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SYNCHROTRON FREQUENCY MEASUREMENTS USING BUNCH BY BUNCH LONGITUDINAL FEEDBACK SYSTEM IN A STORAGE-RING WITH HIGHER HARMONIC CAVITY *

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Abstract

The upgraded Advanced Photon Source (APS) features a 1408 MHz superconducting Bunch Lengthening System (BLS) to improve beam lifetime. The main RF system is significantly affected by ambient 60 Hz-harmonics noise, complicating the measurement of synchrotron frequency under varying higher harmonic cavity conditions. To address this, using Dimtel iGp12 processor-based longitudinal feedback system we developed two methods to measure synchrotron frequency effectively. Our approach involves driving multi-bunch beam modes by considering a span for synchrotron frequency sideband and analyzing mode amplitude changes across the sweep frequency range. The "slow" method scans fixed drive frequencies within a range, recording the beam response at each frequency. The "fast" approach drives the beam with a broadband chirp signal and analyzes the resulting single mode spectrum data. Both methods are tested during beam studies. Synchrotron frequency changes are measured in two setups: First, adjusting BLS voltage manually while keeping beam current constant. Second, BLS voltage varying as a function of decaying beam current. This paper presents, details of the measurement procedure and results from the beam-based machine studies.

INTRODUCTION

The upgraded Advanced Photon Source incorporates a bunch lengthening system [1] featuring a 1408 MHz superconducting 4th harmonic passive cavity to enhance beam lifetime. The beam dynamics will change with harmonic cavity voltage, which affects the synchrotron frequency (F_s) of longitudinal higher-order modes (HOMs). The natural frequency of coupled bunch mode zero remains insensitive to changes in the BLS voltage and is influenced by beam loading effects. To characterize the longitudinal properties of the beam, it is essential to reliably measure the synchrotron frequencies of mode zero and higher-order modes under varying operational conditions, including changes in RF gap voltage, BLS voltage, and beam current. However, the main 352 MHz RF system is significantly affected by ambient 60 Hz harmonic noise, which complicates synchrotron frequency measurements. The bunch spectrum is dominated by peaks at the 60 Hz harmonics, making it challenging to isolate the synchrotron frequency signal. To address this issue, we developed two methods for effective synchrotron frequency measurement within the framework of the longitudinal feedback (LFB) system, which are designed to operate in the presence of ambient RF noise.

The bunch-by-bunch longitudinal feedback system is based on the Dimtel integrated Gigasample processor (iGp) [2], which has been installed in the upgraded APS storage ring for operational use. The beam signal is captured using a button-type beam position monitor (BPM). Front-end electronics detect and convert it into a baseband signal suitable for feedback computations. The iGp12 processor performs real-time feedback calculations and generates correction signals. Back-end electronics process the correction signal generated by the feedback controller. The processed signal is sent to the RF amplifiers, which drive the LFB kickers to apply corrective forces to the beam on a bunch-by-bunch basis.

Synchrotron tune measurements can be realized using an active longitudinal feedback system, since it can generate a signal, drive the beam, and detect the corresponding response. Our approach involves driving multi-bunch beam modes by considering a span of synchrotron sidebands and analyzing mode amplitude changes across the sweep frequency range. The slow method involves scanning the beam response by applying fixed drive frequencies within a predefined range, and recording the beam response at each frequency. The fast method employs a broadband chirp signal to excite the beam across a wide frequency range simultaneously. The next sections present detailed descriptions of the slow and fast methods, along with experimental results from beam studies conducted at the upgraded APS.

SYNCHROTRON FREQUENCY MEASUREMENT PROCEDURE

Drive and data acquisition options available in Dimtel processor are used to develop the synchrotron tune measurement procedures. Drive pattern generator provides the means to generate an excitation signal on a bunch-by-bunch basis. We can drive the beam with a single frequency sine signal or sine-sweep with a span. Drive signal parameters can be changed using the options: amplitude, frequency, span and period. Input frequency is computed using mode number, revolution frequency, and synchrotron sideband. Span is zero for sine signal and non zero for chirp drive. SRAM data acquisition engine collects and postprocesses the beam signal data in the real-time and generates averaged bunch spectrum, single mode spectrum, and modal amplitudes of all multi-bunch modes.

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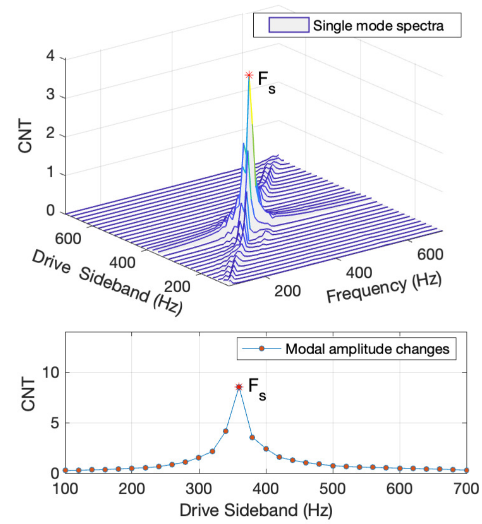

Figure 1: Single mode spectra and modal amplitude changes recorded at each step of drive sideband frequency.

