

COUPLED-BUNCH INSTABILITY STUDY FOR UTEF STORAGE RING

Y. L. Chen¹, S. W. Wang^{*1}, Y. Zhang¹, J. C. Xiao², B. C. Jiang¹,

¹Chongqing University, Chongqing, China

²University of Science and Technology of China, Hefei, Anhui, China

Abstract

The Ultra-fast Transient Experimental Facility (UTEF) at Chongqing University is currently constructing a 500 MeV storage ring. This paper investigates the transverse coupled-bunch instabilities (TCBI) critical to its high-current operation. Building on a method previously developed at Diamond Light Source—which enables the calculation of all coupled-bunch instability modes within a single simulation—this work extends the approach to non-zero chromaticity cases using a multi-particle-per-bunch model. Results for the UTEF ring demonstrate that non-zero chromaticity and synchrotron radiation damping have a negligible impact on the grow-damp curve. On the other hand, the inclusion of short-range impedance brings an obvious shift of the grow-damp curve. This paper provides a detailed account of the simulation and results.

INTRODUCTION

The Ultra-fast Transient Experimental Facility (UTEF) at Chongqing University is constructing a 500 MeV synchrotron light source designed for advanced material analysis, targeting a high beam current of 1000 mA [1]. Achieving this design current presents challenges due to collective effects, particularly the transverse coupled-bunch instability (TCBI) driven by long-range wakefields. The storage ring features a compact four-fold DDBA lattice (Table 1 and Fig. 1). In this paper, we investigate the TCBI for the UTEF ring using a method originally developed at Diamond Light Source [2] to evaluate the grow-damp rates of all coupled-bunch modes across various scenarios.

Table 1: Main Parameters of the UTEF Storage Ring

Parameters	
Circumference	76.78 m
Emittance	4.74 nm
Momentum compaction factor	3.144×10^{-3}
Harmonic number	128
Energy spread	3.8×10^{-4}
Tune	7.161/3.178
Synchrotron tune	0.00716
Natural chromaticity	-13.42/-17.30
Corrected chromaticity	0.0/0.0
Damping time $\tau_x/\tau_y/\tau_s$	58.2/59.0/29.7 ms
Natural bunch length w/o HC	2.0 mm
Natural bunch length with HC	10.7 mm

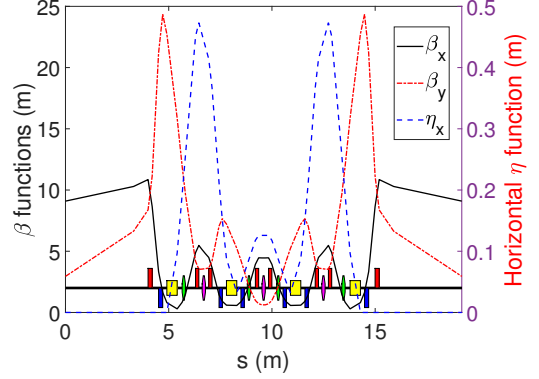


Figure 1: Optics and lattice layout of the UTEF storage ring.

COUPLED-BUNCH INSTABILITY MODES

The transverse coupled-bunch motion of the bunch centroids in a uniformly filled beam is characterised by coupled-bunch modes. The analytical complex frequency shift is given by [3]:

$$\Delta\Omega_\mu = \frac{ecI_0}{4\pi E_0 \nu_\beta} \sum_p Z_\perp(\omega_p) \exp\left(-\left(\omega_p + \frac{\xi\omega_0}{\alpha_c}\right)^2 \sigma_t^2\right), \quad (1)$$

where c is the speed of light, I_0 is the total beam current, and E_0/e denotes the beam energy in eV. $Z_\perp$ represents the lumped impedance following the ELEGANT convention [4]. For one-turn map tracking, ν_β is evaluated as $\nu_\beta = C/(2\pi\bar{\beta})$, where $\bar{\beta}$ is integrated into the impedance via normalisation by the local beta function. The exponential term accounts for the effect of chromaticity, where ξ is the chromaticity, ω_0 is the angular revolution frequency, α_c is the momentum compaction factor, and σ_t is the bunch length. The impedance is sampled at the following frequencies:

$$\omega_p = (\mu + Mp + \nu_\beta)\omega_0, \quad (2)$$

where μ is the mode index ($0 \leq \mu \leq M-1$) and ν_β is the betatron tune. The summation is performed over the integer index p to obtain the total contribution to mode μ . The real and imaginary parts of the complex frequency shift yield the tune shift and the growth rate of the mode, respectively.

