

# SINGLE BUNCH STUDIES AT THE AUSTRALIAN SYNCHROTRON

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## Abstract

Studies using a single high charge electron bunch have been conducted at the Australian Synchrotron to characterise the impedance of the machine at various stages of commissioning and insertion device configuration. This paper will present the results of these studies and show the time evolution of machine impedance with increasing number of insertion devices.

## OVERVIEW

The Australian Synchrotron 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 first phase of beamline development consists of 9 initial beamlines, 5 of which are currently in operation and the other 4 are in late stages of construction. Of these 9 beamlines, 6 will use insertion devices (IDs), 3 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. The single bunch studies presented in this paper were conducted at various times over the last year, as the storage ring became more and more populated with insertion devices.

## BEAM DIAGNOSTICS

There are two diagnostic beamlines at the Australian Synchrotron, an X-ray and an optical beamline. Details of the diagnostics beamlines can be found in [2]. For this analysis, only the optical diagnostic beamline is used.

The Optical Diagnostic beamline uses light from a dipole magnet after it has been passed through an optical chicane. This visible light is then split and analysed by several different devices, giving information about bunch length, beam emittance and the fill pattern. Most important for this analysis is an Optronis streak camera that allows us to determine single bunch length with picosecond resolution.

## SINGLE BUNCH MEASUREMENTS

For these studies we injected electrons into a single bucket of the storage ring. Measurements of bunch length were taken on the streak camera at various currents up to 10 mA total. Single bunch measurements provide a clean way of investigating the longitudinal impedance of the storage ring. Putting large amounts of current into a single

bunch will produce correspondingly large wakefields, allowing subtle effects to be measured.

The impedance of a storage ring is a complex quantity, but can be broken up into its real and imaginary components. The real part of the impedance is the resistance, and manifests as an energy loss of the bunch. This energy loss is characterised by the loss factor  $k_l$  and is expressed in units of V/pC, such that the energy lost by the beam is given by  $\Delta E = -k_l \cdot q^2$ , with  $q$  being the bunch charge. The wake generated by a bunch is stronger at the rear of the bunch than the head and therefore causes an uneven energy loss along the length of the bunch. The imaginary part of the impedance does not lead to a net energy loss within the bunch and thus has no loss factor associated with it. Instead it leads to energy transfer between particles within the bunch, increasing the energy spread of the bunch, and therefore increasing the bunch length.

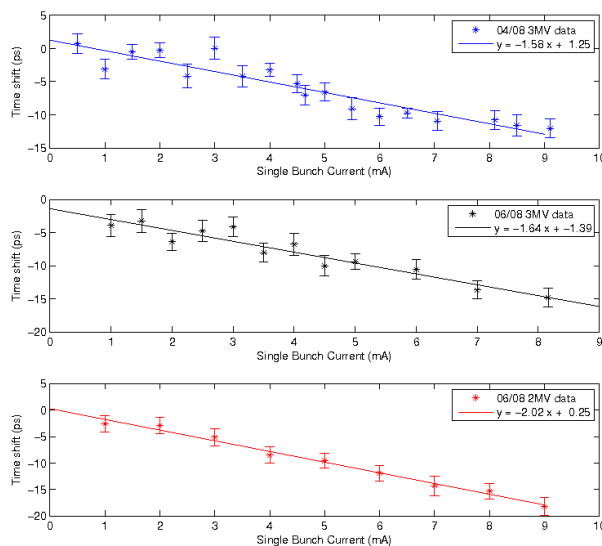


Figure 1: Synchronous phase advance with increasing single bunch current. The top graph was taken in March 2008 with 3 MV RF. The second two were taken in June 2008 with 3MV and 2MV RF respectively.

## Synchronous Phase Advance

In addition to the synchrotron radiation, various components in the machine will generate losses through their impedance and each will have a loss factor associated with it. These loss factors will add up over the whole machine, giving a total loss factor and total energy loss due to resistive impedance in the machine. The extra energy lost must

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also be made up for the bunch to remain circulating. The bunch will therefore move up the phase of the RF cavities in order to gain more energy per turn. The change in synchronous phase of the bunch will give you the energy loss due to the impedance of the machine.

To observe the synchronous phase advance, we used the streak camera on the optical diagnostic beamline. To allow us to see small phase shifts, which manifest as time shifts, a reference phase is needed. We filled ten reference buckets in the ring with 0.1mA each and then one test bucket was filled from 0.5 to 9 mA. As the test bucket was filled, the bunch was observed to move in time with respect to the reference bunches.

This measurement was originally taken in March 2007 and the results were presented previously [3]. The March 2007 data was taken with only 2 ID chambers in the storage ring. Later data sets were taken in April and June 2008 when there were 3 IDs chambers and 2 IVUs installed are shown in Fig. 1.

