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CEPC collective instabilities studies

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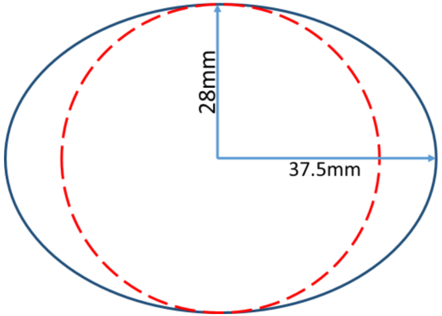
IAS mini-workshop on Accelerator Physics, Jan. 13-14, 2022

Outlines

- Impedance updates
- Single bunch instabilities
- Transverse resistive wall instability
- Beam ion effects
- Electron cloud effects

Impedance updates

- Impedance model is updated regarding the change of the chamber cross section (elliptical→circular), as well as more impedance contributors included.
  - Main impedance contributions are considered.
  - Possible large contributors, including Inj./ext. elements, feedback kickers, absorbers, masks/collimators around the ring, are not included yet.

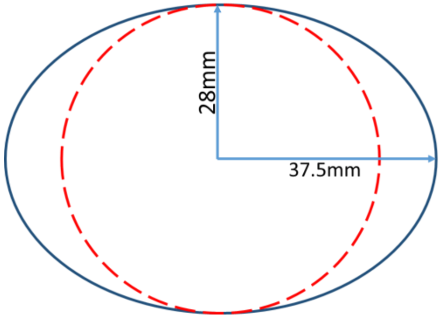


Element	Number	Element	Number
Resistive wall	/	BPMs	1808
RF cavities	60	IR Collimators	16
Flanges	37714	Electro separators	20
Bellows	15949	IP chambers	2
Gate valves	500	ES Transitions	40
Vacuum pumps	5316	IP Transitions	8

Changes on Resistive Wall

Yuting Wang

- Incoherent tune shift due to the quadrupolar impedance is derived from beam oscillation equations.



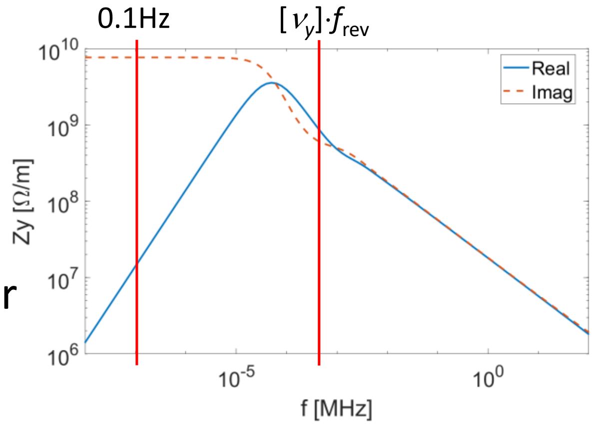
$$\ddot{y}_n(t) + \omega_\beta^2 y_n(t) = -\frac{N r_0 c}{\gamma T_0}\sum_{m=0}^{M-1}\sum_{k=0}^{\infty}[y_m(t-(k+\frac{m-n}{M})T_0)W_1^d(-(k+\frac{m-n}{M})C) + y_n(t)W_1^q(-(k+\frac{m-n}{M})C)], \quad (n=0,\ 1,\ \ldots,\ M-1),$$

$$\Omega - \omega_\beta = -i\frac{N r_0 c}{2\gamma\omega_\beta T_0^2}\sum_{\mu=0}^{M-1}\sum_{p=-\infty}^{\infty}[Z_1^d((\mu+pM)\omega_0+\omega_\beta) + Z_1^q(pM\omega_0)]$$

Incoherent tune slope:

$$\frac{d\Delta\nu_\beta}{dI} = \frac{C}{8\pi^2(E/e)\cdot\nu_\beta}\sum_{p=-\infty}^{\infty}\mathrm{Im}Z_1^q(pM\omega_0)$$

