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MCBI

Mitigation of Coherent Beam Instabilities in CEPC

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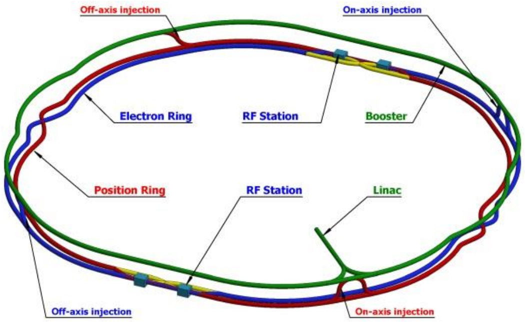
ICFA mini-Workshop on MCBI, Sep. 23-27, 2019, Zermatt, CH

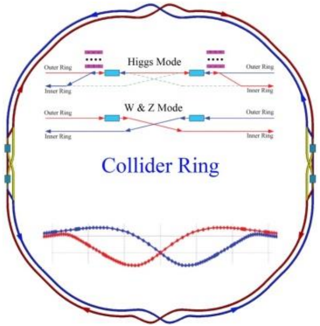
Outline

- Introduction
- Impedance modeling
- Impedance-induced instabilities
- Two-stream instabilities with ions and electron cloud
- Interaction with beam-beam
- Summary

Introduction to CEPC

- Double ring collider with 2 Ips.
- The Z mode shows the most critical restriction on the beam instabilities.





Parameter [unit]	Higgs	W	Z
Beam energy [GeV]	120	80	45.5
Beam current [mA]	17.4	87.9	461.0
Bunch Population $[10^{10}]$	15	12	8
Momentum compaction	1.1×10^{-5}	1.1×10^{-5}	1.1×10^{-5}
Emittance (H/V) [nm]	1.21/0.0031	0.54/0.0016	0.18/0.0016
Natural energy spread	1.0E-3	6.6E–4	3.8E–4
Synchrotron tune	0.065	0.039	0.028
Radiation damping [ms]	46/46/23	157/157/78	843/843/436

Potential restrictions from collective beam instabilities

- Beam current threshold
  - Collective beam instabilities which can induce beam losses
  - Parasitic power dissipation on vacuum components => heat load

- Beam quality degradations
  - Bunch lengthening and beam energy spread increase
  - Synchrotron and betatron tune shifts
  - Emittance blow-up

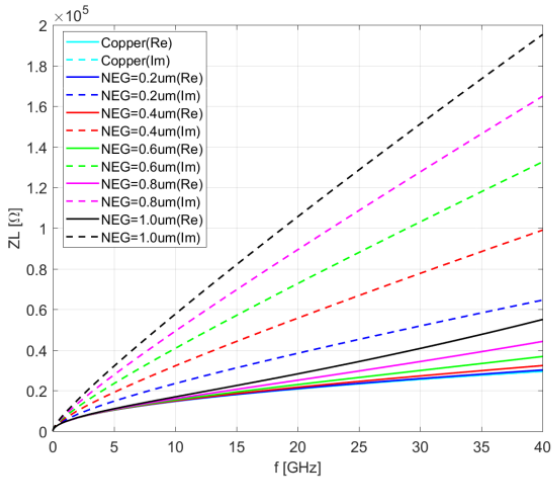
Impedance modeling

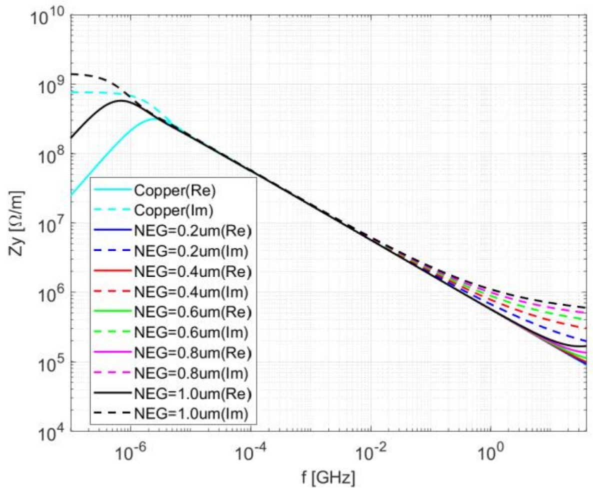
- Dominate impedance contributors are identified
  - Components with large impedance contributions
    - Resistive wall, RF cavities, Electro-separators, Vacuum transitions, IP chambers
  - Components with small impedances in large numbers
    - Flanges, Bellows, Pumping ports, BPMs

