# Software development

New software is under development to study the collective effects in electron rings. It is used both for predicting the instability thresholds based on semi-analytical formulas (CETA) and particle tracking (CETASIM). In the note, we will introduce the code structure, physics models, and algorithms used in CETA and CETASIM. All equations listed here use the Gaussian units closely following the notation in the textbook from Alex Chao [60].

## CETA—Collective Effects Tool and Analysis

### Impedance generation

In CETA code, the impedance data can be either generated from an analytical model, easily to be extended, or read from an external data file. In the impedance generator, CETA contains a resistive wall impedance and a resonator model. Eq. 1‑1 shows the formulas of resistive wall impedance. When the beam pipe is elliptical, the corresponding Yokoya factors are applied [1] for modification. Approximations are frequently used, which simplify the resistive wall impedance to Eq. 1‑2. This simplification brings a lot of convenience from the particle simulation point of view since it relates to a much simpler wakefield, Eq. 1‑21. Equation 1‑3 gives the resonator model used in CETA. The variables in the above equations are defined as: is the conductivity of the beam pipe, *b* is the pipe radius, *c* is the speed of light, is the resonator shunt impedance, *Q* is the quality factor and is the angular frequency of the resonator.

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Figure 1‑1 shows the comparison of the lowest order longitudinal and transverse impedance due to resistive wall obtained from Eq. 1‑1 and Eq. 1‑2. Discrepancies exist both in the low and high-frequency regions. In the medium frequency region, the results from exact and approximation agree well.

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| (a) | (b) |
| Figure 1‑1: Comparison of the longitudinal (a) and transverse (b) impedance from resistive wall, Eq. 1‑1 and Eq. 1‑2. | |

### Loss and kick factor

For the single bunch effect, CETA evaluates loss factor and kick factor according to Eq. 1‑4,

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where is the bunch former factor, is the rms bunch length and is the frequency shift due to chromaticity.

### Haisskinski solver

Haisskinski solver is developed to study the bunch lengthening and bunch shape distortion in the longitudinal direction due to the potential well distortion. In a general case, in a high-energy electron ring, the final longitudinal bunch profile is defined by a combination of the longitudinal wake potential and RF potential from external cavities. The equilibrium bunch shape below the microwave instability threshold can be predicted by a Haisskinski integral equation, Eq.1‑5,

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where is the classic electron radius, is the rms equilibrium beam energy spread, is the Lorenz factor and is the slippage factor. The first term in the *r.h.s.* is the particle Hamiltonian in external RF cavities. The second term in the *r.h.s.* is the particle Hamiltonian due to the wake-field, which also can be dealt with in the frequency domain with the help of the relationship,

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In the CETA code, Eq. 1‑6 is numerically solved in a self-consistent way, where the iteration process is launched to finally get the convergent profile *.* It is noteworthy that the energy spread is assumed as constant in the Haisskinski solver. When the bunch current is beyond the longitudinal MWI threshold, the rms bunch energy spread starts to increase and the prediction from the Haisskinski solver is not suitable any longer.

If only considering the imaginary part of the longitudinal impedance, according to Eq. 1‑6, and assuming the bunch oscillation amplitude is small, the wake potential is still head-tail symmetric and so is the beam distribution. In this case, the numerical solution of the Haisskinski equation always exists. This suggests a good approach for benchmarking between CETA and results from a particle tracking code. Setting the real part of the impedance to zero, Figure 1‑2 (a) shows the comparison of the bunch length as a function of bunch current between CETA and Elegant tracking in USSR electron ring. The bunch lengthening due to the image only longitudinal impedance agrees well from CETA and particle tracking. The beam profile can be found in Figure 1‑3 (a), in which the head-tail symmetry maintains quite well even to 10 mA bunch current. When the real part of the longitudinal impedance is considered, the bunch length from Elegant simulation gets shorter compared to Haisskinski results Figure 1‑2(b) and the distribution profile develops head-tail asymmetry as a function of bunch current Figure 1‑3 (b). The bunch length discrepancy starts from around 1.5 mA, indicating that the energy spread cannot maintain a constant value, which is evidence of the MWI.

