Studies of Beam-Beam Effects at CEPC

Y. Zhang(IHEP), C. Lin(IHEP), K. Ohmi(KEK)

Thanks: M. Zobov(INFN/LNF), M. Migliorati (University of Rome 'La Sapienza')

Outline

1. Introduction
2. Simulation with CEPC Designed Parameters
3. Analysis Study of X-Z instability
4. Summary

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

Crab-waist collision

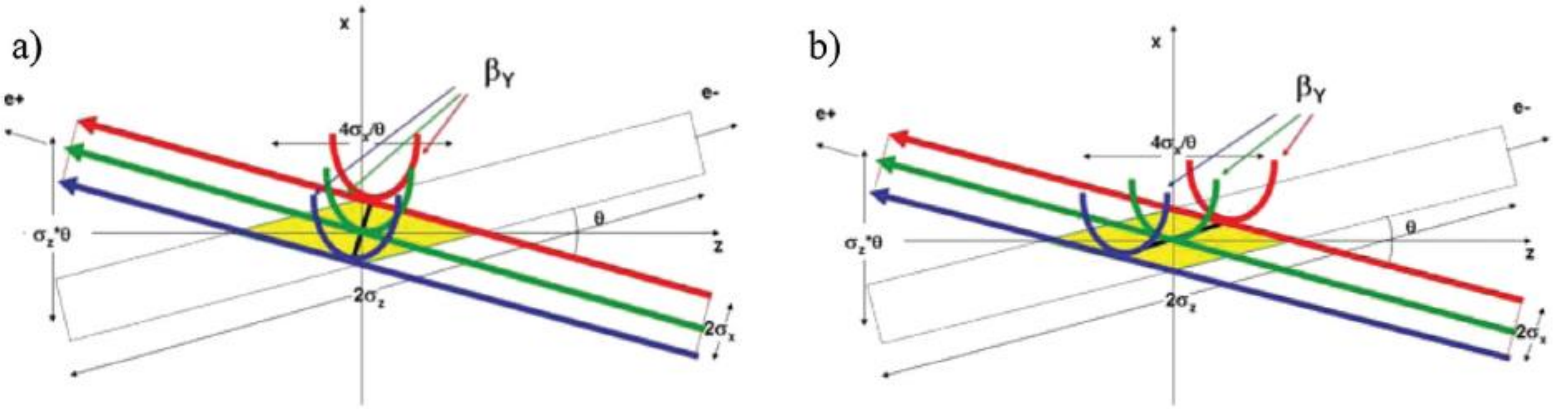


FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

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

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

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

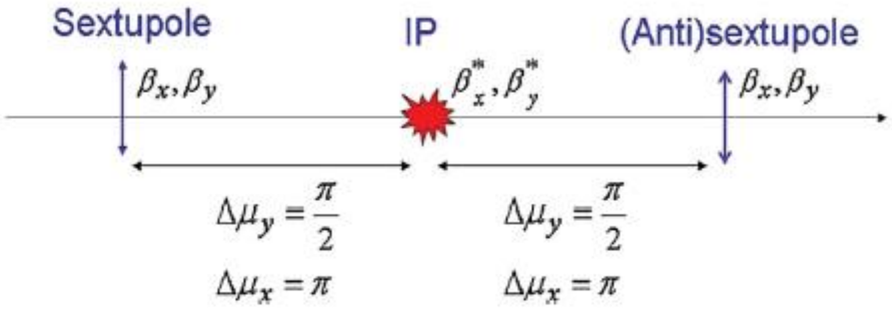
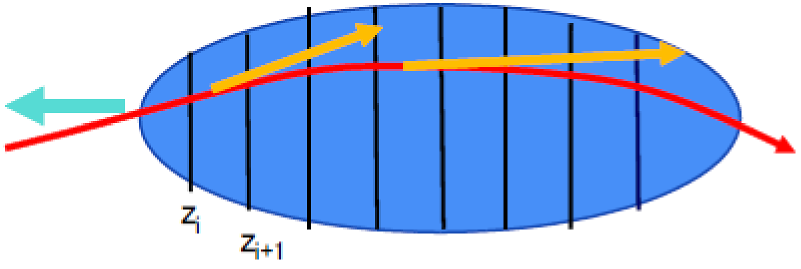


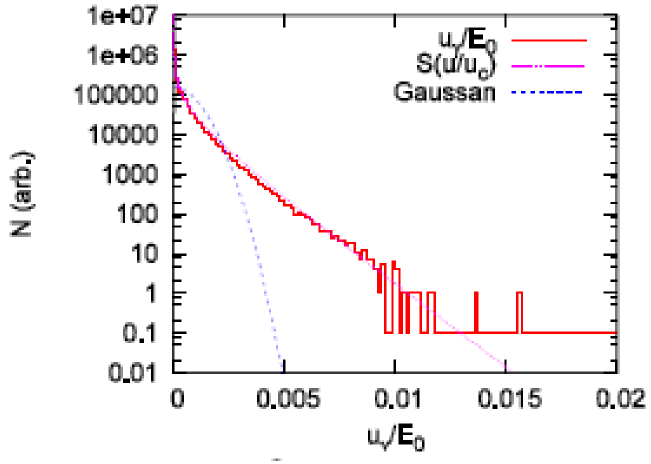
FIG. 2 (color). Crab sextupole locations.

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

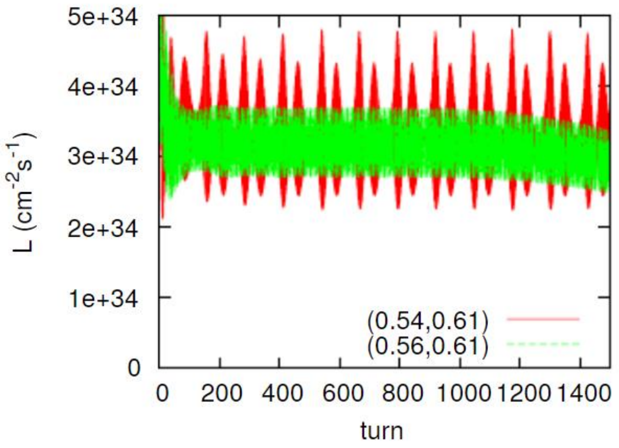
- Synchrotron radiation during beam-beam interaction
- High energy photon -> Momentum acceptance -> Lifetime
- Longer bunch length and Higher energy spread
- Asymmetrical beam blowup: 3D flip-flop





Coherent Beam-Beam Instability with a Large Crossing Angle

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)
K. Ohmi, eeFACT 2018



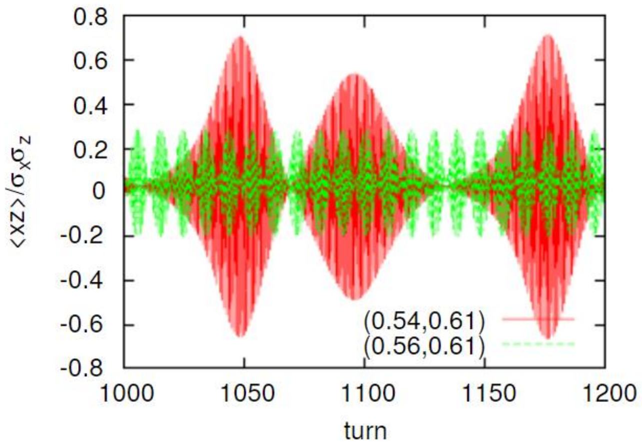


Fig. 5. Luminosity and $\langle xz \rangle$ evolutions given by a strong–strong simulation using BBSS code.

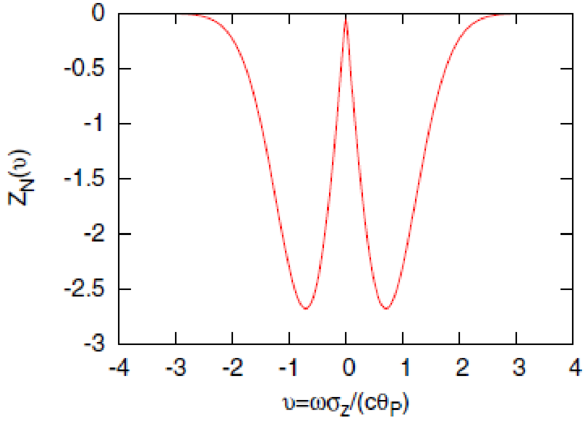


FIG. 3. Imaginary part of normalized cross impedance, where $\upsilon = \omega\bar{\sigma}_z/(c\theta_P)$.

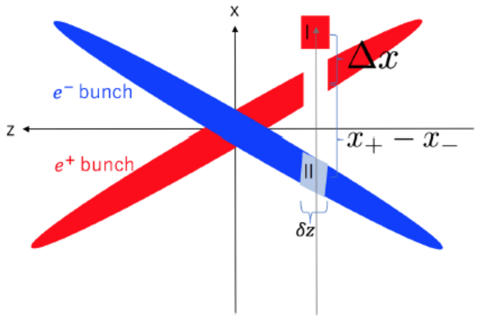


FIG. 1. Illustrative representation of the evaluation of the cross-wake force.

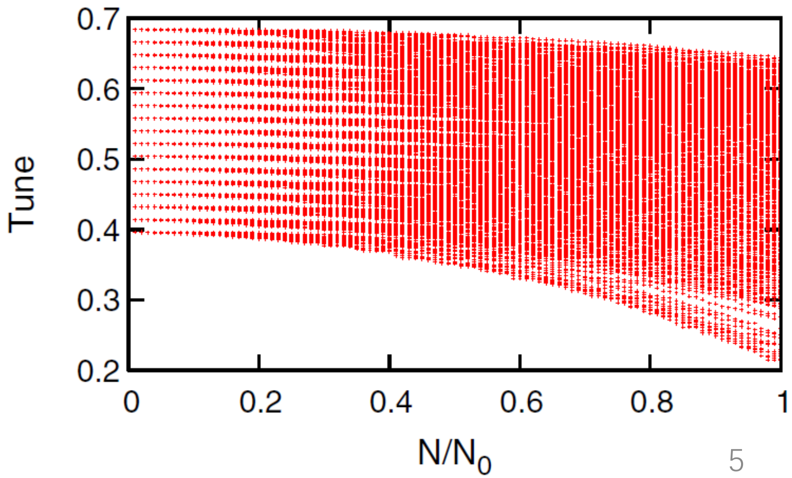
- Usual wake force gives correlation between bunch head to tail. Head-tail instability is induced by synchrotron motion

$$\Delta p_x(z) = -\int_z^\infty W(z - z')\rho_x(z')dz'.$$

- Cross wake field gives correlation of two colliding beam by convolution of each dipole moment.

$$\Delta p_{x,\mp}(z_\mp) = -\int_{-\infty}^{\infty} W_x^{(\mp)}(z_\mp - z'_\pm)\rho_x^{(\pm)}(z'_\pm)dz'_\pm$$

- Cross wake force induced by the beam-beam interaction is localized at IP.



