CEPC collective instability study status

Na Wang, Yuan Zhang, Haisheng Xu, Saike Tian ,
Yudong Liu, Yuting Wang

IHEP

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Outline

- Impedance modeling
  - Resistive wall & geometrical impedance
- Collective instabilities
  - Bunch lengthening and microwave instability
  - Transverse mode coupling instability
  - Coupled bunch instabilities
  - Beam ion effects
- Summary and outlooks

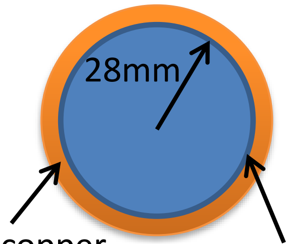
Impedance modeling

- Impedance modeling of the key vacuum components has been performed since the beginning of the project.
- Resistive wall impedance
  - Generated from finite conductivity of the vacuum chambers
  - Calculated with theoretical formulas considering the NEG coating
- Geometrical impedance
  - Generated by the discontinuity of the vacuum chambers
  - Calculated individually with 2D/3D simulation codes

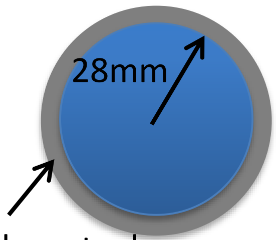
Resistive wall impedance

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

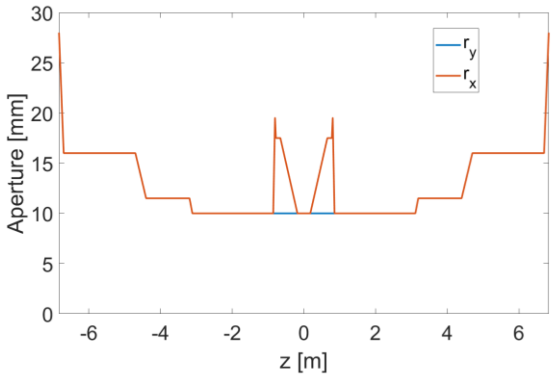
Main chamber:
(L=97km)



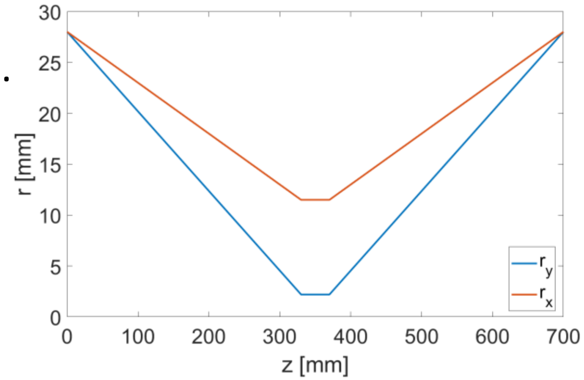
SS chamber:
(L=3km)



MDI chamber:



Collimator:
10 hori.+8 vert.

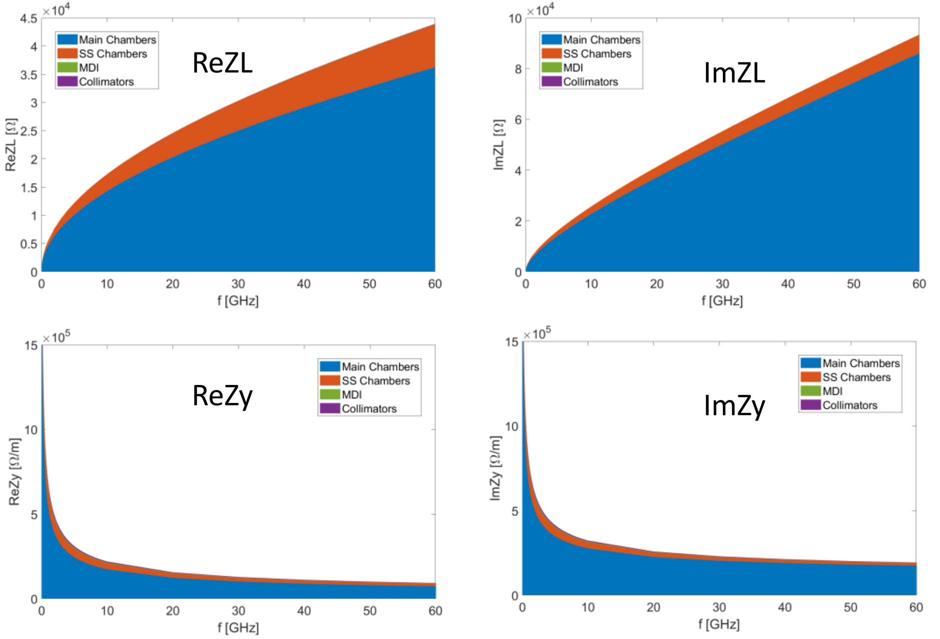


Resistive wall impedance

- The impedance contributed by the main vacuum chamber dominates both the longitudinal and transverse RW impedance. The impedance from stainless steel chambers also shows nontrivial contributions.