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| (a) | (b) |
| **Figure 1‑2: Comparison of the bunch length between CETA and Elegant simulation when only the imaginary longitudinal impedance is considered (a); both real and imaginary impedance are considered (b).** | |

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| (a) | (b) |
| Figure 1‑3: The Haisskinski solution with RW wall and geometrical impedance. (a) Only imaginary impedance is considered; (b) both real and imaginary impedance is considered. In each figure, 21 curves are corresponding to a bunch current evenly varied from 0mA to 10mA. | |
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### Vlasov solver

The beam distribution is assumed to follow the Hamiltonian dynamics which meets the Liouville theory

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where [,] is the Poisson bracket operator, *p* and *q* are canonically conjugate variables. If the Hamiltonian does not have an explicit time dependence, a stationary beam distribution follows

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When there exists perturbation , its first order linearized Vlasov equation can be expressed as

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where the term is the perturbation due to the perturbation in the phase space. It indicates that the evolution of the perturbation is affected both by the and More explicitly, in beam physics, the perturbation in phase space deduces to a perturbation in real space then beam distribution in real space decides the formation of the perturbed Hamiltonian which finally affects conversely. Thus, directly solving the Vlasov equation is not trivial and usually, a self-consistency process is required. In fact, with appropriate eigenmodes decomposition, the eigenmodes analysis of the perturbed system can be used to check if would be motivated and magnified by affection from both and -- if so, this constitutes instabilities.

In the scope of beam instability induced by the wake/impedance, usually, a set of Sacherer integral equations is required to be solved consistently. In the CETA code, we follow the approaches introduced in Ref. [2] and assume that the equilibrium beam profile with a Gaussian type, then the perturbation in longitudinal phase space can be expressed in terms of Laguerre polynomials

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where (*r,)* can be transformed from (*p, q*) by the canonical transformation; *l* and *k* is the azimuthal and radial modes index. Correspondingly, the perturbation in Fourier space and in real space can be expressed with Hermite polynomial,

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| (a) *l=1* | (b) *l=2* | (c) *l=3* |
| Figure 1‑4: The perturbation pattern , which is decomposed into the generalized Laguerre polynomial in phase space. From (a) to (c), the azimuthal mode index *l* varies from 1 to 3, and the radial mode index k=0. | | |

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| (a) | (b) |
| Figure 1‑5: The perturbation pattern in time domain (a) and its spectrum in frequency domain (b). | |

Figure 1‑4 shows the perturbation pattern with the first 3 orders (*k=0, l=1, 2, 3*) of the Laguerre mode decomposition in phase space . Figure 1‑5 shows their profile in the time domain and the corresponding spectrum in the frequency domain. Here we skip the tedious mathematics derivation and give the final results directly. The transverse stability of the beam with transverse impedance is finally converted to an eigenvalue condition that

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in which *,*  are the angular betatron and synchrotron oscillation frequency respectively, is the unit matrix; *M* is the interaction matrix

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where *N* is the number of particles and .

In the CETA code, with a given transverse impedance in the frequency domain, Eq. 1‑13 is solved numerically. The real part of the eigenvalue of the matrix represents the transverse oscillation frequency shift, and the imaginary part gives the instability growth rate for different modes index *l* and *k*. With a zero chromaticity condition, the lowest order of the instability takes place when the mode merges with mode, which is termed Transverse Mode Coupling Instability (TMCI). With a non-zero chromaticity condition, the instabilities are termed head-tail modes or head-tail instabilities.

