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Institute of High Energy Physics
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BB2024
Lausanne

# Beam-Beam Effects at CEPC

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Thanks:
D. Shatilov, K. Oide, M. Migliorati

2-5. September. 2024, EPFL, ICFA mini-Workshop BB24

# Outline

- **Introduction**
- **Instability & Mitigation**
- **Optics distortion and lattice**
- **Summary**

# Design Parameters

**2 IPs, 2x16.5 mrad**
**100 km**

| | Higgs | Z |
|---|---|---|
| Beam Energy [GeV] | 120 | 45.5 |
| Damping Decrement (x/y/z, SR) | 0.75/0.75/1.5 $[10^{-2}]$ | 4/4/8 $[10^{-4}]$ |
| $\beta_x^*/\beta_y^*$ [m/mm] | 0.3/1 | 0.13/0.9 |
| $\epsilon_x/\epsilon_y$ [nm/pm] | 0.64/1.3 | 0.27/1.4 |
| $\sigma_z$ (SR/BS) [mm] | 2.3/4.1 | 2.5/8.7 |
| $\sigma_p$ (SR/BS) [%] | 0.1/0.17 | 0.04/0.13 |
| $\beta_y^*\theta/\sigma_x$ | 1.2 | 2.5 |
| Piwinski Angle | 4.88 | 24.23 |
| $\nu_s$ | 0.0049 | 0.035 |
| Bunch Population $[10^{10}]$ | 13 | 14 |
| $\xi_x/\xi_y$ | 0.015/0.11 | 0.004/0.127 |
| Bunch Number | 268 | 11934 |
| Luminosity/IP $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | 5 | 115 |

DOI:10.1007/s41605-024-00463-y

Radiation Detection Technology and Methods
https://doi.org/10.1007/s41605-024-00463-y

IHEP-CEPC-DR-2023-01

Received: 7 March 2024 / Revised: 7 March 2024 / Accepted: 9 March 2024

IHEP-AC-2023-01

CEPC

*Technical Design Report*

Accelerator

The CEPC Study Group
December 2023

P. Raimondi , *2nd SuperB Workshop, March 2006*
M. Zobov et al., PRL 104, 174801 (2010)

# Crab-waist collision

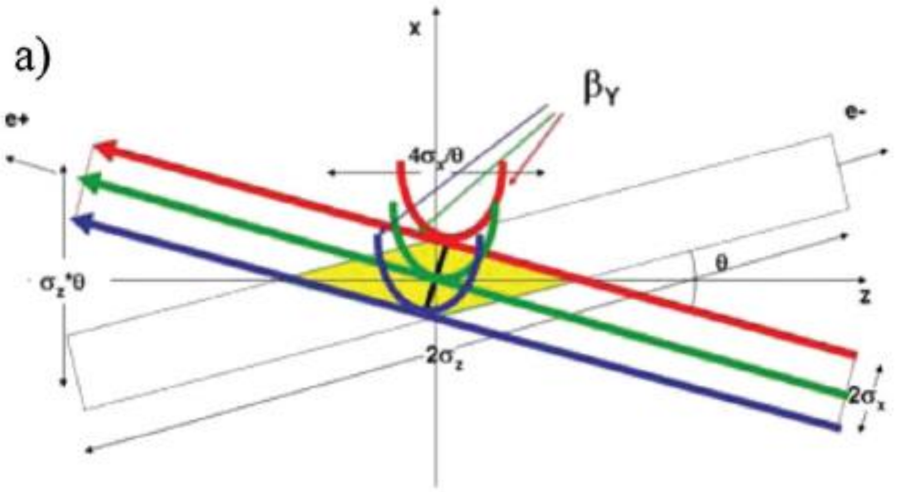
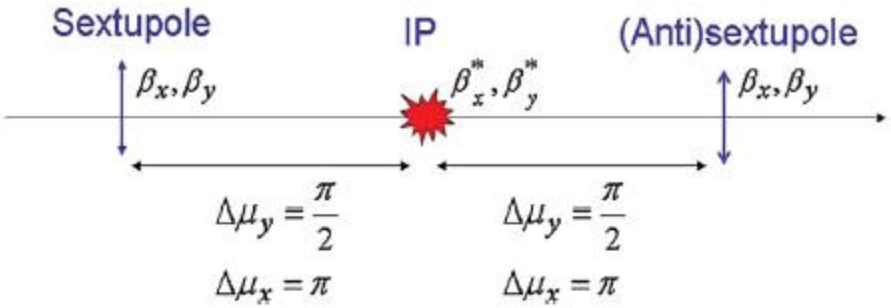


FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding $\beta$ function variations along these trajectories.

$$L \propto \frac{N\xi_y}{\beta_y^*}; \qquad \xi_y \propto \frac{N\sqrt{\beta_y^*/\varepsilon_y}}{\sigma_z\theta}; \qquad \xi_x \propto \frac{N}{(\sigma_z\theta)^2},$$

$$\varphi = \frac{\sigma_z}{\sigma_x}\tan\left(\frac{\theta}{2}\right) \approx \frac{\sigma_z}{\sigma_x}\frac{\theta}{2}.$$

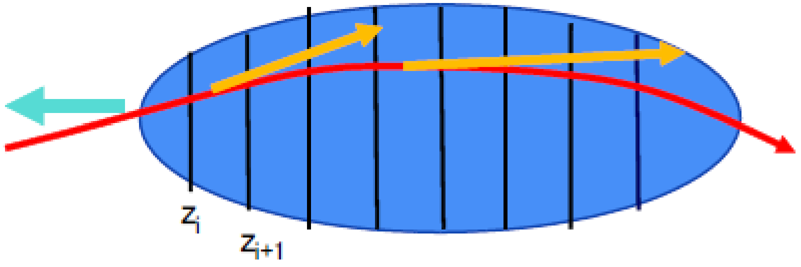
$$\beta_y^* \approx \frac{\sigma_x}{\theta} \ll \sigma_z.$$

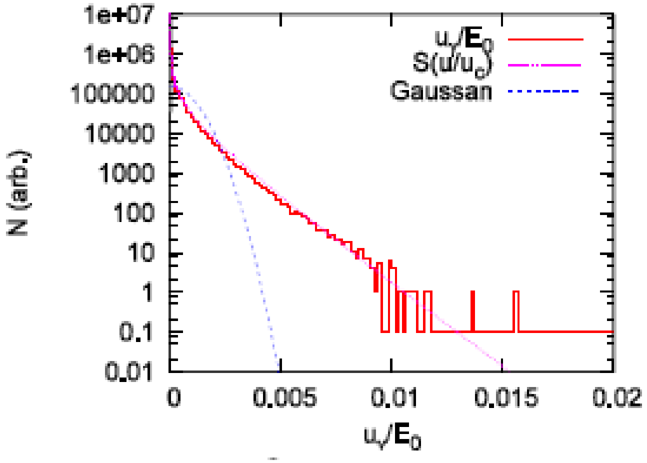


V. I. Telnov, PRL 110, 114801 (2013)
A. Bogomyagkov et al., Phys. Rev. ST Accel. Beams 17, 041004 (2014)
D. Shatilov, ICFA Beam Dyn. Newslett. 72, 30 (2017).

# Beamstrahlung Effect & 3D flip-flop

- Synchrotron radiation during beam-beam interaction
- High energy photon -> Momentum acceptance -> Lifetime
- Longer bunch length and Higher energy spread
- Asymmetrical beam blowup: 3D flip-flop





# Simulation Tool

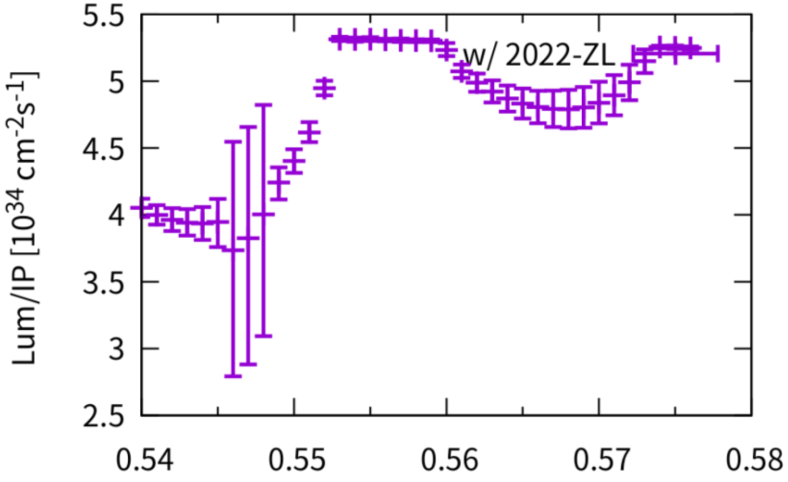
K. Hirata et al., PA 40, 205-228 (1993)
K. Hirata, PRL, 74, 2228 (1995)
Y. Zhang et al., PRST-AB, 8, 074402 (2005)
Y. Seimiya et al., PTP 127, 1099 (2012)
K. Ohmi, IPAC16
Y. Zhang et al., PRAB 23, 104402, (2020)

- Linear Arc Map with SR radiation
- One turn map including general chromaticity
- Horizontal crossing angle: Lorentz boost map
- Bunch slice number is about 10 times Piwinski angle
- Slice-Slice collision: Synchro-beam mapping method (or PIC)
- Synchrotron radiation during collision
- Longitudinal wakefield
- Transverse wakefield
- Space charge

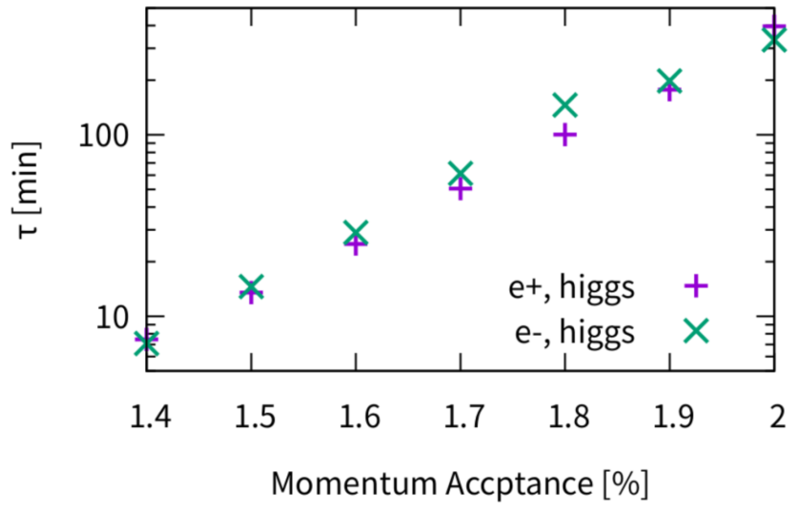
# Higgs (TDR)

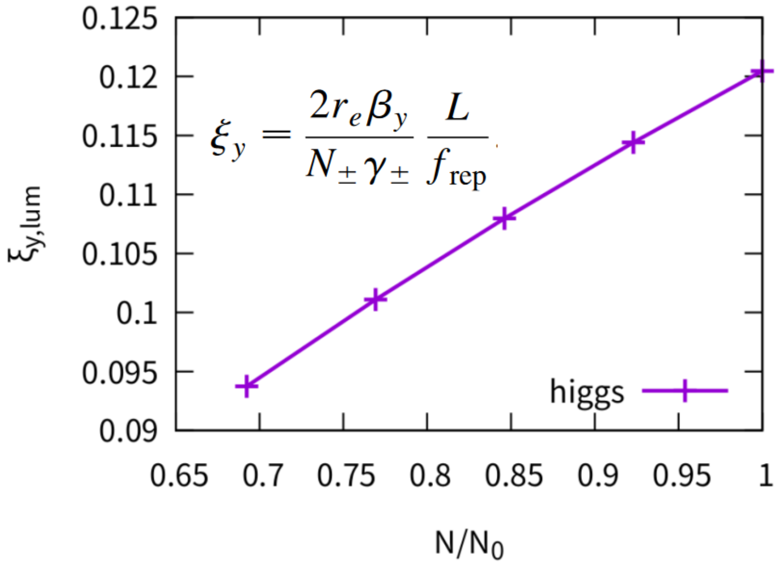
- The beamstrahlung lifetime is very sensitive to the bunch population

