IMPEDANCE EFFECTS IN THE AUSTRALIAN SYNCHROTRON STORAGE RING

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Abstract

The Australian Synchrotron storage ring must maintain a stable electron beam for user operations. The impedance characteristics of the storage ring can give rise to instabilities that adversely affect the beam quality and need to be well understood. Collective effects driven by the resistive wall impedance are particularly relevant at the Australian synchrotron and their strengths are enhanced by small gap insertion devices, such as IVUs. This study will explore the impedance issues identified in the Australian Synchrotron storage ring and current mitigation techniques.

INTRODUCTION

The Australian Synchrotron (AS) is a 3rd generation light source facility located in Melbourne, Australia. Commissioning was conducted in 2006, with beamline operations commencing in April 2007. The 3 GeV storage ring is 216 metres in circumference and can store a beam of up to 200 mA current. A design overview can be found in [1]. The Australian Synchrotron currently has nine operational beamlines. Of these nine beamlines, six use insertion devices (IDs), with three of these devices being In-Vacuum Undulators (IVUs). Both kinds of insertion devices require specialised vacuum chambers and their inclusion has an effect on the impedance of the storage ring. Careful attention will need to be paid to these effects as more insertion devices are added to the storage ring for future beamlines.

SOURCES OF IMPEDANCE

The dominant source of impedance leading to beam instabilities at the Australian synchrotron is the resistive wall effect. Other sources of impedance include vacuum chamber transitions, BPMs and injection elements, however these sources are minor contributors to the total impedance. The standard vacuum chamber used in the storage ring is stainless steel with a typical full height of 32 mm and width of 70 mm. The three standard insertion devices use an elliptical aluminium chamber of 11 mm full height. There are two 3 metre IVUs which close to a gap of 6.6 mm and one 1 meter IVU that closes to 6 mm. While all three IVUs have a thin copper inner layer to minimise resistive wall impedance, their small vertical gap still produces a significant transverse impedance. The longitudinal and transverse impedances from the resistive wall effect are given by [2]

$$\frac{Z_{\parallel}}{n} = \frac{Z_0(1-i)\delta}{2b}\left(\frac{L}{2\pi R}\right)F_0\left(\frac{a}{b}\right) \qquad (1)$$

$$\frac{Z_{\perp}}{n} = \frac{Z_0 L(1-i)\delta}{2\pi b^3}F_{1x,y}\left(\frac{a}{b}\right) \qquad (2)$$

where $\delta = \sqrt{2/\omega\mu\sigma}$ is the skin depth, L is the chamber length, b is the chamber half height, σ is the chamber resistivity, F_0 and $F_{1x,y}$ are geometry shape factors. F_0 is equal to 1, $F_{1x} = 0.411$ and $F_{1y} = 0.822$ for our chamber geometry

LONGITUDINAL INSTABILITIES

Bunch lengthening due to longitudinal impedance in the AS storage ring has been studied in depth in [4]. Since this study the damaged IVU has been repaired and re-installed. Streak camera measurements were repeated and an inductance of 70 nH was extracted from the bunch lengthening fits, corresponding to a Z/n of 0.6 Ω.

We currently see no longitudinal instabilities on the beam. We have not been able to observe the onset of the microwave instability in single bunches of up to 10 mA. We do not fill bunches to above 10 mA as a precaution against induction of high voltages on BPM and other RF pickups in the storage ring, although this limitation may be revisited in the future.

TRANSVERSE INSTABILITIES

The vertical impedance of our vacuum chamber, assuming the standard chamber geometry for the whole storage ring is given by equation 2 as

$$Z_y = 0.94(1-i)\frac{1}{\sqrt{n}}\mathrm{M\Omega m^{-1}} \qquad (3)$$

Using this value for the impedance we can calculate a growth rate for the vertical resistive wall instability. By setting this growth rate equal to the vertical radiation damping rate of 4.8 ms, an estimate of the threshold current for the onset of the instability can be obtained. The effective vertical impedance here is estimated for n_b equally spaced bunches as

$$\begin{aligned} Z_{eff} &= \sum_{p=-\infty}^{\infty} e^{-(\omega_{pn}\sigma_B)^2} Re|Z_y(\omega_{pm})| \qquad (4)\\ Z_{eff} &= 1.201\mathrm{M\Omega m^{-1}} \end{aligned}$$

with $\omega_{pn} = \omega_0[pn_b+n+Q]$ and n_b = 360 (even fill). Using this to calculate the current threshold (for a zero chromaticity lattice) we obtain

$$\begin{aligned} \frac{1}{\tau} &= \frac{1}{2}f_0\frac{I}{E} < B > Z_{eff} \qquad (5)\\ I_{\mathrm{th}} &= 50.3\,\mathrm{mA} \end{aligned}$$

The threshold current calculated here has neglected chromaticity effects, however we can see that the value of 50 mA agrees very well with the observed onset of vertical instabilities for a 360 bucket fill at low chromaticity, as shown in figure 2. The horizontal instability has a much higher threshold at 229 mA, as the horizontal resistive wall impedance is half of the vertical and the average beta functions and horizontal damping times are both lower.