Figure 1‑6 shows the modes shift and coupling comparison between CETA Vlasov solver and Elegant tracking, in which only vertical dipole impedance is considered to have a fair comparison. The blue line is the results from CETA. The contour, Fourier spectrum of the center oscillation, is from Elegant tracking. Both CETA and Elegant give results that *l=0* and *l=-1* modes are coupled when the bunch charge reaches 3 nC and 1.6 nC taking into account only the resistive wall impedance (Fig. 7-6, (a)) and resistive wall plus geometrical impedance (Fig. 7-6, (b)) in USSR, respectively. The results from CETA and Elegant tracking agree well.

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| (a) | (b) |
| Figure 1‑6: Comparison of the TMCI threshold from CETA and Elegant. (a) resistive wall impedance, (b) RW plus geometrical impedance. For a fair comparison, in Elegant tracking, only the vertical dipole impedance is considered. | |

For a better explanation of the head-tail instability, a simplified model is applied here as a demonstration to show how the head-tail modes vary as a function of chromaticity (or head-tail phase shift). Limiting the discussion to only the azimuthal plane, the instability growth rate for the azimuthal mode *l* can be estimated as

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where is the Bessel function of the first kind. With the transverse dipole resistive wall and geometric impedance discussed in USSR and 5 mA bunch current, the growth rate of the head-tail azimuthal mode as a function of chromaticity head-tail phase is shown in Figure 1‑7. Moving the chromaticity to the negative value makes the mode unstable and the higher-order modes stable. In this scenario, extra feedback is required to damp the mode to keep the beam stable. If the chromaticity is set to a positive value, then the mode is damped; however, the higher-order modes get unstable. In this scenario, unstable head-tail modes do not involve mode coupling and the current threshold is determined by a competition between the radiation damping rate and the unstable higher-order modes. As to the first unstable head-tail mode *l=1*, it might lead to a threshold even lower than the TMCI threshold.

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| Figure 1‑7: Azimuthal head-tail mode growth rate as a function of head-tail phase . The transverse dipole resistive wall and geometric impedance of USSR are used for calculation. With positive head phase , the head-tail modes become unstable one after another. The bunch current threshold is determined by a competition between the radiation damping rate and unstable mode growth rate. |
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### Coupled bunch instabilities

In general, element impedance with a high-quality factor can lead to coupled bunch motion. If the ring is filled evenly by *M* electron bunches, the transverse coupled bunch mode coherent oscillation frequency shift can be expressed as

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where is the period of one-turn evolution,  is the coupled bunch mode index, varying from 0 to . The most dangerous mode is one when is as close to zero as possible. The longitudinal coupled bunch coherent oscillation shift can be obtained similarly,

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Unlike the transverse direction, broadband impedance does not play an important role. A more instructive application is when the rf cavity is taken into account which leads to instability of *Robinson* type.

Figure 1‑8 shows the coupled bunch mode instability growth rate and frequency shift as a function of coupled bunch mode index in the transverse direction in the USSR ring. It is assumed that the lattice is with an even filling pattern and the bunch current is 0.015mA. The transverse dipole impedance is from the resistive wall and the geometrical one. Clearly, with a 5 chromaticity, the coupled bunch mode instability cannot be excited either. For zero chromaticity, the most dangerous coupled mode is the one when is as close to zero as possible, indication with a coupled bunch mode index .

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| (a) | (b) |
| Figure 1‑8: The coupled bunch instability growth rate and frequency shift as a function of coupled bunch mode in USSR. It is assumed that the lattice is with an even filling pattern and the bunch current is 0.015mA. The transverse dipole impedance from the resistive wall and the geometrical impedance are applied in the calculation. | |

## CETASim

The code CETASim is an upgraded version of the beam-ion simulation code developed in 2022 [3]. Besides the characteristics of the old version, some new features are added to the code to cover various coupled bunched motions due to the long-range wake both in longitudinal and transverse directions. To relax the numerical simulation burden, approximations listed below are applied in the current stage.

