

OBSERVATIONS OF LONGITUDINAL LOW FREQUENCY OSCILLATIONS AT THE ESRF

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Abstract

A low frequency oscillation at 360 Hz has been observed in the longitudinal plane at the ESRF. This oscillation has all the characteristics of a collective effect, for example it shifts with intensity, has a clear intensity threshold and can be modified by changing the bunch length. The third harmonic of this frequency overlaps with the synchrotron frequency, causing strong perturbations for one particular beamline using dispersive optics. Until now, no clear explanation has been found.

INTRODUCTION

The ESRF-EBS is a 4th generation light source that has been in operation since 2019 with a horizontal equilibrium emittance of 137 pm [1, 2]. The EBS delivers beam in a variety of different filling patterns, splitting the user service time between multibunch filling patterns at a total current of 200 mA (uniform or 7/8+1) or timing modes (4 bunches of 10mA each, or 16 bunches with 92 mA total). These timing modes require slightly different machine configurations to account for single bunch impedance effects (for example, increased vertical chromaticity and reduced injection bump amplitude). Table 1 shows the machine parameters found during operation in 4 bunch mode.

Table 1: EBS Machine Parameters

	Units	Value
Energy E_0	GeV	6
Circumference C	m	843.977
Harmonic Number h		992
Revolution Time t_0	μ s	2.815
Max. Total Current	mA	200
Max. Single Bunch Current	mA	10
Momentum Compaction Factor α	10^{-5}	8.512
RF Voltage V_c	MV	5.5
Momentum Spread σ_e (zero-current)	10^{-3}	0.9356
Bunch Length σ_z (zero-current)	mm	3.235
Sync. Freq. f_s (zero-current)	Hz	1174.51

In 2024 during a week where 4 bunches at 10mA per bunch were being delivered, ID24b reported an oscillation in the energy of the beam. ID24b is a special branch of the beamline ID24 that performs absorption measurements of biological processes [4]. In order to make these measurements, a polychromator is used (rather than a typical monochromator) and the light is focused onto the sample and then detected behind. A synopsis of this optical setup is

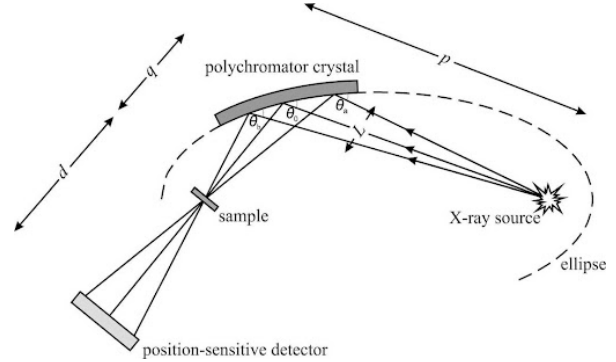


Figure 1: A graphic showing the layout of ID24b [4]. The incoming X-rays reflect off the polychromator in several different places and are focused onto a sample. If the source is oscillating in energy, the focussing onto the sample will also suffer.

shown in Fig. 1. The frequency of oscillation was measured on the beamline and on the storage ring (see Section II) and was found to be a longitudinal oscillation at the synchrotron frequency.

OBSERVATIONS

In order to study the synchrotron oscillation, the horizontal positions from the Beam Position Monitors (BPM) were read-out at a high-sampling rate. From this data (which in some more detailed studies was turn-by-turn, but normally was taken from the Fast Orbit Feedback at 10 kHz), it could be easily concluded whether the observed peaks in the horizontal spectra were longitudinal or transverse, because the longitudinal peaks are only present in the horizontal spectra for BPMs located in the dispersive regions.

During the initial investigation it was found that the true origin of the oscillation was in fact an oscillation at a much lower frequency (~ 360 Hz). This is the so-called Low Frequency Oscillation (LFO). The third harmonic of this mode was overlapping with the synchrotron frequency which drove synchrotron oscillations. With one single bunch at a current of 10mA, the turn by turn data was extracted from a dispersive BPM and, by performing a Fourier analysis, it was found that the contribution of the oscillation at the synchrotron frequency to the total amplitude of the oscillation was about $15 \mu\text{m}$ in the horizontal plane, corresponding to $0.052\sigma_e$ oscillation, whereas only $1 \mu\text{m}$ of oscillation amplitude was coming from the LFO. This means that the LFO does not directly cause the energy oscillation, but only through the excitation of the synchrotron tune is the oscillation created.

