IMPEDANCE AND BEAM STABILITY STUDY AT THE AUSTRALIAN SYNCHROTRON

R. T. Dowd, M. J. Boland, G. S. LeBlanc, M. J. Spencer, Y. -R. E. Tan, Australian Synchrotron,
Clayton, Victoria 3168, Australia.

Abstract

We present the preliminary results of an impedance study of the Australian Synchrotron storage ring. Beam stability thresholds have been determined and an overall impedance budget set.

Broad-band impedance has been evaluated for various components of the vacuum chamber, using both analytical formulae and results from MAFIA simulations. Narrow band resonances have also been investigated, with particular attention paid to higher order modes in the RF cavities and their effect on multi-bunch instabilities.

INTRODUCTION

The Australian Synchrotron is a 3rd generation light source designed to store 200mA of current at an energy of 3.0 GeV. The Storage Ring has a circumference of 216.0 m, with a harmonic number of 360. The electron beam is injected at full energy from a synchrotron booster ring. There are 4 Copper RF cavities, operating at 499.654 MHz, with a combined RF voltage of 3 MV. More details of the lattice design can be found in [1].

Wakefields excited by the beam passing discontinuities in the vacuum chamber walls can have adverse effects on beam stability. Due to the need for diagnostic and injection elements, it is not possible to keep the chamber profile completely smooth all the time. User requirements for a well defined and stable light source mean it is important that these wakefields, characterised by beam impedances, are as low as possible.

In this report the impedance budget for important single bunch and multi bunch instabilities are calculated. An analysis of various storage ring components is then conducted to determine if this budget is met.

IMPEDANCE BUDGET

Single Bunch Thresholds

Single bunch effects arise from the broadband behaviour of structures in the storage ring. Because the broadband resonance supports many frequencies, the resulting time domain impulse is very short and will only affect the particles within the bunch that generated the wake.

The main single bunch instability we are concerned with is the Microwave instability, which can cause bunch lengthening if the peak bunch current is above a certain threshold. The limit on the effective impedance $(Z/n)_{eff}$ is given by [2]

$$\left(\frac{Z}{n}\right)_{eff} < 2\,\frac{\pi\alpha\left(E/e\right)\sigma_p^2}{I_{peak}}$$

Where α is the momentum compaction, E the beam energy, e the particle charge and σ_p the relative momentum spread of the bunch.

I_{peak} for a gaussian bunch is given by

$$I_{peak} = I_{bunch}^{av.}\sqrt{2\pi}\,R/\sigma_b$$

In normal operting conditions the full 200 mA beam current will be spread across most of the 360 RF buckets, with a small gap left to pervent ion trapping. For this calculation we want a rather conservative estimate of the threshold and so assume the 200 mA is spread over ¾ of the 360 available buckets. We therefore have 0.74 mA per bucket with a peak current of 9.11 A resulting in a impedance limit of $(Z/n)_{eff} < 2.11$ Ohms.

There is also a transverse microwave instability, or transverse fast blowup instabilty. For $\sigma_b < b$ the corresponding threshold depends on the average bunch current.

$$\left|Z_\perp\right| < \frac{4Q_s\,(E/e)\,b}{I_{bunch}^{av.}\,\langle\beta_\perp\rangle R}$$

Where Q_s is the synchrotron tune and $<\beta_\perp>$ is the average transverse beta function. The two transverse microwave instability thresholds are

$$\left|Z_\perp\right|_y < 5.18\ M\Omega m^{-1},\ \left|Z_\perp\right|_x < 18.8\ M\Omega m^{-1}$$

Coupled Bunch Thresholds

Coupled bunch instabilities occur when separate bunches are able to couple to each other through a slowly decaying wakefield. These wakefields are generally caused by a higher order mode (HOM) resonance in the cavities.

The growth rate of a coupled bunch mode *l* is given by [2]

$$\frac{1}{\tau} = \left(\frac{a}{a+1}\right) f_0\,\frac{I_0 h\alpha}{EQ_s}\,\mathrm{Re}\left[Z_\parallel\right]_{eff}$$

with f_0 being the revolution frequency, I_0 the beam current, h the harmonic number, α the momentum compaction factor, E the total beam energy and Q_s the synchrotron tune.

If we consider the cavity resonator impedance with ω_r being the resonant frequency,

$$Z_{\parallel}(\omega) = \frac{R_s}{1 + iQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}$$

Taking the worst case situation of the bunch specra line being exactly on the HOM resonant frequency the effective impedance then becomes:

$$\left[Z_{\parallel}\right]_{eff} = \frac{f_r}{f_{RF}} R_s$$

With f_r the HOM resonant frequency, f_{RF} the operating RF frequency of the cavity and R_s the shunt impedance.

