RESISTIVE WALL INSTABILITY AND IMPEDANCE STUDIES OF NARROW UNDULATOR CHAMBER IN CHESS-U*

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Abstract

In a major upgrade of the Cornell Electron Storage Ring (CESR) one sextant of ring will be replaced with double bend achromats (DBAs) and undulator straights for x-ray users. The resistive wall impedance from the narrow gap (4.5 mm) undulator chambers (5 m per straight) may limit total beam. Here we report recent results of modelling and calculation of multibunch instabilities due to the impedance of chamber walls and transition tapers. The short range wakefields and resistive wall impedance are modelled and incorporated in a tracking simulation. The coupled-bunch growth rate found with the tracking study is in good agreement with the analytic approximation. We find that the resistive wall instability can be readily damped by our existing bunch-by-bunch feedback system.

INTRODUCTION

CESR was built in a ½ mile circumference tunnel under a soccer field on the Cornell University campus in 1979. The ring stores counter-rotating beams of electrons (e^-) and positrons (e^+) that are accelerated to high energy ~5 GeV by the fast cycling synchrotron (Fig. 1). Multibunch e^- and e^+ circulate on electrostatically separated pretzel orbits in opposite directions. CESR operated as an e^--e^+ high energy physics collider for nearly three decades.

Since the conclusion of the colliding beam program in 2008, CESR has been primarily used as a dedicated x-ray source, the Cornell High Energy Synchrotron Source (CHESS). To increase x-ray flux, two undulators with a 6.5 mm-vertical gap (chamber gap 4.5 mm) were installed in Fall 2014 (Fig. 1); these provide x-rays for five beamlines [1]. To further enhance performance and to increase the number of beamlines, a major upgrade

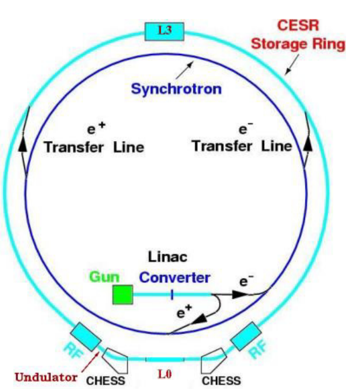

Figure 1: CESR layout and undulators location.

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(CHESS-U) is underway that will replace the sextant of CESR between the east and west RF with DBAs and straights outfitted with undulators to serve x-ray users [2]. Single beam on-axis operation will allow significant reduction the beam emittance. CESR's energy will be increased from 5.3 to 6 GeV to produce high intensity high energy x-rays for users.

The permanent magnet narrow gap undulators will be installed in 5 m straights. In addition, the vertical aperture of the vacuum chambers for new combined function dipoles and quadrupoles in the achromats will reduce by half (50 mm to 22 mm). The resistive wall impedance from these reduced aperture chambers will reduce the threshold of coupled bunch beam instability [3]. We developed a computer model to explore the effect of the wakefields from these vacuum chambers and report recent results in this paper. The resistive wall impedance is modelled and incorporated into a tracking simulation to investigate the coupled-bunch growth. The simulation shows reasonably good agreement with the approximate analytic calculation, confirming that the coupled-bunch growth due to resistive wall impedance is not problematic for operation of CHESS-U and can be damped by our existing bunch-by-bunch feedback. In addition, we investigated the short range wakefields from the undulator chambers and found that the vertical emittance growth due to their wakes is negligible.

THEORY AND MODEL

In metallic vacuum chambers, moving charged particles induce currents in the chamber walls. Due to the finite resistivity of the walls, the currents extend behind those moving charges and their EM fields act back on the charged particles arriving later. These resistive wall wakefields have a long-range effect and can cause coupled-bunch instability. The transverse resistive wall wake function for a vacuum chamber with length L and vertical half aperture b is given by [3].

$$W_{\perp}(z) = -\frac{c}{\pi b^3}\sqrt{\frac{Z_0}{\pi\sigma}}\frac{L}{\sqrt{-z}} \quad . \tag{1}$$

where σ is the conductivity of the vacuum chamber, Z_0 is the impedance of free space, and z is the longitudinal distance from the bunch driving the wakefield. Equation (1) is valid when the following conditions are satisfied:

$$-z >> \sqrt[3]{\frac{b^2}{Z_0\sigma}} \quad \text{and} \quad z < 0 \ . \tag{2}$$

The wakefields induced by the driving bunch will generate a vertical kick to the following bunch arriving at a time Δt later. The vertical kick Δp_y is written as

$$\Delta p_y = \frac{e q_L y_L}{-E_0} W_\perp(-c\Delta t) \ . \tag{3}$$

where e is the electron charge, q_L is the charge of the driving bunch, y_L is the vertical offset of the driving bunch, and E_0 is the beam energy.