The energy loss is  $\Delta E = -k_l \cdot q^2$ , therefore  $\Delta V = -k_l \cdot q = -k_l \cdot I_b / f_0$  Where  $I_b$  is the bunch current and  $f_0$  is the revolution frequency. To recover this energy lost an equal and opposite voltage shift in the RF is needed. For a small shift this would be  $\Delta \hat{V} = V_0 \cos(\phi_s) \cdot \Delta \phi_s$ , equating these we have:

$$\begin{aligned} V_0 \cos(\phi_s) \cdot \Delta \phi_s &= k_l \frac{I_b}{f_0} \\ \Delta \phi_s &= \frac{k_l I_b}{V_0 \cos(\phi_s) f_0} \\ \Delta \tau &= \frac{k_l I_b}{\omega_{RF} V_0 \cos(\phi_s) f_0} \end{aligned} \quad (1)$$

For Gaussian bunches

$$k_l = \frac{R}{2\sqrt{\pi}\sigma} \quad (2)$$

The results of all four data sets are summarised in Table 1. They results show that the resistive impedance has increased with the addition of more ID chambers from 800 to 1600  $\Omega$ .

Table 1: Synchronous phase advance results

Data set	ps/mA	$k_l$ (V/pC)	R ( $\Omega$ )
03/07 2.4 MV	$0.9 \pm 0.16$	$8.7 \pm 1.6$	$802 \pm 128$
04/08 3.0 MV	$1.6 \pm 0.14$	$19.5 \pm 1.8$	$1592 \pm 144$
06/08 3.0 MV	$1.6 \pm 0.15$	$20.4 \pm 1.9$	$1653 \pm 156$
06/08 2.0 MV	$2.0 \pm 0.17$	$15.5 \pm 1.3$	$1588 \pm 105$

### Potential Well Distortion

As a bunch current increases, the wakefields start to modify the RF potential in which it sits, distorting the shape of the bunch from a pure gaussian. The Hassinski equation

[4], describes the equilibrium longitudinal particle distribution within a bunch in the presence of an arbitrary longitudinal wake field. It is given as

$$\lambda(z) = K \cdot e^{\left( \frac{-z^2}{2\sigma_0^2} + \frac{\int_0^z V_{ind}(z') dz'}{V_{RF} \sigma_0^2} \right)} \quad (3)$$

Where  $\sigma_0$  is the natural bunch length,  $V'_{RF} = -(\omega_{RF}/c) \cdot V_0 \cos(\phi_s)$  is the slope of the RF voltage at synchronous phase, and the induced voltage,  $V_{ind}$ , is

$$V_{ind}(z) = - \int_0^\infty W^{\parallel}(z') \cdot \lambda(z - z') dz' \quad (4)$$

This gives a particle distribution that is a gaussian multiplied by a distortion term that depends on the wakefield generated by the bunch, which in turn depends on the particle distribution. If we express  $V_{ind}$  as a simple linear combination of  $\lambda(z)$  and  $\lambda'(z)$ , as would arise from a series combination of fixed resistance R and fixed inductance L we get

$$V_{ind}(z) = -cq[R\lambda(z) + cL\lambda'(z)] \quad (5)$$

and the equation becomes solvable via an iterative method. Using this form we can compare the predicted bunch lengthening with current for a given R and L and compare it with measurements. There are several bunch lengthening data sets, taken between March 2007 and June 2008. To extract the imaginary impedance from these results we used the R values obtained in Table 1 and put them into the Hassinski formula. We varied the value of L until the simulated bunch distortion matched the data. The results of the different data sets are shown in Fig. 2 and summarised in Table 2. The divergence of the high current data points from the line may be due to the emergence of single bunch instabilities beginning having a further effect on bunch shape. In fact, we believe that in the December 2007 and January 2008 results in particular, the microwave instability was influencing the high current end of the graph.

Assuming a predominately inductive machine impedance we can extract the effective machine impedance using

$$\left( \frac{Z}{n} \right)_{eff} = \omega_0 L \quad (6)$$

Table 2: Bunch lengthening results

Data set	#ID chambers	#IVUs	Inductance from fit (nH)	Z/n ( $\Omega$ )
03/04/07	2	0	22.5	0.196
26/06/07	3	0	25	0.218
13/11/07	3	0	33	0.288
10/12/07	3	1	90	0.786
09/01/08	3	3	110	0.960
10/01/08	3	3	110	0.960
02/06/08	3	2	55	0.480
02/06/08 2MV	3	2	55	0.480

