STORAGE RING TUNE MEASUREMENTS USING HIGH-SPEED METAL-SEMICONDUCTOR-METAL PHOTODETECTOR

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Abstract

In any storage ring, the measurement and control of betatron tunes is an integral part of optimising the stability and lifetime of the stored particle beam. This contribution presents a novel relative beam position measurement system relying on a direct synchrotron-light detection using fibre-coupled, high-speed Metal-Semiconductor-Metal (MSM) Photodetectors (PD) in a custom-made balanced RF biasing circuit.

The system will be described along with its first results measuring the tunes for the storage ring at the Australian Synchrotron. The results are compared to the existing electro-magnetic BPM-based tune measurements taken.

INTRODUCTION

The Australian Synchrotron storage ring is a 3.0 GeV electron ring with a circumference of 216 m, situated in Melbourne, Australia [1]. Its nominal characteristics are summarised in Table 1.

Table 1: Nominal Characteristics of the Australian Synchrotron Storage Ring

Characteristic	Value	Unit
Energy	3.0	GeV
Circumference	216	m
Revolution Frequency	1.388	MHz
Betatron Tunes	(13.291,5.220)	(Q_x, Q_y)
	(403.9, 305.4)	kHz
Chromaticity	(3.5, 13)	(ξ_x, ξ_y)

Tune diagnostics systems, typically integrated into the beam position monitoring (BPM) or transverse feedback subsystems, are essential for any synchrotron and are used to control the actual tune working point to prevent the onset of instabilities that can occur if the fractional tune approaches low-order resonances of the accelerator lattice.

The majority of tune measurement systems require excitation of the otherwise stable beam, and measure the resulting beam motion over time. The digitised position data is typically transformed into the frequency domain, where any beam movement corresponding to the tune will show up as a spectral peak. For most systems, a small amount of excitation is required to separate the tune signal from the measurement noise, therefore tune measurements often cannot be performed during user time.

This contribution describes a high-bandwidth, low-noise BPM utilising visible synchrotron radiation that has been successfully tested at the Australian Synchrotron light source. The aim of this system is to utilise the high bandwidth of the system to allow for tune measurements of stable beam.

EXPERIMENTAL SETUP

The synchrotron-light based beam position monitor system (SL-BPM) described in this paper is built on the original Fill Pattern Monitor (FPM), which is based on a single high-speed Metal-Semiconductor-Metal Photodetector (MSM-PD) to measure the electron beam density in real time [2].

Both systems use the synchrotron light that is emitted by the electron passing through one of the main bending magnets, separated from the X-rays using a vertical mirror above the beam axis, focused through a lens, and then guided into an optical hutch where it is split to be used by either system. The visible part of the synchrotron radiation was chosen since the system can be implemented using standard optical components such as mirrors and lenses that also allow for rapid changes in the experimental set-up, and to anticipate a possible future use of the system in the Large Hadron Collider (LHC) that produces synchrotron light with the peak power being in the visible range.

For the nominal SL-BPM system, the light is focussed onto a set of length-matched optical fibres that are grouped to a diamond-type structure as illustrated in Figure 1, and each being individually fibre-coupled to its own MSM-PD.

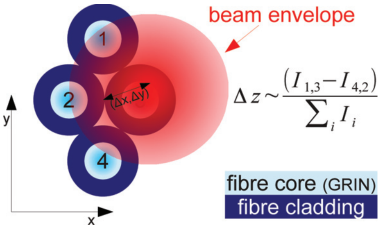

Figure 1: Fibre diamond geometry in relation to the projected synchrotron-light beam spot size.

The SL-BPM uses the same MSM-PDs as the earlier FPM [2, 3], that are robust, very low-noise, cost-effective and with a typical rise-time of 30 ps being ideally suited for high bandwidth measurements. Besides the given model,

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MSM-PDs are widely used in the telecommunication industry and MSM-PDs with bandwidths up to 375 GHz have been demonstrated [4].