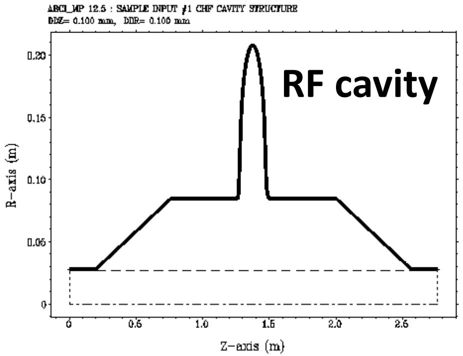
Broadband effective impedance @σ_z=3mm

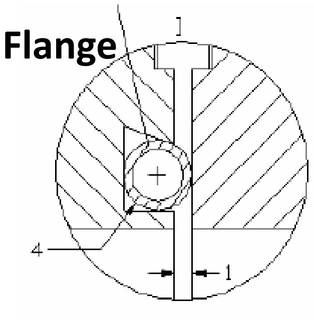
Components	$Z_{\|\|}/n$, mΩ	k_{loss}, V/pC	k_y, kV/pC/m
Main chamber	6.0	350.7	10.9
SS chamber	0.7	73.4	1.6
MDI chamber	6.9E-3	0.7	0.2
Collimators	8.9E-3	0.9	0.3
RW Total	6.7	425.6	13.8
Ring Total	**15.9**	**741.4**	**33.8**

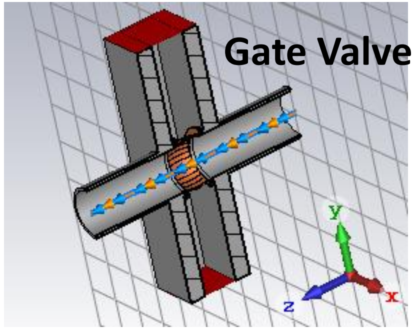


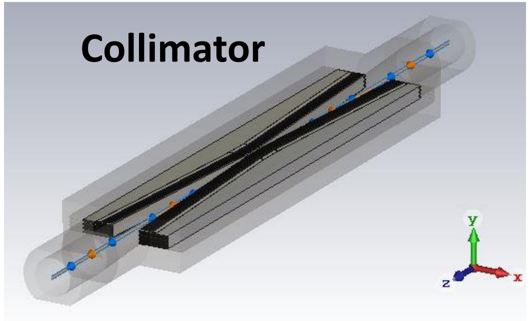
Geometrical impedance

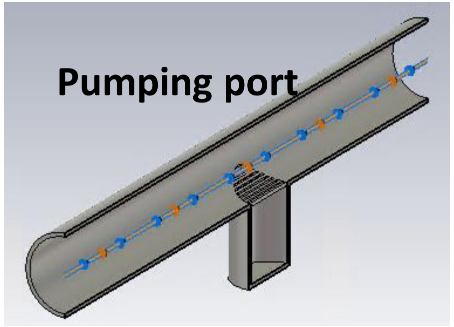
- Main vacuum components considered in the impedance model

