intensity losses and trigger undesired beam dumps. The boundary of the high frequency regime is dictated by the first betatron motion side-band, which for LHC and HL-LHC ($f_{rev} \approx 11245$ Hz, $Q \approx 0.31$) is 3.5 kHz. Normally no emittance growth is expected at lower frequencies, but this is being verified in dedicated machine studies [7].

* Research supported by the HL-LHC project
† davide.gamba@cern.ch

In the following we consider the mid-frequency regime, where ground motion mainly causes closed orbit variation through transverse displacement of the quadrupoles.

The amplification factor between a single quadrupole (q) displacement Δx_q and the beam closed orbit variation Δx_s at a location s, normalised by the local beam size (neglecting the dispersion contribution) is equal to:

$$\frac{\Delta x_s}{\sqrt{\beta_s \epsilon_N/\gamma}\Delta x_q} = \frac{\sqrt{\beta_q}(K1L)_q}{\sqrt{\epsilon_N/\gamma}} \frac{\cos(2\pi\phi_{qs} - \pi Q_x)}{2\sin(\pi Q_x)}, \quad (1)$$

where ϵ_N is the normalised beam emittance, γ is the relativistic factor, $(K1L)_q$ is the integrated strength of the quadrupole, ϕ_{qs} is the phase advance (in units of 2π) between q and s, Q_x the machine tune and $\beta_{q/s}$ are the Twiss beta functions at q and s, respectively. By assuming a perfectly linear machine, the impact of each quadrupole misalignment can be treated independently. The contributions for each quadrupole can be summed up directly or in quadrature depending if the motion is totally correlated or uncorrelated.

LHC is mainly made of two aperture quadrupoles with the exclusion of the triplets on each side of the Interaction Points (IPs) which have a single common aperture. In both cases we assume that a quadrupole transverse displacement affects both beams in a fully correlated way.

Luminosity is one of the key parameter to measure the performance of a collider and, assuming Gaussian head-on colliding beams, is defined as [8]:

$$\mathcal{L} = \frac{N^2 f_{rev} N_b}{4\pi\sigma_{beam}^2} W, \quad (2)$$

where N_b is the number of colliding bunches, N is the number of particles per bunch, σ_{beam} is the beam transverse size (assumed to be equal for both beams and planes) and W is a reduction factor that takes into account for the beam orbit separation at the IP, which is defined as:

$$W = e^{-\frac{1}{4\sigma_{beam}^2}(\delta_s)^2}, \quad (3)$$

where δ_s is the IP orbit separation of the colliding beams.

LHC AND HL-LHC SENSITIVITY

By simply using Eq. (1) one can estimate the sensitivity to ground motion of the beams orbit at IPs and collimators. Equation (1) only depends on the optics implemented in the machine and some known beam parameters. For the following analysis we consider the nominal beam/optics (ATS [9]) currently in operation in the LHC ($\beta^* = 40$ cm, 6.5 TeV, $\epsilon_N = 3.75$ µm) and the baseline for the end of the squeeze in HL-LHC ($\beta^* = 15$ cm, 7 TeV, $\epsilon_N = 2.5$ µm).

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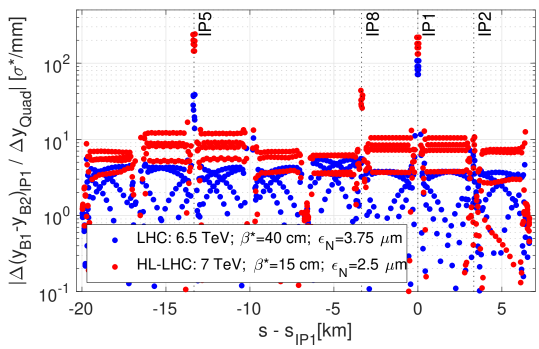

Figure 1: IP1 beam orbit separation amplification factor induced by each quadrupole displacement in LHC (blue) and HL-LHC (red). The location of the IPs is highlighted.

Table 1: Amplification factors between uncorrelated motion at all quadrupoles or IR1/5 triplets only and beams separation jitter in IP1 and IP5. All values are given in r.m.s. beam sigmas per r.m.s. mm of quadrupole displacement.

