VERTICAL EMITTANCE CONTROL USING THE DLS-MBF TUNE PLL EXCITATION AT THE ESRF-EBS

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Abstract

Since the beginning of the ESRF-EBS operation in 2020, the storage ring has been routinely operated with an artificially increased vertical emittance (10 pm, 20 pm, or 40 pm depending on the filling mode) to enhance beam lifetime. Until recently, beam excitation was achieved using pseudo-random noise with a relatively large bandwidth.

We recently have used the "Tune PLL" functionality of the Multi-Bunch Feedback processor, developed at Diamond Light Source (referred to as DLS-MBF), to excite a specific sideband of the transverse betatron resonance with high precision. This technique, initially developed and tested at Diamond Light Source, requires more careful tuning and parameter adjustment but has demonstrated superior performance at the ESRF compared to the previously used white-noise excitation.

In this paper, we describe the implementation of the Tune PLL excitation at the ESRF and present results showing its benefits in terms of beam lifetime improvement, emittance stability, and halo reduction. Using a pinhole emittance measurement, we were able to observe very small emittance fluctuations (down to 50 fm rms) and compare the resulting emittance fluctuations produced by the different blow-up methods.

INTRODUCTION

The ESRF-EBS storage ring, similarly to other fourth-generation light sources (existing or planned), offers an ultra-low horizontal emittance, resulting in a reduced Touschek lifetime. Although the vertical emittance is below 1 pm (after corrections), routine user operation requires an artificial increase to 10 pm, 20 pm, or 40 pm depending on the filling pattern, in order to achieve an optimal compromise between beam lifetime and photon beam quality.

Operation at reduced chromaticity is being considered to enable operation with small in-vacuum undulator gaps [1]. Lowering the chromaticity from the nominal values (10, 8) to (6.3, 4.5) reduces the beam halo, a key limitation for small-gap operation, but degrades the efficiency of the transverse emittance blow-up process [2].

So far, the vertical emittance blow-up has been performed using a magnetic shaker driven by a broadband pseudo-random noise. While robust and simple, this method lacks selectivity and does not optimally transfer excitation into incoherent beam motion. As a result, part of the excitation power drives coherent oscillations of the bunch centroid rather than increasing the occupied phase-space area. To address this limitation, the DLS-MBF Tune PLL method was investigated as a promising alternative excitation technique to improve blow-up efficiency, particularly under low-chromaticity conditions.

In the following, we describe the Tune PLL method and compare the resulting performance with the conventional noise-based excitation, focusing on lifetime and emittance stability. The implementation of this technique at ESRF-EBS was tested during two weeks of user-mode under reduced chromaticity conditions at the end of 2025. The outcome of this test will be discussed.

DIAGNOSTICS

The performance of a blow-up scheme can be assessed through two main criteria: (i) the achievable beam lifetime for a measured vertical emittance, and (ii) the stability of the emittance over a wide range of timescales. Therefore, it is important for this study to have the appropriate diagnostic tools to measure both emittance and the beam lifetime with good accuracy.

The vertical emittance is measured using a pinhole camera system [5]. The system operates at a frame rate of 15 Hz with an exposure time of approximately 10 ms. While absolute calibration remains challenging, the relative measurement stability is excellent, allowing the resolution of very small emittance fluctuations down to about 50 fm rms.

The beam lifetime is obtained from a standard exponential fit of the total beam current. The current is measured either using a Parametric Current Transformer from Bergoz Instrumentation or derived from the sum signal of the BPM electronics, providing consistent and independent measurements.

DIAMOND MULTI-BUNCH FEEDBACK TUNE PLL EXCITATION

The DLS-MBF system, developed at Diamond Light Source in 2017 [6], is a digital bunch-by-bunch feedback processor providing advanced capabilities for transverse beam stabilization and excitation. It was adopted at ESRF soon after [7], replacing a previous in-house system [8], due to its superior performance and flexibility.

In addition to its feedback functionality, the DLS-MBF includes a Tune Phase-Locked Loop (PLL) that enables narrowband excitation by locking onto the phase of the transverse Beam Transfer Function (BTF). This capability is essential for a narrow-band excitation system used for beam emittance blow-up, as it keeps the excitation locked to the resonance frequency. This is important because the betatron tune can drift over time, both slowly and rapidly, due to

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factors such as thermal variations, magnet vibrations, insertion device gap changes, the effect of injection elements and operator-driven tune adjustments.

Parameter Adjustment

Following the same approach as Preston *et al.* [3], different synchrotron sidebands of the betatron resonance were investigated experimentally, along with the Tune PLL parameters. The excitation frequency is controlled by the Tune PLL that maintains the beam phase response at a defined setpoint. This phase setpoint determines the position on the BTF at which the excitation is applied, allowing operation at the peak of the resonance or on either side of it. The optimal phase setpoint, as well as the PLL loop parameters (P and I feedback parameters) were carefully optimized to ensure stable locking and to minimize emittance fluctuations.

