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Study of Beam-Beam Effects at CEPC

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D. Shatilov, K. Oide

Outline

- Introduction
- Instability & Mitigation
- Refined model & Lattice
- Summary

Main 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 $[10^{-4}]$
β_x^*/β_y^* [m/mm]	0.3/1	0.13/0.9
ϵ_x/ϵ_y [nm/pm]	0.64/1.3	0.27/1.4
σ_z (SR/BS) [mm]	2.3/4.1	2.5/8.7
σ_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
ν_s	0.049	0.035
Bunch Population $[10^{10}]$	13	14
ξ_x/ξ_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

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Check for updates

CEPC

Technical Design Report

Accelerator

The CEPC Study Group

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P. Raimondi , *2nd SuperB Workshop, March 2006*
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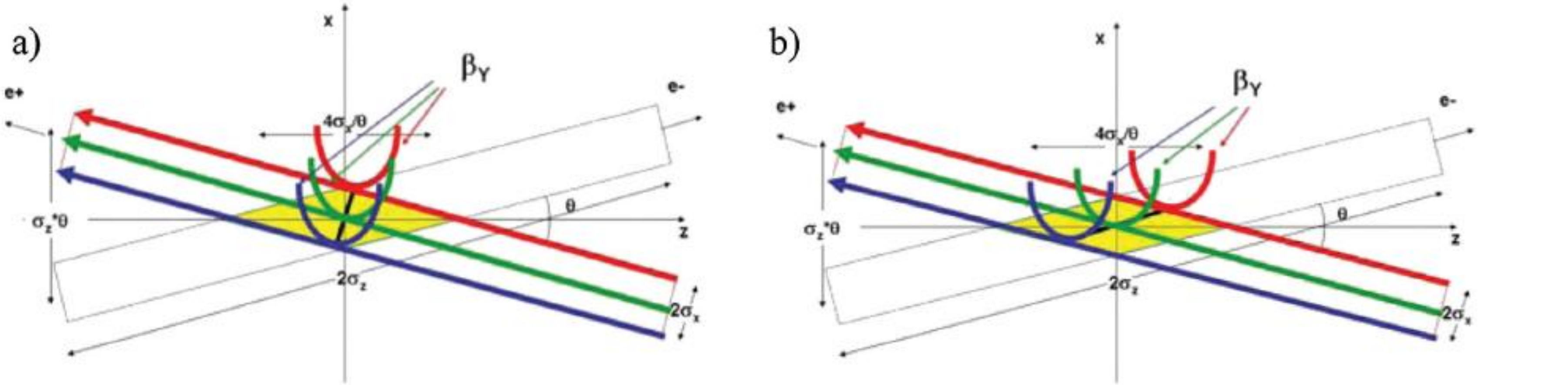
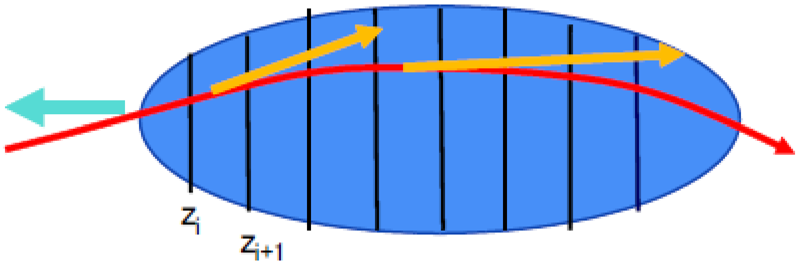
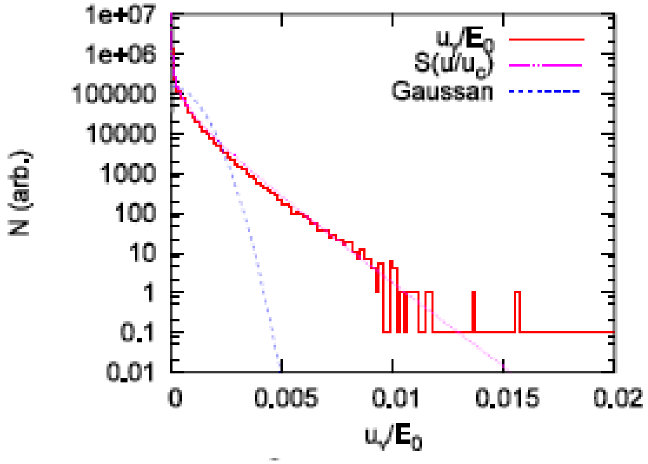
- Crab-waist



- Beamstrahlung Effect & 3D flip-flop





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A. Bogomyagkov et al., Phys. Rev. ST Accel. Beams 17, 041004 (2014)
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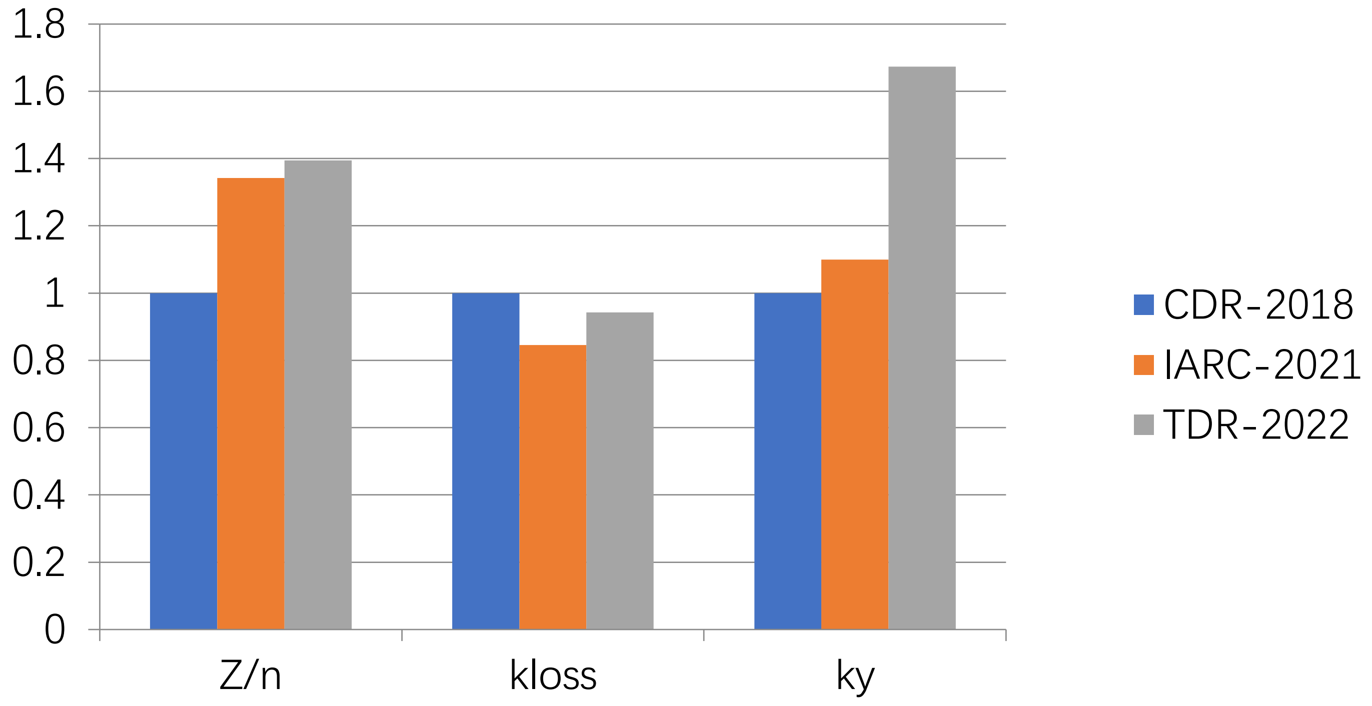
Y. Zhang et al., PRST-AB, 8, 074402 (2005)
Y. Seimiya et al., PTP 127, 1099 (2012)
K. Ohmi, IPAC16
Y. Zhang et al., PRAB 23, 104402, (2020)
Zhiyuan Li etal., NIMA 1064, 169386 (2024)

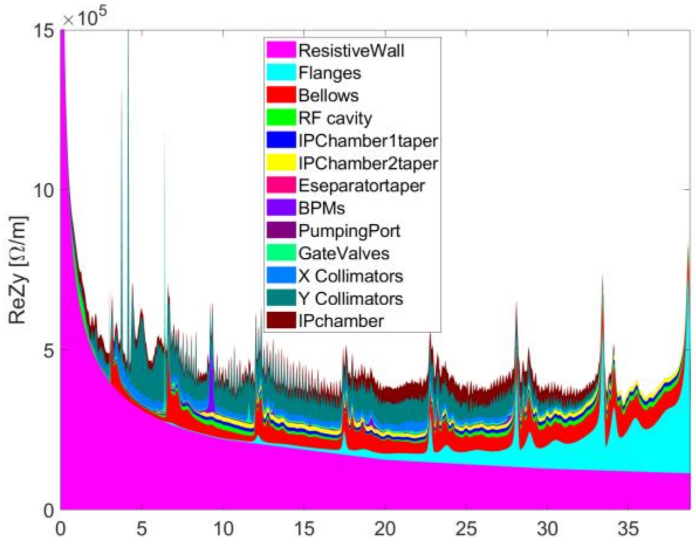
Simulation Tool

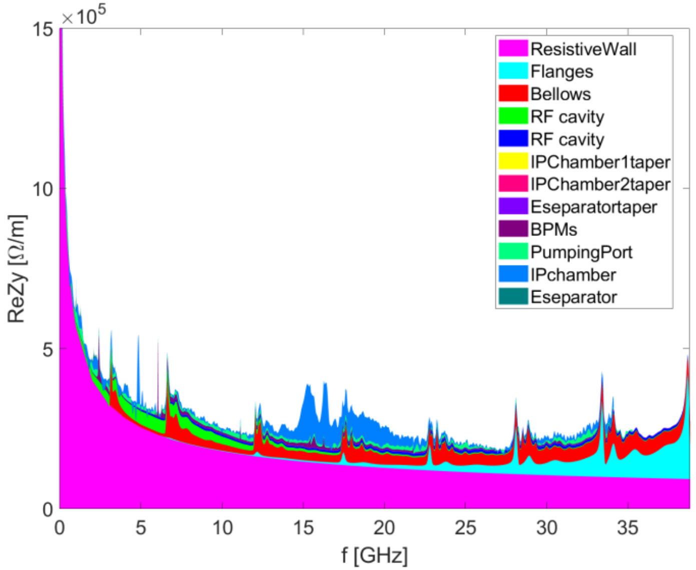
- Linear Arc Map with SR radiation
- One turn map including general chromaticity
- Horizontal crossing angle: Lorentz boost map
- Bunch slice number is about 10 times Piwinski angle
- Slice-Slice collision: Synchro-beam mapping method (or PIC)
- Synchrotron radiation during collision
- Longitudinal wakefield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

