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IMPACT OF VIBRATION TO HL-LHC PERFORMANCE DURING THE FPF FACILITY CONSTRUCTION*

D. Gamba†, H. Bartosik, M. Guinchard, K. Pál, J. Wenninger, K. Widuch
CERN, Geneva, Switzerland

Abstract

The Forward Physics Facility (FPF) is a proposed experimental facility to be installed several hundred meters downstream from the ATLAS interaction point to intercept long-lived particles and neutrinos produced along the beam collision axis and which are therefore outside of the acceptance of the ATLAS detector. The construction of this facility, and in particular the excavation of the associated shaft and cavern, could take place in parallel to beam operation in the CERN accelerator complex. It is therefore important to verify that the ground motion caused by these works does not perturb the standard operation of the SPS and LHC. In this work, the sensitivity to vibration and misalignments of the SPS and LHC rings in the vicinity of the affected area will be presented, together with the expected perturbations on beam operation following the experience gathered during the construction of the HL-LHC infrastructure around the ATLAS experiment.

INTRODUCTION

The installation of FPF [1] requires the excavation of a 65 meter-long and 9.65 meter-wide cavern at about 620 meters in the line of sight of the LHC Interaction Point 1 (IP1). This cavern will be about 10 meters away from the LHC tunnel and will be accessible by a 90-meter-deep access shaft, which will also need to be excavated. A layout of the site with the relevant distances from the nearby LHC and SPS tunnels is shown in Fig. 1.

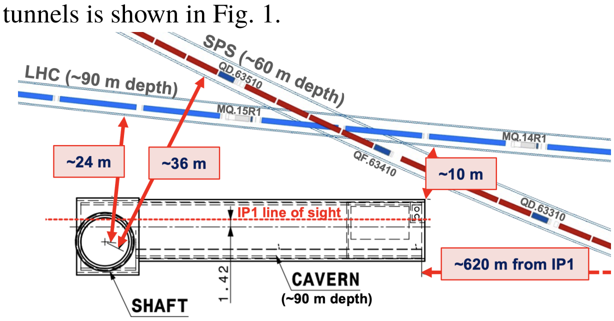

Figure 1: Layout of the proposed location of the FPF facility on the right-hand side of LHC IP1, with relevant distances to nearby tunnels of the CERN accelerator infrastructure.

Excavation works for the shaft and the underground cavern might be performed during HL–LHC Run 4 beam operation. This kind of activity is not new at CERN, and studies on the impact on the operation were performed in the past, for example in preparation for LHC at LEP times [2–5], and more recently in preparation of HL–LHC civil engineering works during LHC operation [6–8]. Also for the proposed FPF facility, a series of feasibility studies have been launched, and the present status is summarised in Ref. [9]. In this paper, we aim at progressing on the following aspects:

- Provide an analysis of SPS and HL–LHC sensitivity to quadrupole displacements;
- Estimate the vibration levels that could impact HL–LHC luminosity production;
- Estimate the impact of possible local deformation of LHC and SPS tunnels on the operability of those accelerators without the need for realignment.

Experience shows that both vibration and tunnel deformation primarily affect the vertical plane, therefore we will concentrate our attention on this plane, even though from a beam optics point of view both planes will be approximately equally sensitive in both machines.

OPTICS SENSITIVITY

In linear optics, the closed orbit distortion Δx_s at a location s caused by a static kick θ_{s_0} generated at a location s_0, is given by:

$$\Delta x_s = \frac{\theta_{s_0}\sqrt{\beta_s \beta_{s_0}}}{2\sin(\pi Q_x)}\cos(\pi Q_x - 2\pi|\phi_{s_0,s}|), \quad (1)$$

where $\phi_{s_0,s} = \phi_s - \phi_{s_0}$ is the phase advance between observation and kick locations. For many kick sources (i) the total closed orbit variation at a generic downstream location s is obtained as the sum over all kicks, and, developing the cos term in Eq. (1), and using exponential notation, one can easily demonstrate that:

$$\frac{\Delta x_s}{\sqrt{\beta_s}} \leq \frac{1}{2\sin(\pi Q_x)}\left|\sum_i \theta_{s_i}\sqrt{\beta_{s_i}}\exp(j2\pi\phi_{s_i})\right|, \quad (2)$$