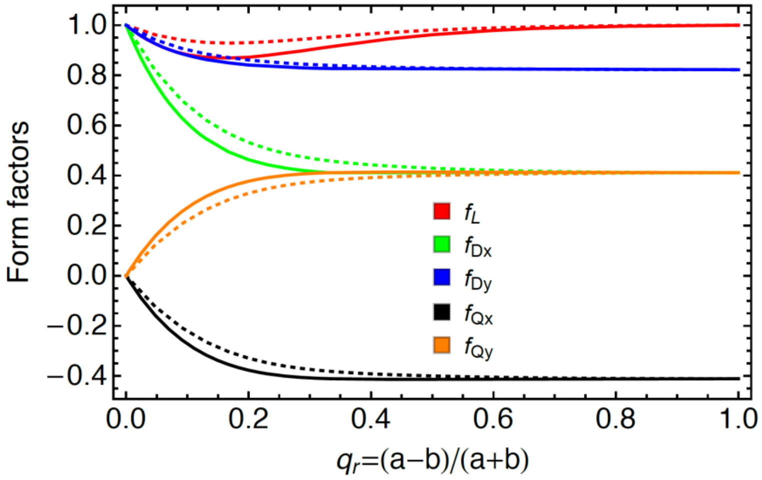
DC value of the quadrupolar impedance dominates



Changes on Resistive Wall

Yuting Wang

- Resistive wall impedance
  - Form factor – Ratio of elliptical and circular chamber (infinite thick wall)
  - RW_ Elliptical multilayer= Form factor * RW_Circular multilayer (σ, μ, dt)



Solid lines: Based on Lutman's method
Dashed lines: Yokoya form factor

With frequency decreases, the skin depth increases and the background material outside the beam pipe should be considered.

Two impedance models:

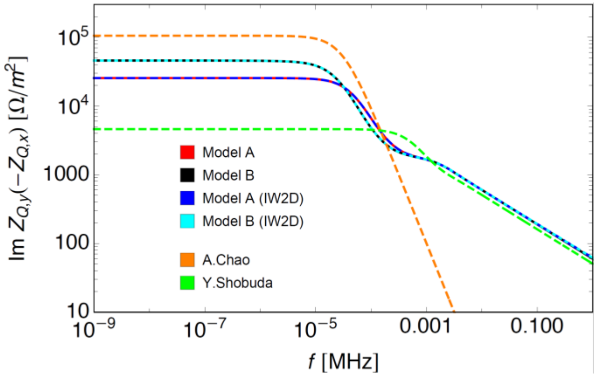
Model A: Vacuum outside the chamber

3mm Cu + Vacuum (Infinite)

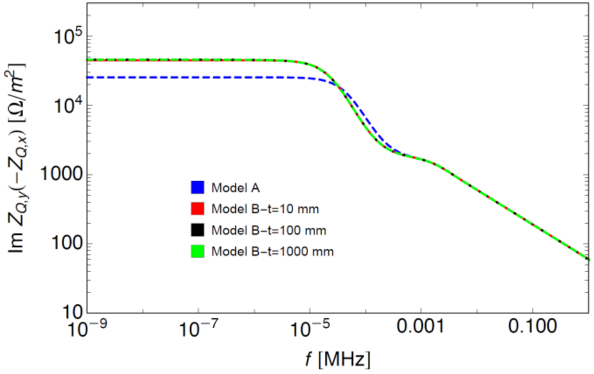
Model B: Magnet outside the chamber

3mm Cu + 100mm Magnet (μ=100) + Vacuum (Infinite)

