Collective effects simulation code CETASim

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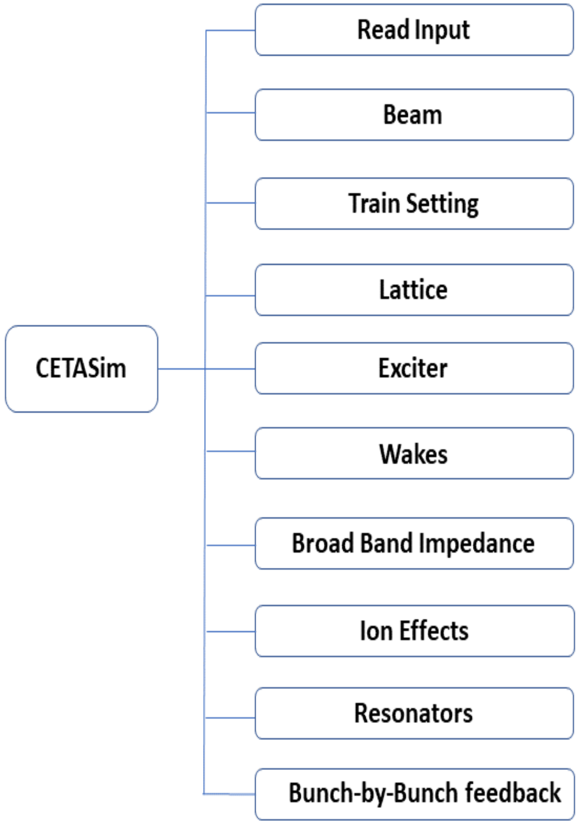
DESY-TEMF Collaboration meeting

Outlines

- Motivation and overview of CETASim.
- Benchmarks and simulation study for PETRA-IV storage ring
- Summary and outlook

Motivation and overview of CETASim

- Motivation:
  - A light and user-friendly tool
  - Includes various collective effects (single bunch, coupled bunch)
  - Arbitrary filling pattern and bunch charge settings
  - Approaches for instability mitigation
  - Easy to maintain and extend to include more physics
- Modules available
  - One-turn nonlinear map.
  - SR damping and quantum excitation
  - Broad band Impedance effect (single bunch)
  - Long range wakes (coupled bunch)
    - model is limited to analytical RLC and RW
  - Transient beam loading effect (fundamental mode from cavities)
  - Coupled bunch mode drive-damped simulation
  - Beam-ion (multi-ion species, mutli-interaction sections)
  - Bunch-by-bunch feedbacks
  - skew quadrupoles (Emittance exchange due to resonance crossing)
  - Open source and developed in C++



- ❑ Set required filling pattern
- ❑ Set macro-particle in bunch train
- ❑ Set transfer map among ion interaction point
- ❑ Set ion species
- ❑ Set ramping term
- ❑ Set external exciter
- ❑ Set FIR filter for bunch-by-bunch feedbacks
- ❑ Set board band Impedance
- ❑ Set short range wakes
- ❑ Set long range wakes
- ❑ Tracking
- ❑ Post process

https://github.com/ChaoLiIHEP/CETASIM

One-Turn matrix

- Particle notation:
  - **x** = (x, px, y, py, dz, δ)
- One-turn map T
  - Chromaticity and amplitude-depended tune are included in phase advances
  - Path-length effect due to dispersion is included

$$\mathbf{T} = \begin{pmatrix} \cos\psi_x + \alpha_x \sin\psi_x & \beta_x \sin\psi_x & 0 & 0 & 0 & T_{16} \\ -\gamma_x \sin\psi_x & \cos\psi_x - \alpha_x \sin\psi_x & 0 & 0 & 0 & T_{26} \\ 0 & 0 & \cos\psi_y + \alpha_y \sin\psi_y & \beta_y \sin\psi_y & 0 & T_{36} \\ 0 & 0 & -\gamma_y \sin\psi_y & \cos\psi_y - \alpha_y \sin\psi_y & 0 & T_{46} \\ T_{51} & T_{52} & T_{53} & T_{54} & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- Longitudinal kicks at RF
  - Numbers of RFs is not limited
  - Higher order momentum compact factor

$$dz_{i+1} = dz_i - L\sum_{j=1}^{3} \alpha_{cj}(\delta_i)^j \qquad d\delta_{i+1} = d\delta_i + \frac{1}{\beta^2 E_0}\left(-U_0 + \sum_n eV_{n,rf}\sin(\omega_{n,rf} d\tau_i + \phi_n)\right)$$

Outlines

- Motivation and overview of CETASim.
- **Benchmarks and simulation study for PETRA-IV storage ring**
- Summary and outlook

Radiation damping and quantum excitation.

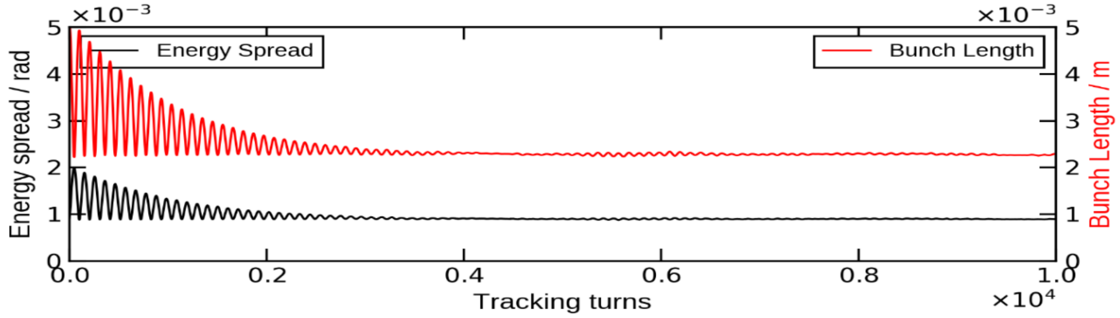
- Algorithm of damping and excitation is the same as the Beam-Beam code from Hirata
- **x** = (x, px, y, py, dz, δ)
- Damping and excitation are treated in **X**-frame
- **B** and **H** are Twiss matrix and dispersion matrix

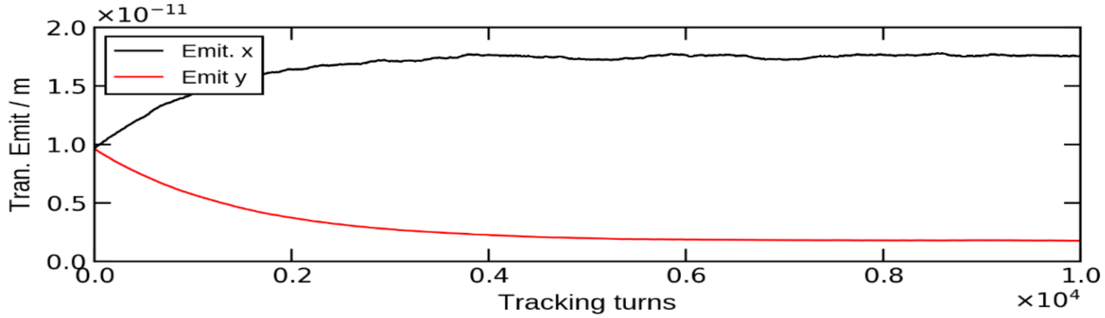
$$\mathbf{X} = \mathbf{B}\mathbf{H}\mathbf{x}.$$

$$\begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_1 \end{pmatrix} = \lambda_x \begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_1 \end{pmatrix} + \sqrt{\epsilon_x(1-\lambda_x^2)} \begin{pmatrix} \hat{r}_1 \\ \hat{r}_2 \end{pmatrix}$$
$$\begin{pmatrix} \mathbf{X}_3 \\ \mathbf{X}_4 \end{pmatrix} = \lambda_y \begin{pmatrix} \mathbf{X}_3 \\ \mathbf{X}_4 \end{pmatrix} + \sqrt{\epsilon_y(1-\lambda_y^2)} \begin{pmatrix} \hat{r}_3 \\ \hat{r}_4 \end{pmatrix}$$
$$\begin{pmatrix} \mathbf{X}_5 \\ \mathbf{X}_6 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \lambda_z^2 \end{pmatrix} \begin{pmatrix} \mathbf{X}_5 \\ \mathbf{X}_6 \end{pmatrix} + \begin{pmatrix} 0 \\ \sqrt{\epsilon_z(1-\lambda_z^4)} \end{pmatrix} \begin{pmatrix} 0 \\ \hat{r}_6 \end{pmatrix},$$

$$\mathbf{x} = \mathbf{H}^{-1}\mathbf{B}^{-1}\mathbf{X},$$

Ref. Hirata, CERN SL-Note-97-57-AP, 1997





- Beam starts from non-equilibrium initial condition
- Target coupling is 10%
- Single RF, no beam loading effect from cavity.
- Beam evolves to equilibrium state as expected.

