LHC ORBIT STABILISATION TESTS AT THE SPS

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Abstract

The LHC, presently being built at CERN, is the first proton collider that requires a continuous orbit control for safe and reliable machine operation. A realistic test of the orbit feedback system was performed in 2004 using already-present LHC instrumentation and infrastructure on a 270 GeV coasting beam in the Super-Proton-Synchrotron. It has been demonstrated that the chosen feedback architecture can stabilise the beam better than 10 micrometres and is essentially limited by the noise of the beam position monitor and the bandwidth of the corrector magnets. The achieved orbit stability is comparable to those found at modern light sources and gives enough operational margin with respect to the requirements of the LHC Cleaning System (70 μm). Estimates for the long-term drifts and achievable stability will be presented based on the experimental results.

INTRODUCTION

Unlike other hadron machines, the Large Hadron Collider (LHC) requires a continuous orbit control for safe and reliable machine operation. The LHC Collimation System has the tightest constraints on orbit stability of $\approx \frac{\sigma}{3}$ (σ= r.m.s. beam size), which corresponds to $\approx 300\,\mu$m at 450 GeV and $\approx 70\,\mu$m at 7 TeV[2]. Other requirements range from 0.5-1 mm for global stabilisation down to 10 μm for physics analysis improvements in the Totem experiment[3]. The number of requirements, their local extent and coupling of the two beams' positions due to the four crossing regions make a global feedback system for both beams necessary. Its prototype was developed and successfully tested at the SPS[1].

ORBIT PERTURBATIONS

There are three important classes of orbit movements for orbit feedback:

1. Machine-inherent sources, such as decay and snap-back of the main dipoles' multipole momenta, changes of the final focus optics squeeze, eddy currents on the vacuum chamber, and ramp-induced dynamic effects. Though this class of orbit perturbations can exceed 20 mm, they should, in general, not pose a problem since their timescale can be adapted within limits to operationally suitable conditions.

2. Machine element failures, in particular of orbit correction dipole magnets (CODS).

3. Environmental sources, such as ground motion, temperature, pressure changes and other effects. These effects affect the beams through the quadrupoles and their girders. The resulting orbit r.m.s. movement Δx_{beam} can be described by an amplification $\kappa(f)$ of the quadrupoles' r.m.s. movement Δx_{quad}:

$$\Delta x_{beam} = \kappa(f) \cdot \Delta x_{quad} \qquad (1)$$

The amplification $\kappa(f)$ depends on the machine optics and is a function of the frequency and coherence of the excitation. For very slow correlated ground motion such as the tides, the amplification κ vanishes, since their wavelength exceed the machine's diameter. Nevertheless, tides still affect the circumference and hence the energy of the ring. For uncorrelated ground motion, $\kappa(f)$ is a constant and is estimated to be $\kappa \approx 28$ for the SPS and $\kappa \approx 20$ and $\kappa \approx 40$ for the LHC injection and the LHC collision optics, respectively. Typical SPS and LHC ground motion spectra are shown in Figure 1. Both tunnels are extremely quiet and are barely influenced by cultural noise. The spectra are essentially the same. Hence, it is possible to predict orbit drifts at the LHC from SPS results.

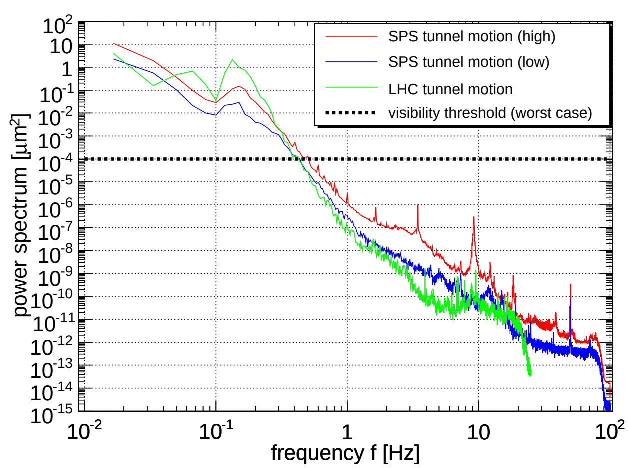

Figure 1: Averaged ground motion power spectra in the SPS and LHC tunnel. The 'high' SPS spectrum was recorded during ongoing installation work. The $\frac{1}{f^2}$ dependence that is typical for Brownian motion and drifts, and the hum around 0.1 Hz due to ocean swelling are visible. The detection threshold corresponds to the ground-motion level having a 1 μm effect on the beam, assuming a worst-case constant propagation factor $\kappa = 100$.