Luminosity versus horizontal tune

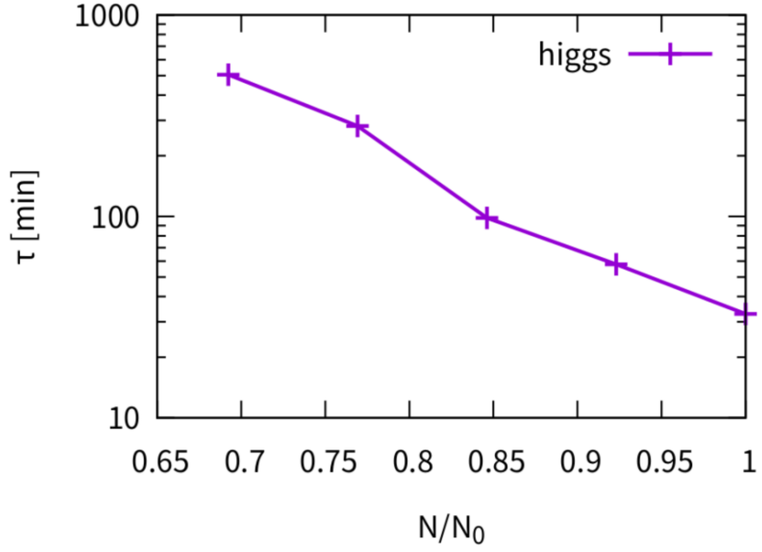


Beamstrahlung Lifetime vs Momentum Acceptance

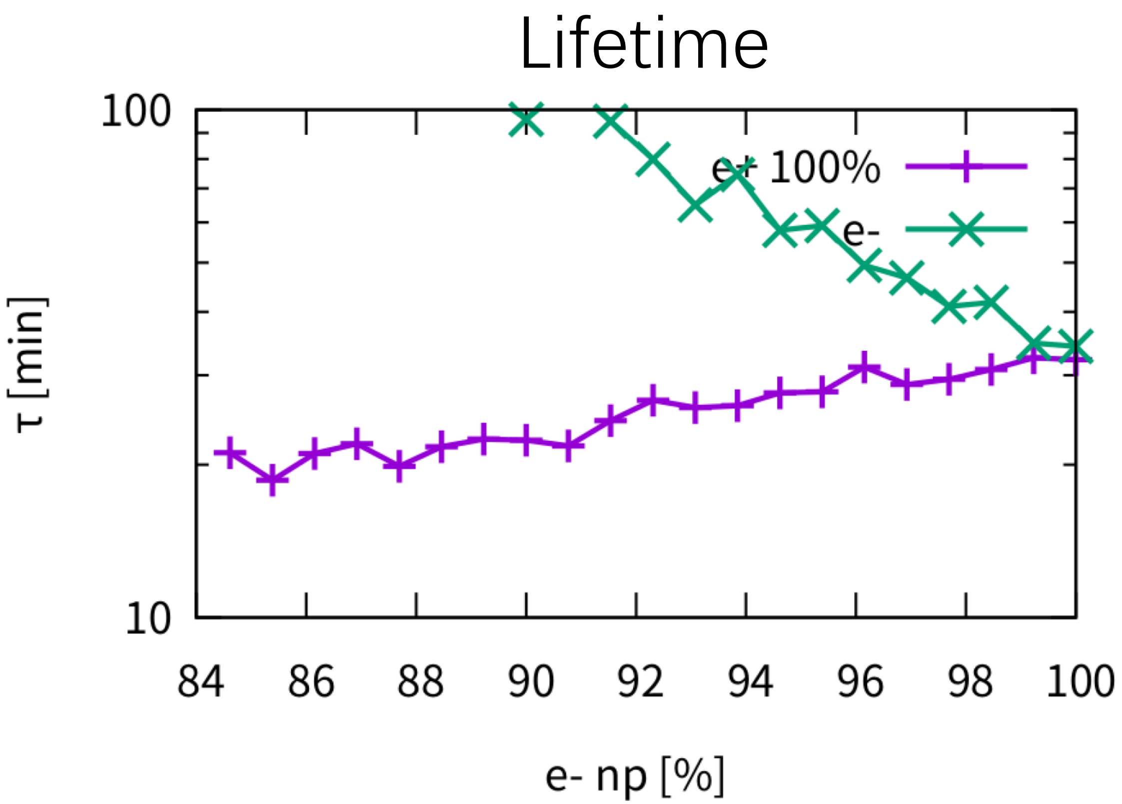


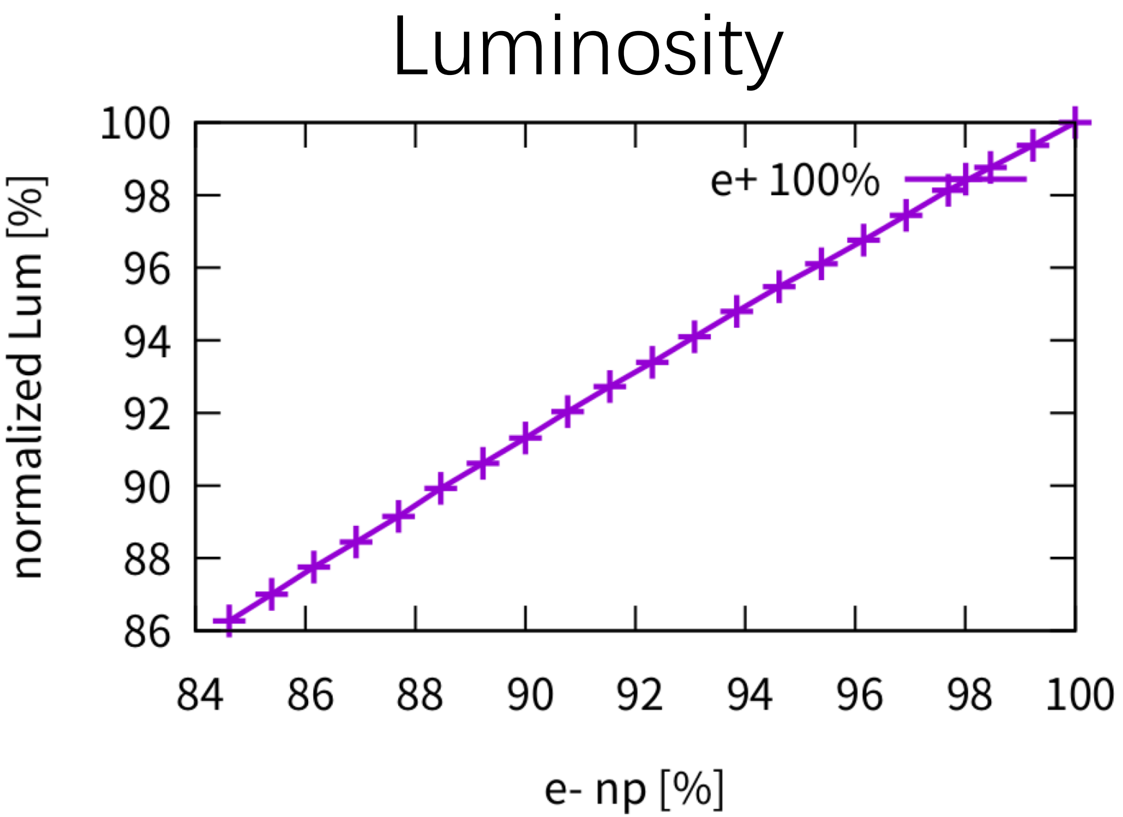


$$\xi_y = \frac{2r_e\beta_y}{N_\pm\gamma_\pm}\frac{L}{f_\text{rep}}$$



# Higgs (TDR) – asymmetric bunch population

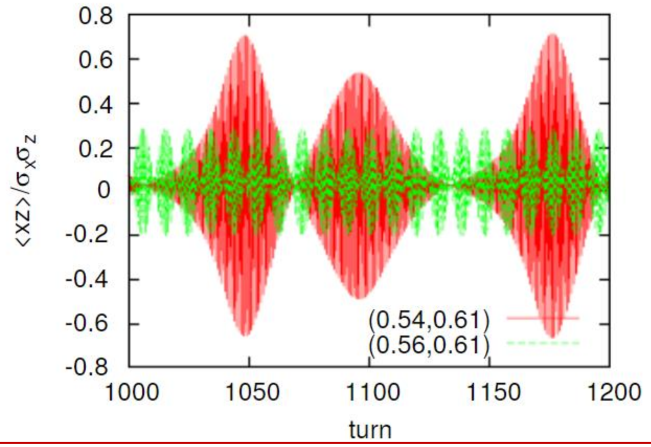




- The weak beam’s lifetime would be about only half with collision between 100% vs 90% bunch population. (100% vs 97%: ~20% lifetime reduction)
- The luminosity scale linearly with the weak beam’s bunch population

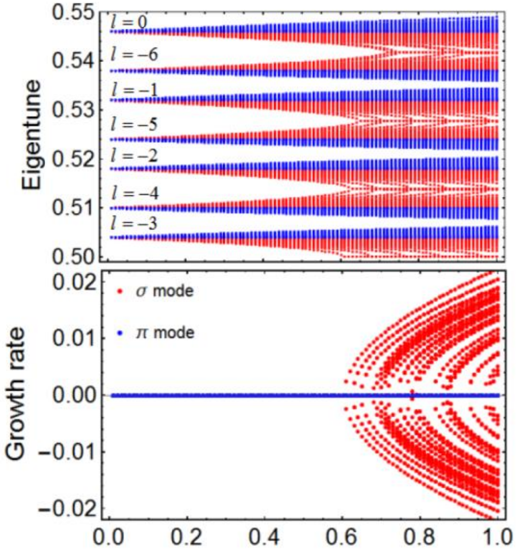
Larger $\nu_s/\xi_x$ is preferred

# Horizontal Beam-Beam Instability (X-Z)

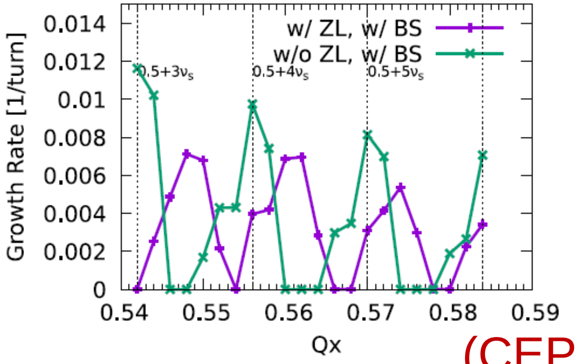


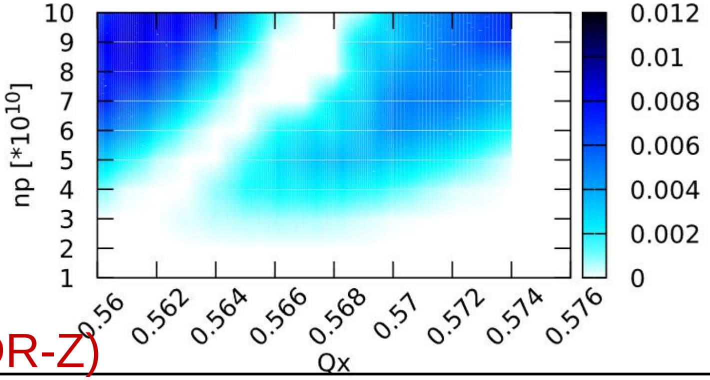
K. Ohmi, Int. J. Mod. Phys. A, 31, 1644014 (2016).
K. Ohmi and et al., PRL 119, 134801 (2017)
N. Kuroo et al, PHYS. REV. ACCEL. BEAMS 21, 031002 (2018)
Y. Zhang etal., PRAB 23, 104402, (2020)
C. Lin etal.,, PRAB 25, 011001 (2022)

**w/o ZL**



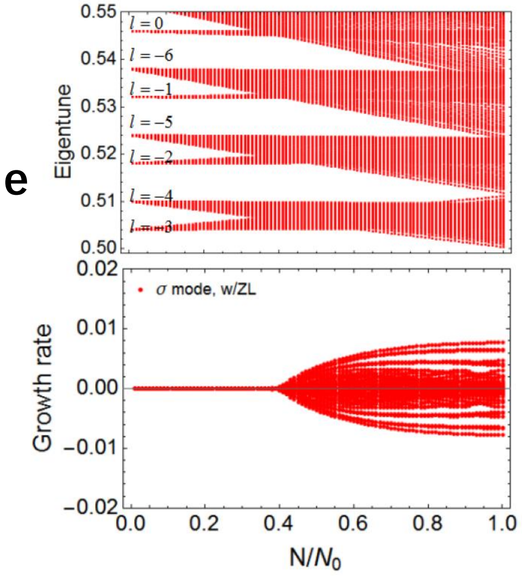
By including the impedance stable areas become narrower and are shifted





