SINGLE BUNCH INSTABILITY STUDIES AT DIAMOND LIGHT SOURCE

E. Koukovini-Platia, M. Apollonio, R. Bartolini[1], R. Fielder, I. Martin, Diamond Light Source Ltd, Oxfordshire, UK
[1]also at John Adams Institute, University of Oxford, UK

Abstract

Single bunch instability thresholds, the associated coherent tune shifts and the bunch lengthening have been studied at Diamond light source for nominal optics. Measurements were taken under different settings of chromaticity, radio-frequency (RF) voltage and aperture of the insertion devices (IDs). The macro-particle code sbtrack was used to evaluate the instability thresholds and bunch lengthening where different impedance contributions are taken into account such as the resistive wall impedance, a broad-band resonator model and inductive impedance for the longitudinal plane. A comparison of simulation using the developed model impedance with measurements is shown for all cases.

INTRODUCTION

Collective effects in a particle accelerator, introduced by the electromagnetic interaction of the beam with its surroundings, can limit its performance causing longitudinal or transverse instabilities and may lead to beam quality deterioration and beam loss. The study of these effects is crucial towards a better understanding of the beam dynamics involved in an operating synchrotron or during the design phase of new accelerators.

The interaction of charged particle beams with the surroundings is expressed via the beam coupling impedance in the frequency domain [1]. As a first approximation, the full ring can be modelled with a total impedance made of two main components, the resistive-wall (RW) and one broad-band resonator (BBR). Vacuum chamber apertures of modern light sources are rather small causing the resistive-wall impedance to become considerable, while a single BBR can approximate the global effect of beam pipe and device discontinuities that exhibit short-lived wakes. Thus for single bunch instabilities a BBR can replace the effect of the actual impedance that consists of many small short-range contributions.

Diamond Impedance Model

For Diamond Light Source, the developed transverse impedance model consists of a BBR and RW, while the longitudinal one required an inductive impedance in addition. The RW impedance is calculated analytically using the average chamber half-apertures of 40 mm horizontally and 12 mm vertically for closed IDs (or 13 mm when IDs are open) and the conductivity of stainless steel vacuum chamber ($\sigma = 1.37 \times 10^6$ S/m).

For the beam-based characterization of the BBR parameters, a set of single bunch measurements was realized including current-dependent transverse tune shift for the transverse impedance model and bunch lengthening for the longitudinal impedance model. The effect of chromaticity, RF voltage and aperture of the IDs was also studied. Previous work on this subject is listed in [2, 3].

LONGITUDINAL SINGLE BUNCH INSTABILITIES

Bunch lengthening measurements due to potential well distortion [4] were taken with increasing beam current using a streak camera [5]. The bunch length data with current are shown in Figure 1 in terms of Full Width Half Maximum (FWHM) for various vertical chromaticity values $Q'_y = 0, 1, 2, 3$ (measured data in red).

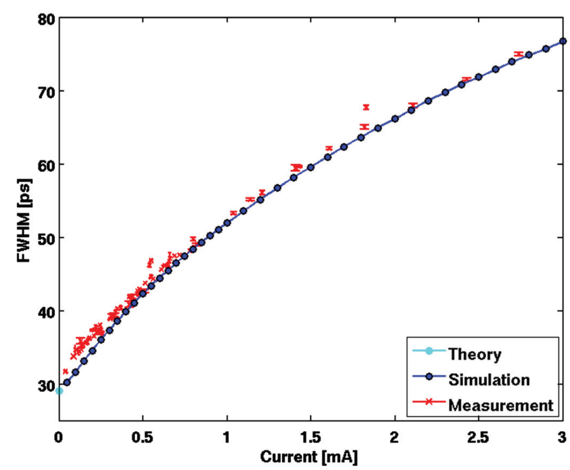

Figure 1: Bunch lengthening as a function of current. The measured data are shown in red and the sbtrack simulation in blue. The longitudinal model impedance consists of RW, a BBR and an inductive impedance.

The Diamond parameters during the measurements were: $E = 3$ GeV, $\alpha_c = 1.6 \times 10^{-4}$, synchrotron tune $Q_s = 0.00416$, $V_{RF} = 2.5$ MV and wigglers on. In the same plot, the 0-current bunch length is calculated theoretically at 29 ps (in cyan). For the simulation, the 6D macro-particle code sbtrack [6] was used for tracking. The longitudinal impedance model used in sbtrack simulation consists of the RW impedance, a BBR and an inductive impedance. The geometrical impedance is modelled by a single BBR with $Q = 1$ and resonant frequency close to the beam pipe's cut-off frequency, $f_r = 8.3$ GHz. The shunt impedance was scanned in order to match the measured bunch length and the best agreement was found for $R_s = 0.5$ kΩ. To reproduce well the measured data, it was necessary to include a purely inductive impedance of $L = 70$ nH.