Considering the a=1, dipole synchrotron mode the growth rate is

$$\frac{1}{\tau} = \left(\frac{1}{2}\right) f_0 \frac{I_0 h \alpha}{EQ_s} \frac{f_r}{f_{RF}} R_s$$

Q_s is the synchrotron tune, α the momentum compaction, h the harmonic number, I_0 the beam current and E the beam energy. Setting the growth time τ equal to the radiation damping time, 2.8 ms, we can get a threshold value for the shunt impedance of the HOM, given by:

$$R_s = \frac{1}{\tau f_0 \frac{I_0 h \alpha}{EQ_s} \frac{f_r}{f_{RF}}}$$

The threshold at 200mA is 55 KΩ/GHz for the longitudinal impedance of higher order modes in the RF cavities. We are not concerned with transverse impedances at this point since transverse beam oscillations can be damped by a fast feedback system. A limit of 20 KΩ/GHz was adopted in the design specification of the RF cavities to allow for a future increase in operating current without the need for cavity redesign.

Narrow band resonances can also occur in other storage ring components that have cavity-like structures. These will be investigated in future studies.

BROAD BAND IMPEDANCE

The impedance of various components in the storage ring has been calculated using MAFIA [3] and analytic expressions.

The 3D time domain solver of MAFIA was used to calculate the wake function for a bunch length of 7 mm (rms). The mesh was chosen to be 1 mm or smaller, (constrained by available memory) and the wake function was simulated for a duration of no less that 4 ns. All components used a 3D model, the BPM model is shown in figure 1. Once the code has obtained the wake potential, the appropriate analytical function could be used to evaluate the impedance of the component.

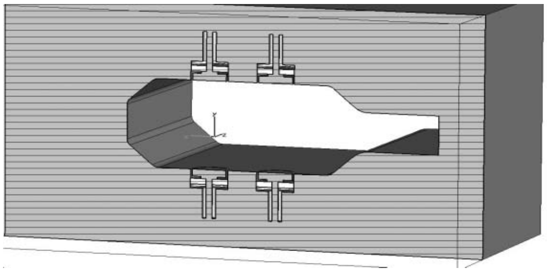


Figure 1: 3D model used for BPM simulation

There are three types of wakes produced by a component; capacitive, resistive and inductive. These types of wakes can be distinguished from their behaviour at very short ranges after the start of the bunch distribution and are shown in figure 2. Once classified, an analytic expression [4,5] can be used to relate the maxima of the wake potential to the impedance.

Table 1: Impedances for a Gaussian bunch distribution.

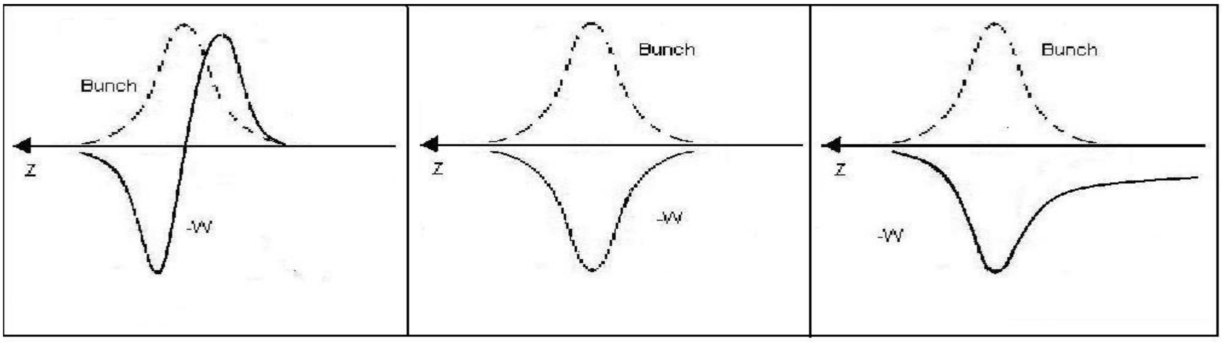
Capacitive:	$Z(\omega) = 1.225(\sigma/c\omega)^{1/2} W_{\max}$
Resistive:	$Z = (2\pi)^{1/2} \sigma/c\, W_{\max}$
Inductive:	$Z(\omega) = \omega(2\pi e)^{1/2} (\sigma/c)^2 W_{\max}$

Where $W_{\max}$ is the maximum of the wake potential, c is the speed of light, σ is the bunch length (rms) $n = \omega/\omega_0$, where ω_0 is the revolution frequency.