Broad band Impedance and wake field model in PETRA-IV

- Geometric impedance is obtained from GDFIDL, element-by-element, 1mm leading bunch (Yong-Chul)
- Resistive wall impedance is from ImpedanceWake2D (Sergey)
- Longitudinal, transverse dipole and transverse quadrupole

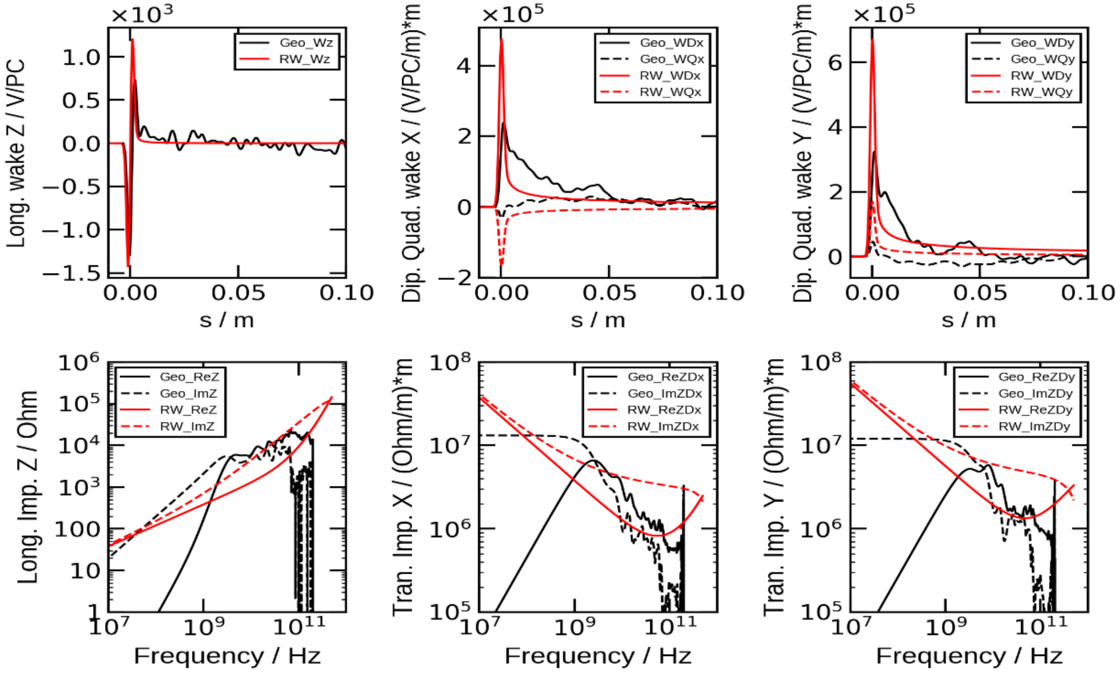
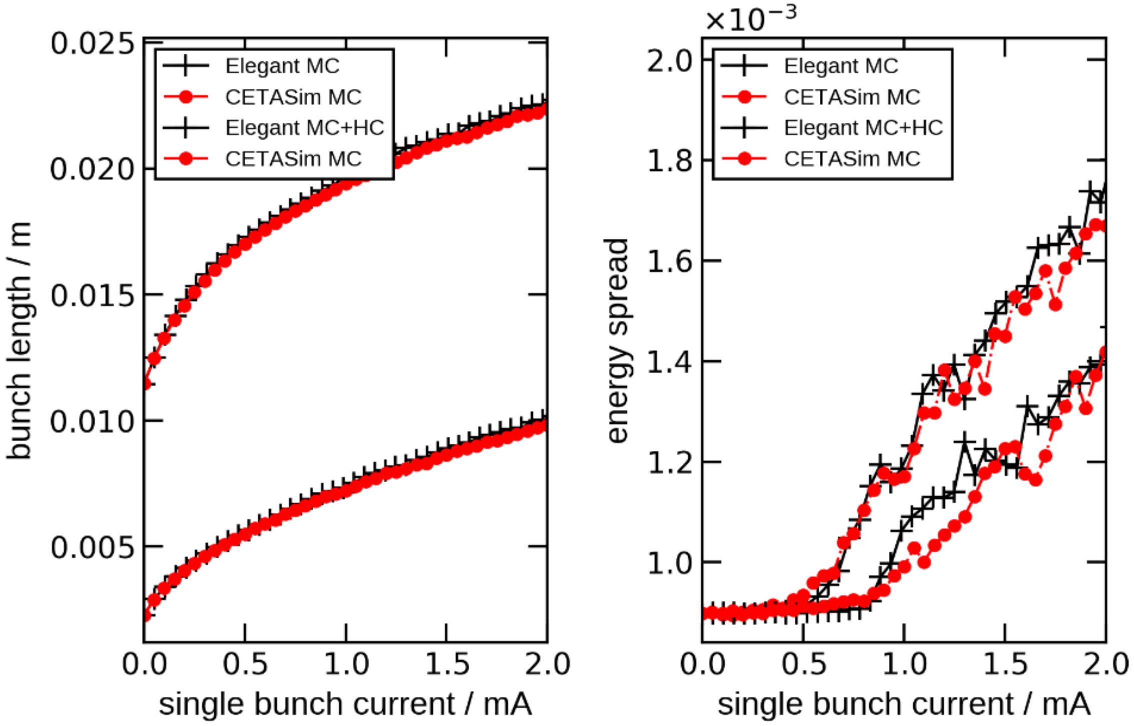


Table 2: Impedance elements and kick/loss factor for a 42 picosecond bunch

element	Number N	β_x m	β_y m	β_z m	Kick Factor $N\beta_y k_y$ V/PC	Loss Factor Nk_z V/PC
General Components (Storage Rings)						
BPM	788	6.18	7.31	1	3.39E+3	1.67E+0
Absorber	576	3.80	4.73	1	3.04E+1	4.15E-3
Bellow	375	2.71	4.25	1	3.84E+3	2.81E-3
Flange	375	2.71	4.25	1	2.38E+2	8.60E-4
ID ARCS (21 × 5 [m] + 5 × 10 [m])						
ID 5 mm	4	5.04	5.04	1	1.47E+3	7.34E-5
ID 6 mm	17	5.04	5.04	1	5.58E+2	2.86E-4
ID 7 mm	5	10.25	10.25	1	5.68E+2	7.42E-5
Absorber	96	5.85	4.4	1	4.71E+0	6.91E-4
Bellow	96	5.7	4.3	1	9.95E+2	7.22E-4
Flange	96	5.8	4.4	1	6.31E+1	2.20E-4
Long Straight Section						
RF	24	20	20	1	2.84E+3	9.43E+0
3V RF	24	20	20	1	2.17E+4	13.43E+0
FCT	6	7.76	8.44	1	1.73E+3	0.27E+0
Short Straight Section						
FB H.	4	12.5	15	1	1.94E+3	0.36E+0
FB V.	4	12.5	15	1	2.29E+3	0.36E+0
Collimators	4	12.5	15	1	1.2E+4	0.14E+0
Injection Straight Section						
Inj. Kicker	30	10	10	1	1.04E+4	5.29E+0
ID Chamber RW impedance						
5mm_ID	4	3.14	3.14	1	6.87E+3	0.15E+0
6mm_ID	17	3.14	3.14	1	1.69E+4	0.52E+0
Super_ID	5	6.08	6.08	1	1.21E+4	0.26E+0
Ring round Chamber RW impedance						
10 mm radius	1	8.0	8.76	1	3.09E+4	2.58E+0
Kick/Loss Factor In Total					1.31E+5	34.45E+0