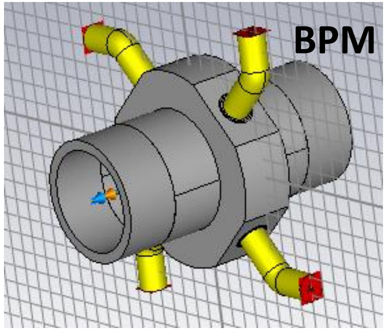


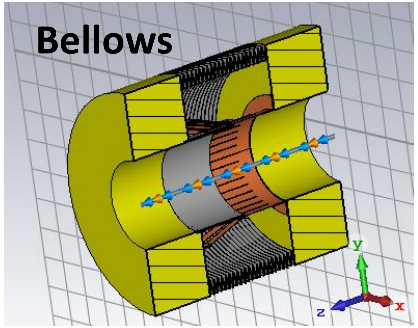


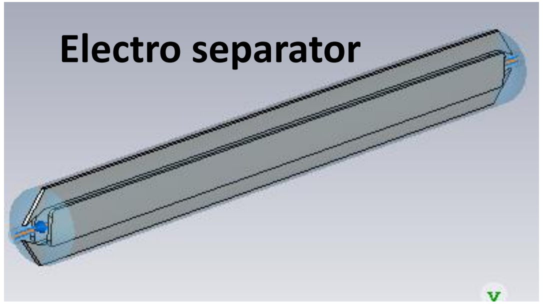




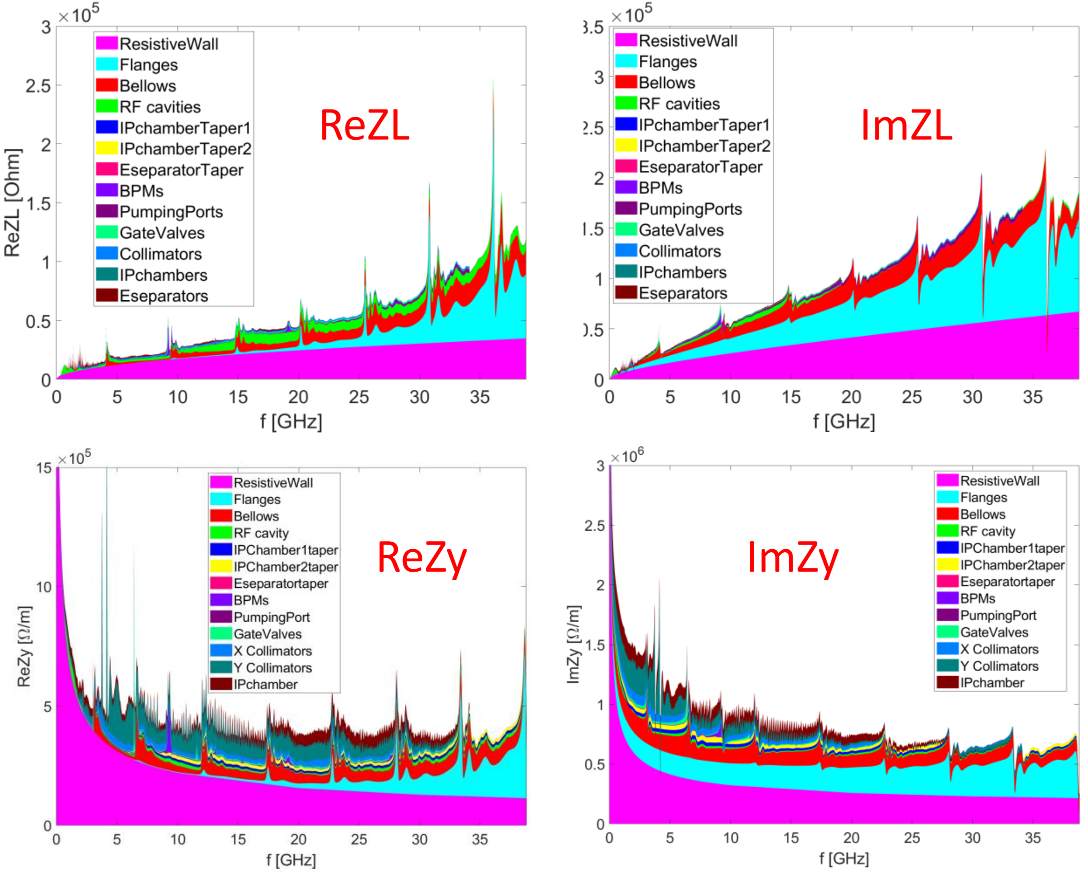








Impedance model



- 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.

Impedance budget @σ_z=3mm

Components	Number	$Z_{\|\|}/n$, mΩ	L, nH	k_{loss}, V/pC	k_y, kV/pC/m
Resistive wall	-	6.7	355.7	425.6	13.8
RF cavities	60	0.5	24.8	101.2	0.5
Flanges	37714	5.2	276.1	37.3	5.2
BPMs	1808	0.04	2.0	9.5	0.2
Bellows	15949	2.9	154.6	87.4	3.9
Gate Valves	500	0.2	11.4	14.5	0.4
Pumping ports	5316	0.3	18.4	2.3	0.2
Collimators	16	0.04	1.8	26.4	4.8
IP chambers	2	0.004	0.2	0.3	2.9
Electro-separators	20	-0.1	-5.4	34.5	0.1
Taper transitions	48	0.04	2.3	2.5	1.8
Total		**15.9**	**842.0**	**741.4**	**33.8**

Impedance evolution

- The impedance model will be continuously updated along with the development of the hardware designs.
  - The effective impedances varies along with the development of the impedance model => apparent increases on both Z/n and ky are shown.

