中国科学院高能物理研究所
Institute of High Energy Physics
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Collective effects studies in CEPC

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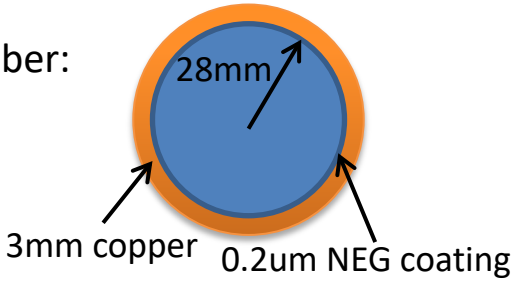
Outline

- Impedance modeling
- Rough instability estimations
- Instability issues for Z
- Beam ion effects

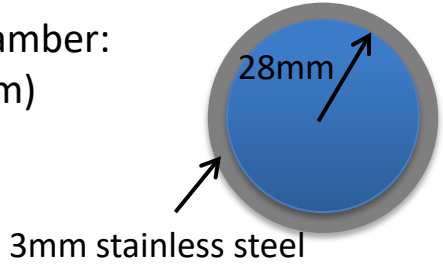
Impedance modeling

- **Resistive wall**
  - Including main chamber, MDI chamber, collimators in the IR region and stainless steel chamber (flanges, bellows, BPMs)

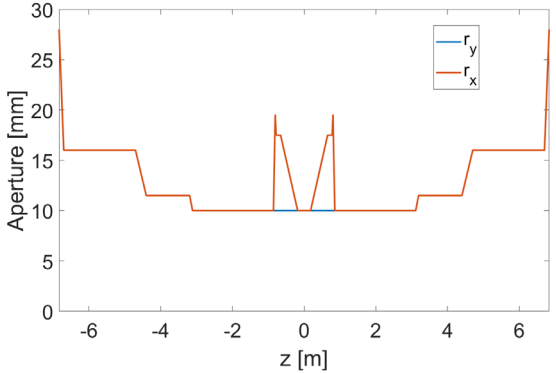
Main chamber:
(L=97km)



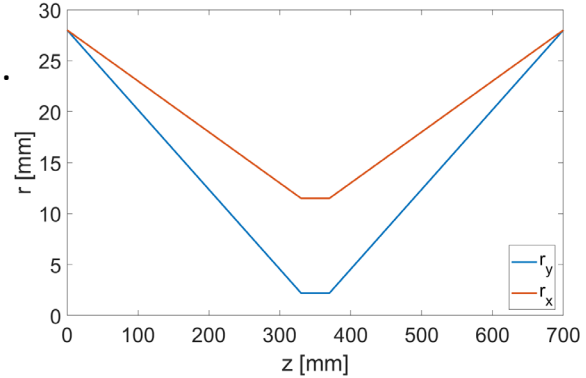
SS chamber:
(L=3km)



MDI chamber:



Collimator:
10 hori.+8 vert.



Resistive wall impedance

- Multi-layer analytical formula is used
- Form factors are considered for non-axialsymmetry chambers.

PRST-AB 10, 111003 (2007)

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

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

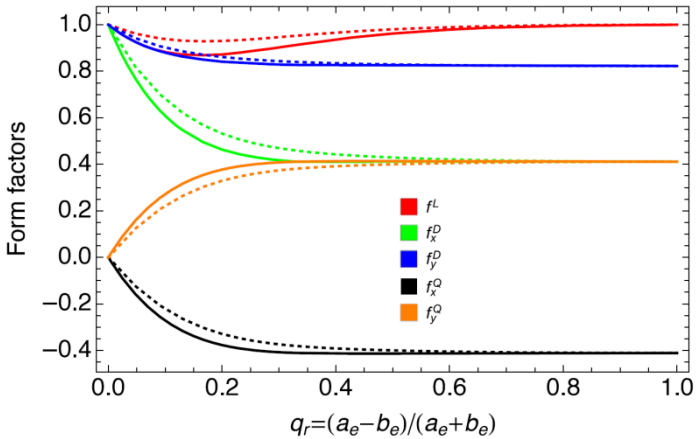
- RW of taper with aspect ratio of θ:

Assume ZL ∝ 1/r, ZT ∝ 1/r^3, the impedance is RW of unit length at smaller radius r_1 multiplied by the following factors:

$$f_{||}^{RW} = \frac{r_1}{\tan\theta} \log(1 + L/r_1 \tan\theta)$$

$$f_T^{RW} = \frac{r_1}{2} \frac{2r_1/L + \tan\theta}{(r_1/L + \tan\theta)^2}$$

NIM-A 1037, 166928 (2022)

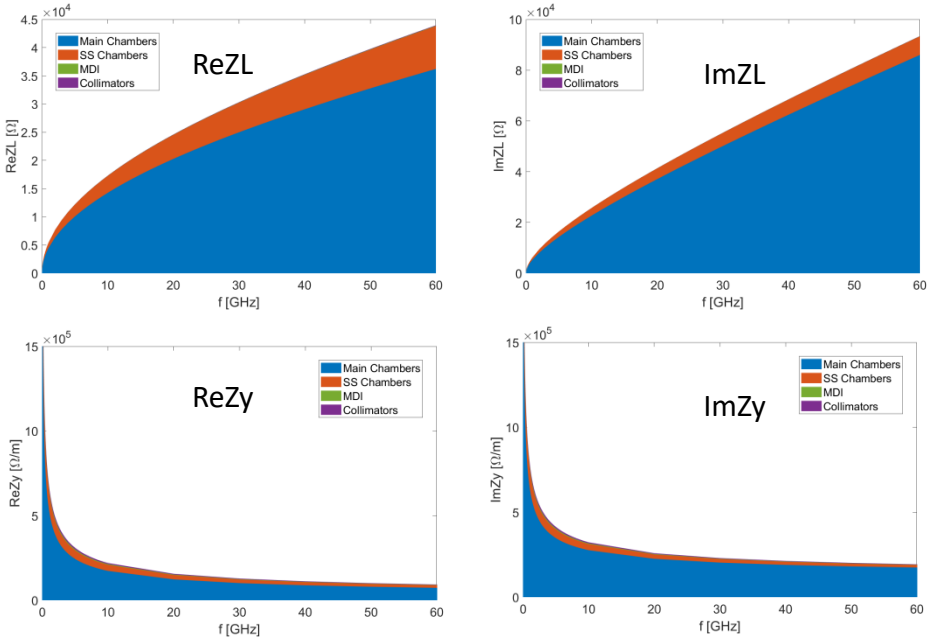


Resistive wall impedance

- Transverse impedance has been normalized by the local beta functions.
- The impedance contributed by the main chamber dominates both the longitudinal and transverse RW impedance.