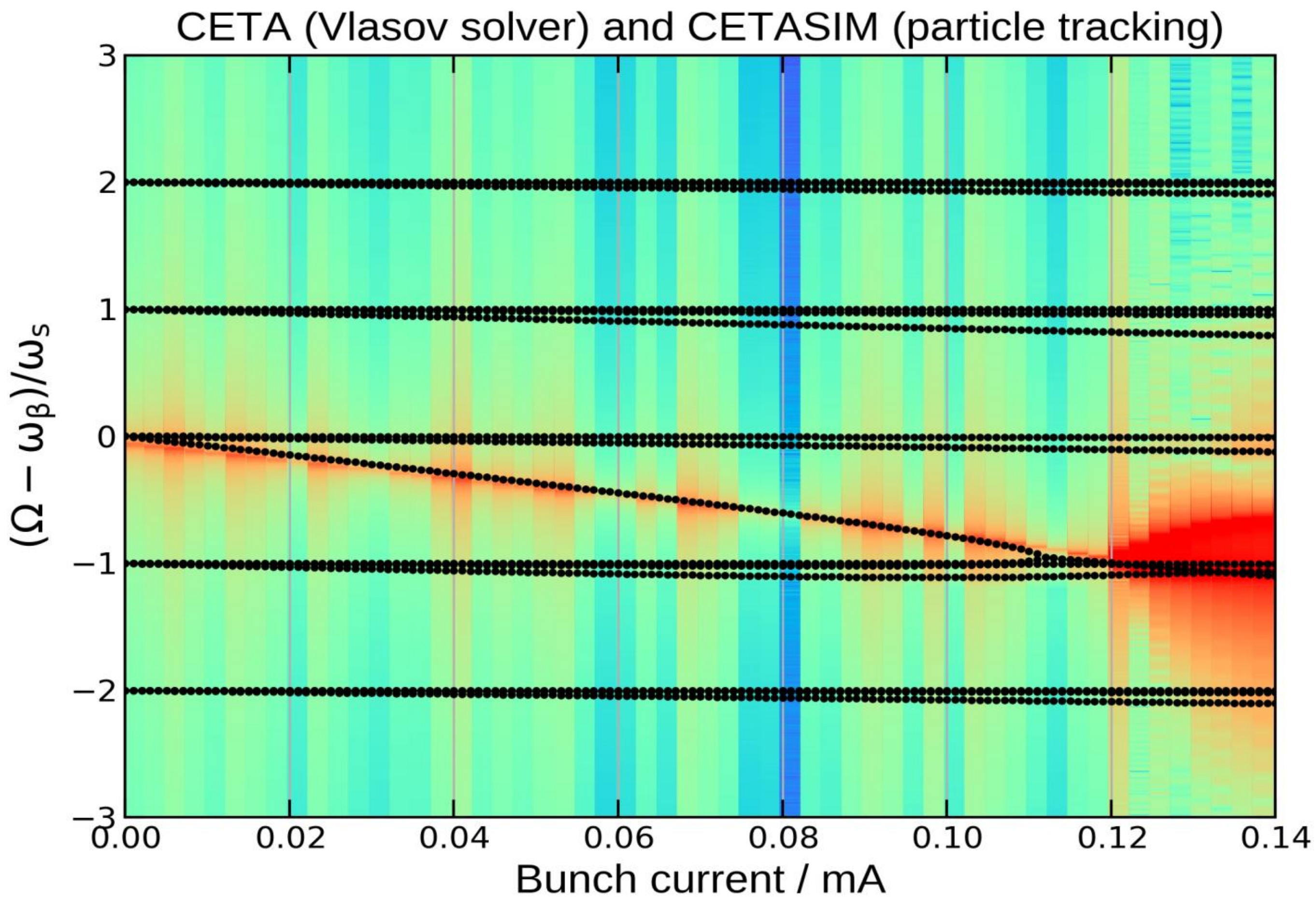
Single bunch effect--longitudinal impedance

- Petra-IV Impedance data and lattice parameters
- Longitudinal impedance only.
- 100K macro-particles and 20K turns tracking.
- RF cavities are ideal elements (no beam loading effect)
- Good agreement with Elegant results



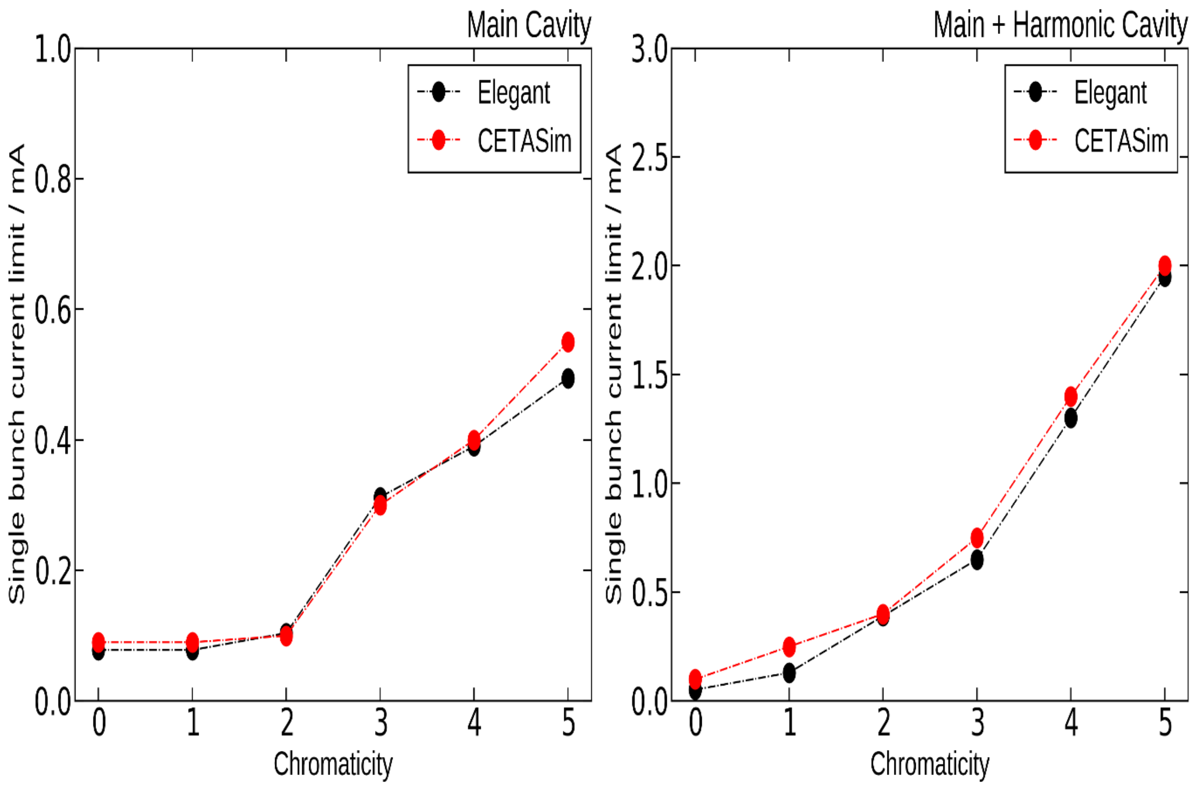
Single bunch effect--TMCI at zero chrom

- Transverse dipole impedance only
- Vlasov solver (analytical) Vs Tracking
- 0.11 mA is the threshold at 0 chrom



Single bunch effect--transverse impedance

- Petra4 Impedance data and lattice parameters
- Longitudinal impedance, transverse dipole and quadrupole impedance.
- 100K Particles 20K turns.
- Single and double RF systems
- RF Cavities are ideal elements (no beam loading effect)
- Good agreement with Elegant results.
- At chrom 5, the threshold is around 0.5mA and 2 mA without and with the 3rd order harmonic cavity



Coupled bunch effects

- Wakes are limited to analytical models
  - RW and RLC wakes
- Tracking is done in time domain
  - Bunch-by-bunch info. of previous turns have to stored in memory in traking
- Bunches are treated as point particles (coherent effect only)
- Exact wake from RW

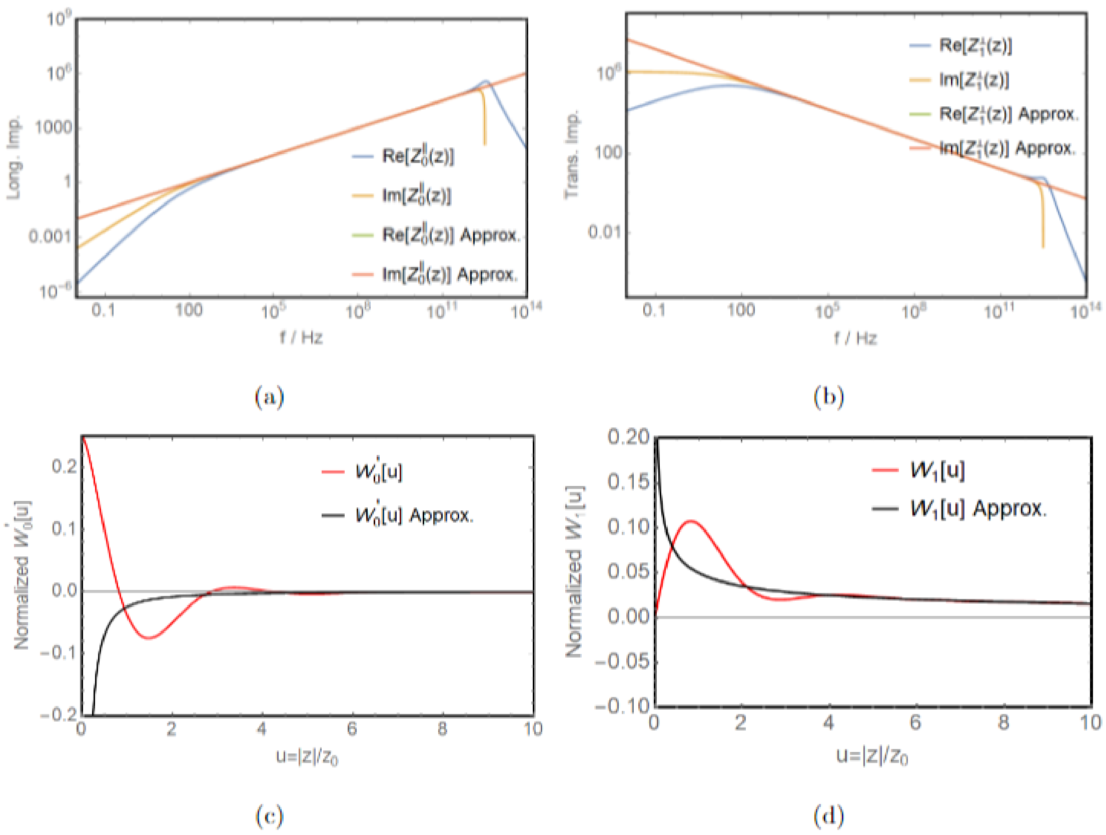
$$W_0'(z) = \frac{1}{b^2}[\frac{e^{-z/z_0}}{3}\cos\left(\frac{\sqrt{3}z}{z_0}\right) - \frac{\sqrt{2}}{\pi}\int_0^\infty dx\frac{x^2e^{-x^2z/z_0}}{x^6+8}]$$