Why have we started with the longitudinal impedance?

1. In the collision scheme with Crab Waist and Large Piwinski Angle the luminosity and tune shifts strongly depend on the bunch length

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

2. For the future circular colliders with extreme beam parameters in collision several new effects become important such as beamstrahlung, coherent X-Z instability and 3D flip-flop. The longitudinal beam dynamics plays an essential role for these effects

Interplay between beam-beam interaction, beamstrahlung and longitudinal impedance

X-Z Instability

1. Tune shift of stable tune areas due to the impedance related synchrotron frequency reduction
2. Reduction of sizes of the stable tune areas
3. Smaller beam blowup presumably due to the synchrotron frequency spread induced by the impedance

In Stable Areas

D.Leshenok and et al. PHYS. REV. ACCEL. BEAMS 23, 101003 (2020)

1. Longer bunch length
2. Smaller energy spread than that due to beamstrahlung alone
3. Eventual damping of the microwave instability due to longer bunches and overall higher energy spread

Code model

CODE: IBB

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

- Linear Arc Map with SR radiation
- Horizontal crossing angle: Lorentz boost map
- Bunch slice number is about 10 times Piwinski angle
- Slice-Slice collision: Synchro-beam mapping and PIC
- Synchrotron radiation during collision
- Longitudinal wake potential is calculated in frequency domain before IP each turn

Try to answer:
if the machine parameter is reasonable

Limit of bunch population by beam-beam interaction:

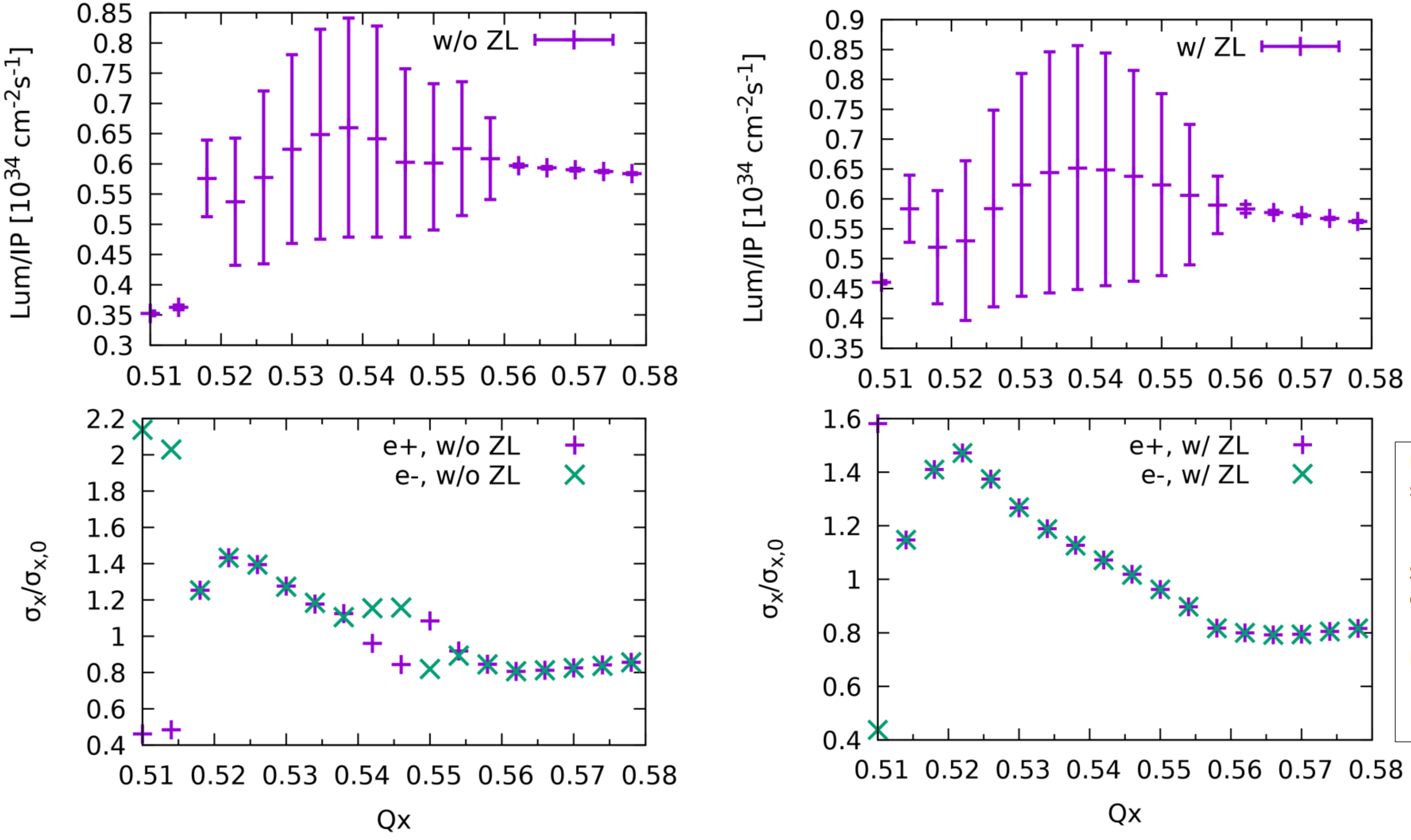
- Beamstrahlung lifetime (ttbar/Higgs)
- If X-Z instability is suppressed (ttbar/Higgs/W/Z)
- If asymmetric bunch current collision is stable
- If there exist large enough stable working point space

ttbar

- Very strong SR damping (longitudinal damping time: 20 turns)
  - Instability may be suppressed?
- Medium Piwinski Angle ~ 1, BEPCII/KEKB: 0.5,   CEPC-Z> 20
  - Beam-beam resonance could not be well suppressed by Crab-Waist
- Horizontal beam-beam parameter: 0.07, still very high

- It is very different from H/W/Z

Luminosity and horizontal beam size versus Qx (ttbar,CW=0.5)



- Design Lum=0.5e34
- Stable width of ν_x~0.01

D. Shatilov, 143rd FCCee Optics Meeting

Excited coherent modes are associated with synchrotron satellites of half-integer resonance:

$$2\nu_x - 2m\nu_s = n$$

Since the wavelength cannot be less than $2L_i$, we get the condition:

$$m \le \phi$$

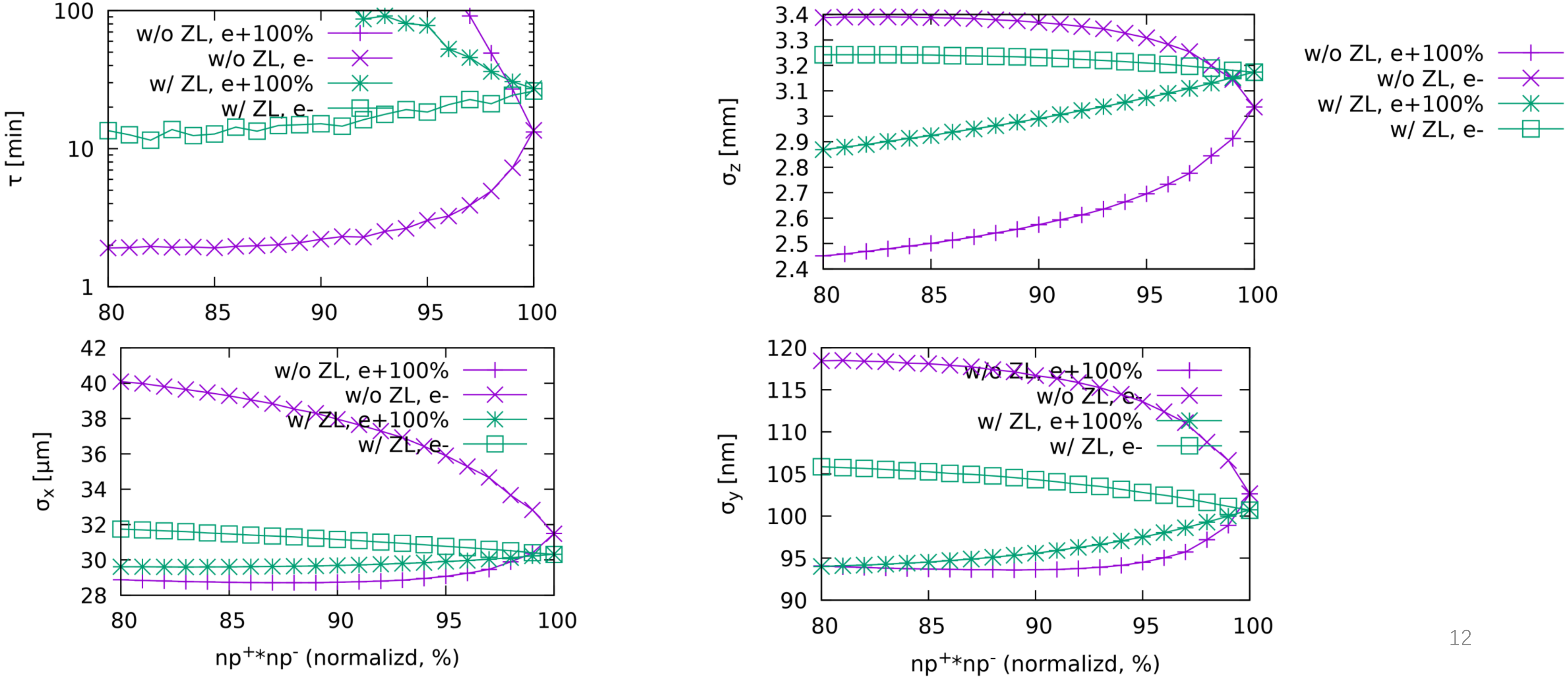
If ϕ is not too large, we can solve the problem by choosing

$$\nu_x > \nu_x^* = 0.5 + \phi\nu_s$$

- 3D flip-flop is suppressed considering longitudinal impedance
- Dynamic effect squeeze horizontal beam size

ttbar: Asymmetrical Collision

- Beam lifetime is increased due to longitudinal impedance
- ~10% asymmetry of bunch population could be accepted for stability