The resistive wall impedance of the insertion devices is calculated as $0.21\,\mathrm{M\Omega m^{-1}}$ for the 2 m long, 6 mm gap device device, and $0.46\,\mathrm{M\Omega m^{-1}}$ for both of the 3 m long, 6.6 mm gap device devices (when they are at minimum gap). Adding this to the storage ring impedance, we obtain a new transverse impedance of $1.54\,\mathrm{M\Omega m^{-1}}$ when the devices are all at minimum gap. The effect of this increased impedance is also clear in Figure 2 as reduced thresholds for when the IVUs are at minimum gap.

Tune shift with current

The transverse impedance will cause a current dependant tune shift in the beam. The tune of a single bunch was measured at various currents up to 10 mA. A clear negative shift in the vertical tune was observed, with no clear signal in the horizontal tune.

Measurements were taken with IVUs at maximum and minimum gap, with the results shown in Figure 1. The tune shift slope, $d\nu/dI$, was found to be 0.256 and 0.336 for IVUs at maximum and minimum gap respectively. The frequency shift from transverse impedance is given by [3]:

$$\Delta\omega = \frac{-i}{2Q\omega_0\sigma_z}\frac{e\beta}{\gamma m_0}Z_{eff}I \tag{6}$$

Using equation 6 we find the effective vertical impedance for the ring as 1.13 $\mathrm{M\Omega}m^{-1}$ with IVUs open and 1.487 $\mathrm{M\Omega}m^{-1}$ with all IVUs closed. These results are in good agreement with the calculated resistive wall impedances shown above.

Increased Chromaticity operation

The effective transverse impedance is determined by the overlap integral of the bunch power spectrum, $h(\omega)$, and the impedance spectrum. The presence of chromaticity in the lattice will introduce a frequency shift in the bunch spectrum, thus altering the effective impedance.

$$Z_{eff}(\omega_\xi) = \frac{\int_{-\infty}^{+\infty} h(\omega-\omega_\xi)Z(\omega)\,d\omega}{\int_{-\infty}^{+\infty} h(\omega-\omega_\xi)\,d\omega} \tag{7}$$

For the resistive wall impedance, applying positive chromaticity has the effect of reducing the effective impedance and therefore raising the instability threshold. Figure 2 shows measurements of the observed onset of vertical instability at different vertical chromaticity and fill pattern. The measurement of the instability onset is difficult due to the difficulty in defining precisely at what point the beam is unstable, but the trends are quite clear. We can see that the shorter the bunch train, the higher the instability thresholds. We also see the effect of the small gap IVUs on the transverse impedance, with a very high chromaticity needed to stabilise the full 200 mA beam with these devices closed. The storage ring is currently set to a chromaticity of 3 in the horizontal and 11 in the vertical to control the resistive wall instabilities for user operations. The harmonic sextupoles have been adjusted to regain dynamic aperture at such high chromaticity. While this has been successful so far we are near the limit of our sextupole magnet's strength and will require an active feedback system if more IVUs are installed in the future.

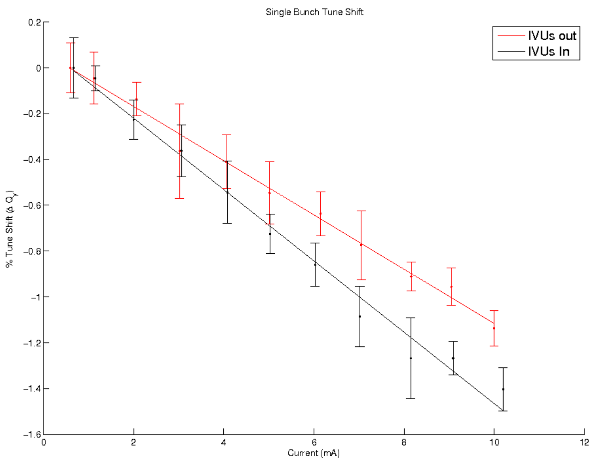

Figure 1: Single bunch tune shift vs. bunch current. Measurement was taken with IVUs wound out (red) and all IVUs wound in to minimum gap (black). Initial Vertical tune is 5.216