SIMULATION

Long-range Wake Model

The particle tracking codes are based on the BMAD subroutine library for relativistic charged-particle dynamics simulations [4]. Multiple bunches in various bunch patterns have been studied. Each bunch is modelled as a single macroparticle and tracked through the CHESS-U lattice for 4000 turns. The resistive wall wake is calculated using Eq. (1) in a custom tracking routine associated with the specific vacuum chamber. When bunch i passes through the vacuum pipe at turn j, a vertical kick due to the resistive wall wake W_{ij} based on Eq. (3) is applied to the bunch. W_{ij} is the sum of all the wakes induced by all the bunches passing by at every previous turn.

The tracking time using the custom routine increases dramatically with the number of turns. An alternative approach is to fit the analytic wake function as a linear combination of damped sinusoidal modes. These wake pseudo modes are similar to a set of cavity modes [3, 4]:

$$W_m(t) = -c\left(\frac{R}{Q}\right)_m e^{-\omega t/2Q} \sin(\omega t + \phi) \ . \tag{4}$$

where m=1 and ϕ=π/2. Seventeen sets of parameters (R, Q, ω) were used to fit Eq. (1) out to 4000 turns ($z \approx 3\times10^6$ m). Using these pseudo modes, the wake generated by bunch j can simply be added to the existing wake without recalculating as required by the custom routine. Thus the computation scales only linearly as the number of turns and the tracking time is significantly reduced.

Tracking

The growth rate from the resistive wall can be calculated analytically if the bunch pattern is uniform and the impedance evenly distributed around the ring. In order to compare our tracking simulation to the analytic formulation [5], we first track a uniform fill pattern through the CHESS-U lattice with a constant vacuum chamber gap of 4.5 mm around the ring. In this lattice, 100 'wake' elements were uniformly distributed around the ring. To find the growth rate for each coupled-bunch mode, we performed a Fourier analysis of the bunch positions for every turn and recorded the amplitudes of the Fourier modes for each turn. The growth rate of each Fourier mode was obtained by fitting an exponential to the amplitude of each mode as a function of turn number.

The initial bunch positions could be set randomly at turn 0 for the mode analysis. However, the obtained Fourier mode amplitudes are noisy. Thus, a new drive-damp method was developed in the simulation, similar to experimental drive-damp measurements. The initial bunch position y and momentum y' were set according to the following:

$$y_i = \sqrt{\varepsilon\beta_i}\cos\left(\frac{2\pi\mu}{N}i\right)$$
$$y'_i = -\sqrt{\frac{\varepsilon}{\beta_i}}\left[\alpha_i\cos\left(\frac{2\pi\mu}{N}i\right) + \sin\left(\frac{2\pi\mu}{N}i\right)\right] \ . \tag{5}$$

where N is the number of bunches, i is the bunch index (i=1,2,…, N), α_i and β_i are the Twiss parameters at the location where bunch i initial coordinates were set, μ is the mode number (μ =0,1,…, N-1), and ε is the drive amplitude, which was kept the same for all μ modes. For each drive configuration only the growth rate of the mode that was driven initially was measured.

The growth rate of the 61 modes from tracking 61 uniformly distributed bunches through a lattice with constant gap is shown in Fig. 2. Here bunch spacing

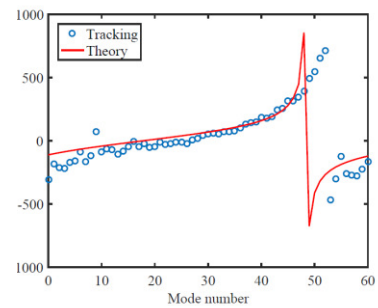

Figure 2: The growth rate from tracking with a uniform fill of 61 bunches in a uniform gap lattice and the theoretical calculation.

ΔT=42 ns, drive amplitude ε=1×10^{-8} m, and bunch current I_b=0.05 mA were used. The vertical tune Q_y of the CHESS-U lattice is 12.615. The analytic calculation of the growth rate using the same parameters is also displayed in Fig. 2. In general, tracking results agree reasonably well with the analytic calculation. The fastest growth rate from simulation is 720 s^{-1} at μ=52, close to that from theory 850 s^{-1} at μ=48. The discrepancy of the peak mode number may be because the Fourier modes are not exactly the normal modes [5].

After validation of our tracking results with the analytic calculation, the CHESS-U lattice with 5 narrow gap undulator chambers was studied with the parameters N=61, ΔT=42 ns, ε=3.9×10^{-7} m, and I_b=3 mA. The growth rates of two lattices with different vertical tunes (12.615 and 12.365) are displayed in Fig. 3a. The lattice with fractional tune below the half integer has smaller growth rate (196 s^{-1}) than the lattice with fractional tune above the half (241 s^{-1}), demonstrating the anticipated greater stability below the half. The ratio of growth rates of the fastest growing mode is 196/241=0.81, consistent with the theoretical prediction [6]:

$$\frac{\Gamma_{Qy=12.365}}{\Gamma_{Qy=12.615}} = \frac{\sqrt{1-0.615}}{\sqrt{1-0.365}} = 0.78 \ .$$