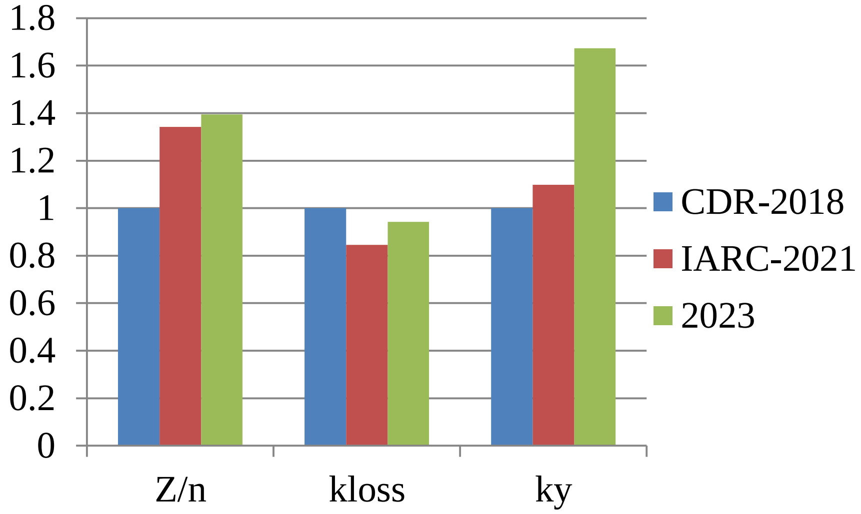
CDR-2018 Elliptical cross section

⇓

IARC-2021 Circular cross section
More contributors included

⇓

2023 More detailed chamber material, collimator updated and betatron function weighing is considered.



Evaluate with rms bunch length of 3mm

Main beam parameters for the collider rings

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

Collective instabilities in the collider rings

- Rough estimations 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)].

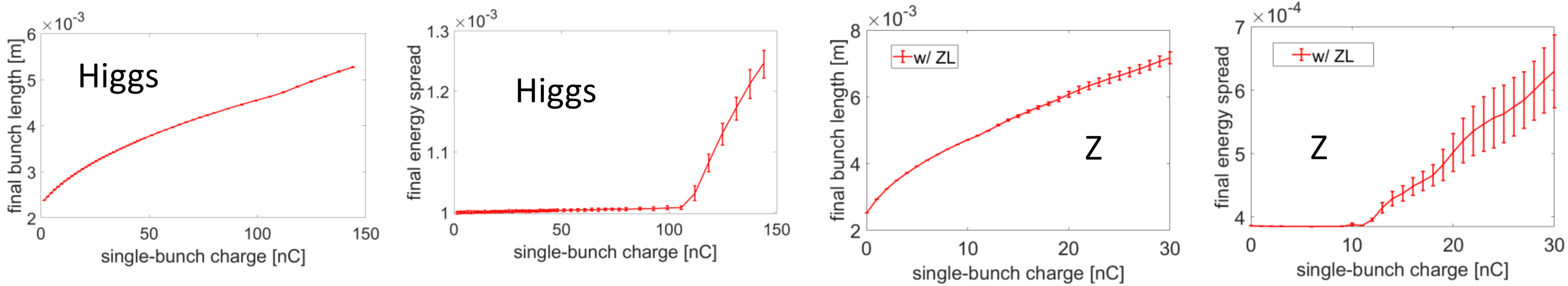
TMCI unstable

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)

Bunch lengthening and microwave instability

- Considering single beam, variations of bunch length and beam energy spread with bunch intensity are calculated by particle tracking simulations.



Higgs:

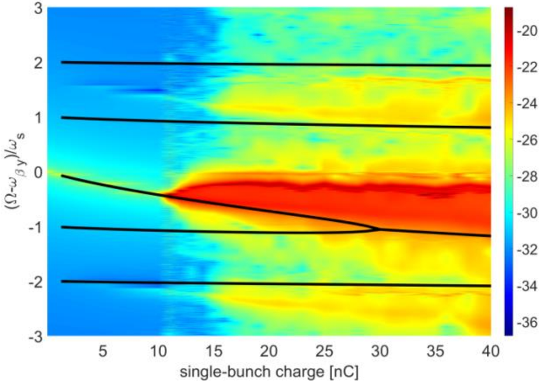
- Instability threshold is around 100 nC $\Rightarrow$ far above the design bunch current.
- At the design bunch intensity, the bunch will be lengthened by ~30% due to the impedance.