Rather than placing the detector directly in the synchrotron-light focal plane, the light is coupled through fibres for two reasons:

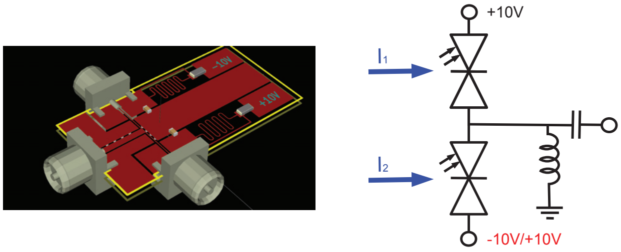
1. The active area of the chosen PD is small (200 μm) compared to the size of the given TO-5 case and cannot be closely packed within the synchrotron light without large dead spaces which the use of fibres lessens, as illustrated in Figure 1. Also, once the light is coupled into the optical fibres, the relative locations of the PDs is unimportant as long as the fibres are matched in length. A further increase in coupling efficiency was achieved by removing the PDs' protective TO-5 cap and providing a custom fibre-to-MSM-PD coupling.
2. Since the MSM-PD's electrical signal should ideally be processed as close to the PD as possible to preserve the bandwidths, signal levels and minimise electromagnetic interferences, longer fibres allow to further separate the fibre-head from the electrical acquisition system that can then be installed in a convenient place elsewhere (e.g. in a low-noise, low-radiation Faraday cage).

The initial tests were performed using large core PMMA plastic optical fibres (diameter about 700 μm). In order to increase the coupling efficiency between the optical fibre and PDs, these were substituted with multi-mode fibres with a smaller core diameter of about 50 um. The usage of multi-mode fibres is considered to be acceptable with respect to the targeted bandwidth (few GHz) and fibre lengths of less than a metre. Gradient-indexed fibres are being investigated as an option, particularly if longer distances between the focal plane of the synchrotron light and MSM-PD circuitry are required.

Since the beam spot is much larger than the active area of the MSM-PD, small movements of the synchrotron-light source causes small variations of the incident photon flux. Using only a single PD (e.g. 'single pixel'), the measurement is indiscriminate of the plane of beam movement, depends on the actual beam spot size and specific beam to fibre alignment. A more robust position estimate is given by the pair-wise difference-over-sum ratio of the incident intensity signal of neighbouring fibres as indicated in Figure 1. A specialised balanced biasing tee circuit has been constructed for the PDs to compute the incoherent sum or difference in the analogue domain before being further processed or directly digitised. The schematic and 3D model of the balanced bias tee is shown in Figure 2.

The balanced bias tee can operate in two modes;

- With one MSM-PD biased to +10 V and one biased to −10 V, the resulting signal output will correspond to the difference in the light intensity incident on the PDs.



(a) 3D Model (b) Schematic

Figure 2: Balanced bias tee configuration. I_1 and I_2 correspond with the incident photon flux on photodetector 1 and 2, respectively.

- With both MSM-PD biased to +10 V the output signal will correspond to the incoherent sum of the signals on each PD, allowing for intensity measurements.

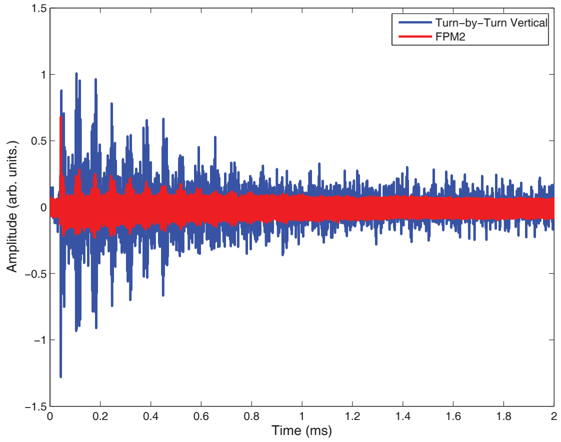
The biased PDs can be considered as current-sources, which can be easily combined and – in comparison to RF hybrids – allow much higher bandwidths and better linearity. Also, it allows to compensate the common-mode bleed-through due to off-centre beams or other intensity imbalances in the detector chain by simply varying the DC-bias voltage of either PD.

TUNE MEASUREMENT

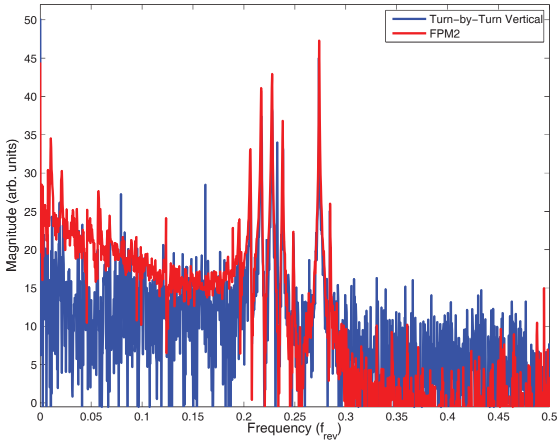
Using this set-up, the tunes for the storage ring at the Australian Synchrotron have been measured and compared to the existing tune measurement system. At the Australian Synchrotron, the data for tune measurements is typically acquired using turn-by-turn data from the storage ring button BPMs while the beam is excited by a combination of four injection kicker magnets [5].