Impedance is being updated

- Different results may use different impedance

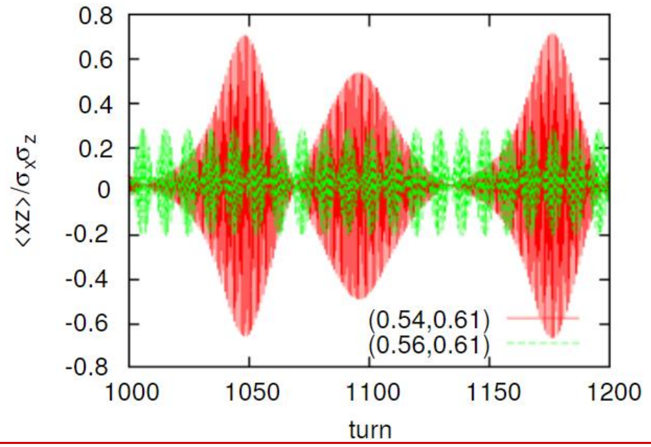






Larger ν_s/ξ_x is preferred

Horizontal Beam-Beam Instability (X-Z)



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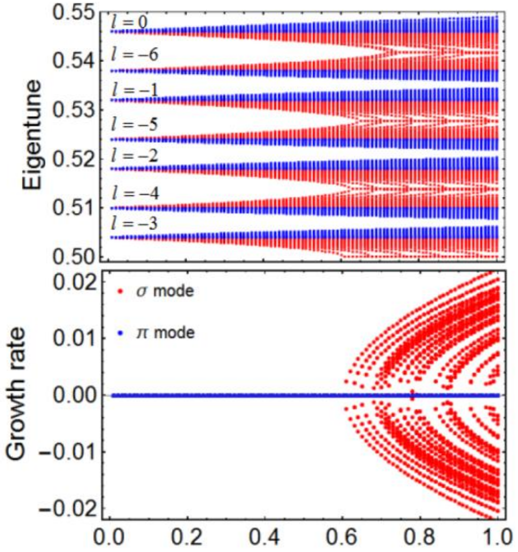
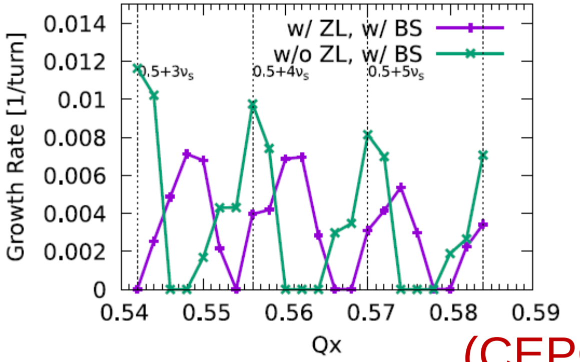
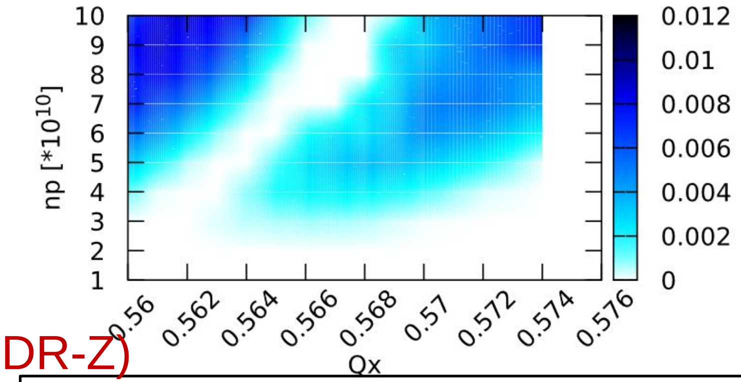
C. Lin etal.,, PRAB 25, 011001 (2022)

w/o ZL



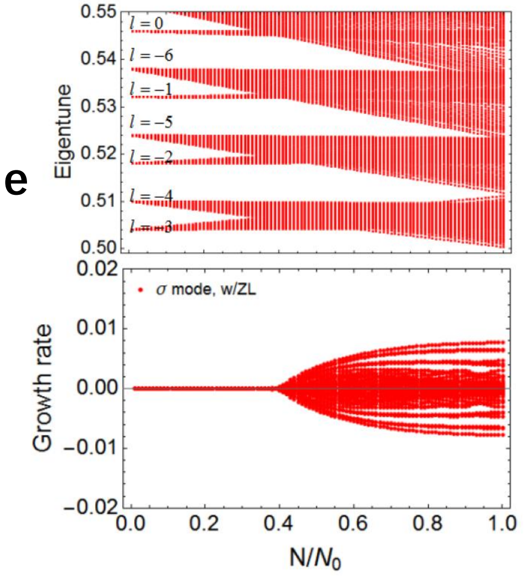
By including the impedance stable areas become narrower and are shifted





(CEPC-CDR-Z)

w/ ZL, σ mode

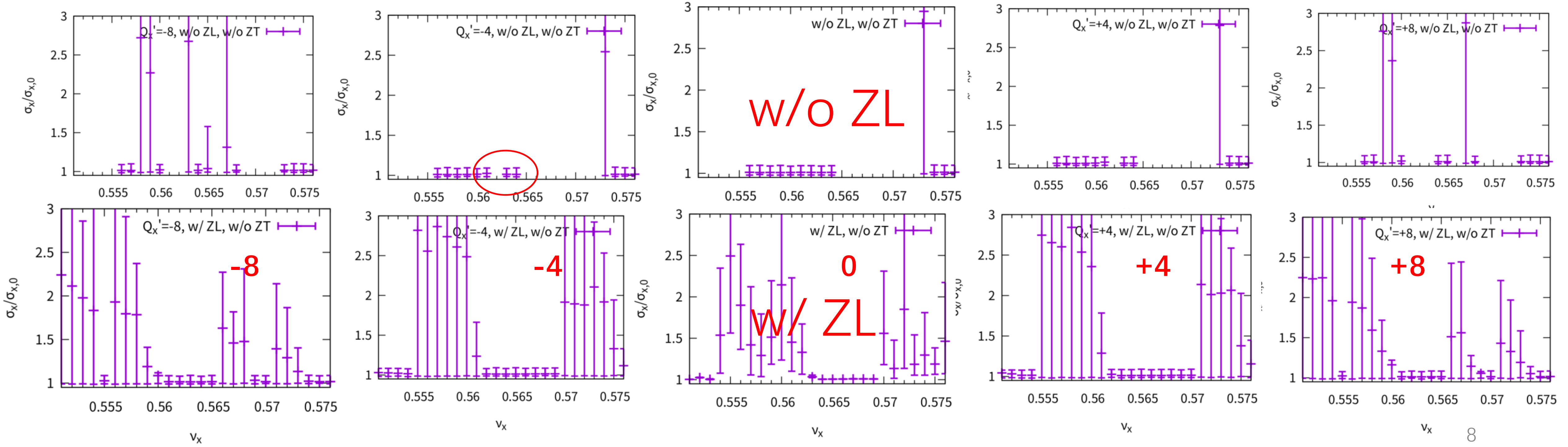


Growth rate versus horizontal tune, w/ and w/o ZL

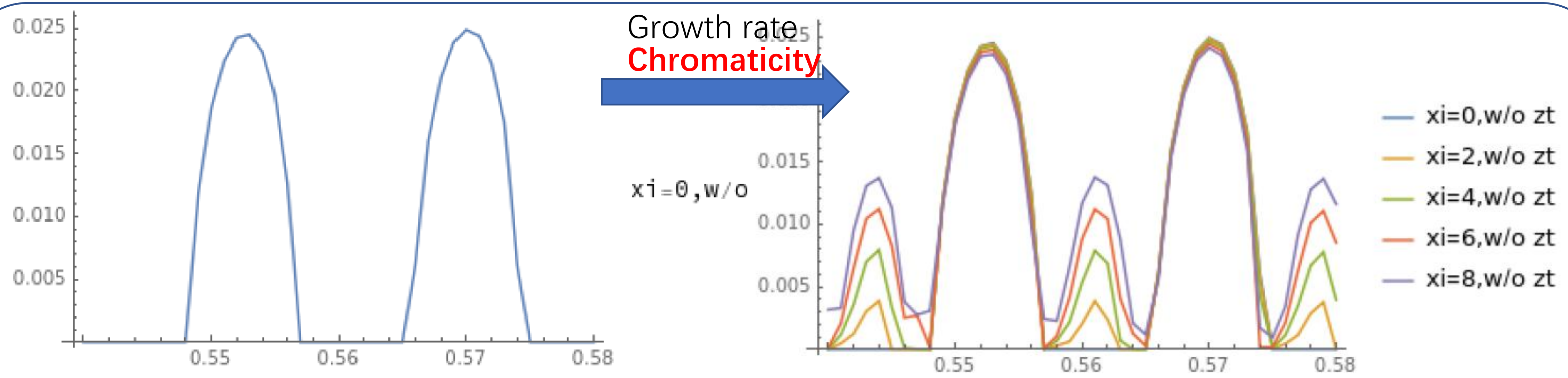
Growth rate versus bunch population, w/ ZL

