

AN OPTICAL INTRA-BUNCH INSTABILITY MONITOR FOR SHORT ELECTRON BUNCHES

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Abstract

An improved understanding of intra-bunch instabilities in synchrotron light source electron bunches is crucial to overcoming the imposed limitations of the achievable intensity. A Multiband Instability Monitor, designed specifically for the short bunches of a synchrotron light source, has been developed to perform measurements of intra-bunch dynamics. The MIM performs real-time measurements at a diagnostic beamline using optical synchrotron radiation incident on a high speed photodetector. Three frequency bands up to 12 GHz were used to identify characteristic frequency signatures of intra-bunch instabilities. Mixed to baseband using RF detectors, these high frequency measurements can be performed without the need for similarly high frequency digitisers. This paper reports on the performance of the system at the Australian Synchrotron.

INTRODUCTION

Individual bunch currents are limited by intensity dependent instabilities. Typical Synchrotron light sources operate with bunch length in the tens of picosecond regime, making direct digitisation costly and limited in resolution due to thermal noise and clock jitter. The Multiband Instability Monitor (MIM) Principle, first demonstrated on the Super-Proton-Synchrotron (SPS), avoids the limitations of digitisation using a unique frequency domain approach to measure fast beam dynamics [1]. Incoming signals are split into multiple frequency bands which are downmixed and analysed simultaneously. Allowing the measurement of high frequency dynamics, such as the head-tail instability, without the need for a digitiser of equivalent bandwidth.

TRADITIONAL MEASUREMENTS

Head-tail instabilities were first measured by Sacherer on the Proton Synchrotron at CERN. Bunch structures were easily resolvable in the 200 ns bunches given the digitisers available at the time, allowing bunch profiles of the first 3 head-tail instability modes to be measured [2]. Bunch lengths have reduced dramatically in modern synchrotron light sources such that readily available digitisers do not have the necessary bandwidth. Electron bunch wave-forms for the Australian Synchrotron's 23 ps bunches are shown in Figure 1. The four lowest head-tail instability modes are shown, $m = 0$ corresponding to a rigid bunch instability while $m = 1$ to $m = 3$ are the first three modes of the head-tail instability. Referring to frequency domain plot,

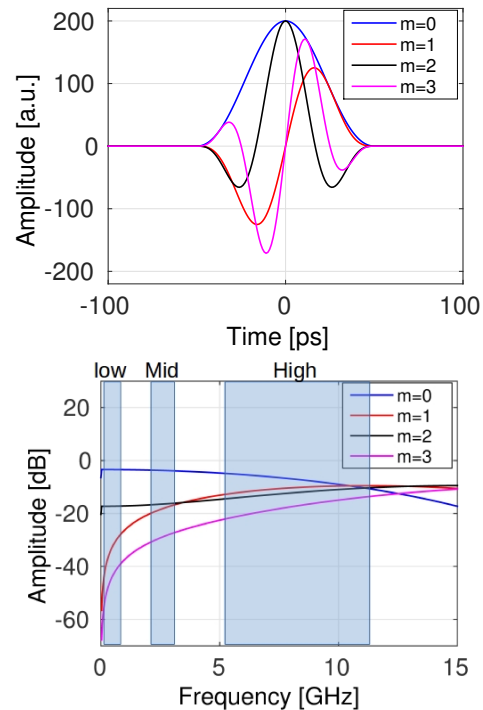


Figure 1: Simulations of the differential BPM signal's wave-forms during the lowest four head-tail instabilities modes given the 23 ps bunch lengths seen at the Australian Synchrotron. Displayed in the time and frequency domain, the $m = 0$ represents the shape of the BPM summation signal as well as the differential during rigid bunch motion ($m = 0$). In the frequency domain, a shift in the peak frequency can be seen for the non-zero head-tail instability modes $m = 1$ to $m = 3$. Shading on the frequency plot represents the MIM's frequency bands.

the third mode demonstrates that to measurements would require bandwidths of at least 40 GHz. Such measurements would be limited by the thermal noise, reducing the effective number of bits (ENOB). To resolve the bunch shape bandwidths of hundreds of gigahertz are required, well beyond the capability of digitisers [3]. Thus another technique must be employed to search for these instabilities.