or more conveniently written as:

$$\frac{\Delta x_s}{\sqrt{\epsilon_G \beta_s}} \leq \left|\sum_i \theta_{s_i} A_i \exp(j2\pi\phi_{s_i})\right|, \quad (3)$$

where A_i is a function that can be computed for a given optics, and the geometric emittance normalisation $1/\sqrt{\epsilon_G}$ is used to conveniently express the displacements in terms of the local beam size, which can be a metric for comparing different optics or machines, even if this does not take into account the available or required aperture (which is not considered here). The phase advance ϕ_{s_i} in Eq. (3) is defined with respect to an arbitrary location.

* Work supported by the Physics Beyond Colliders Study Group
† davide.gamba@cern.ch

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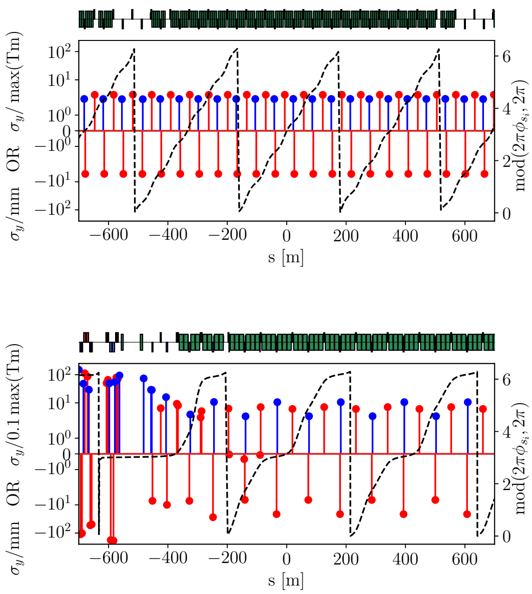

Figure 2: Optics sensitivity of SPS Q26 (top), and HL–LHC B1 (bottom) to vertical misalignments of quadrupoles (red) and for max (SPS) or 10% of max (HL–LHC) available vertical orbit corrector strengths (blue) in terms of A_i (stems) and phase advance (dashed) terms of Eq. (3). Only the ring portions 700 m around the projected intersection between the LHC and SPS tunnel as visible in Fig. 1 are shown.

Kicks generated by misaligned quadrupoles (q_i) can be expressed as:

$$\theta_{q_i} = \Delta X_{q_i} (K_1 L)_{q_i}, \tag{4}$$

and the quadrupole integrated strength $(K_1 L)_{q_i}$ can also be embedded in the A_i term definition of Eq. (3) leaving only the misalignments ΔX_{q_i} as free parameters. Kicks induced by closed orbit correctors are obtained as:

$$\theta_{s_i} = (K_0 L)_i = B_i L / B\rho, \tag{5}$$

where $B\rho$ is the beam rigidity and $B_i L$ the integrated dipole strength of the corrector. They can be used to provide a simple comparison between the effect of quadrupole misalignment and the available orbit corrector strength.

The high-energy beams are the most critical as geometric emittance and available strength from orbit correctors are at their minima. Optics with the highest beta functions and/or quadrupole strength are also critical. Figure 2 shows the optics sensitivity of the SPS and HL–LHC to vertical misalignments assuming the following worst-case scenarios:

SPS: Q26 optics, $\epsilon_G = \epsilon_N/(\beta\gamma) \approx 2\,\mu\text{m}/481$.

HL–LHC: 15 cm β^* optics, $\epsilon_G \approx 2.5\,\mu\text{m}/7461$.

This shows, for example, that 1 mm vertical misalignment of quadrupole MQ.14R1 in HL–LHC, just to the left (in LHC clockwise convention) of the interested area, can induce up to 20 beam σ closed orbit deformation on B1, and that the adjacent orbit corrector (MCBV14R1.B1) can compensate up to 5 mm misalignment (assuming all corrector strength is used only for correcting this misalignment). The quadrupoles next to IP1, at $s \approx -650$ m in Fig. 2, are a factor 10 more sensitive, i.e. a single quadrupole displacement there can induce orbit perturbations up to 200 σ/mm. In this region, the SPS is about a factor of three less sensitive to quadrupole misalignment than HL–LHC. On the other hand, the HL–LHC orbit correctors can in principle be used for locally correcting static quadrupole misalignments of several millimetres, while the SPS orbit corrector strength is limited. This is one of the reasons why, in the SPS at high energy, global orbit correction is performed by voluntary displacements of quadrupoles [10].