COUPLED-BUNCH INSTABILITY FROM RESISTIVE-WALL WAKE

The transverse resistive-wall (RW) long-range wake for the UTEF storage ring is generated for each element using IW2D [5]. A lumped wake element is then calculated by

* wsw290@cqu.edu.cn

summing the wakes, normalised by the local beta functions:

$$W_{\perp,x,y}(t) = \frac{1}{\beta_{0x,y}} \sum_i \beta_{x,y,i} W_{i,\perp}(t), \quad (3)$$

where $\beta_{0x,y}$ represents the horizontal or vertical beta function at the lumped wake location. Summation i is over every element, with $\beta_{x,y,i}$ being the average beta function of element i . The resulting wake function and the imaginary part of the impedance are shown in Fig. 2.

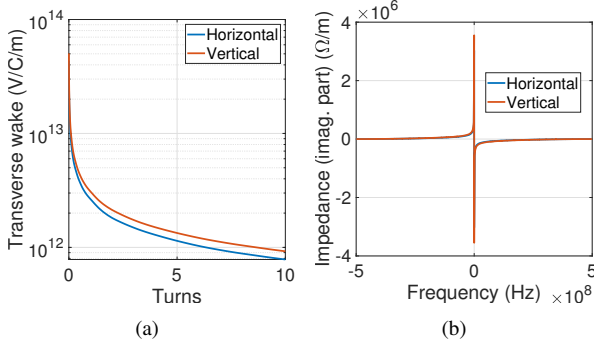


Figure 2: Transverse long-range resistive-wall wake and impedance: (a) Wake function over 10 turns; (b) Imaginary part of the impedance according to the ELEGANT convention.

Given the small vacuum chamber aperture of the UTEF ring, the long-range RW wake is the primary driver of TCBI. Tracking simulations are performed using ELEGANT, employing a linear one-turn map via the ILMATRIX element integrated with a lumped long-range wake (LRWAKE). Simulations use a uniform fill pattern with 10,000 particles per bunch. We track 1,000 turns at beam currents up to 1000 mA—sufficient duration for fitting the growth and damping rates of all coupled-bunch modes. To ensure equal initial amplitudes for all modes, a transverse offset is applied solely to the leading bunch; this approach is inspired by the Discrete Fourier Transform (DFT) of a unit impulse $[1, 0, 0, \dots, 0]$ being a uniform spectrum $[1, 1, 1, \dots, 1]$.

Because turn-by-turn tracking does not inherently account for the betatron phase difference between bunches, an additional phase term is applied to the complex centroid coordinates, yielding the series [2]:

$$z_n = \left[\frac{x_n}{\sqrt{\beta_n}} - i \left(\sqrt{\beta_n} x'_n + \frac{\alpha_n}{\sqrt{\beta_n}} x_n \right) \right] \exp \left(-\frac{2\pi i \nu_\beta (n-1)}{M} \right), \quad (4)$$

where n is the bunch index ($1 \leq n \leq M$), and x_n, x'_n denote the bunch centroid position and slope, respectively. By performing a DFT on $\{z_n\}$ for each turn, the growth rate of each mode is extracted via exponential fitting.

Three scenarios are investigated: (1) zero versus non-zero chromaticity at 1000 mA; (2) the inclusion of synchrotron radiation damping; and (3) the impact of short-range impedance. Cases (2) and (3) are evaluated at both 100 mA and 1000 mA.