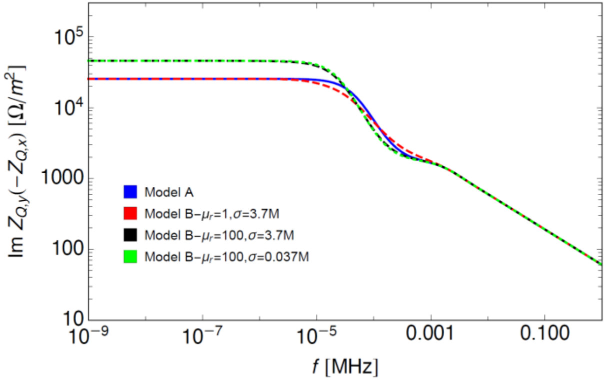
Changes on Resistive Wall



Model A: Vacuum outside the chamber
Model B: Magnet outside the chamber



Dependence on the thickness of the magnets



Dependence on the permeability and conductivity of the magnets

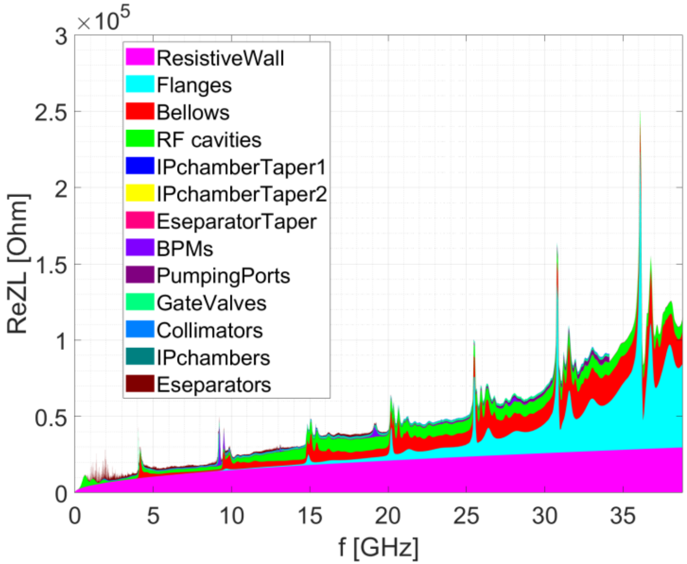
- Consider that 80% of the collider is surrounded by the magnets, the tune shifts are 0.26/-0.25 (A^{-1})
- Main different among different methods can be explained by the impedance model and the form factors used.
- For circular chamber, unsymmetrical magnets (e.g. dipoles) can also generate incoherent tune shift.

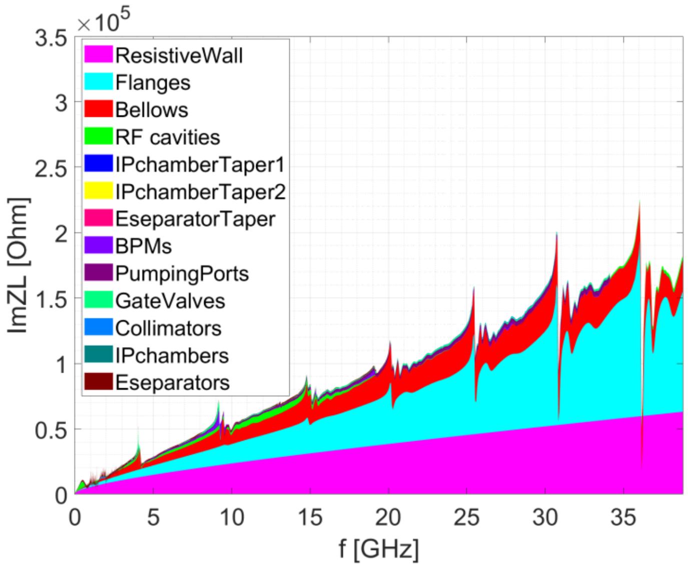
Model	Horizontal/Vertical (A^{-1})	Form factor f_y^Q $(-f_x^Q)$
A. Chao [1]	0.65/-0.64	0.41
Y. Shobuda [2]	0.06/-0.06	0.28
Model A	0.16/-0.15	0.33
Model B	0.28/-0.28	0.33
Model A (20%)+Model B (80%)	0.26/-0.25	0.33

[1] PRST-AB, 5, 111001 (2002), [2] PRE 66, 056501 (2002)

Ring longitudinal impedance

- Broadband impedances are mainly contributed by: resistive wall, flanges, bellows, RF cavities.
- Narrowband impedances need to be further checked.

