Beam stability studies with beam-beam and wakefields based on multiparticle tracking simulations and the circulant matrix model

ICFA Mini-Workshop – September 2024

Roxana SOOS[1,2,3], Xavier BUFFAT[2], Angeles FAUS-GOLFE[3],

Acknowledgements to: K. HIRATA, M. MIGLIORATI and FCC-ee beam-beam working group

1 - Université Paris-Saclay
2 - CERN
3 - IJClab

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Overview

Introduction

Study context for FCC-ee

Outline of the study

2 particle model for beam-beam effects

Model without virtual drifts

Virtual drift, hourglass and crossing angle

Virtual drift and hourglass effects on fundamental modes

Circulant matrix model simulations

Effects of the virtual drifts on mode couplings

Most unstable modes

Beam beam with transverse wakefields

Conclusion and outlook

References

Introduction

Study context for FCC-ee

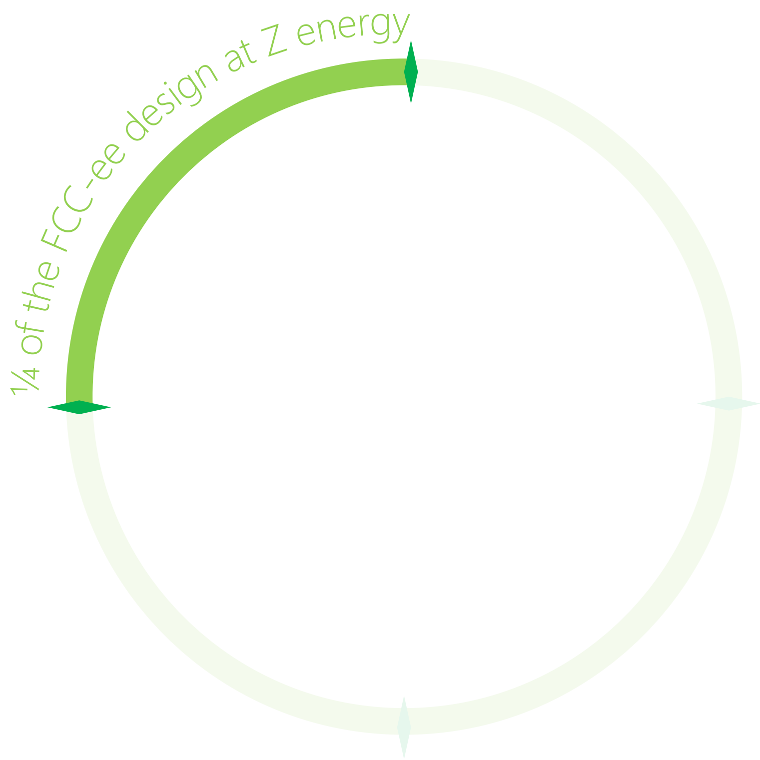
Interplay between impedance (wakefields) and beam-beam has a growing interest for building new accelerators [1]

BimBim (CMM) and Xsuite showed agreement with LHC and VEPP (*round beams*) measurements [2], [3]

Benchmark has been done for wakefields and beam-beam with flat beams and crossing angle [4] [5]

N_0	1.51×10^{10}
Q_y	0.5395
chromaticity	0.0
circumference (km)	90.658728
momentum compaction	2.86×10^{-5}
ϵ_x (m)	7.1×10^{-10}
ϵ_y (m)	7.5×10^{-13}
Crossing angle at IP (mrad)	30.0
Q_s	0.0072
β_x (m)	0.11
β_y (m)	0.0007
σ_z (BS) (m)	0.0156
σ_δ (BS)	0.0011
Energy (GeV)	45.6

(Not the most up to date parameters used)



Only will be considered:

- *Transverse wakefields*
- *Linear transfer maps*
- *Linearized coherent beam-beam kicks (CMM)*

Introduction

Outline of the study

Use CMM to study instabilities due to the interplay between beam-beam and transverse wakefields for colliders with high hourglass factor, flat beams and large crossing angle

CMM = Circulant Matrix Model

Introduction

Outline of the study

Study a 2 particles model, to understand the fundamental effect of the phase advance (*virtual drifts*) in presence of a large crossing angle and hourglass factor

Compare CMM simulations to another mode analysis method results without phase advance considerations

