Influence of Space Charge Effects on Landau Damping in High-Intensity Hadron Synchrotrons

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Abstract

In high-intensity hadron accelerators, longitudinal space charge effects are non-negligible and can modify the beam spectrum, which can lead to loss of Landau damping (LLD). Based on the Hofmann-Pedersen distribution model, we obtain the rf voltage amplitude for a matched beam in CSNS RCS. With the above results, particle-in-cell (PIC) simulations are performed to study the influence of space charge effects on LLD. The simulations show that the dipole-mode frequency shifts outside the beam spectrum as the space-charge parameter increases. The beam response to rf phase modulation and the LLD threshold is investigated under both single and dual harmonic rf systems.

Landau Damping Loss Threshold

- Space charge modifies the incoherent synchrotron frequency spectrum. The Loss of Landau damping (LLD) threshold appears when the coherent dipole oscillation frequency moves out of the incoherent frequency range.
- The synchrotron frequencies for the single and dual-harmonic rf system are given by

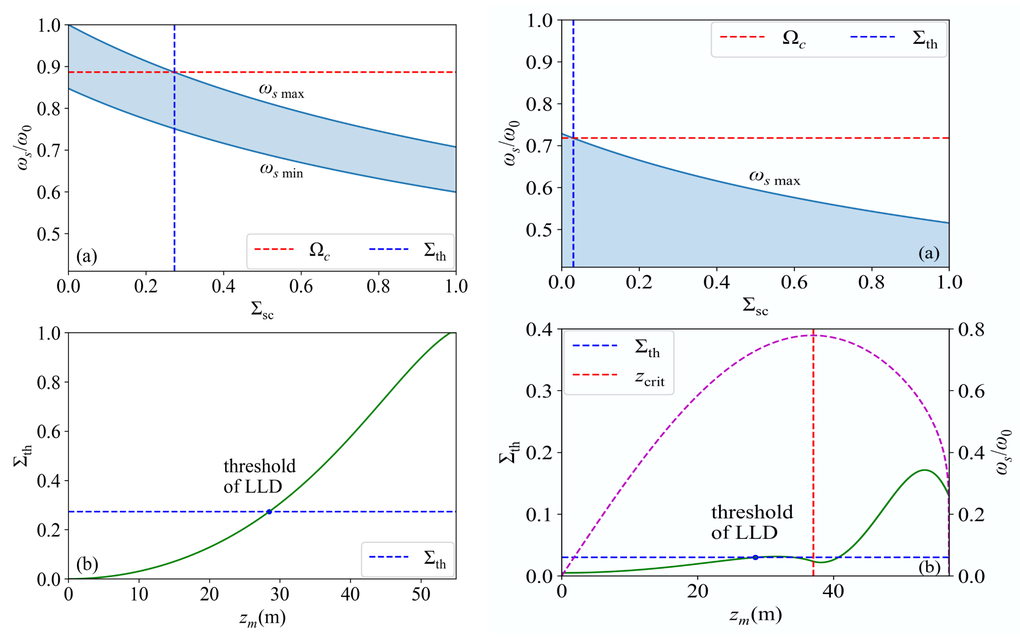
$$\omega_s = \omega_{s0}\frac{\pi}{2}\sqrt{\frac{1}{1+\Sigma_{sc}}}K^{-1}\left[\sin\frac{hz_m}{2R}\right]$$

and

$$\omega_s = \omega_{s0}\frac{\pi}{\sqrt{2}}\sqrt{\frac{1}{1+\Sigma_{sc}}}\frac{\sin\left(\frac{hz_m}{2R}\right)}{K\left[\sqrt{\alpha\left(1+\sin^2\frac{hz_m}{2R}\right)}\right]}$$

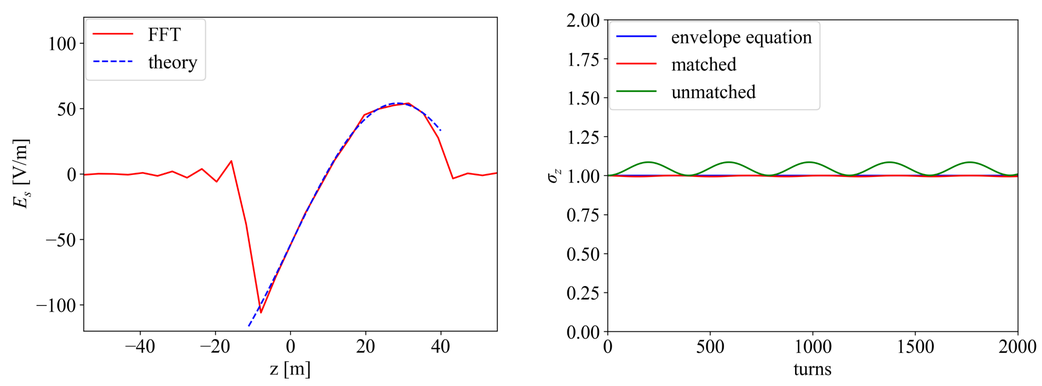
- The dipole oscillation frequency is calculated via a rigid model

$$\Omega_c = \frac{\omega_{s0}^2}{|u_m|}\int_{-z_m}^{z_m}\left(\frac{V_{rf}}{\hat{V}}\right)^2 dz$$