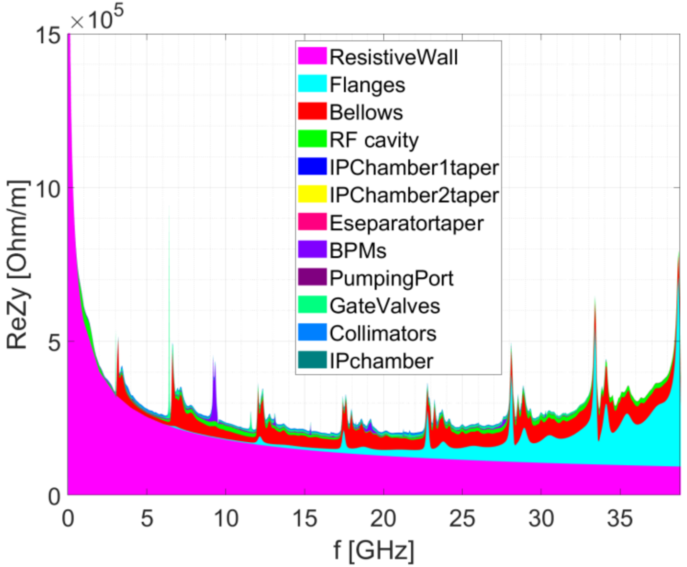


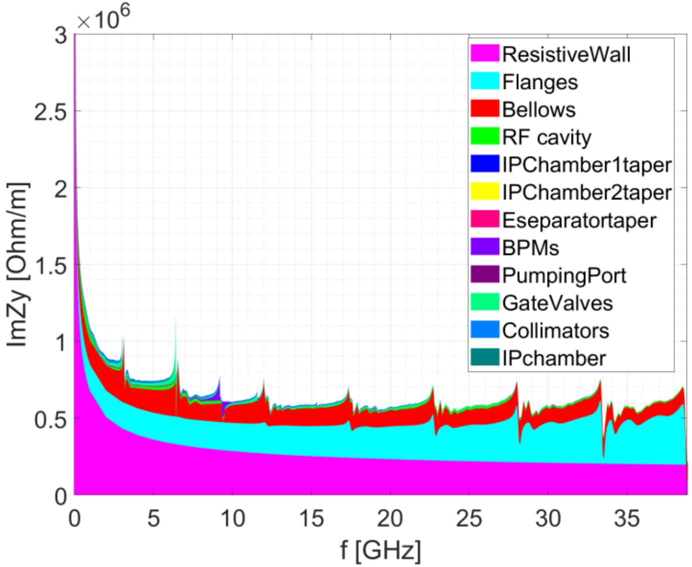


Ring transverse impedance

☐ Broadband impedances are mainly contributed by: resistive wall, flanges, bellows.

☐ Narrowband impedances need to be further checked.





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	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}.

Collective instabilities

- ☐ Instability issues for high luminosity Z are investigated.
  - ➔ High beam current and bunch intensity
  - ➔ Low momentum compaction
  - ➔ Short natural bunch length
  - ➔ Slow radiation damping
  - ➔ Large circumference (ω_0↓, RW↑)
- ☐ Key instability issues
  - ➔ Single bunch effects
  - ➔ Transverse resistive wall instability
  - ➔ Electron cloud effect
  - ➔ Beam ion instability

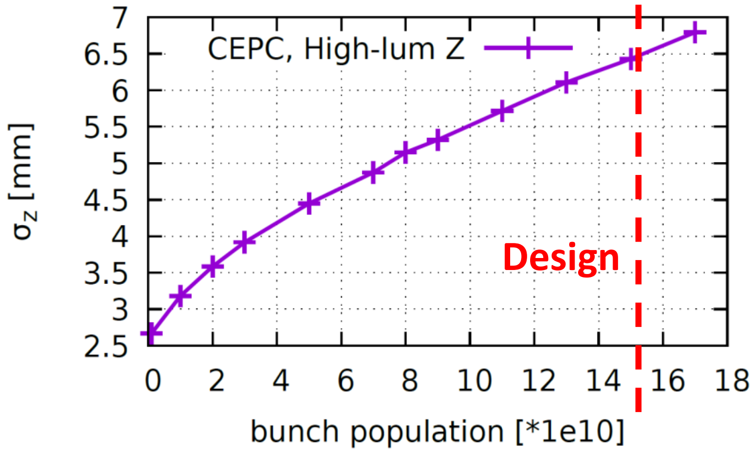
Parameter [unit]	Z-High Lumi
Beam energy [GeV]	45.5
L_{max}/IP (10^{34}cm^{-2}s^{-1})	**105.5**
Emittance (H/V) [nm]	**0.27/0.00135**
Beam current [mA]	**839.9**
Bunch number	**11520**
Bunch Population [10^{10}]	**15.2**
Momentum compaction [10^{-5}]	1.43
Natural bunch length σ_z (mm)	2.75
Natural energy spread	3.78×10^{-4}
Betatron tune ν_x/ν_y	319.10/317.22
Synchrotron tune	0.032
Radiation damping [ms]	849.5/849.5/425.0

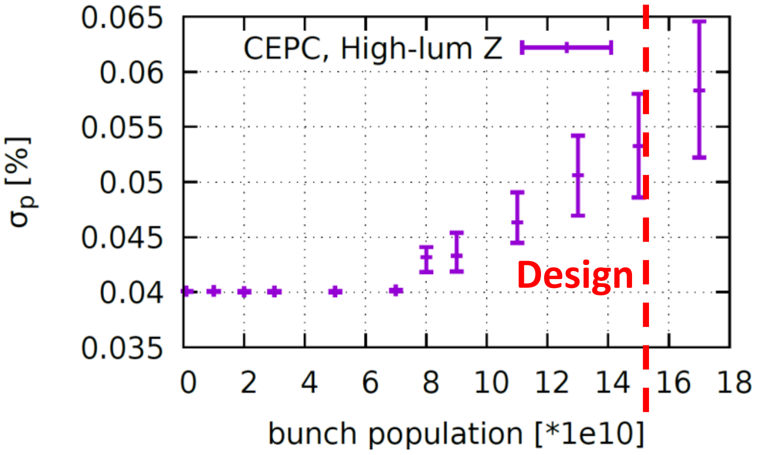
Yuan Zhang

MWI instability & bunch lengthening

- Rarely induce beam losses, but may reduce the luminosity due to the deformed beam distribution and increasing of the beam energy spread.
- The instability threshold is about half of the design bunch intensity.

