ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK010

DIFFERENCES IN CURRENT DEPENDENT TUNE SHIFTS MEASURED BY DIRECT OR ORM BASED METHODS

Y. R. E. Tan*, R. Dowd, Australian Synchrotron, Clayton, Australia

Abstract

The change in the tunes as a function of total beam current is a well documented effect and has been attributed to quadrupole like self induced wakefields. Theoretical models presented by others have utilised direct methods (spectrum analyser) to measure the tunes in the analysis. In this report we shall present observations that show the ORM method, Linear Optics from Closed Optics (LOCO), and direct methods have significantly different tune gradients. The different tune gradients is attributed to the static (ORM) and dynamic (direct) nature of the measurements where in the static case the vacuum chamber is to be considered as a thin wall while in the dynamic case the vacuum chamber wall is to be considered as a thick wall.

INTRODUCTION

A common method of calibrating storage rings is by the technique of linear optics from closed optics (LOCO) [1] that uses an orbit response matrix (ORM) and dispersion measurements as inputs. The method has been proven as a reliable method of determining the linear optics of a storage ring. During a study using LOCO to measure the impedance effect of the in-vacuum undulators (IVUs), the tune gradients from LOCO based analysis were different to the measured tune gradients and could not be explained. This difference in gradient is shown Figure 1. When three of the IVUs were closed to a gap of 7 mm both the measure and LOCO derived tune gradients change, indicating that both are measuring the impedance effect resulting from closing the IVU gap.

To resolve the discrepancy we compared three different tune measurements: swept spectrum analyser (SA) connected to a stripline to excite the beam and a button beam position monitor (BPM) to measure the response, Fourier analysis of turn-by-turn (TbT) data from the BPM system after a fast kicker excites the beam and measuring the notch in the beam spectrum with the bunch-by-bunch (BbB) feedback system in operation. The three different tune measurements were in agreement to within the resolution of the tunes ($\sigma\nu_{x/y} = 1.5 \times 10^{-4}$). With LOCO we tried: ORMs with different amplitudes, unipolar vs bipolar excitation, changed the chromaticity, changed the weighting of the dispersion function in LOCO, disabled the BbB feedback system, reviewed the model, changed fit parameters. At the conclusion, the investigations indicated that both measurements are valid results.

LASLETT TUNE SHIFT MODEL

In electron storage rings, self-induced wakefields do result in tune shifts that are dependent on the average beam

* eugene.tan@synchrotron.org.au

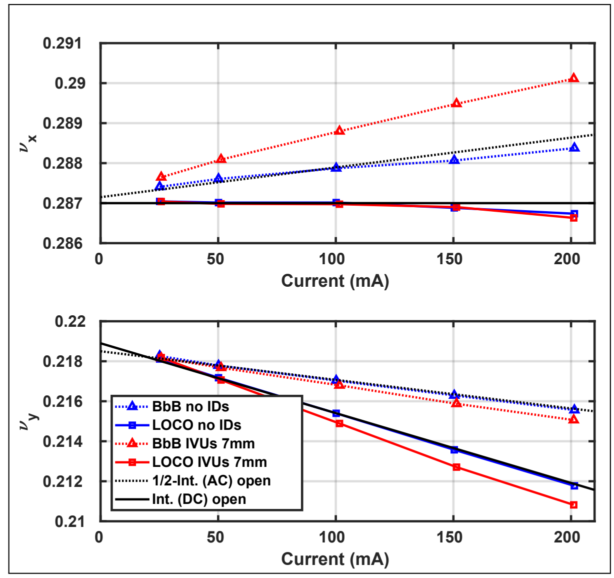

Figure 1: Tunes measured with the BbB system and LOCO derived tunes. The measured and LOCO derived tune gradients are completely different and both clearly display an effect resulting from closing the IVU gap.

current. Both the incoherent and coherent tune shifts can be described using the Laslett formulas for generalised chamber geometries [2–4]. A more recent approach to describe the tune shifts as a wakefiled/impedance problem in a vacuum chamber with a finite thickness. Brunelle [7] consolidates the results of Chao [5] and Shobuda [6] and compares both models against a series of measurements to determine the nature of the wakefield. The measured tune shifts in Figure 1 is compared against the Laslett, Chao and Shobuda models.

To improve the accuracy, piecewise integration of the models is essential [7] and all approximations using $R\nu^{-1}_{x/y}$ have been replaced with $<\beta_{x/y}>$ [3, 7]. In the analysis, parameters in Table 1 are used.

