CETASIM: A NUMERICAL TOOL FOR BEAM COLLECTIVE EFFECT STUDY IN STORAGE RINGS

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Abstract

We developed a 6D multi-particle tracking program CETASim in C++ to simulate intensity-dependent effects in electron storage rings. The program can simulate the beam collective effects due to short-range/long-range wakefields for single/coupled-bunch instability studies. It also features the simulation of interactions among charged ions and the trains of electron bunches, including both fast ion and ion trapping effects. The bunch-by-bunch feedback is also included so that the user can simulate the damping of the unstable motion when its growth rate is faster than the radiation damping rate. The particle dynamics is based on the transfer maps from sector to sector, including the nonlinear effects of amplitude-dependent tune shift, high-order chromaticity, and second-order momentum compaction factor. Users can also introduce a skew quadrupole useful for emittance sharing and exchange studies. This paper briefly introduces the code structure and gives benchmark studies for single and coupled bunch effects. PETRA-IV H6BA lattice parameters are applied as test-bed.

INTRODUCTION

The 4th generation light sources move towards a diffraction-limited storage ring (DLSR) where the intense bunched beam with ultra-small emittance is stored for many hours for X-ray user operations. Because of the small beam dimensions with appreciable beam intensities, various collective effects will limit the performance of the ring in delivering the optimum beam parameters for user operations. The short-range and long-range wakefield effects are the leading causes of instability that we must mitigate; however, in some cases, the ion, beam loading, transverse coupling, and other effects will also significantly impact the beam parameters as well. Since the Touschek lifetime impacts a whole aspect of operation, predicting and improving the lifetime becomes vital. All of these require investigating advanced beam dynamics caused by collective effects.

Multi-particle tracking has been a popular method to investigate the collective effects in the electron storage rings; various codes have been developed, including ELEGANT [1], MBTRACK [2], and PyHEADTAIL cite3 etc. The benchmark between the codes is an ongoing effort in the light source communities. The motivation for developing CETASIm is to have a light and user-friendly tool that includes the fundamental physics of various collective effects and approaches for instability mitigation. It is also beneficial for future studies since CETASim can be updated and upgraded appropriately when new physics needs arise. In the following, we will give an overview of the CETASIM. Then benchmarks of beam performance due to the short-range and long-range wakes will be given. A summary and conclusions are given at the end.

GENERAL CODE OVERVIEW

Figure 1 shows the main classes designed in CETASim [4]. The program generates the specified bunch train and launches the particle tracking task using the input parameters in the run setup. For the multi-bunch problem, the users can set each bunch charge individually while keeping the number of macro-particles per bunch constant. It is a handy feature for investigating transient beam loading compensation and ion cleaning when head and tail bunches are set to accommodate a larger bunch charge (guarding bunches). CETASim can set multiple beam-ion interactions in the ring to investigate ion effects [5]. At each interaction point, multiple ion species, local gas temperatures, and pressures can be set independently. The impedance class uses analytical formulas to construct the model impedance in a ring. At the current stage, two types of impedance elements, resistive wall, and resonator model, are available in CETASim. Meanwhile, CETASim can also import impedance data from an external file. The exciter class can set an external exciter to the electron bunches with a given frequency, which plays as a coupled bunch mode driver in the "drive-damp" simulation. In a particular case of longitudinal coupled bunch motion, the resonator class deals with the transient beam loading effect. The cavity dynamics, driven by the generator current and the beam current, are simultaneously simulated in a self-consistent manner. The bunch-by-bunch feedback class adopts *Finite Impulse Response* (FIR) filter to compute the kicker response based on the multi-turn beam position monitor (BPM) data. The data output uses the SDDS format, which can be post-processed by the SDDS toolkit [6].

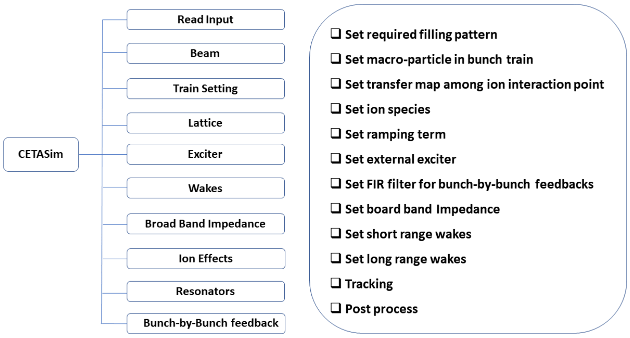

Figure 1: General overview of CETASim code.

SIMULATIONS AND BENCHMARKS WITH PETRA4 H6BA LATTICE

We take the H6BA lattice of the PETRA-IV storage ring [7] as the test bed to show the capability of CETASim.

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An active 3rd-order harmonic cavity is under consideration to lengthening the bunch to alleviate collective effects.