(CEPC-CDR-Z)

**w/ ZL, σ mode**

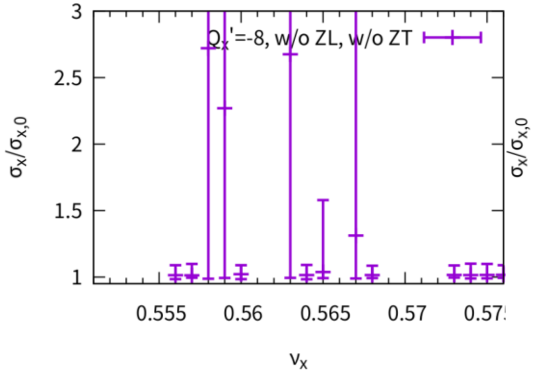


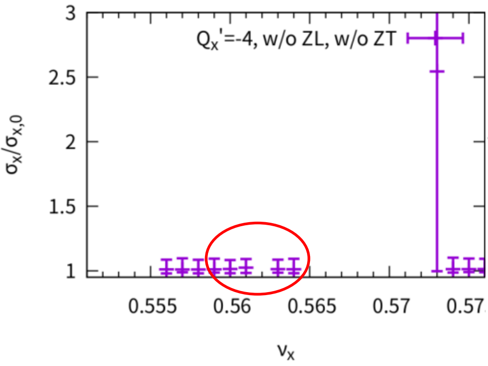
Growth rate versus horizontal tune, w/ and w/o ZL

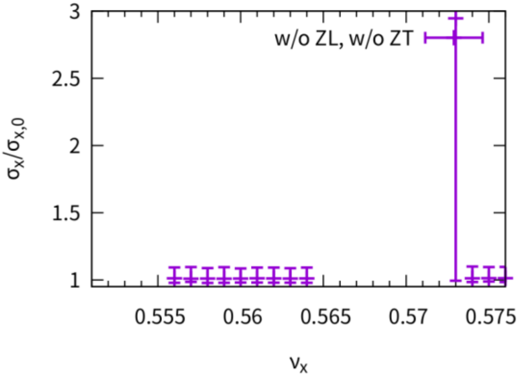
Growth rate versus bunch population, w/ ZL

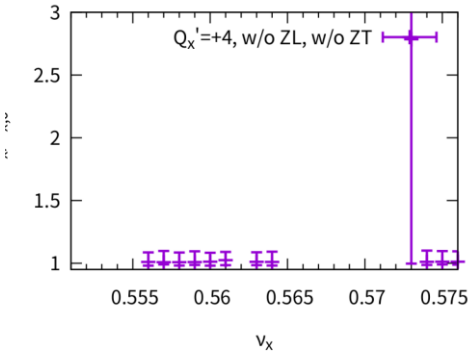
# Effect of Chromaticity on X-Z instability w/o ZL, w/o ZT, simulation

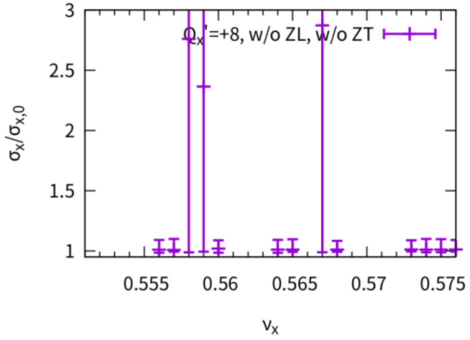
- Qx’=-8/-4/0/4/8 is scanned at different horizontal tune
- Sign of chromaticity make no difference
- New unstable working point appear with finite chromaticity
- Stable working point is more uncertain with large chromaticity
- **Chromaticity is detrimental** (w/o ZL)







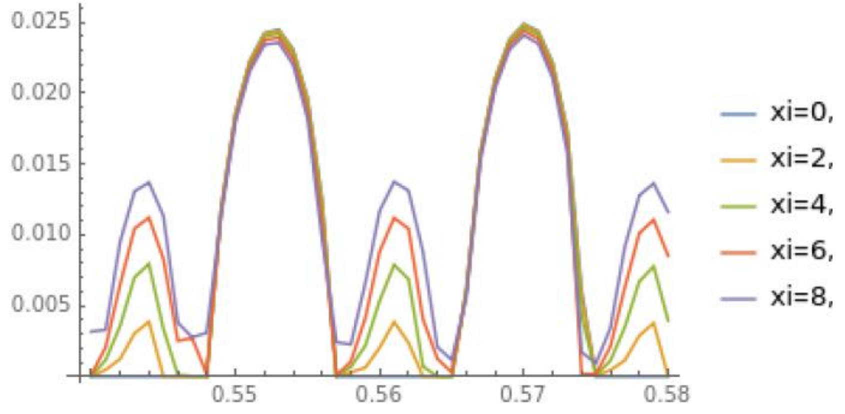




# Effect of Chromaticity on X-Z instability w/o ZL, w/o ZT, analysis

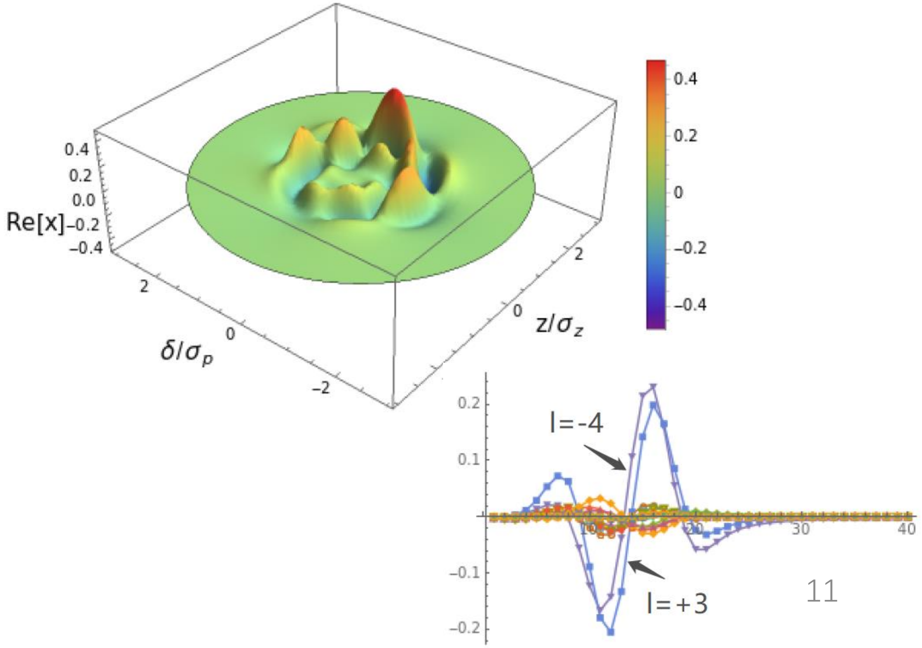
Tune scan at design bunch population

- The growth rate nearly keep unchanged with chromaticity in unstable tune region of zero chromaticity
- New unstable region appear with increase of chromaticity



@Qx=0.559

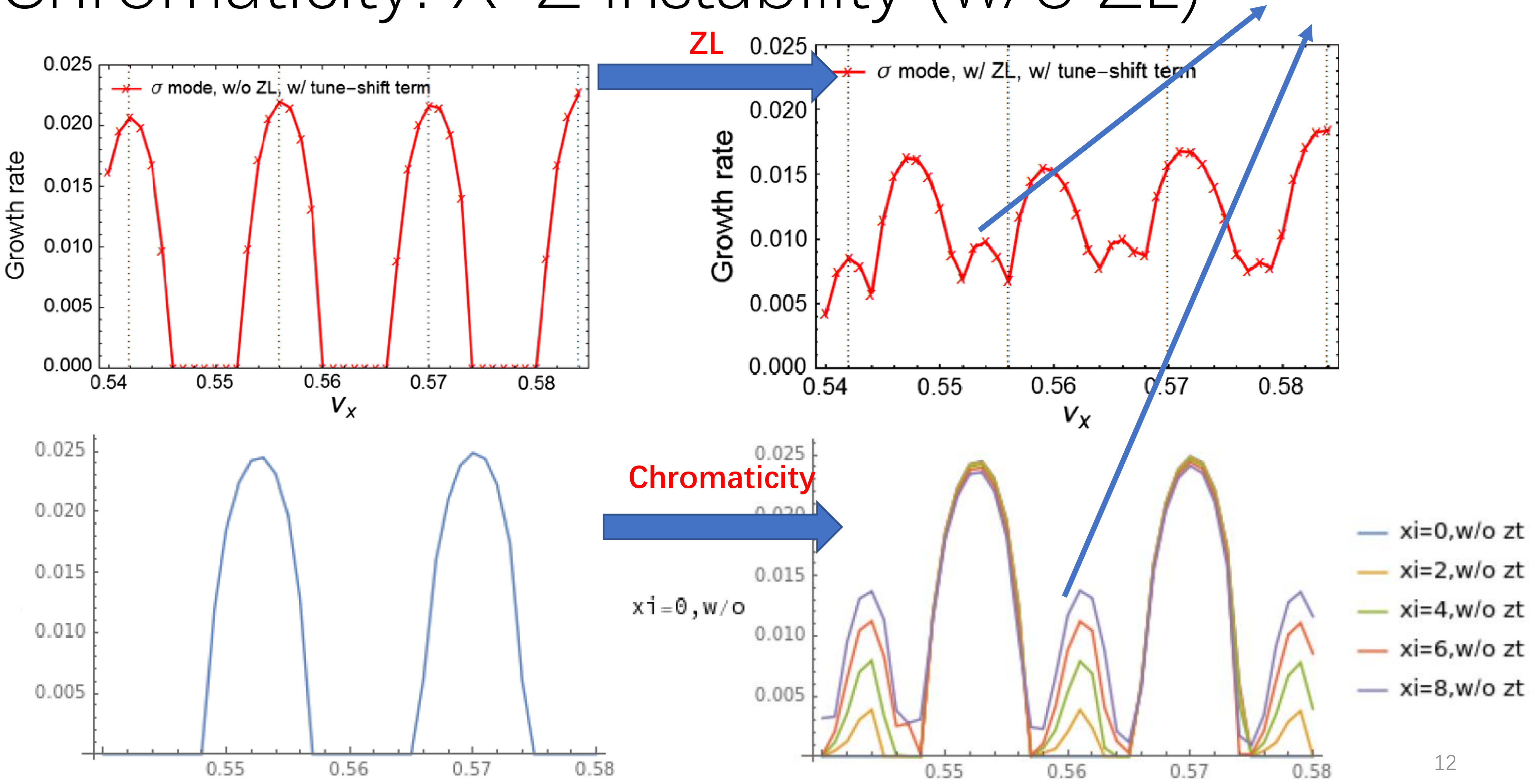
- It is suspected that the most unstable mode would not appear in the simulation,
- Some unstable mode may be induced referring to the simulation (remains to be done)
- More detailed intra-bunch information in the simulation need to be inspected, as well as the unstable mode in the analysis.