σ_l with ZL [mm] (σ_l/σ_{l0}-1)	6.5 (140%)
σ_e/σ_{e0}-1	35%





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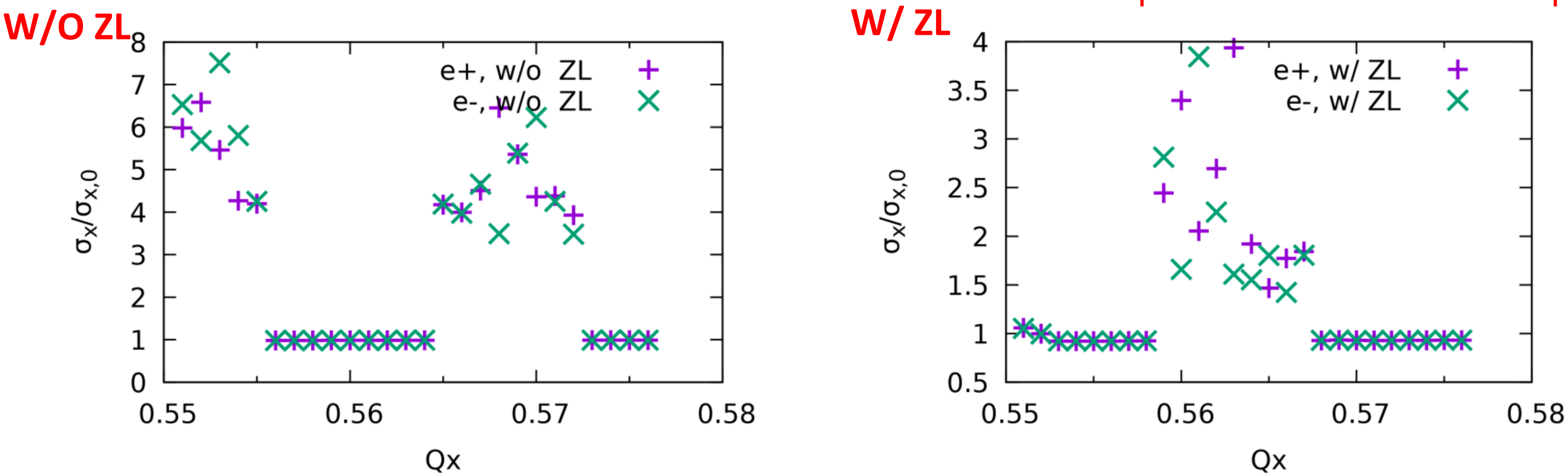
Influence of impedance on beam-beam

- ☐ Less stable region obtained with longitudinal impedance included in the beam-beam simulation consistently.
- ☐ The beam-beam interaction gets more unstable with longitudinal impedance due to the X-Z coupling.

CDR impedance is used in these plots



W/O ZL

W/ ZL

The stable region shrunk and shifted

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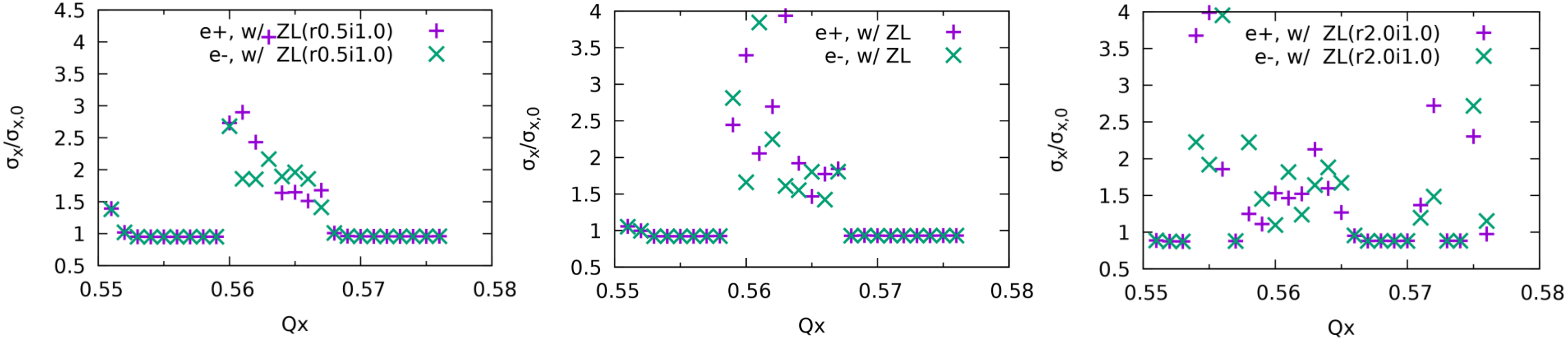
Influence of impedance on beam-beam