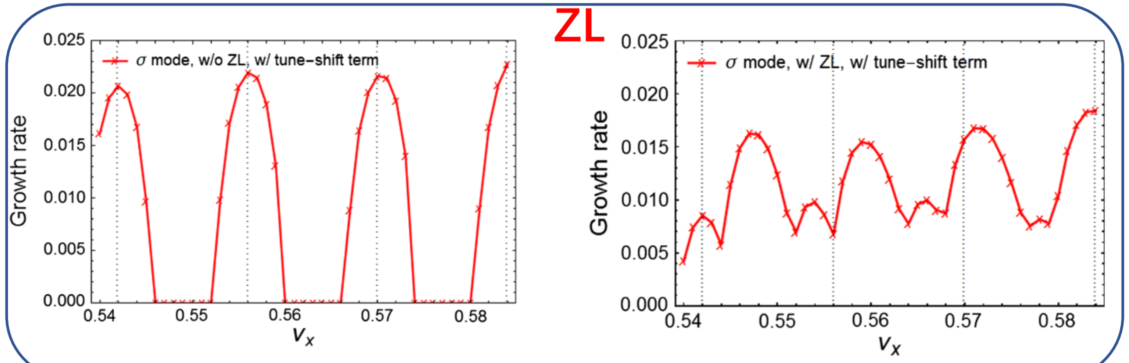
Chromaticity on X-Z instability (simulation)

- Qx'=-8/-4/0/4/8 is scanned at different horizontal tune
- Sign of chromaticity make no difference
- **Chromaticity is detrimental** (w/o ZL)
- **Chromaticity could be helpful** (w/ ZL)

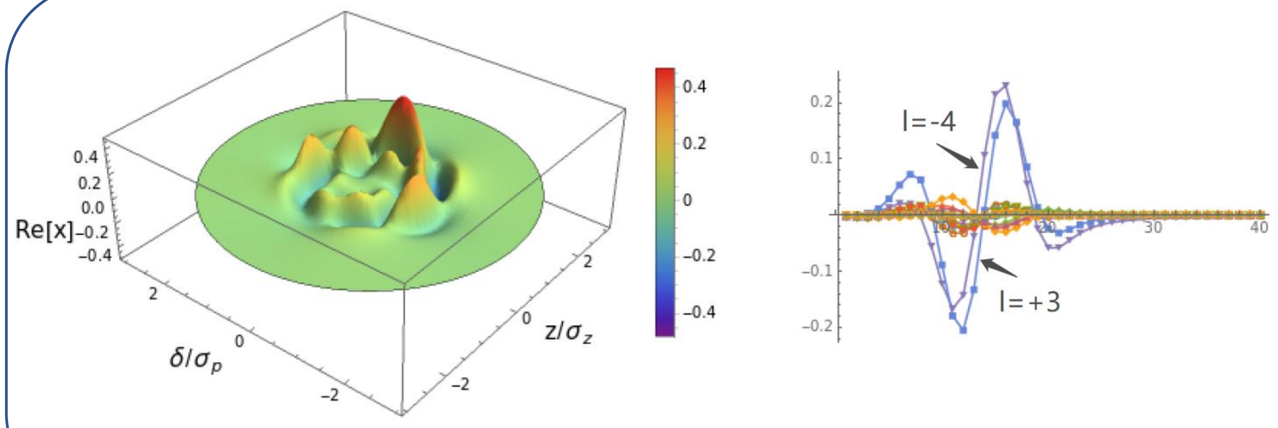


Chromaticity on X-Z instability (analysis, w/o ZL)





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

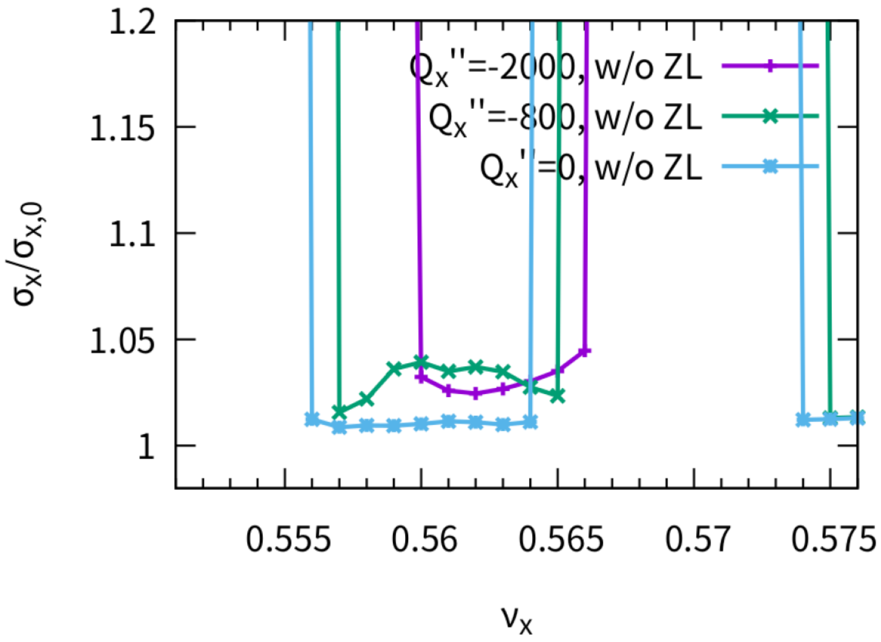


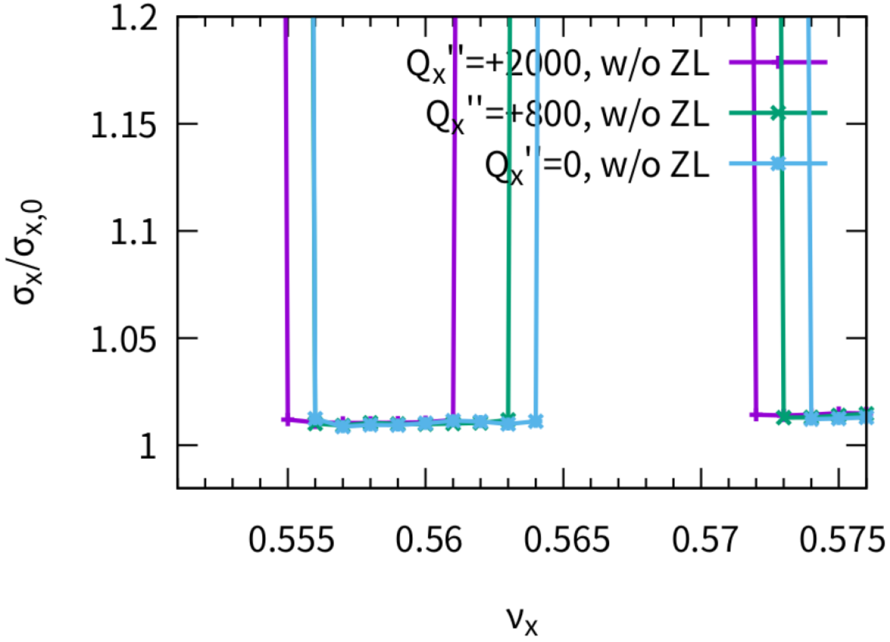
@Qx=0.559，w/ Chromaticity

2^{nd} order chromaticity on X-Z instability (w/o ZL, simulation)

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

- ν_2=-2000/-800/0/+800/+2000 is scanned in simulation
- Finite ν_2 is detrimental for instability





2nd order chromaticity on X-Z instability w/o ZL, w/o ZT, Analysis

- Analysis results agrees with simulation
  - minus 2nd order chromaticity is worse for stability
- The eigen mode distribution induced by finite chromaticity is not singular, and is expected to appear in simulation

2nd 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 ν_2=1000
- With 2nd order chromaticity, one turn map phase advance is

$$\mu_x(J,\phi) = 2\pi\nu_0 + \frac{\nu_1}{\nu_s}\sqrt{\frac{2J}{\beta_z}}\left[\cos\phi - \cos(\phi + 2\pi\nu_s)\right] + 2\pi\nu_2\frac{J}{\beta_z} + \frac{\nu_2}{2\nu_s}\frac{J}{\beta_z}\left[\sin 2\phi - \sin 2(\phi + 2\pi\nu_s)\right]$$

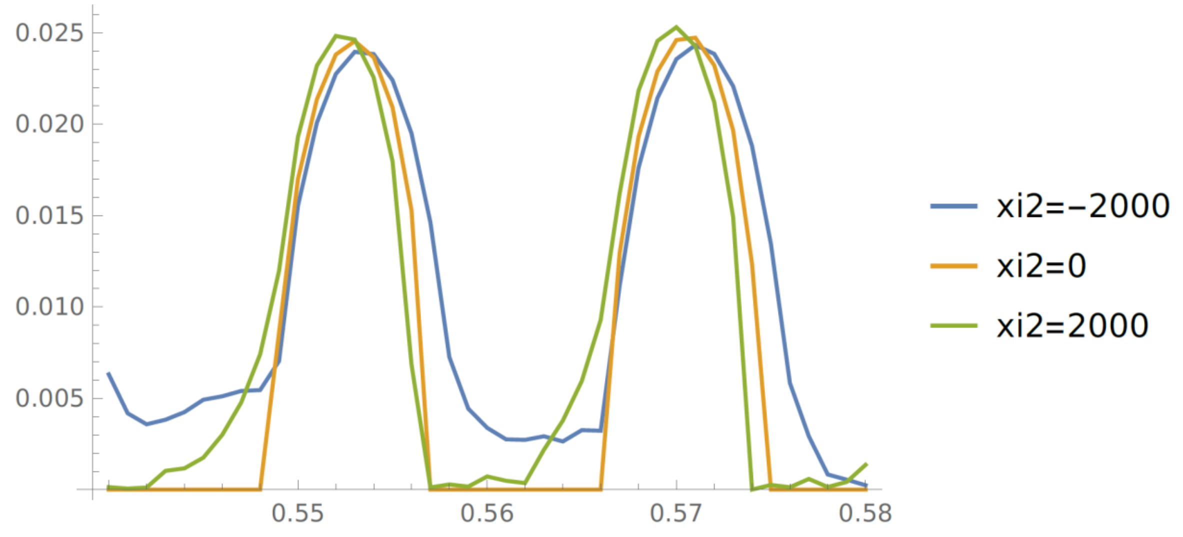
- The arc map with chromaticity is

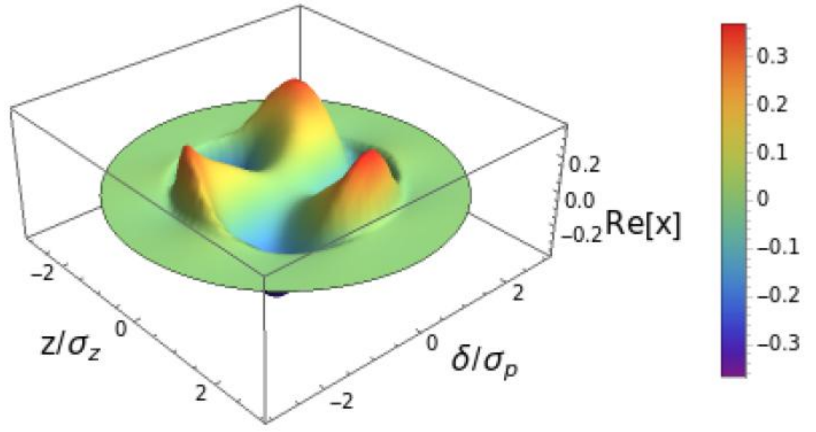
$$x_{l,n+1}(J) = \frac{1}{2\pi}e^{-il2\pi\nu_s}\sum_{l'}\left[+A_{ll'}(J)x_{l',n}(J) + B_{ll'}(J)p_{l',n}(J)\right]$$