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TRANSVERSE SINGLE BUNCH INSTABILITIES

For the study of single bunch instabilities in the transverse plane, measurements were taken with 0 chromaticity to assess the Transverse Mode Coupling Instability (TMCI) thresholds and the associated coherent tune shifts.

Horizontal Plane

In Figure 2, the measured current-dependent horizontal tune shift is displayed for V_{RF} = 2.5 MV and chromaticities $Q'_x = 0$, $Q'_y = 3$.

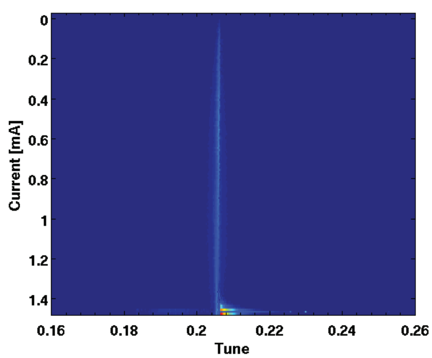

Figure 2: Horizontal measured betatron tune shift with current for $Q'_x = 0$, $Q'_y = 3$ and V_{RF} = 2.5 MV. The measured TMCI threshold is 1.47 mA.

As expected for a flat geometry chamber as in Diamond, in the horizontal plane the dipolar and quadrupolar wakes cancel out [7] leading to a minimal tune shift of mode $m = 0$, which was also confirmed experimentally in Figure 2. The single bunch current limit due to TMCI is (1.47 ± 0.06) mA.

A model horizontal impedance was used in sbtrack for tracking. The model consists of RW impedance, calculated analytically as described above and a BBR. The BBR parameters are $Q = 1$, f_r = 8.3 GHz and by scanning the shunt impedance the best agreement was found for R_x = 5 kΩ/m. In Figure 3 the simulated horizontal centroid position is shown over 30000 turns for increasing currents of 1.4, 1.45 and 1.5 mA. The predicted onset of instability with sbtrack

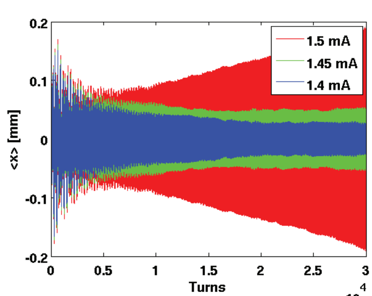

Figure 3: Horizontal centroid position over 30000 turns for single bunch current of 1.4, 1.45 and 1.5 mA. A growth in the centroid amplitude can be observed after 1.45 mA.

is 1.45-1.5 mA, which agrees well with the measurements.

Vertical Plane

For the vertical TMCI measurement, the horizontal chromaticity was kept positive $Q'_x = 3$, and the vertical was corrected to $Q'_y = 0$, while the voltage was kept unchanged at V_{RF} = 2.5 MV. The insertion devices were closed at minimum gap which corresponds to 2.5 mm half-aperture. In Figure 4 the measured vertical tune shift is shown for the center-of-mass ($m = 0$).

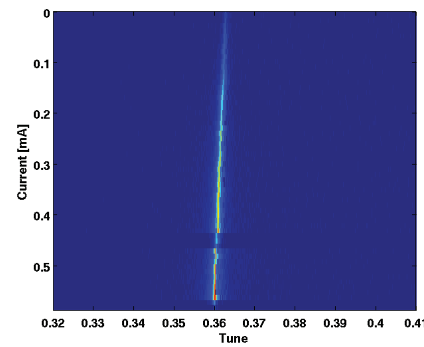

Figure 4: Vertical measured tune shift with current for $Q'_x = 3$, $Q'_y = 0$, V_{RF} = 2.5 MV and closed IDs. The measured TMCI threshold is 0.6 mA.

The measured TMCI threshold is (0.6 ± 0.05) mA which is more than a factor of 2 lower than the horizontal plane due to the generally small vertical chamber size.

The developed vertical impedance model includes a RW using the average half-aperture of 12 mm when the IDs are closed and a BBR impedance with $Q = 1$, f_r = 8.3 GHz and R_y = 0.10 MΩ/m. The simulated normalized tune shift using the above model impedance (in blue) is compared with 3 measured data sets (in black, red and green) in Figure 5.

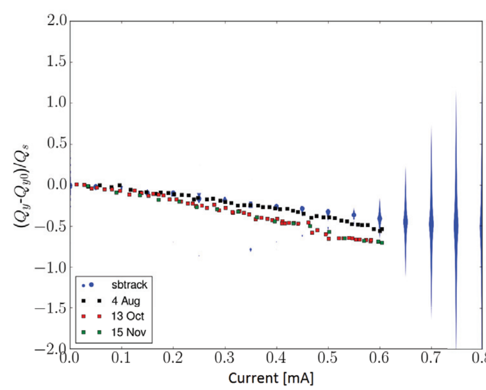

Figure 5: Vertical normalized betatron tune shift with current. The simulation (in blue) predicts a coupling of $m = 0$ with $m = -1$ at around 0.6 mA. The measured threshold is at 0.6 mA.

