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**Executive Summary**

**It is planned to deliver 1) the software CETA (Collective Effect Tool Analysis) for use by the European light source community and its scientific report produced by using CETA applied on PETRA-4 as a specific example, and 2) a report describing possible design solutions of the vacuum chamber components which can help reducing the beam impedance and which can eventually be adapted also to other synchrotron light sources**.

We report the progress we have made in the study of the collective effect under the EURIZON project frame. The tasks were divided among two institutes according to their interest and experience, which includes the single- and multi-bunch instabilities, software development and vacuum chamber optimization.

Major activities include:

1. Code development.
   1. A multi-particle tracking code CETASim is developed for collective effect simulation in electron storage rings [1].
   2. A repository has been set up so that the source code, simulation examples, code references, and code manual are shared among collaborators.
   3. Two reports are produced. One is CETASim\_Reference.pdf, in which the physical models adopted in CETASim are explained in detail. It also includes several simulation studies by using the PETRA-IV storage rings parameter as a demonstration. Users can follow up the simulation by studying the examples in the repository. The other is CETASim\_Manual.pdf, in which the parameters required to set up the simulation are explained in detail.
2. Impedance simulation and optimization.
   1. …

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# Introduction of CETASim

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 [2], MBTRACK [3] and PyHEADTAIL [4] 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, which 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 below, we will briefly introduce the modules in CETASim. Readers who are interested in the details, please jump to the code reference [1]. Physical models applied in CETASim are discussed in detail there.

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| Figure 1‑1 General overview of the code CETASim. |

## Code overview in general

CETASim is developed following the object-oriented concepts in C++ programming language. **Figure 1‑1** shows the main classes designed. The program generates the specified bunch train and launches the particle tracking task using the input parameters in the run setup. The program can simulate the collective effects due to short-range and long-range wakefields for single and coupled-bunch instability studies. It also features to simulate the ion interactions with the trains of electron bunches, including both fast ion and ion trapping effects. As an accelerator design tool, 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 one-turn map, including the nonlinear effects of amplitude-dependent tune shift, high-order chromaticity, and second-order momentum compaction factor. When required, a skew quadrupole can also be introduced, which is very useful for the emittance sharing and the emittance exchange studies.

## Particle convention in CETASim

In CETASim the position of every macro-particle is described by a 6D vector in phase space, where x and y are particle positions in the horizontal and vertical directions, and are the transverse momentum normalized by the reference momentum ; whereas and are the longitudinal positions and momentum deviation with respect to the reference particle. The sign convention is such that the head of the particles has a positive distance, namely,. If time-dependent elements are included, such as RF cavities, is converted to the time deviation by to compute the RF phase, where is the relativity factor and is the speed of light.

## Bunch distribution and bunch train generation in CETASim

For a single bunch simulation study, CETASIm can generate the 6D bunch distribution composed of a given number of macro-particles. The coordinates information of this bunch can be referenced by an instance of a bunch object.

For a given filling pattern, the bunch train (beam) can be generated. The bunch train (beam) is essentially an array, each element of this array is an instance of a bunch object. The bunch train can be referenced by an instance of a beam object. Meanwhile, the charge of each bunch and the time distance between adjacent bunches are also stored in the instance of the beam object. In Mutli-bunch simulations, each bunch can composed of multi-macro-particles. The charge of each bunch can be set differently, which is a very useful feature for ion-cleaning and transient beam-loading compensation studies.

## One-turn transformation in CETASim

The beam transfer in the transverse plane is modeled by a 6 by 6 matrix transportation. The transfer matrix is built up by the given Twiss parameters. To handle the beam-ion effect simulation when multipole beam-ion interaction points are set, CETASim can also split the ring into several sections, correspondingly, the user has to supply the Twiss parameters at the interaction points as well. Although the beam is transported by a 6 by 6 matrix, the chromaticity, and the amplitude-dependent tune shift can be included in the simulation as well. For a given particle , the phase advance adopted to build up the 6 by 6 matrix varies accordingly.

The beam transformation in the longitudinal plane is always simulated once per turn. The number of different harmonic cavities is not limited. Multi-RFs can be set in simulation, where the voltage and phase of each harmonic cavity are required.

The algorithm used for synchrotron radiation and quantum excitation is the same as that applied in the Beam-Beam code from Hirata [5]. During the simulation, the target natural emittance and emittance ratio in the transverse plane are fixed numbers.