- The impedances of the components are carefully designed and optimized
  - Reduce parasitic power dissipation
  - Increase beam instability threshold

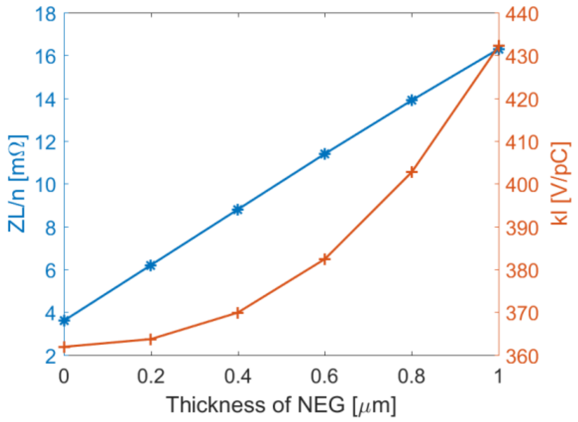
➢ Resistive wall impedance

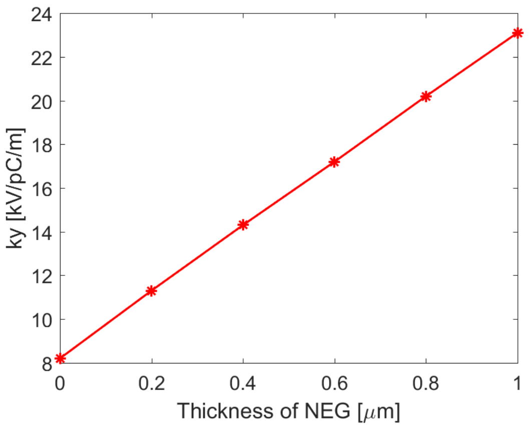
- NEG coating is adopted on the copper beam pipe for vacuum pumping and electron cloud mitigation.
- The effect of different coating thickness on the longitudinal and transverse impedance is studied => Impedance is reduced with thinner NEG coating.





- the effective impedance are calculated to identify the influence of the coating thickness on the impedance





In the frequency range of interest, the NEG coating has

- Significant effect on the imaginary part of the effective impedance

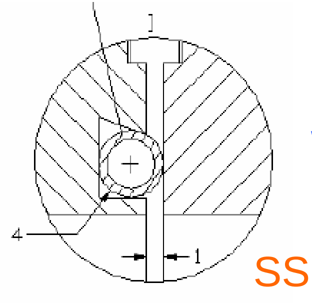
  => bunch lengthening and tune shift

- Less effect on the real part of the impedance

  => beam energy spread or instability growth rate

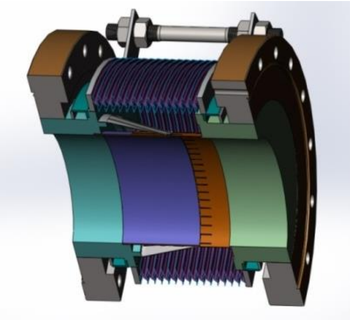
- The result is dependent on σ_z and pipe radius.

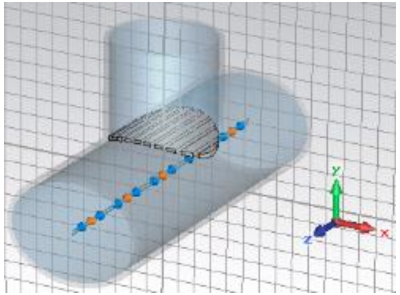
➢ RF shielding adopted for cavity structures



One cylindrical cavity:
width = 1mm
depth = 1mm

SSRF or BEPCII design





➢ Taper transitions of 1/10 are adopted at aperture discontinuities

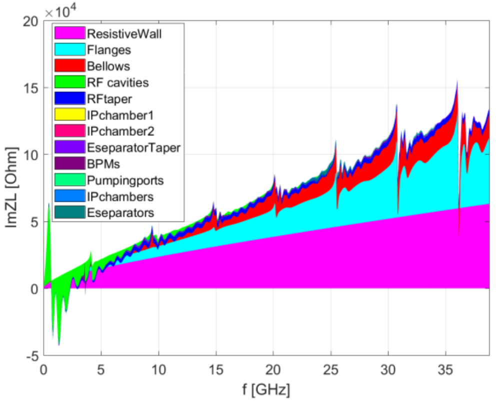
	Number	Aperture1 [mm]	Aperture2 [mm]
RF taper	112	78	28
IP chamber taper1	4	15	28
IP chamber taper2	4	12	15
E-seperator taper	44	55	28