C. Lin etal,PRAB 25, 011001 (2022)

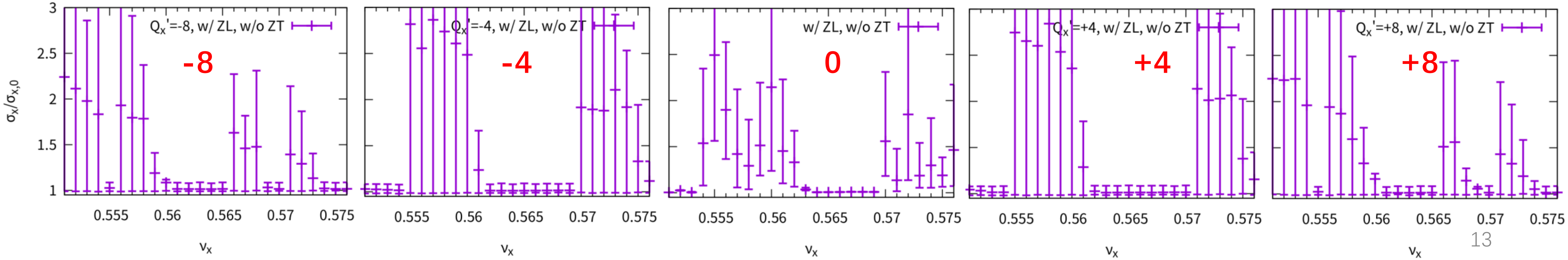
# Chromaticity: X-Z instability (w/o ZL)

**Similar?**



# Effect of Chromaticity on X-Z instability w/ ZL, w/o ZT, simulation

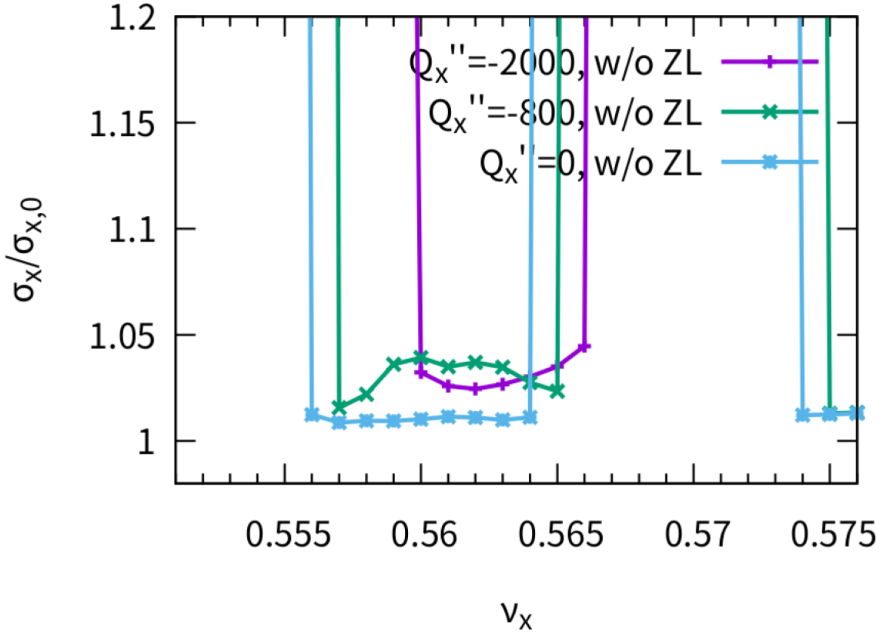
- Qx’=-8/-4/0/4/8 is scanned at different horizontal tune
- Sign of chromaticity make no difference
- Stable tune area increase with proper chromaticity (Qx’=+-4)
- Stable tune area may reduce with large chromaticity
- Chromaticity could be helpful (w/ ZL), since Chromaticity and PWD both induce coupling between different parity mode.

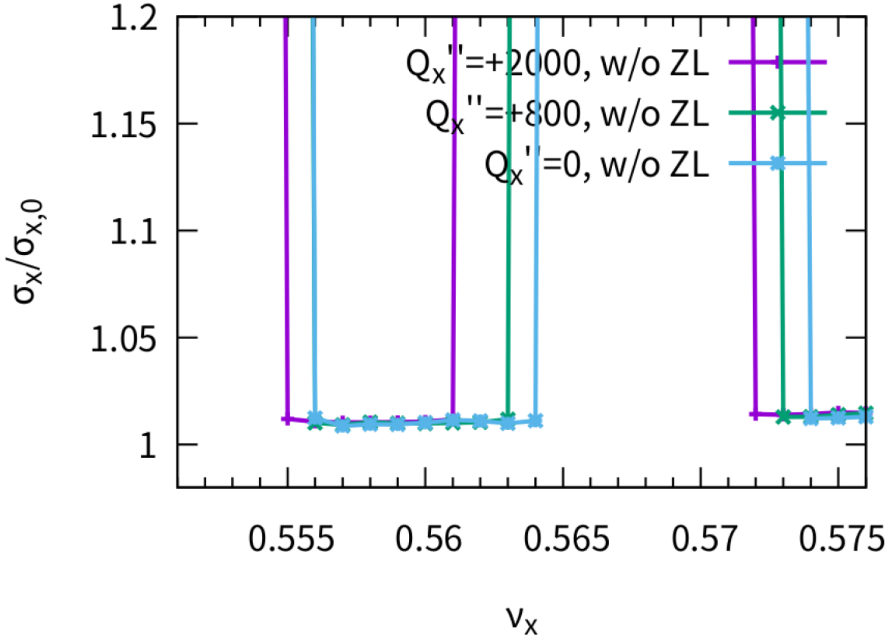


# $2^{nd}$ order chromaticity on X-Z instability w/o ZL, w/o ZT, simulation

$$\nu(\delta) = \nu_0 + \nu_1\delta + \nu_2\delta^2$$

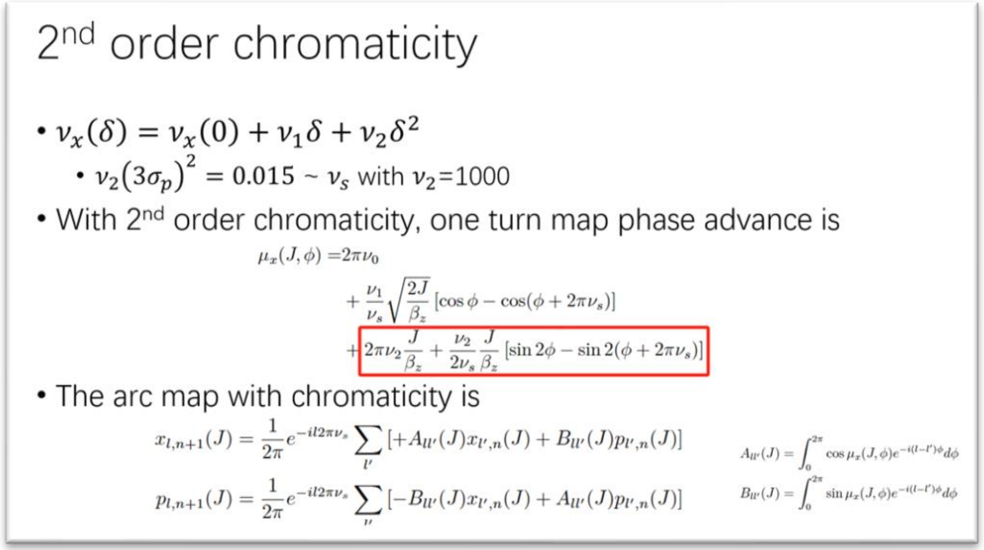
- $\nu_2$=-2000/-800/0/+800/+2000 is scanned in simulation
- Finite $\nu_2$ is detrimental for instability
    - The left(right) side of stable tune region ($\nu_2$=0) may become unstable for minus(positive) $2^{nd}$ order chromaticity





# $2^{nd}$ order chromaticity on X-Z instability w/o ZL, w/o ZT, Analysis

- Analysis results agrees with simulation basically
- The eigen mode distribution induced by finite chromaticity is not singular, and is expected to appear in simulation



## $2^{nd}$ order chromaticity

- $\nu_x(\delta) = \nu_x(0) + \nu_1\delta + \nu_2\delta^2$
  - $\nu_2(3\sigma_p)^2 = 0.015 \sim \nu_s$ with $\nu_2$=1000
- With $2^{nd}$ order chromaticity, one turn map phase advance is

$$\begin{aligned}\mu_x(J,\phi) =&2\pi\nu_0\\ &+\frac{\nu_1}{\nu_s}\sqrt{\frac{2J}{\beta_z}}\,[\cos\phi-\cos(\phi+2\pi\nu_s)]\\ &+\boxed{2\pi\nu_2\frac{J}{\beta_z}+\frac{\nu_2}{2\nu_s}\frac{J}{\beta_z}\,[\sin 2\phi-\sin 2(\phi+2\pi\nu_s)]}\end{aligned}$$

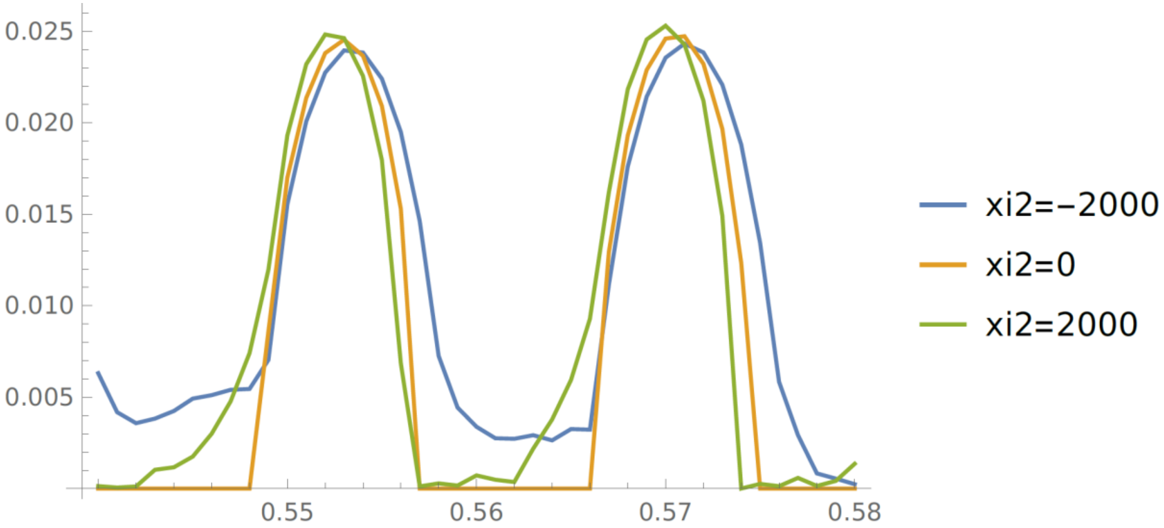
- The arc map with chromaticity is

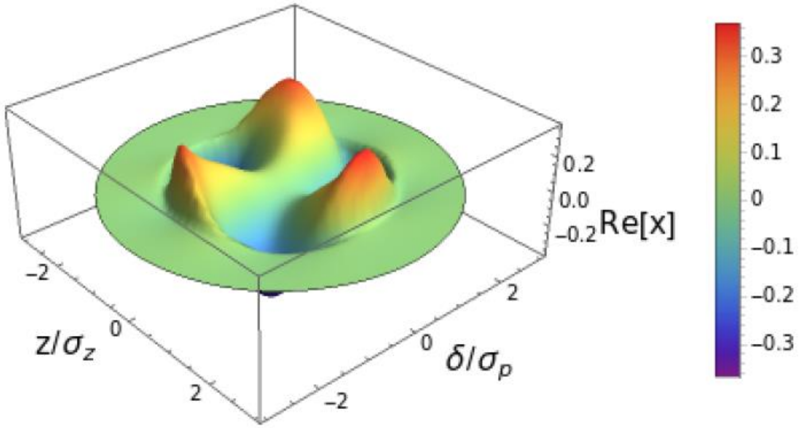
$$x_{l,n+1}(J) = \frac{1}{2\pi}e^{-il2\pi\nu_s}\sum_{l'}[+A_{ll'}(J)x_{l',n}(J) + B_{ll'}(J)p_{l',n}(J)]$$

$$p_{l,n+1}(J) = \frac{1}{2\pi}e^{-il2\pi\nu_s}\sum_{l'}[-B_{ll'}(J)x_{l',n}(J) + A_{ll'}(J)p_{l',n}(J)]$$