RESULTS AND DISCUSSION

Impact of Chromaticity

Simulations were conducted for chromaticity (ξ) ranging from -2 to 2 . The resulting grow-damp trends for various modes are illustrated in Fig. 3. At zero chromaticity, the evolution of the modes can be fitted directly using an exponential function. For non-zero chromaticity, however, an additional oscillation is observed superimposed on the exponential trend. This oscillation frequency corresponds to the synchrotron tune; consequently, the peak values (indicated by the black dashed lines) are selected for the exponential fit. The resulting grow-damp curve, presented in Fig. 4, appears insensitive to variations in chromaticity.

According to Eq. (1), this behaviour is primarily attributed to the relatively large momentum compaction factor (α_c) of the UTEF lattice. A large α_c suppresses the frequency shift term ($\xi \omega_0 / \alpha_c$) within the exponential damping factor, at non-zero ξ values. The grow-damp curves for chromaticity 0 and 2 are nearly identical, and both remain consistent with the analytical predictions.

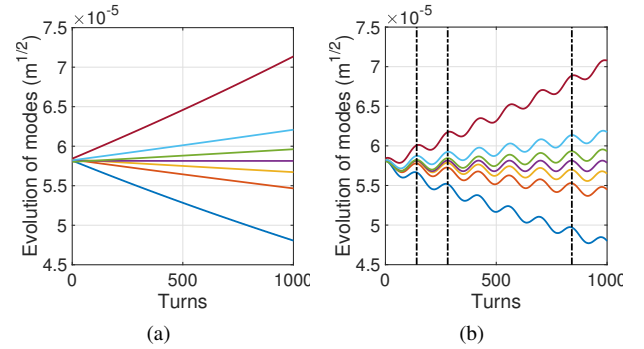


Figure 3: Evolution of several transverse coupled-bunch modes in the frequency domain for (a) zero chromaticity and (b) chromaticity $\xi = 2$. The different colours indicate different modes. The dashed lines show the peak values used for exponential fitting.

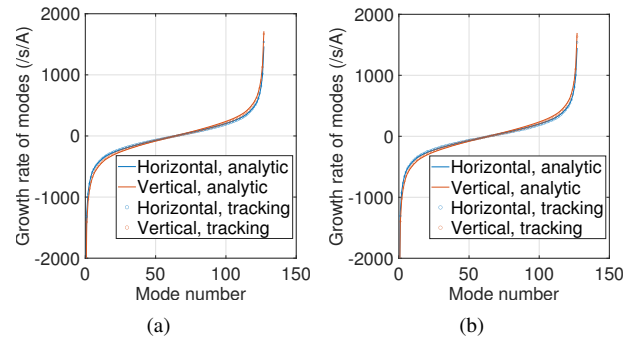


Figure 4: Benchmark of tracking simulations against analytical predictions: grow-damp curves for (a) $\xi = 0$ and (b) $\xi = 2$.

Impact of Synchrotron Radiation and Short-Range Impedance Effect

The effects of synchrotron radiation (SR) damping and short-range impedance were also investigated. The SR damping rate for the UTEF storage ring is notably low (approximately 17 s^{-1}). At high beam currents, the impact of SR is virtually negligible. Its influence only becomes slightly visible at lower currents; for instance, as shown in Fig. 5(a), the grow-damp curve exhibits a slight shift consistent with the SR damping rate.

In contrast, the introduction of short-range impedance leads to a shift in the grow-damp curves across all coupled-bunch modes. This shift is observed to be proportional to the beam current, reflecting the proportionality between short-range impedance effects and individual bunch current. Furthermore, when the chromaticity is negative, the grow-damp curve shifts upwards; conversely, a downward shift is observed for positive chromaticity. This aligns with the standard operational practice in electron storage rings, where chromaticity is adjusted to a small positive value to suppress head-tail instabilities.

