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Collective effects studies for CEPC

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IHEP

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Main beam parameters

Parameter [unit]	Higgs	W	Z	tt-bar
Beam energy [GeV]	120	80	45.5	180
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	5	16	115	0.5
Emittance (H/V) [nm]	0.64/0.0013	0.87/0.0017	0.27/0.0014	1.4/0.0047
Beam current [mA]	16.7	84.1	803.5	3.3
Bunch number	249	1297	11934	35
Bunch Population [10^{10}]	13	13.5	14	20
Momentum compaction [10^{-5}]	0.71	1.43	1.43	0.71
Bunch length σ_z (natural/total) [mm]	2.3/4.1	2.5/4.9	2.5/8.7	2.2/2.9
Energy spread (natural/total) [10^{-4}]	10/17	7/14	4/13	15/20
Betatron tune ν_x/ν_y	445.10/445.22	317.10/317.22	317.10/317.22	445.10/445.22
Synchrotron tune	0.049	0.062	0.035	0.078
Radiation damping [ms]	44/44/22	156/156/78	850/850/425	14/14/7

Resistive wall impedance

- Cylindrical beam pipe with radius of 28mm (Copper + 0.2μm NEG coating)
- Multi-layer analytical formula is used

PRST-AB 10, 111003 (2007)

Multilayer formula from field matching:

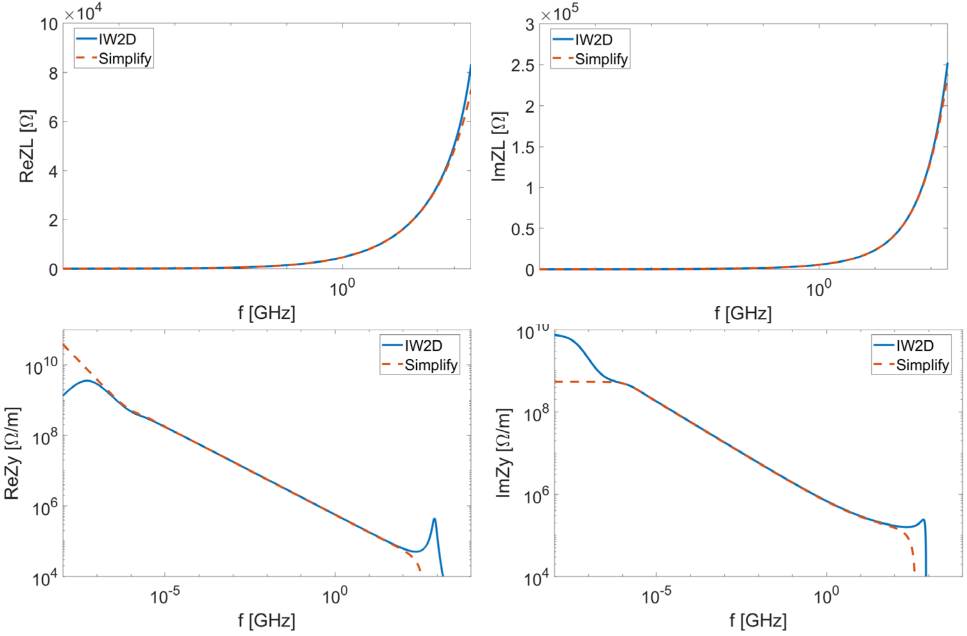
$$Z_{\parallel}^{RW}(\omega)=\frac{iZ_0 c k_r}{2\pi\omega a_2}\frac{I_0(k_r a_1)I_0(k_r r)}{I_0(k_r a_2)}\left[\frac{\kappa M}{\kappa M I_1(k_r a_2)+I_0(k_r a_2)}\right]$$

$$Z_{T}^{RW}(\omega)=\frac{iZ_0 c k_r^2}{\pi k\omega}\frac{I_1(k_r a_1)I_1(k_r r)}{a_1 r}\left[\frac{p_{s1}}{q_{s1}}\frac{K_1(k_r a_2)}{I_1(k_r a_2)}\right]$$

Simplified formulas are derived for coated metallic chamber:

$$Z_{\parallel,rw}(\omega)=\frac{Z_0}{2\pi c}\left[\frac{\delta_2\mu_2\omega[\mathrm{sgn}(\omega)-i]}{2a_2\mu_0}\times\frac{\alpha\tanh(x_1)+\tanh(x_2)}{\alpha+\tanh(x_1)\tanh(x_2)}\right],$$

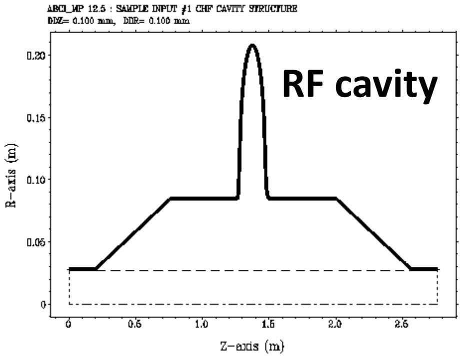
$$Z_{\perp,rw}(\omega)=\frac{4-k_r^2a_2^2}{\sqrt{(\omega^2/c^2+k_r^2)}}\frac{1-i\mathrm{sgn}(\omega)}{4\pi a_2^3\delta_2\sigma_2}\times\frac{1+\alpha\tanh(x_1)\tanh(x_2)}{\alpha\tanh(x_2)+\tanh(x_1)}$$

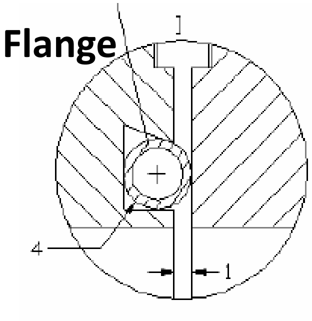


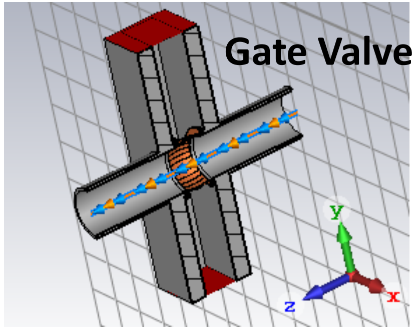
Benchmark of the simplified formula with ImpedanceWake2D and shows excellent agreements in the frequency range of interest

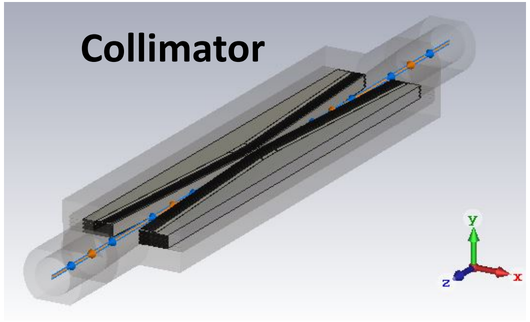
Geometrical impedance

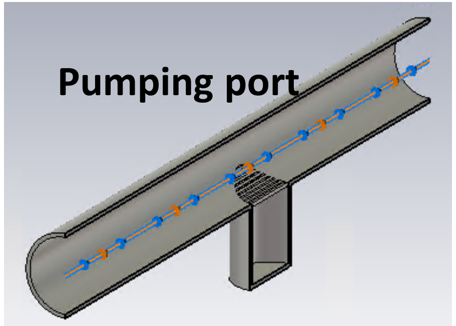
- Main vacuum components considered in the impedance model