- With the real/imaginary longitudinal impedance roughly multiplied by a factor, the influence of the impedance on the beam-beam interaction is further investigated.
- ReZL (0.5→1→2), ImZL (1)

CDR impedance is used in these plots



Distinct influence shown with the real part of the impedance increased by a factor of 2

Locations of the stable regions are mainly fixed.

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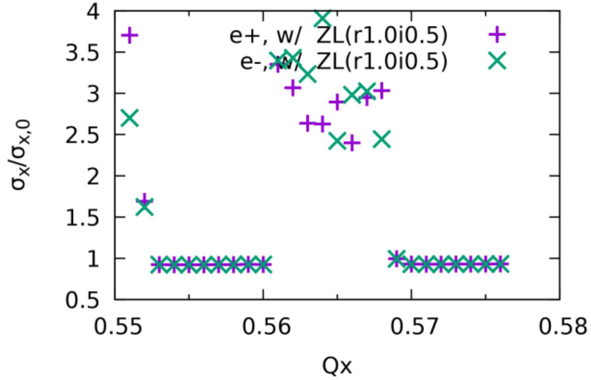
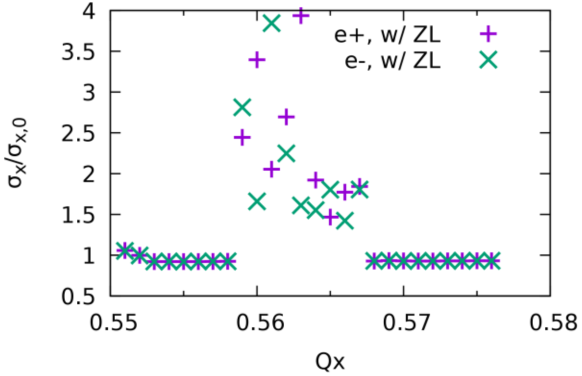
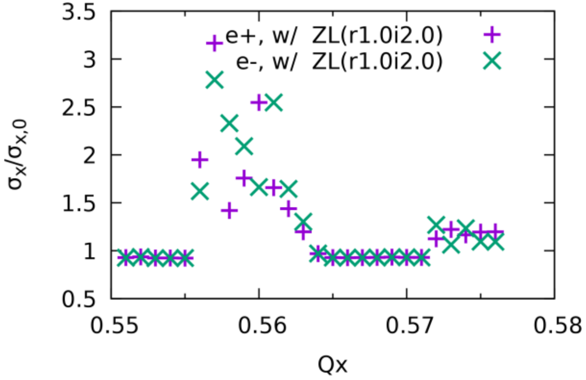
Influence of impedance on beam-beam

- ☐ ReZL (1), ImZL (0.5→1→2)