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

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

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





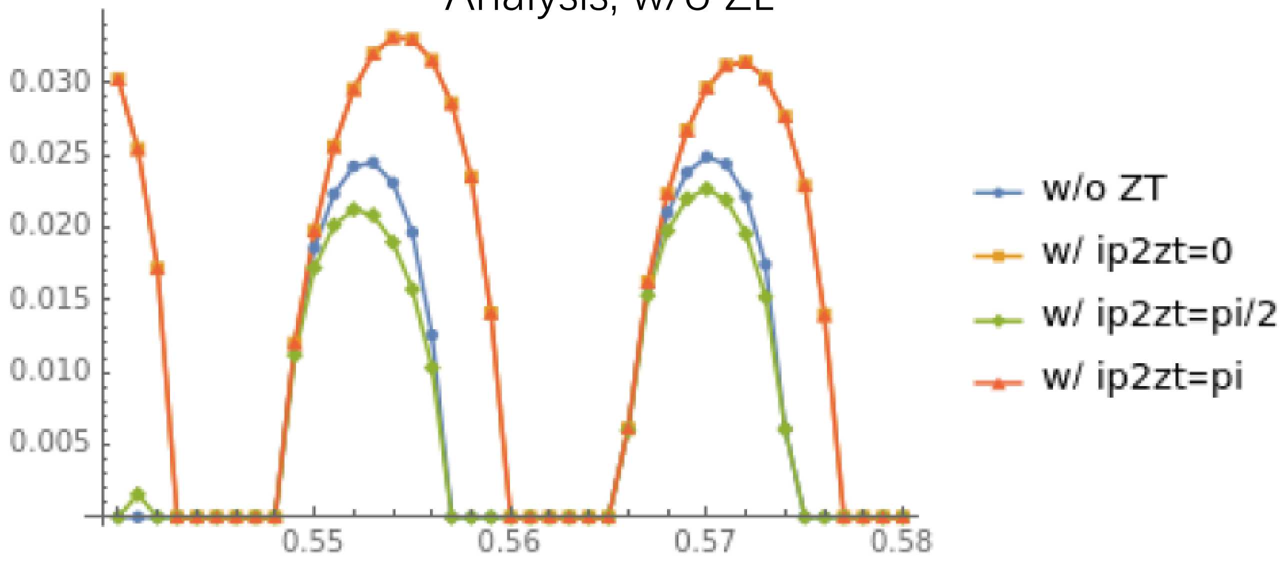
Eigen-mode distribution: Qx=0.558, ν_2=-2000

Effect of local ZT on X-Z instability

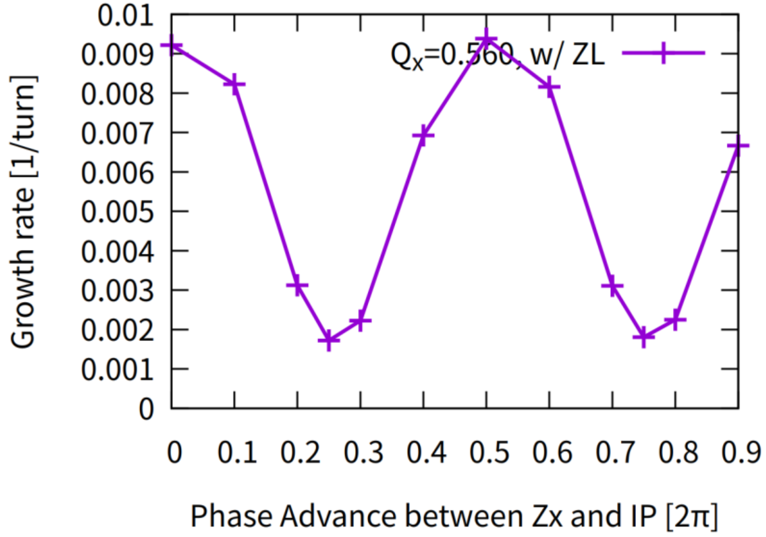
X-Z instability comes from localized property of Beam-Beam