Currently streak cameras are most commonly used to measure intra-bunch dynamics in the picosecond regime. With bandwidths of up to 1 THz these imaging systems are easily capable of resolving intra-bunch structure. Unfortunately

streak cameras are unable to be implemented as an instability diagnostic tool due to two main limitations:

1. Sampling rates are limited to only a few Hertz
2. Post processing is required so real-time measurements aren't a possibility

These limit streak cameras as diagnostic tools for instability diagnostics as instability rise-times are on the order of microseconds [4].

MIM PRINCIPLE

The MIM principle, first implemented on the SPS and LHC's proton beams uses a unique frequency domain approach to measure intra-bunch motion. By comparing the signals from the Beam Position Monitors (BPM) in different frequency bands, one can determine the presence of a head-tail instability [1]. This is done by measuring the summation (Σ) and the differential signal (Δ) between two opposing BPMs. The Δ signal will contain positional information and therefore be dependent on the bunch profile. Resulting is a shifting peak frequency for different instability modes, as was demonstrated in Figure 1. During a stable bunch, the BPM's Σ frequency spectrum differs from the Δ of the zeroth mode by a multiplication factor. Therefore presence of a non-zero mode head-tail instability can be defined through the ratio of the Σ to Δ signals with respect to frequency. Nominal bunch lengths at the Australian Synchrotron are 23 ps meaning the bandwidths of these frequency bands need to be in the tens of gigahertz regime. High frequency signals from the bands can be processed, in parallel, through RF detectors which downmix the signals to baseband and can be digitised simultaneously.

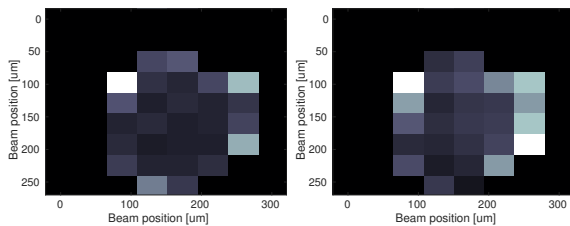


Figure 2: The Q/f_{rev} ratio for the vertical (left) and horizontal (right) tunes. For signals where the total intensity was less than 500 mV, the signal was set to zero as the modulating tune signals became indistinguishable from the noise floor. Transverse fluctuations are seen to be most sensitive on the edge of the active region of the photodetector.

EXPERIMENTAL SETUP

Given the frequency at which the measurements needed to be performed a few novel techniques were implemented. A system was developed to performed the intra-bunch measurements, outlined in Figure 3. Electrostatic BPMs at the Australian Synchrotron are limited to 500 MHz to reduce thermal noise making them unsuitable for the high frequency measurements. Instead a new optical BPM was implemented

on the optical diagnostic beamline of the Australian Synchrotron measuring the bunch motion up to 12 GHz. The signals from this BPM were then filtered into multiple frequency bands by the new MIM system and digitised simultaneously.

Optical BPM

Implementing the MIM principle required the determination of the equivalent sum and differential signals from the optical BPM consisting of a single photodetector. Assuming a single bunch is injected in the storage ring, the intensity of the optical synchrotron radiation at the revolution frequency, 1.388 MHz, will represent the sum signal. Transverse oscillations in the focal point result from the betatron motion in the beam and modulate the revolution intensity at 300 kHz and 400 kHz for the vertical and horizontal tunes respectively. This modulation by the tunes will represent the differential signal given it contains positional information. A low noise photodetector was measured the bunch dynamics up to 12 GHz. A 10 V bias on the photodetector improves its sensitivity to small fluctuations. The properties of this photodetector were discussed at a previous proceedings [5].

Vital to the function of the BPM is the location of the synchrotron radiation's focal point. Figure 2 demonstrates the optical BPM's sensitivity to the modulation by the betatron tunes with respect to the focal point location normalised to the beam intensity. Focusing the synchrotron radiation close to the edge of the active region of the photodetector maximises the modulation level making it the optimal position for the MIM system.

Multiband Instability Monitor

Output from the optical BBQ is the bunch motion up to 12 GHz. To prepare the signals for filtering section a 24 dB wideband amplification is applied. Conventional filtering techniques, such as stripline coupling and passive components, could not be used for these high frequency signals. In order to create high frequency band pass filters, and not lose signal through splitting, two diplexers were connected in series. This, along with the analog bandwidth of the subsequent amplifiers, created three frequency bands: 200 – 700 MHz (low), 2.4 – 2.8 GHz (mid) and 5.5 – 12 GHz (high). Transmission plots for each of the bands are demonstrated in Figure 4. Following the filtering, simultaneous downmixing of the three bands is performed with zero-bias RF detectors, bringing the high frequency signals down to baseband frequencies. Removal of higher order f_{rev} signals is performed by band-pass filtering from 200 kHz to 2 MHz after downmixing, consequentially also removing unwanted noise from the system.