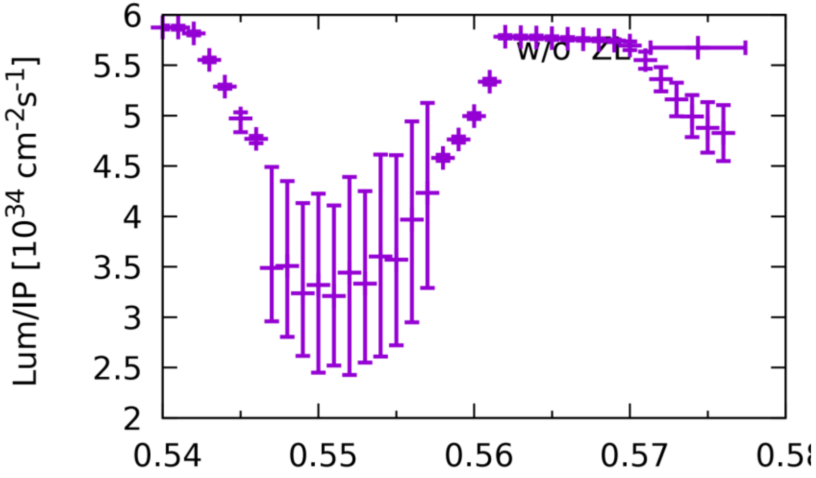


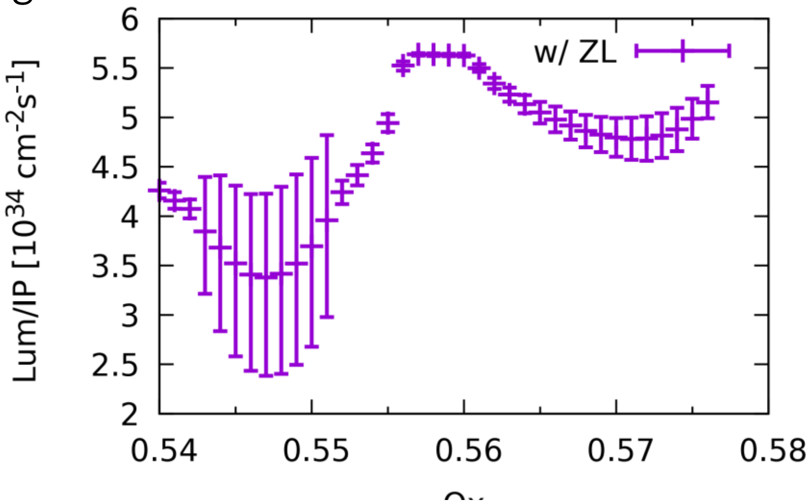
- Large Piwinski Angle~6 (CW=0.8)
- Beamstrahlung Lifetime
- X-Z instability

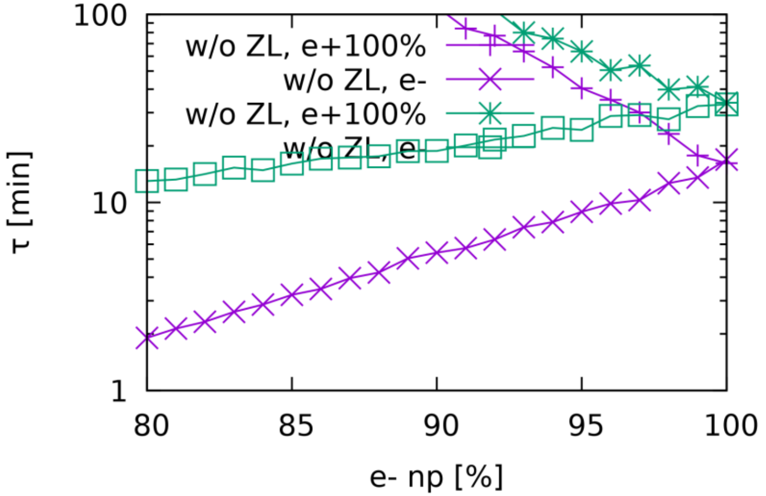
Higgs

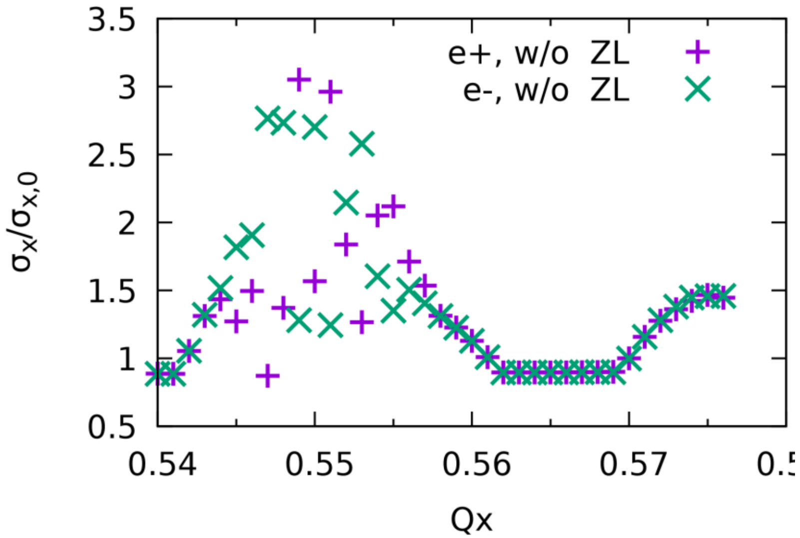
- Design Lum=5e34
- Stable width of Qx~0.004 considering ZL

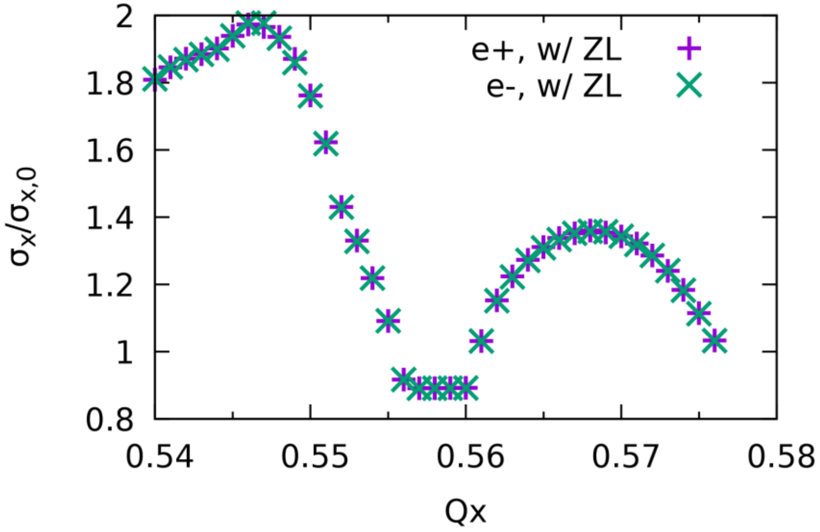
- Beam lifetime is increased due to longitudinal impedance
- 10% asymmetry of bunch population could be accepted.









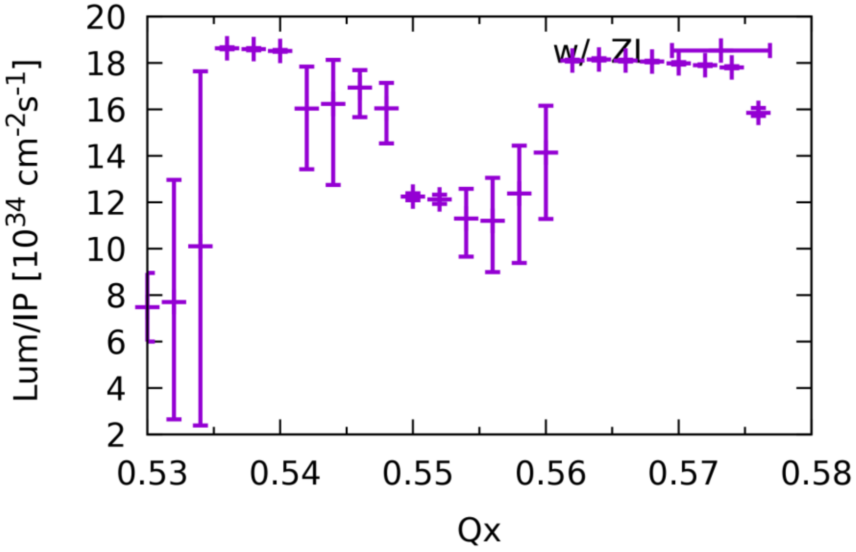


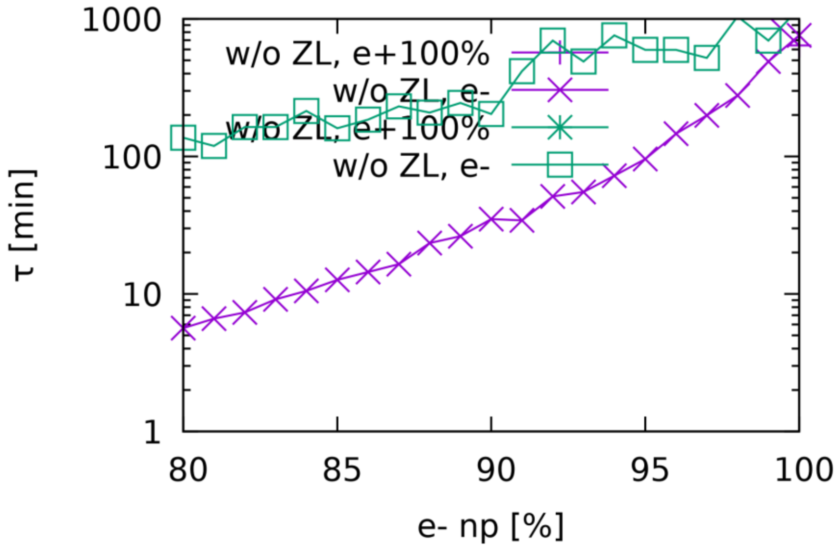
W

- Piwinski angle is similar to that of Higgs(CW=0.8)
- Beamstrahlung lifetime is not an issue
- X-Z instability

- Design Lum=16e34
- The optimized nux is near 0.57 w/ and w/o longitudinal impedance.
- Stable tune width ~ 0.007 considering ZL

- Beam lifetime is increased due to longitudinal impedance
- 10% asymmetry of bunch population could be accepted.