The results of the simulation are shown in Table 2. Not all components of the storage ring have yet been simulated, with the vacuum chamber flanges and bellows being the main omission. They are not expected to contribute significantly to the overall impedance however, since they have been designed with RF seals to reduce their impedance.

Table 2: Longitudinal Impedance

Component	Number	Total Z/n (Ω)
BPMs	392	0.027
Injection Kickers	4	0.090
Horizontal Kicker	1	0.004
Vertical Kicker	1	0.009
Stripline	1	0.001
RF cavities	4	0.164
Cavity Tapers	2	0.130
Total		0.425



Inductive Resistive Capacitive

Figure 2: The longitudinal wakes for inductive, resistive and capacitive components. The solid line represents the longitudinal wake potential (V = -W) and the dashed line represents the charge distribution of the bunch.

Resistive Wall Impedance

The impedance due to the resisitive wall effect is given by[6]

$$Z(\omega) = \frac{Z_0 L}{4\pi b}\left(\frac{2\varepsilon_0}{\sigma}\right)^{1/2} |\omega|^{1/2}\left[1 - i\,\mathrm{sgn}(\omega)\right]$$

By making the substitution $\omega = n\omega_0$, where $\omega_0 = 2\pi c / L$ is the angular revolution frequency of the ring, we can obtain the reduced longitutinal broadband impedance.

$$\frac{Z(n\omega_0)}{n} = \frac{Z_0 c}{2b}\left(\frac{2\varepsilon_0}{\sigma\omega_0}\right)^{1/2} |n|^{1/2}\left[\mathrm{sgn}(n) - i\right]$$

Giving us a longitudinal resistive wall impedance of $Z = 4.18(1-i)\sqrt{n}\ \Omega$

The transverse impedances for the x and y directions are calculated using the equations for rectagular vacuum chambers found in [7]

$$Z_x = 6.44\times10^6(1-i)\sqrt{n}\ \Omega m^{-1}$$

$$Z_y = 12.89\times10^6(1-i)\sqrt{n}\ \Omega m^{-1}$$

CAVITY HIGHER ORDER MODES

As calculated earlier, to avoid a longitudinal coupled bunch instability we require the impedance of any higher order modes to be below 20 KΩ/GHz. The RF cavities have higher order mode dampeners installed to achieve this limit, detail of which can be found elsewhere in this conference [8].

The Q values of the higher order modes of the cavities were measured during an on-site low power test. The threshold Q which corresponds to the impedance threshold for each mode is calculated and compared against the measured values. A summary of the results is presented here.

Table 3: Cavity HOM Measurements

Mode	Freq. MHz	Threshold Q	Measured Q
TM011	790.1	453	394
TM020	1313.2	1538	1487
TM021	1355.5	1001	>50
TM022	1725.7	1175	>50

CONCLUSION

A first study of the Australian Synchrotron's storage ring impedance has been conducted. Some components, such as flanges and bellow, have yet to be included, but their impact on the overall impedance budget is expected to be minimal. The current results show that the longitudinal broadband impedance is currently well within the required single bunch instability threshold. Coupled bunch instabilities from resonances in the RF cavities are also not expected to present a problem due to the HOM dampening scheme. Further work will be done to investigate transverse impedances and narrow band resonances.

REFERENCES

[1] J. W. Boldeman, D. Einfeld, 2004 Nucl. Instr. And Meth. A 521, 306
[2] M .S. Zisman, S. Chattopadhyay and J. J. Bisognano, "ZAP User's Manual", LBL-21270, 1986
[3] "MAFIA User's Guide", CST, Darmstadt.
[4] K. L. F. Bane, "Bunch lengthening in the SLC Damping Rings", SLAC-PUB-5177, 1990
[5] S.Heifets, "Broad-Band Impedance of the B-Factory", SLAC/AP-93, 1992
[6] A. Chao, "Physics of Collective Beam Instabilities in High Energy Accelerators", 1993, John-Wiley & Sons Inc.
[7] R. Gluckstern, j. Zeijts, B. Zotter, "Coupling impedance of beam pipes of general cross section", Phys Rev E, 47 656, 1993
[8] J. Wantabe, K. Nakayama, K. Sato, H.Suzuki et. Al, "Higher Order Mode (HOM) Damper of 500MHz Damped Cavity for ASP Storage Ring", this conference.