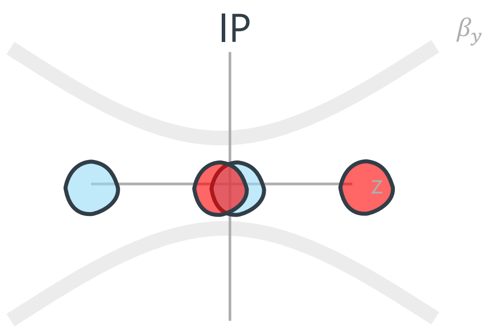
Observe the effect of the phase advance for real machine parameters, with a converged model (n_s x n_r >1800)

Use CMM to study instabilities due to the interplay between beam-beam and transverse wakefields for colliders with high hourglass factor, flat beams and large crossing angle

CMM = Circulant Matrix Model

2 particle model for beam-beam effects

Model without virtual drifts



$x_{B1,1}$, $x_{B2,1}$, $x_{B1,2}$ and $x_{B2,2}$ projected to the IP after 1 turn

$$\hat{x}'_{B1,1} = x'_{B1,1} + 2k_{BB}\left(x_{B1} - x_{B2}\right)$$

change in angle induced by the beam-beam force

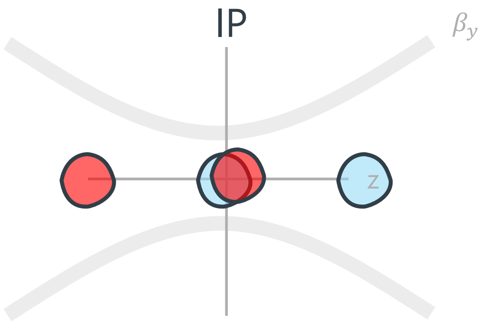
$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2k_{BB} & 1 & 0 & 0 & -k_{BB} & 0 & -k_{BB} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2k_{BB} & 1 & -k_{BB} & 0 & -k_{BB} & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -k_{BB} & 0 & -k_{BB} & 0 & 2k_{BB} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ -k_{BB} & 0 & -k_{BB} & 0 & 0 & 0 & 2k_{BB} & 1 \end{pmatrix} \begin{pmatrix} x_{B1,1} \\ x'_{B1,1} \\ x_{B1,2} \\ x'_{B1,2} \\ x_{B2,1} \\ x'_{B2,1} \\ x_{B2,2} \\ x'_{B2,2} \end{pmatrix}$$

Why to consider 'virtual drifts' [7] ?

The phase advance/delay of particles arriving at the IP at different times cannot be taken into account. The beam-beam kick would be the same for all particles. The effect of the hourglass and crossing angle cannot be properly studied.

2 particle model for beam-beam effects

Model without virtual drifts



$x_{B1,1}$, $x_{B2,1}$, $x_{B1,2}$ and $x_{B2,2}$ *projected to the IP after 1 turn*

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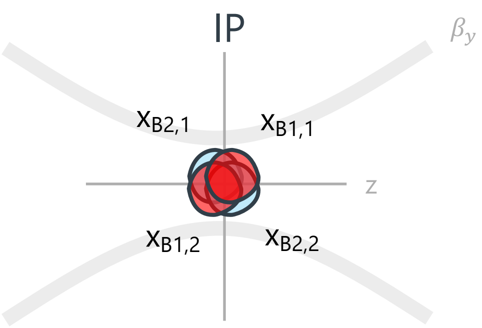

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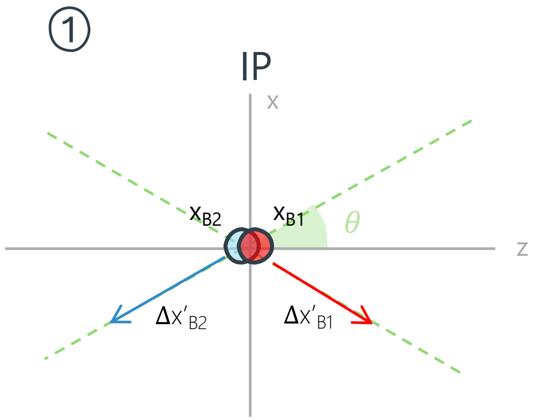
2 particle model for beam-beam effects