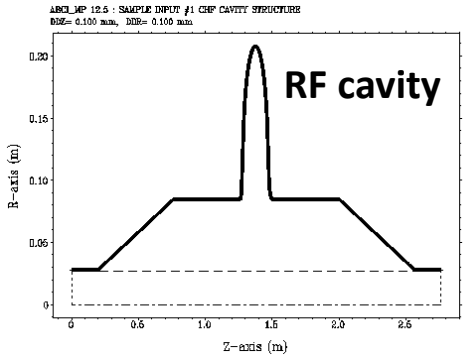
Broadband effective impedance @σ_z=3mm
Average betatron function for each transition has been used

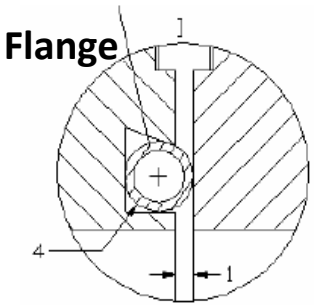
Components	$Z_{\|\|}/n$, mΩ	k_{loss}, V/pC	k_y, kV/pC/m
Main chamber	6.0	350.7	10.9
SS chamber	0.7	73.4	1.6
MDI chamber	6.9E-3	0.7	0.2
Collimators	8.9E-3	0.9	0.3
RW Total	6.7	425.6	13.8
Ring Total	**15.9**	**741.4**	**33.8**

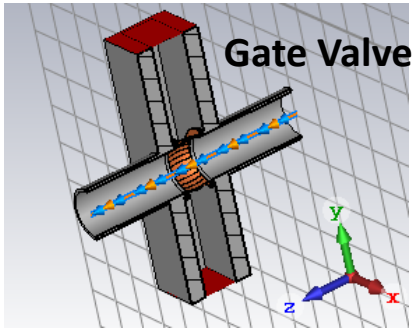


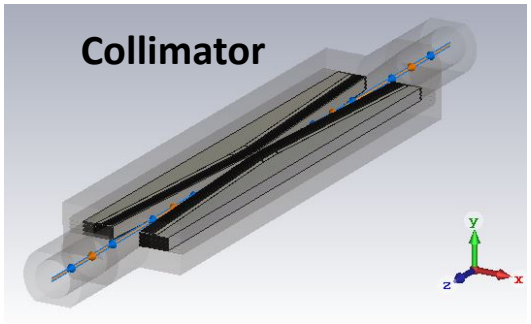
Geometrical impedance

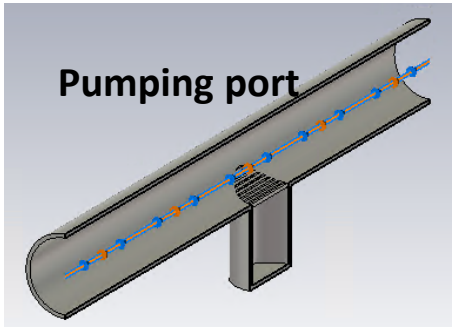
- Main vacuum components considered in the impedance model

