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TRANSVERSE BUNCH BY BUNCH FEEDBACK OPERATIONS AT THE AUSTRALIAN SYNCHROTRON LIGHT SOURCE

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Abstract

The Australian Synchrotron light source has recently put in operation its transverse bunch-by-bunch feedback system during user beam mode. Getting to the stage of stable operation has been a long road and this paper will outline the many difficulties that were encountered. Chief among these are the apparent strong, high frequency, vertical resonances that appear when the storage ring's three in-vacuum undulators are closed to specific gaps. The behaviour of these resonances and their effects on achieving stable feedback operation will be explored in detail.

INSTABILITY SOURCES

The vacuum chamber of the Australian Synchrotron storage ring is stainless steel and therefore a major source of resistive wall impedance. The impedance effects have been measured previously [1] with the strongest effect in the vertical plane due to the aspect ratio of the vacuum chamber. The main instability sources have been the in-vacuum undulators (IVUs). The storage ring contains two 3-metre long IVUs (IVU03 and IVU13) that close down to a 6.6 mm pole gap and one 2 metre undulator (IVU05) that closes to 6 mm. While these devices have copper wakefield shields with flexible transitions at either end, they have been the source of very strong, high frequency resonances at particular gap positions that cause primarily vertical instabilities. The high frequency nature of these instabilities poses a much stronger challenge to the successful operation of the transverse feedback system than the resistive wall effects.

IVU Resonance Mapping

Attempts to map out these resonances in order to understand their source have been conducted. These resonance maps are difficult to obtain without the beam becoming so unstable that we experience beam loss and so may be incomplete, however they do show a strong pattern of instability mode number vs. IVU gap, with the instability mode increasing by 1 for every 0.3 mm of gap change. Table 1 and Figure 1 show one such mapping, performed at low chromaticity. Later measurements performed at lower chromaticity indicate this pattern of instabilities continues into the 8-9 mm gap range.

The regular repetition of the instability at gaps of every 0.3 mm suggests a trapped mode resonance in the IVU chamber. On a simple analysis of a vertical resonance between the two pole faces however, a change in IVU gap of 0.3 mm does not correspond to a frequency change of 1 revolution harmonic (1.38 MHz), which is implied by the unit change in instability mode number. The type of resonance is still not clear to us, although there are some possibilities, including a fast ion instability, or a situation similar to a klystron instability [6] (due to the similar geometry of the IVU device to a klystron tube).

Table 1: IVU gap setting vs peak resonance mode number. The relative spacing of the resonance modes is also shown

IVU05 Pole Gap (mm)	Peak Instability Mode	Δ (mm)
7.59 - 7.62	220	
7.28 - 7.32	221	0.30
6.98 - 7.04	222	0.28
6.68 - 6.74	223	0.30
6.40 - 6.47	224	0.27
6.12 - 6.15	225	0.32

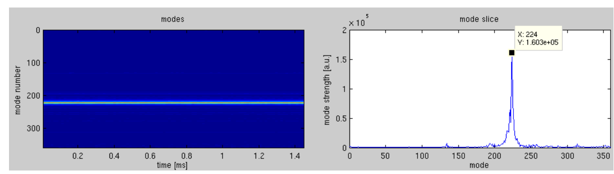

Figure 1: Instability Mode analysis of IVU05 at 6.4mm gap. Mode 224 is the strongest mode, but the neighbouring modes are also excited, indicating a resonance with width of multiple revolution harmonics.

FEEDBACK SYSTEM

Overview

While the transverse feedback system used at the Australian synchrotron has been described in detail previously [2],[3], and only a brief overview will be presented for clarity. Signals from a BPM block are sent through a hybrid mixing unit to produce X and Y signals which are sent to a mixing front-end unit, where the signal is mixed with a 1.5 GHz clock down to base band.

The mixing unit then sends the baseband signal to a pair of feedback processing units. The feedback units and frontend were supplied from Instrumentation Technologies [4].

The output waveforms are then fed through 100 W broadband amplifiers and sent to the storage ring stripline kickers. A programmable delay line before the amplifiers allows for timing of the output pulses in 20 ps steps in order coincide the peaks of the correction pulses with the arrival of the electron bunches. The overall system architecture is shown in Figure 2.