The measured tune gradient (BbB) is compared against the three models and the results are shown in Table 2. The Laslett model was found to compare favourably with the measured results, moreover the model accounts for two scenarios where the fields do or do not penetrate the vacuum chamber. Ng's [4] revision of the Laslett formula is repeated here and has been simplified for relativistic electron storage rings. The formula for the penetrating fields is

$$\Delta\nu^{DC}_{x/y} = -\frac{N r_0 <\beta_{x/y}>}{\pi\gamma}\left(\frac{\xi^1_{x,y}}{b^2} + \mathcal{F}\frac{\xi^2_{x,y}}{b_m^2}\right), \qquad (1)$$

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK010

Table 1: Storage ring vacuum chamber and magnet gap parameters, where b is the chamber half-height, b_m is the magnet half-gap, t the chamber wall thickness and L_m is the magnet length. * In normal chambers where there are dipole magnets L_m = dipole magnet length, otherwise $L_m = 0$.

	b (mm)	b_m (mm)	t (mm)	L_m (m)
IVU (ID03, ID13)	19	19.1	0.1	3
IVU (ID05)	19	19.1	0.1	2
SCW (ID08)	5	7.6	2.0	2
Narrow gap (ID12, ID14)	5.5	50.0	3.0	4
Normal	16	21	3.0	*

Table 2: Measured tune gradients compared against the three models: Laslett, Chao and Shobuda. The geometric factor used in the Shobuda model was $D_{2xy} = 0.33$.

	$\Delta\nu_x$ (10^{-3})	$\Delta\nu_y$ (10^{-3})
Measured	+5.3	-15.2
Laslett	+7.4	-14.3
Chao	+14.6	-23.5
Shobuda	+3.2	-3.2

and non-penetrating fields is

$$\Delta\nu^{AC}_{x/y} = -\frac{N r_0 < \beta_{x/y} >}{\pi\gamma}\left(\frac{\epsilon^1_{x,y}}{b^2} + \mathcal{F}\frac{\epsilon^2_{x,y}}{b_m^2}\right), \quad (2)$$

where N is the number of electrons, r_0 is the classical electron radius, $\beta_{x/y}$ is the Twiss function, γ is the relativistic factor, b is the vacuum chamber half-height, b_m is the magnet half-height, $\mathcal{F}$ is the fraction of the vacuum chamber with magnets and $\xi^{1,2}_{x,y}$ and $\epsilon^{1,2}_{x,y}$ are chamber geometry coefficients. Coefficients for the parallel plate model is used in the analysis:

$$\begin{aligned} \xi^1_x &= 0 \quad \xi^1_y = +\pi^2/16 \quad (chamber) \\ \xi^2_x &= 0 \quad \xi^2_y = +\pi^2/16 \quad (magnet) \\ \epsilon^1_x &= -\pi^2/48 \quad \epsilon^1_y = +\pi^2/48 \quad (chamber) \\ \epsilon^2_x &= -\pi^2/24 \quad \epsilon^2_y = +\pi^2/24 \quad (magnet). \end{aligned} \quad (3)$$

In-Vacuum Undulator Gap and Capping

To test the model, two experiments were conducted: one, the tune gradient is measured with three IVUs closed to a gap of 7 mm and, two, a 3 mm thick capping was installed around unused straight sections to add ferro-magnetic material external to the vacuum chamber (Figure 2).

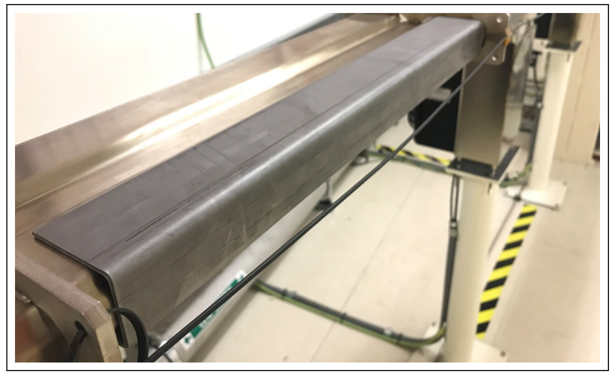

Figure 2: 3 mm thick ferro-magnetic capping made from mild steel (250 grade).

The results in Table 3 appear to qualitatively support the Laslett model however it does overestimate the $\Delta\nu^{AC}_x$ by 50% compared to measurements. Though the addition of the capping was modelled to have a small effect on the gradient, the measured result do appear to support the predictions. Additional measurements are planned in the future to collect sufficient statistics to confirm the effect of the capping.

Table 3: Comparison of the measured tunes, $\Delta\nu^m_{x,y}$, against predictions using the Laslett formulas under three different scenarios.

IVU Gap	$\Delta\nu^m_x$	$\Delta\nu^m_y$	$\Delta\nu^{AC,DC}_x$	$\Delta\nu^{AC,DC}_y$
BbB (Half-Integer; AC; 10^{-3})				
38 mm	+5.3	-15.2	+7.4	-14.3
7 mm	+14.0	-17.7	+20.6	-19.2
38+cusps	+5.9	-16.8	+8.2	-14.6
LOCO (Integer; DC; 10^{-3})				
38 mm	-1.7	-35.9	0	-34.9
7 mm	-2.0	-42.3	0	-45.8
38+cusps	-1.6	-36.8	0	-35.4

Fill Pattern Depenedence

The tune gradients has been measured for different fill patterns and the results plotted in Figure 3 show that the tune shift is not related the individual bunch current but rather is a cumulative effect over the entire bunch train [7]. There is however a dependence on the fill pattern as shown in Table 4. By definition the Laslett model assumes a continuous unbunched charged particle beam the tune gradient with all 360 bunches would likely be more accurate. If we assume a linear dependence on the fill pattern, the tune gradient for a full fill of 360 bunches can be extrapolated from the measured data. The extrapolated values do to appear converge on the Laslett model.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK010
Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