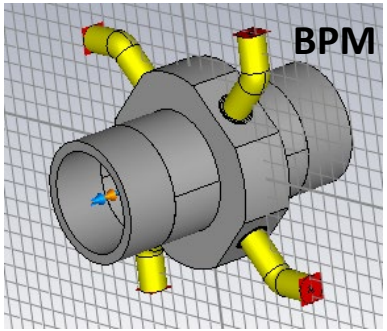


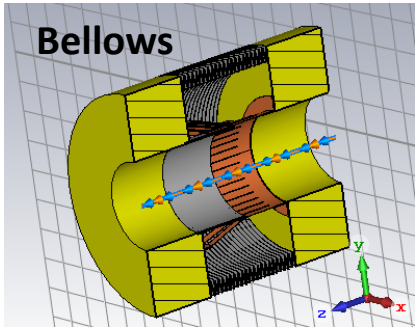


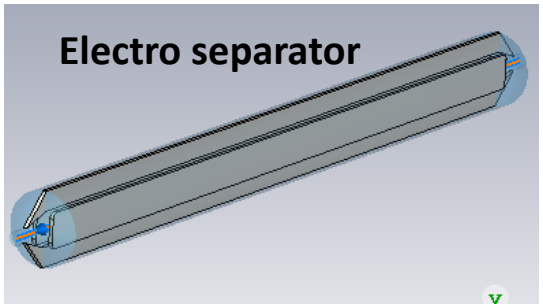




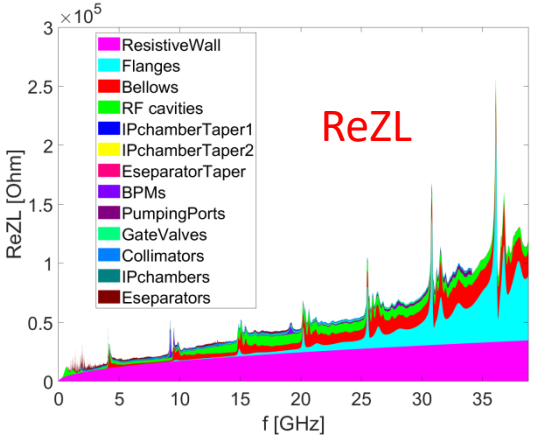


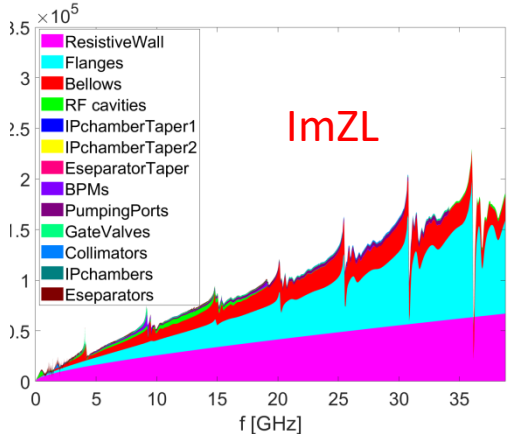


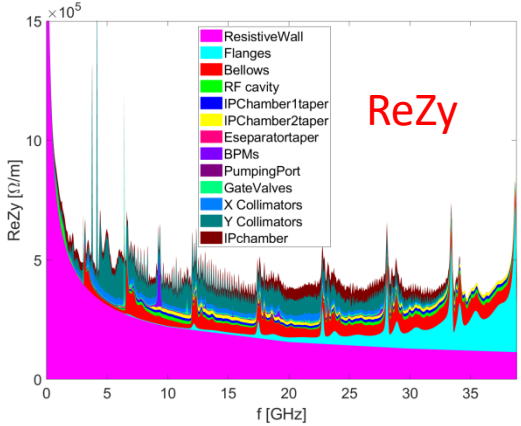


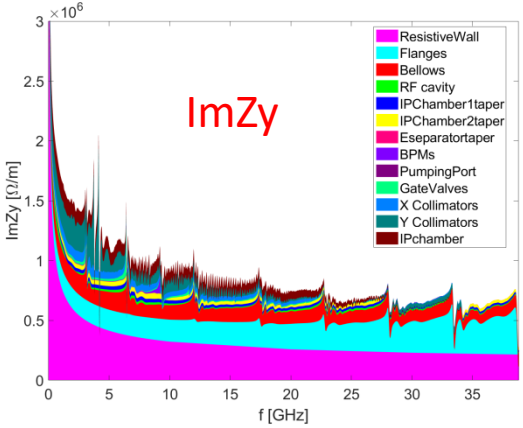


Impedance model









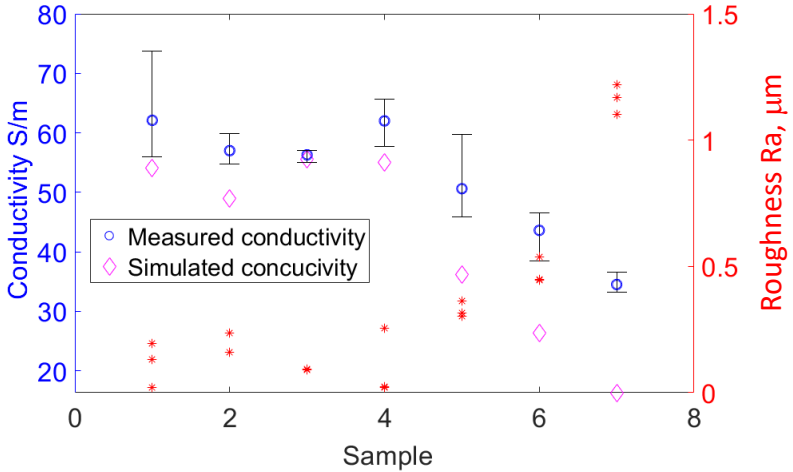
- The longitudinal broadband impedance is dominated by the RW, flanges and bellows.
- The transverse impedance is dominated by the RW, flanges, bellows and collimators.
- Inj./ext. elements, feedback kickers, absorbers, masks and collimators outside the IR region are still missing.
- The impedance model will be continuously updated along with the development of the hardware designs.

Conductivity measurement for the collimator jaw

- The baseline choice for the material of the collimators
  - Copper for the background collimators
  - Carbon for the machine protection collimators
- The conductivity is measured with resonant cavity at f_r=13GHz.

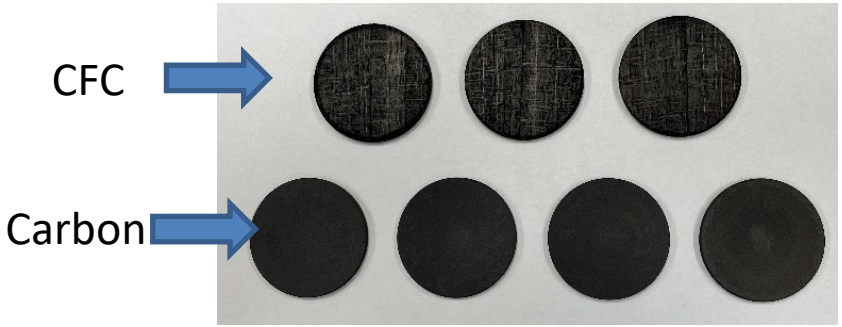
Conductivity of 7 copper sample with different surface conditions:

- σ_{DC}=57 MS/m
- The conductivity at high frequency has an inverse correlation with the surface roughness
- The results show reasonably good agreement with CST macro toolbox.



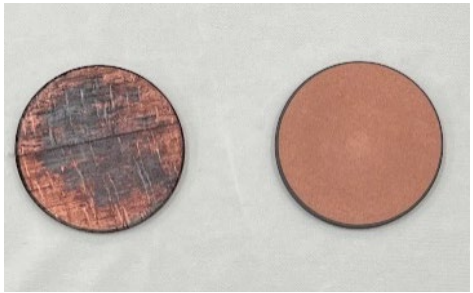
Conductivity measurement for the collimator jaw

- Influence of a layer of copper coating on the conductivity is also tested.

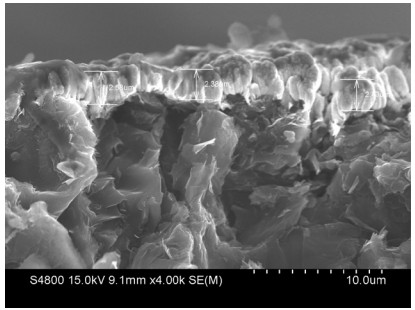


	Carbon	CFC
DC conductivity [MS/m]	0.1	0.2
W/O coating @13 GHz [MS/m]	0.04	0.05
With coating @13 GHz [MS/m]	2	0.3

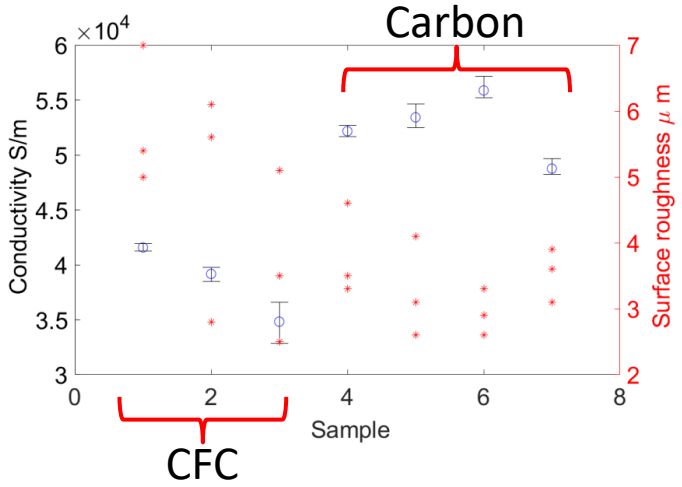
There are powder fell off when wipe the surface



Carbon + 2.5µm Copper coating



Measurement with SEM



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

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

Although the criterion usually underestimates the threshold, we do observed its influence on the beam-beam interaction [PRAB 23, 104402 (2020); PRAB 25, 011001 (2022)].