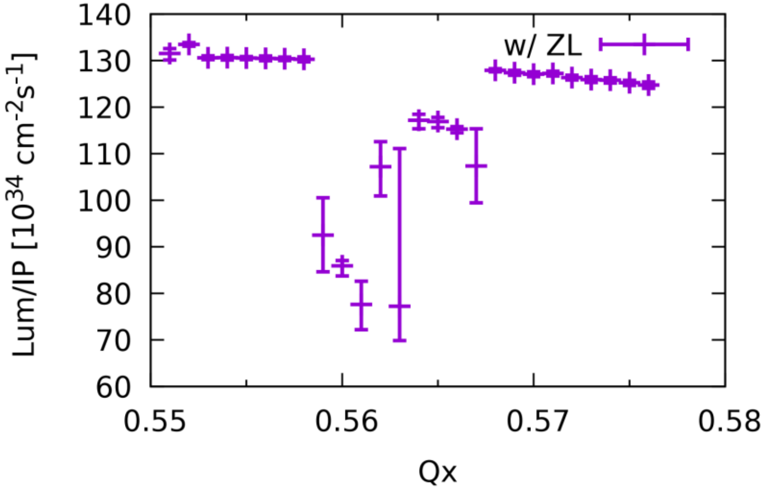




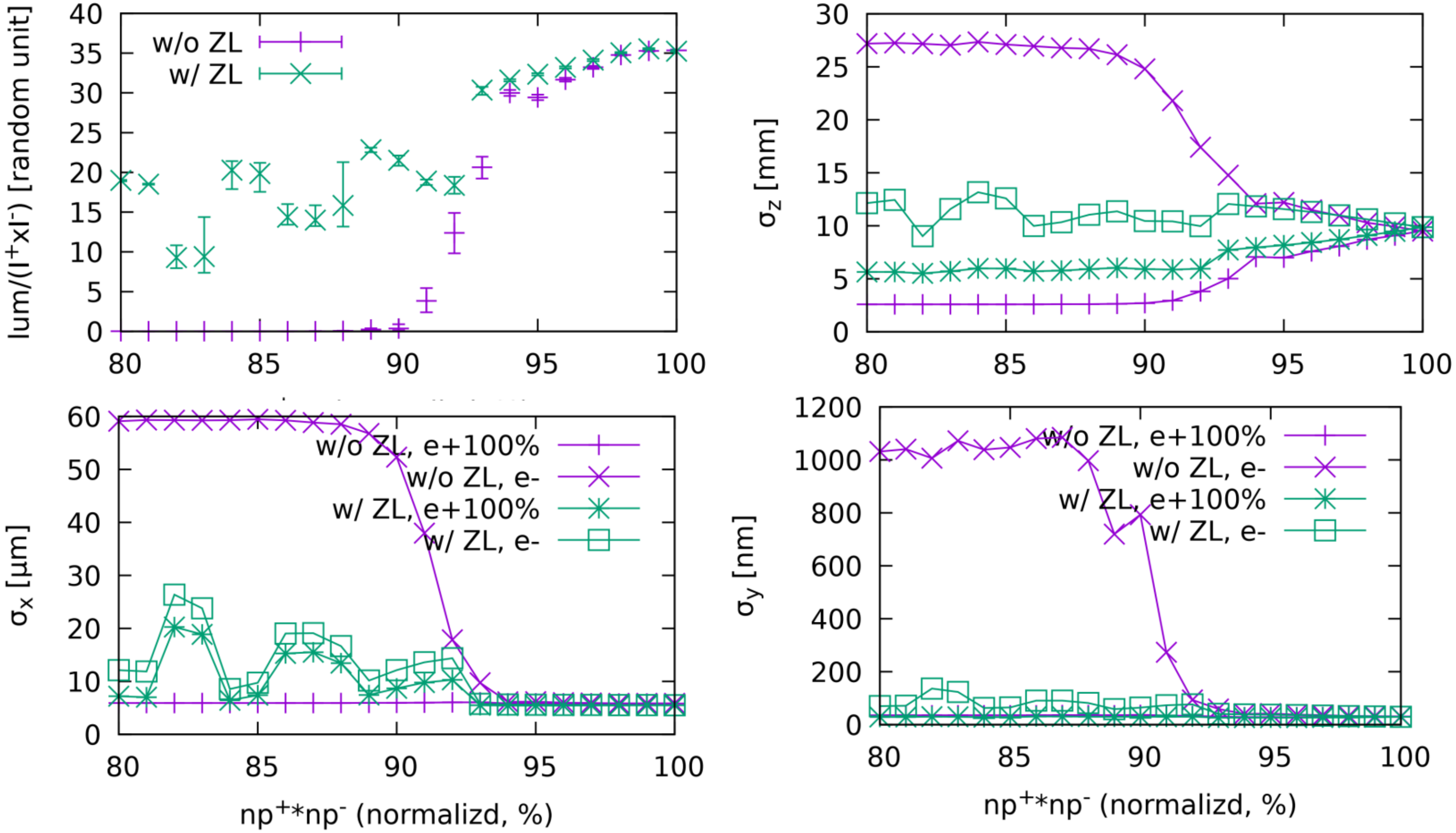
Z

- Piwinski Angle: 25 (CW=1)
- FODO CELL: 60/60
- X-Z instability

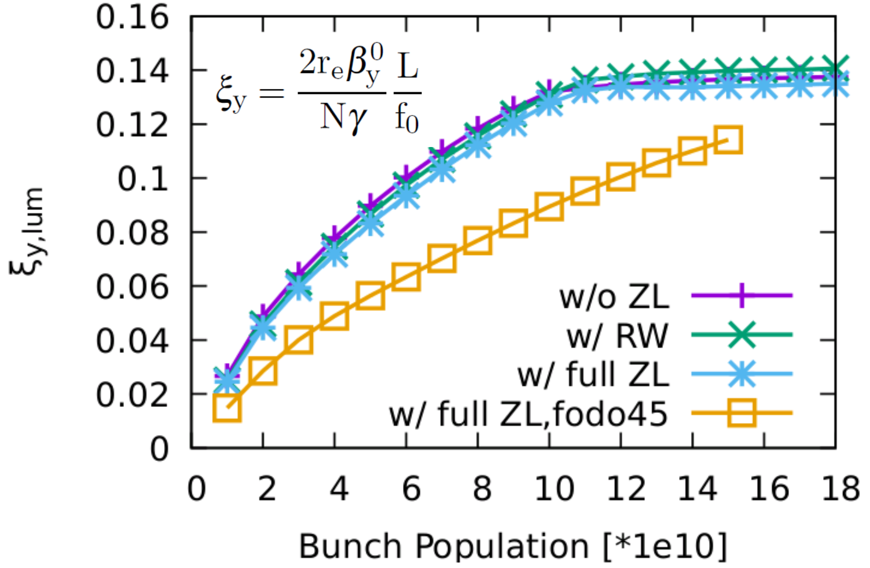
- Design Lum=115e34
- Stable width of ν_x~0.01

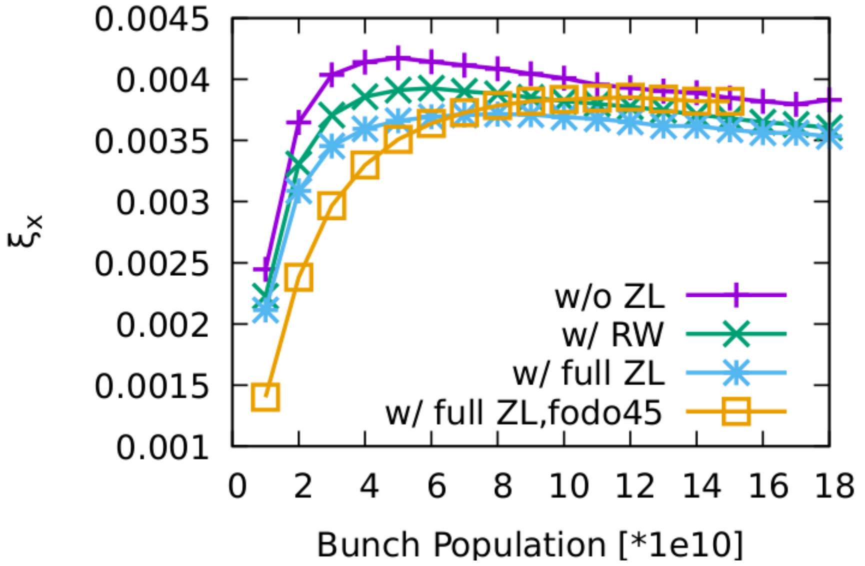


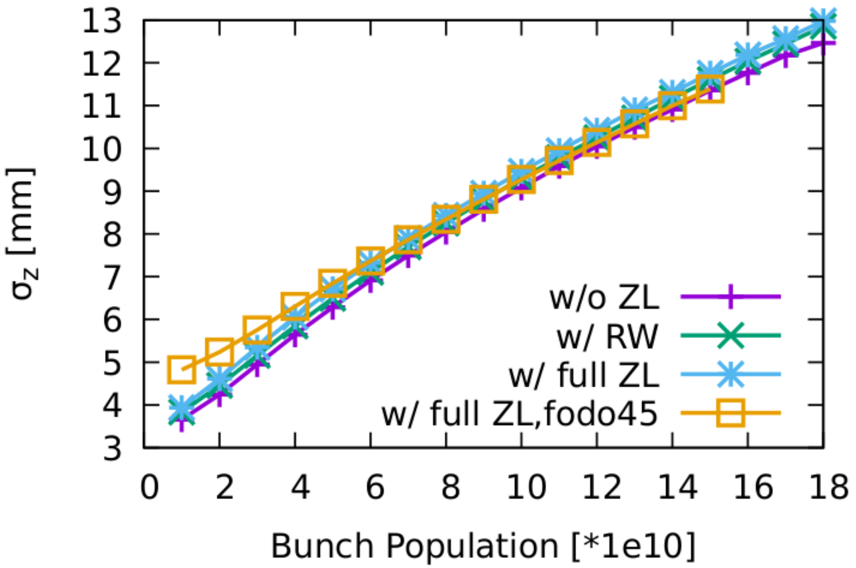
Only 5% asymmetry of bunch population could be accepted.