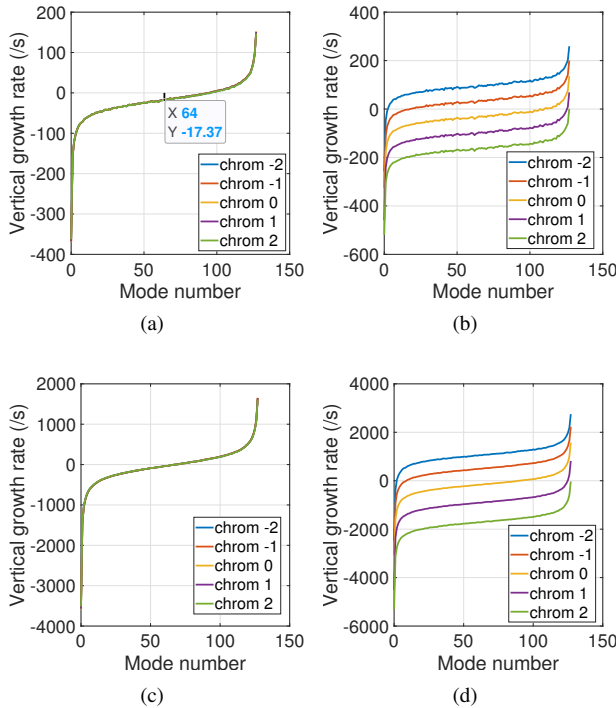


Figure 5: Comparison of grow-damp curves under various conditions: Left column (a, c) includes synchrotron radiation (SR) damping only; right column (b, d) includes both SR and short-range impedance. Top row (a, b) at 100 mA; bottom row (c, d) at 1000 mA.

Beam Stabilisation with TMBF

As demonstrated in the preceding sections, coupled-bunch effects induce instabilities at the nominal operating chromaticity of zero. To mitigate this and ensure beam stability,

a Transverse Multi-Bunch Feedback (TMBF) system will be implemented.

With the TMBF coefficients appropriately configured relative to the betatron tune [6], simulations were performed at a beam current of 1 A and zero chromaticity, incorporating both short-range impedance and the TMBF model. A similar filling pattern was employed, with initial transverse offsets of 1 mm (horizontal) and 0.1 mm (vertical) applied to the leading bunch, while subsequent bunches remained at zero centroids. The beam was tracked for 100,000 turns to evaluate long-term stability, with the results illustrated in Fig. 6.

The upper plot in Fig. 6 shows that the leading bunch is rapidly damped by the TMBF system, while no instability is triggered in the following bunches over the entire 100,000-turn duration. The lower plot provides a detailed view of the first 500 turns, highlighting the efficiency of the damping process. These results validate that the TMBF system can effectively suppress transverse coupled-bunch instabilities in the UTEF storage ring at 1000 mA, thereby ensuring stable operational conditions.

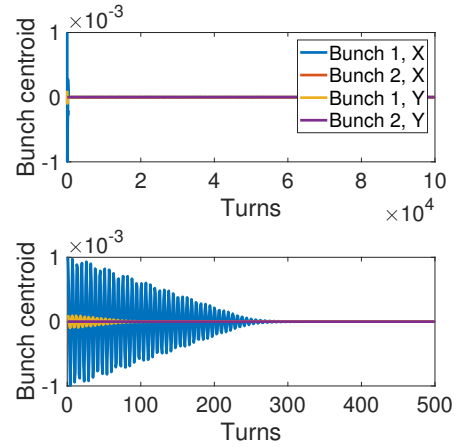


Figure 6: Bunch centroid evolution with Transverse Multi-Bunch Feedback (TMBF) at 1000 mA: the upper plot shows long-term stability over 100,000 turns, while the lower plot provides a detailed view of the initial damping over 500 turns.

CONCLUSIONS

This paper generalises a simulation method for calculating the growth rates of all coupled-bunch modes within a single simulation, extending the model to include multi-particle-per-bunch dynamics. The grow-damp characteristics of the transverse coupled-bunch instability, driven by long-range resistive-wall wakes, were investigated for the UTEF storage ring across various scenarios. The results demonstrate that while increased chromaticity and synchrotron radiation effects yield only marginal changes to the grow-damp curves, the inclusion of short-range impedance induces a distinct, chromaticity-dependent shift. To mitigate TCBI at the design current of 1000 mA, a TMBF system was evaluated and proven to effectively suppress these instabilities.

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