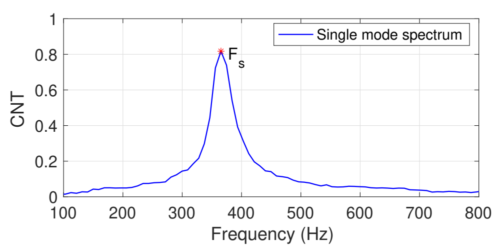

Figure 2: Chirp drive response in single mode spectrum.

Slow Method

The beam is driven at discrete, fixed frequencies spanning the synchrotron frequency sideband range. At each drive frequency, the beam response is recorded, capturing the amplitude of the excited mode and single mode spectrum data. Example data from slow measurement procedure is shown in Fig. 1. The frequency corresponding to the peak amplitude within the input drive frequency range is F_s. This method provides high-resolution data but requires longer measurement times (about 2 min with averaging of 4 points) due to the sequential nature of the frequency sweep.

Fast Method

A chirp signal, in the range 100-900 Hz, is applied to the beam. The resulting beam response is analyzed using the single mode spectrum generated from SRAM data. Example data from fast measurement procedure is shown in Fig. 2. The frequency corresponding to the peak amplitude with in the sweep range is F_s. The measurement takes about 8 sec with averaging of 10 points. Data downsampling is set to 3. Acquisition length is set to match drive period.

SYNCHROTRON FREQUENCY MEASUREMENTS

Both methods detailed earlier are tested during beam studies. Synchrotron frequency changes are measured by varying BLS voltage in two ways: first as a function of decaying beam current, and second by manually adjusting it while maintaining constant beam current.

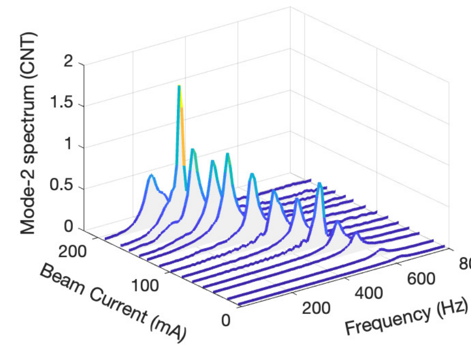

Figure 3: Mode-2 chirp drive responses in Setup #1.

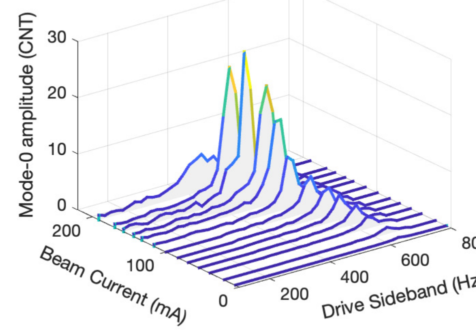

Figure 4: Mode-0 sine drive responses in Setup#1.

BLS Voltage Versus Decaying Beam Current

In this set of studies, detuning of the BLS cavity was fixed hence the BLS voltage varied as the beam current decayed. Synchrotron frequencies for mode-0 and mode-2 are measured at every 15 mA decrease in beam current. The measurements are conducted using two operational setups:
Setup #1: 216-bunch pattern, RF voltage of 5.3 MV, initial beam current of 200 mA, and BLS voltage of 1100 kV.
Setup #2: 48-bunch pattern, RF voltage of 4.25 MV, initial beam current of 130 mA, and BLS voltage of 900 kV.

The single-mode spectrum response of mode-2 to a chirp drive with an amplitude of 0.5 and a frequency range of 100–900 Hz is shown in Fig. 3. For mode-0 F_s measurements, the slow method proves more effective than the fast method. The single-mode spectrum chirp response is highly noisy, with 60 Hz harmonic peaks obscuring the synchrotron resonance, making it difficult to reliably identify F_s as the frequency corresponding to peak amplitude within the sweep range. Consequently, the slow method is used for mode-0 F_s analysis. Figure 4 shows mode-0 modal amplitude variations for sine drives in the 100–800 Hz range, with 20 Hz steps. A higher drive amplitude of 0.9 is required to obtain reliable mode-0 response data in the presence of 60 Hz harmonic noise. Similar measurements are performed in Setup #2.

Figure 5 shows the measured synchrotron frequency variations with beam current decay for mode-0 and mode-2 across two test setups. For Setup #1 (RF voltage: 5.3 MV), mode-2 F_s ranged from 180 Hz to 640 Hz, and mode-0 F_s ranged

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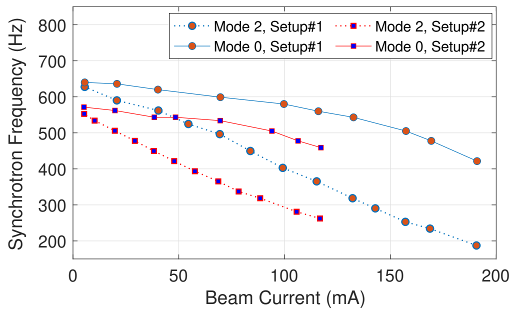

Figure 5: Mode-0 and Mode-2 synchrotron frequency measurements during beam current decay.