➢ HOM damping are considered for resonant structures

- RF cavities
- IP chambers
- Electro-separators

- Impedance budget (@σ_z=3mm)

Components	Number	$Z_{\|\|}/n$, mΩ	k_{loss}, V/pC	ky, kV/pC/m
Resistive wall	-	6.2	363.7	11.3
RF cavities	240	-1.0	225.2	0.3
Flanges	20000	2.8	19.8	2.8
BPMs	1450	0.12	13.1	0.3
Bellows	12000	2.2	65.8	2.9
Pumping ports	5000	0.02	0.4	0.6
IP chambers	2	0.02	6.7	1.3
Electro-separators	22	0.2	41.2	0.2
Taper transitions	164	0.8	50.9	0.5
Total		**11.4**	**786.8**	**20.2**

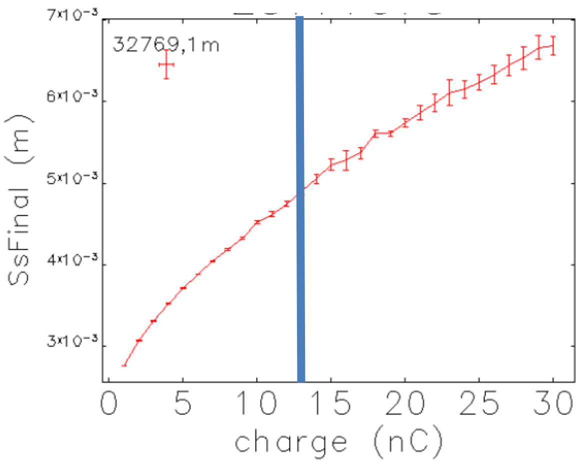


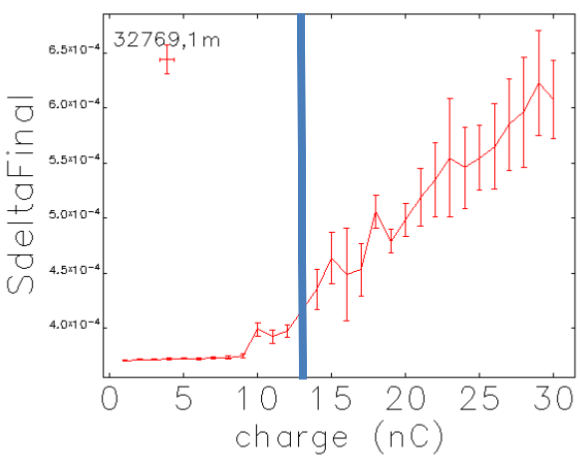
- The broadband impedances are dominated by the RW, flanges and bellows.
- The loss factor is mainly contributed by the resistive wall and the RF cavities.
- More components, such as the collimators, absorbers and kickers, should be included.

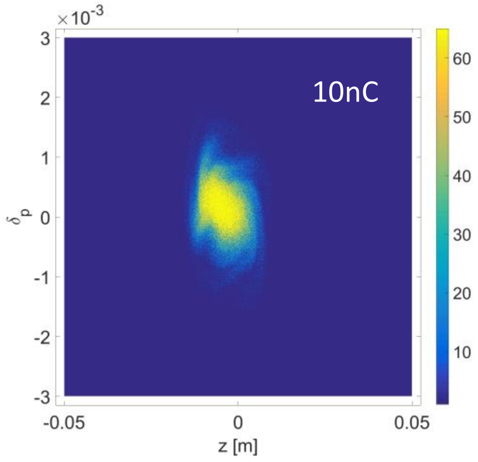
Impedance-induced instabilities

- Single-bunch effects
  - Microwave instability and bunch lengthening
  - Transverse mode coupling instability
- Multi-bunch effects
  - Transverse resistive wall instability
  - HOMs

- Microwave instability and bunch lengthening
  - The microwave instability will rarely induce beam losses, but may reduce the luminosity due to the deformed beam distribution and increasing of the beam energy spread.
  - With the impedance model developed, the microwave instability and bunch lengthening are simulated with the code Elegant => the design bunch intensity is just above the threshold, and turbulent distributions are observed above the threshold.