$$W_1(z) = -\frac{32}{b^3}(2\chi)^{1/3}[\frac{e^{-z/z_0}}{12}\cos\left(\frac{\sqrt{3}z}{z_0}\right) - \frac{1}{4\sqrt{3}}e^{-z/z_0}\sin\left(\frac{\sqrt{3}z}{z_0}\right) - \frac{\sqrt{2}}{\pi}\int_0^\infty dx\frac{x^2e^{-x^2z/z_0}}{x^6+8}].$$

- Approximation applied in CETASIM

$$W_0'(z) \approx \frac{1}{2\pi b}\sqrt{\frac{c}{\sigma}}\frac{1}{|z|^{3/2}} \qquad W_1(z) \approx -\frac{2}{\pi b^3}\sqrt{\frac{c}{\sigma}}\frac{1}{|z|^{1/2}}.$$

RW impedance (above) and wakes (bottom)



Coupled bunch mode in transverse (Petra-IV parameters)

- RW parameters shown in table
  - 4 sectors in total
- Long-range Wakes last 20 turns, specified in input
- Coupled bunch mode growth rate can be re-constructed with the TBT, bunch-by-bunch data.
- Momentum info is required and the mode growth rate can be obtained by exponential fitting of the signal in Fourier space

$$z_\mu = \left(\frac{x_\mu}{\sqrt{\beta_x}} - i(\sqrt{\beta_x} p_{x,\mu} + \frac{\alpha_x}{\sqrt{\beta_x}} x_\mu\right) e^{-i\frac{2\pi\nu_x(\mu-1)}{M}},$$

- Coupled bunch mode growth rate can be found analytically as well

TABLE II. Simplified resistive wall sections in Petra4.

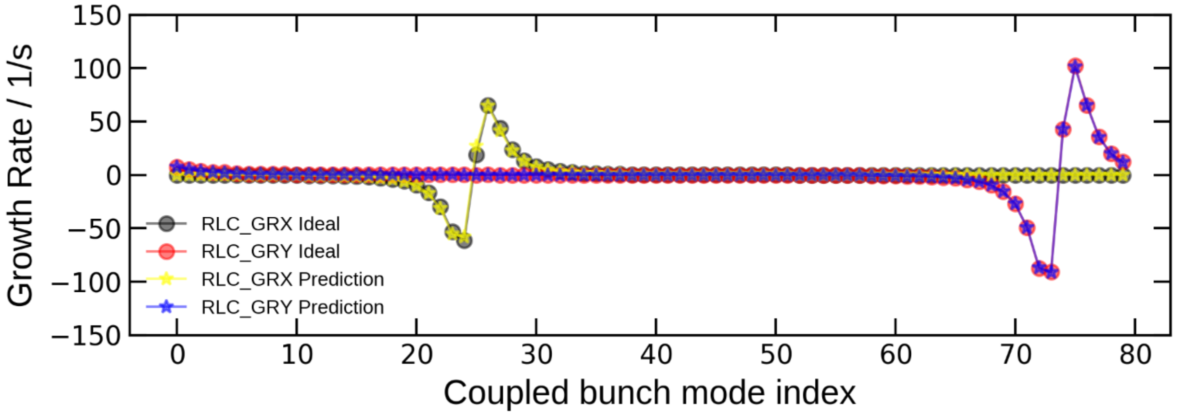
section	number	Length / m	gaps / mm	β_x / m	β_x / m	conductivity σ / $\Omega^{-1}m^{-1}$	z_0 / m
5 mm ID	4	5	5	3.14	3.14	2.5E+7	1.74E-5
6 mm ID	17	5	6	3.14	3.14	2.5E+7	1.97E-5
7 mm ID	5	10	7	6.08	6.08	2.5E+7	2.18E-5
ring	1	2149	10	2.71	4.25	5.9E+7	2.08E-5

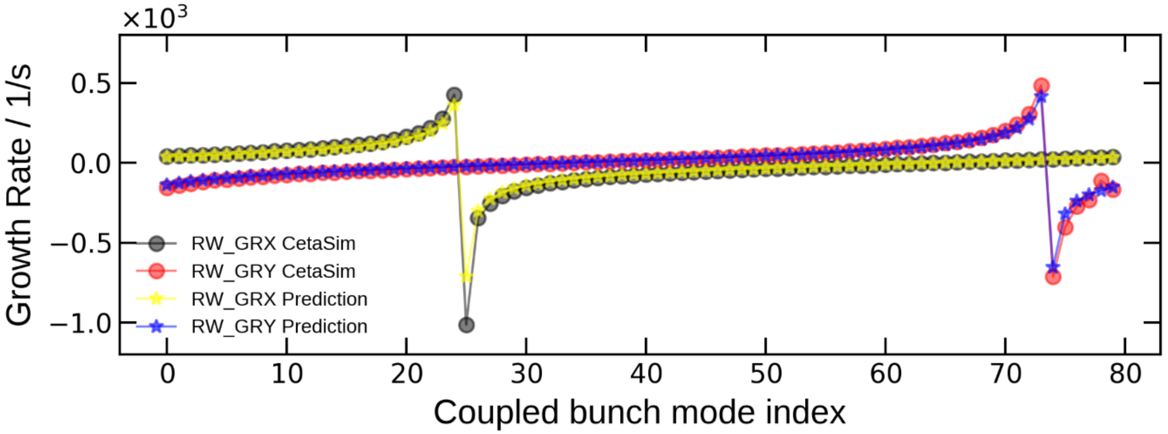
$$(\Omega^\mu - \omega_\beta)_\perp = -i\frac{MNr_0c}{2\gamma T_0^2\omega_\beta}\sum_{p=-\infty}^{\infty} Z_1^\perp[\omega_\beta + (pM+\mu)\omega_0]h(\omega-\omega_\xi,\sigma_t)$$

$$(\Omega^\mu - \omega_s)_\parallel = i\frac{MNr_0\eta}{2\gamma T_0^2\omega_s}\sum_{p=-\infty}^{\infty}(\omega_s + pM\omega_0 + \mu\omega_0)Z_0^\parallel[\omega_s + pM\omega_0 + \mu\omega_0]h(\omega,\sigma_t)$$

Coupled bunch mode in transverse

- Petra-IV timing operation mode, 80 bunches, 80 mA
  - 3840=80*(1b+47g)
- Two examples
  - RW
  - RLC, Rs=5E+9 ohm/m/m, Q=1E+3, fr=4.986E+8 Hz
- Coupled bunch mode growth rate shows good agreement between simulation and analytical prediction.