The optimal parameter set is strongly machine-dependent and varies with operational conditions such as filling mode and chromaticity [4]. At ESRF-EBS, the storage ring is operated with relatively high chromaticity values, resulting in a BTF with multiple well-defined synchrotron sidebands (Fig. 1).

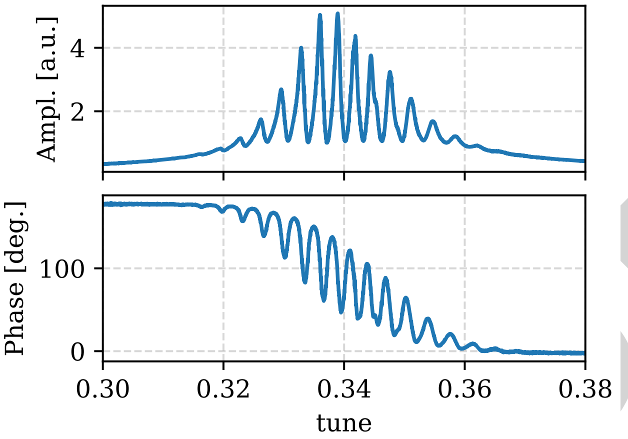

Figure 1: Vertical BTF measured with the DLS-MBF on mode 20 (uniform mode, 200 mA, (10, 8) chromaticity).

Excitation of sidebands far from the central betatron peak was found to be suboptimal, as it predominantly affects particles with large energy deviation. This leads to a non-Gaussian transverse beam profile characterized by a dense core and a diffuse halo-like cloud surrounding it. Consequently, our studies focused on excitation of the central peak and the first few synchrotron sidebands.

Experimental results indicate that excitation of the first synchrotron sideband above the betatron tune provides the best compromise, yielding an improvement in beam lifetime together with stable emittance. Excitation at the central betatron peak was also tested and provides acceptable performance, although less effective than the sideband excitation. This can be understood as a consequence of selectively driving off-energy particles, thereby enhancing dilution in the transverse phase-space through chromatic effects and therefore increasing emittance blow-up efficiency.

RESULTS

Comparison of Noise and Tune PLL Excitation

The performance of the conventional noise-based blow-up and the DLS-MBF Tune PLL excitation was compared under identical machine conditions: uniform filling, chromaticities set to (10, 8), a total current of 200 mA, and a vertical emittance of 10 pm. The results are summarized in Table 1.

Table 1: Comparison of Excitation Methods

Method	Lifetime [h]	Emittance Stability [pm rms]
Noise	27.5	0.265
Tune PLL	29.5	0.058

For a comparable measured emittance, the Tune PLL excitation provides a noticeably higher beam lifetime. This indicates a more efficient transfer of excitation power into incoherent motion, with reduced contribution from coherent oscillations of the beam centroid.

The improvement in emittance stability is even more pronounced. The measured emittance fluctuations are reduced by more than a factor of four when using the DLS-MBF Tune PLL excitation. This is illustrated in Fig. 2, which shows the power spectral density of the emittance value for both excitation schemes. In the case of the noise-based emittance blow-up, a distinct peak is observed at 3.5 Hz, corresponding to the repetition frequency of the pseudo-random excitation pattern at 108.5 Hz (the frequencies are different due to undersampling). This feature is absent when using the Tune PLL, resulting in a significantly cleaner spectrum and improved stability.

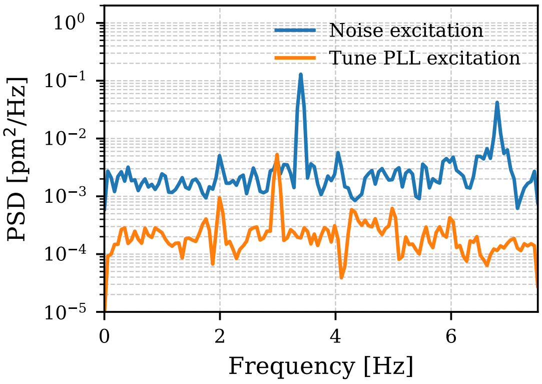

Figure 2: Comparison of emittance fluctuations for the two excitation methods.

Performance in User-Mode

The DLS-MBF Tune PLL excitation was used during user operation in uniform filling mode under reduced chromaticity conditions. While the method demonstrates superior performance in terms of beam lifetime, occasional instabilities of the excitation frequency were observed.

