COUPLED-BUNCH INSTABILITY STUDY FOR UTEF STORAGE RING

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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

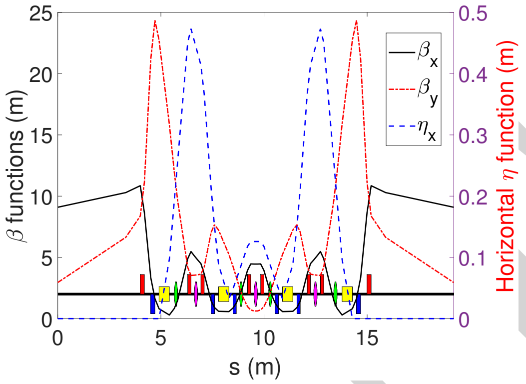

Figure 1: Optics and lattice layout of the UTEF storage ring.

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]:

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

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, and α_c is the momentum compaction factor. The impedance is sampled at the following frequencies:

$$\omega_p = (\mu + Mp + \nu_\beta)\omega_0, \tag{2}$$

where μ is the mode index ($0 \le \mu \le M-1$) 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 summing the wakes, normalised by the local beta functions:

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

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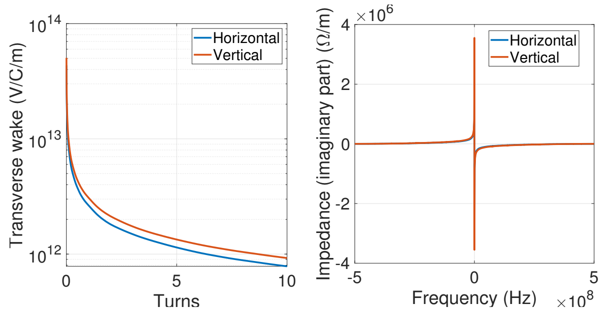
where $\beta_{0x,y}$ represents the horizontal or vertical beta function at the lumped wake location. The resulting wake function and the imaginary part of the impedance are shown in Fig. 2.



(a) (b)

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 $[1, 0, 0, \ldots, 0]$ being a uniform spectrum $[1, 1, 1, \ldots, 1]$.

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]:

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

where n is the bunch index ($1 \le n \le M$), 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.

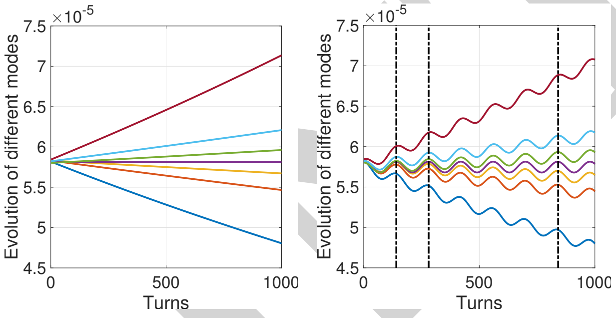
Three scenarios are investigated: (1) zero versus non-zero chromaticity at 1000 mA; (2) the inclusion of synchrotron radiation damping; and (3) the impact of short-range impedance. Cases (2) and (3) are evaluated at both 100 mA and 1000 mA.

RESULTS AND DISCUSSION

Impact of Chromaticity

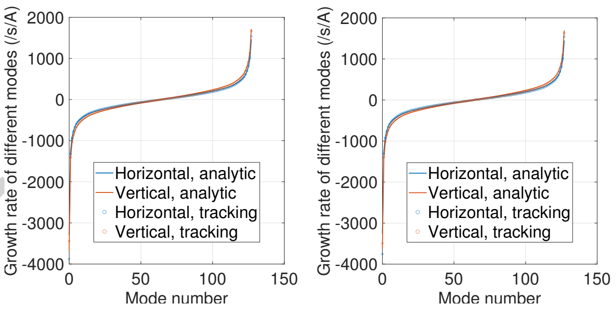
Simulations were conducted for chromaticity (ξ) ranging from −2 to 2. The resulting grow-damp trends for various modes are illustrated in Fig. 3. At zero chromaticity, the evolution of the modes can be fitted directly using an exponential function. For non-zero chromaticity, however, an additional oscillation 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.



(a) (b)

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



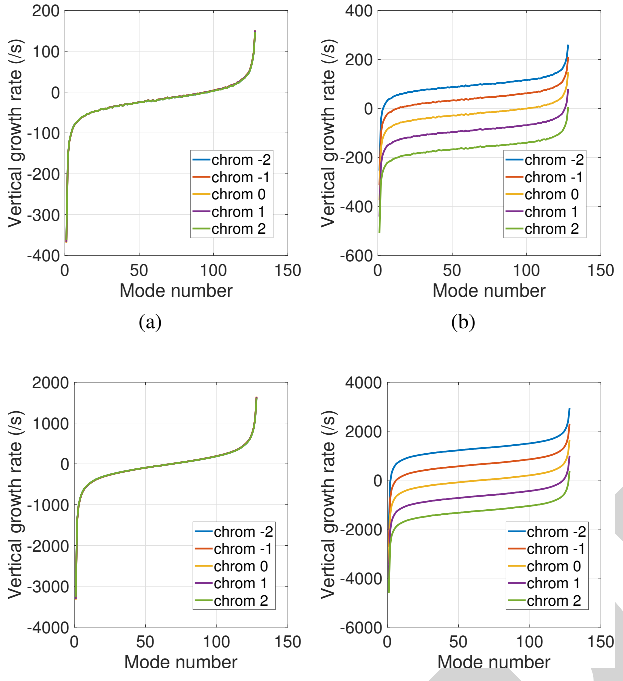
(a) (b)

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.



(a) (b)

(c) (d)

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 1 A, thereby ensuring stable operational conditions.

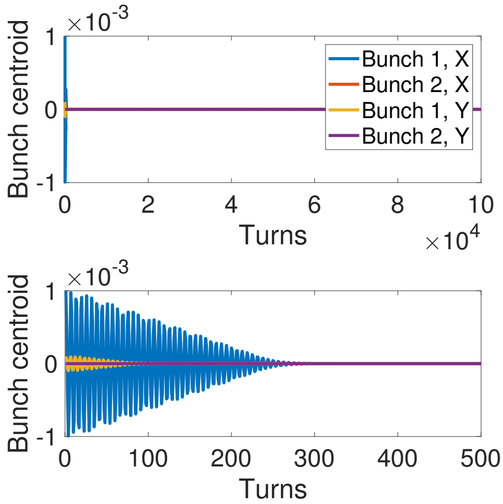


Figure 6: Bunch centroid evolution with Transverse Multi-Bunch Feedback (TMBF) at 1 A: the upper plot shows long-term stability over 100,000 turns, while the lower plot provides a detailed view of the initial damping over 500 turns.

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 1 A, a TMBF system was evaluated and proven to effectively suppress these instabilities.

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