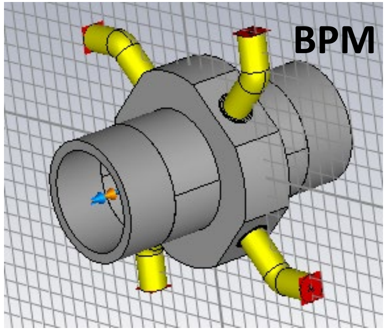


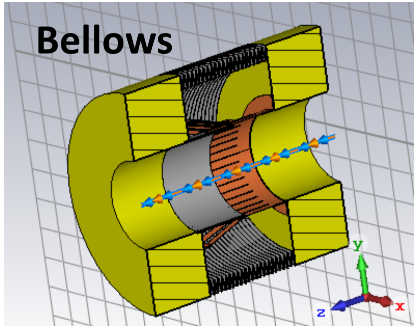


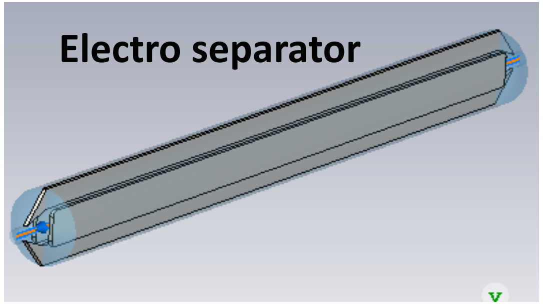




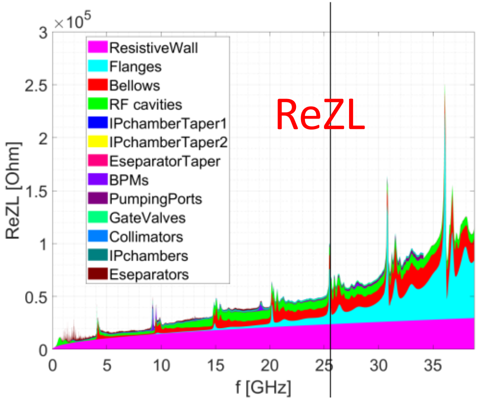


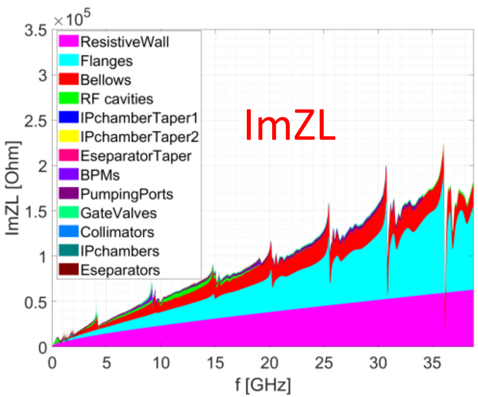


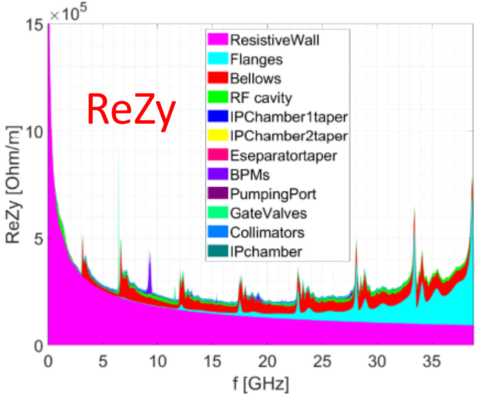


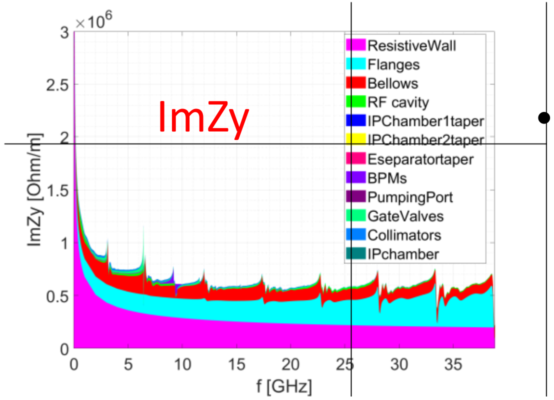


Impedance model









- Resistive wall, flanges, and bellows dominates the longitudinal and transverse broadband impedances.
- Inj./ext. elements, feedback kickers, absorbers, masks and collimators outside the IR region are not included yet.
- The impedance model will be continuously updated along with the development of the hardware designs.

Impedance budget @σ_z=3mm

Components	Number	$Z_{\|\|}/n$, mΩ	k_{loss}, V/pC	k_y, kV/pC/m
Resistive wall	-	6.2	363.7	11.3
RF cavities	60	0.5	101.2	0.5
Flanges	37714	5.2	37.3	5.2
BPMs	1808	0.04	9.5	0.2
Bellows	15949	2.9	87.4	3.9
Gate Valves	500	0.2	14.5	0.4
Pumping ports	5316	0.3	2.3	0.2
Collimators	16	0.04	23.4	0.6
IP chambers	2	0.004	0.3	0.05
Electro-separators	20	-0.1	34.5	0.1
Taper transitions	48	0.04	2.5	0.09
Total		**15.3**	**676.6**	**22.5**
CDR Total		**11.4**	**786.8**	**20.2**

- Longitudinal and transverse broadband impedances are dominated by the RW, flanges and bellows.
- The loss factor is mainly contributed by the resistive wall, RF cavities and bellows.
- Compare to the CDR budget, we have larger Z/n and k_y, but smaller k_{loss}.

Rough instability estimations

- Preliminary estimation of the instability threshold based on analytical criterions.

	Higgs	W	Z	ttbar
Single bunch (longitudinal) $Z_{\|\|}/n$ [mΩ]	6.5	4.1	0.7	14.4
Single bunch (transverse) k_y [kV/pC/m]	69.7	40.2	12.4	109.8
Multi-bunch SR(longitudinal) $f\mathrm{Re}Z_{\|\|}e^{-(2\pi f\sigma_l)^2}$ [GHz·GΩ]	4.5	0.1	6.5E-4	171.2
Multi-bunch SR (transverse) $\mathrm{Re}Z_y e^{-(2\pi f\sigma_l)^2}$ [GΩ/m]	3.0	0.08	8.9E-4	72.7

Impedance budget	
$Z_{\|\|}/n$, mΩ	15.3
k_y, kV/pC/m	22.5

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Impedance budget	
$Z_{\|\|}/n$, mΩ	15.3
k_y, kV/pC/m	22.5

- The longitudinal impedance above the threshold of Higgs, W, Z ⇒ bunch lengthening, energy spread increase, synchrotron tune shift and spread
- Although the criterion usually underestimates the instability threshold, we do observed its influence on the beam-beam interaction [PRAB 23, 104402 (2020); PRAB 25, 011001 (2022)].