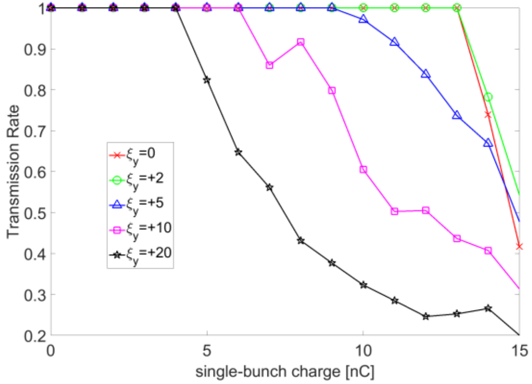
Z:

- Instability threshold is about half of the design bunch intensity.
- At the design bunch current, the bunch length and the beam energy spread are increased by ~140% and ~35%, respectively.

Transverse mode coupling instability (TMCI)

- Main constraint on the single bunch current for Z.
- For the single beam, consistent studies with both transverse and longitudinal impedance show reduction of the instability from longitudinal impedance.
  - TMCI threshold at ξ=0 →10nC (design value: 22.4nC, Impedance: IARC-2021)
  - Threshold beam current decreases with increase of chromaticity





Head-tail phase shift over the bunch:

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

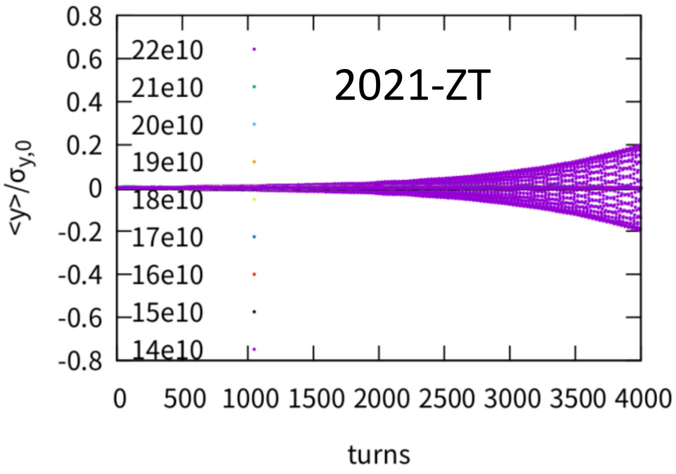
High order modes maybe excited with large chromaticity

TMCI with lengthened bunch from BS and ZL

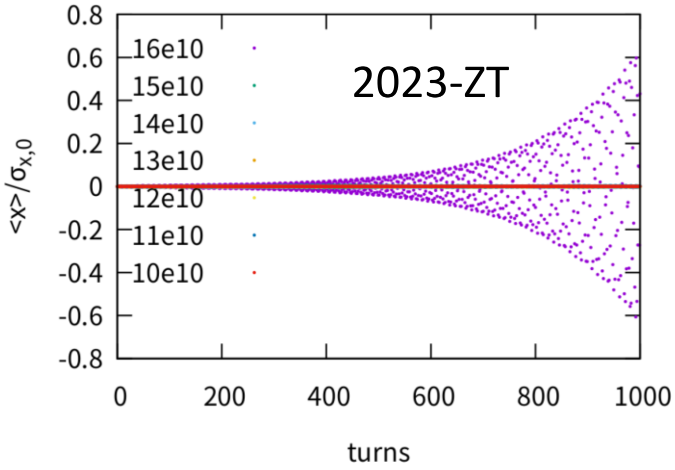
Yuan Zhang'talk for detail

- Simulations are performed, considering bunch lengthening and energy spread increase @14e10, with the beam-beam code developed by Yuan Zhang.
  - ⇒ Increase of the TMCI threshold due to the reduction of bunch density
  - ⇒ Threshold decreases dramatically due to the increase of impedance

TMCI threshold: 21e10 (33.6nC)



TMCI threshold: 15e10 (24nC)