Single Bunch Effect

The impedance from the resistive wall and the geometric are considered in the single bunch effect. The impedance budget in detail can be found in Ref. [9]. With the impedance database, we study the single-bunch effect for two scenarios, with and without the 3rd-order harmonic cavity. When the harmonic system is included in tracking, the cavities parameters settings satisfy the ideal bunch lengthening condition. Figure 2 shows the single bunch length and energy spread as a function of the bunch current. In each sub-figure, two groups of curves are given. The red ones are from CETASim and the black ones are from Elegant. The bunch length variation as a function of beam current given by these two codes agrees well. As to the energy spread on the right side, we notice some discrepancies above the microwave instability threshold. The detail might be contained in the number of particles, namely, 100k for Elegant vs. 30k for CETASim used in the simulation.

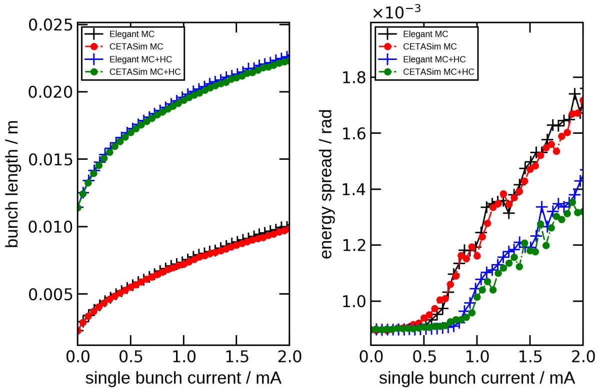

Figure 2: Single bunch length (left), energy spread (right) as a function of bunch current.

In the transverse plane, the impedance leads to the Transverse Mode Coupling Instability (TMCI) and head-tail instabilities. The azimuthal modes shift as the single bunch current increases. At a certain point, these azimuthal modes collide and merge; then the beam becomes unstable. One way to increase the transverse single-bunch current limit is to set a non-zero chromaticity ξ. The chromaticity introduces a head-tail phase advance and shifts the mode spectrum. Figure 3 shows the single bunch current limit as a function of chromaticity without and with 3rd harmonic cavity. The transverse dipole, quadrupole impedance, and longitudinal impedance are all considered in the simulation. The threshold current is the lowest bunch current, with zero particle loss at the elliptic aperture of $(a, b) = (15, 10)$ mm. Results given by CETASIM and Elegant agree reasonably well.

Transverse Coupled Bunch Effect

The frequency shift of multi-bunch coherent modes can be obtained in an analytical way as shown in Ref. [8].

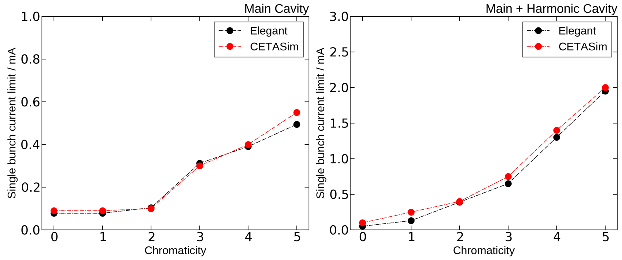

Figure 3: The single bunch current threshold as a function of chromaticity without (left) and with (right) the 3rd harmonic cavity.

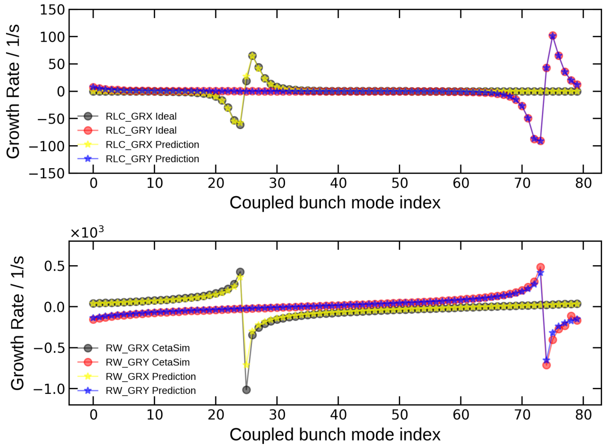

Figure 4: Growth rate of the transverse coupled bunch modes from RLC (top) and RW (bottom) wakes.

Nodoubtly, the coupled bunch mode can also be reconstructed when the bunch-by-bunch and turn-by-turn data are available. CETASim has two analytical models to generate the long-rang wakes: the RLC model and the RW model. Below, two examples are given for the transverse coupled bunch effect study. In the first case, the transverse impedance modeled by an RLC resonator with the parameters $R_s = 5 \times 10^9\ \Omega/\mathrm{m}^2$, $Q = 1 \times 10^{-3}$ and $\omega_r = 2\pi \times 4.996 \times 10^8$ 1/s. The second one is a simplified resistive wall impedance of the PETRA-IV storage ring, where the vacuum chamber is grouped into 4 types of sections [4]. In the simulation, the ring is filled uniformly by 80 bunches, and each bunch has a current of 1 mA. The long-range wakes are truncated at the 20th turn. The synchrotron radiation damping is turned off. In Fig. 4, we give the results of the coupled bunch mode growth rate from CETASim tracking ('Ideal') and analytical predictions ('Prediction'). The results obtained from tracking show very good agreements with predictions for both RLC and RW impedance.