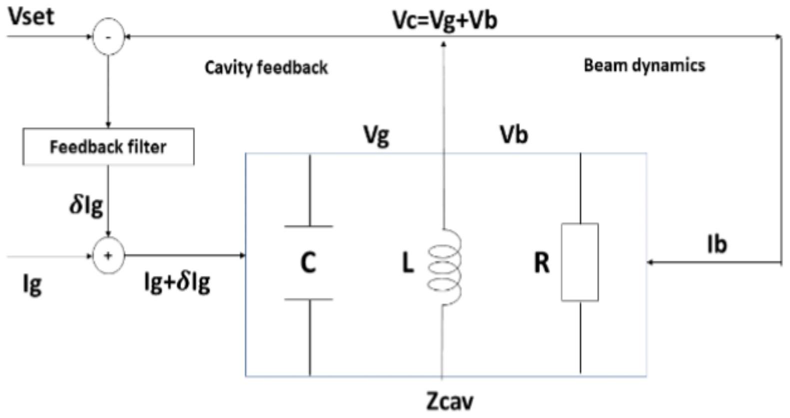


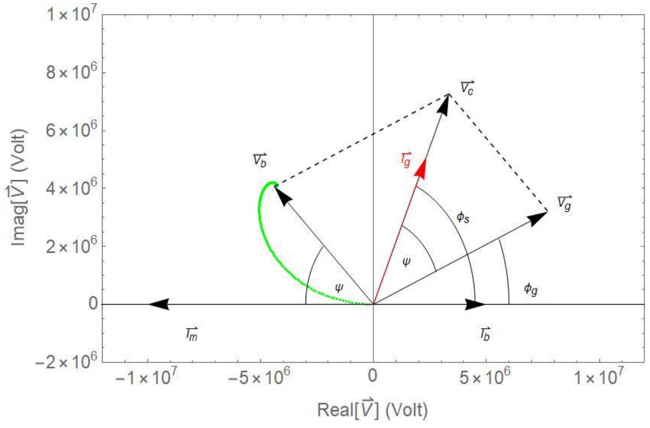
Transient beam loading effect

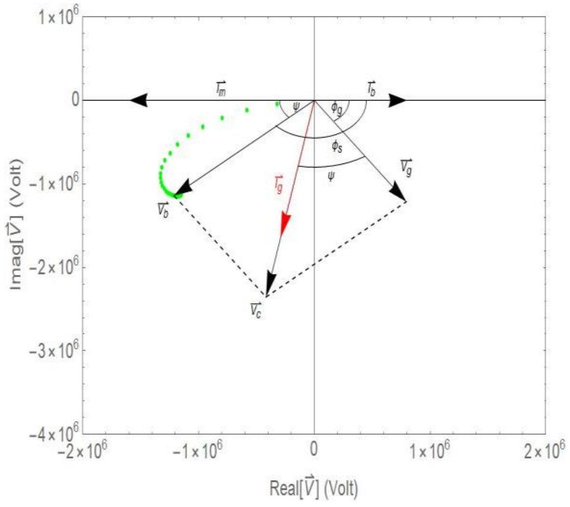
- Longitudinal coupled bunch instability.
- Bunch length and centeriod variation.
- Treated in phasor frame. (P. B. Wilson)

Table 3: Nominal settings of the double RF system in the H6BA lattice.

Parameter	Symbol	Main RF ($n = 1$)	Harmonic RF ($n = 3$)
RF Freq. (Hz)	$f_{rf,n}$	4.997E+8	1.499E+9
RF Freq. (Hz)	$\omega_{rf,n}$	$2\pi f_{rf,n}$	$2\pi f_{rf,n}$
ID Closed			
Ref. Voltage (V)	$V_{c,n}$	8E+6	2.223E+6
Synchronous Phase (rad)	ϕ_n	2.516	-0.237
ID Open			
Ref. Voltage (V)	$V_{c,n}$	8E+6	2.625E+6
Synchronous Phase (rad)	ϕ_n	2.954	-0.063







Ref. P. Wilson, "Fundamental-mode rf design in e+ e- storage ring factories

Main cavity

3rd harmonic cavity

Transient beam loading effect

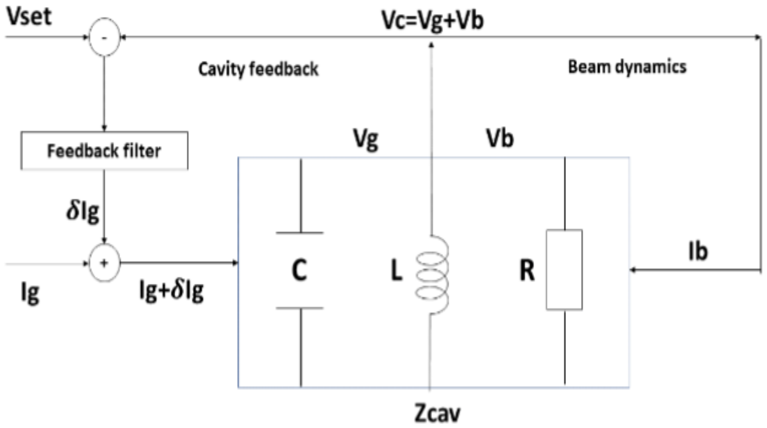
- Have to self-consistent deal with the generator dynamics and beam dynamics
- For a given initial generator current Ig, Vg is tracked as a function of time.
- Beam induced voltage Vb is tracked in phasor frame by:

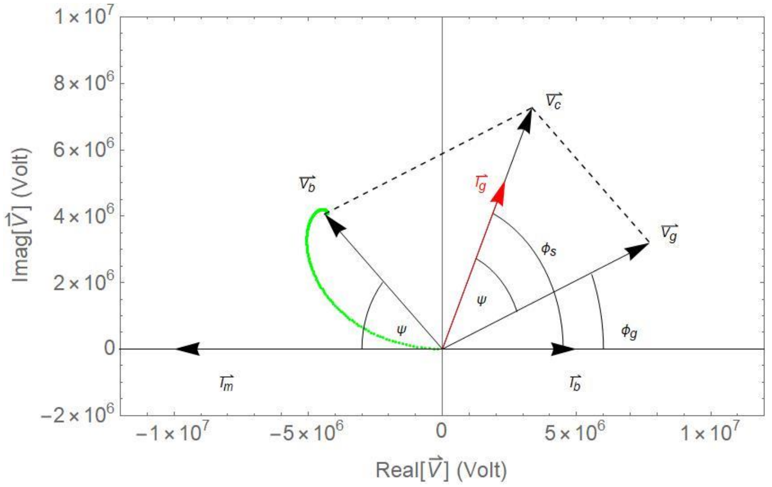
$$\tilde{\mathbf{V}}_{\mathbf{b}}(t) = (\tilde{\mathbf{V}}_{\mathbf{b}}(t - \Delta t) + \tilde{\mathbf{V}}_{\mathbf{b0}}/2)] \exp(\alpha \Delta t), \quad \alpha = -\frac{1}{\tau_f}(1 - i \tan \Psi)$$

- Sample Vc at time n*Trf, generator current Ig

$$\delta \tilde{\mathbf{I}}_{\mathbf{g}}(nT_{rf}) = -\frac{1}{a_0} \sum_{i=1}^{N} a_i \delta \tilde{\mathbf{I}}_{\mathbf{g}}((n-i)T_{rf}) + \frac{1}{b_0} \sum_{j=0}^{M} b_j \delta \tilde{\mathbf{V}}((n-j)T_{rf})$$

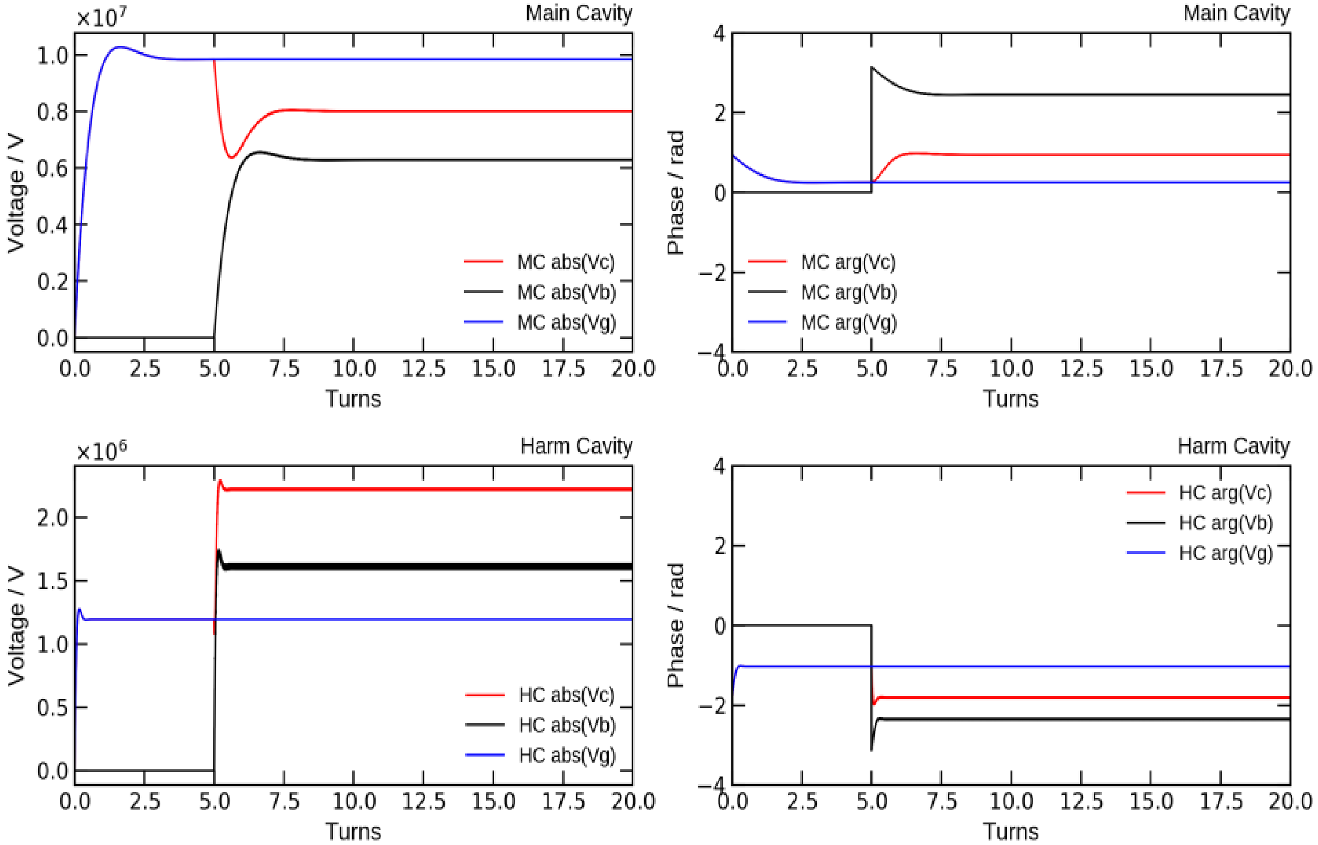
$$\frac{d^2}{dt^2}\tilde{\mathbf{V}}(t) + \frac{\omega_r}{Q_L}\frac{d}{dt}\tilde{\mathbf{V}}(t) + \omega_r^2 \tilde{\mathbf{V}}(t) = \frac{\omega_r R_L}{Q_L}\frac{d}{dt}\tilde{\mathbf{I}}(t),$$





Transient beam loading effect

- Petra 4 double RF parameters
- Generator voltage Vg and beam induced voltage Vb are build up with given initial conditions.
- Beam goes into cavity at the 5th turn.
- Bunches are assumed on axis and the instability is turned off.
- The red curve shows the cavity voltage Vc beam would sample.

