CETA-A CODE PACKAGE BEING DEVELOPED FOR COLLECTIVE EFFECT ANALYSIS AND SIMULATION IN ELECTRON STORAGE RINGS*

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Abstract

The code Collective Effect Tool Analysis (CETA) is under development to study the collective effects in the electron storage ring. With the impedance either generated by itself or imported from an external file, CETA can calculate the loss and kick factors, the longitudinal equilibrium bunch length from a Haissinski solver, and the head-tail mode frequency shift from a Vlasov solver. Meanwhile, the code CETASim, which can track particles to study coupled-bunch instabilities caused by long-range wakefield, ion effects, transient beam loading effect, bunch-by-bunch feedback, etc., is also under development. In this paper, we describe the code status and give several simulation results from CETA and CETASim to show how these codes work.

INTRODUCTION

The design goal of the diffraction-limited storage ring is to have an ultralow emittance in combination with a high beam current, which naturally requires careful studies on both the single bunch and coupled bunch effects due to wakefield, beam-ion effet, transient beam loading, and the bunch-by-bunch feedbacks, etc. [1]. However, the numerical analysis of the beam instability is not straightforward due to the complexity of the intrabunch and interbunch beam dynamics characteristics. In the past decades, simulation codes such as Elegant [2], MBTrack [3], PyHeadTail [4], etc. are developed and are capable to cover various beam dynamics problems in this field. In this paper, we will introduce two codes recently developed, CETA and CETASim. The main purpose of CETA is to supply researchers quick and rough estimation of the influence from impedance to electron beam, meanwhile, CETASim is supposed to be a light version of the collective effect simulation code. In sections 2 and 3, simulation results obtained with different scenarios are given as demonstrations to show how CETA and CETASIm work. Plans for future studies are given in section 4.

RESULTS FROM CETA

Kick and Loss Factor

Figure 1 shows the kick and loss factors as a function of bunch length in Petra4, where 1 mA bunch current is assumed as the default setting. In the transverse direction, the resistive wall is one of the main impedance sources. Compared with the zero chromaticity results, at chromaticity 5, the kick factor due to the resistive wall is reduced roughly by a factor of two. However, the kicker factors of other elements are well suppressed by chromaticity 5. In the longitudinal direction, the resistive wall, the 3rd order harmonic cavity, and the kickers contribute most of the total loss factors.

Haisskinski Solver

The Haisskinski solver is used to study the bunch lengthening and longitudinal bunch shape distortion due to the longitudinal impedance. In CETA, the Haisskinski equation is numerically solved in a self-consistent way, where an iteration process is launched to ensure a convergent bunch density profile. Figure 2 shows the final bunch density profile where the resistive wall impedance is taken into account in a 40 ESRF-Cell type storage ring. Figure 3 shows the comparison of the bunch length obtained from CETA and Elegant simulation. The energy spread is assumed constant in the Haisskinski solver, it indicates that the prediction from the Haisskinski solver is not suitable anymore when the bunch current is beyond the longitudinal macro-wave-instability (MWI) threshold.

Vlasov Solver and TMCI

The Vlasov solver in CETA deals with the linearized Scaherer equations [1] in the frequency domain, in which the equilibrium beam profile is assumed as a Gaussian type and the perturbation is expressed in terms of Laguerre polynomials. Correspondingly, the perturbations in the real space is expressed by the Hermite polynomial. With a given transverse impedance, the interaction matrix M is established and solved numerically. Figure 4 shows the modes frequency shift comparison between results from the CETA Vlasov solver and Elegant tracking in the 40 ESRF-cell machine. The blue lines are the results from CETA. In Elegant simulation, only the vertical dipole impedance is considered, which ensures a fair comparison against CETA. The contour is the Fourier spectrum of the center oscillation from Elegant tracking. Both CETA and Elegant show that the $l = 0$ and $l = -1$ modes are coupled when the bunch charge reaches 1.6 nC.

RESULTS FROM CETA

The code CETASim is an upgraded version of the beam-ion simulation code developed in 2020 [5]. In the updated version, some new features are added to cover various coupled bunched motions due to the long-range wake. In bellow, we will give the beam-ion interaction in the transverse direction and the transient beam loading in the longitudinal direction Petra4 (lattice version 3.3).