Virtual drift, hourglass and crossing angle

Considering the crossing angle with the virtual drifts



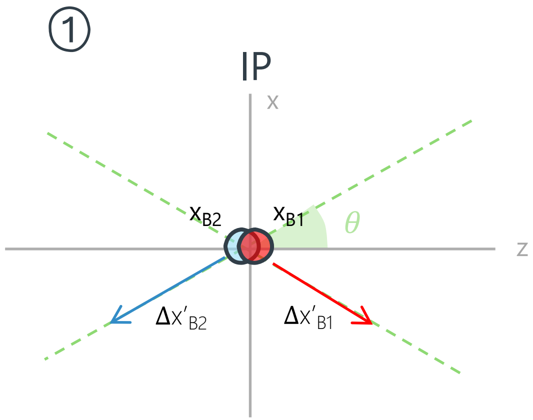
x_{B1} and x_{B2} projected on the IP after one turn map. In reality, x_{B1} already passed and x_{B2} has not arrived yet.

x_{B1} and x_{B2} have angles $\Delta x'_{B1}$ and $\Delta x'_{B2}$ but no offsets:
$\Delta x_{B1} = \Delta x_{B2} = 0$

2 particle model for beam-beam effects

Virtual drift, hourglass and crossing angle

Considering the crossing angle with the virtual drifts



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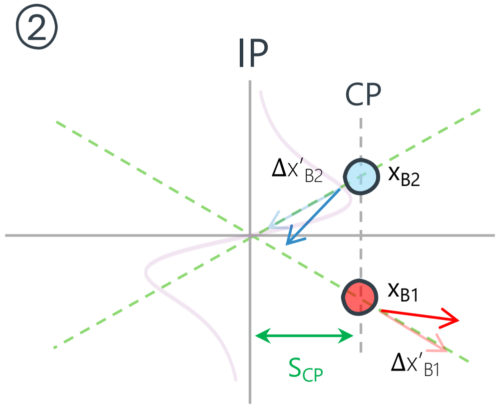


x_{B1} drifts of $+S_{CP}$ and x_{B2} drifts of $-S_{CP}$. x_{B1} and x_{B2} collide at CP changing their angle.

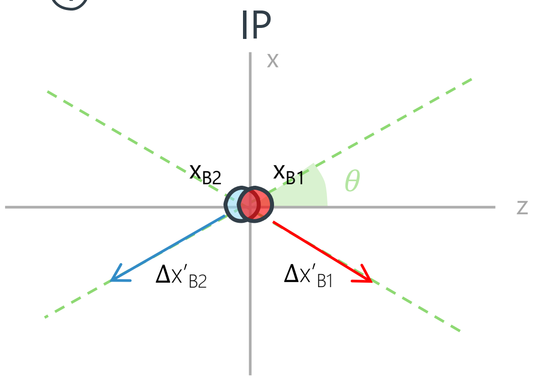
$\Delta x_{B1} = k_{BB}(x_{B1} - x_{B2})$ and $\Delta x_{B2} = k_{BB}(x_{B2} - x_{B1})$

2 particle model for beam-beam effects

Virtual drift, hourglass and crossing angle

Considering the crossing angle with the virtual drifts

①



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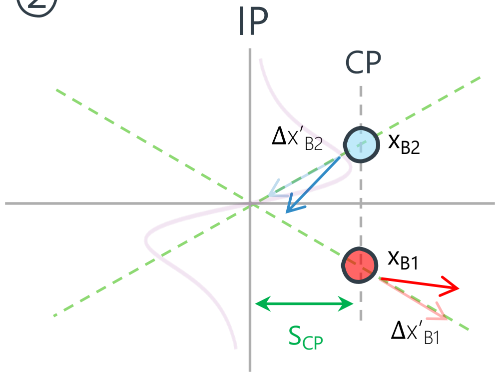
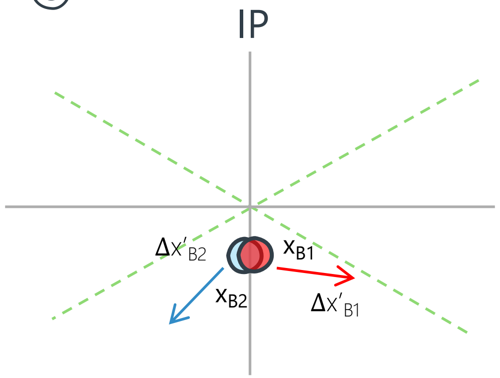


x_{B1} drifts of $+S_{CP}$ and x_{B2} drifts of $-S_{CP}$. x_{B1} and x_{B2} collide at CP changing their angle.