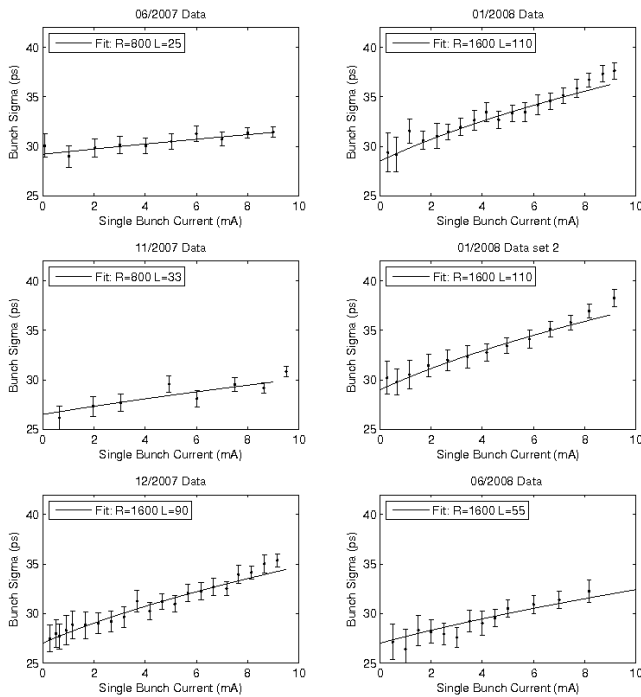


Figure 2: Bunch lengthening results and fits for data sets between March 2007 and June 2008.

The results show a clear increase in impedance when the first IVU was installed. The increase of 60 nH, from around 30 nH to 90 nH was far in excess of expectations and quite alarming. After the next two IVUs were installed the impedance only increased by 20 nH, much more in line with expectations from modeling. This result, combined with an unusual vacuum event during commissioning of the first IVU, prompted us break vacuum and investigate this IVU. We discovered that an internal screw had become loose, rolled onto to the wakefield shield directly above the beam and melted. Once the damaged IVU was removed the impedance has been observed to drop back down to more reasonable levels.

### Single Bunch Tune Shift

The transverse impedance can be explored by observing the change in betatron tune as the bunch current is increase. This tune shift comes about from the imaginary component of the transverse impedance and is given by [7]:

$$\frac{d\nu_{\beta}}{dI} = -\frac{e < \beta > R}{4\sqrt{\pi} E \sigma_z} \text{Im}(Z_{\perp}^{\perp})_{eff} \quad (7)$$

Measurements of the vertical tune shift with single bunch were taken in April and November 2007 and the results are shown in Fig. 3. Unfortunately more recent results are not currently available. The two  $d\nu/dI$  slopes are -2.88 and  $-3.10 \times 10^{-4}/\text{mA}$  and using equation 7 we obtain a value of 0.85 and 0.92  $M\Omega/m$  for  $\text{Im}(Z_{\perp}^{\perp})_{eff}$ . This compares very favorably with a previously calculated value of 05 Beam Dynamics and Electromagnetic Fields

0.94  $M\Omega/m$  [3]. Horizontal tune shift was not observable with the resolution of our spectrum analyser.

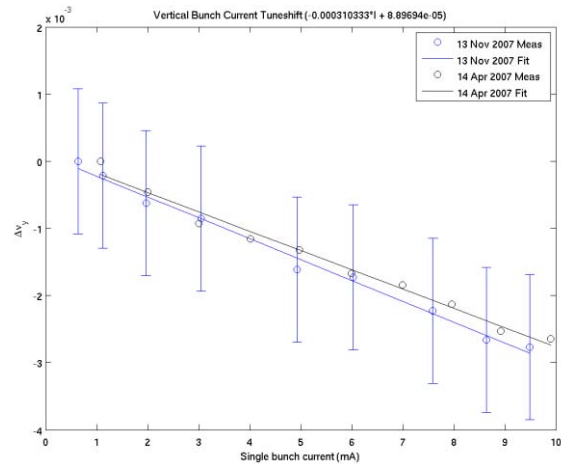


Figure 3: Plots of vertical tune shift with increasing single bunch current. Linear fits to the two data sets are shown.

## CONCLUSION

Through single bunch studies we have observed the evolution of the total effective longitudinal impedance of the Australian Synchrotron storage ring over time. These studies allow us to monitor the evolution of the machine impedance in order to anticipate possible problems with instabilities and plan accordingly. They have also proved important in the early diagnosis of a problem with one of the IVUs. Our current effective longitudinal impedance is estimated to be around  $0.48\Omega$ , with each ID contributing around  $0.1\Omega$ . The effective vertical transverse impedance was also measured as 0.92  $M\Omega/m$ . Further measurements of this type are planned using a more accurate tune measurement system.

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