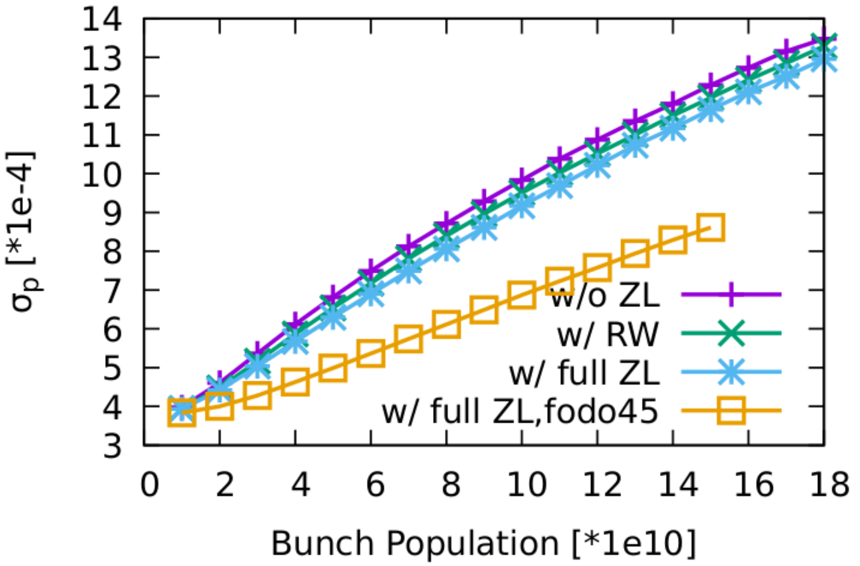


Evolution of Parameters during Injection









X-Z instability tune scan with and without beam coupling impedance (CEPC CDR)

By including the impedance stable areas become narrower and are shifted in frequency

After the horizontal beam function reduction from 0.2 m down to 0.15 m

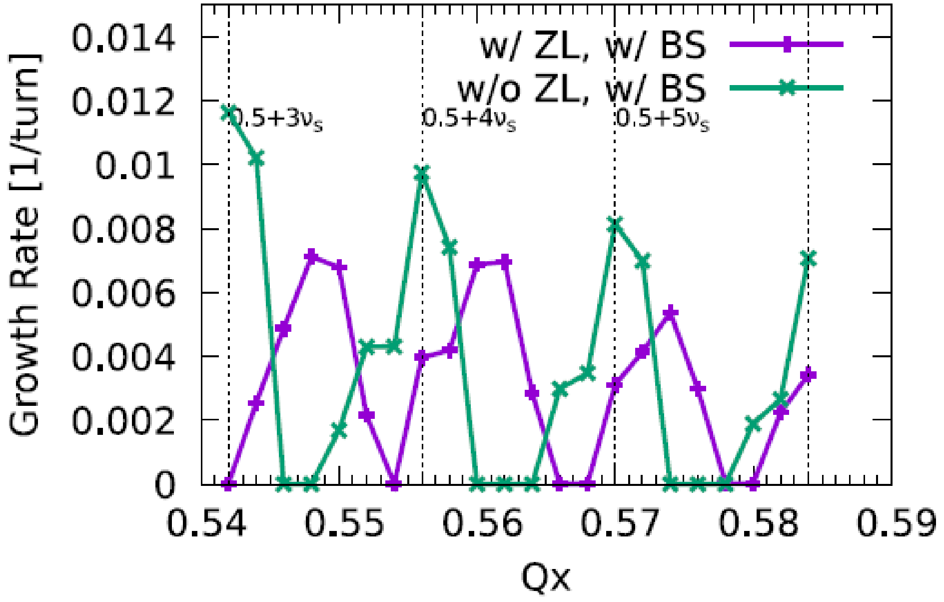
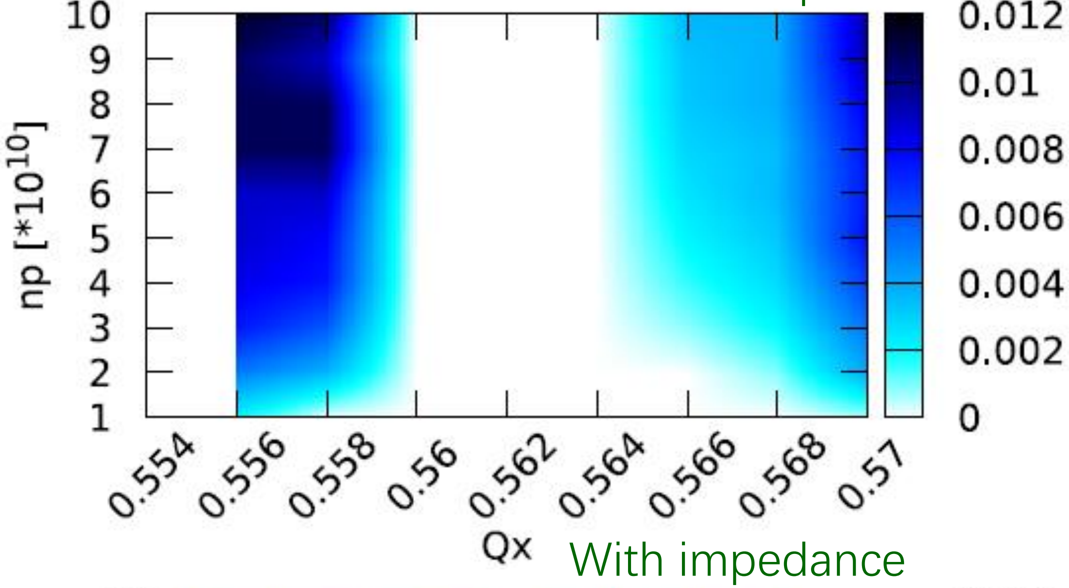
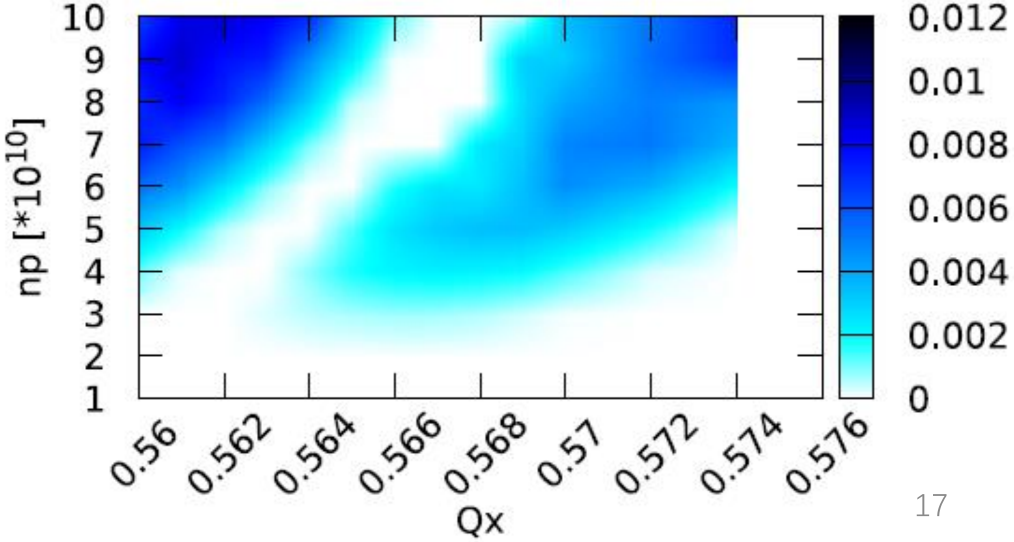


FIG. 3. The horizontal beam size growth rate versus horizontal tune with and without longitudinal coupling impedance (ZL) Beamstrahlung (BS) effect is turned on.

Without impedance



With impedance



PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 104402 (2020)

Potential well distortion with Longitudinal Impedance

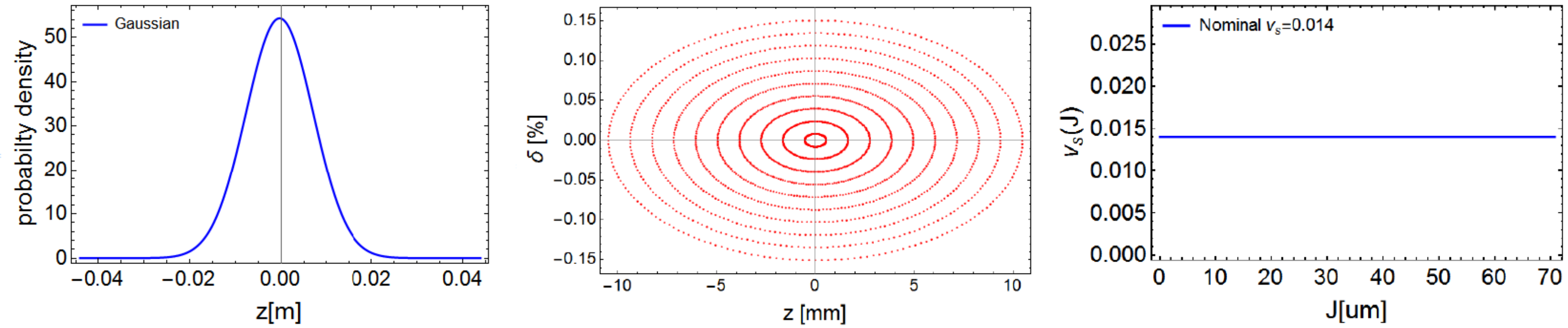


Figure: Longitudinal beam dynamics without longitudinal impedance

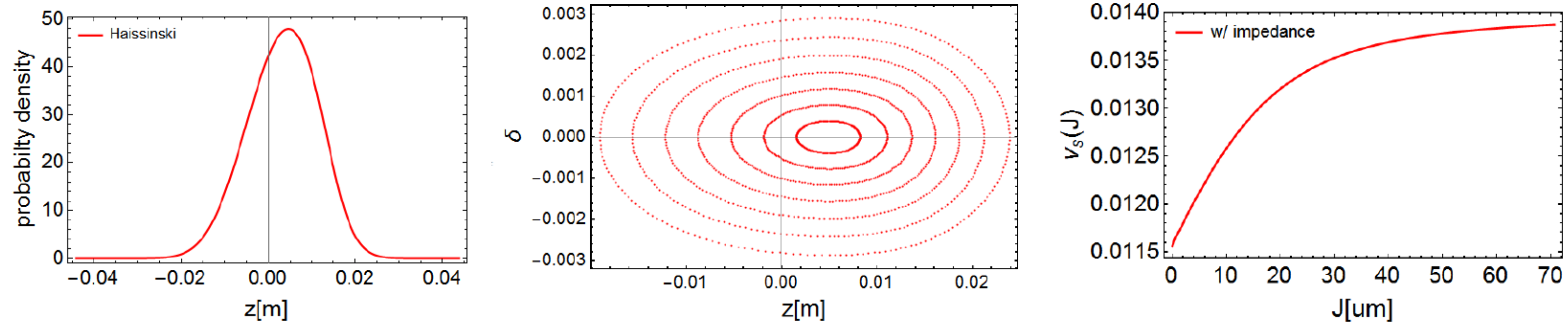


Figure: Longitudinal beam dynmics with longitudinal impedance

Analysis without PWD

- Azimuthal and Radial Mode Expansion:

$$x(J,\phi;t) = \sum_{l,k} x_{kl}(t)\sqrt{\frac{k!}{(|l|+k)!}}\hat{J}^{|l|/2}L_k^{(|l|)}(\hat{J})e^{il\phi}$$

$$p_x(J,\phi;t) = \sum_{l,k} p_{kl}(t)\sqrt{\frac{k!}{(|l|+k)!}}\hat{J}^{|l|/2}L_k^{(|l|)}(\hat{J})e^{il\phi}$$

- Synchrotron-betatron motion of dipole moment vector (x_{kl}, p_{kl}) in Arc

$$M_0 = e^{-2\pi i l \nu_z}\delta_{kk'}\delta_{ll'}\begin{pmatrix}\cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x\end{pmatrix}.$$

For example,
$k_{\max} = 80,\ l_{\max} = 8$

- Momentum Kick due to localized Wake force(beam-beam)

$$M_W = \begin{pmatrix}1 & 0 \\ -2M_{klk'l'} & 1.\end{pmatrix} \qquad \Delta p_{kl}(t) = -2\sum_{k'l'} M_{klk'l'}x_{k'l'}(t).$$

$$M_{k\ell,k'\ell'} = \pm\frac{\beta_x}{2}i^{l-l'-1}\int_{-\infty}^{\infty} d\omega Z(\omega)g_{kl}(\omega)g_{k'l'}(\omega),$$

where $$g_{kl}(\omega) = \frac{1}{\sqrt{2\pi k!(|l|+k)!}}\left(\frac{\omega\sigma}{\sqrt{2}c}\right)^{|l|+2k} e^{-\omega^2\sigma^2/2c^2}.$$

- Stability analysis of $M_0 M_W$

C. Lin, K. Ohmi and Y. Zhang, Submitted to PRAB

Analysis with PWD

- Azimuthal Mode Expansion

$$x(J,\phi)=\sum_{l=-\infty}^{\infty} x_l(J)e^{il\phi}, \quad p_x(J,\phi)=\sum_{l=-\infty}^{\infty} p_l(J)e^{il\phi}$$

- Synchro-betatron motion in Arc

$$\begin{pmatrix} x_l(J) \\ p_l(J) \end{pmatrix} = e^{-2\pi i l \nu_s(J)} \begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix} \begin{pmatrix} x_l(J) \\ p_l(J) \end{pmatrix} \equiv M_0 \begin{pmatrix} x_l(J) \\ p_l(J) \end{pmatrix}$$

- Action Discretization

we truncate l at $\pm l_{max}$, and discretize J at $J_1, J_2, ..., J_{n_J}$.

$$\begin{pmatrix} x_l(J_i) \\ p_l(J_i) \end{pmatrix} = e^{-2\pi i l \nu_s(J_i)} \begin{pmatrix} \cos\mu_x & \sin\mu_x \\ -\sin\mu_x & \cos\mu_x \end{pmatrix} \begin{pmatrix} x_l(J_i) \\ p_l(J_i) \end{pmatrix} \equiv M_0 \begin{pmatrix} x_l(J_i) \\ p_l(J_i) \end{pmatrix}$$

For example,

$n_J = 40$, $l_{\max} = 8$

- Momentum Kick due to localized Wake force(beam-beam)

$$M_W = \begin{pmatrix} 1 & 0 \\ \beta_x M_{lil'i'} & 1 \end{pmatrix}.$$

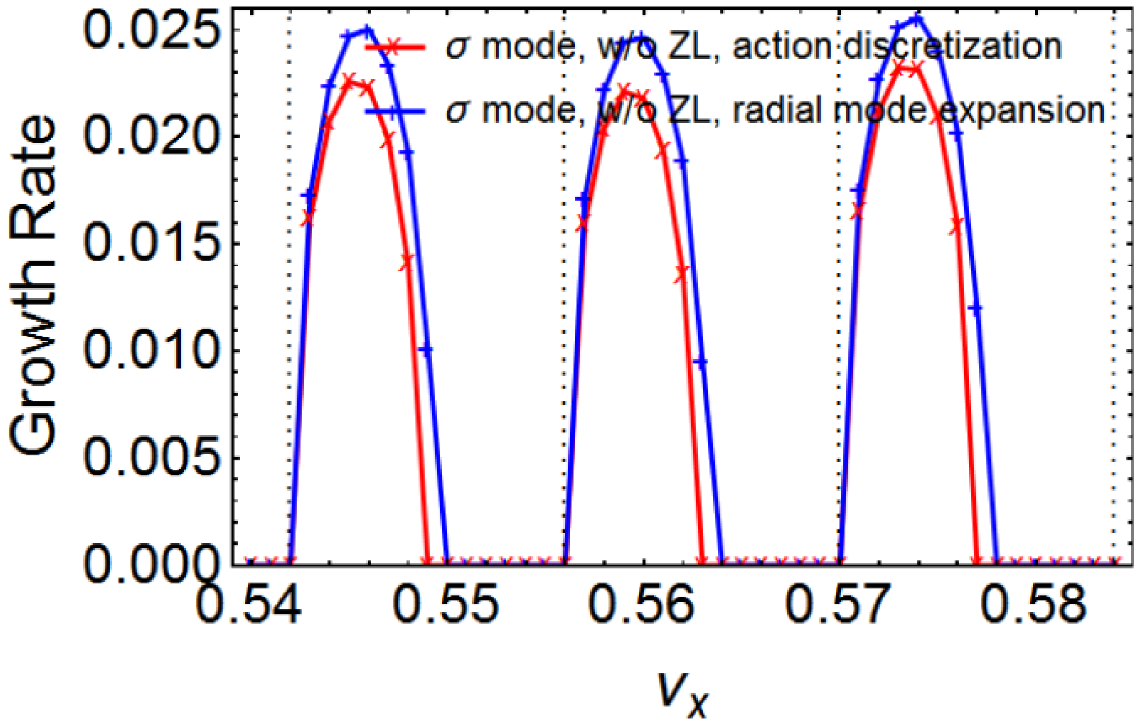
$$\Delta p_l(J_i) = \mp\frac{\beta_x}{2\pi}\sum_{l'}\sum_{i'}\Delta J_{i'} W_{ll'}(J_i, J_{i'})\psi(J_{i'})x_{l'}(J_{i'}) \equiv \beta_x M_{lil'i'} x_{l'}(J_{i'}).$$

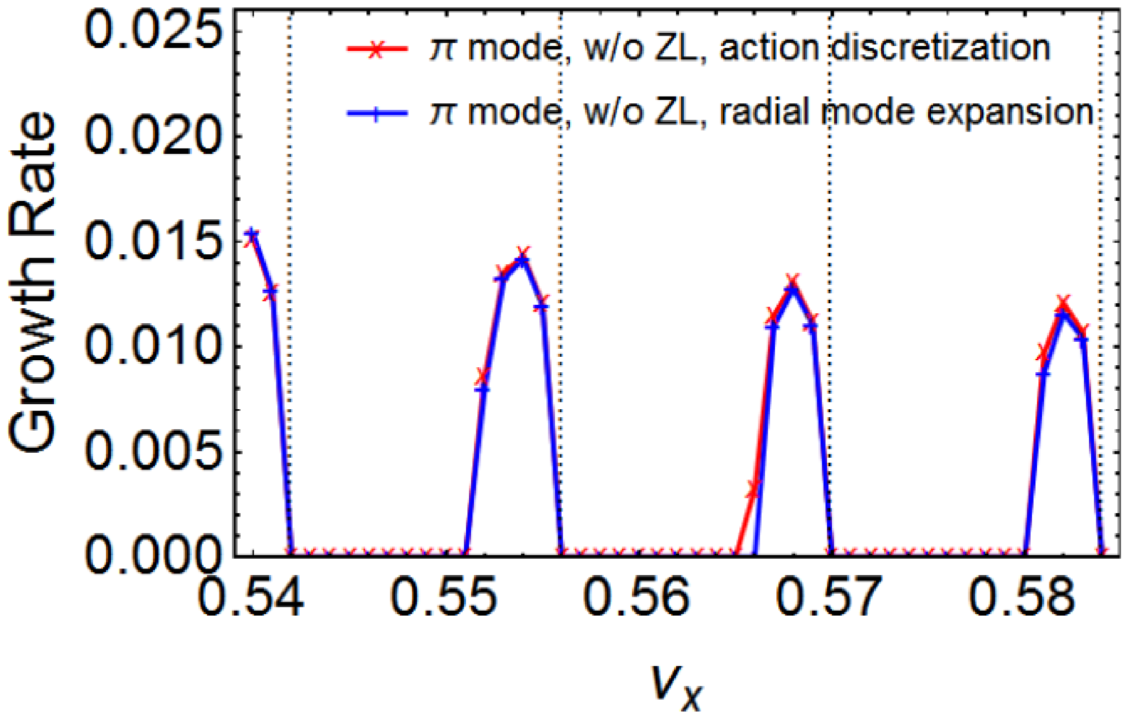
- Stability analysis of $M_0 M_W$

$$W_{ll'}(J_i, J_{i'}) = \sum_j \sum_{j'} e^{-il\phi_j + il'\phi_{j'}} W_x(z(J_i,\phi_j) - z(J_{i'},\phi_{j'}))\Delta\phi_j\Delta\phi_{j'}.$$