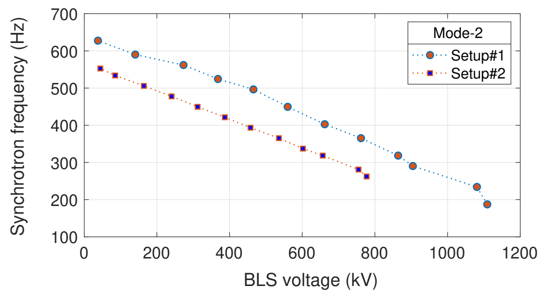

Figure 6: Mode-2 synchrotron frequency measurements with varying BLS voltage at different RF gap voltages.

from 440 Hz to 640 Hz as the beam current decayed from 190 mA to 5 mA. For Setup #2 (RF voltage: 4.25 MV), mode-2 F_s ranged from 260 Hz to 552 Hz, and mode-0 F_s ranged from 460 Hz to 570 Hz as the beam current decayed from 117 mA to 5 mA. Future mode-0 F_s measurements can benefit from reduced span and finer step sizes for improved resolution. The measurements match calculated F_s with no BLS and beam-loading for Setups #1 and #2.

Figure 5 shows that mode-0 oscillates with a different natural frequency than the higher-order modes. Mode-0 F_s increases with decaying beam current due to beam loading effects. Mode-2 F_s is primarily influenced by the BLS voltage and increases as the beam current decays. This reduction in BLS voltage causes F_s to increase, as shown in Fig. 6. We measured F_s variations for other HOMs, with results similar to the mode-2 findings.

BLS Voltage Versus Constant Beam Current

In this study, the BLS voltage was manually varied from 750 kV to 50 kV in 50 kV steps by adjusting the higher harmonic cavity settings, while maintaining a constant beam current of 100 mA. The test used 48-bunch pattern with RF gap voltage of 4.35 MV, closely resembling Setup #2 in the previous section. Synchrotron frequency for mode-16 was measured at each step using the slow method, with the drive sideband frequency swept from 100 Hz to 700 Hz in 10 Hz increments. Mode-0 F_s was not measured, as the constant beam current resulted in no change in beam loading. The measured modal amplitude variations of mode-16 at different BLS voltage settings are shown in Fig. 7.

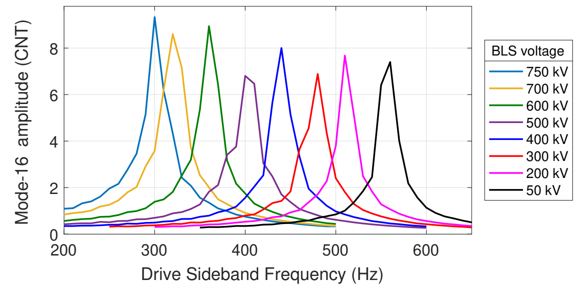

Figure 7: Mode-16 amplitude responses to sine drive at different BLS voltages with constant 100 mA beam current.

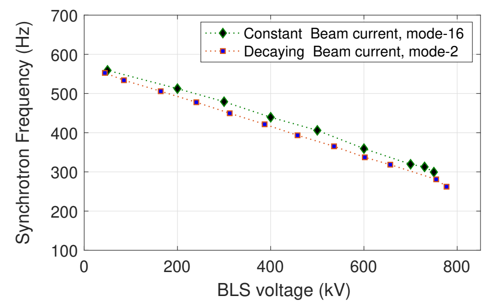

Figure 8: Higher order mode synchrotron frequency measurements with varying BLS voltage.

Measured F_s variations with BLS voltage of higher order mode-16 with constant beam current and higher order mode-2 with decaying beam current are compared in Fig. 8. The results are similar, with minor differences in F_s values attributed to the slightly lower RF gap voltage in mode-2 measurements.

CONCLUSIONS

Using the longitudinal feedback framework, we developed two effective methods for measuring synchrotron frequency in the presence of RF noise. The fast method, based on chirp response data, is effective for measuring higher-order mode F_s and is comparable the slow method. However, for mode-0 F_s, the slow method involving scanning individual frequencies proves more reliable. The chirp response data for mode-0 is highly noisy due to 60 Hz harmonics, making it difficult to identify synchrotron resonance and characterize F_s. We are working to improve mode-0 data analysis algorithms. Both methods have been successfully tested during beam studies and applied to F_s measurements across various operational settings. We continue to measure synchrotron frequency and analyze the tune spread using single-bunch phase spectrum obtained from turn by turn BPM.

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[2] Dimtel. Inc., `http://dimtel.com/`