EXPECTED VIBRATION EFFECTS

The effect of vibration induced by civil engineering (CE) works in the area has been recently studied for HL–LHC and summarised in [6]. The main concern was the possible vibration of the final focusing triplet magnets, which could lead to beam orbit oscillation, loss of luminosity and eventually trigger beam dumps. The impact of vibration or tunnel movements on the SPS was deemed negligible, as the CE works for HL–LHC was several tens of meters away from the SPS tunnel. To minimise the risk of perturbation of LHC operation, a network of ground motion sensors was deployed [11], and it was agreed that CE activity should be stopped if vibration levels were reaching a given threshold and that most of the underground caverns were to be excavated during the Long Shutdown 2 (LS2).

Figure 3 shows the measured vertical ground motion levels next to IP1, and the corresponding magnet vibrations over the last five years. Note the few events that crossed the 1% luminosity threshold in 2018. They had negligible impact on luminosity production and beam losses [6]. Higher vibration levels were constantly detected during LS2, especially in 2019 when caverns a few tens of meters away from IP1 were excavated. These observations give good confidence in

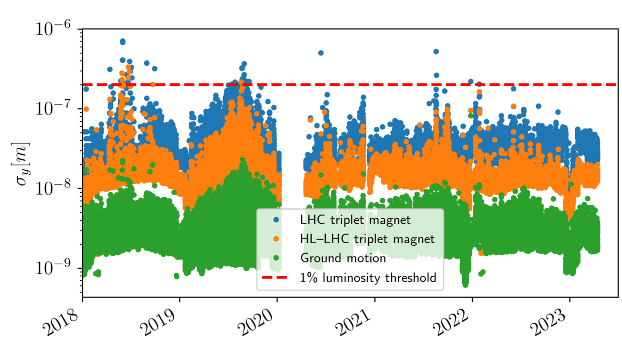

Figure 3: Vertical rms ground motion measured at IP1 in the 3 to 100 Hz frequency range, sampled every 30 minutes (green). This data is amplified using simulated HL–LHC (orange) and measured LHC triplet magnet transfer functions [6]. The dashed red line indicates the threshold above which a 1% luminosity loss would be expected in HL–LHC.

the ground motion model studied in [8] which can then be

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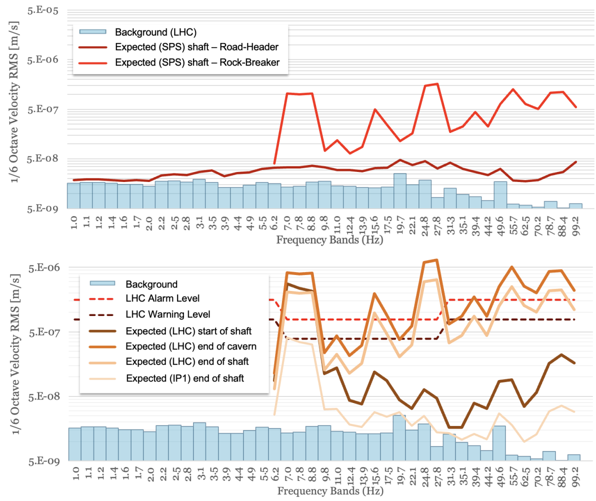

Figure 4: Expected vibration levels in different frequency bands from a few Hz to 100 Hz in the SPS tunnel using rock-breaker and road-header excavators (top) and HL–LHC tunnel using rock-breaker (bottom). For the HL–LHC tunnel, the alarm thresholds used during the HL–LHC civil engineering works are also shown [12].