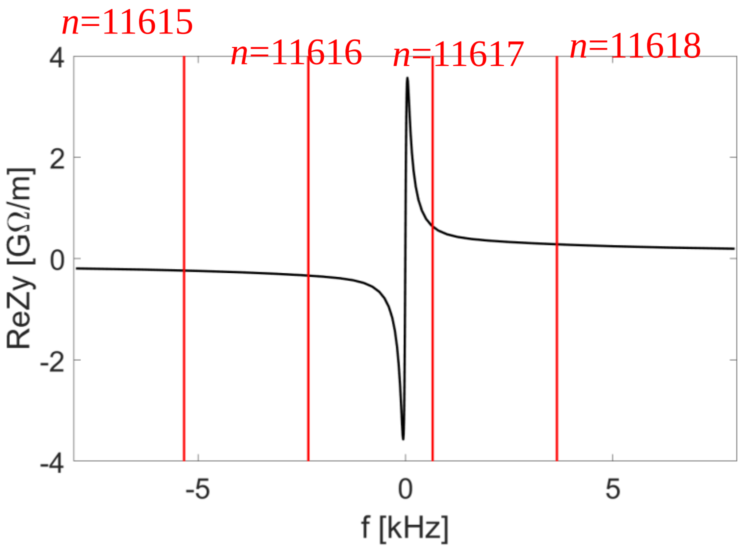


Transverse resistive wall instability

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

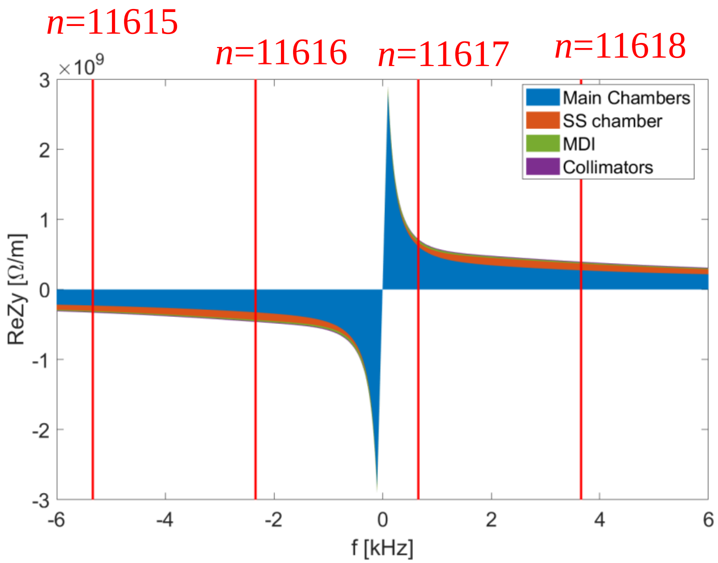
Transverse resistive wall instability (cont.)

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

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

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)

→ 1.7ms



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

Transverse resistive wall instability (cont.)

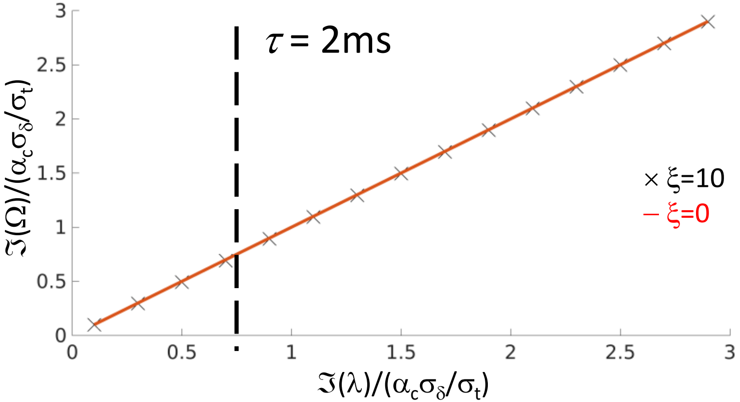
- Stabilizing effect of chromaticity is checked according to the theory developed in [PRAB 24, 024402 (2021)]