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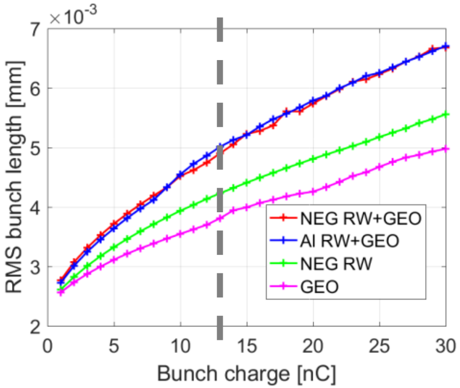
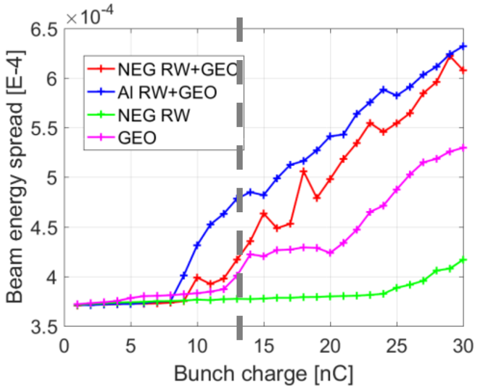
  - With the impedance model developed, the microwave instability and bunch lengthening are simulated with the code Elegant => the design bunch intensity is just above the threshold, and turbulent distributions are observed above the threshold.
  - To mitigate the effect:
    - Impedance reduction
    - Beam parameter optimization

Keil-Schnell criterion: $$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e}\sigma_{e0}^2\sigma_l}{R\left|\frac{Z_\parallel}{n}\right|_{eff}}$$

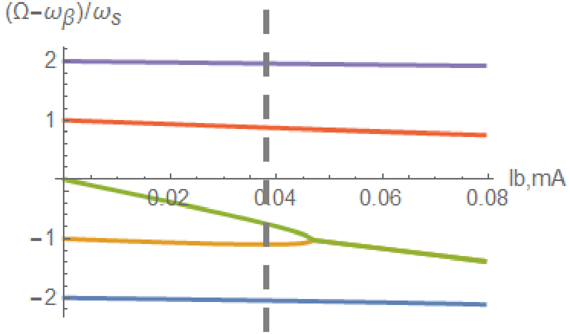




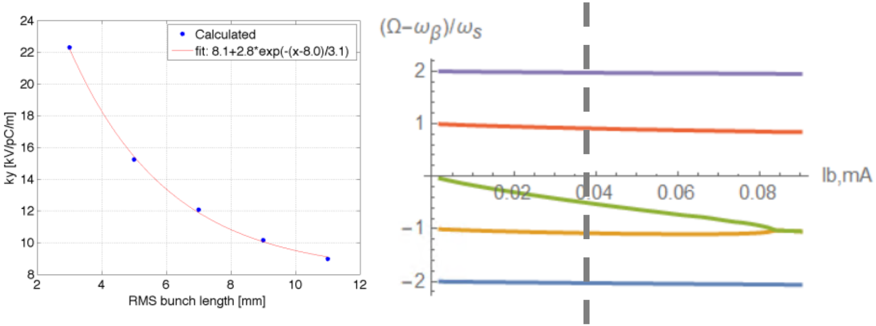
- Transverse mode coupling instability
  - The threshold for the TMCI is estimated using both analytical formula and Eigen mode analysis.

$$I_0^{th} = \frac{2Q_s \omega_0 E/e}{\sum_j \beta_{\perp,j} k_{y,j}}$$

  - When considering bunch lengthening due to the impedance or beamstrahlung, the transverse effective impedance decreases due to its dependence on the bunch distribution => TMCI threshold increases.



Threshold is comparable with the design current without considering bunch lengthening.

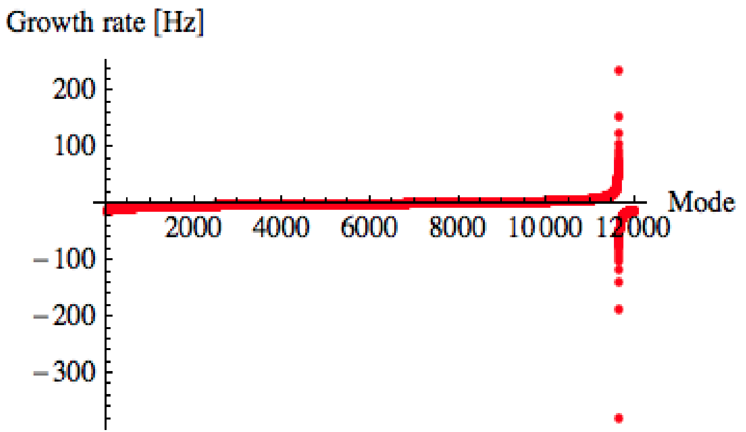


Larger safety margin obtained when considering bunch lengthening effects.