$\Delta x_{B1} = k_{BB} (x_{B1} - x_{B2})$ and $\Delta x_{B2} = k_{BB} (x_{B2} - x_{B1})$

③



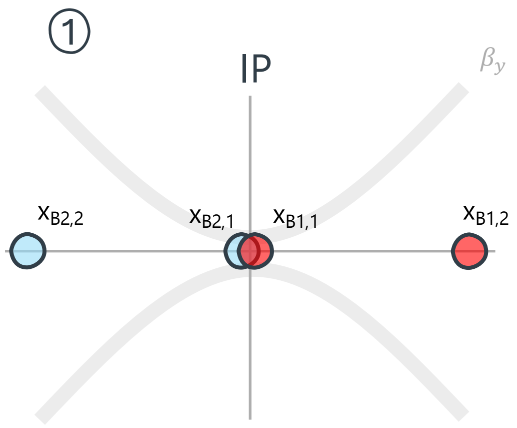
Projection back to the IP, x_{B1} drifts of $-S_{CP}$ and x_{B2} drifts of $+S_{CP}$. Their transverse position is no longer 0.

$\Delta x_{B1} = \Delta x_{B2} \neq 0$

2 particle model for beam-beam effects

Virtual drift, hourglass and crossing angle

Considering the hourglass effect with the virtual drifts



$x_{B1,1}$ and $x_{B2,1}$ colliding at the IP with a force k_{BB}

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{BB} & 1 & 0 & 0 & -k_{BB} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -k_{BB} & 0 & 0 & 0 & k_{BB} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

2 particle model for beam-beam effects

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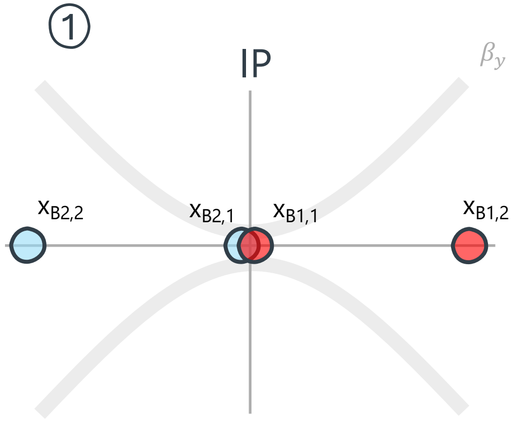

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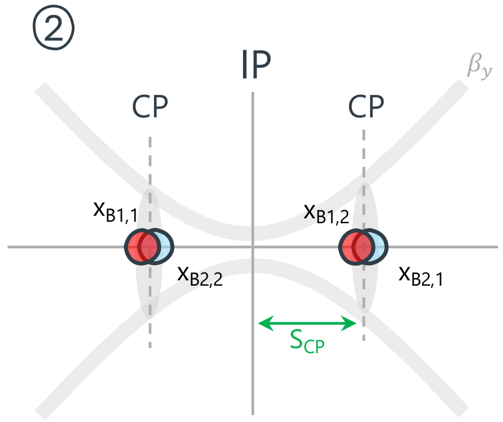


$x_{B1,1}$ and $x_{B2,2}$ colliding at the CP
$x_{B1,2}$ and $x_{B2,1}$ colliding at the CP
with a force $k_{CP} \neq k_{BB}$