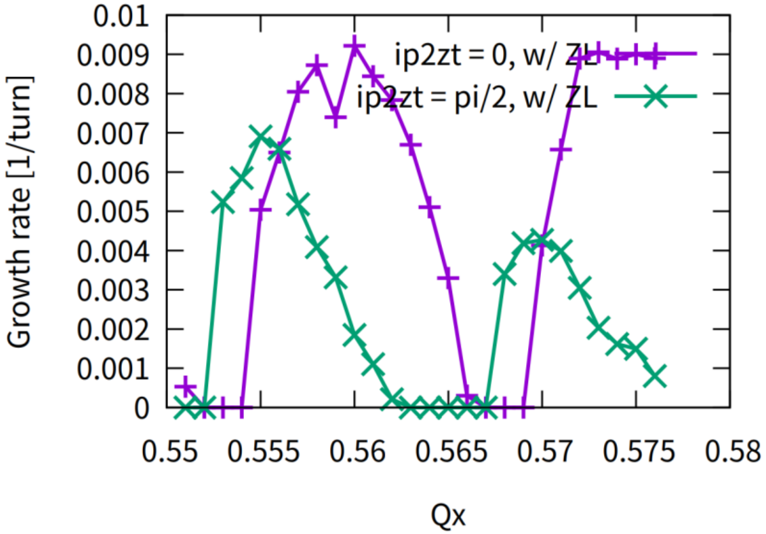
- ip2zt = Pi/2, growth rate is lowest

Analysis, w/o ZL



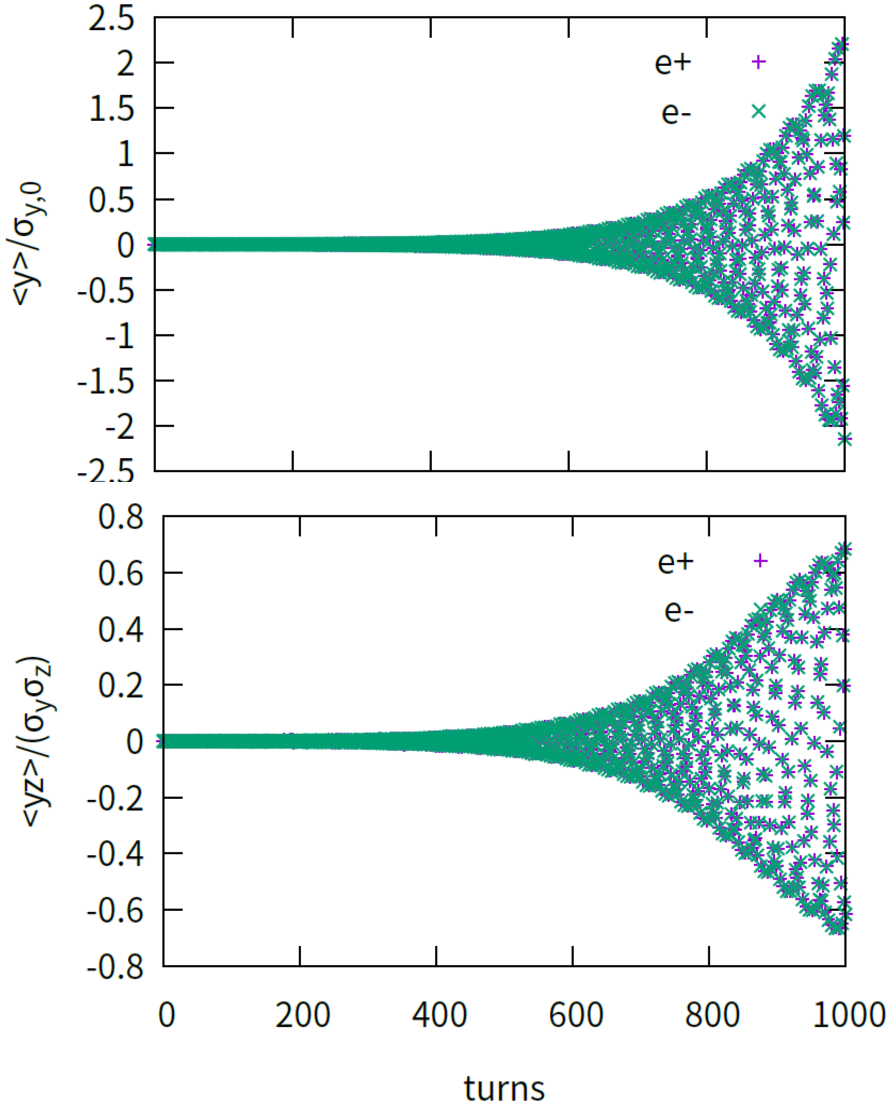
Simulation

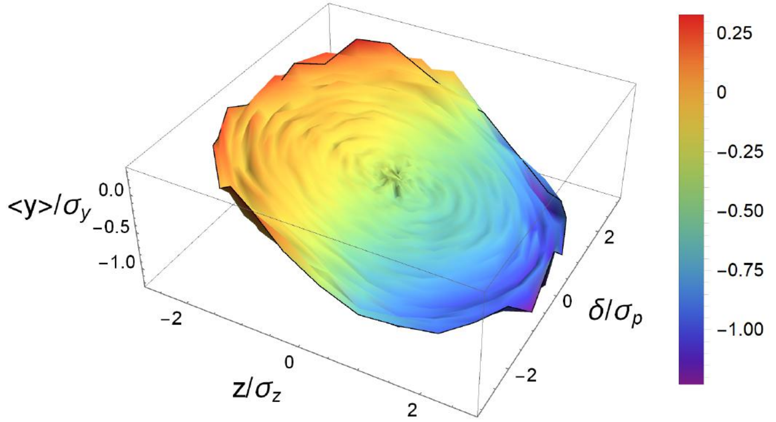




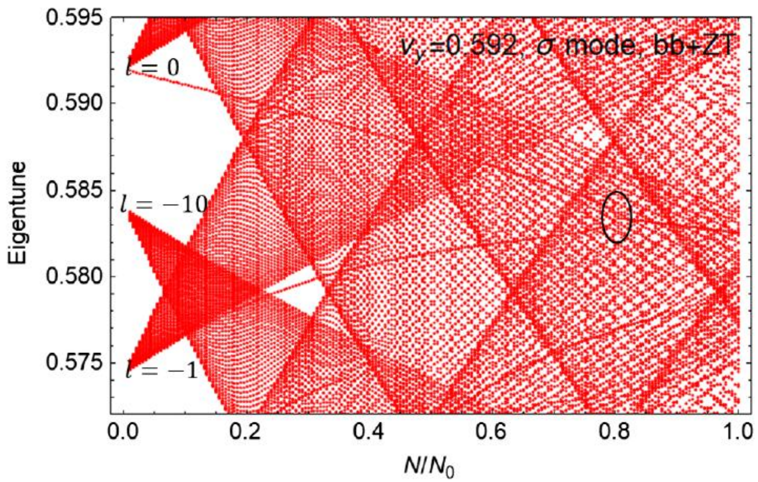
Y. Zhang et al., PRAB 26, 064401 (2023)
K. Ohmi et al., PRAB 26, 111001 (2023)

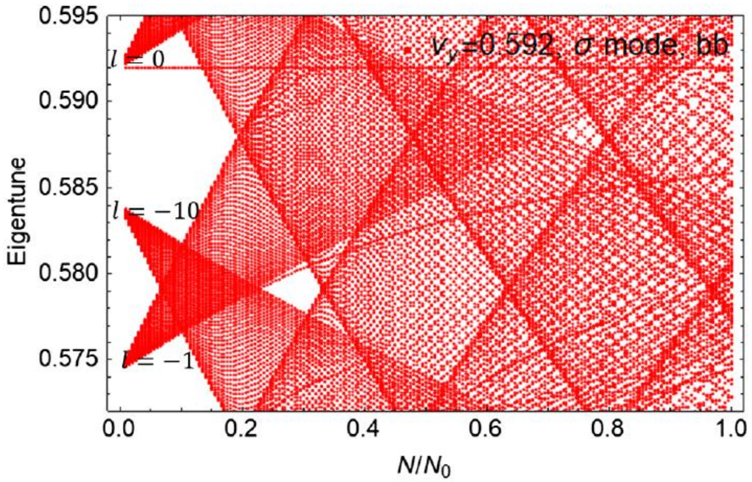
Vertical mode coupling with ZT($\boldsymbol{\sigma}$-mode)





TMCI threshold is reduced from about 21e10 to 11e10

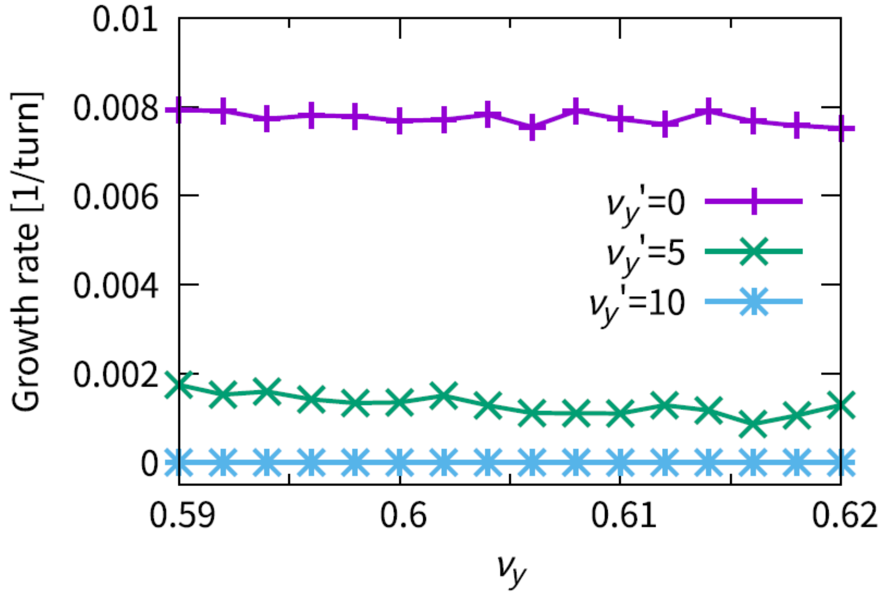




Y. Zhang et al, PRAB 26, 064401 (2023)

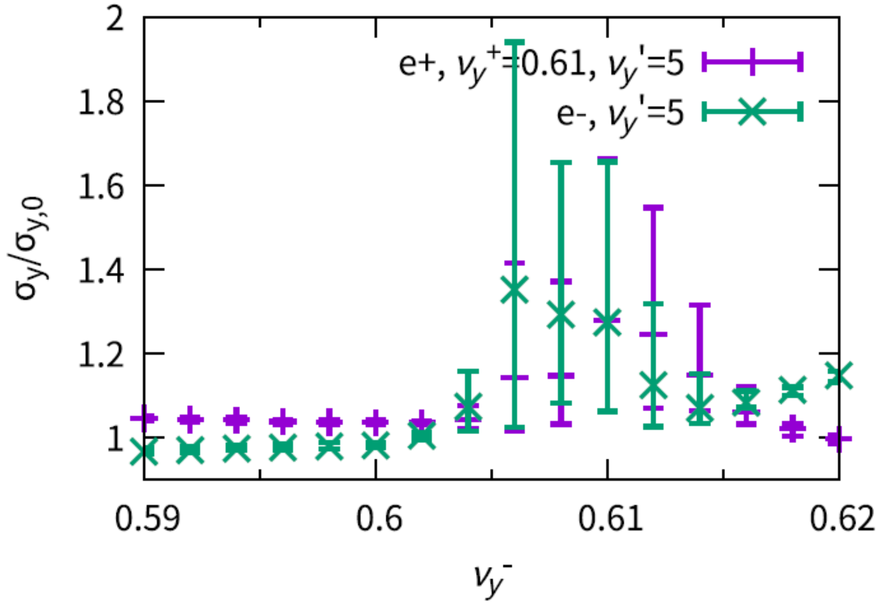
Mitigation of Vertical TMCI (BB+ZT)

Chromaticity



Growth rate of vertical centroid versus tune with different vertical chromaticity.

Asymmetrical Tunes + Chromaticity

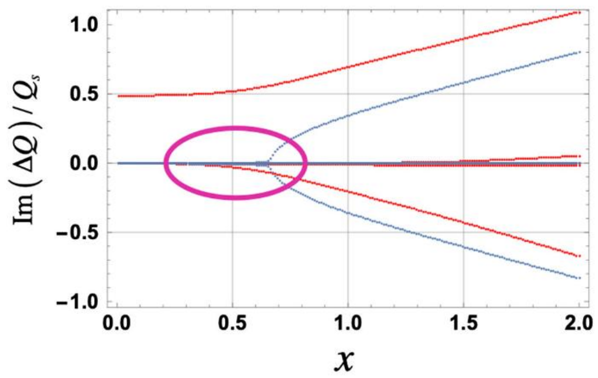


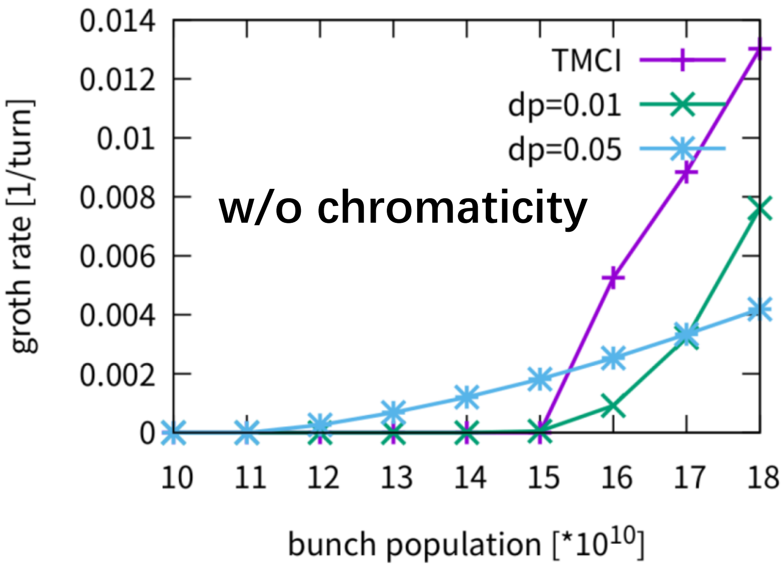
Vertical beam size versus one beam's vertical tune. The other beam's tune is fixed at 0.610.