$\Rightarrow$ **Limited damping from ξ for Z**

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

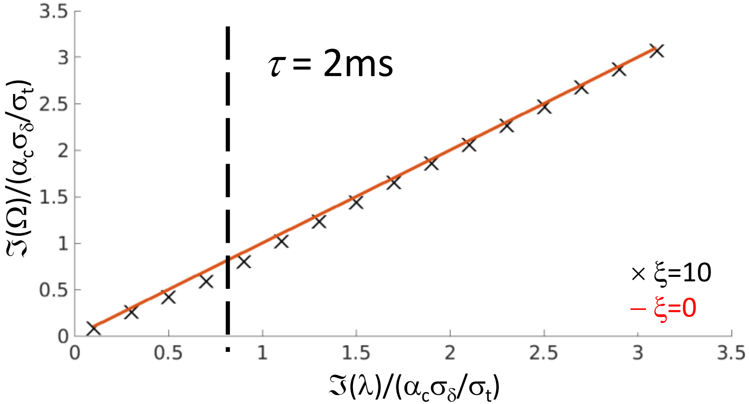
Natural bunch length or energy spread

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

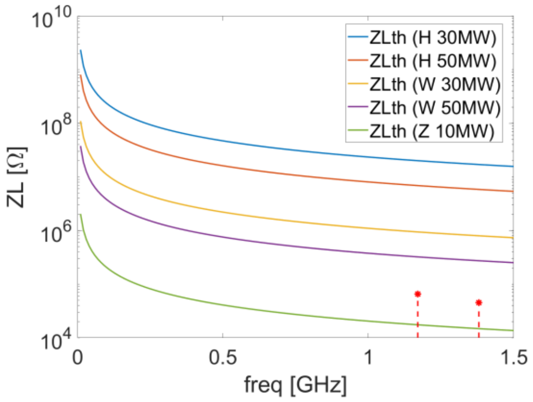


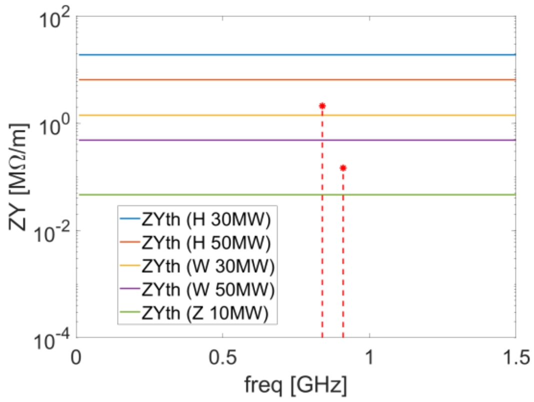
Complex growth rate in terms of zero chromaticity growth rate

RF HOMs

Courtesy of JiYuan Zhai

- For the operation mode of Higgs, W and low luminosity Z (with total beam power of 10 MW), the 2-cell 650MHz RF cavities will be adopted.
  - The longitudinal and transverse HOMs below the cutoff frequency are measured.
  - The impedance is above the SR threshold for Z in both longitudinal and transverse planes. In the resonant case, the instability has a growth rate of 114 ms and 19 ms, respectively.
  - The W operation mode will also be unstable in transverse when consider only SR damping. In the resonant case, the instability has a growth rate of 105 ms.

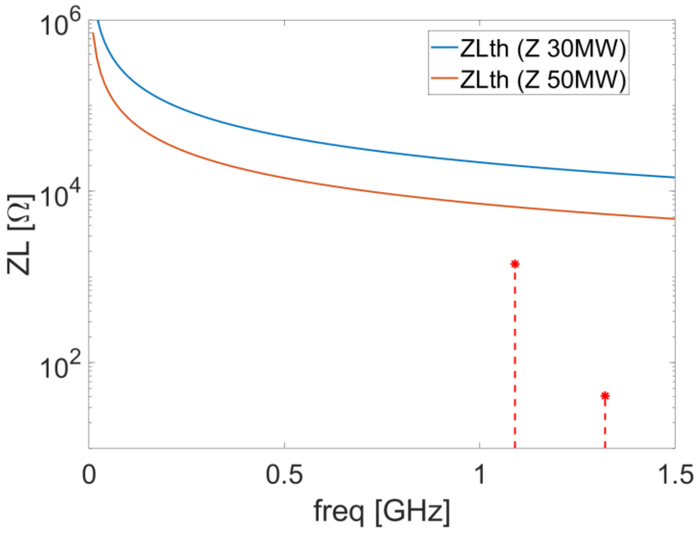


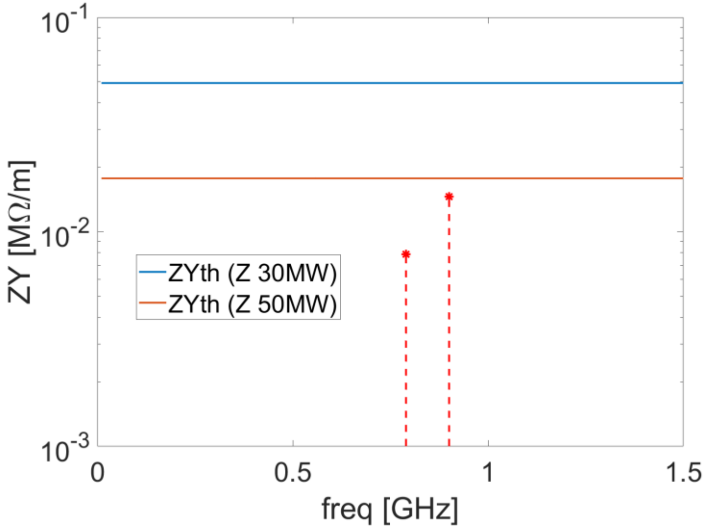


RF HOMs (cont.)