	IP1		IP5	
	$\sigma_{\Delta x}$	$\sigma_{\Delta y}$	$\sigma_{\Delta x}$	$\sigma_{\Delta y}$
LHC all quads	360	274	360	275
LHC IR1/5 only	353	264	354	294
HL-LHC all quads	721	758	719	755
HL-LHC IR1/5 only	703	736	704	735

Orbit Separation at IP

Figure 1 shows the amplification factors between each LHC/HL-LHC quadrupole vertical displacement and the induced Beam 1 (B1) and Beam 2 (B2) vertical orbit separation at IP1 computed using Eq. (1). To be noted the non-local impact of a triplet displacement: especially in HL-LHC, a displacement of the IP5 triplet can induce an orbit separation in the far IP1 of comparable amplitude to a displacement of the local IP1 triplet. In HL-LHC the impact of the arcs adjacent to IP1/5 is also enhanced with respect to the LHC due to the introduction of the ATS optics, but it remains well below the impact of the IP1/5 triplets.

Assuming a fully un-correlated and uniformly distributed ground motion along the whole accelerator one can sum in quadrature all contributions of each quadrupole obtaining the values reported in Table 1 for both IP1/5 and planes. Note that the obtained values are dominated by the contributions of the triplets in IP1 and IP5. The HL-LHC will be in general a factor 2 more sensitive to ground motion than LHC.

The Interaction Region (IR) from Q3 left to Q3 right of an IP has a length of approximately 100 m. The values in Table 1 have been computed assuming that each quadrupole vibrates independently of each other. Figure 2, instead, shows the maximum amplification from ground motion to beam orbit separation for a single transverse wave that propagates along the IR with no dissipation, for different wavelengths. The non-local behavior is reproduced also in this case: an

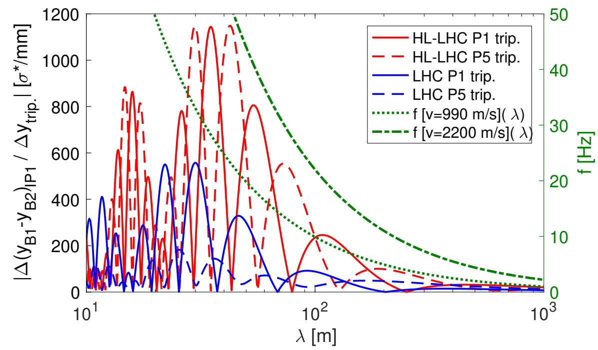

Figure 2: Maximum vertical beam orbit separation at IP1 under the effect of a sinusoidal vibration along IR1 (solid) or IR5 (dashed) for LHC (blue) and HL-LHC (red) as a function of the vibration wavelength. The green curves give the wave frequency (right axis) assuming two extreme wave propagation speeds.

oscillation in IR5 has an equivalent impact on IP1 than an oscillation in IR1 but for slightly different wavelengths.

With respect to the values obtained in the uncorrelated case (Table 1), the fully correlated case could give about a factor 2 higher ground motion to orbit separation amplification for higher frequencies. However, in absence of strong single-frequency narrow-band excitations, the ground motion correlation quickly drops to zero over short distance for frequencies above a few Hz [10, 11], therefore the assumption of un-correlated motion seems reasonable. On the contrary, for low frequencies the correlation might be preserved and therefore in this regime the un-correlated estimations from Table 1 might be strongly overestimated. Depending on the wave propagation speed (V), one can estimate the corresponding frequency as $f = V/\lambda$. The typical wave speeds measured in the CERN tunnels are 990 m/s for shear and 2200 m/s for pressure waves. Assuming a conservative 10 Hz as frequency separation between the two regimes, this would correspond to about 100 to 200 m wavelengths which is of the order of the IR length. In absence of strong local ground motion sources it is therefore unlikely to see the large amplification shown in Fig. 2.

Orbit Excursion at Collimators

Figure 3 shows the amplification factor between each LHC/HL-LHC quadrupole displacement and the maximum beam 1 (B1) vertical orbit variation at the primary collimators (TCPs). The computed integrated values assuming uncorrelated ground motion along the whole machine for each beam and plane are reported in Table 2. Note that also the orbit at collimators is dominated by the effect of the low beta triplets, and that there will be an enhancement of sensitivity of about a factor 2 between LHC and HL-LHC.

MEASUREMENTS

Ground motion sensors have been installed in the vicinity of IP1 and IP5 and on surface [12]. Figure 4 shows the

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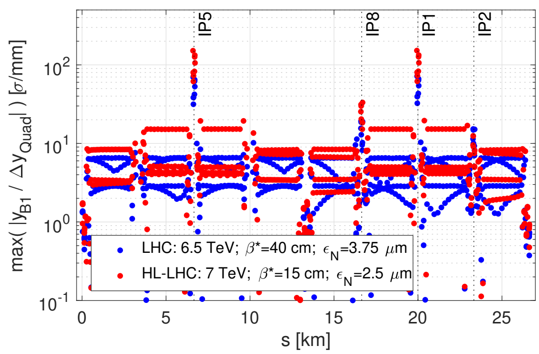

Figure 3: Maximum vertical beam 1 orbit variation at the primary collimators induced by each quadrupole vertical displacement in LHC (blue) and HL-LHC (red). The location of the IPs is highlighted.