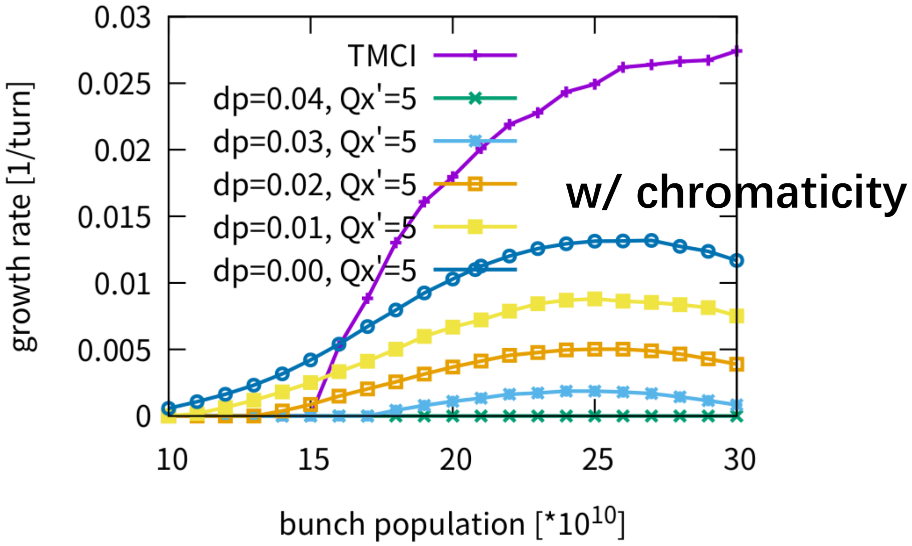
E. Metral, PRAB, 24, 041003 (2021)
K. Ohmi et al., eeFACT2022

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

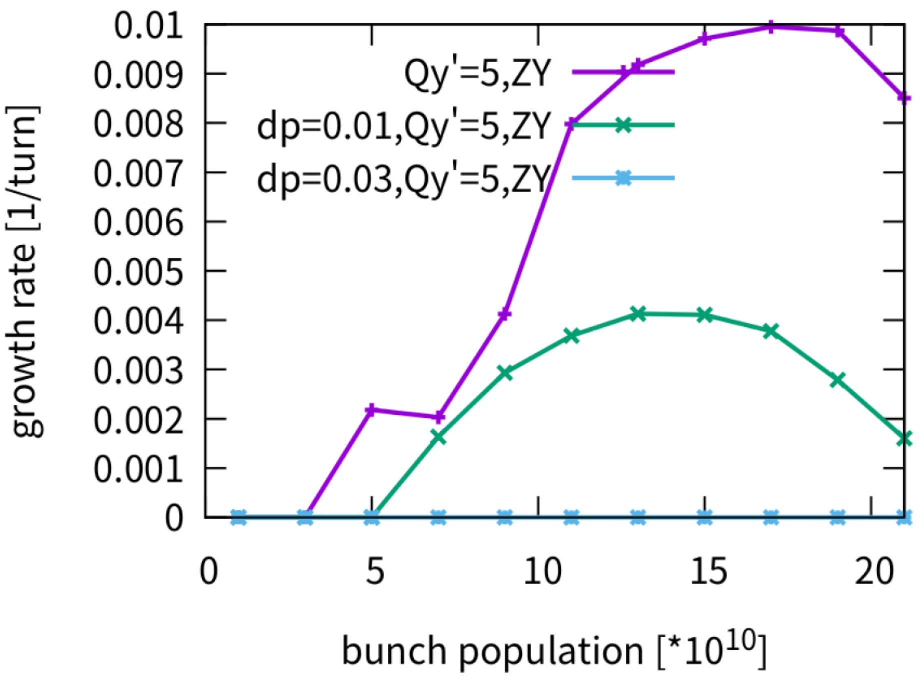
- A simplified resistive damper is used: $\Delta p_i = -2d_p p_i$
- Strong feedback reduce the TMCI threshold
- Growth rate is lower with feedback above threshold
- w/ chromaticity, strong feedback could be helpful

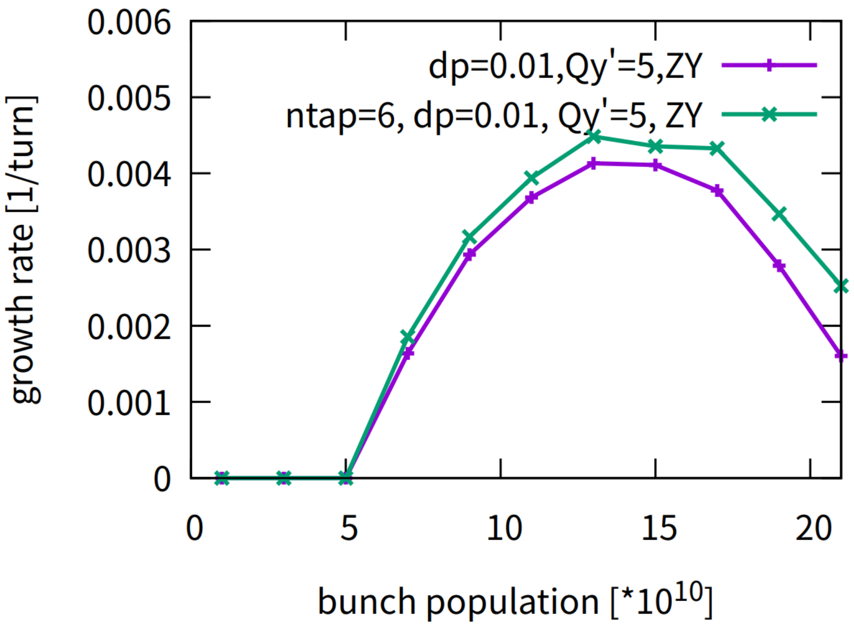






Feedback on vertical TMCI (Qy'=5)





- Pickup-> kicker, pi/2
- FIR coefficient
  +0.846493,
  -0.928427,
  +0.040751,
  +0.322141,
  -1.080667,
  +0.799708

$$\Delta p_K(n) = A \sum_{k=0}^{N_{tap}-1} C(k)x(n-k)$$

- With finite tune chromaticity, resistive feedback is helpful to mitigate the instability
- No additional effect from ideal multi-tap (ntap=6) feedback

Some issues on accurate modeling

- X-Y rotation in Gaussian approximation (See Derong @ BB2024)
- Crab-Waist Transformation ($\frac{1}{2\theta} x p_y^2$) vs Crab-Waist Sextupoles
- Solenoid instead of drift during collision (cp <-> ip)
  - Solenoid in the lab frame is constant $(B_{x,sol}, B_{y,sol}, B_{z,sol})$
  - In the boost frame, the field is

$$E'_x = E_x = 0, \quad B'_x = B_x = B_{x,sol}$$

$$E'_y = \gamma_{lorentz}(E_y - c\beta_{lorentz} B_z) = -c \tan\theta B_{z,sol}, \quad B'_y = \gamma_{lorentz}(B_y + \frac{\beta_{lorentz}}{c} E_z) = \frac{1}{\cos\theta} B_{y,sol}$$

$$E'_s = \gamma_{lorentz}(E_z + c\beta_{lorentz} B_y) = c \tan\theta B_{y,sol}, \quad B'_s = \gamma_{lorentz}(B_z - \frac{\beta_{lorentz}}{c} E_y) = \frac{1}{\cos\theta} B_{z,sol} \quad ($$

Tracking of collision in detector solenoid

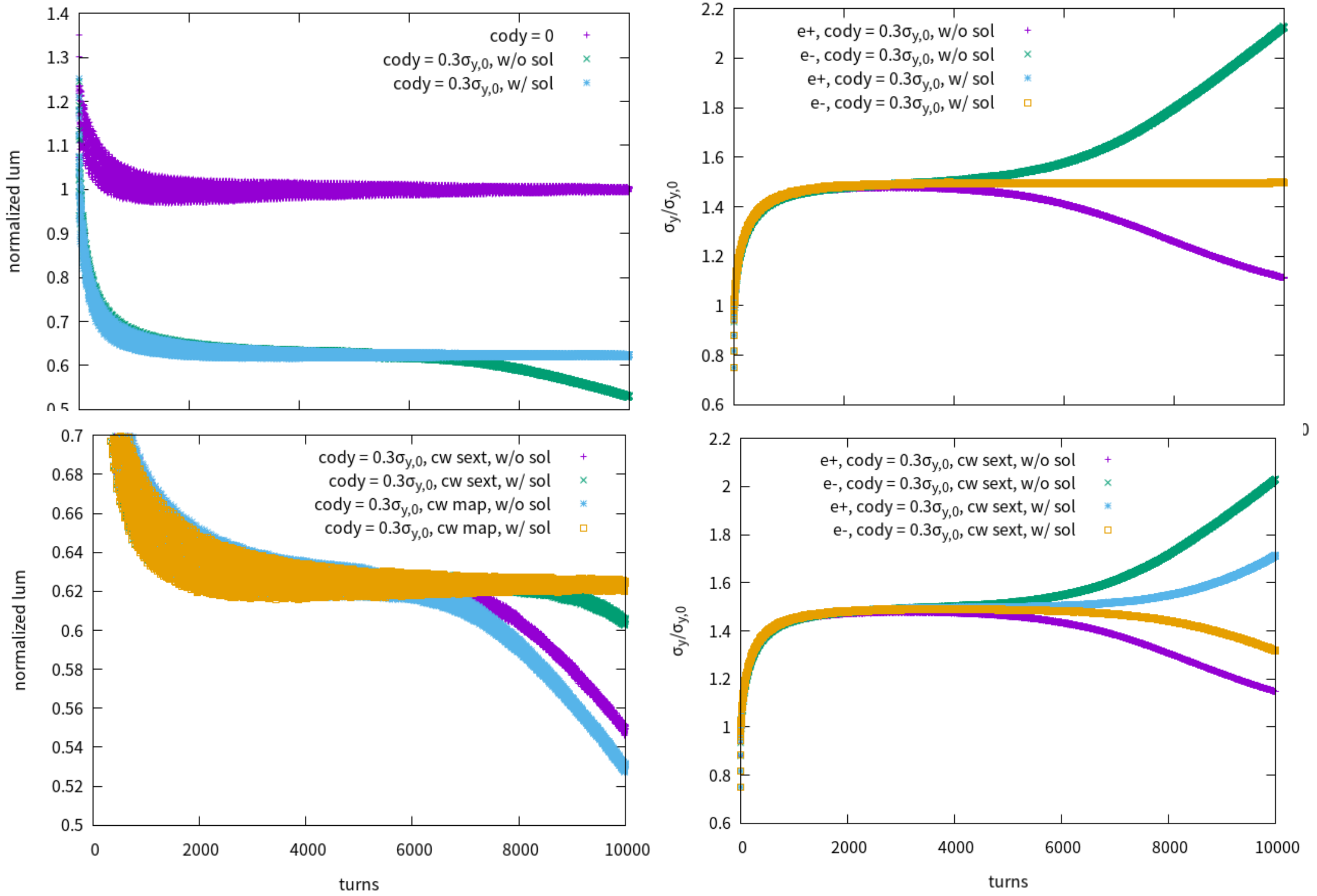
- Step-by-step Tracking
  - Lorentz Boost (Hirata)
  - IP -> CP
    - L/2 solenoid
    - Momentum kick of (p_x, p_y, δ)
    - L/2 solenoid
  - Collision (beam rotation is considered)
  - CP -> IP
  - Inverse Lorentz Boost

$$
\begin{aligned}
H(x,p_x,y,p_y,z,\delta;s) = {} & \frac{\gamma mc^2}{\beta_0 c P_0} + \sqrt{(1+\delta)^2-(p_x-a_x)^2-(p_y-a_y)^2} \quad \text{(solenoid)} \\
& + \frac{q}{P_0}\frac{B_{y,sol}}{\cos\theta}x \\
& + \frac{q}{P_0}(\tan\theta \boxed{B_{z,sol}} - B_{x,sol})y \\
& - \frac{q}{P_0}\tan\theta B_{y,sol} z
\end{aligned}
$$