## Broadband Impedance and short-range wakes

CETASim can get the broadband impedance from an external file, which includes the frequency, longitudinal, transverse dipole, and quadrupole impedance (real and imaginary parts). CETASim can also generate broadband impedance itself, but it is limited to analytically available models, such as resistive wall impedance and resonator models. In this case, the user has to supply the related parameters. If the resistive wall parameters are given for an elliptical pipe, the Yokaya former factor is considered as well.

If the impedance is obtained, for a given bunch distribution, CETASim gets the wake potential in the frequency domain first. Then, an inverse Fourier transform is applied to get the wake potential in the time domain. Particles are kicked and transferred thereafter.

Subroutines are supplied in CETASim to generate a “quasi-green function” wake as well. The wake potential to kick bunch can be found by convolution in the time domain directly. At this moment, the “quasi-green function” is limited to the analytical model only. We suggest using the impedance function to study the single bunch effect instead.

## Coupled bunch by long-range wakes

The long-range wakes are limited to the resistive wall and resonator model only. The user has to specify how long the long-range wakes last in the unit of turns. The whole bunch experiences the same kick from the long-range wakes so only the coherent effect is considered at this moment.

Besides long-range wakes from the analytical models, CETASim also supplies a function that can simulate the effect from an external exciter. The exciter frequency and strength have to be specified by the user as well. This extra exciter can be applied to simulate the ‘excited-damp’ coupled bunch motion which is the same procedure as in an experiment [6].

## Beam-ion effect in CETASim

The beam ion effect is simulated based on the Bassetti-Erskine formula, which describes the direct space charge force generated by a 2D Gaussian beam. The ions are dynamically generated at the interaction points when the electron bunch passes by. At this moment, multi-interaction points and multi-gas are supported if the gas species, pressure, and temperature information are given section by section along the ring. If multi-gas is set in simulation, the effect from ions to the electron beam is tracked gas by gas.

The ions are generated due to the electron beam dynamically and also could get lost because of the beam pipe. After a long term of tracking, the ions would move to a dynamical equilibrium state. It is noticeable that the transverse profile of the equilibrium of ions does not follow the Gaussian type. If one wants to do the ‘Strong-Strong” simulation, the Bassetti-Erskine model would be not accurate. Even though, in CETASim, we supply the user with the option to do the ‘strong-strong’ simulation. In the future, we plan to replace the beam-ion simulation model with a self-consistent particle-in-cell algorithm.

## Transient beam-loading effect

The longitudinal dynamics due to the RF mode in the cavity can be simulated as well. CSTASim follows the algorithm used in P.B. Wilson’ paper [7], where the beam-induced voltage is treated in the phasor frame. The kick from the beam included voltage in the phasor fame is equivalent to kicks from the long-range wakes. The transient beam loading effect particularly references the fundamental mode, which is also the mode applied to build up the acceleration field in the cavities.

In simulation, if the cavity is passive, it means we only need to take care of the beam-induced voltage. If the cavity is active, the generator-induced voltage has to be taken into account as well. It brings extra complicity especially one who wants to include the cavity feedback further in the simulation. In CETASim, if the cavity is active, the generator voltage is consistently simulated in the time domain. Together with the beam-induced, particles are kicked longitudinal accordingly.

Cavity feedback is one of the approaches for the transient beam loading compensation. In CETASIm, the ideal is to sample the difference between cavity voltage and required voltage, then use this signal to get how much the generator current should be modified. At this moment, The cavity feedback is not fully ready yet in CETASim.

## Bunch-by-bunch feedbacks

The bunch-by-bunch feedback can mitigate the coupled bunch instabilities. It detects the transverse or longitudinal positions and creates the kicker signal, processing the position signal by a digital filter, to damp the bunch oscillations. The module of bunch-by-bunch feedback is available, however, the user must supply appropriate digital coefficients.

CETASIm also supplies two parameters that limit the maximum kick strength the beam experiences. One is the maximum power available at the kicker, the other is the shunt impedance at the kicker. Then the maximum kick strength could be obtained accordingly.

## I/O

CETASim takes a file with normal text format as input. All of the key parameters have to be set in the input files. The variables are defined in the format as *“string\_variable =* *values”.* During the operation, CETASim scans the *string\_variale* in the input line-by-line, where the upper and lower cases are not distinguished. Thereafter the *string\_variable* is compared with the *key-word* defined in code to get the values correspondingly for further simulation. The previous definition *“string\_variable =* *values”* will be overwritten by thelatter ones and only the latest ones will be applied in the simulation. The inner structure of the input looks like the *namelist* format in Fortran. It is only for a better parameter classification.