A comparison between the traditional button BPM-based system and SL-BPM system is shown in Figure 3. While for most measurements the output has been directly digitised using a fast sampling oscilloscope, the signal for this specific measurement has been post-processed and down-mixed using a simplified version of a Base-Band Tune (BBQ) RF schottky diode detector (as described in Ref. [6]). This significantly reduced the requirements in terms of bandwidth and resolution, as the resulting signal wasbeing processed un-amplified and with a low-resolution (≈10 bit) oscilloscope.

Clear tune peaks at $(Q_x, Q_y) = (0.273, 0.227)$ can be seen. The high vertical chromaticity visibly enhances the synchrotron side-bands around the tunes, which is apparent in both sets of data. The datasets show a similar signal-to-noise ratio for both the existing turn-by-turn ring-BPM based system and the tested SL-BPM. This indicates that the sensitivity of the down-mixed SL-BPM is at least equivalent to standard method. Since the MSM-PD's dark-current is an order of magnitude smaller than the measured signal levels, it is believed that the measured noise floor is likely due to the digitisation noise of the acquisition system.



(a) Turn-by-turn position data, taken simultaneously with the standard BPMs and the SL-BPM system.



(b) The position data transformed into the frequency domain. High chromaticity induces a splitting of the vertical tune lines.

Figure 3: A comparison between the optical tune measurement system and the existing turn-by-turn BPM system. Clear agreement between the different methods is evident. The fractional tunes for this measurement are $(Q_x, Q_y) = (0.273, 0.227)$

Figure 4 is an overlay of two sets of data taken with the prototype SL-BPM system, utilising the balanced bias tee configuration. In this experiment, the storage ring tunes were altered from (Q_x, Q_y) = (0.29,0.22) to (Q_x, Q_y) = (0.32, 0.26). Both sets of tunes lines have a high signal-to-noise ratio and were observed to move to the correct location after the tune alteration.

CONCLUSIONS AND FUTURE WORK

Preliminary results from the prototype optical beam position measurement device described above are promising. The system has demonstrated the ability to track the temporal evolution of the tune and is in good agreement with the existing BPM diagnostics. Future improvements will include a more refined post-processing and higher-resolution digitisation of the available analogue signals to fully exploit the achievable signal-to-noise ratio of the MSM-PD.

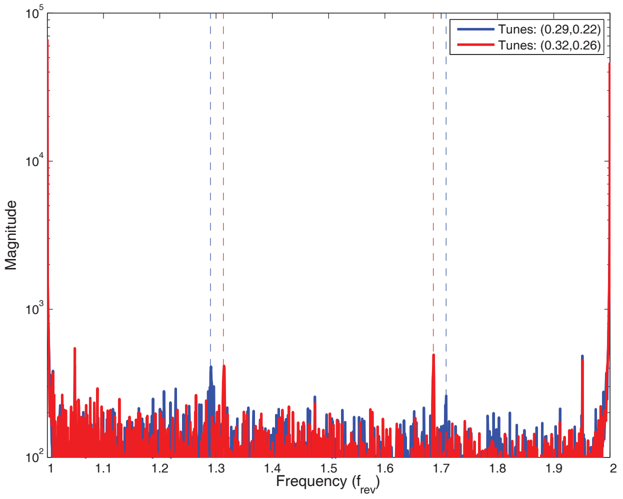


Figure 4: Two tune measurements utilising the SL-BPM BPM system. Between the two measurements the storage ring tunes shifted from (Q_x, Q_y) = (0.29,0.22) to (0.32, 0.26)

A future goal of this project is to leverage the high bandwidth position data to diagnose higher-order head-tail instabilities at the LHC. Head-tail instabilities occur when the motion of leading edge of a bunch is coupled to the tail and can lead to an increase in beam size or total beam loss. By coupling the MSM-PDs to a suitably high bandwidth data acquisition chain, the position of multiple slices of a single bunch can be obtained and monitored over many turns.

It is also anticipated that the system will find application in next-generation electron accelerators such as CLIC and will be tested at CTF3 in the near future.

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