Beam-Ion Effect

The updated version of CETASim is extended to cover multi-gas and multi-interaction points in the beam-ion sim-

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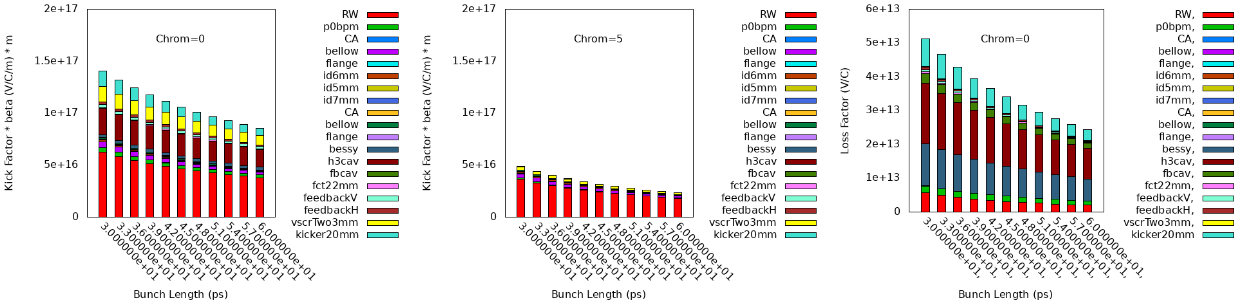

Figure 1: The kick and loss factor as a function of bunch length in Petra4, where 1 mA bunch current is assumed.

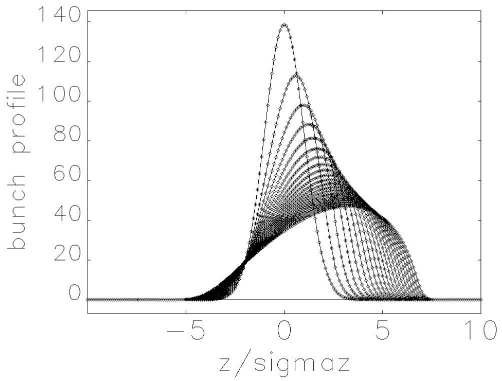

Figure 2: The Haisskinski solution when the RW wall impedance is taken in account in the 40 ESRF-cell machine. There exists 21 curves corresponding to a bunch currents evenly varied from 0 mA to 10 mA.

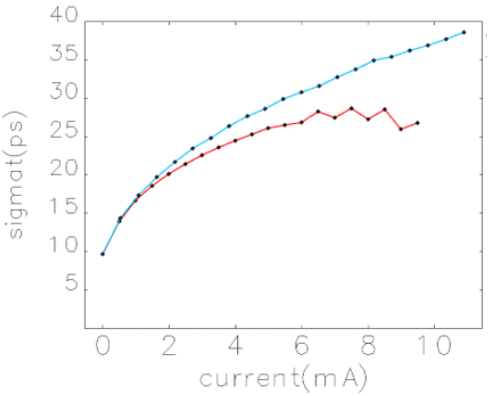

Figure 3: Comparison of the bunch length between CETA (red) and Elegant simulation (blue).

ulations. Table 1 shows the gas components in the APS-U ring [6, 7], which is applied here as a reference. Assuming the machine is operated in the brightness mode, with a 300 K gas temperature and 1 nTorr total gas pressure, after 10K turns tracking, the accumulated total ion charge, ions gas component percentage, and bunch amplitude growth rates as functions of bunch current are given in Fig. 5. It shows that more ions are trapped at a medium bunch current range (around 40mA). H_2 is over-focused and hardly interferes with the electron bunches. The maximum bunch amplitude growth rate is around 300 (1/s) in the range from 20 mA to 30 mA, which can not be cured by the synchrotron radiation damping 100 (1/s) and has to be resolved by the feedback system.

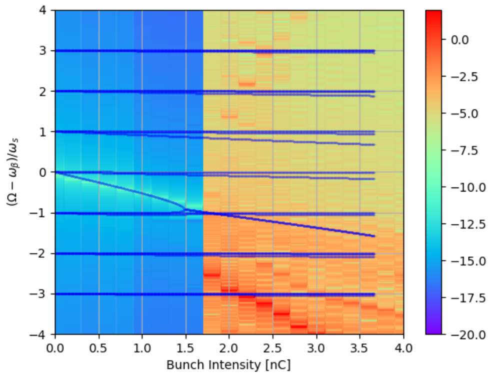

Figure 4: Comparison of the TMCI threshold from CETA and Elegant. For a fair comparison, in Elegant tracking, only the vertical dipole impedance is included.

Table 1: Initial Gas Species and Pressure Percentage

Gas type	H_2	CH_4	CO	CO_2
Percentage	0.43	0.08	0.36	0.13

Transient Beam Loading

A 3rd harmonic cavity is adopted to lengthen the bunches in Petra4 to alleviate the intensity-dependent effects, however, the performance of the bunch lengthening would be strongly influenced by the transient beam loading effect in this double RF system. In CETASim, the cavity is represented by a resonator and the beam-induced voltage can be obtained by a phasor rotation bunch-by-bunch. Table 2 shows the main and harmonic cavities parameters applied in CETAsim simulation in Petra4.