1. Rigid bunch approximation, where the bunch is repressed by a single macro electron particle, hence, only dipole mode effects can be described.
2. Wake function approximation, where the wake function is used instead of the wake potential in the long-range coupled bunched simulation, neglecting the influence of the individual bunch distribution on the wakefield.
3. Bassetti-Erskine formula, which assumes the rigid bunch generates space-charge field the same as that from a Gaussian distribution. The Bassetti-Erskine formula is used in the beam-ion interaction simulation.

In general, the bunch motions are coupled by the long-range wake, with a decay time in many turns, and it requires a multi-turn multi-bunch simulation. The key for that is to get the time between the “leading” bunch and the “tailing” bunch correctly. Assuming there is bunches in total, the transverse kick at the *jth* bunch at the *nth* turn from the *mth* order of transverse wake can be expressed as

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where

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and *h* is the harmonic number. In CEATSim, users have to choose the number of previous turns to be taken into account to ensure both the simulation precision and a reasonable simulation time.

The longitudinal effect from long-range wake can be obtained similarly. In the future, the code will be extended to cover the problems due to the transient beam loading effect.

### Beam-ion simulation

The beam-ion effect module maintains the basic features of the old code [3]. As mentioned, a weak-strong model is applied in CETASim and the Bassetti-Erskine formula is adopted to get the interaction between electron bunch and ions. The ions are dynamically generated at the interaction points when the electron bunch passes by. In the updated version, multi-interaction points and multi-gas are supported, which means the local gas pressure and environment temperature, composed of different gas types along the ring can be fed into the code. The module is applied to the USSR simulation. If with uniform local gas pressure and environment temperature condition, it is found 10 interaction points along the rings is a good compromise between precision and simulation speed. Compared with a single gas scenario (CO for example), multi-gas simulation results give a weaker beam-ions instability as expected.

### RW coupled bunch instability

Limiting the impedance to the lower order cases that *m* equals zero and one in Eq. 1‑1, the longitudinal and transverse wake functions can be obtained, see Eq. 1‑19 and Eq.1‑20, in which /c is defined as the characteristic time. If the approximation of the resistive wall impedance Eq. 1‑3 is applied, the wake functions take the asymptotic form Eq.1‑21.

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Figure 1‑9 shows the discrepancy between the exact wake function, Eq. (1‑19, 1‑20), and the asymptotic form, Eq. 1‑21. Both expressions agree well in the long-range region. The bunch separation time is typically much longer than the characteristic time. For this reason the asymptotic wake is usually used in the coupled-bunched simulation which relaxes the computing load significantly from the complex integration. The asymptotic form is applied in the CETASim code for simulations of the coupled bunch motion excited by the resistive wall impedance.

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| Figure 1‑9: Comparison of the exact and asymptotic forms of the resistive wake function. They agree well in the long-range region. The asymptotic is usually used in the coupled-bunched simulation which releases the computing load significantly. | |

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| Figure 1‑10: (left) Comparison of single bunch multi-turn transverse growth rate obtained from CETASim and analytical prediction for a rigid bunch which is affected by self-induced long-range resistive wall wakefield, Eq. 1‑21. In the simulation, the growth rate is obtained by exponential fitting of the bunch center envelope oscillation. Roughly, setting the long-range wake filed truncation turns to above 50 turns does not help the convergence significantly. In the simulation, 50 turns long-range wakefield truncation could be a good comprise of simulation speed and accuracy. (right) Comparison of the coupled bunch mode growth rate in the transverse direction obtained from CETASim and analytical prediction. Again, Eq. 1‑21 is applied and Eq.1‑2 gives the impedance. With Petra4 lattice in brightness mode, where M=80 and the transverse tune are 135.27 and 86.26 in x and y direction, modes 25 and 74 are the most unstable coupled bunch mode respectively according to the discussion below Eq.1‑16. The detail of the approaches for coupled bunch mode growth calculation can be found in IPAC2022, WEPOMS010. In the simulation here, the bunch centers are randomly distributed within a Gaussian noise | |

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| Figure 1‑11: Coupled bunch oscillation (top) and coupled bunch mode amplitude (bellow) as function of tracking turns due to the resistive wall impedance. Results are consistent with results shown in Figure 1‑10. In the simulaton, the initial noise is added into the bunch centers. |

### HOM

The wake of HOM is directly obtained from the Fourier transform of the resonator impedance shown in Eq.1‑3. Here we explicitly give the expression of the wakes in longitudinal and transverse used in CETASim.