Rough instability estimations

- Preliminary estimation of the instability threshold based on analytical criterions.

	Higgs	W	Z	ttbar
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Impedance budget	
$Z_{\|\|}/n$, mΩ	15.3
k_y, kV/pC/m	22.5

- The transverse impedance above the threshold of Z ⇒ TMCI unstable (fast instability, normally with beam losses)

Rough instability estimations

- Preliminary estimation of the instability threshold based on analytical criterions.

	Higgs	W	Z	ttbar
Single bunch (longitudinal) $Z_{\|\|}/n$ [mΩ]	6.5	4.1	0.7	14.4
Single bunch (transverse) k_y [kV/pC/m]	69.7	40.2	12.4	109.8
Multi-bunch SR(longitudinal) $f\mathrm{Re}Z_{\|\|}e^{-(2\pi f \sigma_l)^2}$ **[GHz·GΩ]**	**4.5**	**0.1**	**6.5E-4**	**171.2**
Multi-bunch SR (transverse) $\mathrm{Re}Z_y e^{-(2\pi f \sigma_l)^2}$ **[GΩ/m]**	**3.0**	**0.08**	**8.9E-4**	**72.7**

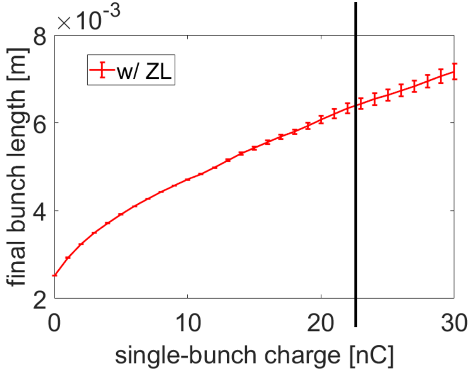
  - Tight narrowband impedance requirements for Z (at least ~two orders higher for the other energies) ⇒ HOMs need to be well controlled to meet the requirements from Z

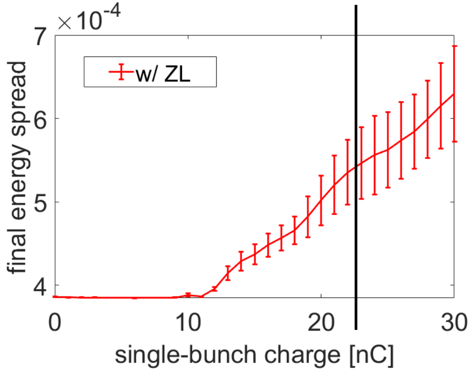
Instability issues for Z

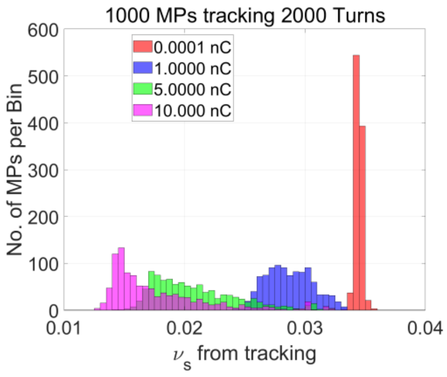
- Microwave instability
- Transverse mode coupling instability (TMCI)
- Cross talk between ZT and beam-beam
- Mitigation with impedance optimization
- Transverse resistive wall instability
- Beam ion instability

Microwave instability

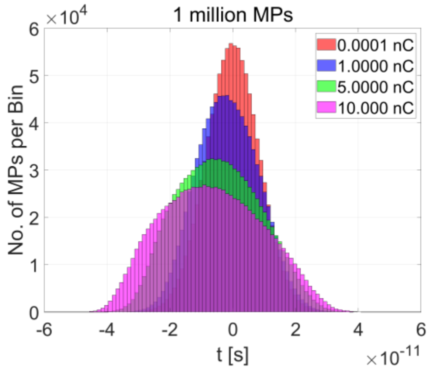
- Longitudinal broadband impedance will induce bunch lengthening/distortion, beam energy spread, as well as synchrotron tune shift & spread.







- With bunch lengthening and energy spread increase due to beamstrahlung, the perturbation induced by the impedance will be mitigated.
- On the other hand, the impedance will further influence the beam-beam interaction. Consistent simulations including beam-beam and impedance can be found in Yuan Zhang's talk.

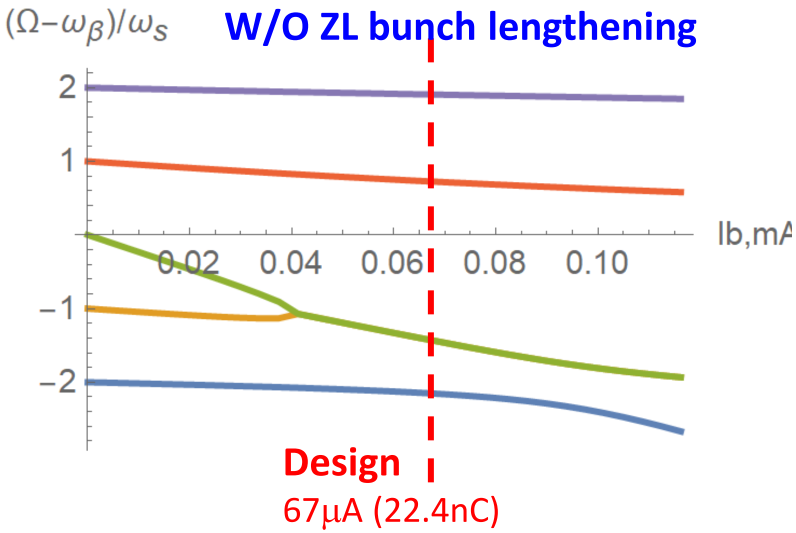


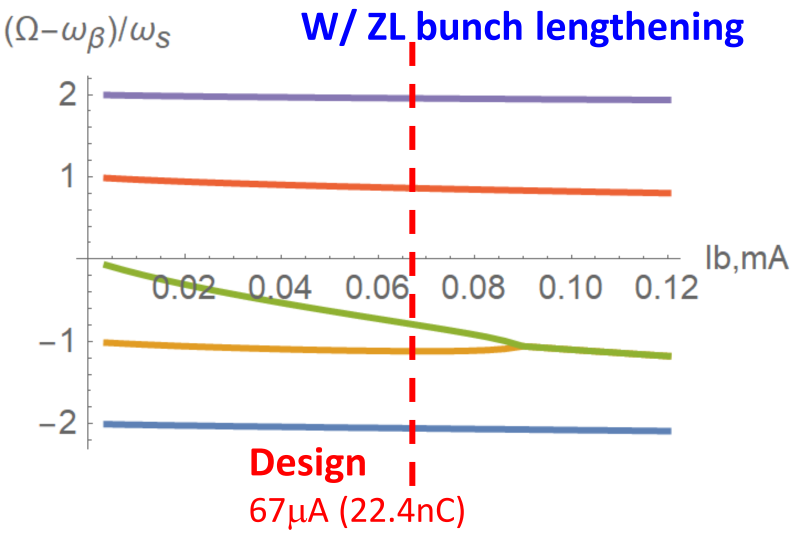
Transverse mode coupling instability

- Main constraint on the single bunch current.
- The instability is investigated in three different ways
  - Analytical estimation with classical vlasov solver
    - Mode analysis with and without impedance induced bunch lengthening
  - Macro particle simulations
    - Study the transverse beam dynamics more consistently including the longitudinal impedance
  - Analytical estimation considering the longitudinal perturbations
    - Mode analysis with perturbations from longitudinal impedance, as well as lengthened bunch from beamstrahlung.