Transient Beam Loading Effect

Transient beam loading brings two effects: the longitudinal coupled bunch instability and an unexpected bunch lengthening. In CETASim, the coupled bunch instability can be turned off by ignoring the dynamical variation of

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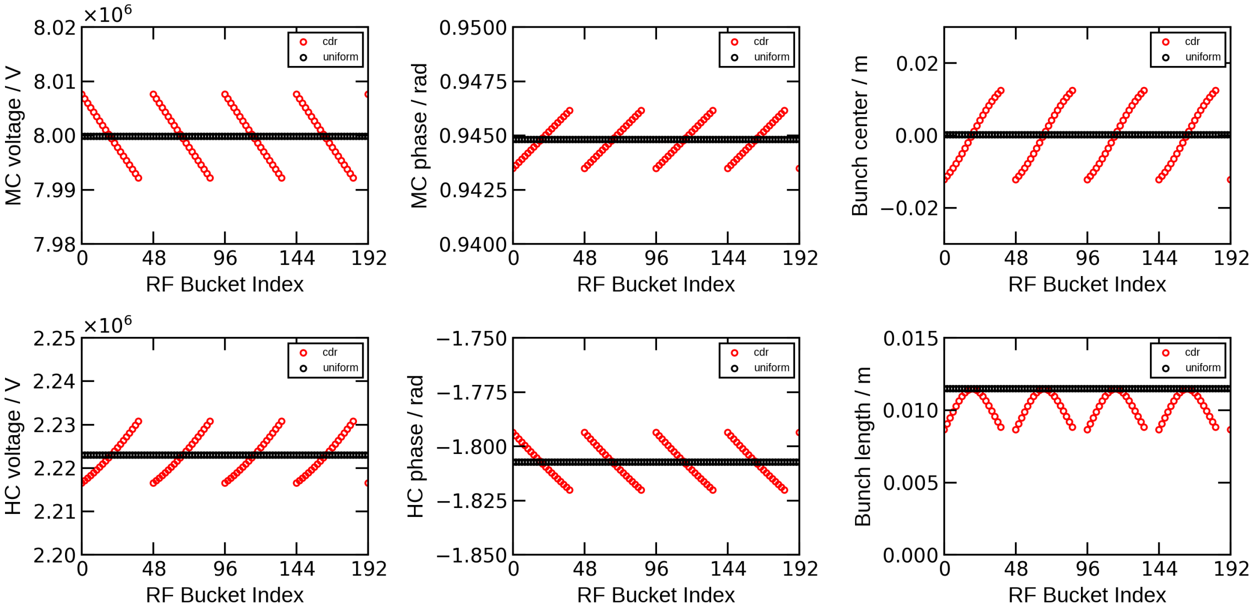

Figure 5: The cavity voltage $Abs(\tilde{\boldsymbol{V}}_{\boldsymbol{c}})$ (left), cavity phase $Arg(\tilde{\boldsymbol{V}}_{\boldsymbol{c}})$ (middle) bunch sampled as functions of RF bucket index at the main cavity (top) and harmonic cavity (below); the right column gives the bunch center and bunch length as functions of RF bucket index.

the beam-induced voltage. In that case, the tracking results always converge to an equilibrium state. If tracking is set up as that one bunch is composed of one macro-particle, according to the phase and voltage bunches sampled, the bunch profiles can be found analytically [4]. If multi-particles are set per bunch, then the bunch profile can be obtained by binning the distribution longitudinally in real space. The RF parameters of the main cavity and the 3rd harmonic systems in PETRA-IV can be found in Ref . [4]. The cavities are de-tuned to the 'optimized' condition for the lowest power consumption. The filling pattern of the ring is set as $h = 3840 = 80 \times (20 \times (1 + 1) + 8)$. There exist 80 bunch trains, and in each bunch train, every bucket is occupied by the electron beam except the last 8 buckets. The total beam current is 200 mA. Figure 5 shows the simulation results by setting one macro-particle per bunch. The sub-figures on the left and middle depict the cavity voltage and phase sampled by the bunches in the first 4 bunch trains. The sub-figures on the right show the bunch center shift and length variation. The periodic filling pattern leads to a periodical voltage sampling, further reducing to a periodical bunch center offset and bunch lengthening effect.

SUMMARY AND OUTLOOK

In this paper, we briefly introduce the status of the particle tracking code CETASim. The benchmarks studies against Elegant on the single bunch effect are given. The benchmark studies against analytical prediction on transverse coupled bunch mode are given. Other futures as synchrotron radiation and quantum excitation, ion-effect, bunch-by-bunch feedback, RF-feedback, exciter, *etc.* are not discussed here. Interested readers can find more in detail in reference [4].

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