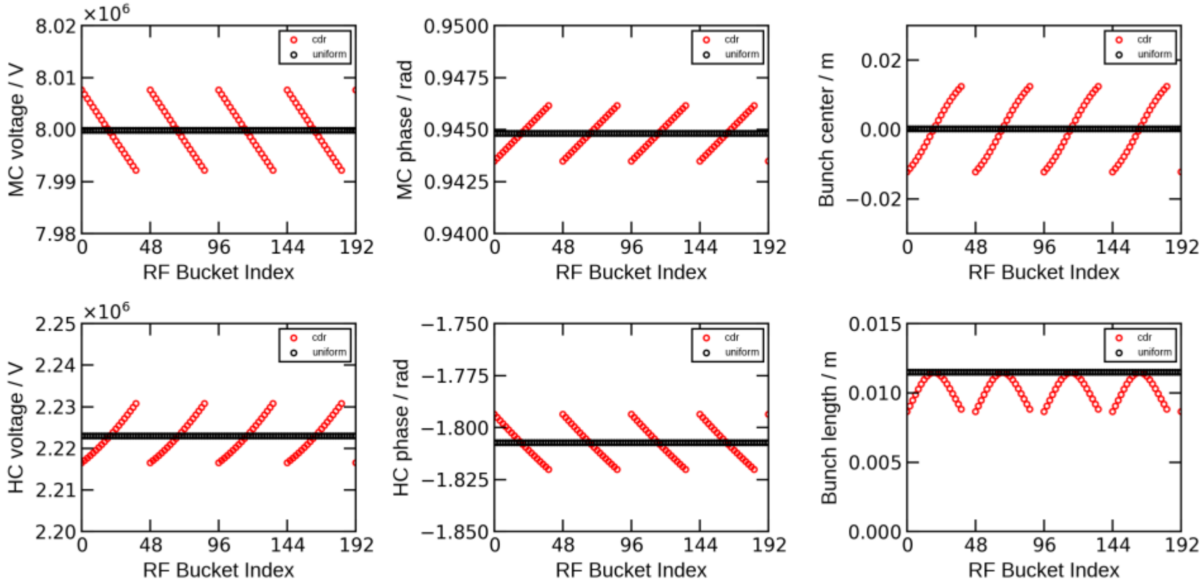


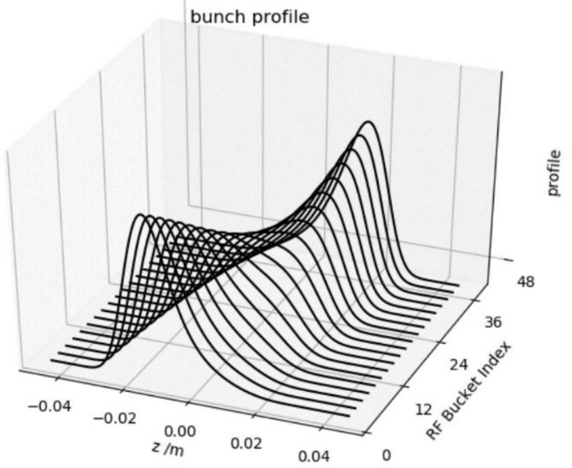
Transient beam loading effect

- Brightness mode operation
  - 3840=80*(20*(1b+1g)+8g)
- Set one macro-particle per bunch
- Longitudinal coupled bunch instability
  - turned off in simulation
- Once cavity voltage and phase bunch sampled, bunch profile, center and bunch length can be found by:

$$\rho(z) = \rho_0 \exp\left(-\frac{1}{2\pi h f_0 \alpha_c \delta^2} H_1(z)\right),$$

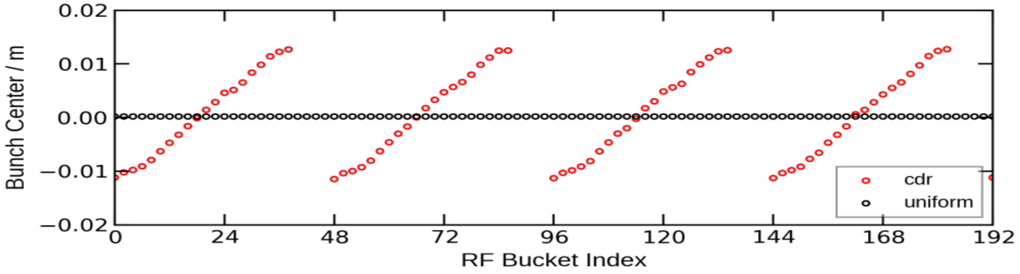
$$H_1(z) = \frac{\omega_0 e}{2\pi\beta^2 E}\frac{2\pi h f_0}{\beta c}\left(Re\sum_n \int_0^z \tilde{\mathbf{V}}_{\mathbf{c},\mathbf{n}}(z')dz' + \int_0^z \int_{z''}^{\infty} e\rho(z')W_0'(z''-z')dz'dz''\right).$$

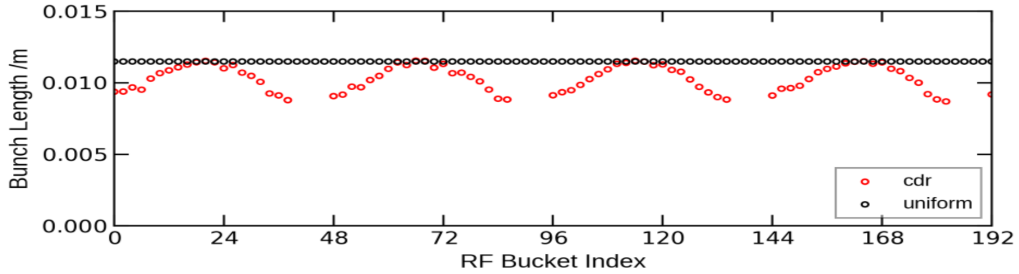


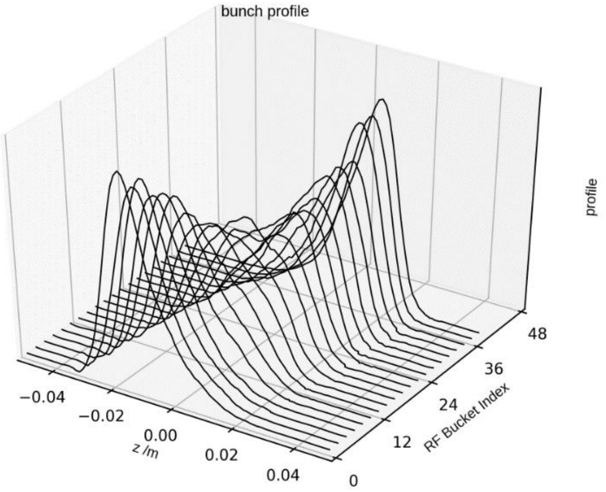


Transient beam loading effect (soft bunches)

- Brightness mode operation.
  - 3840=80*(20*(1b+1g)+8g)
- Set 1000 macro-particle per bunch
  - Bunches are histogram into bins
  - Bin-by-bin then bunch-by-bunch tracking
- Longitudinal coupled bunch instability
  - turned off in simulation
- Bunch length and center info are directly from simulation.
- If turn off the instabilities, it agrees with one-particle model simulation.