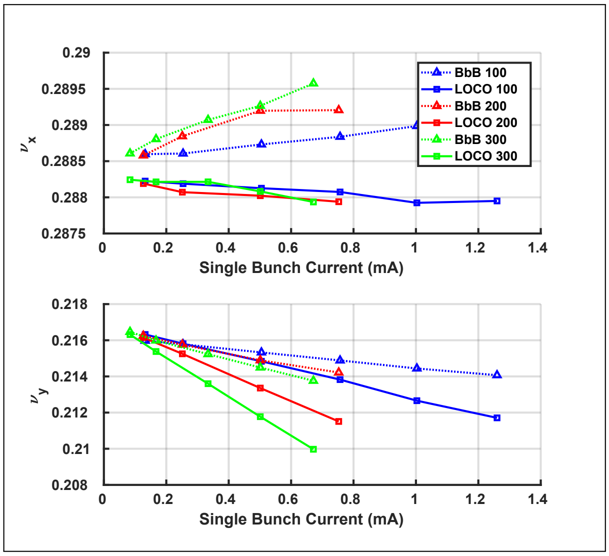

Figure 3: Tune shift for different fill patterns plotted against the equivalent single bunch current in the storage ring. The changing gradient for both measured and LOCO tune gradients shows the effect is unrelated to the single bunch current.

Table 4: The measured tune gradients for different fill patterns. Using the measure data we can extrapolate to 360 bunches assuming it is linear (†)

Fill pattern	$\Delta\nu_x^m$	$\Delta\nu_y^m$
BbB (Half-Integer; AC; 10^{-3})		
100 bunches	+4.1	-17.2
200 bunches	+5.0	-16.2
300 bunches	+5.3	-15.2
360 bunches†	+5.8	-14.6
Laslett	+7.4	-14.3
LOCO (Integer; DC; 10^{-3})		
100 bunches	-2.7	-41.2
200 bunches	-1.8	-37.2
300 bunches	-1.7	-35.9
360 bunches†	-1.3	-33.9
Laslett	0	-34.9

DISCUSSION

The two formulas of the Laslett model has so far proved consistent with the measured results. If this is true then the effect of the impedance "observed" by measuring the tunes is different to the effect when using LOCO. One possibility is the difference in the method of measurement that spans two dissimilar frequency domains. One is a high frequency excitation of the electron beam followed by a spectral analysis of the beam motion (usually >10 kHz). The other is a measurement of the closed orbit distortion after sufficient time has been given for the perturbation (change in corrector) to damp.

Tune measurements only measure the response of the electron beam to AC fields and the frequencies of these fields are typically high enough that the AC fields do not penetrate the vacuum chamber. Therefore such measurements will sample the state of the electron beam where vacuum chamber is thick walled. However in the closed orbit case, this is a DC measurement that only responds to DC fields that penetrate the vacuum chamber. Therefore in the closed orbit case the vacuum chamber is effectively a thin wall. This would explain why the measured and LOCO derived tune gradients are so different.

CONCLUSION

The difference between the measured and LOCO derived tune gradients can be attributed to the two different frequency domains in which they were measured. Both the measured and LOCO derived tune gradients can be described using the Laslett formulas for non-penetrating and penetrating fields (respectively). The results indicate that the two methods measure two different aspects of the wakefields on the electron beam, therefore the use of ORM methods in studying wakefields and impedances must be carefully considered before proceeding. Moreover the difference in the effect of the impedance needs to be accounted for when using ORM methods like LOCO to calibrate the storage ring.

REFERENCES

[1] J. Safranek, "Experimental determination of storage ring optics using orbit response measurements", *Nucl. Instr. Meth.*, vol. 388, pp. 27–36, 1997.

[2] Laslett, L. J., "On Intensity Limitations Imposed by Transverse Space-Charge Effects in Circular Particle Accelerators", in *Proc. 1963 Summer Study on Storage Rings, Accelerators and Experimentation at Super-High Energies*, C630610, pp. 324, 1963.

[3] B. Zotter, "Betatron frequency shifts due to image and self-fields", in *Proc. 2nd CERN Accelerator School: General Accelerator Physics*, pp. 253–266, 1986.

[4] K. Y. Ng, "Betatron Tune Shifts and Laslett Image Coefficients", Fermilab, Rep. FERMILAB-TM-2152, 2001

[5] A. Chao, S. Heifets, B. Zotter, "Tune shifts of bunch trains due to resistive vacuum chambers without circular symmetry", *Phys. Rev. ST Accel. Beams*, vol. 5, pp. 111001, 2002.

[6] Y. Shobuda, K. Yokoya, "Resistive wall impedance and tune shift for a chamber with a finite thickness", *Phys. Rev. E*, vol. 66, pp. 056501, 2002.

[7] P. Brunelle, R. Nagaoka, R. Sreedharan, "Measurement and analysis of the impact of transverse incoherent wakefields in a light source storage ring", *Phys. Rev. Accel. Beams*, vol. 19, pp. 044401, 2016.