- Transverse resistive wall instability
  - The coupled bunch instability can be driven by the resonance at zero frequency of the transverse resistive wall impedance.
  - The most dangerous mode has a growth time of ~4.3ms (~12 turns), which is much faster than the radiation damping (~843ms).

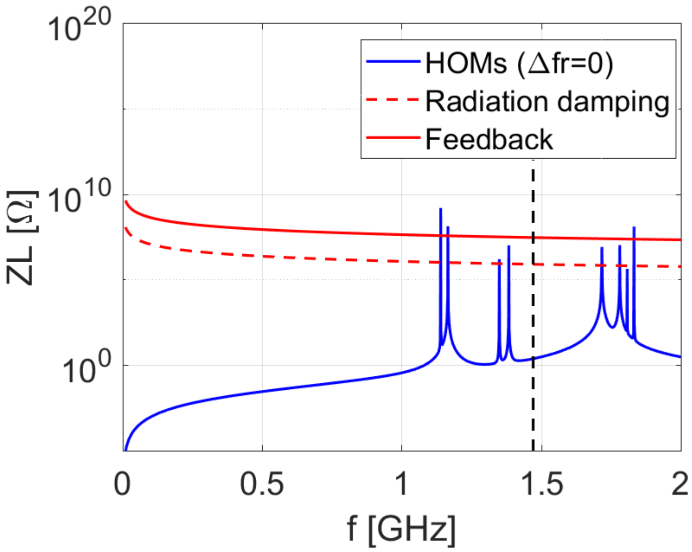
    ⇒ An effective feedback system is required.

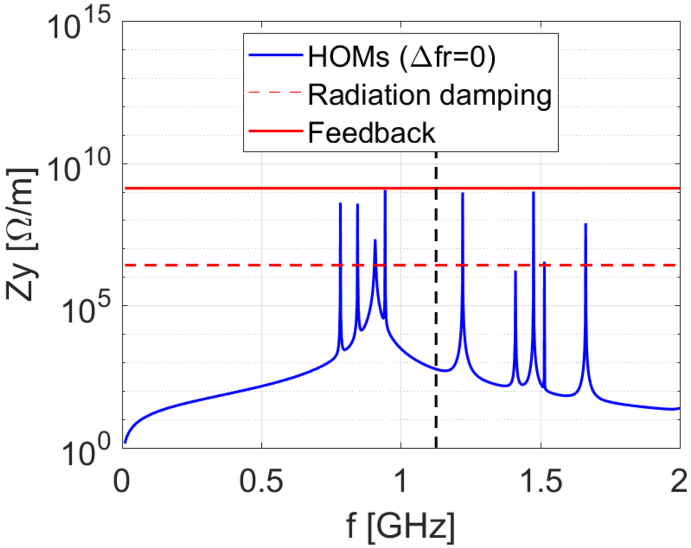
    ⇒ A nonzero chromaticity can also help to shift the sampled impedance frequencies.



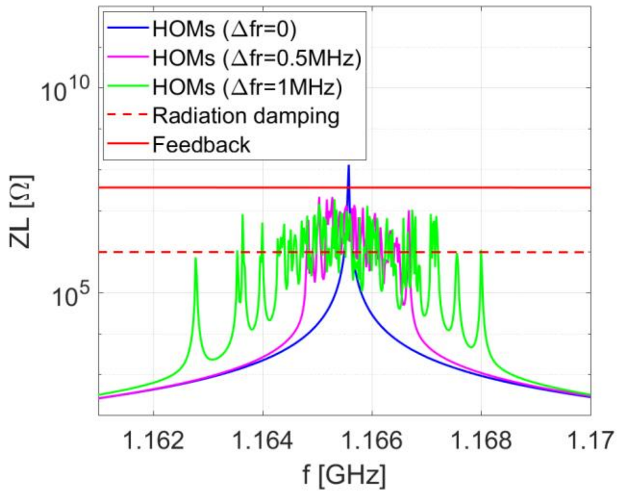
  - NEG coating has little effect on this instability.

- RF HOMs
  - 120 2-cell SC RF cavities (650MHz) will be used for Z mode. The CBI driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.