EXPERIMENTAL RESULTS

Preliminary measurements from the MIM system were performed during machine studies at the Australian Synchrotron using a single bunch injected into the storage ring.

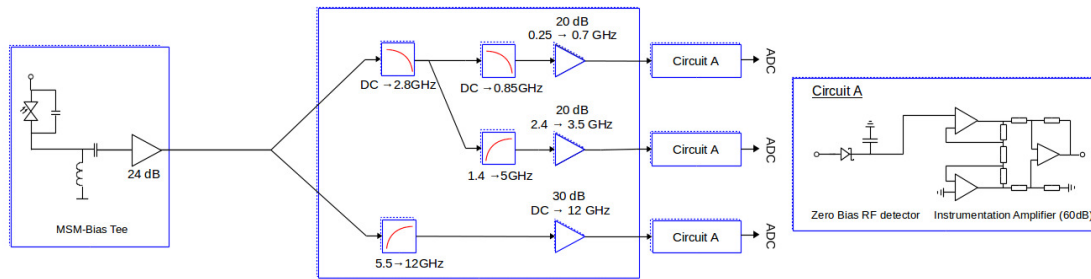


Figure 3: Multiband Instability Monitor at the Australian Synchrotron with a MSM photodetector pickup. The circuit can be separated into three sections: Pickup, Filtering and Downmixing.

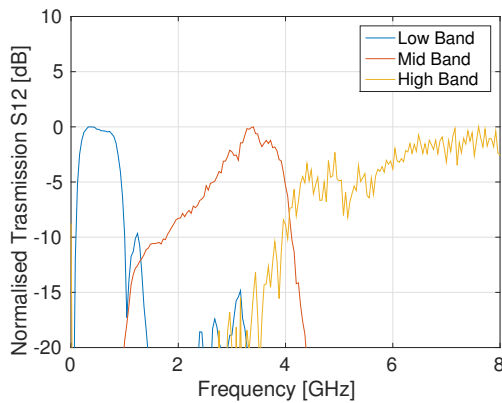


Figure 4: Transmission for the three MIM bands with respect to frequency. It can be seen that there is at least a 10 dB drop between frequency bands.

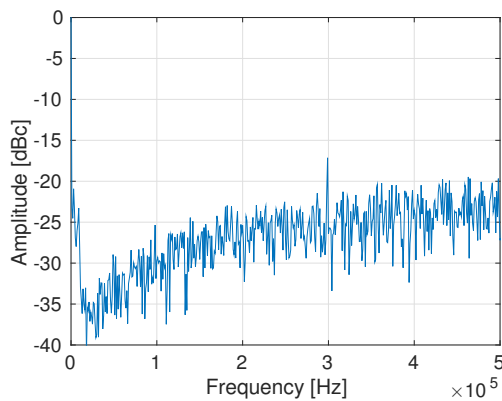


Figure 5: Tune measurement performed on a single bunch injected into the storage ring set to the nominal 0.66 mA. Optimised for the vertical tune the baseband signal can be seen at 300 kHz.

Tune Measurements

Tune measurements using the MSM photodetector have been performed previously and can be found here [6]. The signal-to-noise ratio was found to be similar for the buttons and the photodetector though, with only 500 MHz of analog bandwidth, the button BPMs at the Australian Synchrotron aren't fast enough to measure intra-bunch dynamics.

Measuring single bunches in a bunch train requires a low minimum on the dynamic range. Injecting the nominal user beam bunch current of 0.66 mA into a single bunch in the storage ring, the tunes were measured using an excitation from an injection kicker. Optimised for vertical oscillations, the vertical tune is visible at the nominal 300 kHz, 6 dB above the noise floor (Fig. 5). Given this single bunches could be measured in a bunch train with appropriate gating.

Intra-bunch Instability Measurements

Taking the signal from the optical BPM, the signal was passed through the MIM system. Testing of the system was performed on a 10 mA single bunch injected into the storage ring. Initial testing required the establishment of the noise floor.