In the simulation, the total 3840 buckets are evenly occupied by 40 periodic bunch trains. The empty RF bucket between adjacent bunch trains is set to 26. In each train, 5 bunches are evenly distributed within 70 RF buckets. In

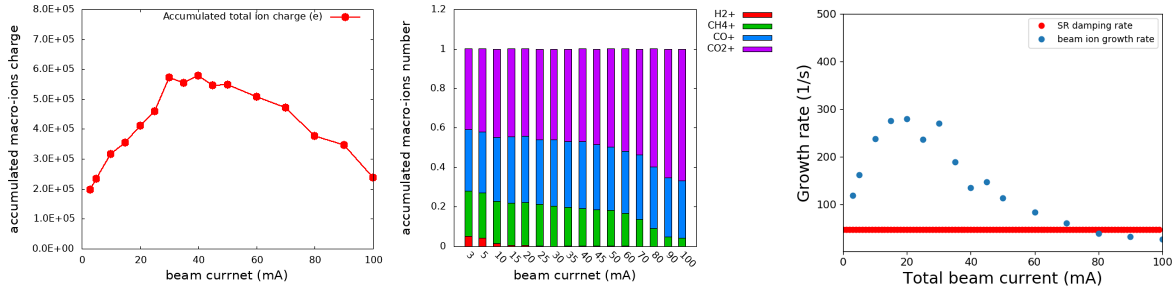

Figure 5: Beam-ion effect simulation results given by CETASim: the total accumulated ion charge as a function of bunch current (left); The final gas percentages as a function of bunch current (middle); The growth rate due to beam-ion effect as a function of bunch current.

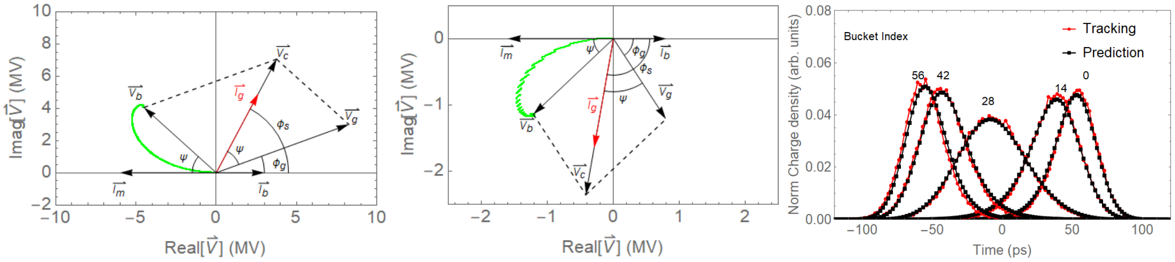

Figure 6: The phasor diagram of the required voltage $\tilde{V}_c$, generator voltage $\tilde{V}_g$, and beam-induced voltage $\tilde{V}_b$ in the main cavity (left) and the harmonic cavity (middle). The sub-figure on the right side shows the longitudinal bunch profile obtained from CETASim tracking and Haisskinski prediction.

Table 2: Parameters of the Main and Harmonic Cavities

	$h = 1$	$h = 3$
Q_0	29600	17000
Q_L	7400	2700
R_s (MOhm)	81.6	36
detuning angle Ψ	-0.733	0.755
Voltage(MV)	8	2.391
phase(rad)	1.08	-1.76
beam induced voltage (MV)	6.06	1.66
beam induced voltage (rad)	2.41	-2.38

total, 200 bunches in total are tracked and each bunch is made up of 20K macro-electrons. The first two sub-figures in Fig. 6 show the phasor diagrams of the required voltage, generator voltage, and beam-induced voltage in the main and harmonic cavities at 200mA beam current. The green dots show how the beam-induced voltages are built up from the cold conditions. The third sub-figure on the right side shows the longitudinal distribution of bunch obtained by the Haisskinski and by the CETASIm tracking. . The particle distribution obtained by the two approaches agreed well and give results as expected. The 5 bunch density distributions correspond to the bucket index (0,14,28,42,56) in the first bunch train, where the index 0, 28 and 56 are the bunch train head, center, and tail respectively. Cavity voltage and phase vary when different bunches passed by, leading to different bunch lengthening and bunch profiles.

SUMMARY AND OUTLOOK

In this paper, we introduce the status of the code CETA and CETASim. In the future, more modules will be added in CETASim to cover various problems in the beam collective effects simulations. This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 871072.

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