When the wakefields from the reduced-aperture dipole and quadrupole chambers are also included in the tracking model, the fastest growth rate increases from 280 s^{-1} to 338 s^{-1} in Fig. 3b. This indicates the narrow gap undulator chambers are the dominant source of resistive wall impedance with tracking parameters N=100, ΔT=24 ns, ε=3.5×10^{-8} m, I_b=2 mA, and Q_y=12.615. Different bunch patterns have been studied and the average of the fastest growth rates is about 350 s^{-1}, corresponding to a growth time of 2.9 ms, which is significantly shorter than the radiation damping time of 20 ms. Thus, a bunch-by-bunch feedback system is needed to damp the coupled-bunch instability. During the operation in the current CHESS lattice, the measured vertical damping time for a 2 mA bunch using installed DIMTEL bunch-by-bunch feedback is 0.2 ms with a low shift gain of 2. Using the Twiss parameters at the same pickup and kicker locations of the feedback in the CHESS-U lattice and the same shift gain, the estimated damping time in the CHESS-U lattice is 0.4 ms, which is much shorter than the instability growth time. Therefore, our feedback system should be able to damp this coupled bunch instability.

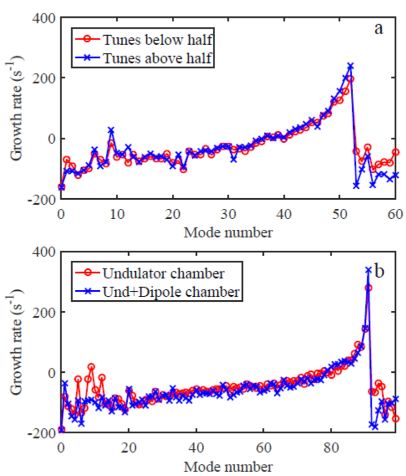

Figure 3: The growth rate from (a) two lattices with two different tunes, and (b) with and without narrow aperture dipole chambers.

Undulator Dipole and Quadrupole Wakes

The electromagnetic simulation suite ACE3P that was developed at SLAC was used to calculate the wakefields from the undulator chamber [7]. The three-dimensional structure of the undulator was first constructed using the the finite element mesh toolkit CUBIT [8], and then imported to the time domain wakefield solver T3P to calculate the longitudinal wake. The transverse wakes were then calculated from the longitudinal wake using the Panofsky- Wenzel theorem [9]. Fig. 4a shows the CUBIT full model of the undulator chamber with taper. An inverse model was used to satisfy constraints of the Weiland integration method used in T3P. In the model the chamber gap is at the end and the taper in the center. Because the chamber has top-down symmetry, its transverse monopole wake is zero. The transverse dipole wake is much larger than the quadrupole wake as shown in Fig. 4b. A 16 mm bunch length σ_z was used in T3P, same as the bunch length in the CHESS-U lattice.

Tracking Simulation

If a bunch passes through the center of the chamber, the kicks from both dipole and quadrupole wakes are zero. When the bunch is displaced from the center of the pipe, the particles in the bunch will get finite kicks from both dipole and quadrupole wakes. The dominant dipole kicks will blow up the vertical beam size [10]. However, if the bunch is generally not precisely centered on the axis of the chamber, an effective monopole wake will tilt the bunch in the vertical-longitudinal plane [11]. In practice the orbits are normally adjusted to ensure that the beam passes very near the center of the undulators. Thus, a tracking simulation with dipole and quadrupole wakes included have been explored. The trajectory through five undulators is displaced with random vertical offsets of order 200 μm. A single bunch with 1000 macroparticles is tracked for 50K turns. There was no indication of emittance growth or beam tilt in the single bunch.

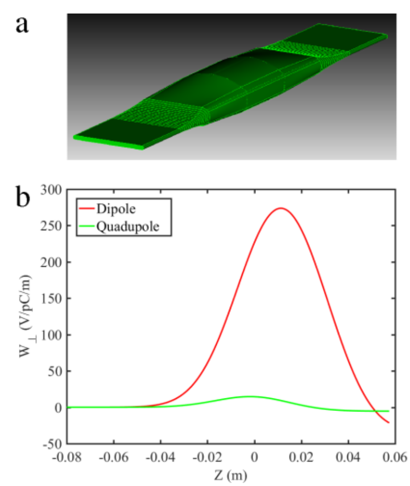

Figure 4: (a) CUBIT full model of undulator chamber (b) Transverse dipole and quadrupole wakes of the undulator chamber.

CONCLUSION

Simulations have been developed to calculate the coupled-bunch instability growth rate due to resistive wall impedance and showed a good agreement with the analytic calculation. It was then used to check the coupled-bunch instability threshold due to resistive wall wakefields of the undulator chambers in the CHESS-U lattice. Moderate instability growth rates were found for various bunch patterns that can be readily damped by the already installed bunch-by-by feedback system. In addition, the short range transverse dipole and quadrupole wakes of undulator chambers were calculated and incorporated into a tracking simulation, and we find no obvious emittance growth and beam crabbing at anticipated levels of misalignment of the closed orbit.

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