Solenoid increase from 2 T to 5 T， the collision is no difference

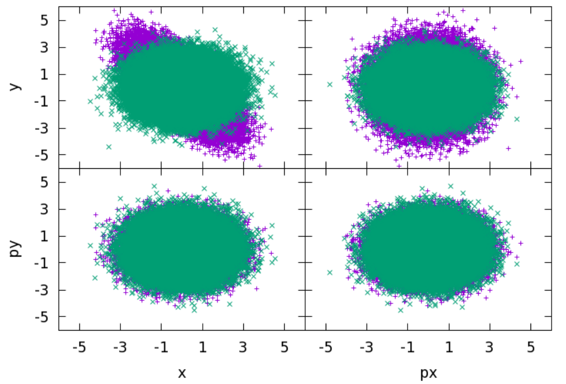
Different model with $\boldsymbol{\Delta y}$@IP ($0.3\boldsymbol{\sigma_y^*}$) preliminary

- w/o sol + CW map, flip-flop
- w/ sol + CW map, stable
- CW sext, flip-flop
- More stable with solenoid



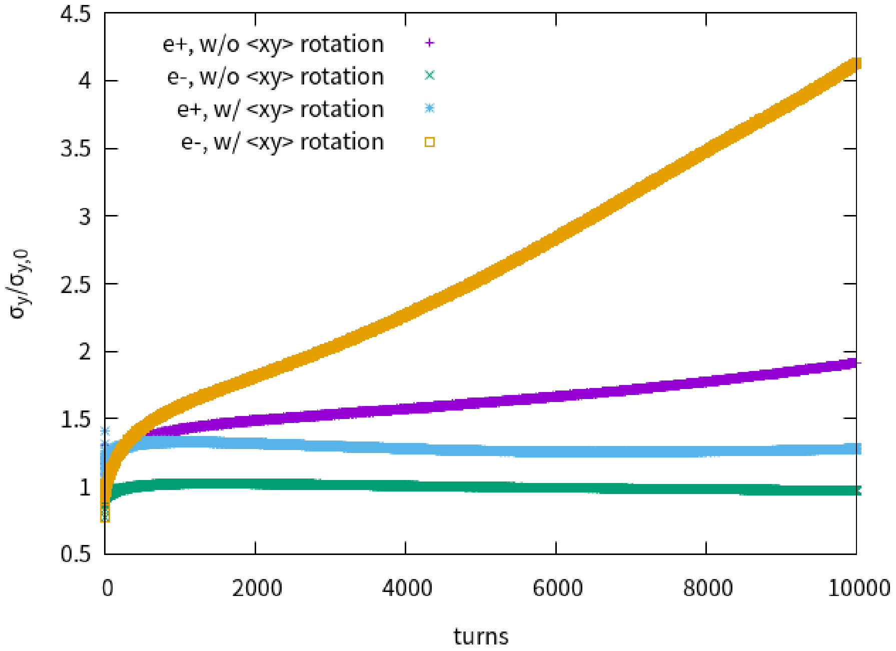
preliminary

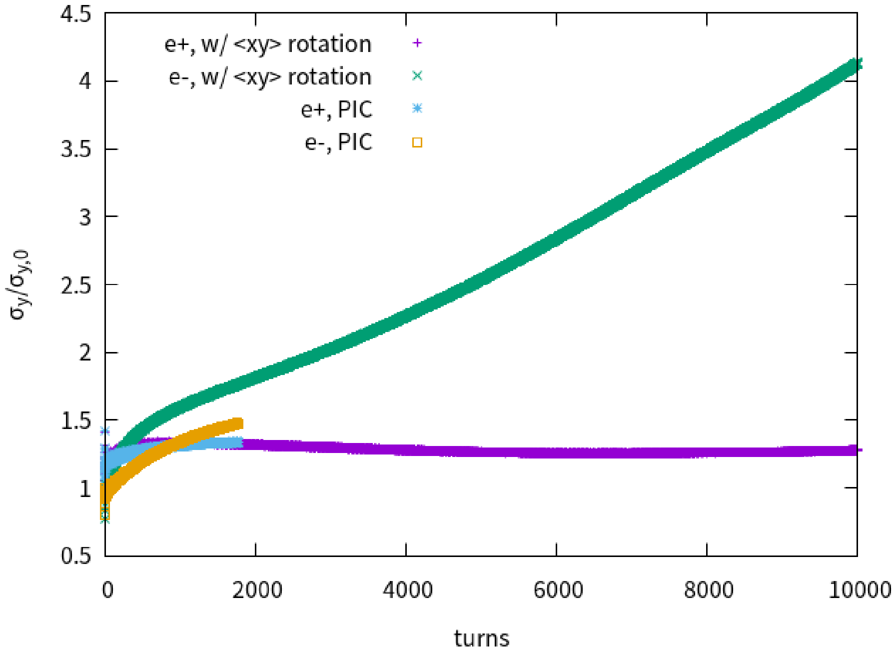
Different model with finite R1@IP



- w/o X-Y rotation, **e+ blow up** (nearly stable)
- w/ X-Y rotation, **e- blow up**
- PIC simulation confirm the model w/ X-Y rotation

R1= 60e-4 (only e+)
- geometrical luminosity loss 10%
- X-Y rotation: 6 mrad

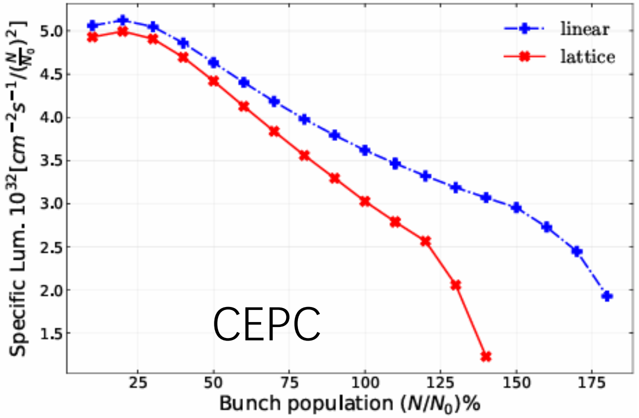


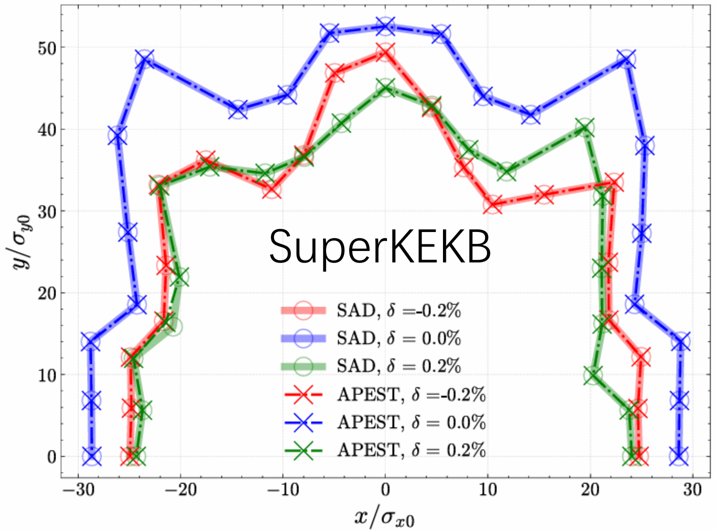


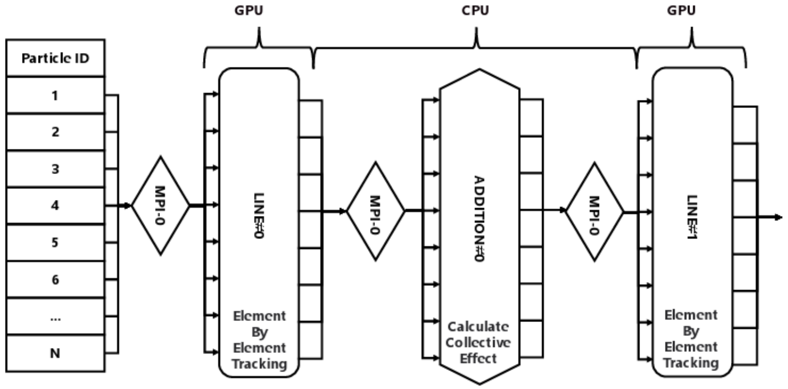
Zhiyuan Li etal., NIMA 1064 (2024) 169386