TMCI unstable

Impedance budget	
$Z_{\|\|}/n$, mΩ	15.9
k_y, kV/pC/m	33.8

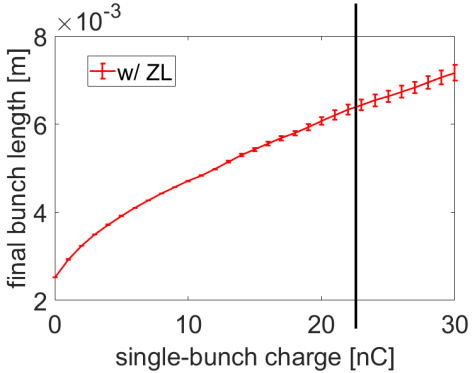
Tight narrowband impedance requirements for Z
(at least ~two orders higher for the other energies)

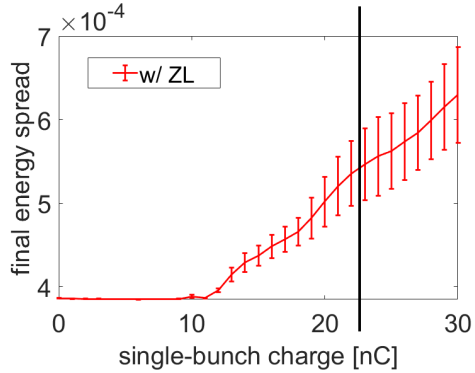
Instability issues for Z

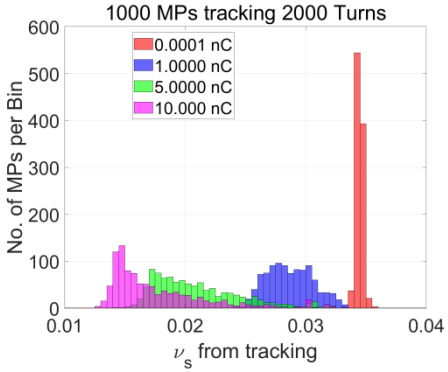
- Single bunch effect
  - Bunch lengthening and microwave instability
  - Transverse mode coupling instability (TMCI)
- Transverse resistive wall instability

Microwave instability

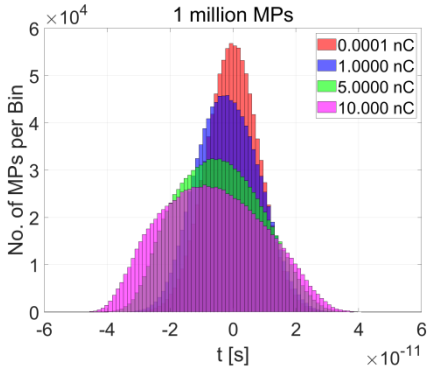
- Longitudinal broadband impedance will induce bunch lengthening/distortion, beam energy spread, as well as synchrotron tune shift & spread.







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

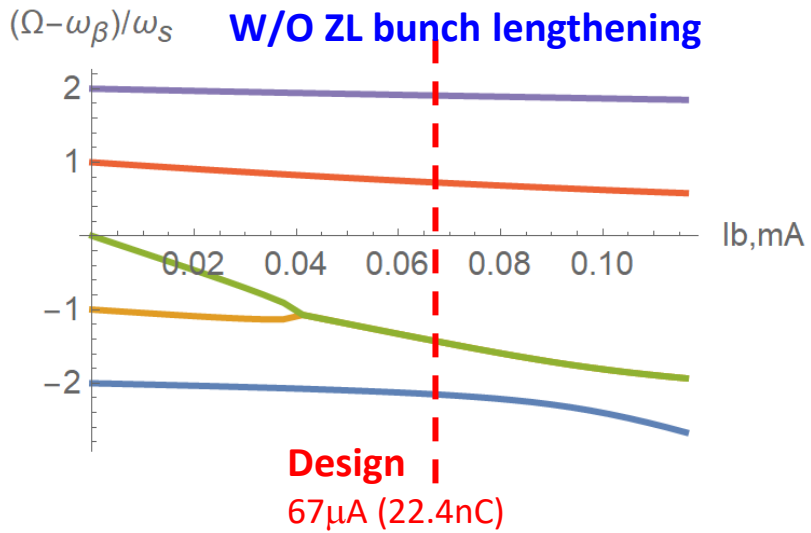


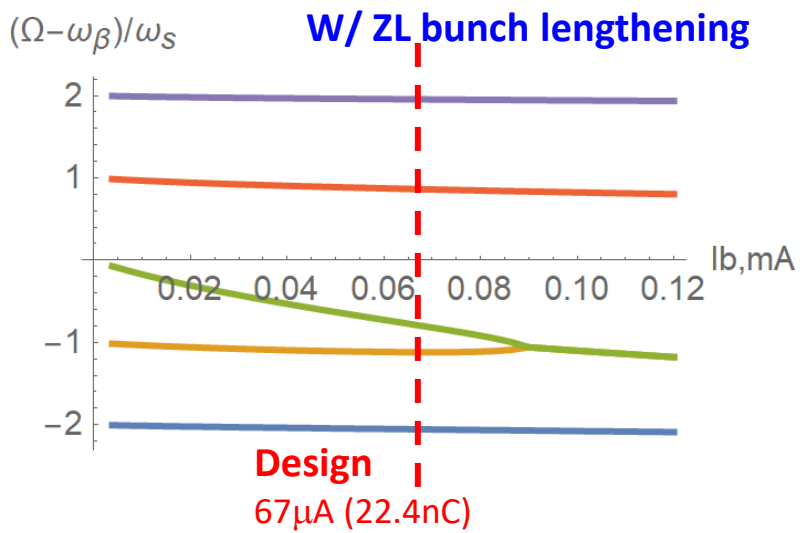
Transverse mode coupling instability

- 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 and mitigations
    - 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 ….**