Table 2: Maximum orbit excursion at a primary collimators (TCP) under the effect of uncorrelated ground motion. All values are given in beam sigmas per mm of ground motion.

	B1		B2	
	Δx	Δy	Δx	Δy
LHC all quads	205	207	212	169
LHC IR1/5 only	179	187	189	146
HL-LHC all quads	393	454	418	227
HL-LHC IR1/5 only	367	425	394	195

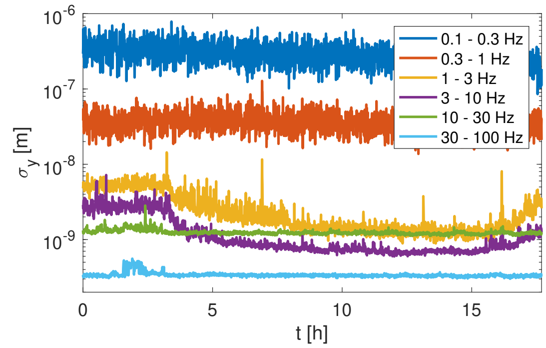

Figure 4: Measured vertical ground motion in LHC P1 integrated over different band of frequencies as a function of time from the start of a typical LHC fill.

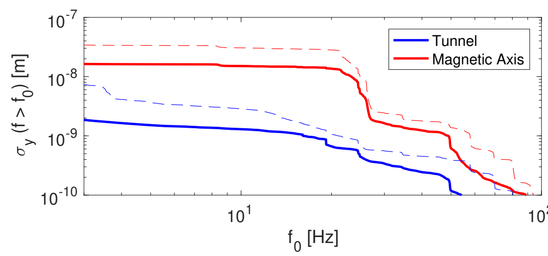

Figure 5: Integrated PSD of the mean (solid) and max (dashed) ground motion during an LHC fill with (red) or without (blue) amplification measured in [5].

typical r.m.s. ground motion measured in P1 integrated over a series of frequency bands along a fill in 2017. The variation in the frequency range from 1 to 10 Hz is a repetitive pattern showing the different noise levels between day and night.

The amplification between ground motion and magnetic center motion of a spare LHC Q1 magnet has been measured in [5] for frequencies above 3 Hz. With the assumption of fully uncorrelated ground motion, this can be used to estimate the effective motion of the quadrupole axis. Figure 5 shows the integrated power spectral density (PSD) for $f > 3$ Hz. From such an estimation the expected r.m.s. vertical motion of the triplets should be below 0.04 µm. In such a condition and by considering the amplification factors in Tables 1 and 2, and by using Eq. (3) to compute the expected luminosity reduction, one obtains the values in Table 3. We assume that the motion at frequencies below 3 Hz fall in the correlated case which should have a much lower impact (see Fig. 2) and/or would be taken care of by the present orbit feedback. During the fill under analysis the measured luminosity and orbit variation at the primary collimators did not show any visible impact of ground motion, which is consistent with the values in Table 3.

Table 3: Expected max r.m.s. beam orbit separation at the IP, consequent luminosity loss and orbit at the collimators for uniform and uncorrelated ground motion of 0.04 µm r.m.s.

	LHC	HL-LHC
Orbit sep. IP1/5 [σ_{beam}]	0.01	0.03
Luminosity loss [%]	< 0.1	< 0.1
Orbit at TCPs [σ_{beam}]	0.01	0.02

OUTLOOK AND CONCLUSIONS

From our analysis we conclude that HL-LHC will be approximately a factor 2 more sensitive to ground motion than LHC. Despite of that, with the present estimation of ground motion and its impact on magnetic center motion, no luminosity loss due to orbit jitter should be expected. This estimate relies on the assumption that the new HL-LHC triplet mechanical assembly will behave similarly to the preset LHC one. A verification of this is envisaged.

Excavation works in preparation for HL-LHC will start soon and they will partially overlap with beam operation. During those works the magnets motion should not exceed 1 µm according to the present estimate [5]. As a worst case scenario, according to our model this could give up to 3% luminosity loss and $0.2\sigma_{beam}$ orbit oscillation at the primary collimator. The observation of the actual beam behaviour will be fundamental to systematically verify how conservative are our assumptions and model. The search for common signatures in the spectra of motion sensors and beam signals (beam losses, beam position, luminosity) are ongoing.

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Studies to evaluate the impact on emittance blow-up at various frequency regime are also ongoing [7].

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