Analytical estimations with lengthened bunch

- Analytical estimations show that threshold current will increase when consider impedance bunch lengthening. The instability is supposed to be further detuned if consider the further bunch lengthening due to the beamstrahlung. **However ….**

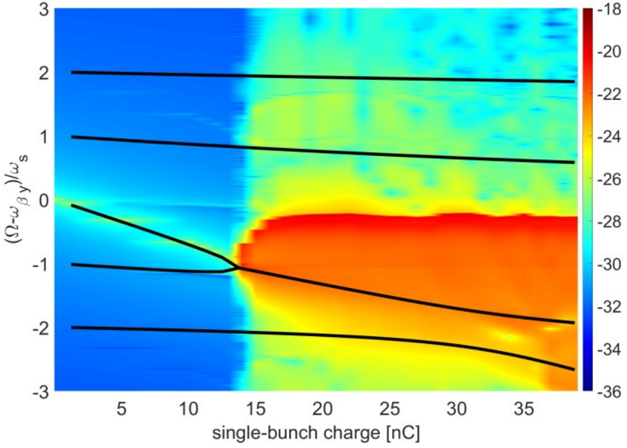




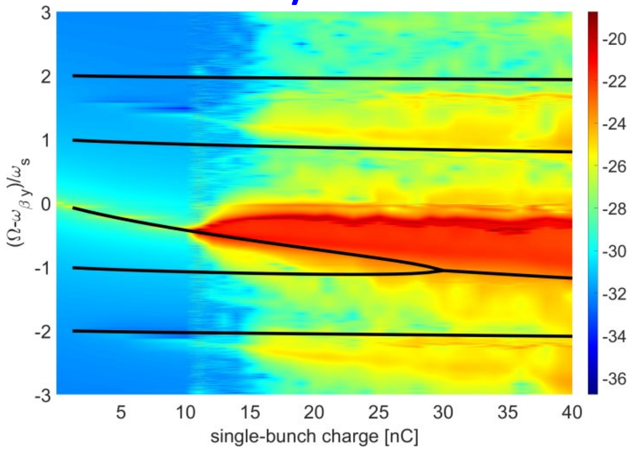
Simulations on TMCI with longitudinal impedance

- Particle tracking simulations performed with Elegant shows that the TMCI get more unstable when including the longitudinal impedance.
  - Without ZL: TMCI threshold→14nC (consistent between simulation and theory)
  - With ZL: TMCI threshold →10nC (much lower than the theoretical estimation only with bunch lengthening: 30nC, shift of the mode 0 below the threshold still consistent)

W/O ZL

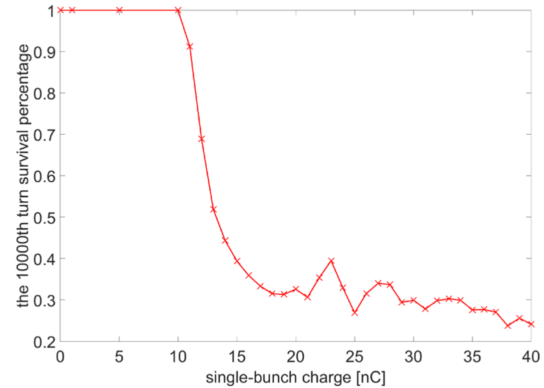


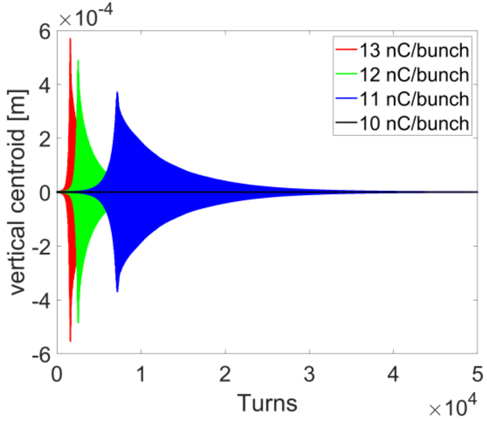
W/ ZL

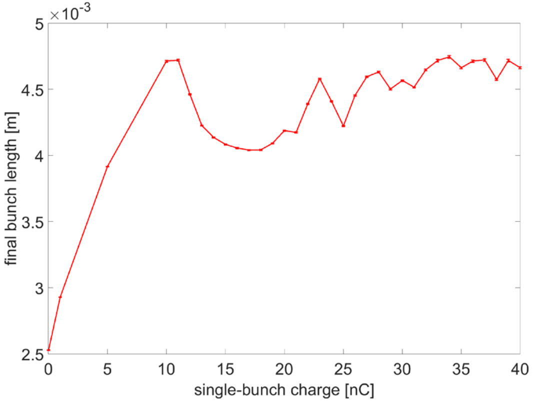


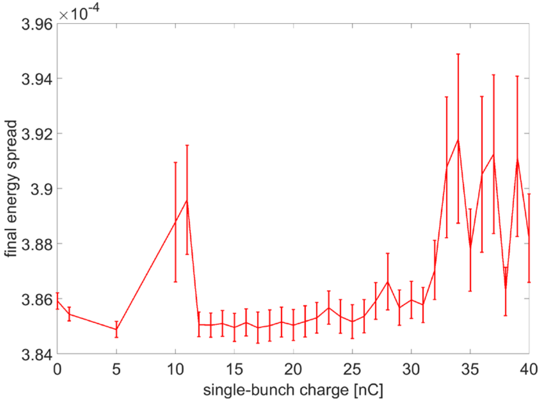
Detail analysis on simulations

- Apparent beam losses are observed above 10nC (6.2E10) with ZL.
  - Transverse centroid oscillations are observed above threshold
  - Bunch length and beam energy spread are crashed due to the sudden beam loss
  - The instability is suspected to be induced by the enhanced mode coupling due the smaller synchrotron tune and the deformed tune spread.