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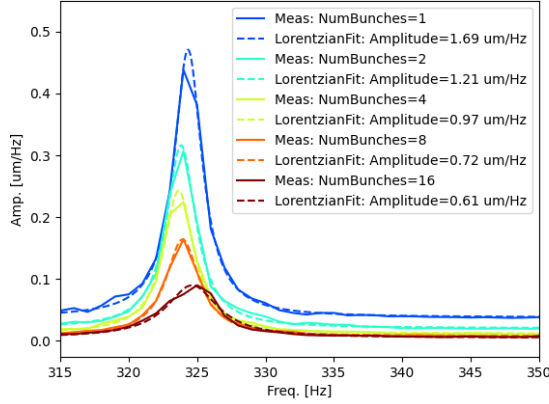


Figure 2: The LFO mode measured with symmetrically filled patterns of 4mA bunches. The amplitude reduces, confirming that the bunch oscillations are not correlated.

The first step into the study of the LFO was to try and understand if the source of this mode was being driven externally (by a vibration or coming from the RF cavities directly) or if there was coupled bunch motion. An easy way to determine this was to see if the phase of the LFO on each bunch is correlated.

Figure 2 shows the peak at ~ 325 Hz as a function of the number of symmetrically filled bunches of $I_b = 4$ mA. As can clearly be seen, the amplitude of oscillation reduces and the amplitude scales approximately as $1/\sqrt{N}$ where N is the number of bunches. This measurement shows that the bunch oscillations have random phases, because the total amplitude of the mean oscillation reduces with an increase in statistical error. For an infinite number of bunches, this oscillation amplitude would drop to 0. This shows that the origin of the oscillation is from a mechanism within the bunch itself. Additional measurements were also performed by acquiring turn-by-turn data from the Transverse Bunch-by-Bunch Feedback. The data was acquired in 16 bunch filling mode while the mode was present. By looking at the phase of the Fourier Transform of each bunches oscillation, it also clearly confirmed the lack of correlation between the bunch phases for this frequency.

A scan of the single bunch current was performed to understand how the mode behaved, and the results can be found in Fig. 3. As can be seen, there is a clear threshold current (between 1.0 and 2.0 mA) above which the mode appears, as well as a frequency shift with current. The mode first appears at a much lower frequency (~ 225 Hz) with a very broad peak, before becoming much more narrow and well defined at moderate currents. At this point the frequency shift with current is approximately linear.

From seeing this threshold, between 1 and 2 mA, it seemed to suggest that the origin of the mode could be linked to the microwave threshold (MWT). The MWT had been measured and benchmarked during the commissioning [3], however at the time the RF Voltage was 6MV, and the MWT was never measured at the new operating voltage of 5.5MV. So to see if

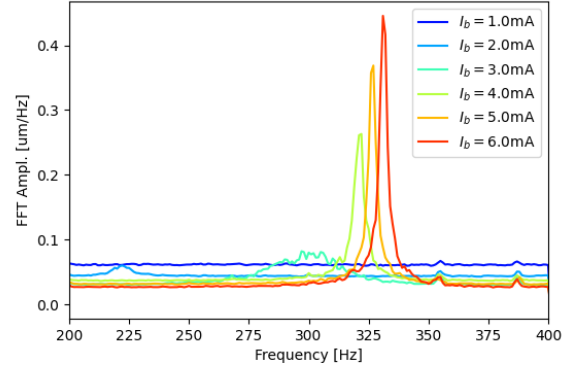


Figure 3: Single bunch current scan, as can be seen, the mode appears quite abruptly above a threshold, and continues to shift with increasing current.

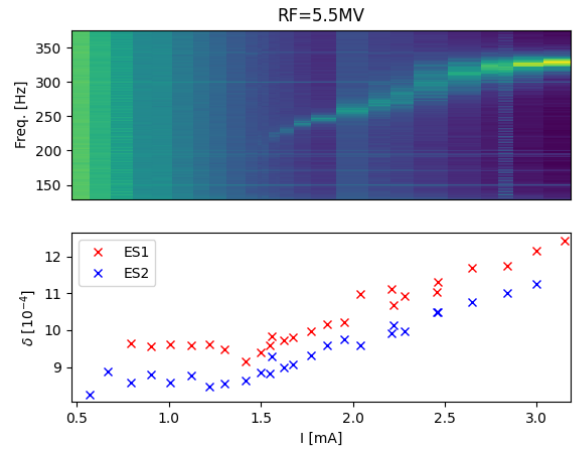


Figure 4: Upper: Average spectrum of all dispersive BPMs vs single bunch beam current. The color bar is arbitrary, and simply shows the amplitude of the mode growing, with a threshold at around 1.6mA. Lower: On the same current scale, the 2 energy spread measurements at the ESRF, showing the MWT around 1.4mA.