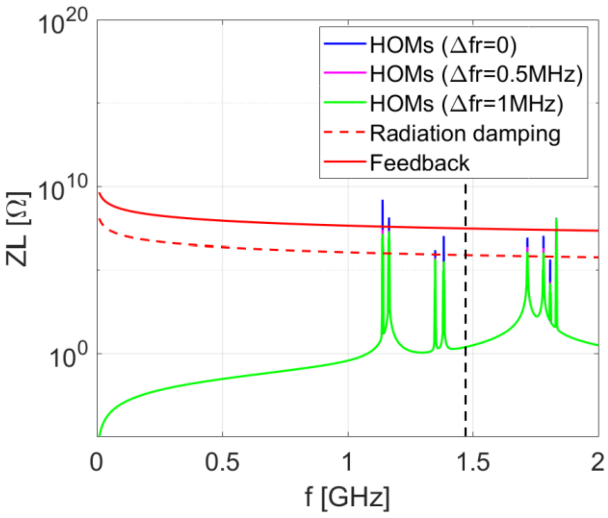


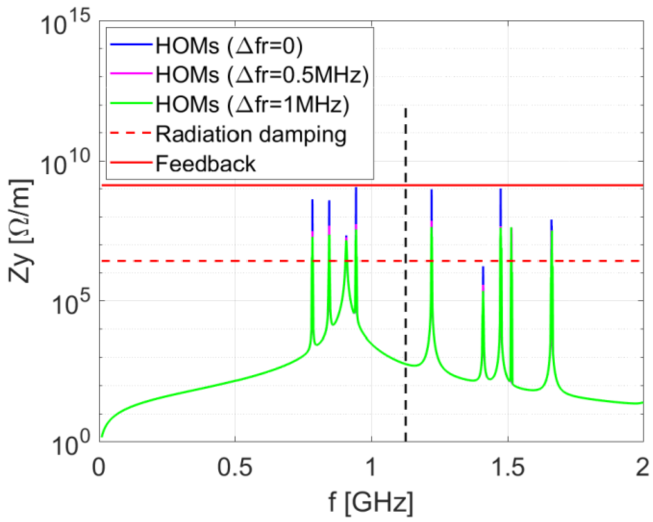


- RF HOMs
  - 120 2-cell SC RF cavities (650MHz) will be used for Z mode. The CBI driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.
  - When consider the whole RF system, HOM frequency spread due to the actual tolerances of the cavity construction can further relax the instability.
  - The measured HOM frequency shift among 650MHz 2cell RF cavities is around 0.5MHz~1MHz.
  - With a frequency spread of 1MHz, the shunt impedance can be reduced by a factor of 10.



- RF HOMs
  - 120 2-cell SC RF cavities (650MHz) will be used for Z mode. The CBI driven by the sum of the RF HOMs is faster than the radiation damping or even feedback damping.
  - Taking into account the HOM frequency spread, the impedance is well below the threshold determined by feedback damping.



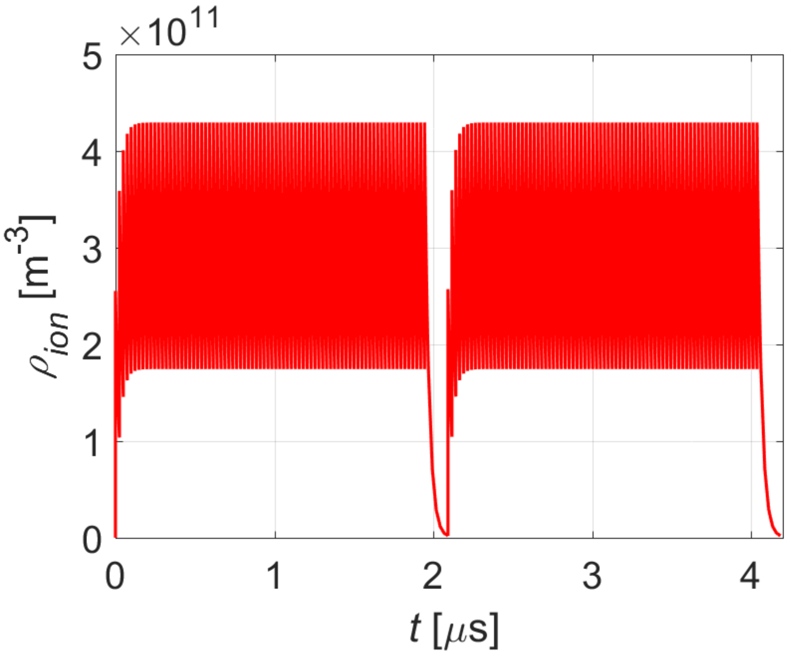


Fast beam ion instability

- The beam ion instability for the electron beam can be serious due to high beam current and small emittance in order to reach high luminosity.
  - Emittance blow-up
  - A positive tune shift along the bunch train

- Mitigations adopted:
  - Low vacuum level
  - Multi-train filling pattern
  - Transverse feedback system

- The build-up of the ions and the instability growth rate are investigated.
- An efficient transverse feedback is required to damp the instability.
- More detailed simulation studies are underway.