$$A_{ll'}(J) = \int_0^{2\pi}\cos\mu_x(J,\phi)e^{-i(l-l')\phi}d\phi$$

$$B_{ll'}(J) = \int_0^{2\pi}\sin\mu_x(J,\phi)e^{-i(l-l')\phi}d\phi$$

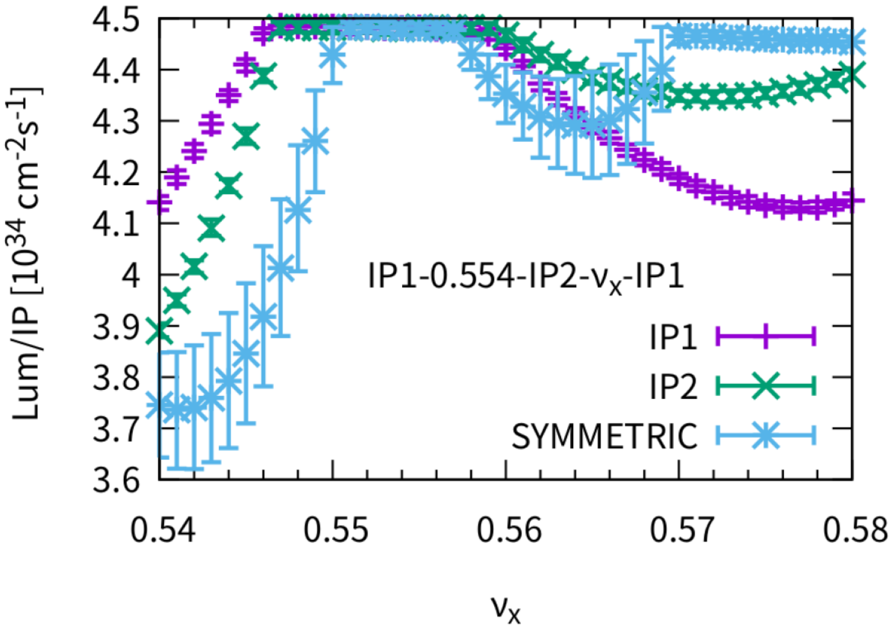


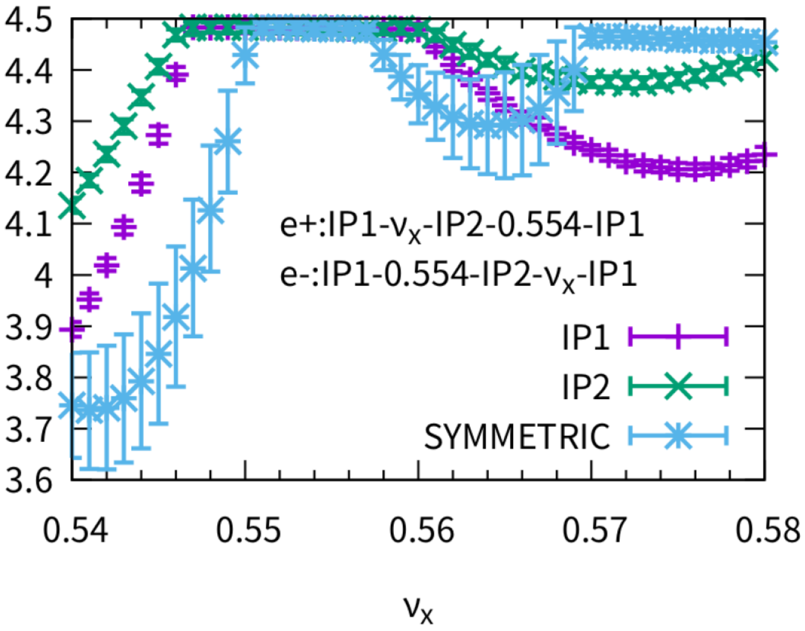


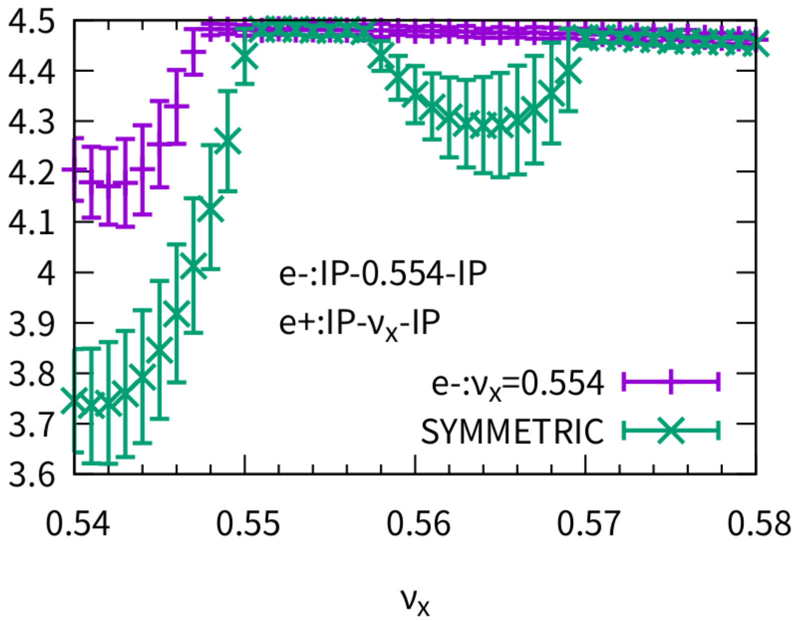
Eigen-mode distribution: Qx=0.558, $\nu_2$=-2000

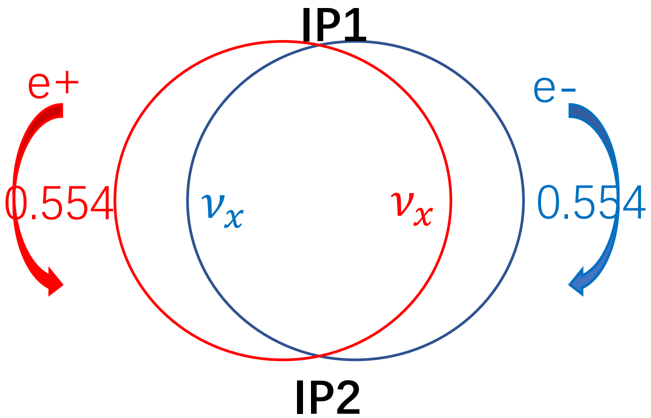
**It is best for same phase advance between two half rings in one ring.**

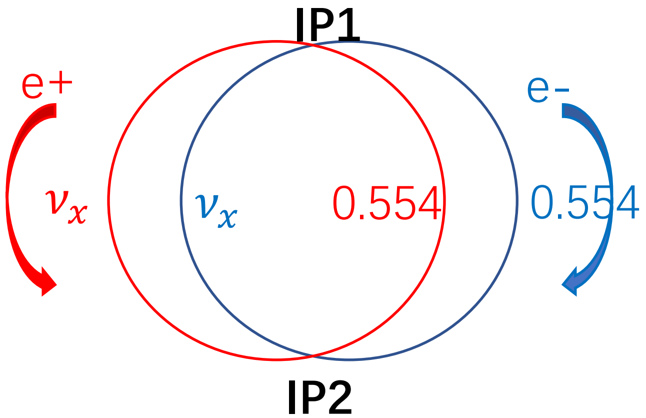
# X-Z instability: Asymmetric two half rings

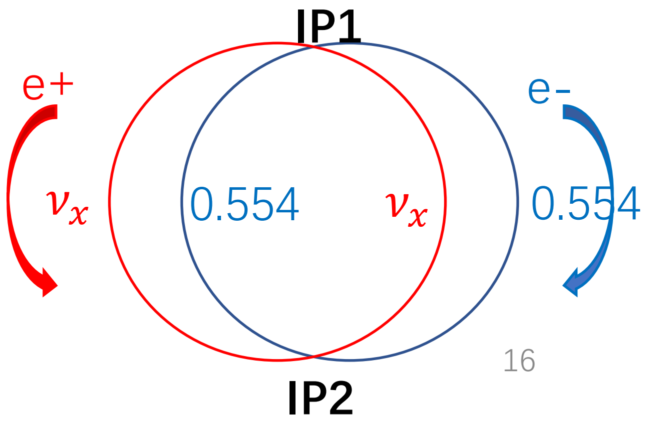






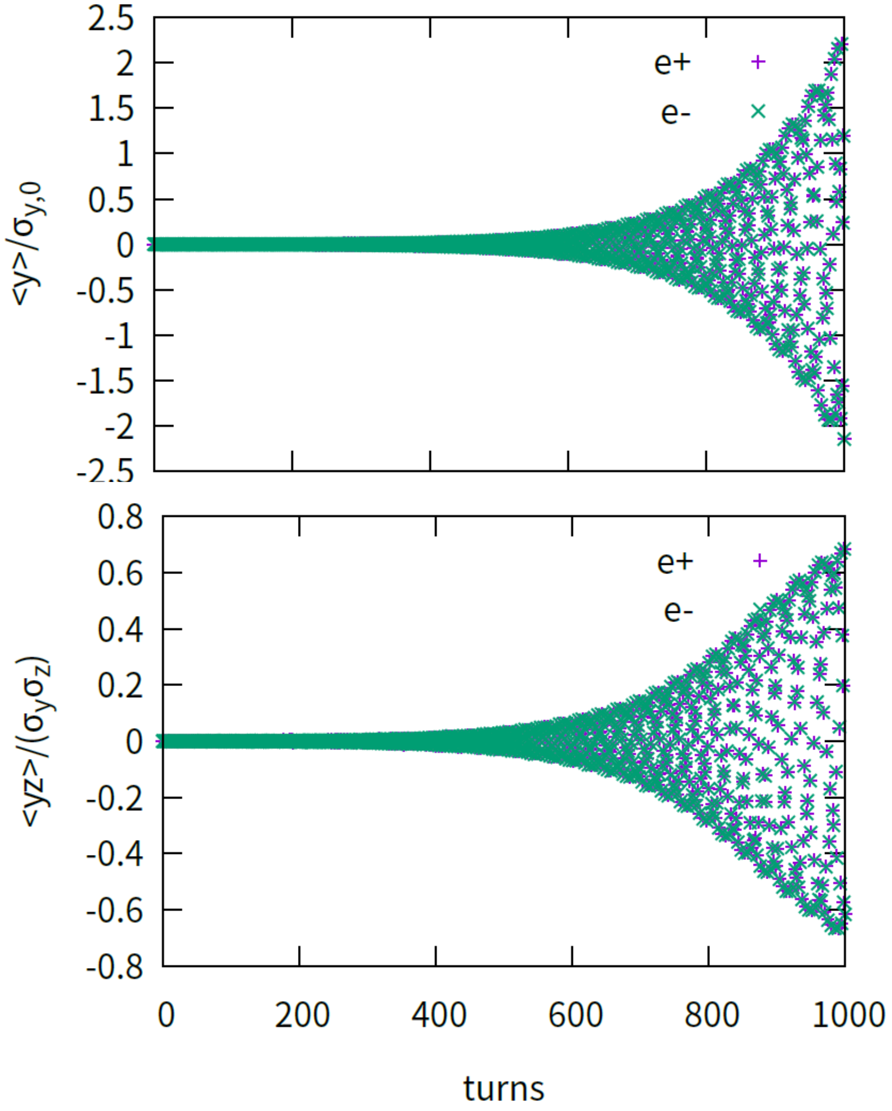


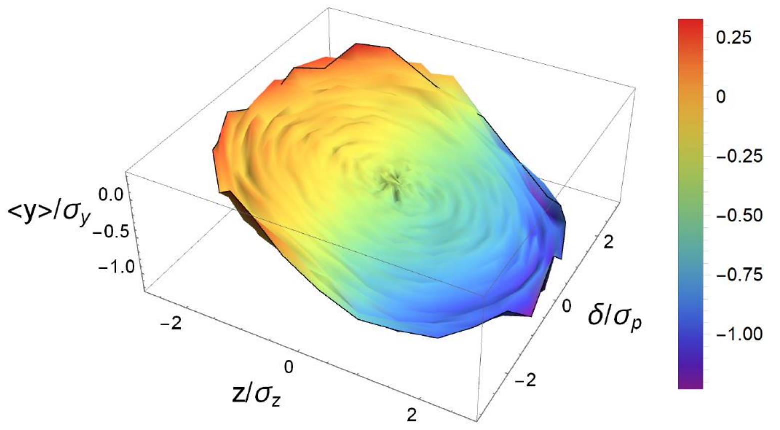




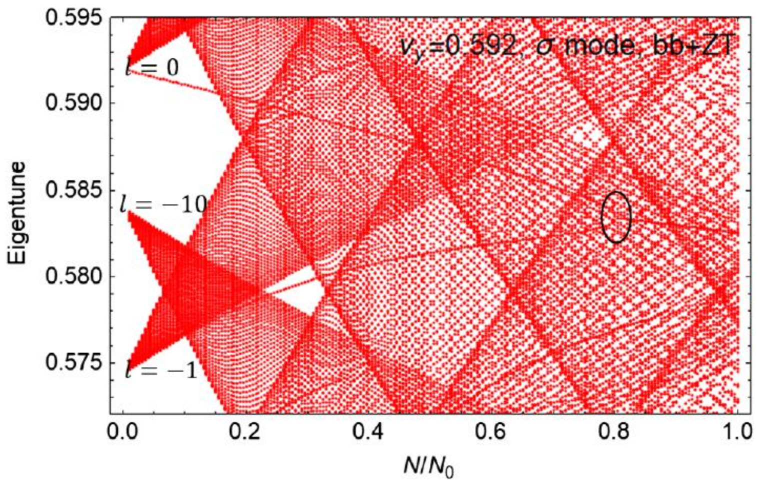
Y. Zhang et al., PRAB 26, 064401 (2023)
K. Ohmi et al., PRAB 26, 111001 (2023)