CDR impedance is used in these plots





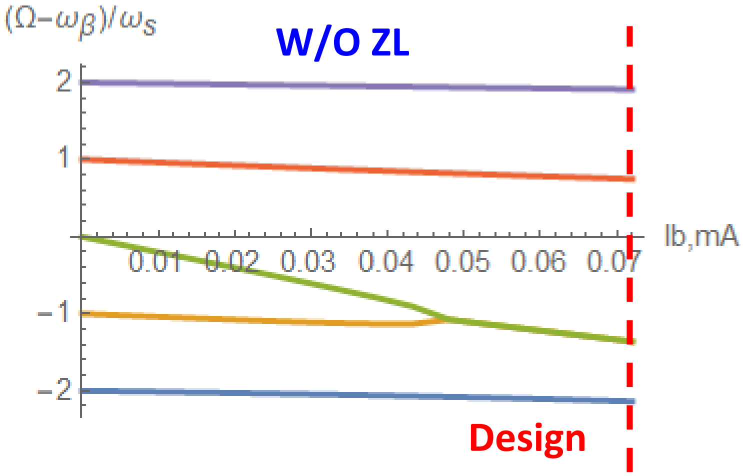


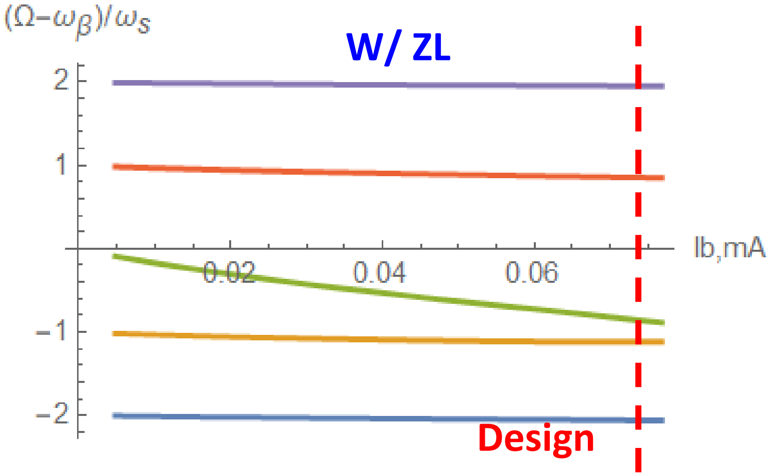
Reasonable large stable region even with the imaginary part of the impedance increased by a factor of 2, only with shift of the stable region.

⇒ To optimize the impedance to mitigate this effect, the real part of impedance should be well controlled, while the imaginary part can be more relaxed (NEG coating may not be necessarily less than 1μm).

Transverse mode coupling instability

- Fast instability, normally with beam losses.
- The instability threshold extends from 45μA to 85uA when considering bunch lengthening due to the longitudinal impedance.
- The instability will be further detuned when considering the bunch lengthening due to the beamstrahlung.



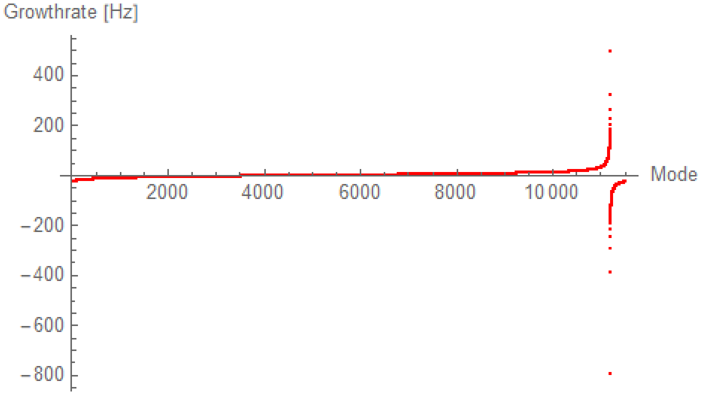


Transverse resistive wall instability

- ☐ The coupled bunch instability can be driven by the resonance at zero frequency of the transverse resistive wall impedance.
- ☐ An efficient bunch by bunch feedback damping of ~3 turns is required.
  - ☐ Multiple of feedback systems around the ring
  - ☐ Single mode damping specially for the RW is under consideration
  - ☐ A positive chromaticity tends to provide some extra damping

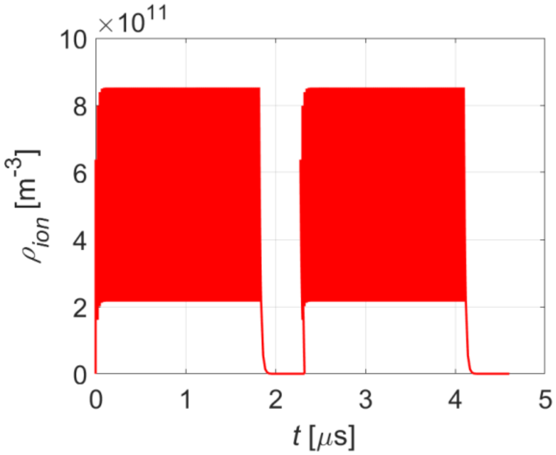
	Z-High Lumi
Instability growth time [ms]	2.0 (~6 turns)
Radiation damping [ms]	840
Bunch by bunch feedback [ms]	1.0 (~3 turns)

