ANALYSIS OF SINGLE BUNCH MEASUREMENTS AT THE ALBA STORAGE RING

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Abstract

Measurements of the vertical single bunch mode detuning and the TMCI threshold at zero chromaticity were carried out and their results were compared to the theoretical expectation. Around 65% of the found mode detuning can be explained by a developed transverse impedance model. A good bunch length parametrisation with current contributed essentially to this result. The analysis of single bunch measurements at non-zero chromaticity will also be presented.

INTRODUCTION

In order to crosscheck the transverse impedance model at ALBA, single bunch tune shift and instability thresholds in the vertical plane have been studied at zero and positive chromaticity (henceforth defined as $\xi = \Delta\nu_\beta/\delta$, with ν_β the vertical betatron tune and δ the energy spread). Two approaches were tried: the first makes use of the improved version of the mode coupling program MOSES [1] and the second of the tracking program HEADTAIL [2]. Both codes have been compared in the past [3]. In the meantime, MOSES has been improved with features like resistive wall (RW) impedance and the inclusion of quadrupolar detuning. A forthcoming note is foreseen to provide more details.

TMCI-REGIME

The transverse mode coupling instability (TMCI) could be very well observed on the tune monitor upon increasing gradually the bunch current. The mode m=-1 showed up very closely to the m=0 peak just before the onset of the instability at 8.8 mA. The measurement was repeated with open in-vacuum undulators where the threshold was reached at 9.8 mA.

During the measurements the bunch length σ_τ was monitored. For its parametrisation, as well as the one of the incoherent synchrotron tune ν_s with current I, the following equations [4] were used assuming that the MW-instability was not reached during the measurements:

$$\left(\frac{\sigma_\tau}{\sigma_{\tau 0}}\right)^3 - \left(\frac{\sigma_\tau}{\sigma_{\tau 0}}\right) = \frac{\alpha Im(Z/n) I}{\sqrt{2\pi}(E/e)\nu_{s0}^2(\omega_0\sigma_{\tau 0})^3}; \quad \nu_s(I) = \frac{\alpha\delta}{\omega_0\sigma_\tau(I)} \qquad (1)$$

where α stands for the slipping parameter, E for beam energy, ν_s (ν_{s0}) for (zero current) synchrotron tune, ω_0 for revolution frequency and $\sigma_\tau/\sigma_{\tau 0}$ for zero current normalized bunch length.

Moreover, the agreement of the incoherent synchrotron tune with the measured coherent one at zero current was required. This way the values $\nu_{s0} = 0.0063$ for the zero current synchrotron tune and $\sigma_{\tau 0} = 20.75$ ps (Fig.1) were obtained.

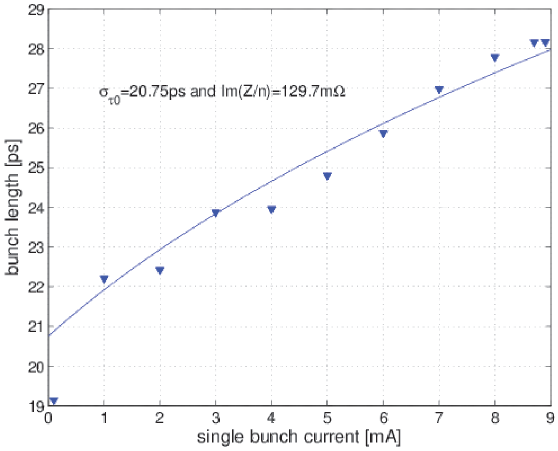

Figure 1: Bunch length parametrisation with current.

Analysis using MOSES

The bunch length fit yields a reduced longitudinal impedance of $Im(Z/n)$=130 $m\Omega$ (Fig.1). Both parametrisations were implemented in MOSES to compute the model tune shift with varying bunch length. The impedance model [5] is summarized in Table 1 in terms of β-function weighted kick factors, which have rather simple relation with the tune shift: $\Delta\nu/\nu_s = \frac{I}{2\omega_s(E/e)}(\beta\kappa)_V$ and hide the bunch length dependence.

Table 1: Computed Vertical Impedance Budget

Type	**Geometrical** $[\frac{kV}{pC}]$	**RW** $[\frac{kV}{pC}]$
Dipolar $(\beta\kappa)_V$	4.86	7.86
Quadrupolar$(\beta\kappa)_V$	1.625	3.93
Total $(\beta\kappa)_V = 18.28$	6.485	11.79
Total equivalent $(\beta Z_{\text{eff}})_V = 1426k\Omega$@22ps		

For comparison a common normalization of the measured and model data on the zero-current synchrotron tune was chosen. Therefore the tune shifts computed by MOSES had to be adapted to it. With adapted and varying bunch length and synchrotron tune, the vertical model TMCI threshold decreases from 17.5 mA [5] to 13 mA, closer to the measured value of 8.8 mA. For the inclusion of the impedance quadrupolar part in the detuning slope, the quadrupolar part had to be recalculated for a larger medium bunch length of 22 ps. For the RW part, MOSES did it; for the geometrical part, the recalibration was done by switching to the frequency domain.