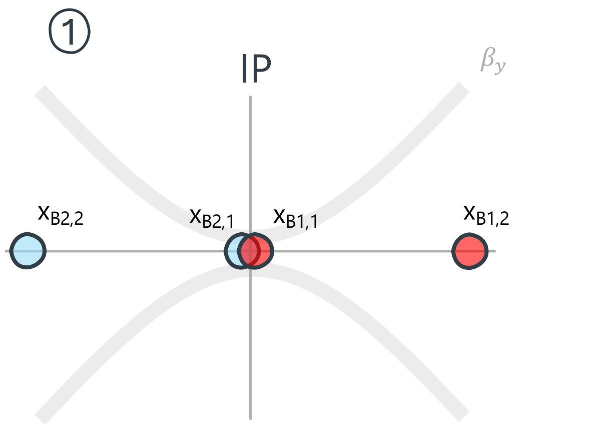
$x_{B1,1}$ and $x_{B2,1}$ have different angles from the previous collision not represented on the scheme

$$
\begin{pmatrix}
1 & -S_{CP} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & S_{CP} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -S_{CP} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & S_{CP} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
k_{CP} & 1 & 0 & 0 & 0 & 0 & -k_{CP} & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & k_{CP} & 1 & -k_{CP} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & -k_{CP} & 0 & k_{CP} & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
-k_{CP} & 0 & 0 & 0 & 0 & 0 & k_{CP} & 1
\end{pmatrix}
\begin{pmatrix}
1 & S_{CP} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -S_{CP} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & S_{CP} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -S_{CP} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}
$$

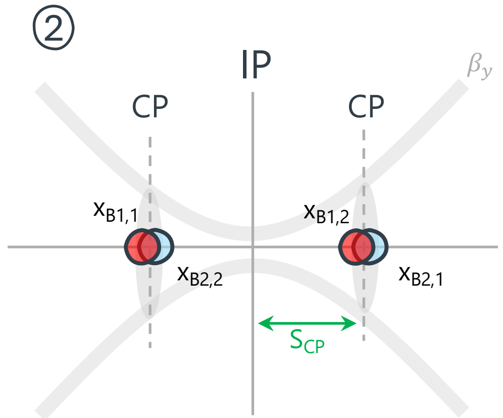
2 particle model for beam-beam effects

Virtual drift, hourglass and crossing angle

Considering the hourglass effect with the virtual drifts



$x_{B1,1}$ and $x_{B2,1}$ colliding at the IP with a force k_{BB}



$x_{B1,1}$ and $x_{B2,2}$ colliding at the CP
$x_{B1,2}$ and $x_{B2,1}$ colliding at the CP
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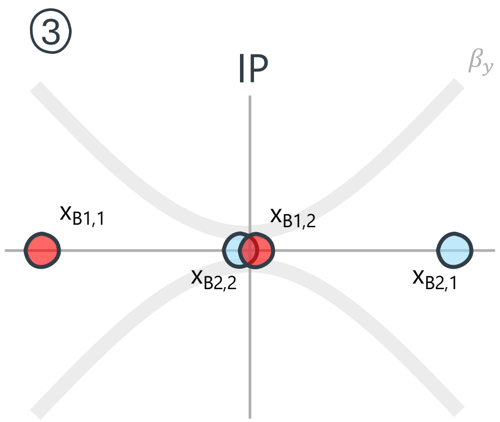
$x_{B1,1}$ and $x_{B2,1}$ have different angles from the previous collision not represented on the scheme



$x_{B1,2}$ and $x_{B2,2}$ colliding at the CP with a force k_{BB}

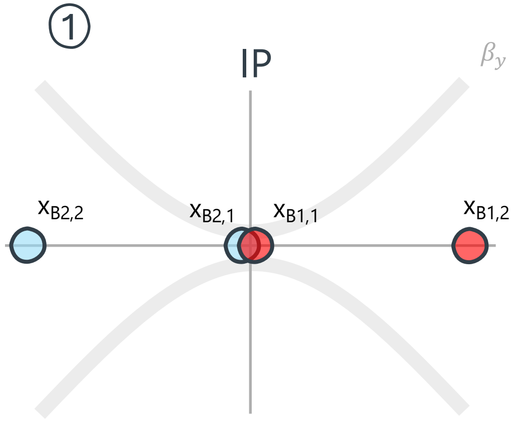
All particle have different angles from the previous collisions not represented on the scheme

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{BB} & 1 & 0 & 0 & -k_{BB} & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -k_{BB} & 0 & 0 & 0 & k_{BB} & 1 \end{pmatrix}$$