Signals from the 3 MIM bands are displayed in the top row of Figure 6 for a stable bunch at nominal chromaticity $(Q'_x, Q'_y) = (3.5, 13)$. Normalising the signals to the carrier, it can be seen there is less than 2 dB variation between the three bands during a stable beam. Reducing the chromaticity incrementally to $(Q'_x, Q'_y) = (-0.8, 0)$, an intra-bunch instability was induced in the bunch. The lower row of plots demonstrates the MIM band signals during this instability. Given the normalised f_{rev} , it can be seen there is a 7 dB decrease in the Q/f_{rev} between the lower band and upper band.

Given the width of the bands for the current prototype, a quantitative analysis of the instability mode is not possible though a qualitative determination on the presence of an intra-bunch instability can be made.

FUTURE WORK

Future work on the system will look at measuring bunches without a catastrophically unstable beam and checking the dynamic range of the system with respect to instability strength. Such measurements will be performed using a statistical analysis on the MIM signals for the stable and unstable beam. To integrate the MIM system into the diagnostics system, it will be important to consider the display of the MIM data. Using a set of bar graph, the MIM data is displayed for a stable and unstable beam in Figure 7. The stability of the bunch can be determined from the gradient between the three bands.

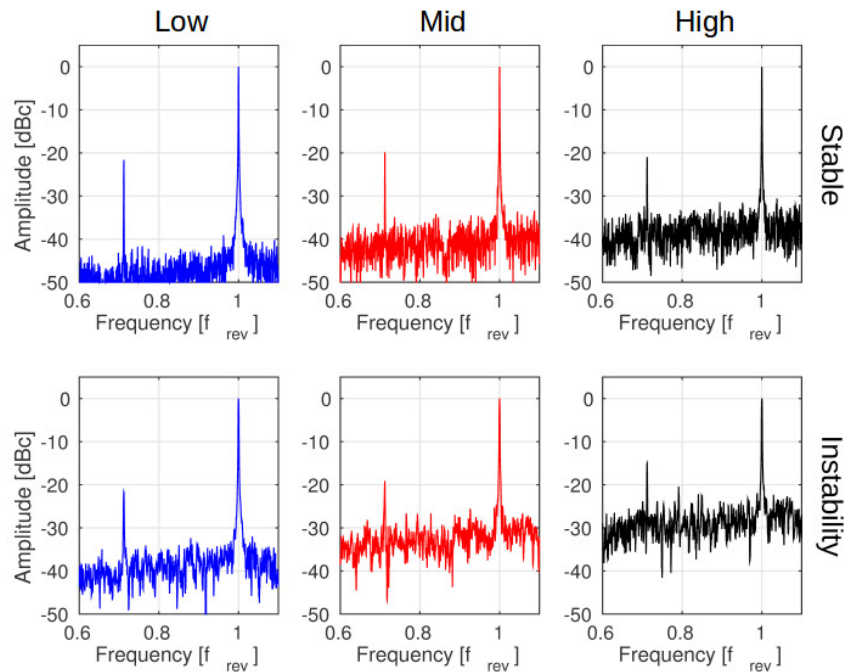


Figure 6: MIM's three frequency band for a stable (top) and unstable (bottom) single bunch. Normalising the signals to the f_{rev} carrier, it can be seen that the stable beam's tune signals are similar amplitudes. In comparison a decrease in the Q/f_{rev} ratio is seen with an increase in frequency during the induced intra-bunch instability.

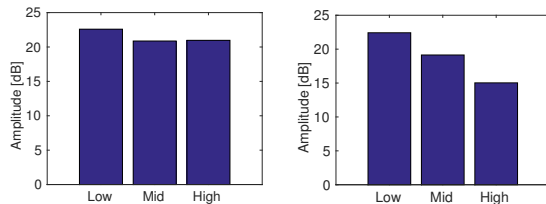


Figure 7: Q/f_{rev} signals for the stable (left) and unstable (right) beam plotted for the three MIM bands. A constant Q/f_{rev} across the bands is indicative of a stable beam whereas a decrease in the Q/f_{rev} ratio is indicative of an intra-bunch instability.

CONCLUSIONS

Initial measurements from the MIM system have displayed the ability to measure intra-bunch instabilities at GHz frequencies. Currently the system only offers qualitative diagnostics of intra-bunch instabilities but future systems will be designed to offer insight into the instability mode number.

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