Figure 3 shows the evolution of the relative excitation frequency (PLL NCO Offset) together with the excitation

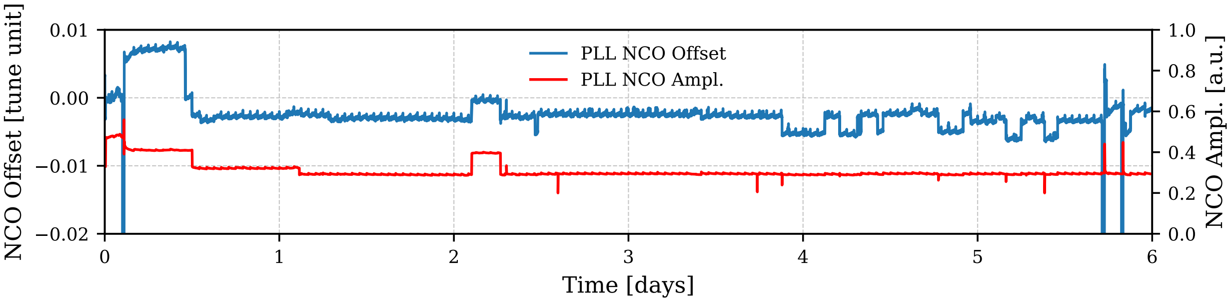

Figure 3: Evolution of the Tune PLL excitation parameters during user operation in uniform filling mode (between Nov. 4th and Nov. 10th 2025). The PLL NCO Offset (blue, left axis) represents the relative excitation frequency with respect to the targeted synchrotron sideband (with zero corresponding to the first upper sideband), while the PLL NCO Gain Scalar (red, right axis) indicates the excitation amplitude. A slow feedback loop adjusts the gain to maintain constant emittance. Transitions in the offset correspond to changes in the excited resonance.

amplitude (PLL NCO Gain Scalar) over several days of operation. During operation, the Tune PLL did not consistently remain locked to its target sideband and exhibited multiple transitions between different resonance peaks. In particular, the system drifted toward the central betatron peak, which became the dominant excitation frequency for extended periods. These transitions resulted in observable, albeit moderate, variations in beam lifetime, reflecting the different efficiency associated with each resonant peak.

The origin of these frequency jumps is not fully understood, but they are likely related to perturbations of the BTF. Possible sources include transient vacuum activity (e.g., outgassing events) or RF system disturbances, which can modify the tune spectrum and affect the stability of the PLL locking process.

DISCUSSION

The results demonstrate that the performance of the Tune PLL excitation strongly depends on the stability of the BTF. In practice, the observed transitions between different resonance peaks show that the BTF may experience transient instabilities.

In addition, there are significant differences in the BTF between filling modes due to collective effects. This sensitivity to machine conditions makes the identification of a universally optimal excitation configuration challenging.

It should also be noted that the present study was conducted with the bunch-by-bunch feedback switched off, which is the normal condition for the ESRF-EBS ring. Other light source storage rings usually operate with an active transverse feedback system. The interplay between feedback damping and controlled excitation is therefore expected to introduce additional complexity and would require further investigation.

CONCLUSION

The Tune PLL excitation implemented with the DLS-MBF system provides a more efficient and selective method for vertical emittance blow-up compared to conventional broadband noise excitation. It enables improved beam lifetime and significantly enhanced emittance stability.

However, this approach is also more complex and sensitive to machine conditions. In particular, the stability of the BTF is critical for reliable operation, and the observed frequency jumps highlight current limitations in robustness. As a result, the method is not yet sufficiently mature for routine user operation with the ESRF-EBS ring. Further developments are required to fully exploit the potential of this technique.

REFERENCES

[1] N. Carmignani *et al.*, “Vertical beam halo characterisation at the ESRF EBS for operation with reduced in vacuum undulator gap”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 973-976. doi:10.18429/JACoW-IPAC2024-TUCN1

[2] N. Carmignani *et al.*, “Emittance blow-up with a magnetic shaker at different chromaticities”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 1274–1277. doi:10.18429/JACoW-IPAC2024-TUPG26

[3] S. Preston *et al.*, “Measurements for Emittance Feedback based on Resonant Excitation at Diamond Light Source”, in *Proc. IBIC’22*, Kraków, Poland, Sep. 2022, pp. 492–495. doi:10.18429/JACoW-IBIC2022-WEP37

[4] S. Preston *et al.*, “Emittance feedback for the Diamond-II storage ring using resonant excitation”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 1498–1501. doi:10.18429/JACoW-IPAC2022-TUPOMS035

[5] F. Ewald *et al.*, “Vertical Emittance Measurement at the ESRF”, in *Proc. DIPAC’11*, Hamburg, Germany, May 2011, paper MOPD61, pp. 188–190.

[6] M. G. Abbott *et al.*, “A new transverse and longitudinal bunch by bunch feedback processor”, in *Proc. ICALEPCS’17*, Barcelona, Spain, Oct. 2017, pp. 1649–1654. doi:10.18429/JACoW-ICALEPCS2017-THPHA115

[7] B. Roche, “Experience on the integration of Diamond MBF-2 @ ESRF”, presented at the ARIES-ADA Workshop on Next Generation Beam Position Acquisition and Feedback Systems, Barcelona, Spain, Nov. 2018 `https://indico.cern.ch/event/743699/contributions/3112117/`

[8] E. Plouviez, P. Arnoux, F. Epaud, J. M. Koch, G. A. Naylor, and F. Uberto, “Bunch by bunch Transverse Feedback Development at ESRF”, in *Proc. EPAC’08*, Genoa, Italy, Jun. 2008, paper THPC132, pp. 3297–3299.