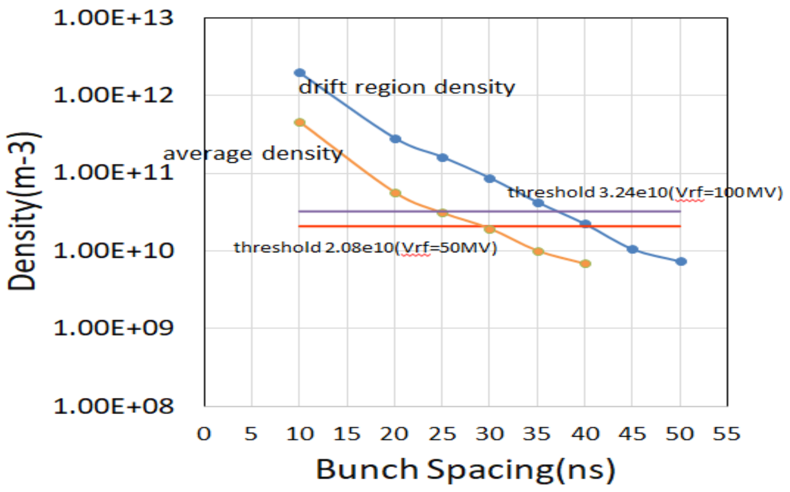
Parameters	value
$L_{sep}\omega_{ion}/c_0$	1.4
$\rho_{ion,ave}$[m^{-3}]	2.7E11
τ_e [ms]	2.3
$\Delta\nu_y$	0.009

Electron cloud effects

- Electron cloud can degrade the beam through
  - Coupled bunch instability => beam losses
  - Single bunch instability => beam size blowup

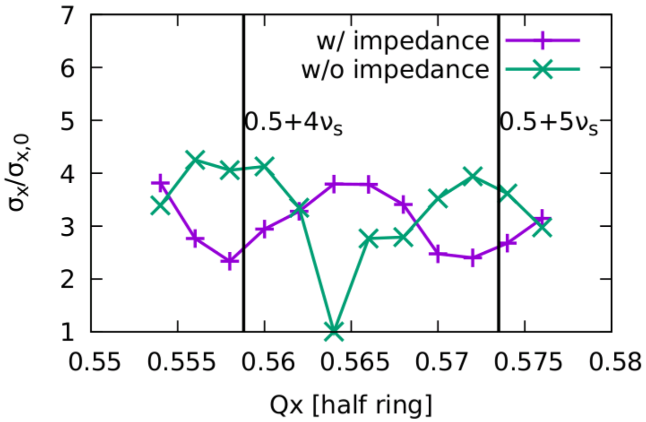
- Mitigations adopted:
  - Multi-train filling pattern with certain bunch spacing
  - Coating the vacuum chamber with NEG (low SEY)
  - Transverse feedback

- Electron cloud build up is simulated with different bunch spacing
  - The average electron cloud density in dipole and drift region is around 3.2e10 m^{-3} with SEY=1.6 & bunch spacing=25ns
  - Comparable with the threshold determined by the single bunch instability.
  - A lower SEY is expected with NEG coating.