used to predict the ground motion levels to be expected in HL–LHC and SPS tunnels during the excavation of the FPF facility. The expected CE machines to be used for the FPF facility excavation are rock-breaker and road-header excavators. Rock breakers induce much stronger vibrations than road headers, but they are also more efficient and typically preferred for tunnel excavation works. Figure 4 shows the expected ground motion levels in the SPS and LHC tunnels during the excavation of the FPF facility [12]. During the excavation of the cavern, the expected vibration levels remain close to the alarm threshold only next to IP1 (i.e. worst case scenario and most sensitive location), while vibrations up to a factor of ten above the threshold are to be expected in the nearby tunnel portions. Here, on the other hand, the sensitivity of the optics is a factor of 10 lower than the triplet (See Fig. 2), so the impact on HL–LHC is expected to be comparable to what was observed in 2018 [6]. The expected vibration levels in the SPS are comparable, but the sensitivity of the optics is even lower, so no major disruptions are expected. In case of problems, the use of a road header will drastically reduce the vibration levels for both SPS and HL–LHC (not shown), and can be considered as a backup solution.

EXPECTED TUNNEL DEFORMATION

A local movement of the LHC tunnel of up to 1.5 mm over a length of about 50 m have been observed in August 2019 during the excavation of an HL–LHC cavern (about five-meter wide, thirty-meter long) just about five meters above the tunnel, as shown in the data in Fig. 5, while no other sudden displacements of the tunnel have been observed during the shaft and nearby underground gallery works.

The excavation of the LEP tunnel underneath the SPS tunnel caused vertical movements of the SPS tunnel by ap-

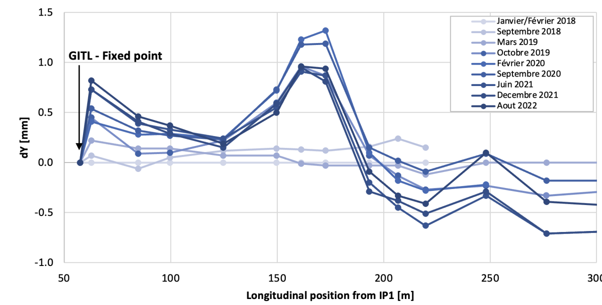

Figure 5: Measured vertical movement of LHC tunnel next to IP1 during excavation works of HL–LHC [13, 14].

proximately 6 mm in the proximity of cell 606, on the left of P1 [2]. This area is also known to be unstable and requires continuous vertical alignment [10]. On the other side of P1, i.e. in SPS cell 635, where the FPF facility should be excavated, no displacements were recorded during LEP tunnel excavation [2], and this area is just at the end of the unstable area reported in Ref. [10]. It could be concluded that up to about 1 mm tunnel movements are to be expected in the proximity of excavation works, i.e. on a portion of the tunnel between 50 and 100 meters long. In this case, local orbit corrector strengths should be enough to correct for sudden misalignment of quadrupoles in HL–LHC, while some aperture reduction might be expected in the SPS due to the limited available orbit corrector strength. The SPS vertical aperture is of the order of 30 mm [15], which corresponds to about 45 beam sigma at top energy, hence a movement of a few local quadrupoles by about 1 mm, and corresponding orbit movements of the order of 5 to 10 beam sigma (see Fig. 2) should be tolerable, even considering the SPS fixed-target beams with typically a factor of two to four larger emittance. This amplitude of misalignment is also comparable to the voluntary quadrupole displacements performed during or after yearly shutdowns for SPS beam-based alignments, which, if required, could be also performed during a one-day-long technical stop. Detailed site investigations with core drilling are ongoing at the exact location of the FPF shaft to confirm the geological composition of the ground [9], and to give a more precise estimate of possible tunnel movements.

CONCLUSION

The optics sensitivity of HL–LHC in the area of the FPF facility excavation works is about a factor of 10 smaller than in the triplet area, and a factor of 3 more than in the SPS optics. Vibration levels and associated impact on orbit stability and luminosity production are expected to be comparable to what was observed during HL–LHC civil engineering works during the LHC 2018 run. In case of excessive vibration levels, road headers might be employed instead of rock breakers. No major tunnel deformations are expected. If any, they could be compensated during the run with orbit correctors (at least for the HL–LHC) followed by re-alignment of the concerned area during a winter shutdown. The general conclusion is that no major disruption of HL–LHC and SPS performance is expected during the FPF excavation works.

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