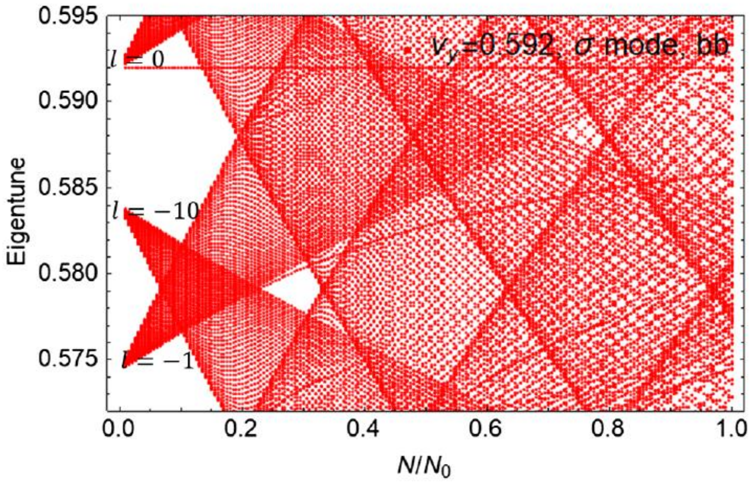
# Vertical mode coupling with ZT($\boldsymbol{\sigma}$-mode)





TMCI threshold is reduced from about 21e10 to 11e10 (2022 impedance)



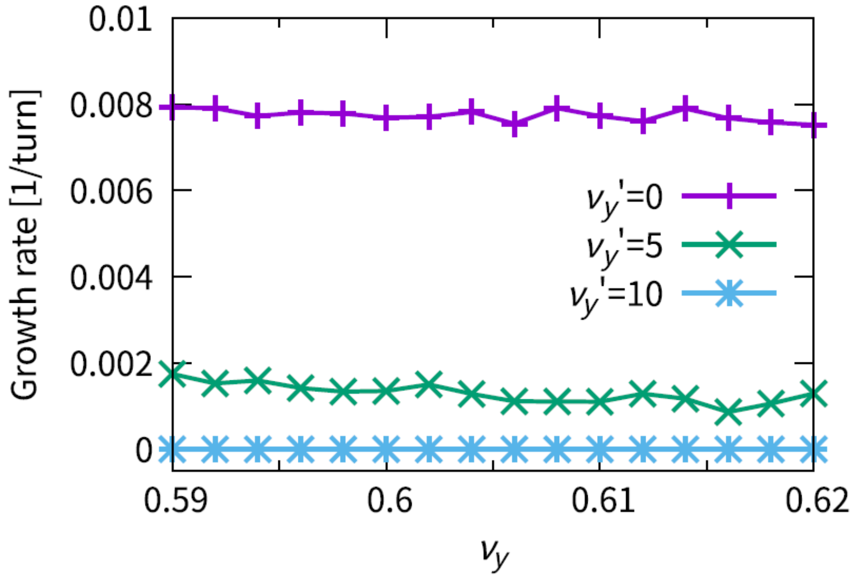


Y. Zhang et al, PRAB 26, 064401 (2023)
Thanks: K. Oide

# Mitigation of Vertical TMCI (BB+ZT)

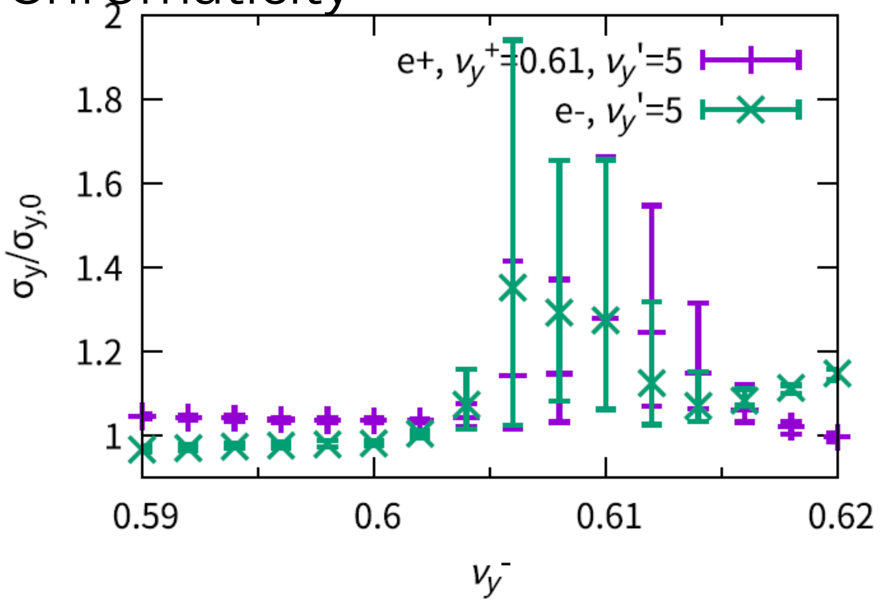
(2022 impedance)

## Chromaticity



Growth rate of vertical centroid versus tune with different vertical chromaticity. Both transverse and longitudinal impedance are considered.

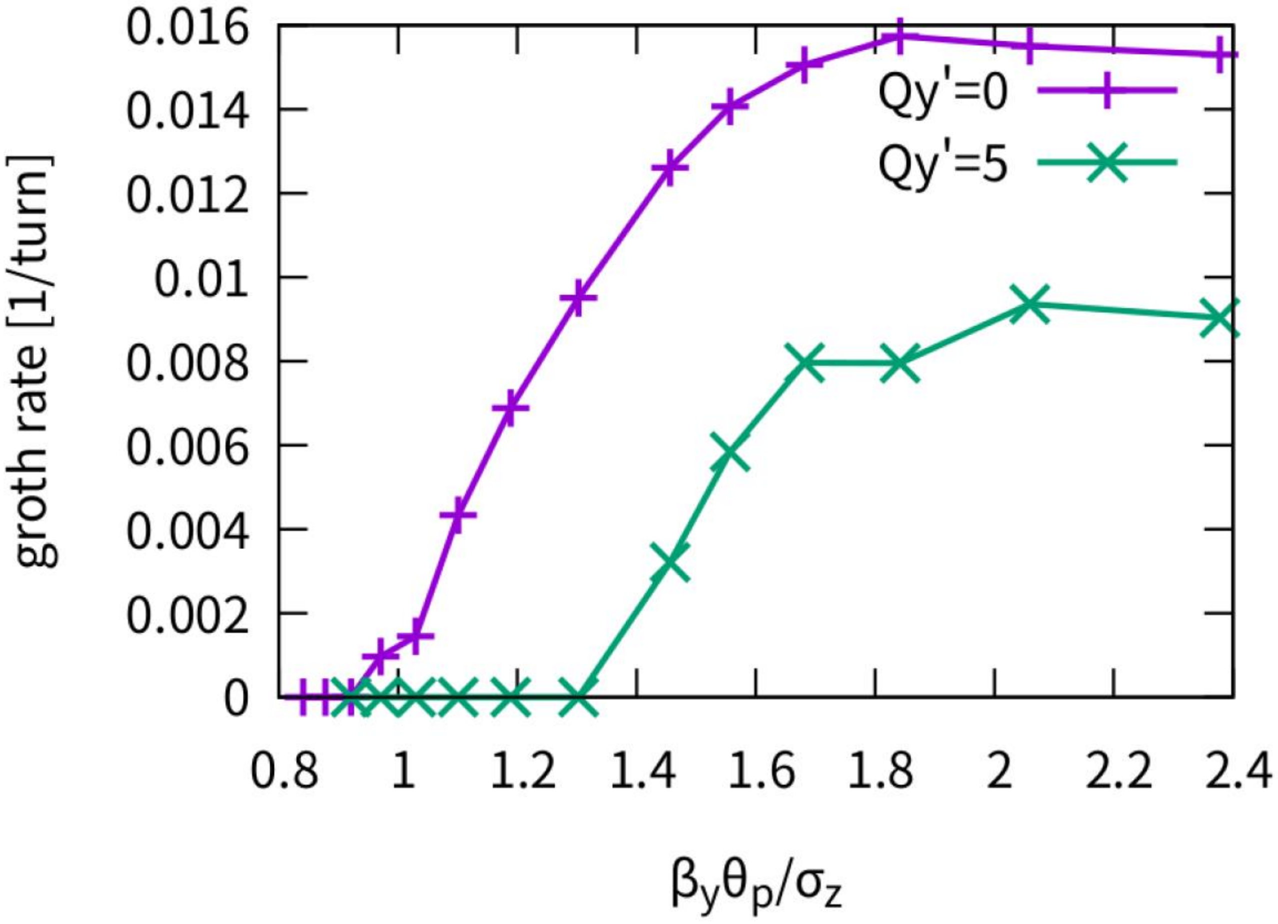
## Asymmetrical Tunes + Chromaticity



vertical beam size versus asymmetric vertical tunes with different vertical chromaticity. Both transverse and longitudinal impedance are considered. One beam’s vertical working point is fixed at 0.610.

Thanks: K. Ohmi

# Hourglass effect on vertical TMCI



Hourglass effect may help mitigate vertical TMCI when $\frac{\beta_y}{\sigma_z/\theta_p} < 1.6$.

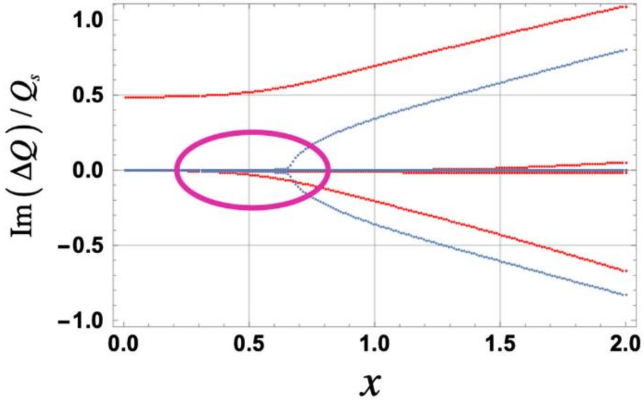
- Scan emitx, w/ ZY, w/ ZL
- Off beamstrahlung, but similar bunch length and energy spread

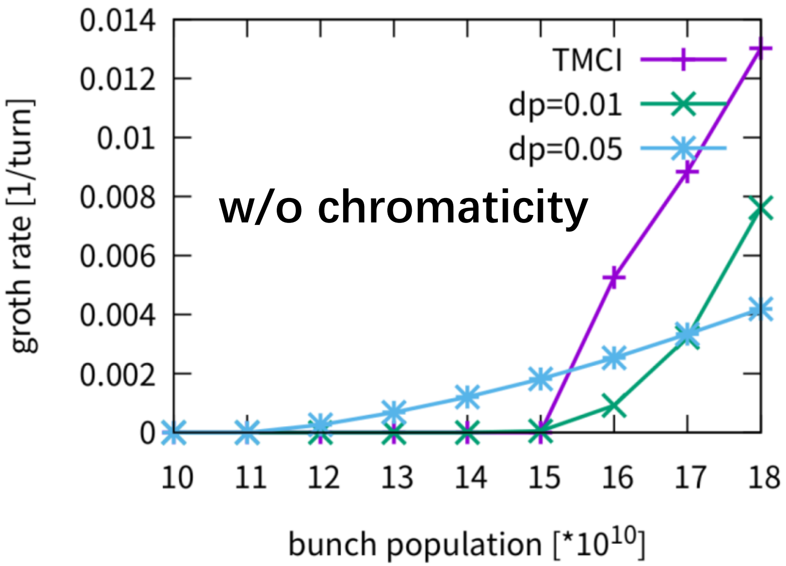
Thanks: M. Zobov, M. Migliorati

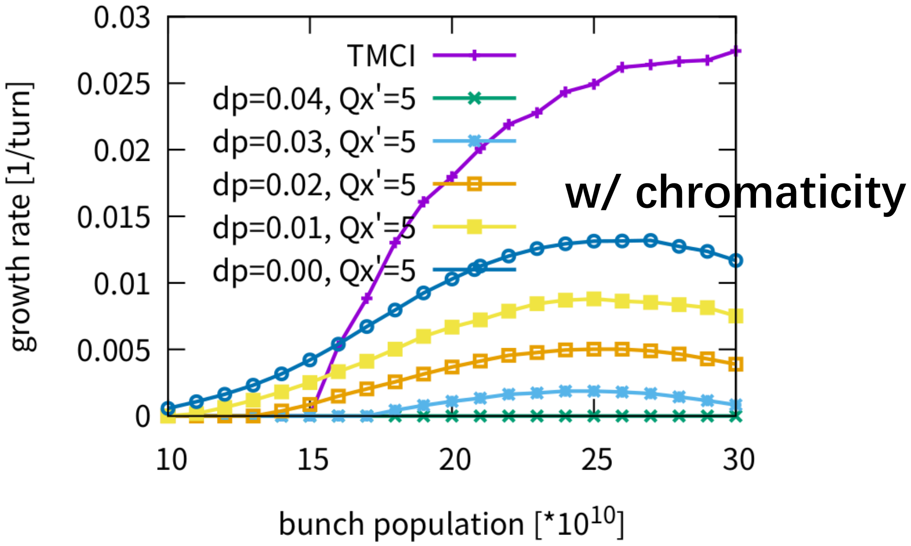
# Effect of feedback on **single bunch** instability (w/o and w/ chromaticity)