The output of the data given by CETASIm follows the SDDS [8] format. All the data files printed out are in the ASCII format. Users can easily get the meaning of the data by the header of the files. These data can be manipulated by the SDDS tools as well.

# Code implementation and benchmarks

## Single bunch effect.

With the broadband impedance data in PETRA-IV project, we perform a study of the single-bunch effects. The longitudinal impedance leads to a potential well distortion and bunch lengthening. Once the single bunch current increases further and the longitudinal microwave instability threshold is reached, the energy spread starts to increase as well. In below, we show two scenarios studied by CETASim: the main cavity only and the main cavity together with a 3rd harmonic cavity. In both scenarios, the beam loading effect is not included. In the double RF case, the generator voltage and phase are set to maintain the ideal bunch lengthening condition. **Figure 2‑1** shows the single bunch length and energy spread as a function of the single 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 given by CETASim agrees well with the results given by Elegant. Noticeably, there are discrepancies in the energy spread when the single bunch current is above the longitudinal microwave instability threshold which is usually out of practical interest.

**Figure 2‑2** 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 taken into account in the simulation. The threshold current is defined as the lowest bunch current, which leads to a non 100\% transmission during the tracking, where an elliptical chamber with a radius (15, 10) mm is applied as the particle loss criteria. The particle loss occurs only in the vertical direction. The results from Elegant and CETASim show a good agreement.

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| **Figure 2‑1: Single bunch length (left), energy spread (right) as function of single bunch current. Results from CETASim and Elegant show very good agreements** |

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| **Figure 2‑2:** **The single bunch current threshold as a function of chromaticity without (left) and with (right) the 3rd harmonic cavity. Results from CETASim and Elegant show a good agreement.** |

## Coupled bunch effect

In general, if the impedance is known and the filling pattern of the ring is uniform, the coupled bunch mode frequency shift and growth rate can be found analytically [9]. In particle tracking studies, the coupled bunch mode can be reconstructed when the bunch-by-bunch and turn-by-turn data is available. In below, we give two examples for the transverse coupled bunch effect study. The first one is transverse impedance given by an RLC model with the parameters ohm/m/m, and 1/s. The second one is a simplified resistive wall impedance of PETRA-IV storage ring. In the simulation, the ring is filled uniformly by 80 bunches and each bunch has 1 mA current. The long-range wakes are truncated at 20 turns. The synchrotron radiation damping is turned off. In **Figure 2‑3**, we give the results of the coupled mode growth rate from CETASim tracking and analytical predictions of these two cases. 'Ideal' and 'Prediction' legend indicates the results are obtained from tracking and analytical prediction respectively. The results obtained from tracking show very good agreements with predictions for both RLC and RW impedance.

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| **Figure 2‑3:** **Growth rate of the transverse coupled bunch modes from RLC (top) and RW (bottom) wakes. ohm/m/m, and 1/s. The ring is filled uniformly by 80 bunches and each bunch current is 1 mA. The long-range wakes last 20 turns and the SR damping is turned off. 'Ideal' and 'Prediction' indicate the results are obtained from CETASim tracking and analytical model respectively.** |

## Bunch-by-bunch feedback

**Figure 2‑4** shows the comparison of the transverse coupled bunch mode growth rate due to the RW wakes with and without bunch-by-bunch feedback. The simulation conditions are the same as those applied in **Figure 2‑3**. A 10-tap FIR filter bunch-by-bunch feedback is also applied in tracking. All modes are suppressed as expected. With the same beam condition, we also give the motions of the 80 bunch centroids in the "grow-damped" simulation in **Figure 2‑5**. During the tracking, the bunch-by-bunch feedback is turned on from 1000 to 1300 turns and from 1600 to 3000 turns. Clearly, without the feedback, the bunches are unstable due to the transverse long-range RW wakes. When the bunch-by-bunch feedback is turned on, oscillations of all of the bunches can be stabilized to zero.

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| **Figure 2‑4:**  **Comparison of the transverse coupled bunch growth rate due to the RW with and without bunch-by-bunch feedback. The simulation condition is the same as those applied in Figure 2‑3. A 10 taps bunch-by-bunch feedback is applied in tracking.** |

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| **Figure 2‑5:**  **Trajectories of the 80 bunches centroids. The bunch-by-bunch feedback is turned on from 1000 to 1300 turns and from 1600 to 3000 turns during tracking. The long-range RW wakes are turned on during the wholes simulation.** |

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