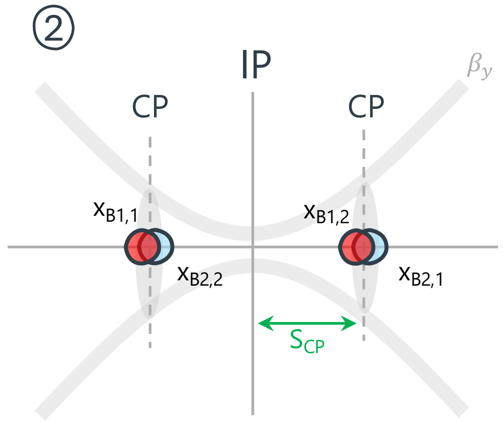
2 particle model for beam-beam effects

Virtual drift, hourglass and crossing angle

Considering the hourglass effect with the virtual drifts



$x_{B1,1}$ and $x_{B2,1}$ colliding at the IP with a force k_{BB}



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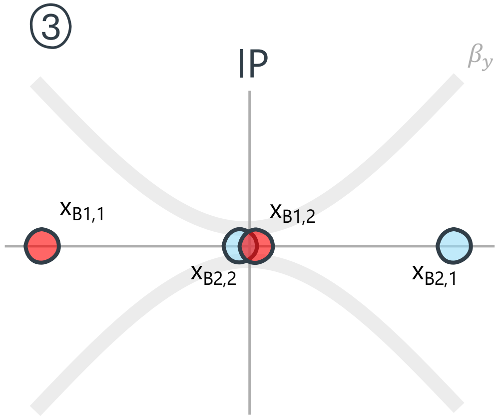

$x_{B1,2}$ and $x_{B2,2}$ colliding at the CP with a force k_{BB}

All particle have different angles from the previous collisions not represented on the scheme

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{BB} & 1 & 0 & 0 & -k_{BB} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ -k_{BB} & 0 & 0 & 0 & k_{BB} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

KICK

$$\begin{pmatrix} 1 & -S_{CP} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & S_{CP} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -S_{CP} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & S_{CP} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

DRIFT

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ k_{CP} & 1 & 0 & 0 & 0 & 0 & -k_{CP} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{CP} & 1 & -k_{CP} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -k_{CP} & 0 & k_{CP} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ -k_{CP} & 0 & 0 & 0 & 0 & 0 & k_{CP} & 1 \end{pmatrix}$$

KICK

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DRIFT

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{BB} & 1 & 0 & 0 & -k_{BB} & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -k_{BB} & 0 & 0 & 0 & k_{BB} & 1 \end{pmatrix}$$

KICK

2 particle model for beam-beam effects

Virtual drift and hourglass effects on fundamental modes

Why should we consider the virtual drifts for FCC-ee?

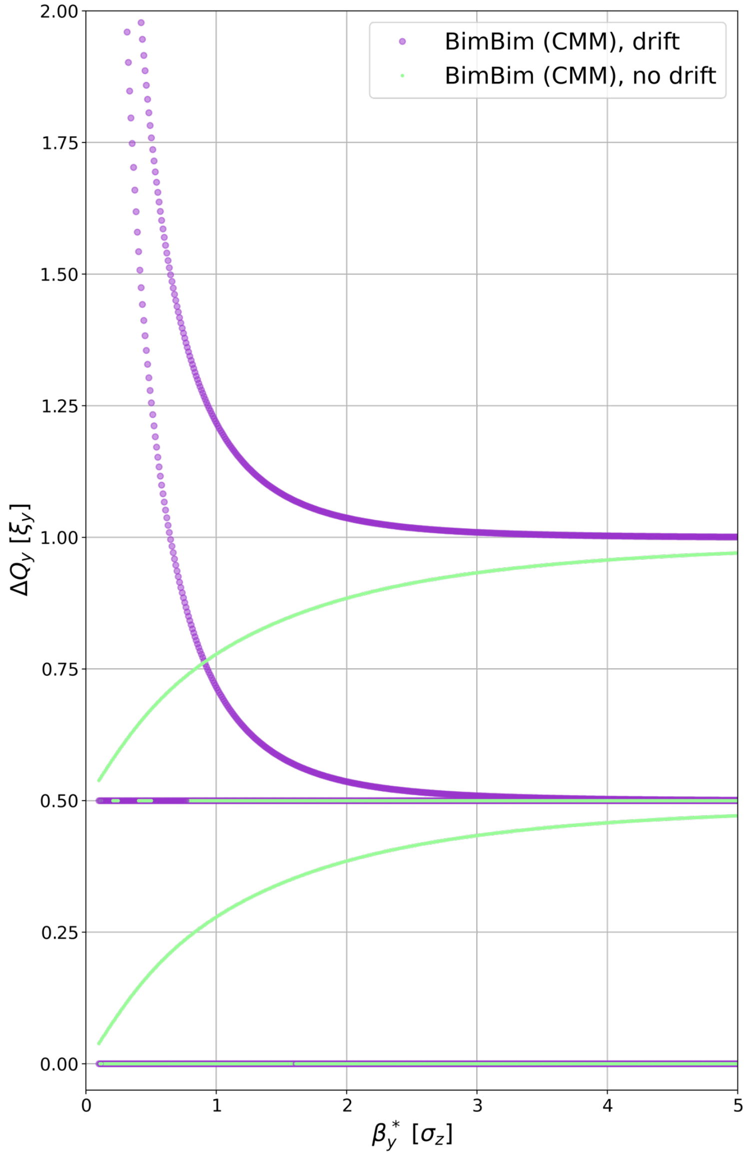
Considering the virtual drifts and the hourglass effect changes the fundamental oscillation modes of the two beams.