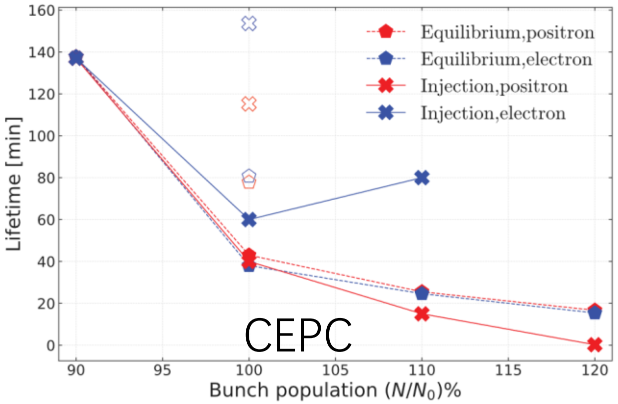
Strong-strong Beam-beam + Lattice

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

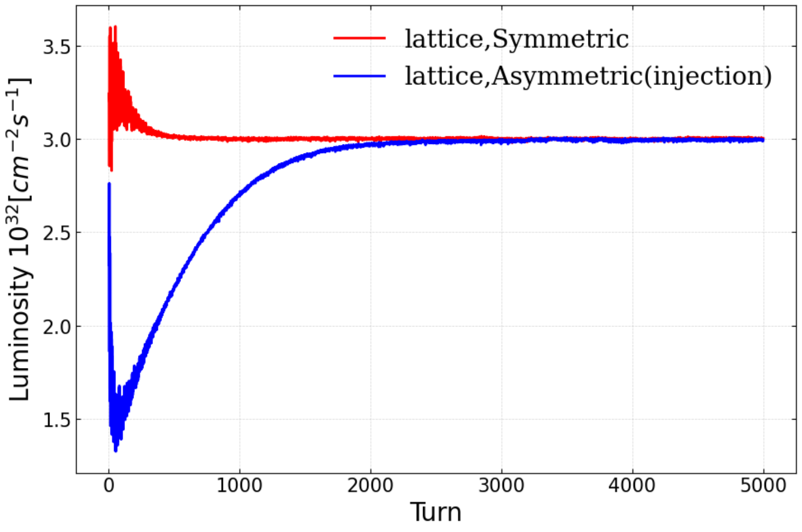


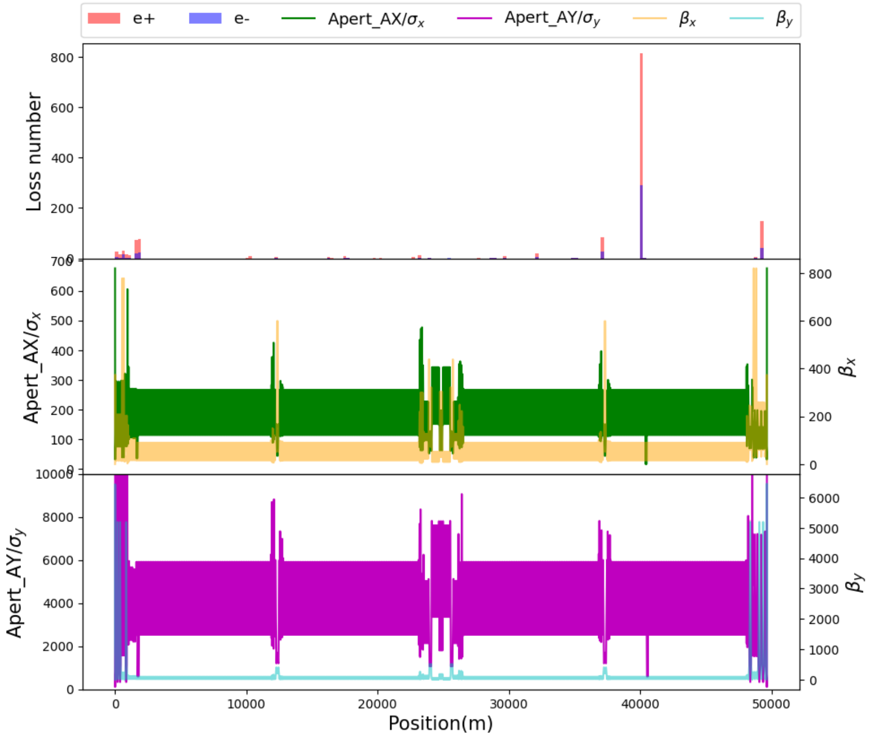


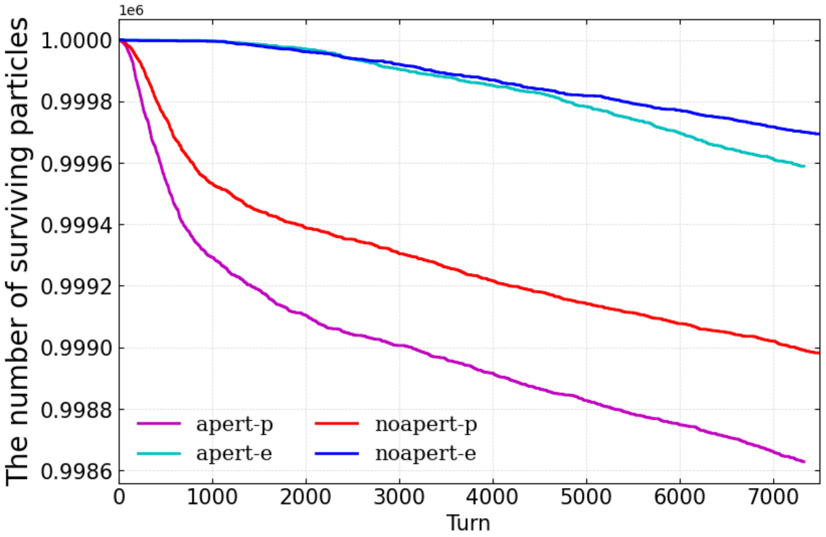




Asymmetric Collision – Swap out injection



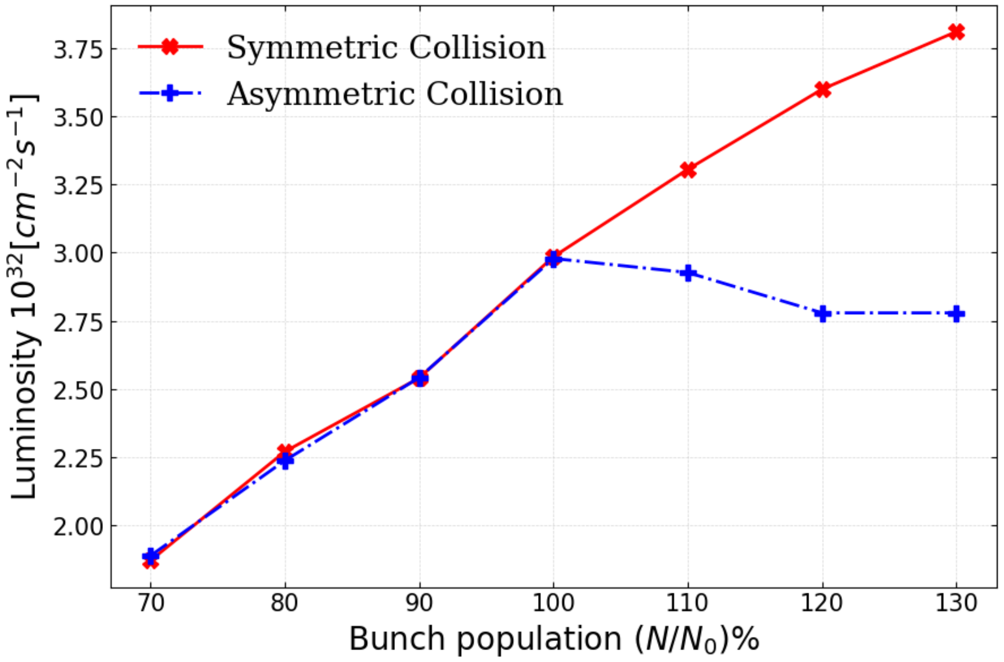




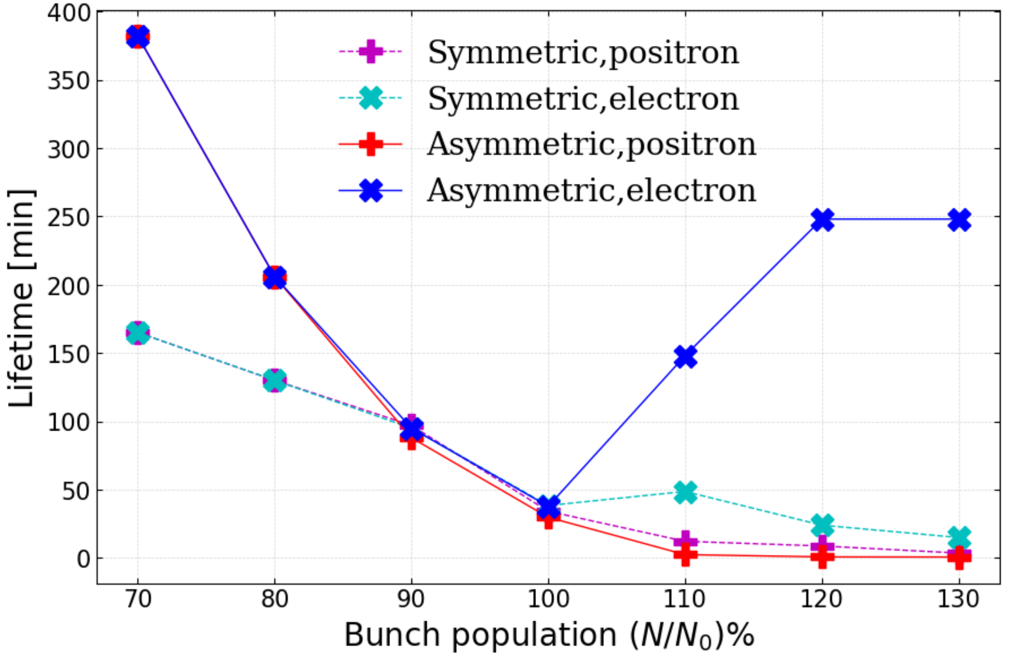
e+(inj.) / e-
w/o apert: 39/42(min)
w/ apert: 29/37(min)

- **Initial beams: e+ (collider SR equilibrium) vs e- (booster SR equilibrium)**
- Luminosity: same between symmetric(collision equilibrium) and asymmetric collision
- **Clear lifetime reduction (e+) with physical aperture**

Collision versus bunch intensity (w/ aperture)



Luminosity



Lifetime

- Symmetric: Increase linearly with bunch population
- Asymmetric: Peak value at design bunch population

- Meet requirements at design bunch population
- Bad lifetime if N/N_0 > 10%

Summary

- Analysis and simulation of the combined effects between beam-beam and impedance provide clear insights into the underlying beam dynamics
- New simulation tools have been (and are being) developed to enhance both the accuracy and predictive capacity of related study