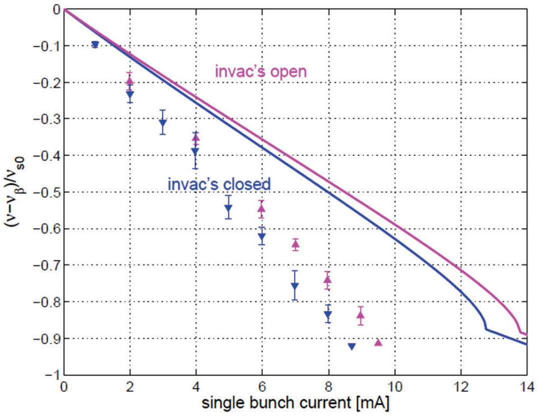

Figure 2: Comparison of the measured mode m=0 detuning with the resulting detuning of the vertical impedance model at $\xi = 0$ with closed and open in-vacuum undulators.

In Fig.2, the zero current value of the measurements could be produced by extrapolating the measured slope. The comparison shows that measured mode detuning is stronger and TMCI-threshold is lower than the model. Therefore, a 55% higher model impedance would be necessary to reproduce the measured values. Furthermore, from the difference in the slope, the effect of opening the 2 in-vacuum undulators was estimated: $(\beta Z_{\text{eff}})_V$=256 $k\Omega$ for 22 ps to be compared with the model value of 113 $k\Omega$.

Analysis using HEADTAIL

The impedance model mentioned above was used including the 4 broadband resonators (BBR) and the 6 multi-layer resistive wall (dipolar and quadrupolar terms) contributions which were calculated with the ImpedanceWake2D package [6]. A difference between the model used for MOSES is that the injection kickers were not yet included since the exact geometry is necessary for the CST Microwave Studio® [7] modeling.

HEADTAIL simulation results match very well with the measured instability onset by adding a 5^{th} dipolar BBR to the existing model with resonant frequency f_r = 1 GHz, quality factor Q = 1 and transverse shunt impedance of 1.6 MΩ/m. The total transverse model used summing the 6 resistive wall contributions plus the 5 BBRs is illustrated in Fig. 3.

The relative tune shift with respect to the zero-current tune and normalized to the synchrotron tune is plotted in Fig. 4 together with the measured data of m=0 (in red). Modes 0 and -1 are observed to move and couple at 9 mA, causing a TMCI for closed (top plot) in vacuum undulators. HEADTAIL successfully predicts the threshold at 10 mA for open in vacuum undulators (bottom plot) as well. As seen from the comparison of simulated to measured tune shift in Fig. 4, HEADTAIL predicts the observed TMCI thresholds and explains around 85% of the found mode detuning if this 5^{th} BBR is added in the model.

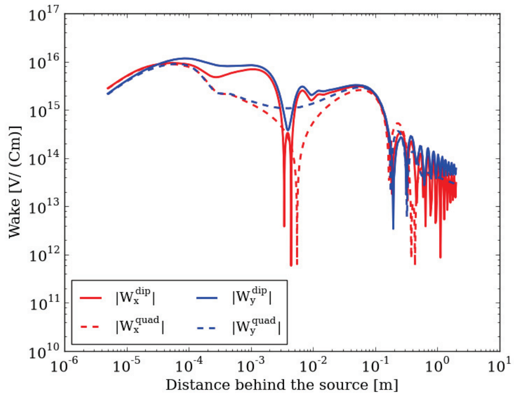

Figure 3: Transverse wake function model in HEADTAIL.

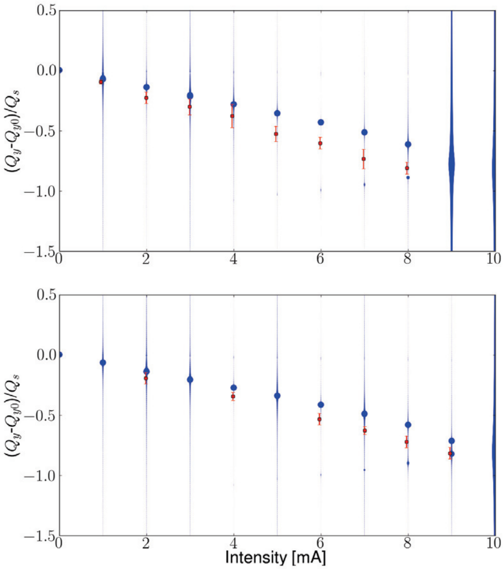

Figure 4: Mode spectrum of the vertical coherent motion for zero chromaticity, as function of the single bunch intensity for closed (top) and open (bottom) in-vacuum undulators.