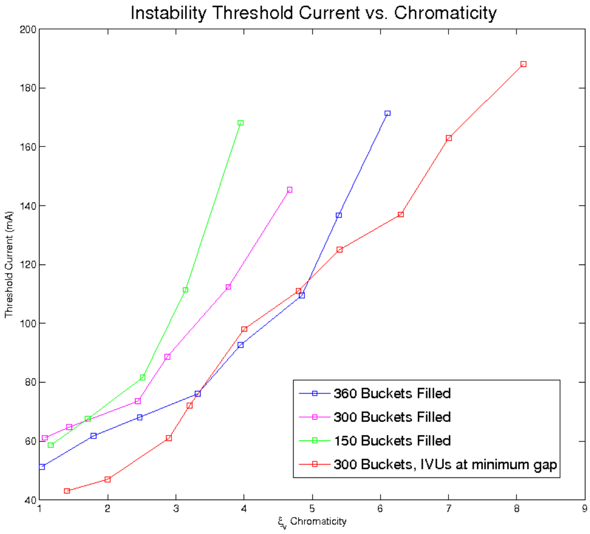

Figure 2: Measured onset of Vertical instability for different fill patterns and vertical chromaticity.

Transverse Feedback

A transverse Bunch-by-bunch feedback system has been designed and is currently being commissioned at the Australian synchrotron [6]. The system has been able to damp the resistive wall instabilities quite well but has had some difficulties due to the IVUs. When the IVUs are near their minimum gap, there is often the sudden emergence of a high frequency coupled bunch instability, at mode number 228. While this seems to imply a resonance in the IVU chamber, 3D electromagnetic simulations of the IVU chamber geometry have so far not been able to determine a source of the resonance.

COUPLING EFFECTS

Growth Rate vs Coupling

A series of coupling settings have been devised at the Australian Synchrotron [5], allowing the emittance coupling ratio to be finely controlled. During testing of the grow/damp measurements [7] of the feedback system we noticed that the instability growth rates would change depending on coupling. While conventional wisdom says that a higher beam transverse coupling should reduce the growth rate of the vertical instabilities by allowing extra damping in the horizontal plane, we see the opposite effect. As coupling is increased, the growth rate seems to increase. Figure 3 shows the vertical instability growth rates vs chromaticity for three different coupling settings. The growth rate shown is for the strongest resistive wall mode and is consistently higher at the higher coupling settings.

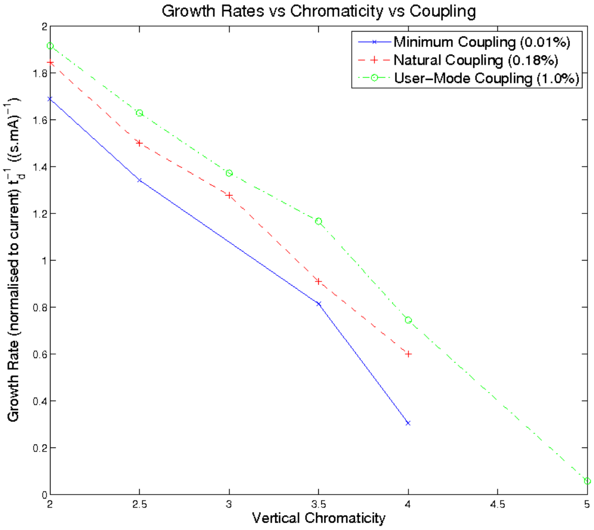

Figure 3: Normalised growth rates for vertical coupled bunch instability at different chromaticity. Measurements were taken at three different coupling settings.

Tune shift vs Coupling

To further investigate this effect a series of single bunch vertical tune shift measurements were taken at various emittance coupling settings. The results are shown in Table 1 and show a clear increase of the tune shift with higher coupling. Combined with the growth rate results, this seems to indicate that the effective impedance is increased by having a larger emittance coupling. It is not yet known what exactly is causing this and it is hoped further study will reveal the underlying effect.

Table 1: Current dependant tune shifts vs. coupling

Coupling (%)	Tuneshift (dν/dI)
0.01	-0.2465 ± 0.020
0.18	-0.2452 ± 0.022
0.3	-0.2594 ± 0.016
0.5	-0.2579 ± 0.024
0.8	-0.2681 ± 0.021
1.0	-0.2745 ± 0.032
20	-0.2922 ± 0.018

CONCLUSIONS

Studies of the impedance of the Australian synchrotron storage ring show that the dominant source of impedance driven instability is the resistive wall effect. Measurements of both the onset of instabilities and beam tune shifts point to a total machine impedance that is very close in magnitude to the expected resistive wall impedance. An interesting connection between emittance coupling and effective impedance has been observed in both tune shift and growth rate measurements and needs to be studied further.

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