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where is the shifted frequency, represents the field filling or damping time in the resonator.

In Figure 1‑12, it shows the Reboinson damping (left); growth rate comparison with the prediction one as a function of turns, where the info has to be supplied (middle); and the damping and anti-dumping growth rate as a function of de-tune frequency. Figure 1‑13 shows the comparison of the coupled bunch mode growth rate and analytical prediction. Both in the main cavity and the harmonic cavity, the results from CETASIM agree with the prediction.

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| Figure 1‑12: The fundamental mode of the main cavity of Petra4 is applied here for benchmarking. Set one rigid bunch in simulation and the longitudianl wake is truncated till the last 50 turns. The third figure shows the bunch growth rate as a function of the fundamental mode detuned frequency, which agrees well with the analytical prediction. (have to turn off the longitudinal damping and also substract the “stastic term” in simulation) | | |

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| Figure 1‑13: Comparison of the longitudinal coupled bunch mode growth rate between tracking and analytical prediction. The parameters of MC and HC cavities in Petra4 are applied here. To have a clear comparison, the static potential well distortion effect is excluded in the simulation. The potential well term only gives a “static” effect on the beam. 80 bunches and 1mA/bunch. | |

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| Figure 1‑15: Comparison of the longitudinal coupled bunch mode growth rate between tracking and analytical prediction. The parameters of MC cavity of petra4 is applied as a demonstration. The phasor approach for beam loading is used in CETA simulation. The figure on the left side shows the Robion’s damping and antidamping when the cavity resonant frequency is tuned refers to the rf frequency. The figure on the right shows the coupled bunch mode growth rate. In both cases, the theory prediction agrees well with CETASIM simulation. Notification: to get the coupled bunch mode growth rate, The potential well distortion term, or static term, have to be removed in simulation. To have a better comprism, with subroutine beamVec[0].BunchTransferDueToLatticeLMatarix for longitudinal tracking. Left(10mA); Right (80mA/ 80 Bunches). | |

2022-10-12: both in phasor and long range approaches, if there is only one bunch in ring, there there is, when do the benchmark with growth rate, -- no need to sunstract the potential well term.

### beam loading

#### beam loading in general

Here the basic model and equation to be used in the transient beam loading study is listed in the following. For clarity, the notation here is the same as that used in N.G. Bill’s book.

The impedance of the cavity can be expressed as,

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Where is the resonant frequency of the cavity, is the frequency of the external driving frequency from the generator. is defined as the detune angle,

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When there exists in current , the voltage generated at the cavity can be found .

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The and are not at “in phase” condition. The angle between and is decided by the detuning angle . Assuming the current with an average value , then the magnitude of the can be found

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Where is the voltage when the cavity and generator stay at the “on-resonance” condition, where .

In an electron ring, to accelerate the beam appropriately, the generator driving frequency has to meet the condition , where h is the number of the harmonic, is the electron revolution frequency.

Assume beam with average current , the image current will be generated in the opposite direction that (short bunch assumption). If the detune angle , then the average beam-induced voltage is will rotate in a clockwise direction refers to . The same as the current and voltage pairs () due to generators.