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ORBIT STABILITY

For the LHC, uncorrelated ground motion dominates over correlated ground motion. Though the latter may have a stronger amplification of up to a factor of $\kappa(f) \approx 60$ for frequencies above 3 Hz, they contribute less, because the power spectra decreases rapidly above this frequency. Assuming a detection threshold of 1 μm for an orbit change, it is possible to estimate the frequency range of ground motion that needs to be considered for the orbit feedback. From Figure 1, and assuming $\kappa \approx 100$, it is evident that ground motion above 1 Hz does not pose a problem at the LHC, whether the movement is correlated or not.

In 2004, long-term measurements were performed with a 270 GeV coasting beam in the SPS. Figure 2 shows an example of the vertical beam motion power spectra of a 270 GeV and 26 GeV coasting beam in the SPS that was sampled at a monitor with LHC readout electronics ($\beta \approx 100\,\mathrm{m}$). A prediction ($\kappa = 28$) for the spectrum due to uncorrelated tunnel motion is shown. The orbit movements of the 270 GeV beam are much smaller than at 26 GeV, which indicates that the earlier measurements in 2003 may have been dominated by machine-inherent effects such as drifts of magnetic fields rather than by ground motion. This measurement[1] confirms that in the range of 0.01-0.7 Hz the tunnel ground motion is highly coherent, in agreement with seismological measurements performed elsewhere. Measurements described in [4, 5] identify and locate the cause of the hum around 0.1 Hz to be due to storms on the northern oceans during the Northern Hemisphere winter and southern oceans during the Southern Hemisphere winter. From the SPS diameter, one can estimate the coherence length of this type of ground movement to be at least 2 km.

FEEDBACK DESIGN

Steering of the LHC beams is done with more than 1000 beam position monitors and 530 correction dipole magnets (CODs). The closed orbit data is sent by about 70 BPM front-end computers through the Gigabit-Ethernet to the central orbit feedback controller (OFC). This performs the correction and sends the new COD deflections to the 50 power converter front-end computers controlling the CODs that will move the beam. The OFC uses a SVD-based correction algorithm for the space domain. In the time domain, a standard PID controller with Smith-Predictor extension is implemented for each COD to improve the feedback response and to compensate for constant transmission delays. The targeted feedback frequency of 25 Hz is sufficient for the expected orbit drifts and is matched to the superconducting LHC COD small signal bandwidth of 1-2 Hz.

[1]The measured quadrupole girder response does not show damping for this frequency range, which would explain the missing signal.

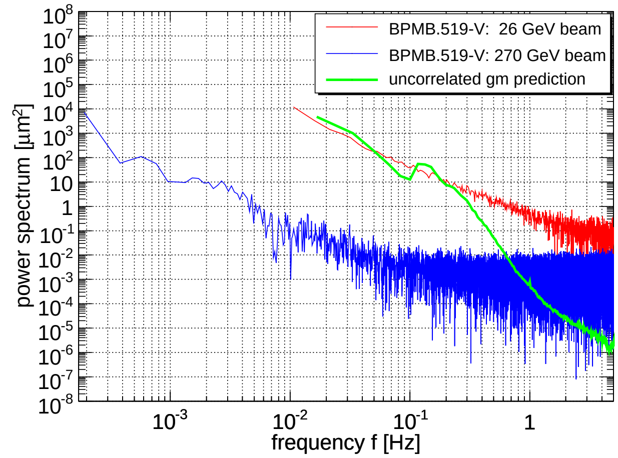

Figure 2: Power spectra of orbit movement at 26 GeV and 270 GeV in the SPS. The white-noise floor of the BPM for high frequencies is visible. The 26 GeV coast might be dominated by slow drifts of the magnetic fields rather than by ground motion. The predicted power spectrum for a worst-case (fully uncorrelated) propagation of the tunnel motion on the beam is shown. In comparison with the actual 270 GeV coasting beam, it is evident that the peak due to the ocean hum is, to a large extent, correlated.

FEEDBACK AND BPM STABILITY

The network connecting the BPMs, the OFC and COD front-ends was identified to be the bottleneck of the 2003 feedback prototype. Under high network load, non-deterministic delays affected the feedback response and its reliability. During the 2003/2004 shutdown, the SPS network infrastructure was upgraded to the same hardware foreseen for the LHC. The new network provides hardware-based quality of service queues, of which one is dedicated to the transport of orbit feedback data[2]. Latency tests[3] for data delivery over kilometre-long distances have shown that the total delay between the feedback front-ends is below 300 μs, which is negligible for a 25 Hz feedback frequency. The delay is actually dominated by the speed of light in the optical fibre transmission. The delays created in the front-end computers are an order of magnitude larger and more critical for the reliability of the total system.