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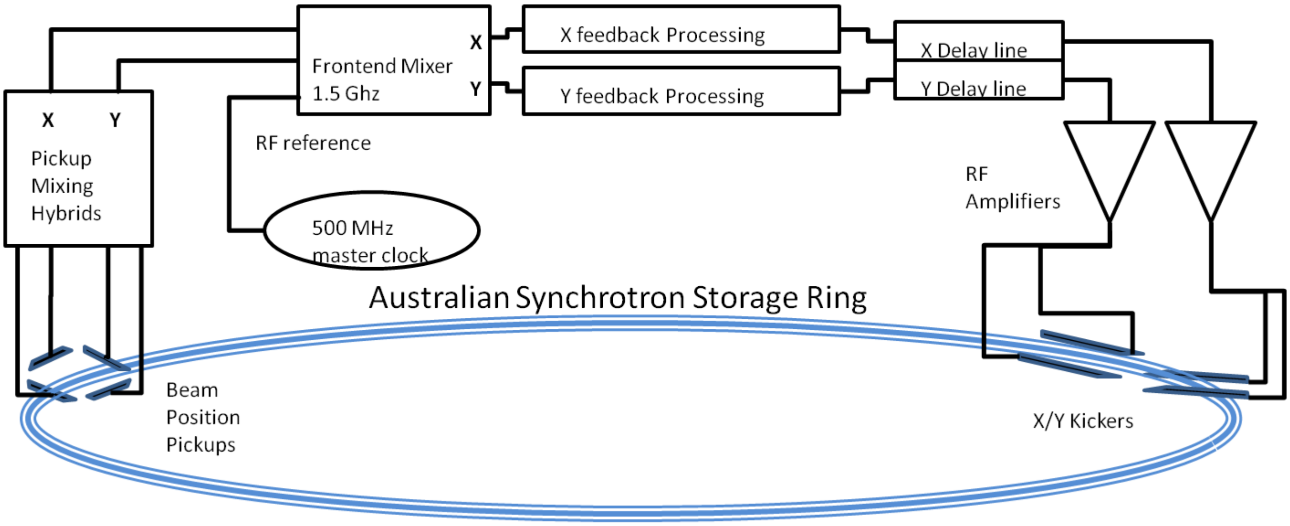

Figure 2: Overall layout of the transverse feedback system at the Australian Synchrotron

Recent Status

Initial commissioning of the system was performed some years ago [5] however stable operations of the system remained elusive, with the main problem being reproducibility. While the system could be made to work during a machine shift one week, the same results were often not reproducible the next and constant re-tuning was required. Additional problems were encountered when using the storage ring scrapers, which were physically located near the system's beam position pickup in the storage ring and found to induce high levels of noise.

To correct these issues, an overhaul of the system was conducted in 2012-2013, with the following changes

- System (including beam pickup and electronics rack) relocated away from scrapers.
- Bandwidth output of feedback units increase from 250 MHz to 500 MHz
- mixing hybrids at beam position pickup upgraded
- General cabling and EMC improvements

Tuning studies were conducted throughout 2014 to methodically understand and resolve the inability to achieve consistent operation. The improvement in the output bandwidth was significant due to the improvement in bunch isolation gained. Since our main trouble was with high frequency modes, poor bunch isolation was a major obstacle to damping the instabilities. Upgrading the output bandwidth had an immediate positive effect on the effectiveness of the system. Other cabling and mixing issues were resolved, and in late 2014 the system was put through a number of day-long tests during machine studies with the IVUs being randomly moved to different pole gaps in order to check stability among all resonances. A tuning setup was established that consistently damped all instabilities and gave repeatable results.

OPERATIONAL EXPERIENCE

The Australian Synchrotron started operating user beam with feedback in late January 2015 and we have collected almost 3 months of operational experience thus far. The long term operation has been valuable in revealing previously unseen drifts in relative beam phase that affected system stability.

Machine Performance

Operating at a lowered chromaticity of $\xi_x = 1, \xi_y = 3$ has a number of benefits for the operation of the storage ring. The more immediate benefit is in injection efficiency. The extremely large vertical chromaticity ($\xi_y = 13.5$) in operations without feedback lead to a very large tune shift induced by the amplitude of the injection oscillations. An analysis of this spread over tune space showed that a significant portion of the beam would hit a third order resonance and be lost during injection. After the chromaticity was lowered the typical injection efficiency rose from 70-80% to 98-99%.

Going back to low chromaticity has also had a positive impact on beam diagnostics. The large tune spread from the vertical chromaticity had introduced some difficulties in tune measurements and other tune based diagnostics, primarily due to the splitting of the tune peak. This made it hard for automated measurements to distinguish which was the central peak.

Beam lifetime was unchanged with the lowered chromaticity, due to the current way the storage ring is operated. The Australian Synchrotron storage ring has been running at a reduced RF voltage of 2 MV (instead of 3 MV nominal) for over a year now in order to reduce energy consumption by shutting down one of the 4 RF stations. Consequently, the current beam lifetime is dominated by RF energy acceptance and so increasing the dynamic aperture by lowering the chromaticity has not improved beam lifetime. This is not a concern however due to top-up operations keeping

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stored beam levels constant.