C. Lin, K. Ohmi and Y. Zhang, Submitted to PRAB

Crosscheck between two analysis methods





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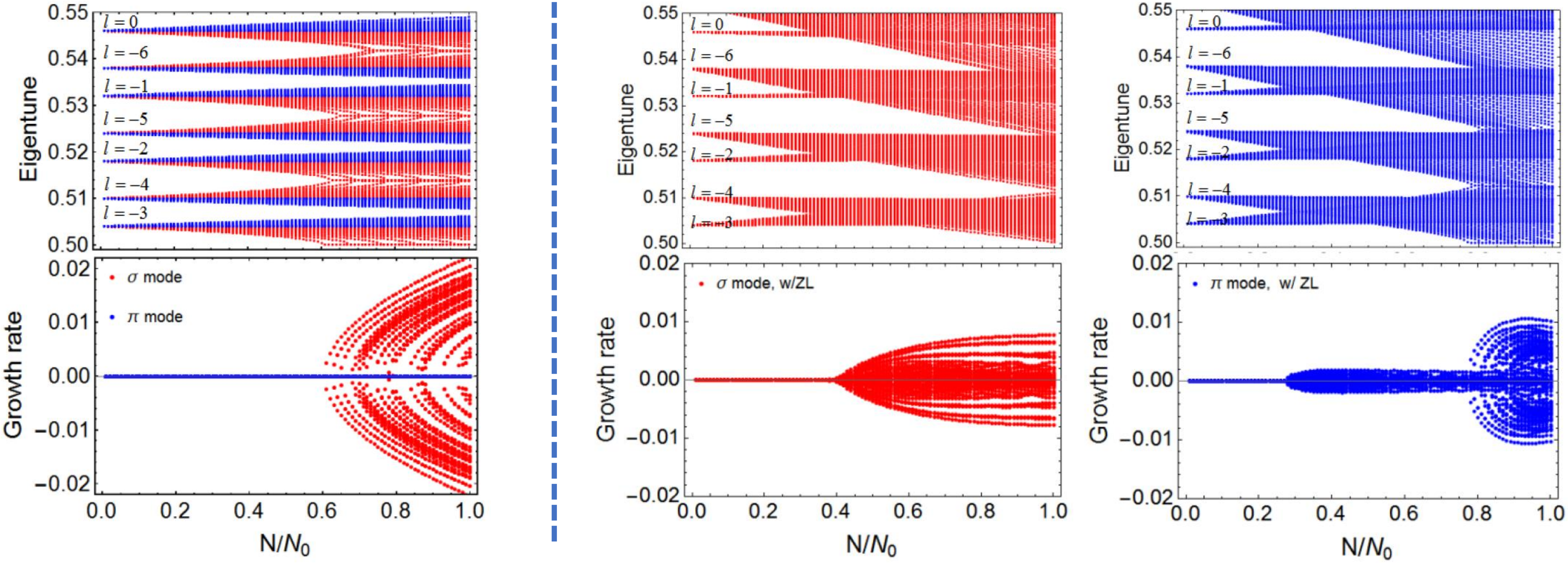
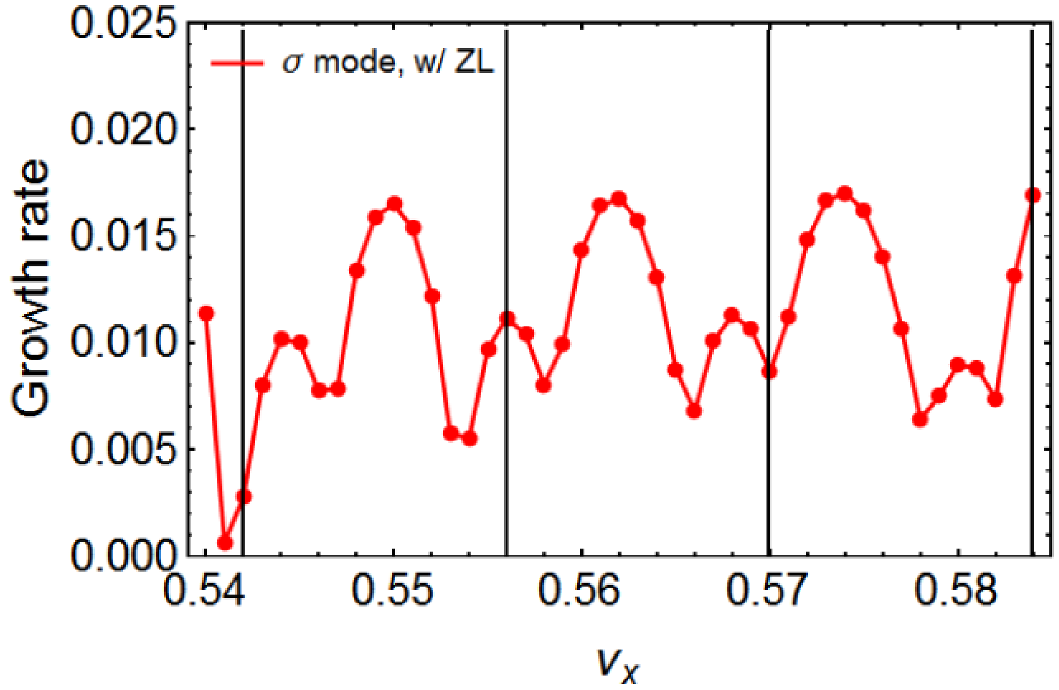
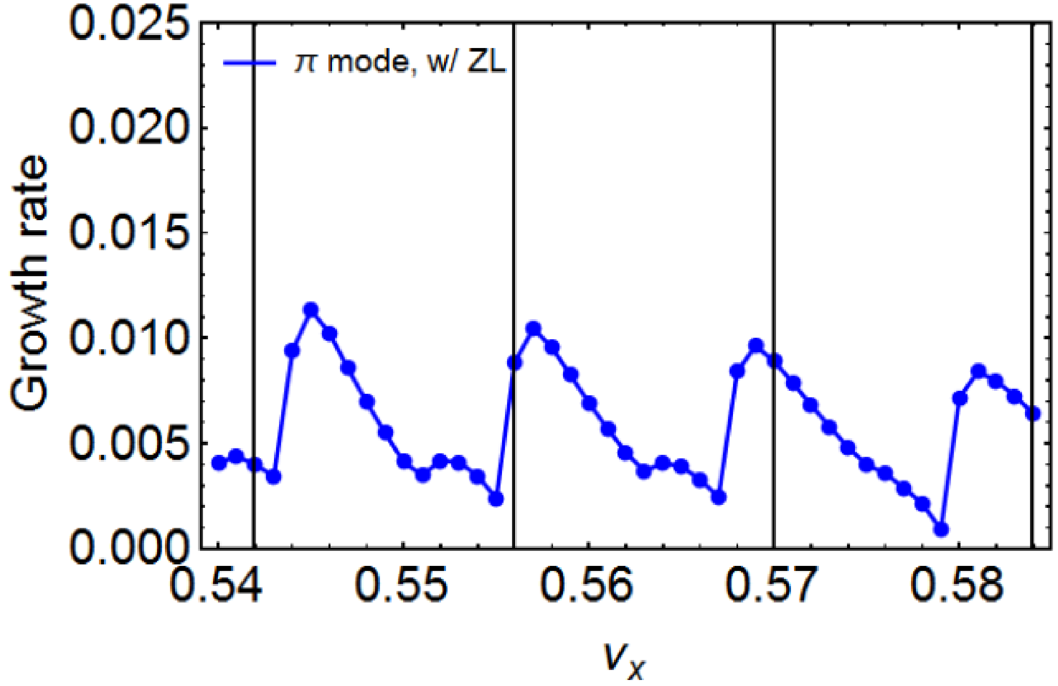
ν_x=0.546, CEPC CDR

Eigen-Mode Analysis w/o and w/ ZL



Tune Scan w/ ZL





- Gap between neighboring peaks reduces from 0.014 to ~0.011
- New resonance structures appear

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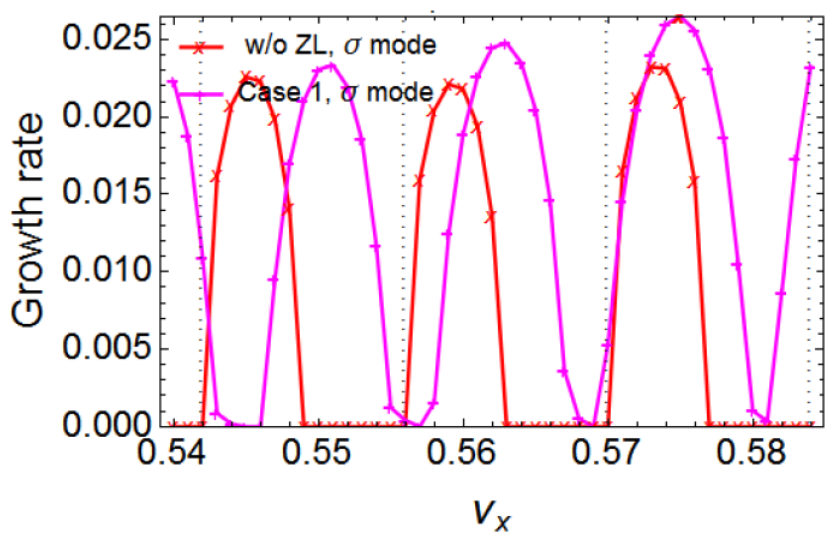
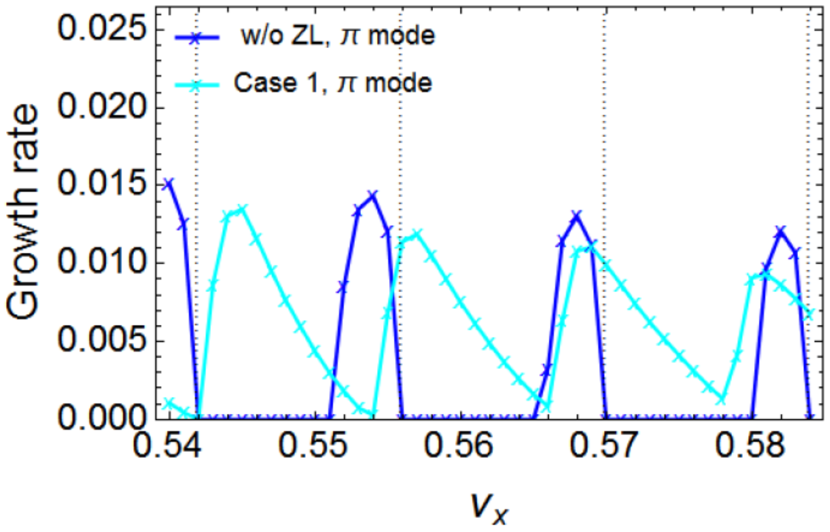
Effects of Incoherent Synchrotron Tune Shift