- A simplified resistive damper is used: $\Delta p_i = -2 d_p p_i$
- Strong feedback reduce the TMCI threshold.
- Growth rate is lower with feedback above threshold
- w/ chromaticity, strong feedback could be helpful

Fig. 3, E. Metral, PRAB, 24, 041003 (2021)





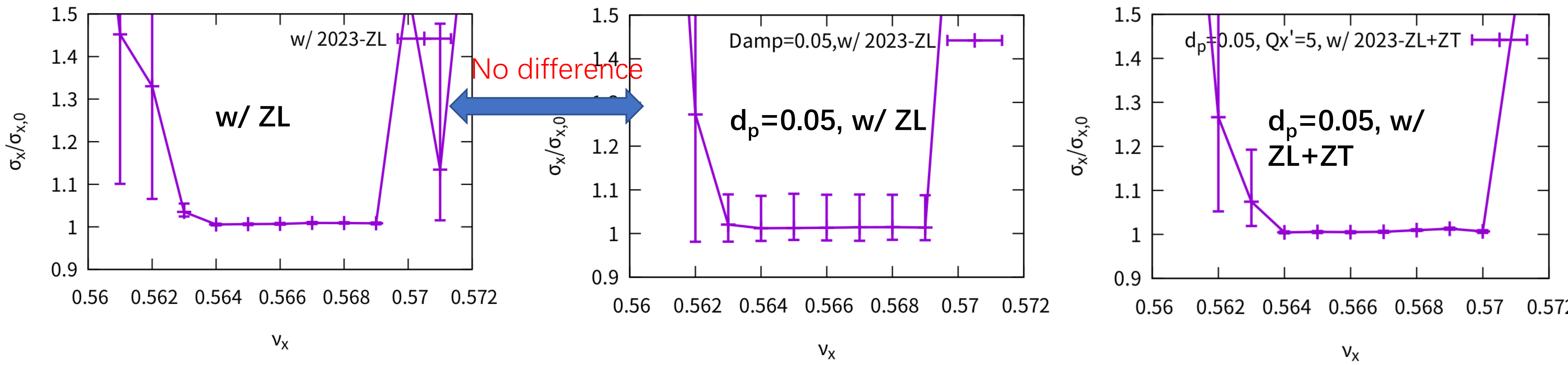


D. Shatilov,
*ICFA Beam Dyn.Newslett.* 72 (2017) 30-41

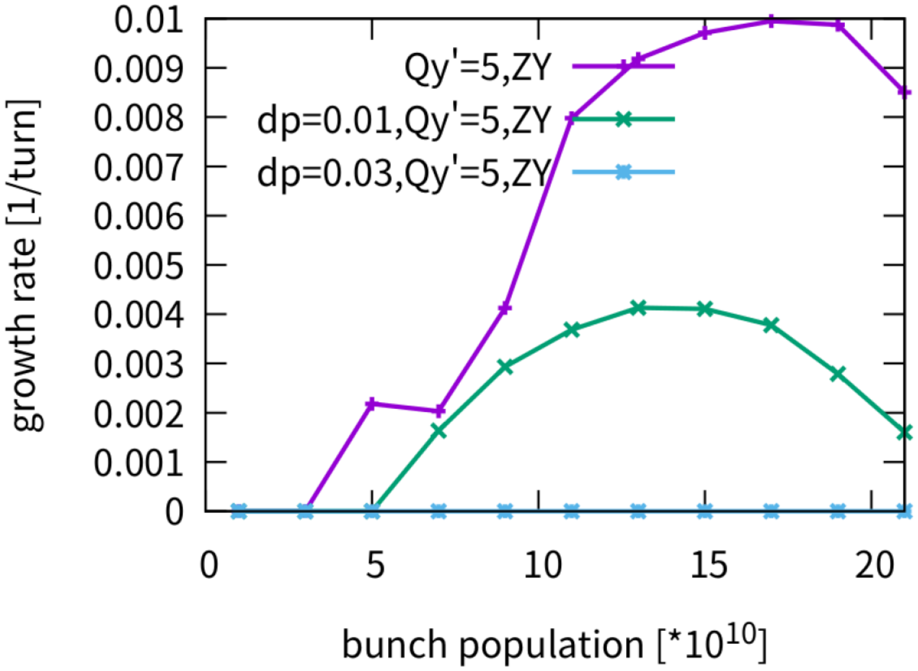
# Resistive feedback on X-Z instability

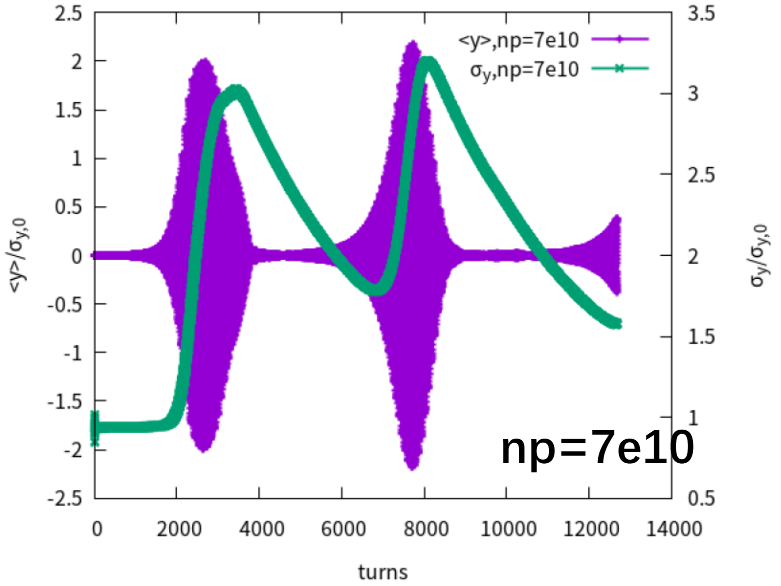
- Not helpful to mitigate X-Z instability
- X-Z instability could not be suppressed by feedback, since no dipole oscillations

- w/ ZT, no stable working point at design bunch population due to TMCI (not shown)
- Strong resistive feedback (with finite chromaticity) could help mitigate TMCI, similar to single bunch
- The stable tune region (w/ ZT+feedback) is same as that (w/o ZT and w/o feedback)



# Resistive feedback on vertical TMCI (Qy’=5)

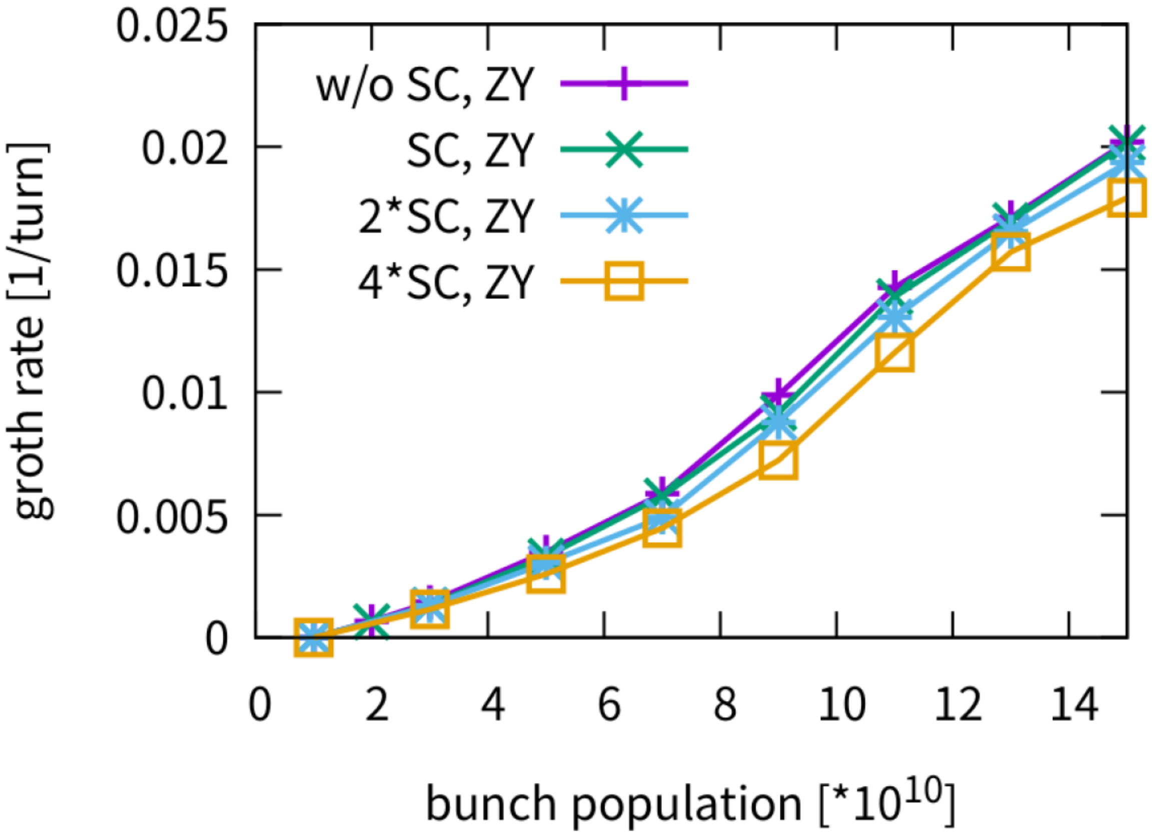




- With finite tune chromaticity, resistive feedback is helpful to mitigate the instability
- Damp rate from chromaticity would increase with bunch population, which induces that the growth rate near 20e10 is even slower than that at low bunch population.