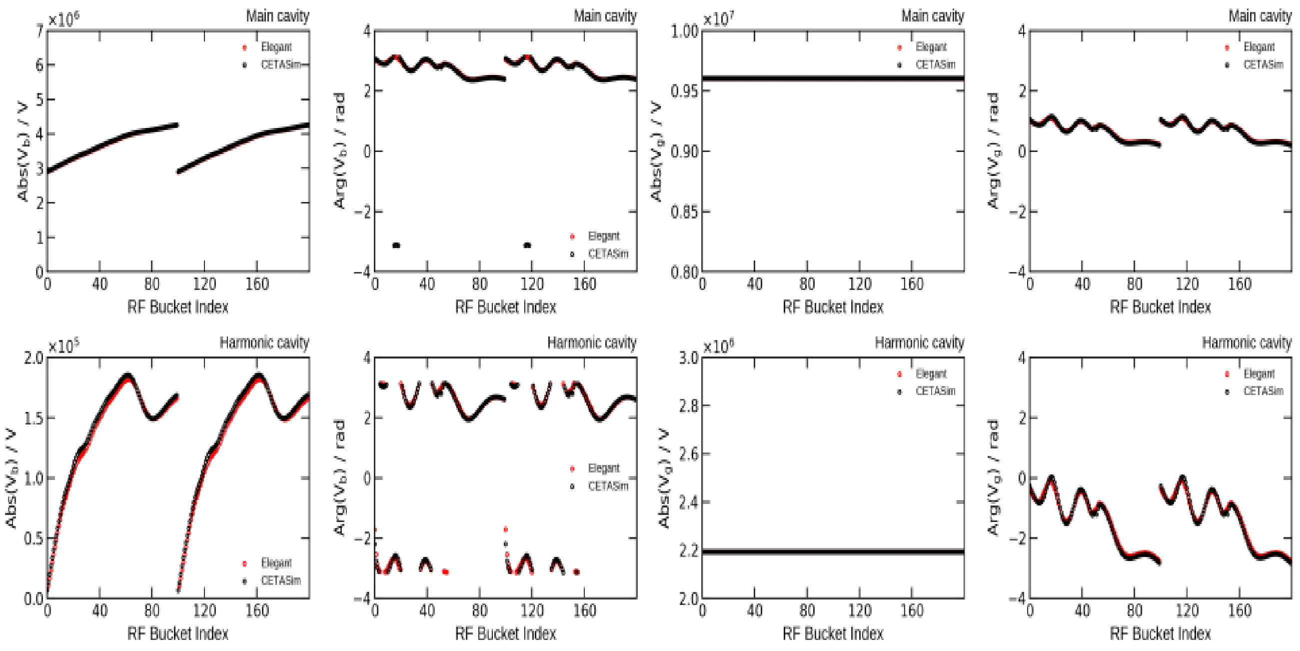




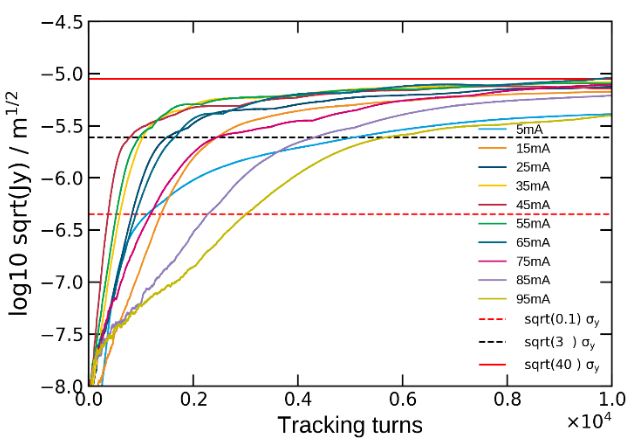


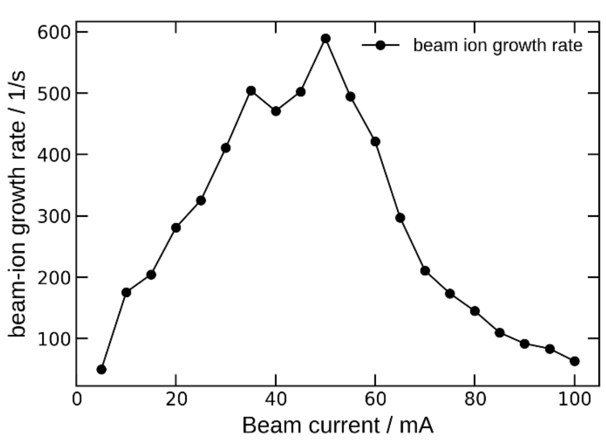
Transient beam loading effect (soft bunches with instability)

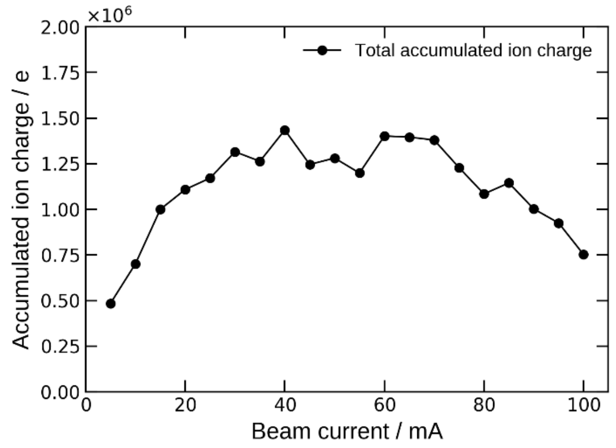
- Filling pattern:
  - 3840=2*(100*(1b+9g)+920g)
- Set 1000 macro-particle per bunch
  - Bunches are histogram into bins
  - Bin-by-bin then bunch-by-bunch tracking
- Longitudinal coupled bunch instability
  - turned on in simulation
- Vb and Vg obtained by CETASim and Elegant agree well.
- Bunch length and center are also agrees (not shown here)



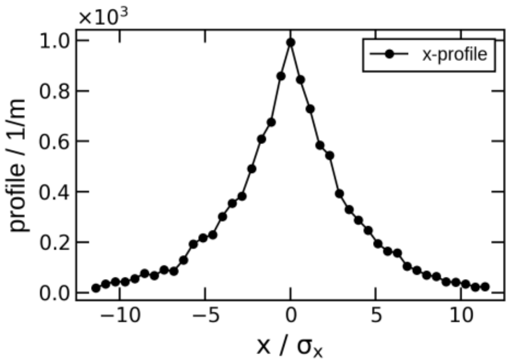
Beam-ion effect (single ion)

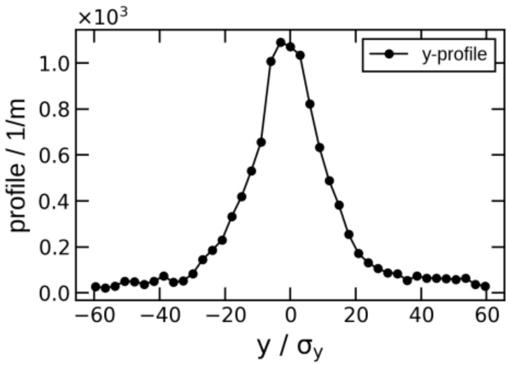






- Bassetti-Erskine formula for direct space charge effect between ions and electrons
- Brightness mode 3840=80*(20*(1b+1g)+8g)
- CO, 300K, 1nTor
- Bunch oscillation is self-saturated, within10 rms bunch size
- In the medium current range (30mA to 70mA) accumulate the ions most.
- Medium current give the largest growth rate.
- Ion profile is not Gaussian.