Courtesy of JiYuan Zhai

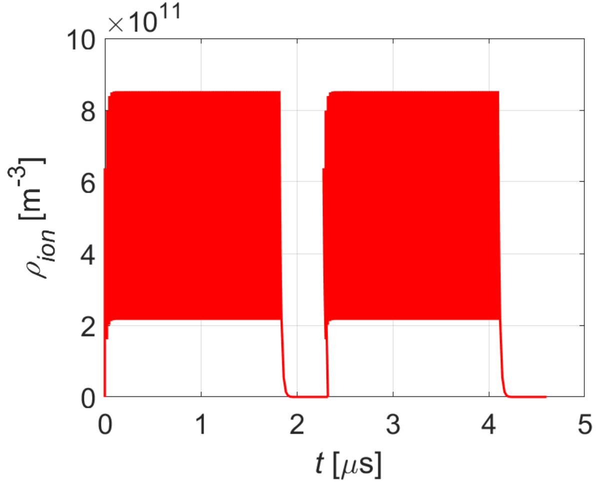
- For the high luminosity Z, the RF cavities will be replaced by the 1-cell cavities.
  - HOMs can be well damped (loaded Q of 100 has been considered) below the threshold that determined by the SR damping.





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.

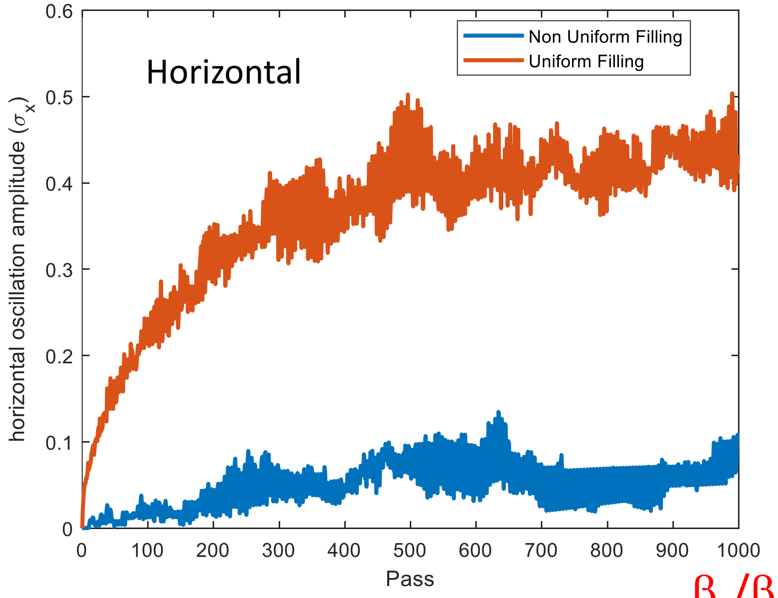


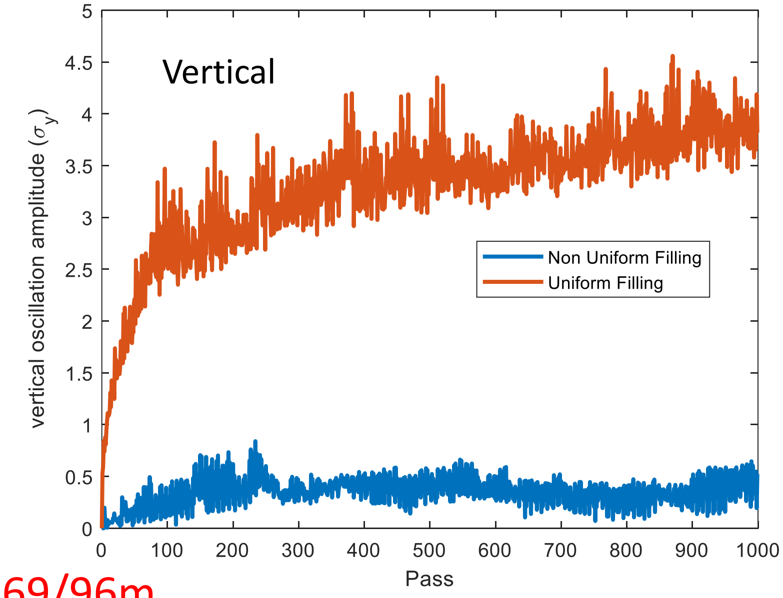
Build-up of ions along the bunch train

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

Macro-particle simulations for Z

- 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 and outlooks

- Main constraints from the beam collective effects are mainly focused on Z
  - Transverse impedance restrict the single bunch current for single beam, as well as the stability of the beam-beam interaction.
  - Tough requirement on feedback from TRWI $\Rightarrow$ effective damping should be demonstrated.
- Comprehensive or consistent studies considering coupling among different factors are needed for accurate estimate of the machine performance:
  - impedance-beam beam, longitudinal-transverse, collective effect - feedback
- Impedance model needs to be further evolved or optimized
  - Constraint on the luminosity for the high performance Z.
  - Kickers and machine protection collimators (or mask) can give nontrivial contributions, which are not included yet.
  - HOM should be further checked for some key element, e.g. electro-separators.
- Further investigation of the two-stream instability is still needed.

Thank you for your attention!