Simulation with sbtrack shows the center-of-mass ($m = 0$) to shift down as the current increases, while a higher order mode, $m = -1$, exhibits a positive tune shift and the two modes merge at around 0.6 mA. The predicted TMCI threshold and slope are in good agreement with the measurements.

Figure 5 (as well as Figure 6 in the next session) indicates a small difference in the measured slope between August (black), before the shut-down, and October/November (red/green) after the shut-down. However, the TMCI thresholds were well reproducible, i.e. around 0.58-0.6 mA in all measurements. From the list of changes that occurred during the shut-down in August 2015, no additional impedance source was found that could be responsible for the slightly different slopes. Moreover, looking at Figure 7, which only includes measurements from October (red) and November (green) for V_{RF} = 1.7 MV, i.e. both measured data were taken after the shut-down, a small difference in the slopes can still be observed. That led to the conclusion that this small discrepancy is due to the measurements accuracy.

Effect of Open IDs

The effect of opening IDs to the maximum gap (half-aperture at 15 mm) was also studied. The measured TMCI threshold moved to a higher current of 0.74 mA. To simulate this in sbtrack, the vertical BBR model was unvaried and only the average half-aperture was increased to 13 mm to account for the change of resistive wall impedance. The simulated and measured normalized tune shift with current can be seen in Figure 6.

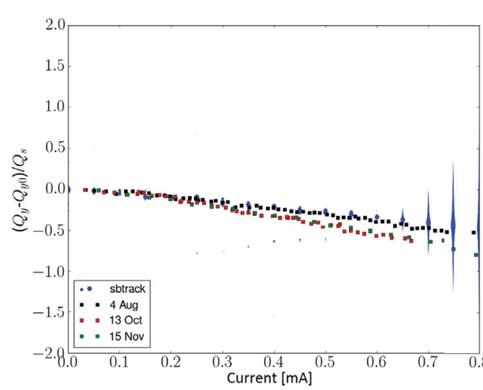

Figure 6: Vertical normalized betatron tune shift with current for open IDs. The simulation (in blue) predicts a coupling of $m = 0$ with a higher order head-tail mode $m = -1$ at around 0.7 mA. The measured threshold is at 0.74 mA.

Sbtrack simulations predict the fast head-tail threshold at around 0.7 mA, in good agreement with the measured limit at 0.74 mA. Therefore the effect of the IDs can be sufficiently explained by the resistive wall impedance.

Effect of Different Voltage

To further validate the developed impedance model, measurements were also taken for different RF voltages. For a lower V_{RF} = 1.7 MV the measured instability onset was detected at 0.51 mA due to the lower synchrotron tune (despite the longer bunch length). Similar observations were made in ALBA, Barcelona [8]. A summary of the measured TMCI thresholds under different voltages is shown in Table 1.

Table 1: Vertical TMCI Thresholds

RF Voltage [MV]	TMCI threshold [mA]
1.7	0.51
2	0.54
2.5	0.59
2.8	0.61
3.4	0.64

Good agreement between sbtrack and measurements with Q'_x = 3 and Q'_y = 0 was also found in this case in terms of slope and threshold, an example of which is shown in Figure 7. For the sbtrack simulation only the parameters of voltage, synchrotron tune and bunch length were changed while the vertical model impedance was unmodified.

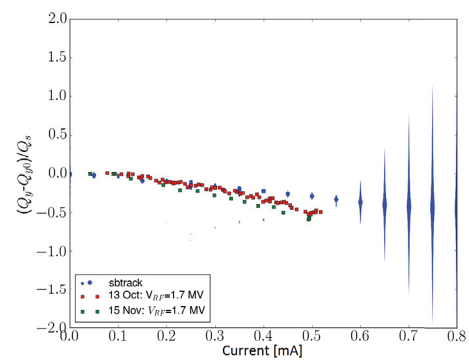

Figure 7: Vertical normalized betatron tune shift with current for V_{RF} = 1.7 MV. The simulation (in blue) predicts a coupling of $m = 0$ with a higher order head-tail mode $m = -1$ at around 0.55-0.6 mA. The measured threshold is at around 0.51 mA.

CONCLUSION

Single bunch measurements at nominal optics have been carried out at Diamond light source and compared with sbtrack macro-particle code simulations. The comparison was done for transverse and longitudinal planes, different RF voltages and state of IDs (closed or open). A satisfactory agreement was found in the longitudinal plane, leading to a first approximation model with RW, a BBR and an inductive impedance while for the transverse plane a RW and BBR model is sufficient to explain the measured coherent tune-shifts and TMCI thresholds. The developed vertical impedance model can predict well the effect of open IDs just by changing the resistive wall impedance via the bigger half-aperture.

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