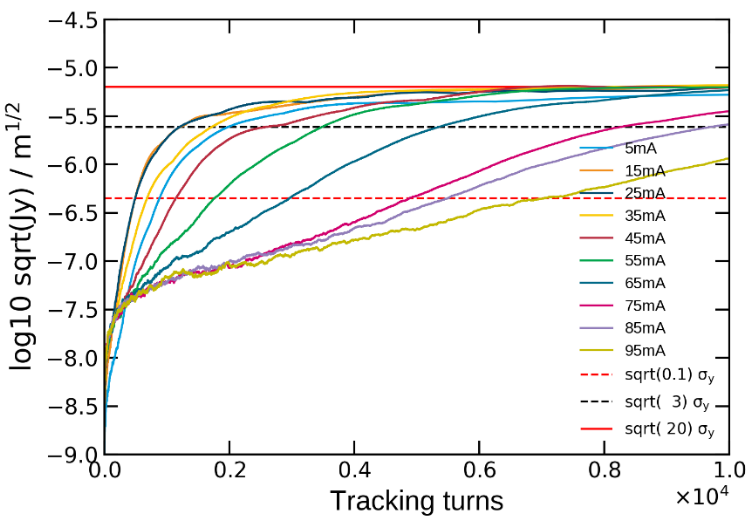


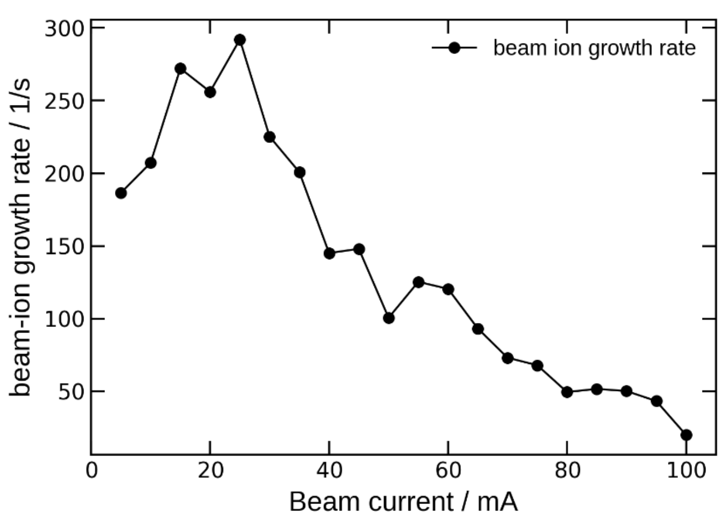


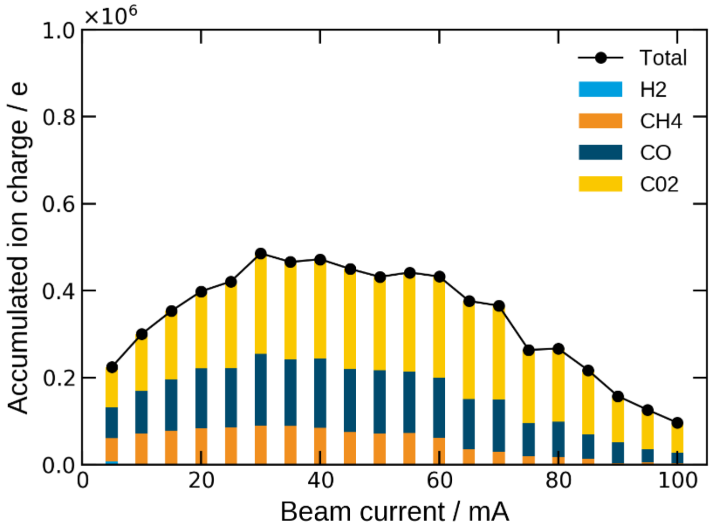
Beam-ion effect (multi-ions)

- self-saturation around 5 rms beam size
- In the medium current range (30mA) accumulate the most ions
- Lighter ions are hardly trapped
- The largest growth rate is roughly 300(1/s) around 20mA.

	H_2	CH_4	CO	CO_2
Initial	**0.43**	**0.08**	**0.36**	**0.13**







Bunch-by-Bunch Feedback system

T. Nakamura, http://accweb.spring8.or.jp/~nakamura/reports/Feedback_with_FIR_Filter_draft1.pdf.

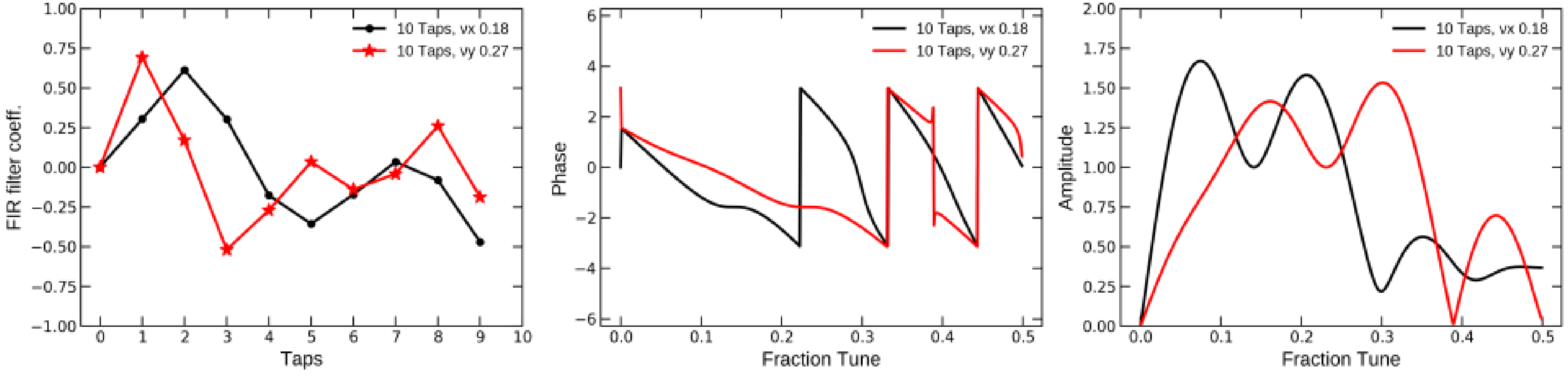
Definition and simulation model of the FIR filter:

$$\Theta_{x,n} = K_x \sum_{k=0}^{N} a_{k,x} x_{n-k},$$

$$\Theta_{y,n} = K_y \sum_{k=0}^{N} a_{k,y} y_{n-k},$$

$$\left[\begin{pmatrix} x_{n+1} \\ x'_{n+1} \\ y_{n+1} \\ y'_{n+1} \end{pmatrix}\right] = M_0 \left[\begin{pmatrix} x_n \\ x'_n \\ y_n \\ y'_n \end{pmatrix} + \begin{pmatrix} 0 \\ \Theta_{x,n} \\ 0 \\ \Theta_{y,n} \end{pmatrix}\right]$$

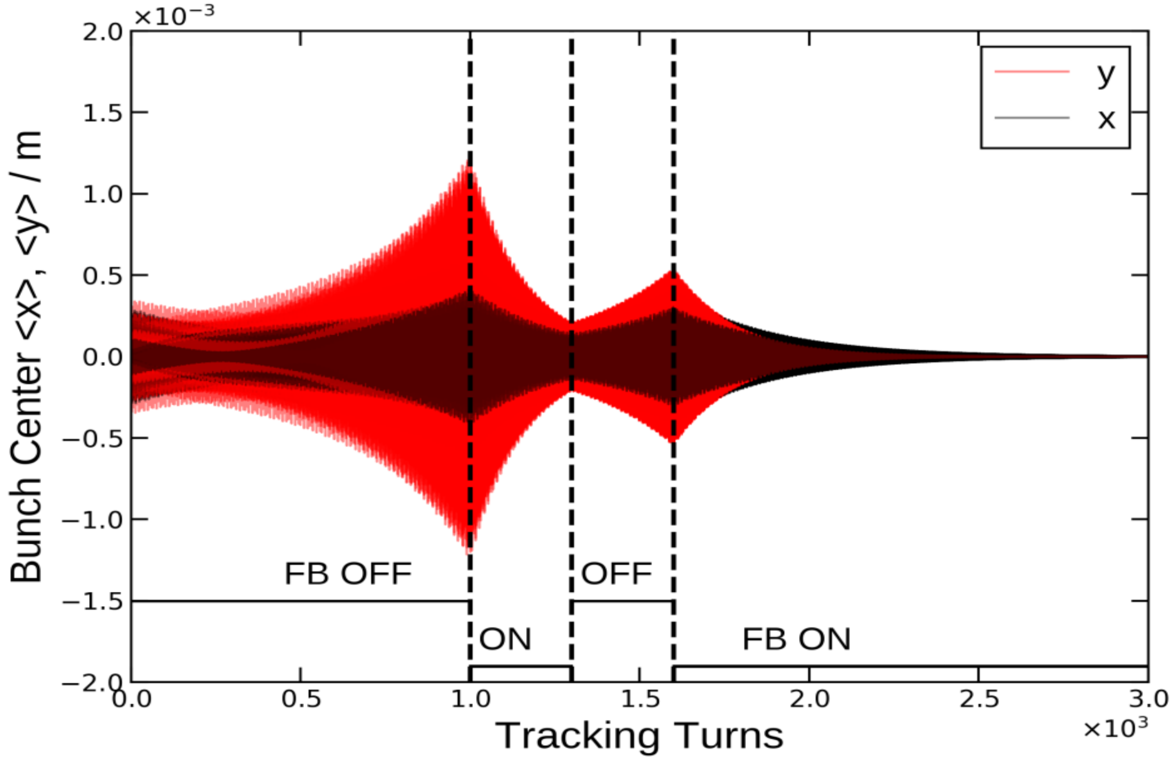
The TDLSF method is applied for FIR filter design



Frequency and phase response of the designed 10 taps filter, target tunes are 0.18 and 0.27

Bunch-by-Bunch Feedback system (transverse)

- Timing mode option
  - 3840=80*(1b+47g)
- RW long range wakes.
- Coupled bunch instability can not damped by SR damping
- The preliminary 10 taps FIR filter feedback.
  - Target tunes are 0.18 and 0.27
- Feedback is turned on between 1000~1300 and 1600 to 3000 turns.
- All 80 bunches all well damped by the feedback



Summary and outlook

- Modules for single and coupled bunch collective effect simulation are available
- Well benchmarked with analytical model and Elegant results
- Coupled bunch instability mitigation by bunch-by-bunch feedback
- We are working on cavity feedback model for transient beam loading compensation
- Code parallelization in the future.
- Welcome to download and feel free to use, I am very glad to explain the details. **https://github.com/ChaoLiIHEP/CETASIM**

Thanks for your attention!