# Space charge (Z)

- $\Delta\nu_{y,sc} = -\frac{Nr_e}{(2\pi)^{3/2}\sigma_z\beta^2\gamma^3}\oint ds\,\frac{\beta_y}{(\sigma_x+\sigma_y)\sigma_y} \sim -\mathbf{0.02}$ (full ring)

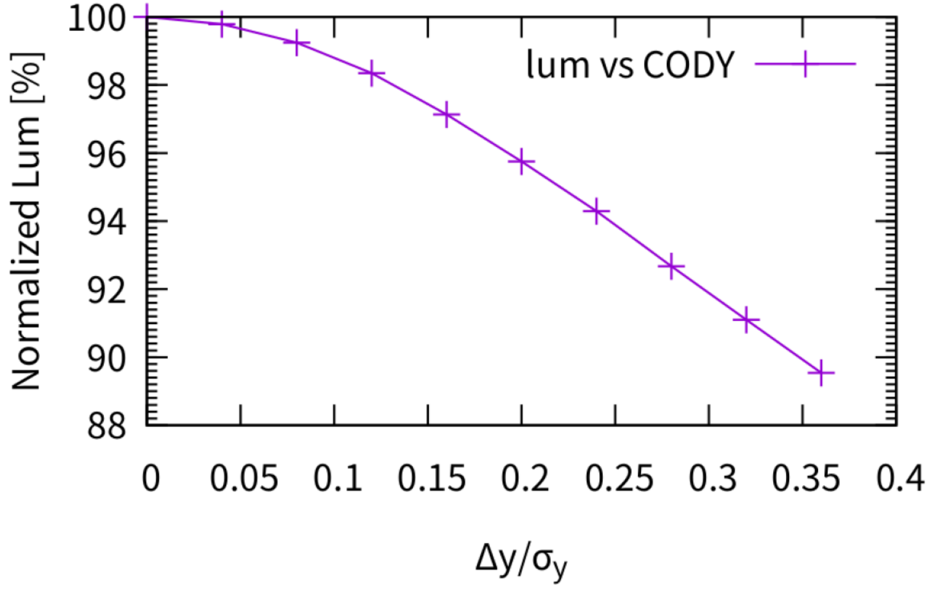


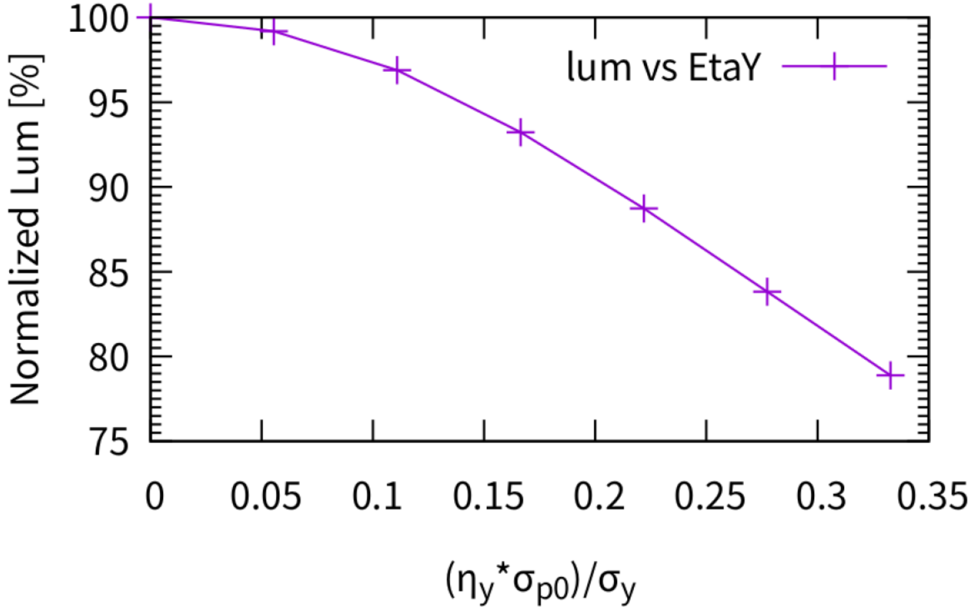
- Mitigation effect coming from space charge is found, while limited
- Beamstrahlung effect is included, initial bunch length is that of the designed bunch population

Error only exit in one beam(ring)

# Optics distortion: Vertical COD and Vertical Dispersion

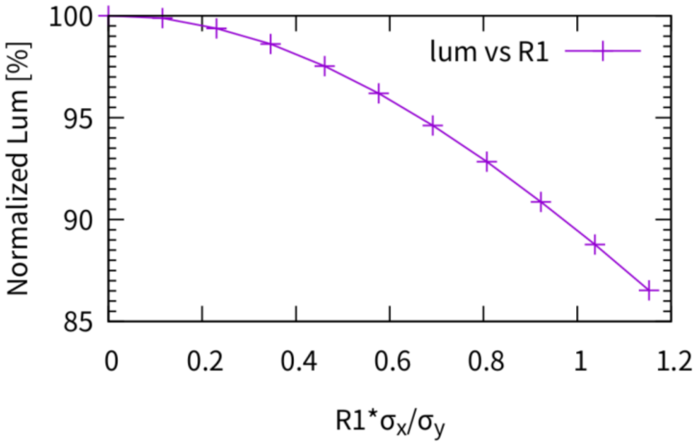
- $\Delta y < 0.3\sigma_y$ is required to keep luminosity loss < 10%
- $\eta_y \sigma_{p,0} < 0.2\sigma_y$ is required to keep luminosity loss < 10% (beamstrahlung + vertical emittance increase) (asymmetric effect)

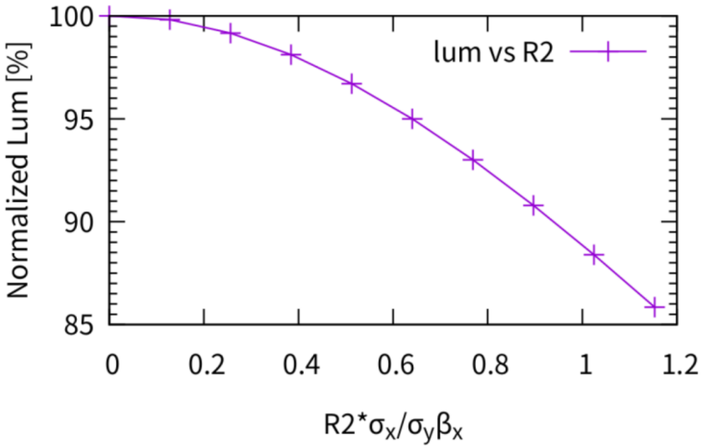


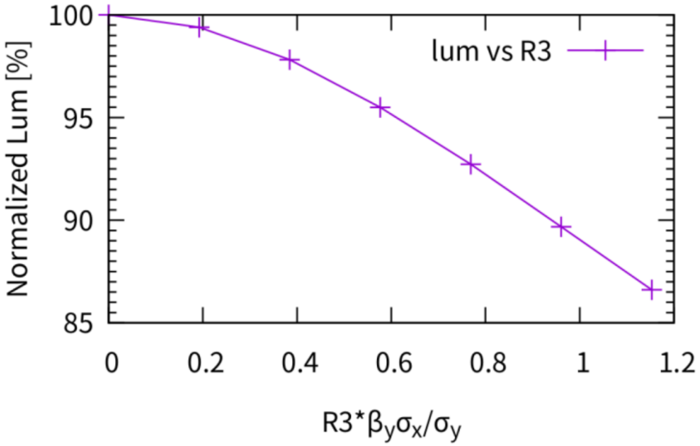


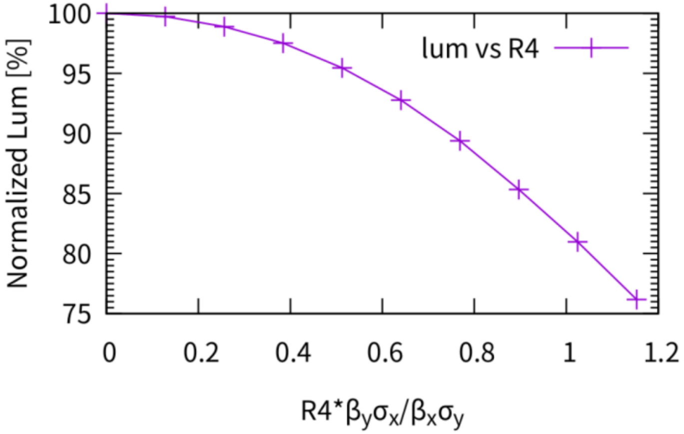
Error only exit in one beam(ring)

# Optics distortion: local coupling at IP









- The scaled R1/R2/R3/R4 have similar effects, where the scaled parameters should $< 1$ to keep luminosity loss < 10%.

$$\sigma_y^2(0) \sim \sigma_{y,0}^2 + \sigma_x^2\left[R_1^2 + \frac{R_2^2}{\beta_x^2}\right]$$

$$\sigma_y^2(s) \sim \epsilon_x\left[\beta_x(-R_1 + R_3 s)^2 + \frac{1}{\beta_x}(R_2 + R_4 s)^2\right] + \epsilon_y\left[\beta_y + \frac{s^2}{\beta_y}\right]$$

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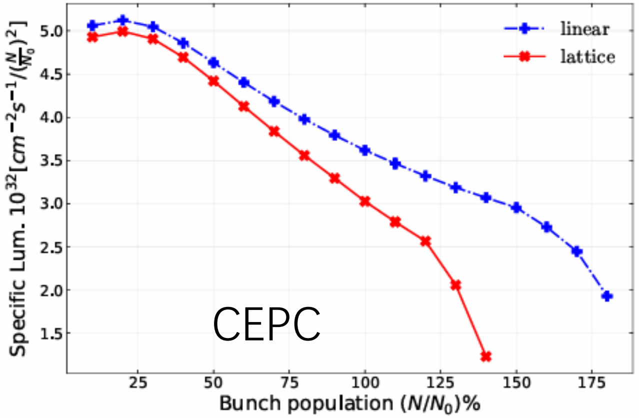
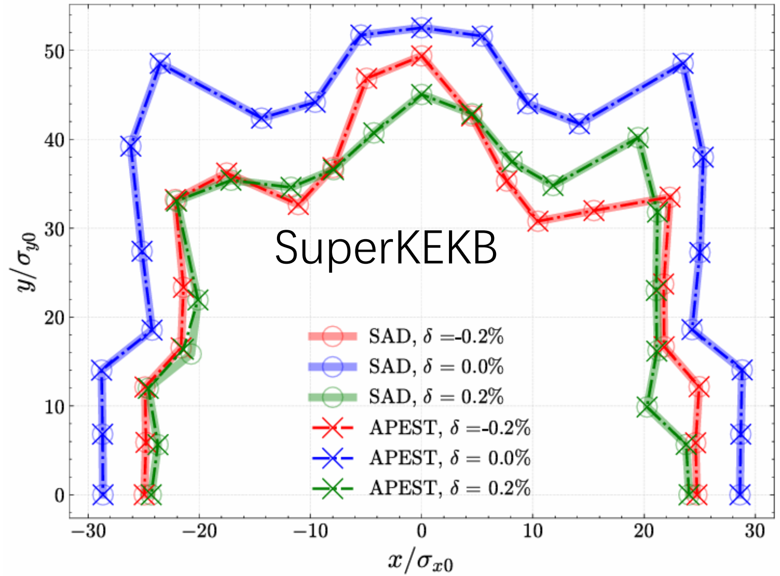
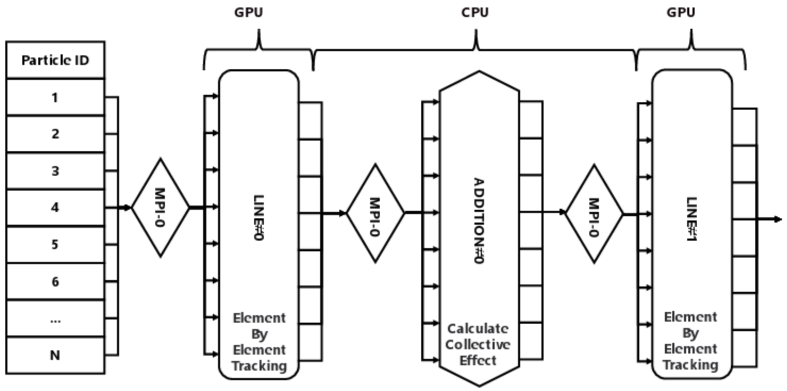
In collaboration with KEK team

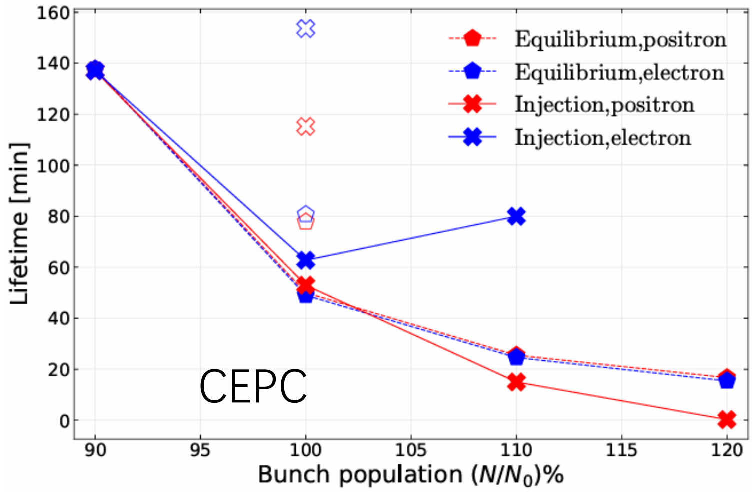
# Strong-strong Beam-beam + Lattice (APES-T)

- SAD lattice is fully supported
- Dynamic aperture benchmark with SAD
- Parallel: MPI+GPU
- First-time strong-strong simulation in ee machines with element-by-element tracking in arc









# Summary

- With the publish of CEPC TDR, some performance evaluation / optimization work has been done
- Horizontal/vertical beam-beam instability and their mitigation methods (chromaticity, asymmetric tunes, feedback)
- Initial optics error effects
- New code has been developed to support strong-strong bb + lattice tracking