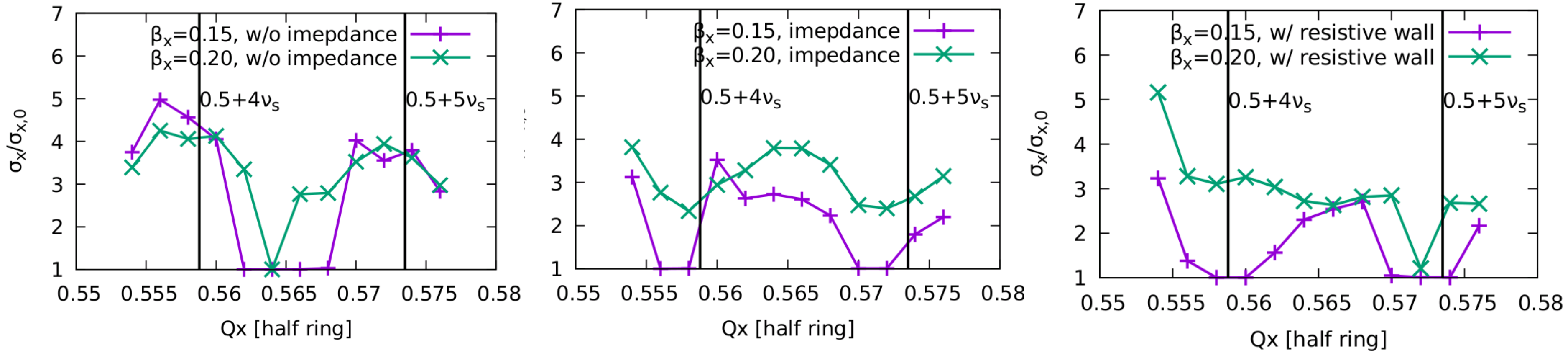
Interaction with beam-beam

- In conventional e+e- storage ring colliders
  - Longitudinal dynamics is not quite sensitive to beam-beam interaction
  - Lengthened bunch is used in beam-beam simulation
- In CEPC
  - The bunch will be lengthened during beam-beam interaction by beamstrahlung
  - More self-consistent to consider impedance in beam-beam simulation



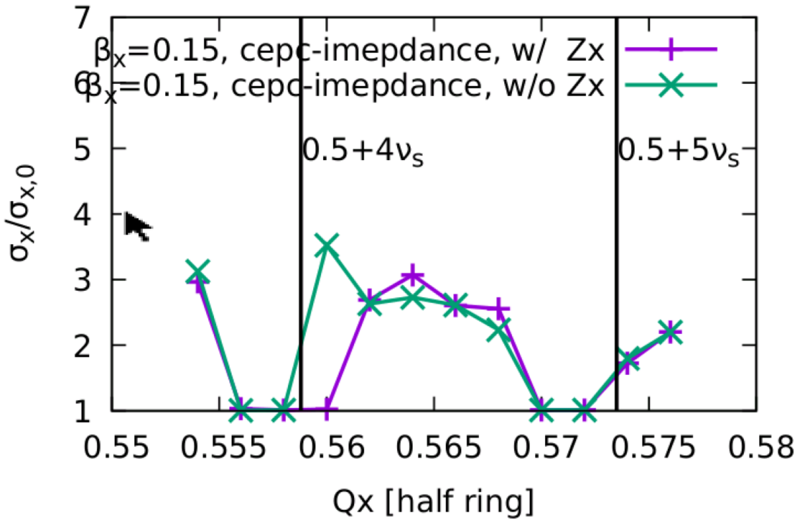
- Only one working point is stable without impedance.
- The beam-beam interaction gets more unstable with longitudinal impedance due to the X-Z coupling.
- Possible mitigations:
  - ✓ Beam parameter optimization
  - ✓ Impedance reduction

- According to the recent studies by K. Ohmi # and D. Shatilov *, smaller $\beta_x{}^*$ is preferred for X-Z coupling.
  - Larger stable region is obtained by reducing the $\beta_x{}^*$from 0.2m to 0.15m
- By including the longitudinal impedance
  - The stable region is reduced and shifted
  - With only RW, a smaller tune shift and larger stable region are observed
- Beam parameters and impedance should be further optimized.



K. Ohmi, et al., Coherent Beam-Beam Instability in Collisions with a Large Crossing Angle, Phys. Rev. Lett. 119, 134801 (2017).
* D. Shatilov, FCC-ee parameter optimization, ICFA Beam Dynamics Newsletter 72, 30 (2017).

- Preliminary studies with transverse impedance shows no significant influence of the transverse wake field on collision.
  - $\beta_x{}^*$= 0.15m
  - With longitudinal and horizontal impedance
- More detailed studies are underway.



Summary

- The collective beam instabilities are potential restrictions in CEPC to achieve high luminosity performance. Different strategies used to mitigate these effects are considered.
- The single bunch instability is dominated by the microwave instability, which can induce longitudinal phase space distortions and couple with the beam-beam interaction. The beam parameters and impedance need to be further optimized to get larger stable region in tune.
- The coupled bunch instabilities need to be damped by efficient feedback systems.
- The two stream instabilities need multi-train filling pattern with certain bunch spacing, along with feedback and vacuum conditioning.