the LFO is linked with the MWT, the RF voltage was varied, which modifies the bunch length and therefore modifies the MWT. For each RF voltage, both threshold (MWT and LFO) were measured. An example of one such measurement can be found in Fig. 4. The upper plot shows the average spectrum from all dispersive BPMs vs current, with the corresponding energy spread measured from a combination of 2 of the 4 pinhole cameras in operation on the EBS (see [3] for more information on diagnostics relating to collective effects at the ESRF). Each case shows a clear threshold for the LFO, and also shows the frequency shift with the initial current.

The full results of the measurements can be found in Table 2. As can be seen, the LFO begins to emerge shortly beyond the MWT, showing a clear link between the two effects.

Extensive simulations have been performed with the ESRF-EBS short range wake potential model. Despite a

Table 2: The threshold values as a function of RF Voltage (in MV). The MWT and LFO Thresh. are in units of mA, whereas the first frequency seen (LFO Freq.) is given in Hz. Reducing the voltage, and therefore increasing the bunch length, increases the MWT, which pushes the onset of the mode to higher currents.

V_c	MWT	LFO Thresh.	LFO Freq.
5.5	1.4	1.6	230
3.96	1.85	2.05	210
3.42	2.25	2.4	193

discrepancy in the MWT between measured and simulated, a LFO was never observed in simulation up to $I_b = 30\text{mA}$.

POSSIBLE EXPLANATIONS

LFOs have been observed in many third generation light sources (3GLS) [5, 6], however they are not necessarily linked to the MWT. For 3GLS's, they were normally driven by cavity higher-order-modes (HOMs). A typical mechanism is that a strong impedance source causes resonant growth of the beam (usually coupled bunch mode when considering HOM driven growth). The beam amplitude grows, dilutes and becomes Landau damped, whereby the amplitude reduces due to the synchrotron radiation. This is a mechanism for how a MHz-GHz scale impedance can cause oscillations on the order of a few 100s Hz. However, in the ESRF case, it is not certain that this is relevant. The beam does not grow in any serious amount of amplitude and no bunch length oscillations are observed. Streak camera measurements were made, but only the synchrotron frequency was visible.

Clearly the MWT is a key factor in the onset of this instability. Simulations have been made for the MAXIV 3GeV ring that show an LFO (see Fig. 3b of [7]), however they were not critical for operation due to the fact that it did not resonate with the synchrotron frequency, and so it was not studied. Preliminary simulations for the SOLEIL-II [8] impedance model suggest the presence of a LFO linked to the MWT. In their simulations, the LFO is suppressed with the inclusion of the harmonic cavity in the models. Work is underway to more deeply probe the necessary ingredients into the SOLEIL-II LFO instability, while simultaneously developing and pushing the wake potential model of the ESRF to understand why we can not see it in simulations.

OPERATIONS CONSIDERATIONS

Due to the dependence of the mode frequency on the MWT, and due to the strong dependence of the MWT on the bunch length. It was found that modifying many machine parameters simultaneously can ultimately affect the frequency of the LFO. For example, closing the undulators (in-air and in-vacuum) reduced the frequency of the LFO by about 40 Hz, but also reduced the synchrotron frequency by about 100 Hz. Modifying the RF voltage certainly reduced the frequency of the LFO, it also changes the synchrotron frequency in the same direction.

In order to try and improve the operational conditions for the ID24b during 4 bunch mode, the RF voltage was increased to 6.5 MV. This was found to produce the lowest oscillation amplitude at the synchrotron frequency, with undulators in delivery settings.

Meanwhile, the beam line scientists found that by increasing the energy range of their detectors, they were able to be less sensitive to the energy oscillations. While it was not possible to damp the oscillations, it became more manageable during operation.

CONCLUSIONS

A low frequency longitudinal oscillation has been observed at the ESRF. The threshold current of the oscillation is slightly above the microwave threshold. The third harmonic of this mode overlaps with the synchrotron frequency, causing synchrotron oscillations that perturb one beamline in particular.

Studies demonstrate a clear link with the MWT, but the exact mechanism is unknown. Further simulations are being performed to reproduce and study this effect.

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