Growth of the most dangerous mode vs. damping factors



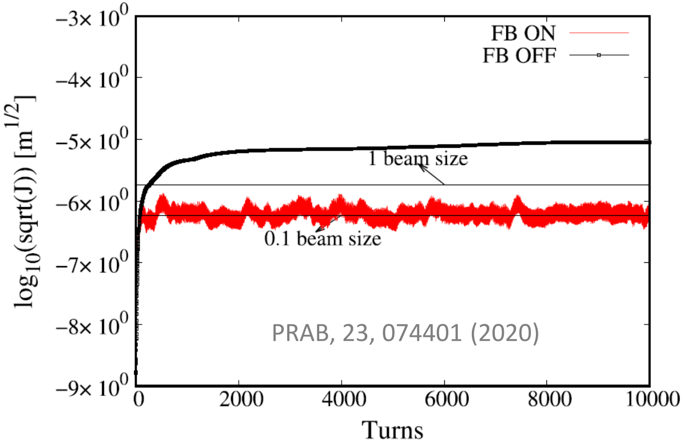
Beam ion effects

- Induce emittance blow-up and a positive tune shift along the bunch train.
- Filling pattern: {Ntrain=144, Bunch spacing=23ns, Gap=492ns}
- Beam size increase due to the beam ion interaction are foreseen.



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



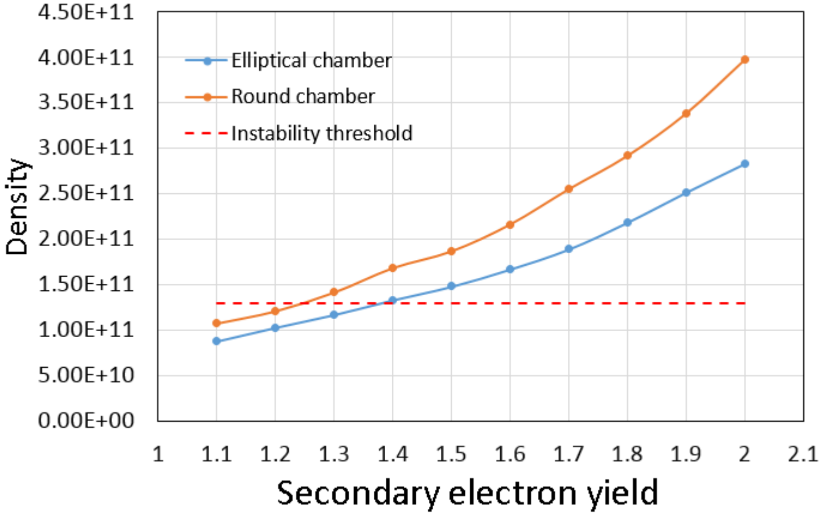
PRAB, 23, 074401 (2020)

Bunch by bunch feedback can be effective on damping this effect

Yudong Liu

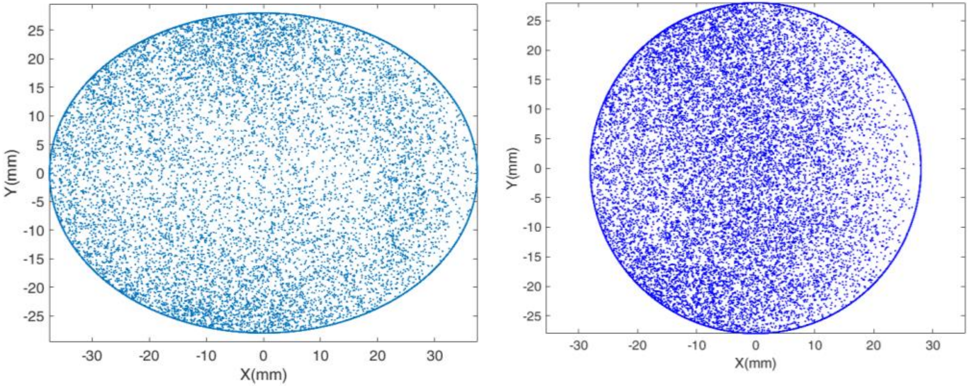
Electron cloud effects

- ☐ The electron density is increased due to the change of the chamber cross section. The SEY needs to be reduced to <1.2 by introducing NEG coating.
- ☐ More detailed simulations as well as evaluation of its induced heating are under going.



Elliptical chamber: SEY<1.3

Round chamber: SEY<1.2



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Summary

- ☐ Impedance model is updated regarding the change of the chamber cross section (elliptical→circular), as well as more impedance contributors included
- ☐ Key instability issues for high luminosity Z are investigated:
  - ☐ Coupling of the longitudinal impedance and the beam beam effects results in reduce of the stable beam-beam interaction region, the real part of the impedance should be well controlled.
  - ☐ TMCI is OK considering bunch lengthening induced by longitudinal impedance.
  - ☐ Resistive wall instability needs an efficient feedback damping of ~3 turns
  - ☐ Ecloud requires an SEY of less than 1.2 or adding antechambers.
  - ☐ Beam size increase due to the beam ion effect are foreseen ⇒ feedback system is needed to damp this effect.

Thank you for your attention!