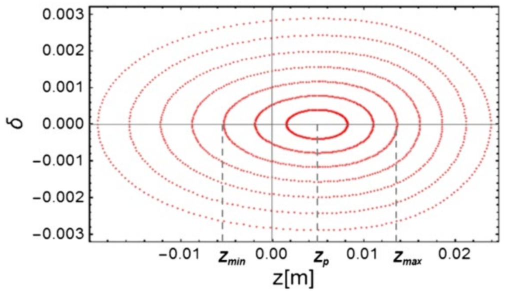






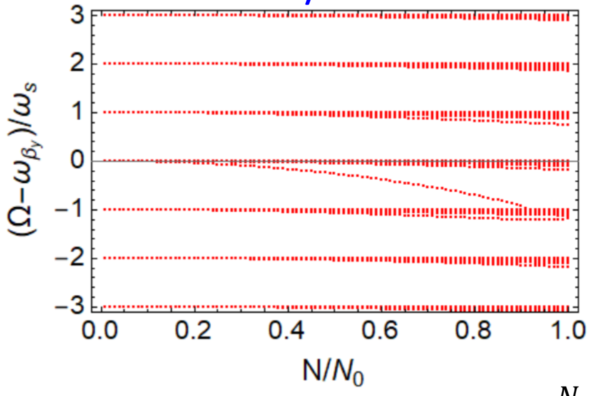
Mode analysis with longitudinal impedance

- ☐ Including the longitudinal perturbance in mode analysis
- ☐ Considering longer bunch with beamstrahlung.
  - ◆ TMCI threshold without ZL is increased due to lengthened bunch; Including ZL, the higher order modes shift to mode 0 with wider bandwidth, and TMCI threshold is decreased.

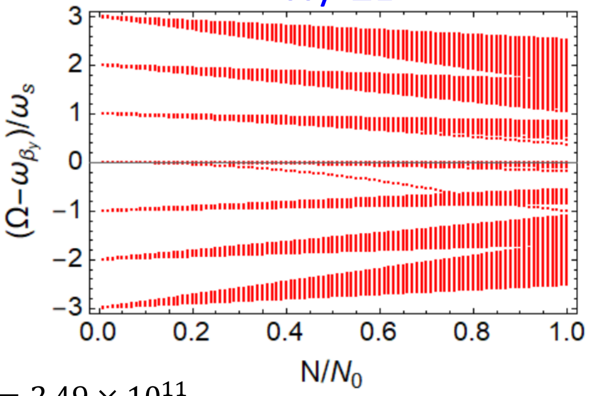


PRAB 25, 011001 (2022)

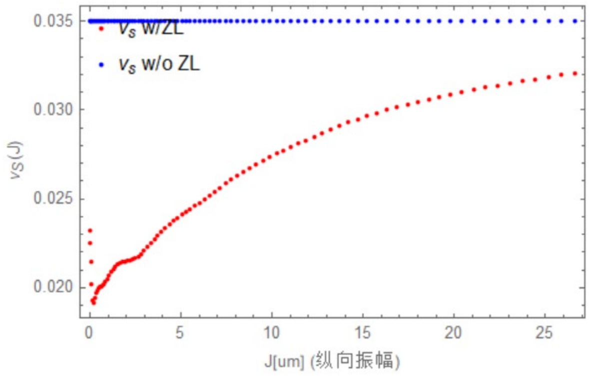
W/O ZL



W/ ZL



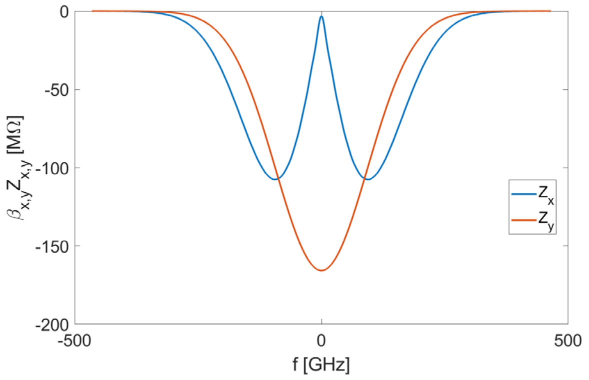
$N_0 = 2.49 \times 10^{11}$



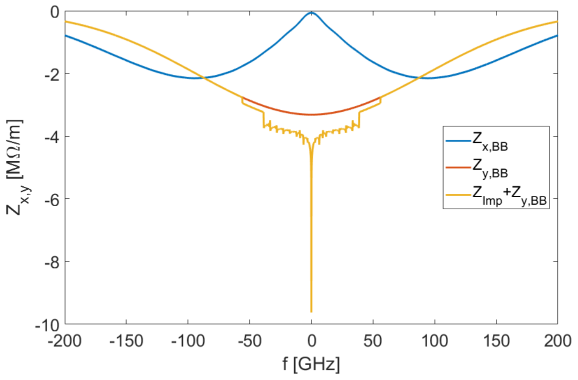
Influence of cross-wake force on TMCI

- Transverse impedance also has an impact on the beam-beam interaction. Consistent simulation studies including beam-beam, ZL and ZT can be found in Yuan Zhang's talk.
- Preliminary analytical studies are performed
  - Vertical Cross Wake force are derived in a similar way as to the horizontal case
  - Numerical estimations are given based on the CEPC parameters $\Rightarrow$ The vertical beam-beam impedance can be treated as a constant imaginary impedance, like the space charge impedance, in the frequency range of interest
  - Beam-beam impedance is included in the total ring impedance budget

Beam-beam impedance:

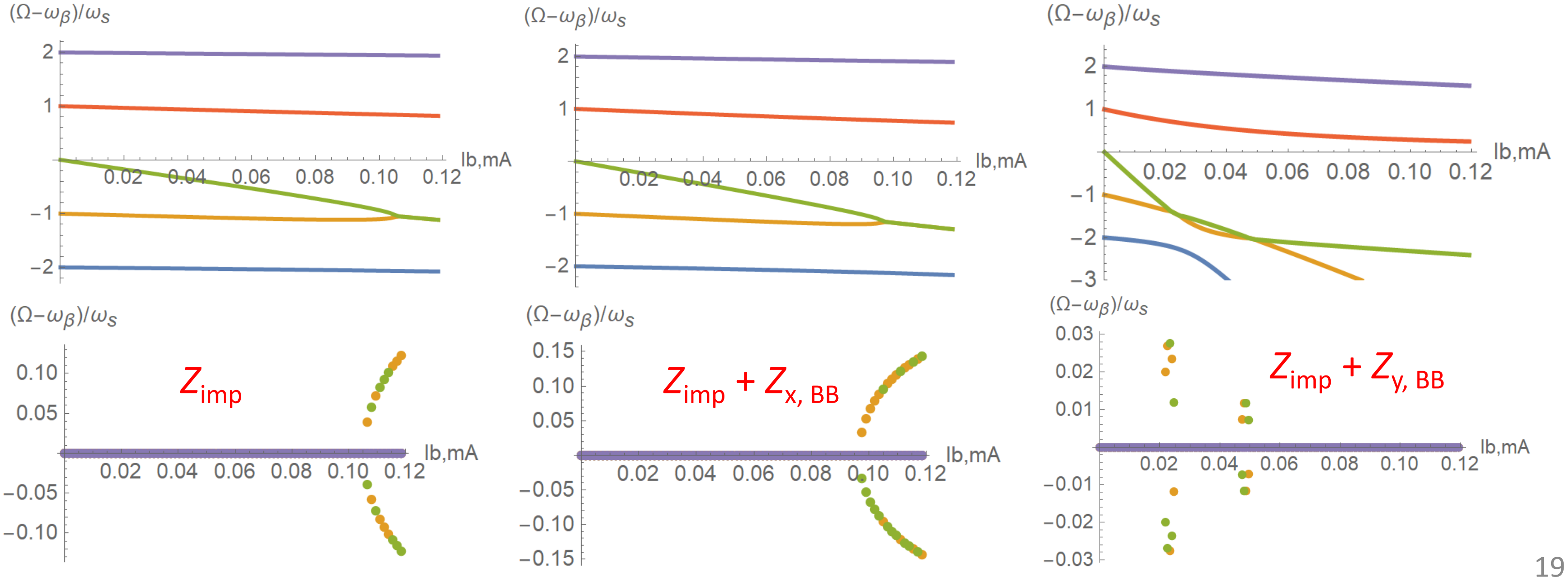


Compare with ring impedance:



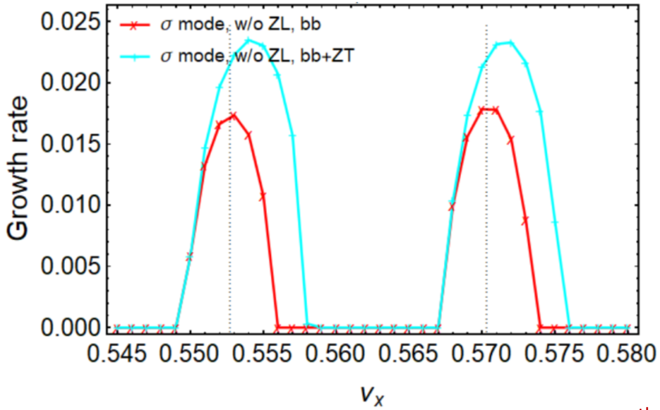
Influence of cross-wake force on TMCI

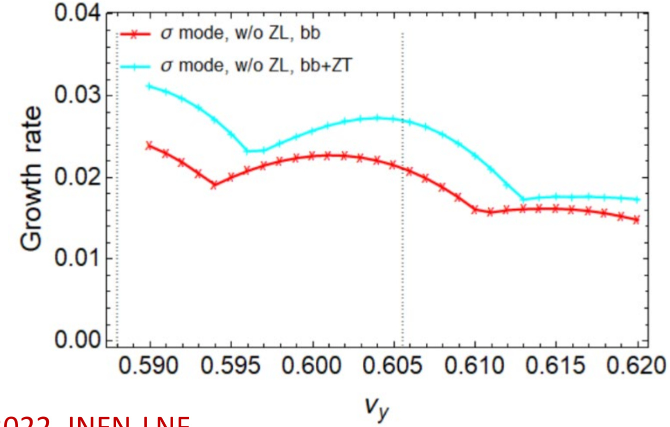
- Conventional TMCI analysis is performed with beam-beam impedance included:
  - With only ring beam coupling impedance and lengthened bunch, the TMCI threshold is ~22×10^{10}.
  - Including the horizontal BB impedance, the threshold reduced to 20×10^{10} (↓9%)
  - Including the vertical BB impedance, the threshold reduced to 4.5×10^{10} (↓80%)



Cross talk between ZT and beam-beam

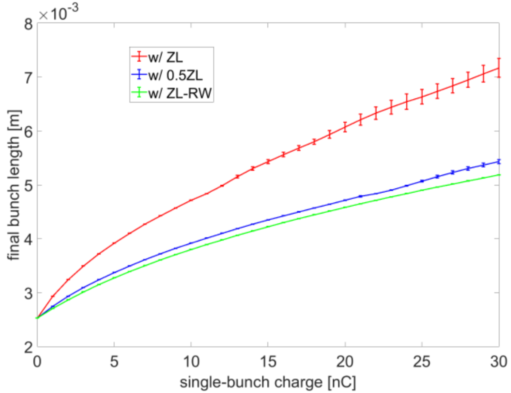
- Local beam-beam model
  - In horizontal direction: combined effect of X-Z instability and TMCI
    - Instability growth rate gets faster + unstable tune area increases
  - In vertical direction: TMCI like instability
    - Pure beam-beam is unstable due to ignorance of strong nonlinearity?
    - It is also found enhance of instability when considering ZY
  - More detailed studies are undergoing.

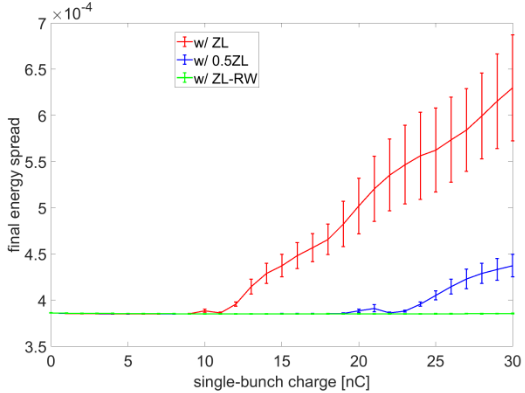


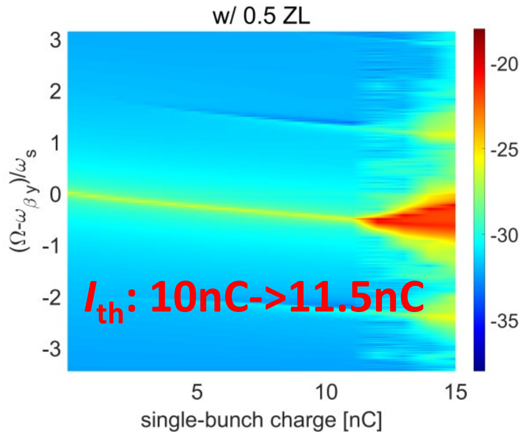


Mitigation with impedance optimization

- Longitudinal impedance reduce TMCI threshold as well as the stable beam beam interaction region (Yuan Zhang and Chuntao Lin's talks) ⇒reduce the longitudinal perturbation
  - Larger momentum compaction and synchrotron tune
  - **Lower longitudinal impedance** (transverse impedance normally decreases accordingly, but with less bunch lengthening)





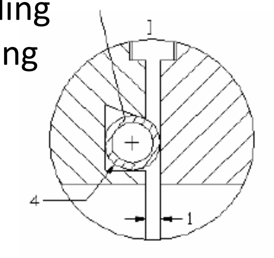


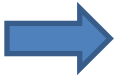
Transverse impedance unchanged

Possible impedance optimizations

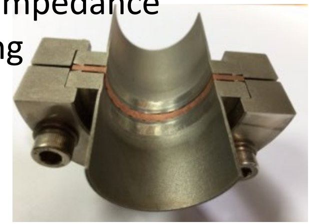
- Flanges and bellows takes more than 40% of the total broadband impedance budget.
- Detailed simulations on the mitigation of the TMCI and beam-beam interaction with the reduced impedance model is under study.