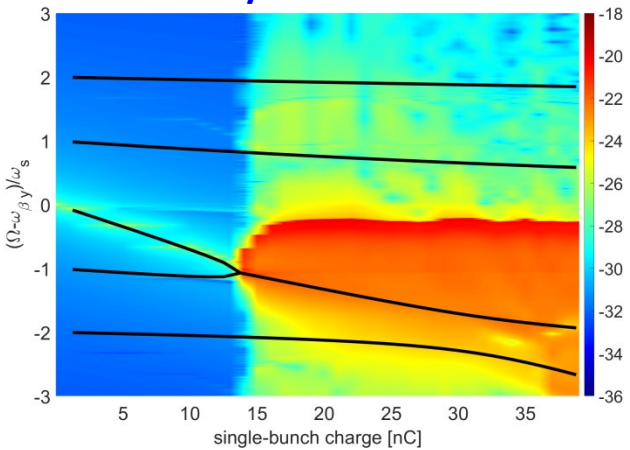


Simulations on TMCI with ZL

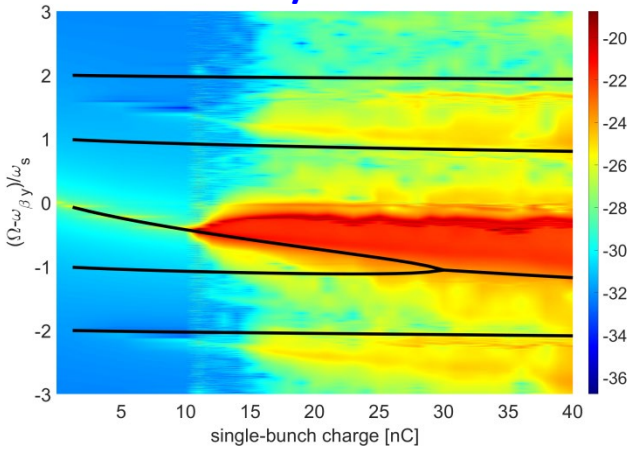
Haisheng Xu

- 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



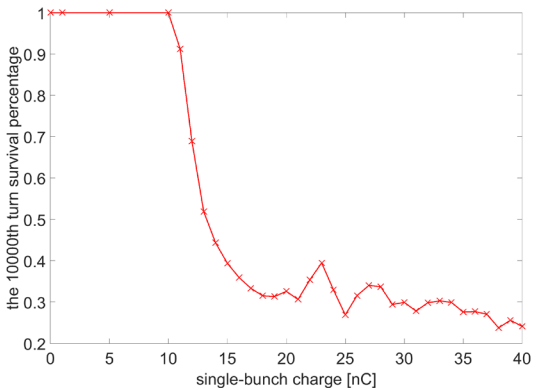
W/ ZL

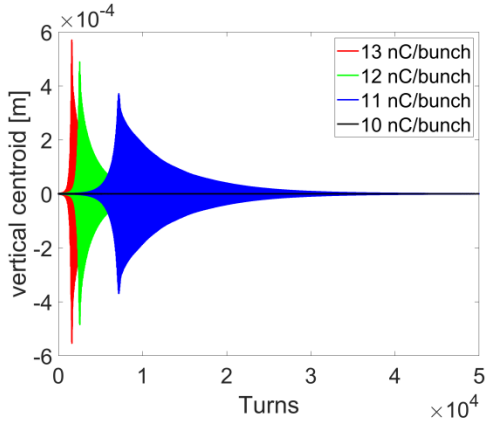


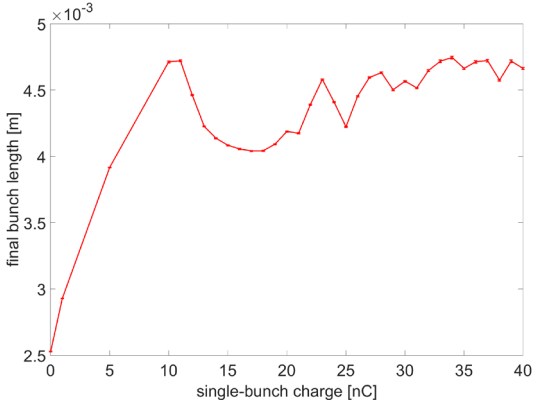
Detailed behaviors on beam dynamics

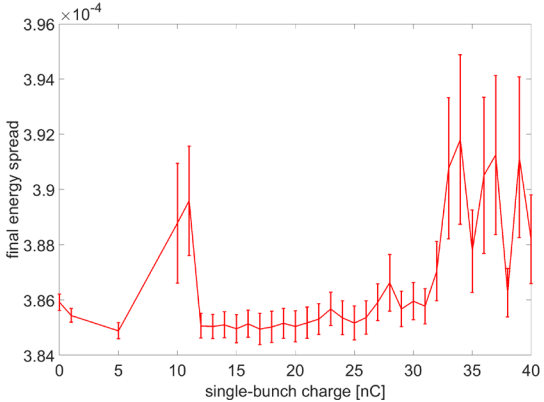
Haisheng Xu

- 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.





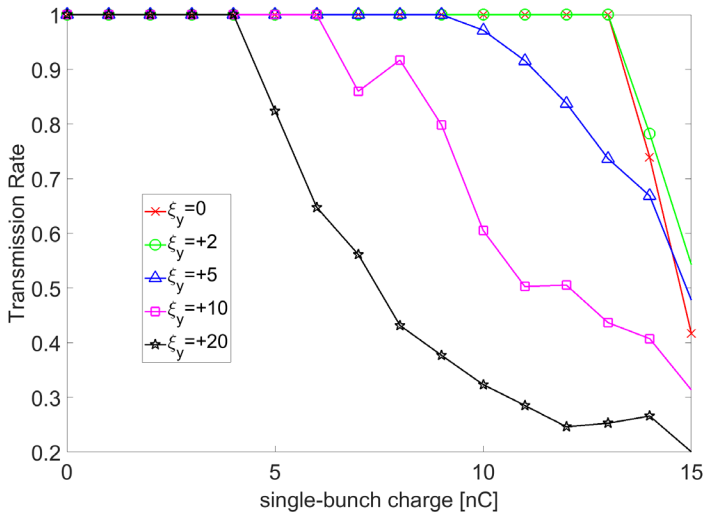




Possible mitigations

Haisheng Xu

- Influence of positive chromaticity.
  - Threshold beam current decreases with increase of chromaticity.
  - Nonlinear effects due to the variation of the transverse tune with amplitude is not included yet, which should provide further damping.



Head-tail phase shift over the bunch:

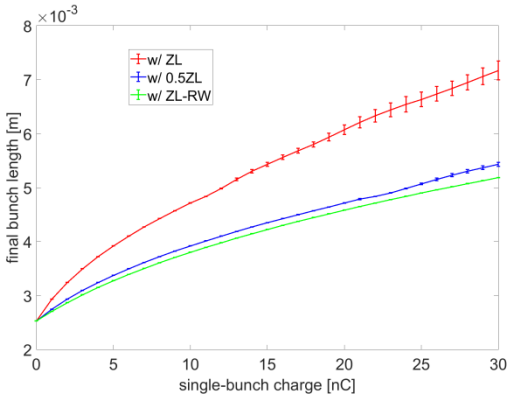
$$k_\xi \sigma_z = \frac{\xi \omega_0}{\alpha_c c} \sigma_z < 1$$

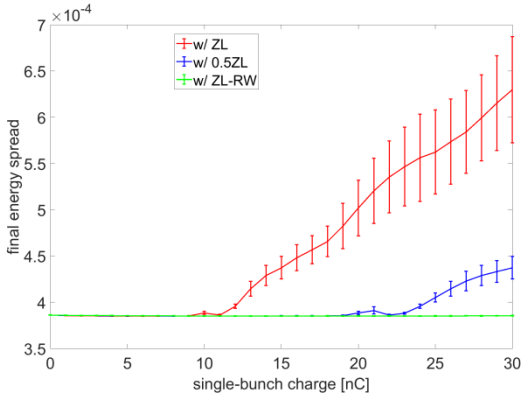
High order modes maybe excited with large chromaticity

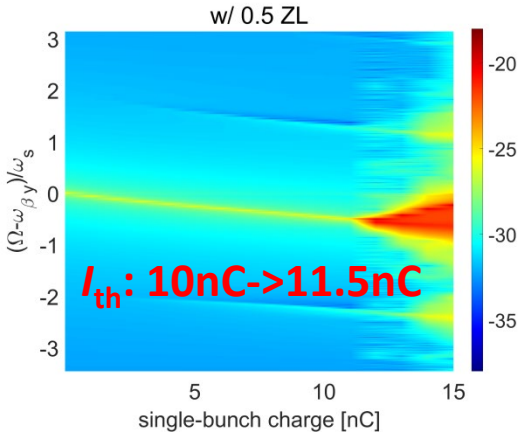
Possible mitigations

Haisheng Xu

- Mitigation by reducing the longitudinal perturbations.
  - Larger momentum compaction and synchrotron tune, or longer bunch.
  - **Lower longitudinal impedance** (transverse impedance normally decreases accordingly, but with less bunch lengthening).
  - By considering only the RW or total ZL reduced by a factor of 2, the TMCI threshold is increased limitedly from 10nC to 11.5nC.