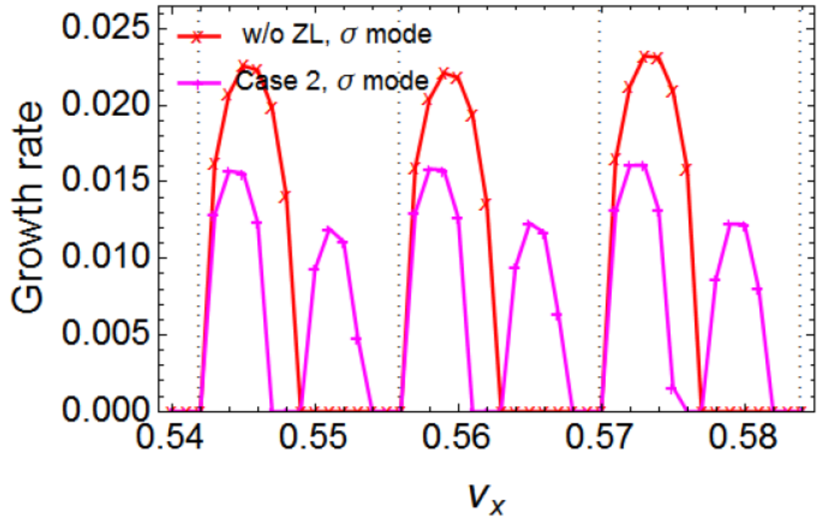


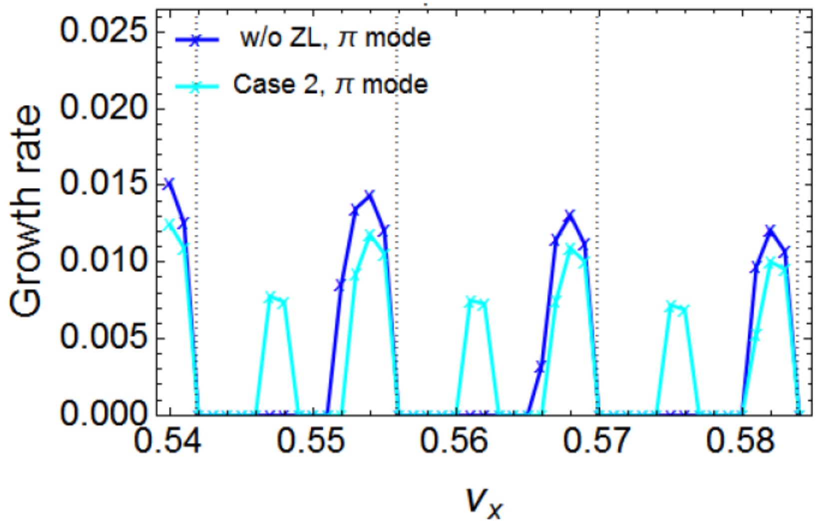


- Phase space distortion is not included w/ ZL
- Only incoherent ν_s is considered
- Instability peak is shifted and gap between peaks is squeezed
- No resonance structure between peaks

C. Lin, K. Ohmi and Y. Zhang, Submitted to PRAB

Effects of Phase Space Distortion





- Phase space distortion is considered w/ ZL
- Synchrotron tune ν_s is kept constant (0.014)
- gap between peaks is unchanged
- new unstable tune appear

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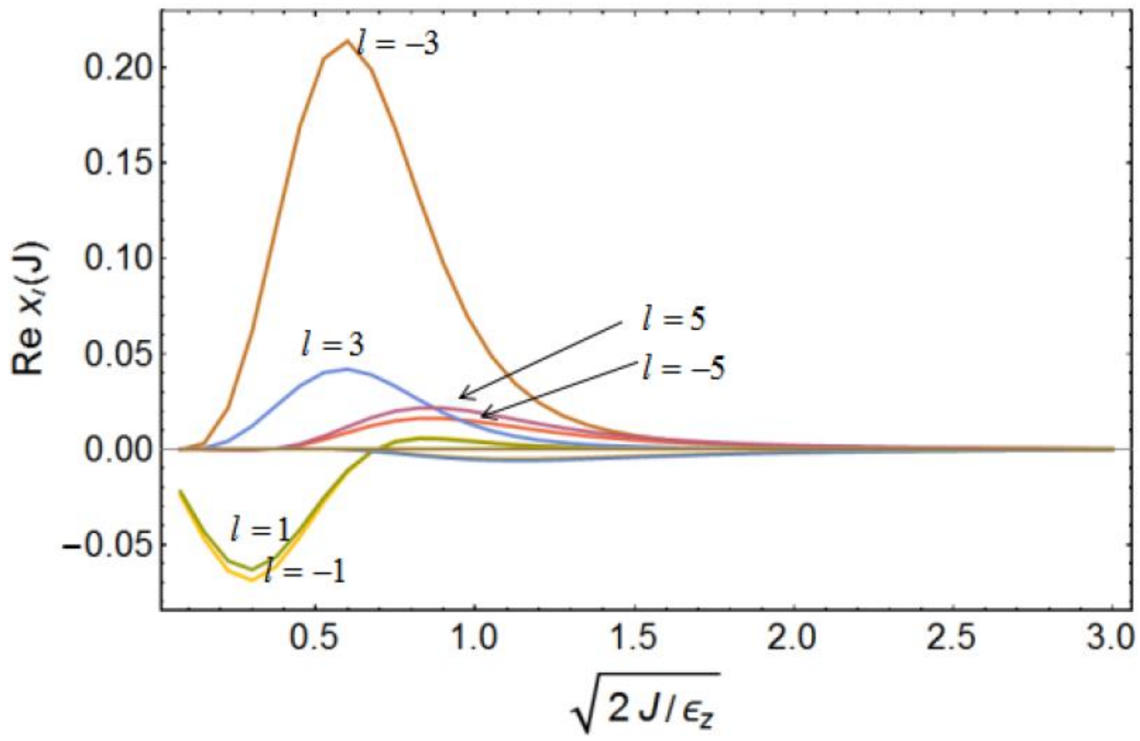
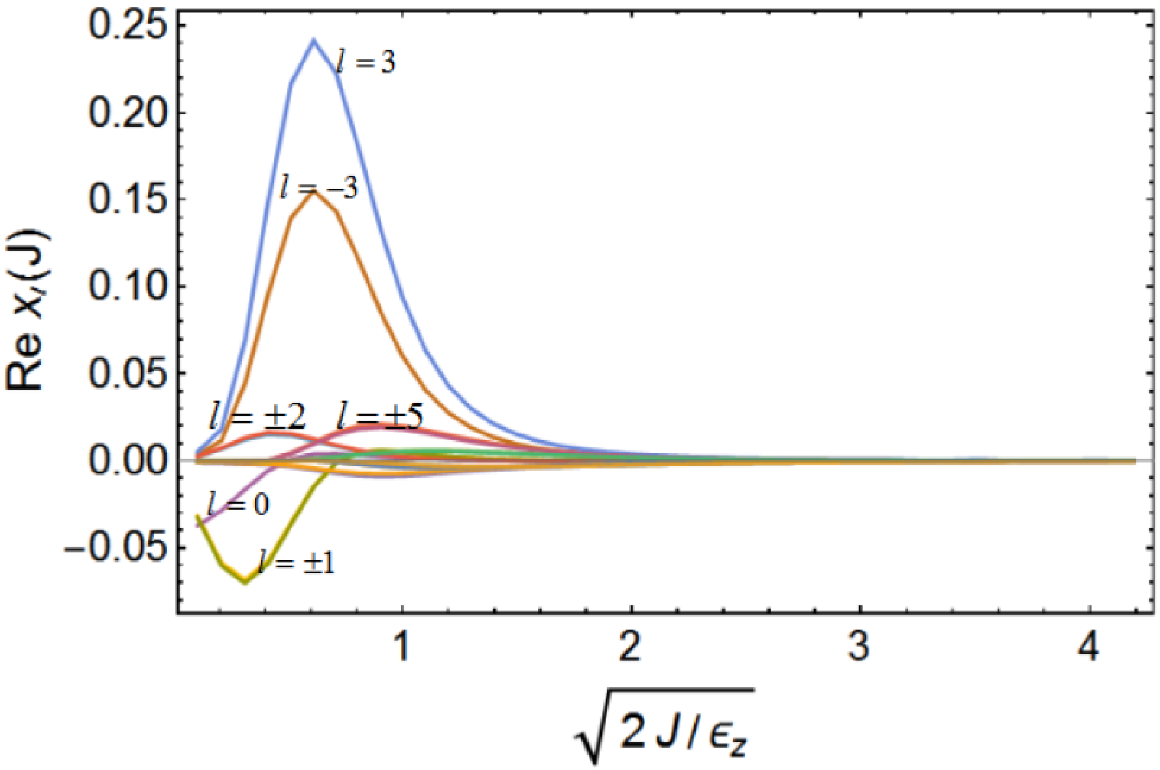
$N = N_0, \nu_x$=0.546, CEPC CDR

Eigen Vector Analysis w/o and w/ ZL





W/O ZL, excited modes exsit **only for $l = \pm1, \pm3, \pm5$ … and not for $l = 0, \pm2, \pm4$ … .**

W/ ZL but only consider distortion of longitudinal phase space and keep $\nu_s(J)$ unchanged. **All parity modes for $l = 0, \pm1, \pm2, \pm3$ … are excited and could be mixed.**

Summary

- Beamstrahlung lifetime is increased by ZL, while X-Z instability is enhanced
- The X-Z instability is well suppressed at W/Z for newest machine parameters.
- The stable working point space for CEPC-Higgs is about Qx~0.004 when considering ZL.
- 10% asymmetry of bunch population could be accepted for ttbar/Higgs/W. But only 5% asymmtry for Z.
- New analysis method has been developed to understand the combined effect (BB+ZL)