RF shielding with spring

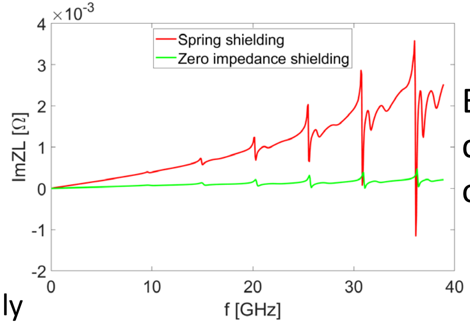




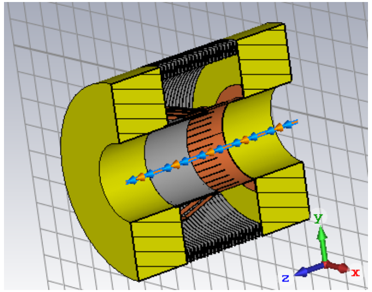
"zero" impedance shielding

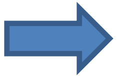


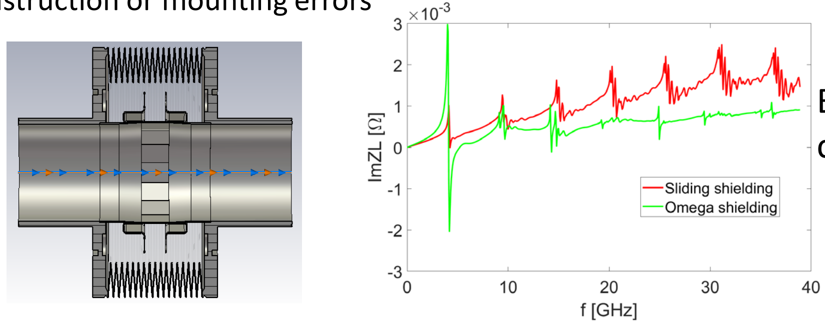
Test model in HEPS: impedance is mainly given by construction or mounting errors



Broadband impedance can be reduced to ~1 order smaller.







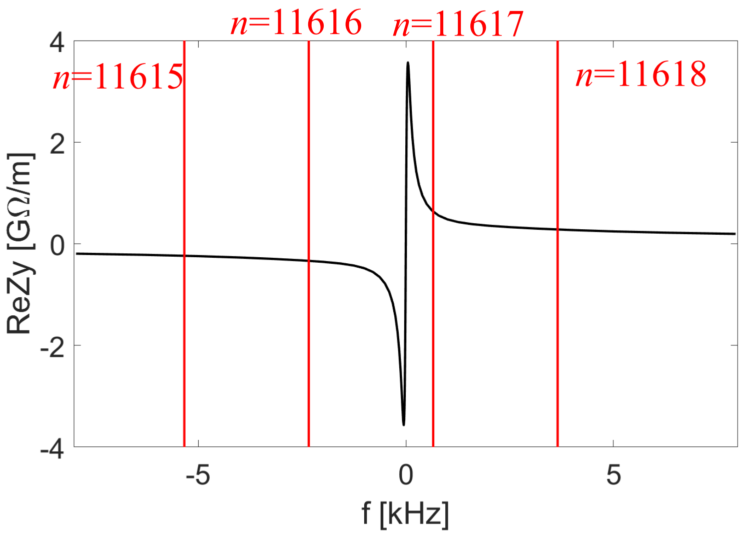
Broadband impedance can be reduced by half.

Transverse resistive wall instability

- Instability growth rate much faster than the synchrotron radiation damping (τ=850ms).

$$\tau^{-1} = \frac{I_0 c_0}{4\pi(E_k/e)\nu_\beta} \sum_{\mu=0}^{M-1} \sum_{p=-\infty}^{\infty} Z_1\left((\mu + PM)\omega_0 + \omega_\beta\right)$$

f [kHz]	Mode index	Growth *t* [ms]
-2.338	11616	2.2 (7 turns)
-5.335	11615	3.2 (10 turns)
-8.332	11614	4.0 (12 turns)
-11.330	11613	4.6 (14 turns)

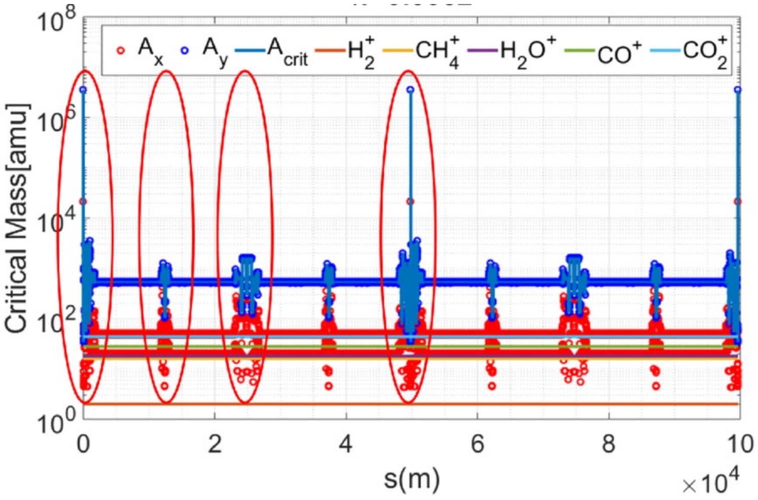


- Tough requirement on feedback damping (broadband feedback + mode feedback?)

Beam ion instability

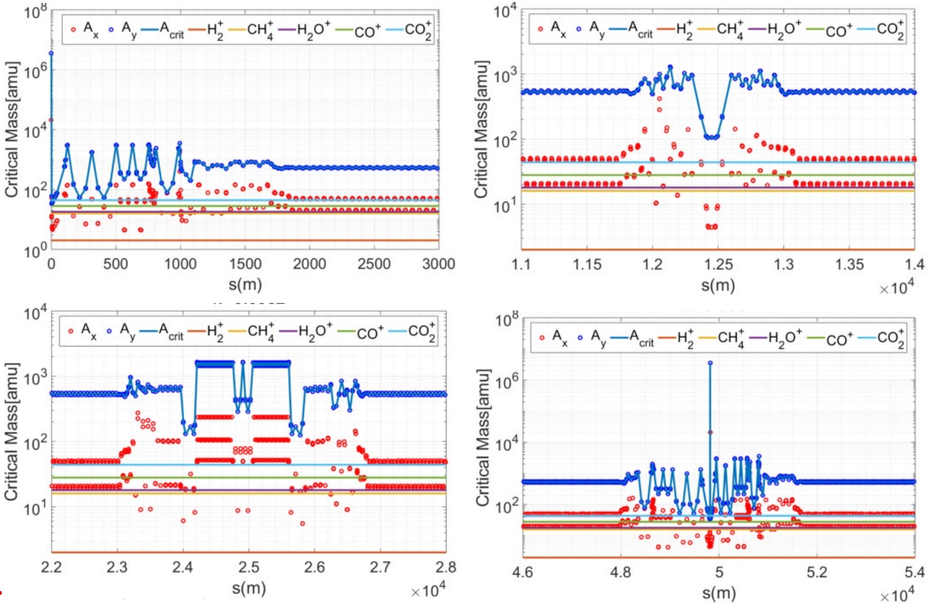
- Trapped ions can induce bunch centroid oscillation and emittance growth.
- The possibility of ion trapping and fast beam ion instability are investigated.