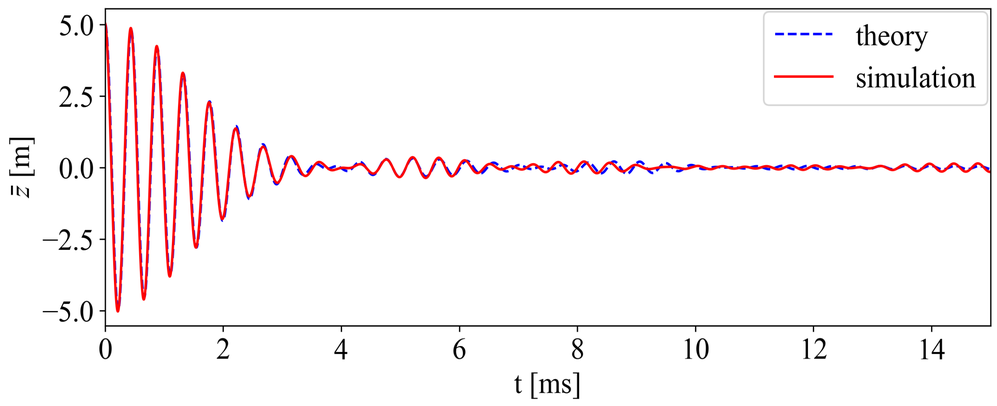
Longitudinal Tracking Program

- The tracking program advances particles using a turn-by-turn map equation. At each turn, the space-charge-induced energy kick is added using an FFT-based method.
- Benchmark 1 (left): Space charge field.
- Benchmark 2 (right): Matched longitudinal dynamics.

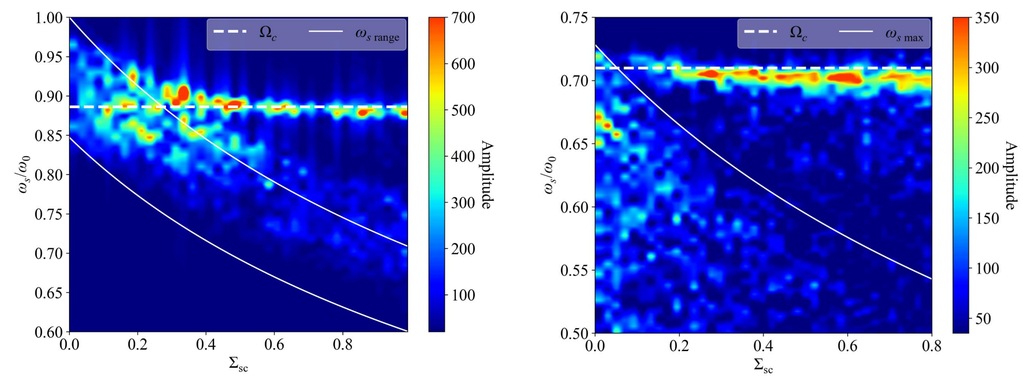


PIC Simulation

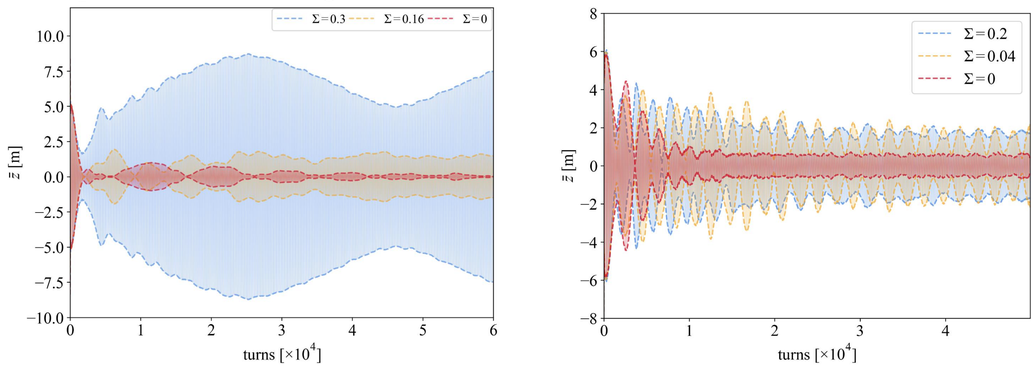
- In the absence of space charge, each particle oscillates at the synchrotron frequency determined by its initial position. The resulting decoherence causes the decay of the bunch-centroid motion.



- The oscillation of bunch centroid driven by the initial noise of the particle distribution, is recorded and analyzed via FFT to obtain the frequency spectrum.
- As space charge parameter increases, the coherent frequency moves out of the incoherent frequency range, as observed in the simulation.



- An initial offset and phase modulation are applied for both single- and dual-harmonic rf system in the simulation.
- The calculated thresholds for single- and dual-harmonic rf system are 0.27 and 0.03, respectively. Above these thresholds, the resonant growth driven by the phase modulation cannot be damped due to LLD and the centroid motion amplitude remains large.



- Simulation parameters based on CSNS RCS

Harmonic number	Circumference [m]	Beam energy [MeV]	Revolution frequency [Hz]	Number of macro-particle	Bunch length [m]
2	227.92	80	511051	50000	57

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