Beam Phase Drift

The first 4 weeks of operation were very smooth, with no stability problems encountered. In the 5th week however, the system was not able to damp an IVU resonance. It was found the phase of the 1.5 GHz mixing signal in the front-end unit needed to be shifted by almost 30 degrees to re-establish the same mixing levels as the system had been originally tuned. Similar phase shifts occurred in following weeks and a correlation with humid weather events was noticed. After some investigation, it was found that the beam pickup signal phase (referred to as 'beam phase') was shifting relative to the front-end unit's reference RF. Phase drift in the beam signal to the front-end mixing unit will effectively change the gain of the transverse feedback loop, potentially sending it into instability.

To measure the beam phase we used the cavity antenna pickup of the idle RF station and compared this 500 MHz beam signal against the master 500 MHz input to the storage ring RF stations. The cavity pickup was ideal as the high Q of the resonator formed a stable 500 MHz signal that was phase locked to the beam arrival time in the cavity. The correlation between beam phase and humidity in the technical hall is shown in Figure 3. It can be seen that after a rapid shift in humidity in the technical hall the beam phase starts to move with a 2 hour lag. There was no such correlation to technical hall air temperature.

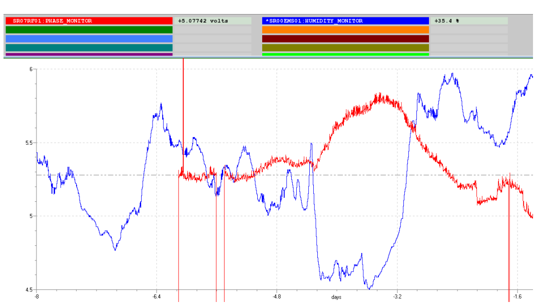

Figure 3: Stripchart of recorded humidity (Blue) and beam phase (Red) over several days (arbitrary units).

It was found that the low level electronics (LLE) for the storage ring RF stations were sensitive to small changes in air humidity, causing a shift in the overall RF phase, which consequently causes the beam phase to move with it. RF phase drifts of up to 8 degrees were observed in a single day, which sent the system into instability. It is thought that these LLE induced phase shifts have always been happening, however the the transverse feedback system is the first storage ring system that is sensitive to changes in the beam phase.

Phase Tracking

To overcome the humidity induced RF phase shifts and their effects on the feedback system we have implemented a beam phase tracking system. This system uses the measured beam phase from the idle cavity and compares it to the master RF signal. If there is any deviation of the beam phase from a preset calibration, a correction phase shift is applied to the storage ring RF phase. Changes in beam loading from insertion devices being wound in and out will also change the measured beam phase due to a change in the synchronous phase. This new beam phase tracking system will also compensate for this beam loading, ensuring that the beam is phase locked to the master RF phase. As shown in Figure 4, the phase tracking system has now eliminated any drift in the beam phase.

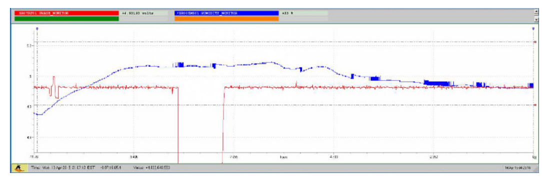

Figure 4: Stripchart of recorded humidity (Blue) and beam phase (Red) over several days (arbitrary units).

PLANNED IMPROVEMENTS

A dedicated beam phase monitor will also need to be developed, as the idle RF cavity is only a temporary solution. We have designed a 500 MHz quarter wave resonator which will be fed a signal from a spare storage ring BPM button in order to generate a beam phase signal. The quarter wave resonator is a compact, cheap and effective solution and can be easily installed in an equipment rack. Over the next month we will also be upgrading cabling to allow remote monitoring of signals at all points of the feedback chain, to aid in fault diagnosis. The current 16 tap FIR filters used in the feedback system are not optimized to have low gain in the other plane of motion. Recently, during operation some coupled motion has been observed on the Y plane due to instabilities in the X plane. Filter optimization will be revisited in May to eliminate this coupling. It is planned to investigate the IVU resonances further by inserting an RF antenna into the IVU chamber. Spectral analysis of the signal could provide valuable insights and a correctly placed antenna may act as a HOM dampener.

CONCLUSIONS

The transverse bunch-by-bunch feedback system has been put into operation during user beam at the Australian Synchrotron. Investigation of IVU induced instabilities has revealed an unusual resonance pattern that will require further investigation to understand. Experience gained by running the system for extended periods has highlighted some previously unknown drifts which have affected system performance in the past. A beam phase control loop has been implemented to eliminate these phase drifts and is now in successful operation.

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