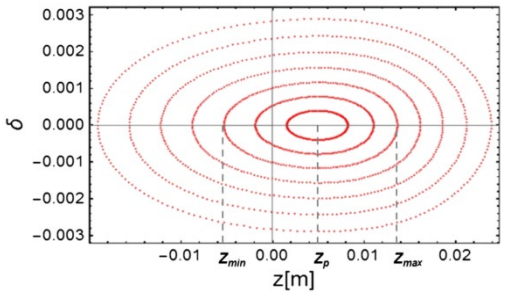


Transverse impedance unchanged

Mode analysis with long. perturbations

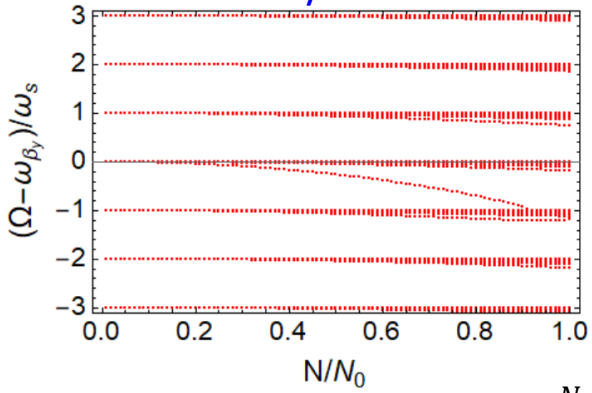
Chuntao lin

- 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.

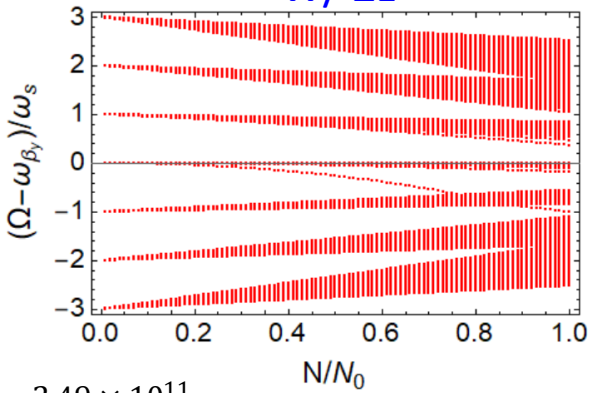


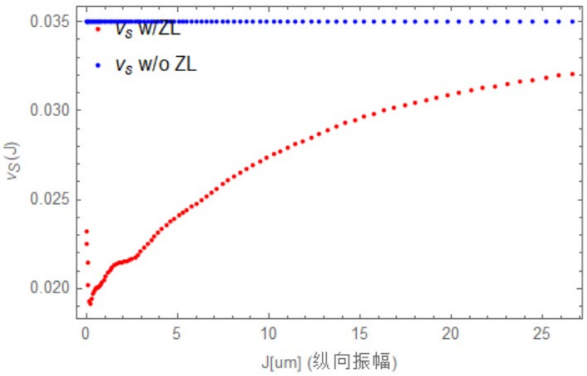
PRAB 25, 011001 (2022)

W/O ZL



W/ ZL





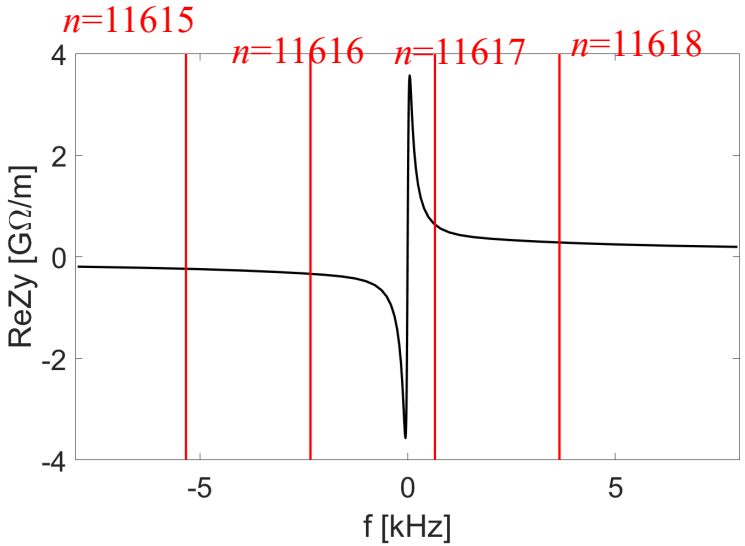
$N_0 = 2.49 \times 10^{11}$

Transverse resistive wall instability

- Assuming the whole ring is made of copper with coating, the 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)

Transverse resistive wall instability

- With more detailed RW impedance model, the instability growth rate can be further reduced by the stainless steel components. Contributions from the MDI and collimators are limited.

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

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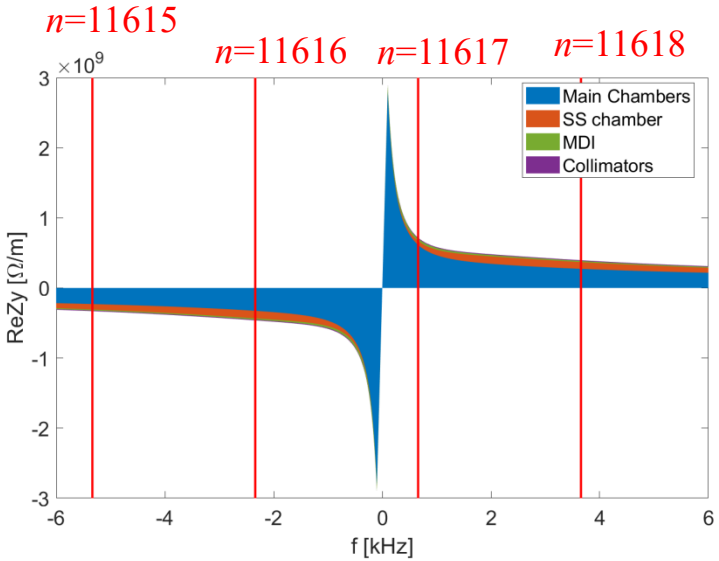
-11.330	11613	4.6 (14 turns)