Ions with relative molecular mass larger than critical mass $A_{x,y}$ will be trapped.



eeFACT2022, Sep.

Only CO^+ will be trapped around IP with large beta function β_y. (Percent of lattice<0.1%)

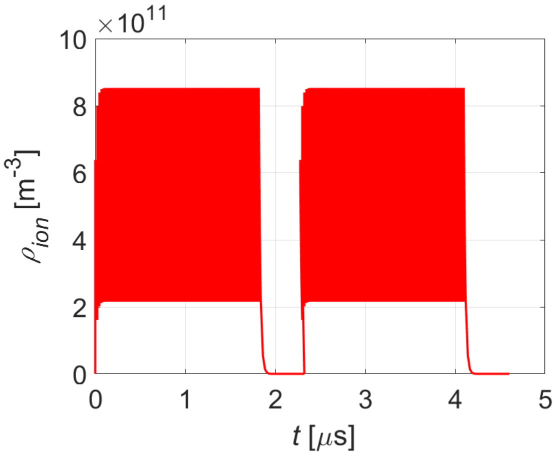


Fast beam ion instability

- Multi bunch train filling pattern are suggested

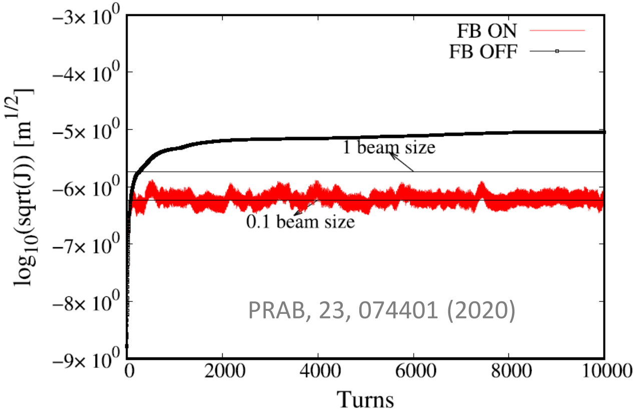
  {Ntrain=149, Bunch spacing=23ns, Gap=410ns}

Analytical estimations: *P*=1nTorr, CO only
Ion damping during the bunch space is considered



Build-up of ions along the bunch train

Parameters	Z-30MW
$L_{sep}\omega_{ion}/c_0$	0.8
$\rho_{ion,ave}$[m^{-3}]	4.3E11
τ_e [ms]	0.1
τ_H [ms]	4.0
$\Delta\nu_y$	0.016



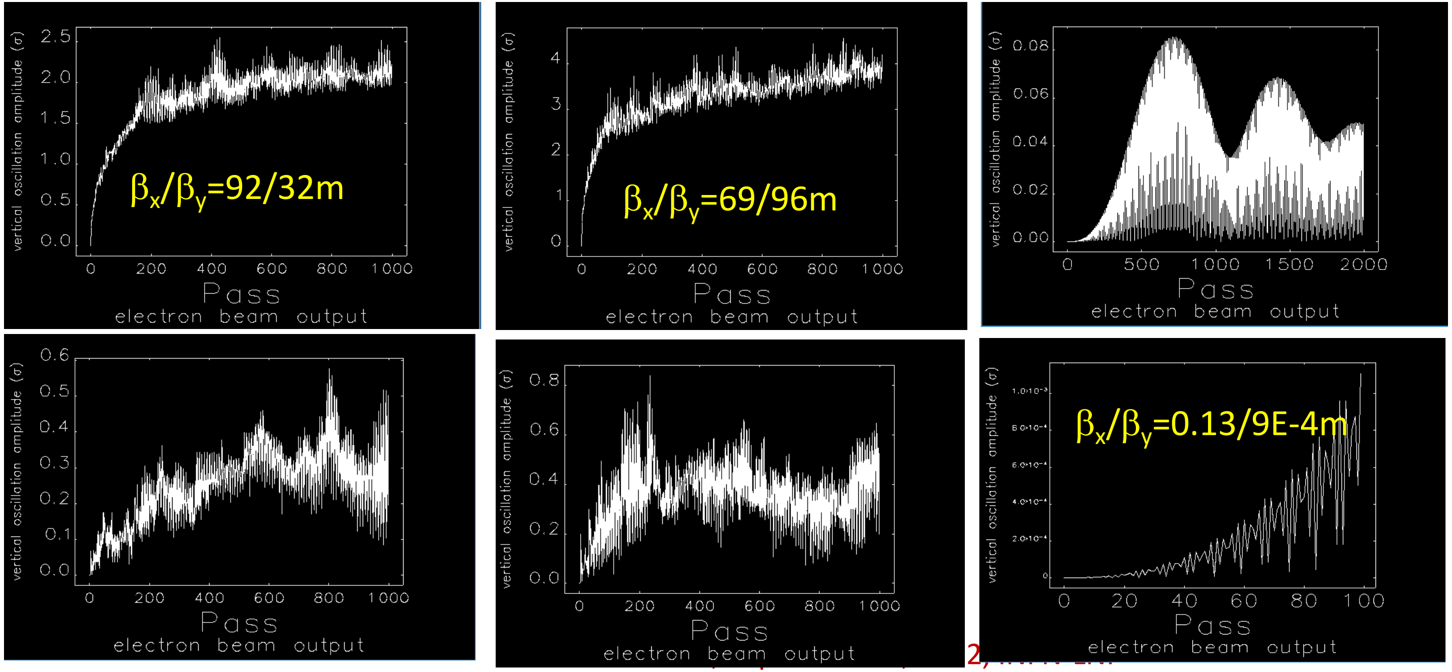
Bunch by bunch feedback can be effective on damping this effect

Fast beam ion instability

- Particle tracking simulations with uniform filling and multi-train filling
  - Although multi-train filling is effective in mitigating the beam ion instability, emittance growth is still foreseen.

uniform

multi-train



Summary

- No apparent showstoppers from collective effects for Higgs, W (however, influence the stable beam-beam tune area.)
- Main constraints for Z include:
  - TMCI threshold is bellow the design current when including both longitudinal and transverse impedance in tracking simulations, more detailed analysis on exploring the physics underline and possible mitigations are ongoing.
  - Preliminary analytical studies show crosstalk between transverse impedance and beam-beam interaction.
  - Tough requirement on feedback damping is given by TRWI.
  - Beam ion instability needs to be damped by multi-train filling and bunch-by-bunch feedback.
  - Collective effects studies need to get more involved with beam-beam and hardware designs.

Thank you for your attention!