To maximize the generator efficiency, the cavity is chosen to be at “off-resonance” condition, detune by , when the generator current and target cavity voltage are in phase condition as shown in Figure 1‑14. The optimization tune condition requires

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| Figure 1‑14: Phasor plot of the main cavity when it is de-tuned in optimized condition. 0.2mA average beam current is assumed. |

Equation 1‑27 and Equation 1‑28 can be applied to estimate the beam-induced voltage (DC estimation). The main cavity parameter of Petra4 is listed in Table 1‑1. Figure 1‑14 also shows the phasor plot of beam-induced voltage , and required generation voltage . Clearly is the term which kicks particle turn by turn.

Table 1‑1 Main cavity parameter of petra4

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|  | Main cavity | 3rd Harmonic Cavity |
| Quality factor ­ | 29600 | 17000 |
| Loaded Quality factor | 7400 | 2700 |
| Cavity coupling factor | 3 | 5.3 |
| Shunt impedance (Ohm) | 8.16E+6 | 36E+6 |

#### Transient beam loading effect

In reality, the bunch pass through the cavity one by one, and the beam-induced voltage is a sum of the induced voltage pulsed bunch by bunch. Assume n bunches with the same bunch charge passed by, then the beam-induced voltage can be expressed as,

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in which is the induced voltage by one bunch. is at the direction of (-1,0). Note as time space between bunches, Equation 1‑30 gives the equations which connect cavity parameters to and and .

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Figure 1‑14 also shows how the transient beam loading is accumulated and turns into a steady state (The green dot). If the bunches evenly occupy the RF buckets, the final steady state beam-induced voltage agrees well with the DC estimation. In general, the transient beam loading effect lies in non-ideal beam filing patterns or charge variation in different bunches, et. ac.

In CETASIM code, to ensure the cavity preload condition, the beam-induced voltage is calculated in advance for the given filling pattern. With a converged and the required cavity voltage , the ideal can be found. In the simulation, we keep the can also be modified by a simple cavity voltage and phase feedback loop.

To evaluate the inner bunch structure, each bunch can be divided by density histogram. The beam-induced voltage is then stimulated sequent bin by bin and then bunch by bunch.

The cavity voltage seen by the particle is

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where n is the cavity number, is the synchrotron phase for each cavity, is the cavity voltage phasor and + , is the loss factor of cavity and can be found by Equation 1‑29.

The longitudinal map during particle tracking is given by Equation 1‑32. Clearly,

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### Bunch-by-bunch feedback

The bunch-by-bunch feedback [4] simulation is modeled based on the FIR filter. If the FIR filter coefficients are given, the beam momentum change at the kicker in the *nth* turn due to the bunch-by-bunch feedback can be modeled as

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in which *N* is the order of the filter, and is the filter coefficient, is the bunch centroid of the *kth* previous turn at the pickup, is the kicker strength decided by the hardware settings.

### interaction between beam and borad band impedance

Due to some resoan I am not quite sure, (mybe the data structure I designd and vector template in C++), the simulation with impdance is very slow. For example, set tracking 6000 turns in total and the impedance data is pow(2,16), it takes around 24 hours to ge the final results.

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| Figure 1‑16: CETASim and elegant comprism for single bunch effect, where only the longitudinal impedacen is considered. The lattice parameter are from petra4 with 1mA (8nC) single bunch current. The same impedance data sued in Petra4 storage ring is applied here. The one turn matrix is applied for tracking. From top to bottom, it shows the bunch center, bunch length and bunch energy spread for two cases, system with and without harmoinc cavity. With harmonic cavity, the ideal bunch lengening condition is feeded as initial condition. |

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| Figure 1‑16: CETASim and elegant comprism for single bunch effect, where only the longitudinal impedacen is considered. The same impedance data sued in Petra4 storage ring is applied here. The one turn matrix is applied for tracking. It shows the bunch length (left) and bunch energy spread (right) for two cases, system with and without harmoinc cavity. With harmonic cavity, the ideal bunch lengening condition is feeded as initial condition. Which shows good agreement. As to the energy spread wth harmonic cavity case, since only 6000 tuns in total is set in tracking. The final value still no damped the equilibrium state. |