The LHC prototype feedback system showed good overall performance and could maintain an orbit stability of 2 μm r.m.s (corresponds to about $\frac{2}{1000}\sigma$, with σ the r.m.s. beam size) over the length of one coast as shown in Figure 3. Though the SPS orbit correctors are capable of steering the beam with an effective bandwidth of about 14 Hz, the feedback gains, that we used for the feedback tests, limited the effective bandwidth to about 0.3 Hz. Since the effective bandwidth of the LHC correctors is higher than the tested effective bandwidth, the above results should, to first order, apply to the LHC.

[2]This is almost equivalent to a dedicated network for the feedback.
[3]data courtesy of M. Zuin, CERN

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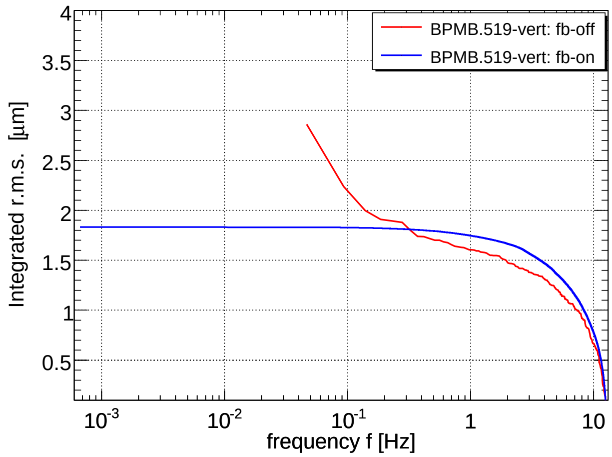

Figure 3: Integrated r.m.s. orbit stability with feedback 'on' and 'off' for a 270 GeV beam in the SPS. The stability is limited by the residual 1.8 μm BPM measurement noise. The excitation of the orbit to the BPM noise level for frequencies above the effective orbit feedback bandwidth of 0.3 Hz is visible.

The present system is essentially limited by the residual noise of the BPM system, visible in Figure 2, which relies on a wide band normaliser bunch-by-bunch measurement as described in [6]. Each closed orbit measurement is obtained by averaging all bunch positions over 255 turns. This default value corresponds to 20 ms in the LHC. It was chosen to suppress potential 50 Hz noise of the BPMs. Due to the very high inductances of nearly all the LHC magnets, the propagation of the 50 Hz power converter ripple through the magnets on the beam is not evident. From the measurements shown in Figure 3, the single-turn measurement noise is less than 115 μm, which scales down to 85 μm for the LHC BPM aperture.

LONG-TERM STABILITY AND RELIABILITY

The BPM electronics is designed to be linear to 1% of the half-radius over a 34 dB dynamic range[6]. Experimental results confirm the remaining systematics, which depend both on intensity and position correspond to a measurement error of up to 135 μm. Compensation of these errors may be necessary for long-term stability required at the collimator locations.

Since delays and their determinism in the data processing of the front-ends affect feedback stability, the numerical implementation of algorithms becomes important. The numerical complexity of the OFC tested at the SPS is negligible because only six monitors were used. The complete LHC system consists of more than 1000 monitors and 530 correctors per plane. With the present SVD-based orbit correction strategy, the correction algorithm in the OFC involves about $4 \cdot 10^6$ operations that require tens of milliseconds of computation time even on high-end machines. Since the feedback runs continuously during all operational phases, it is important to test the OFC under real load and in realistic conditions. A testbed complementary to the OFC was developed, which simulates a realistic open loop orbit response in real time, eight times faster than the OFC, in order to accurately simulate effects due to delays, BPM and magnet responses and to test the OFC with a realistic load. To simplify debugging, the testbed has essentially the same control interfaces as the real machine to make it transparent for the OFC.

CONCLUSIONS

BPM systematics and delays in the feedback loop are the major challenges for reliable long-term orbit stability. The test results of the prototype LHC BPM and feedback systems correspond to the design. Delays due to the network have not been observed and should not pose a problem for the feedback. Ground motion contributions to orbit drifts are less critical for the LHC as compared to machine-inherent sources (e.g. due to optics changes). It has been demonstrated that the present LHC orbit feedback prototype can steer on the micrometre level and can maintain an absolute orbit within the collimation requirements over one run, provided the systematic effects of bunch lengths and intensity on the BPM readings are within limits. The remaining BPM systematics and their possible compensation will be further investigated.

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