HEAD-TAIL REGIME $\xi > 0$

For the intensity range scanned during the measurement, the azimuthal modes are not observed to couple, while higher order modes get unstable according to the concept of head-tail (HT) instability. The threshold was measured at 4.8 mA for ξ = 1.8, whereas no threshold was encountered up to 12 mA for ξ = 5.2.

Analysis using MOSES for $\xi > 0$

The onset of the threshold was computed by MOSES to be around 2 mA (for a 55% stronger impedance it would be even at lower current). On the other hand, MOSES did not find a threshold at ξ = 5.2, in agreement with the observation.

The apparent important disagreement at $\xi = 1.8$ could be explained by an additional damping effect, for instance by Landau damping due to synchrotron tune spread caused by the potential well distortion effect. A strong damping of HT-excitation due to synchrotron tune spread was already observed at the ESRF [8].

Although further investigation is still necessary, in a second round of measurements, distinct head-tail modes and their detuning could be observed at $\xi = 1.4$, 2.7 and 5.3 (no threshold for 5.3) up to the onset of instability (Fig.5) which is therefore considered as HT-instability. The low threshold for m=-1 is partly the result of the nonlinear behaviour of the growth of the mode with current due to the interaction with other modes. If Sacherer's equation linear in I is used for the computation of the HT growth rate of mode m=-1:

$$\frac{1}{\tau} = -\frac{I}{16\sqrt{\pi}(E/e)\sigma_\tau} \frac{\sum\limits_{p=-\infty}^{\infty} Re(\beta Z)_\perp(\omega_p)\cdot h_1(\omega_p-\omega_\xi)}{\sum\limits_{p=-\infty}^{\infty} h_1(\omega_p-\omega_\xi)} \qquad (2)$$

with $\omega_p = (p + \nu_\beta + m\nu_s)\omega_0$, $\omega_\xi = \frac{\xi}{\alpha}\omega_0$ and $h_m(\omega)$ as Hermite base functions, the threshold yields at ~4mA.

The different scaling factors to apply (Fig. 5) for the reproduction of the measurements at different chromaticity could be an indication for stronger lack of impedance at low frequency. Note that MOSES takes different bunch lengths due to different applied RF-voltages for both sets of measurements ($\xi = 0$ and $\xi > 0$) into account.

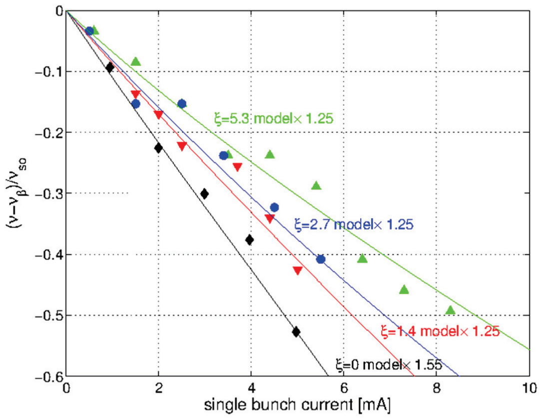

Figure 5: Detuning of mode m=0 for ξ=0, 1.4, 2.7 and 5.3. The detuning according to the model ×1.55 for ξ=0 and ×1.25 for ξ>0 is superimposed.

Analysis using HEADTAIL for $\xi > 0$

HEADTAIL simulations were performed for positive chromaticity of 1.8 and 5.2. By comparing the rise time of the instability with the vertical damping time of the ring (5.3 ms), the threshold of instability can be defined. For ξ=1.8, HEADTAIL predicts a threshold at 2.5 mA while 4.8 mA was the measured instability onset. For ξ=5.2, the disagreement is even stronger with HEADTAIL predicting a threshold at 1 mA while actually no instability was observed.

The agreement between HEADTAIL simulations and measurements for zero chromaticity but the disagreement in the positive case, could be explained by a missing quadrupolar term in the added 5^{th} BBR. Further studies are planned to investigate the missing impedance from the existing model that would match both zero and positive chromaticity regimes. CST simulations will be done to include the kickers in the existing model used by HEADTAIL.

CONCLUSION

Single bunch measurements at ALBA have been compared with results from MOSES and HEADTAIL codes. Although the agreement is in general satisfactory, it points out that the description has still potential of improvement. In particular, it was found that the model lacks of impedance particularly in the low frequency range (<2GHz). The results could be better reproduced using MOSES with a further improved bunch length σ_τ and incoherent synchrotron tune ν_s parametrisation. On the other hand, results using HEADTAIL could match the TMCI experimental measurements by adding a 5^{th} dipolar BBR to the existing model, but there is still a disagreement with results at $\xi > 0$.

For this reason, further investigation will be carried out in two directions: 1) find a better parameterization of σ_τ and ν_s with current and 2) a thorough analysis of the injection kickers impedance contribution and other missing impedance sources. For the time being, since the storage ring is only equipped with 6 low gap chambers, ALBA has still some margin in terms of transverse impedance.

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