1.7ms



Transverse resistive wall instability

Jintao Li

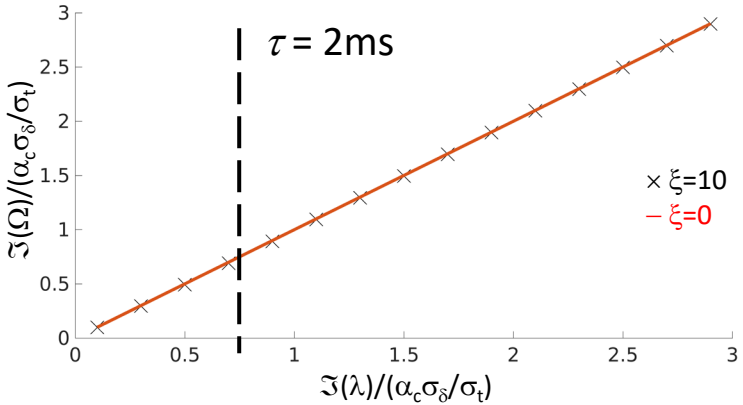
- Stabilizing effect of chromaticity is checked according to the theory developed in [PRAB 24, 024402 (2021)]

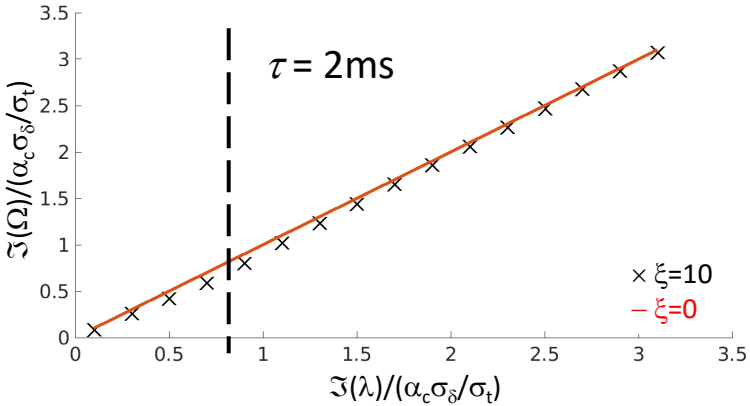
⇒ **Limited damping from ξ for Z**

Head-tail phase shift over the bunch: $k_\xi \sigma_z = \frac{\xi \omega_0}{\alpha_c c} \sigma_z$

Natural bunch length or energy spread
σ_z=2.5mm, σ_δ=4×10^{-4}, $k_\xi\sigma_z$=0.1

With impact of ZL and beamstrahlung
σ_z=8.7mm, σ_δ=13×10^{-4}, $k_\xi\sigma_z$=0.4

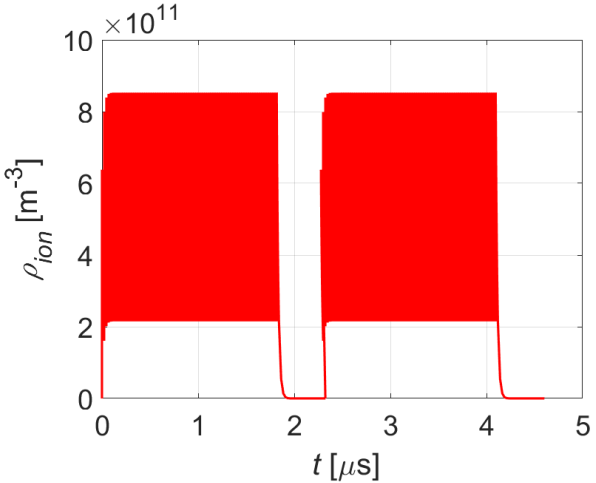




Complex growth rate in terms of zero chromaticity growth rate

Beam ion effects

- Trapped ions can induce bunch centroid oscillation and emittance growth.
- The possibility of ion trapping and fast beam ion instability are investigated.
- With vacuum pressure of 1nTorr, and CO has been considered as the only ion species
- Consider multi bunch train filling pattern, the instability growth calculated by the analytical theory for W and Z are faster than SR damping.



Build-up of ions along the bunch train

Parameters	Higgs	W	Z-30MW	ttbar
$L_{sep}\omega_{ion}/c_0$	6.2	2.4	0.7	14.7
$\rho_{ion,\ ave}[e^{11}\ m^{-3}]$	0.6	0.8	4.1	0.1
τ_e [ms]	7.9	1.9	0.1	105.4
τ_H [ms]	**44.1**	**24.3**	**4.3**	**220.5**
SR damping [ms]	**44**	**156**	**850**	**14**
FB damping [ms]	0.5			
$\Delta\nu_y$	0.00061	0.0017	0.016	0.000068

FBII simulations for Z

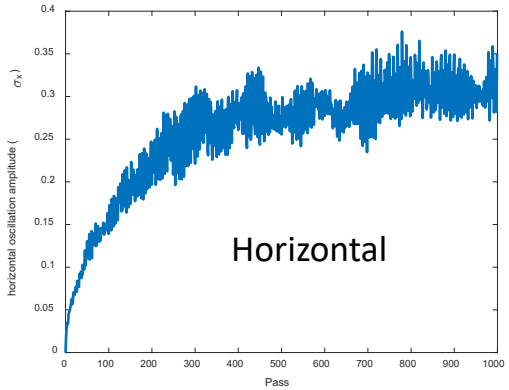
Saike Tian

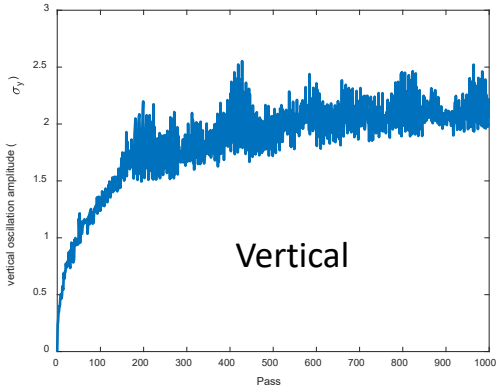
- Particle tracking simulations for uniform filling with different beta functions

β_x/β_y=92/32m:

low vertical beta function in FODO

⇒Both H and V beam centroid oscillation amplitude increased by larger than 0.1σ

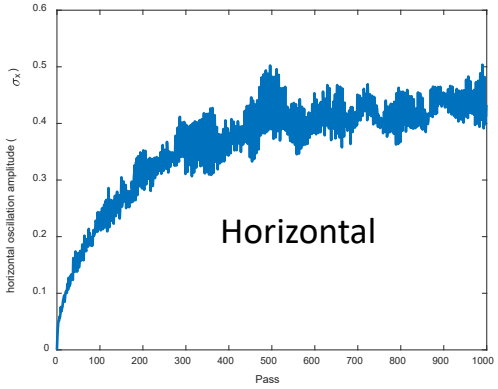


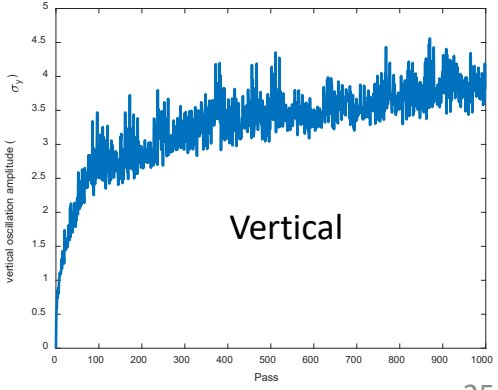


β_x/β_y=69/96m:

Ring average beta function

⇒Both H and V beam centroid oscillation amplitude increased by larger than 0.1σ





FBII simulations for Z

Saike Tian

- Particle tracking simulations for uniform filling with different beta functions

β_x/β_y=0.13/9E-4m:

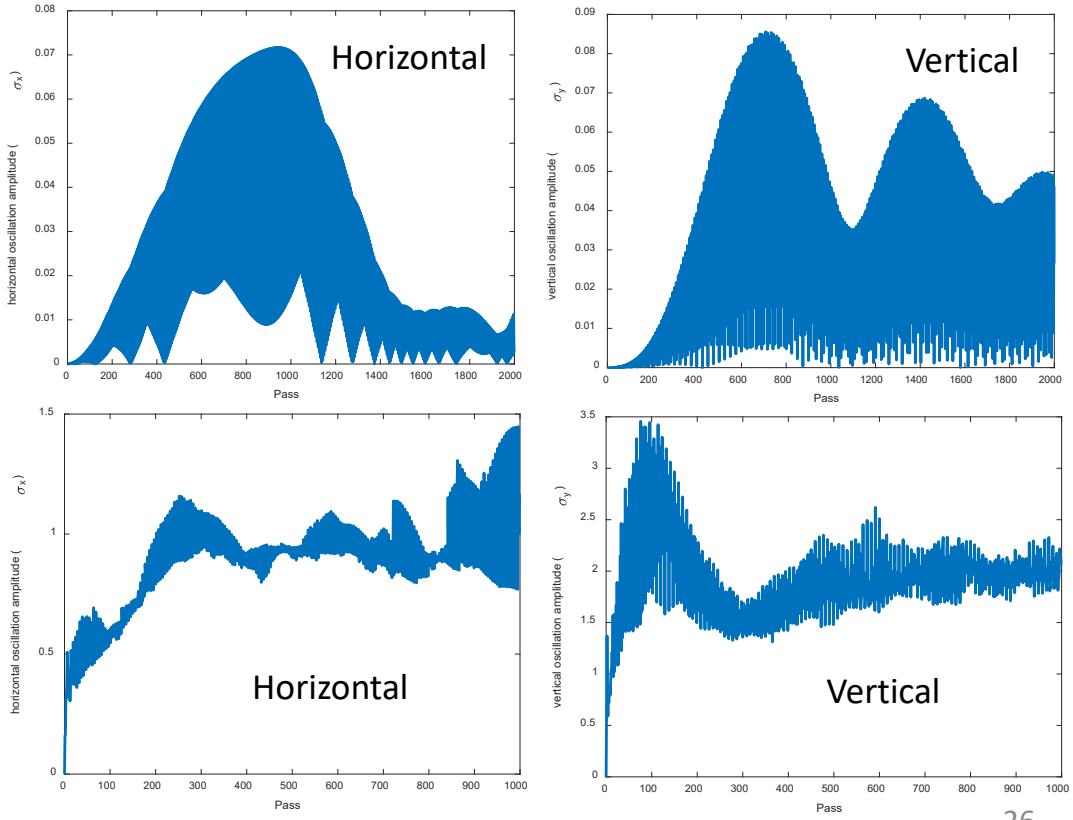
Interaction point

⇒Small increase on beam centroid oscillations, ions are over-focused due to the small beam size and can not accumulate.

β_x/β_y=151/4.4km:

Ultra-large beta function at IR

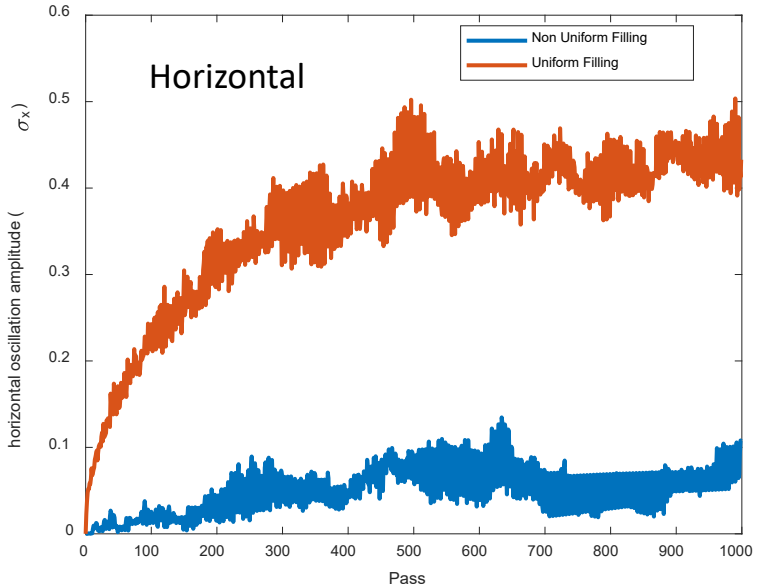
⇒Both H and V beam centroid oscillation amplitude increased to larger than 0.1σ in few turns, then saturate at around the scale of beam size.

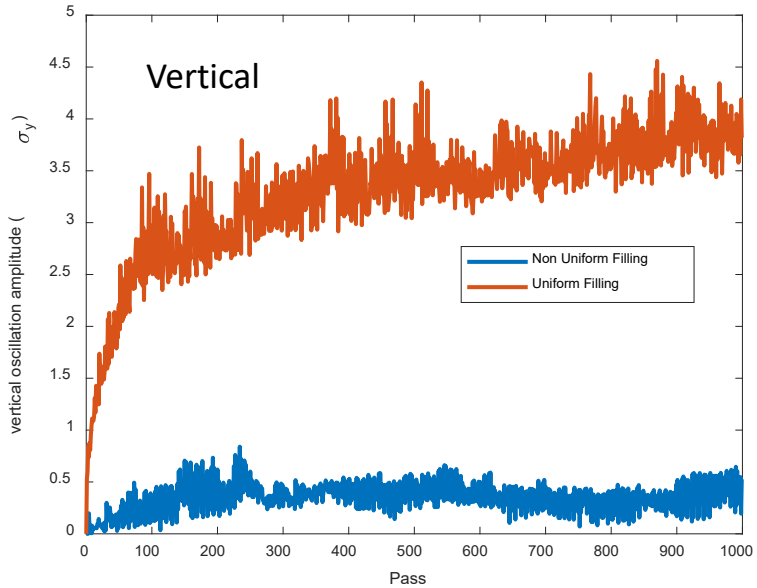


FBII simulations for Z

Saike Tian

- Filling pattern: 144 bunch trains, each train contains 83 bunches with spacing of 23ns
- Multi-train filling is effective in mitigating the beam ion instability. However, beam emittance growth is still foreseen ⇒bunch by bunch feedback is needed.





β_x/β_y=69/96m

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, possible mitigations are investigated.
  - 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!