There is no crossing angle considered here.

The crossing angle strengthens this effects as the angle would change at collision point (CP) different from the interaction point (IP).

The hourglass effect strengthens this effects as the forces at the CP are very different from those at the IP.

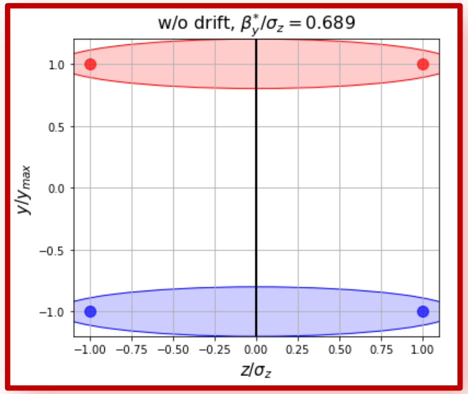
4 modes of the 2-particle case, with, and without virtual drifts. $Q_s = 0$



2 particle model for beam-beam effects

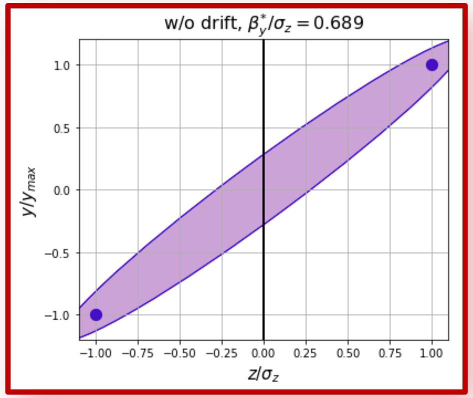
Virtual drift and hourglass effects on fundamental modes

1

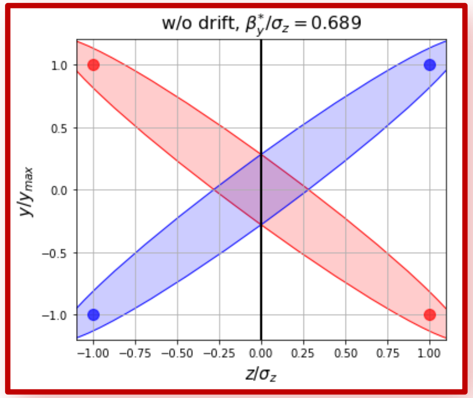


Pi-mode

2



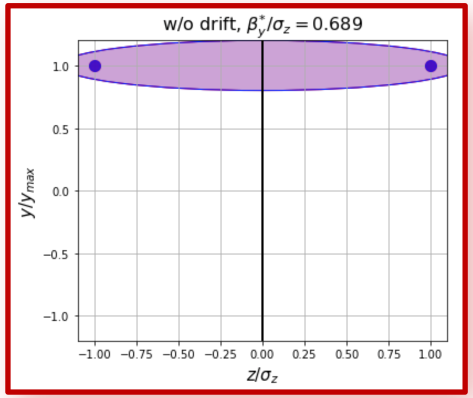
3



Sidebands

sigma-mode

4



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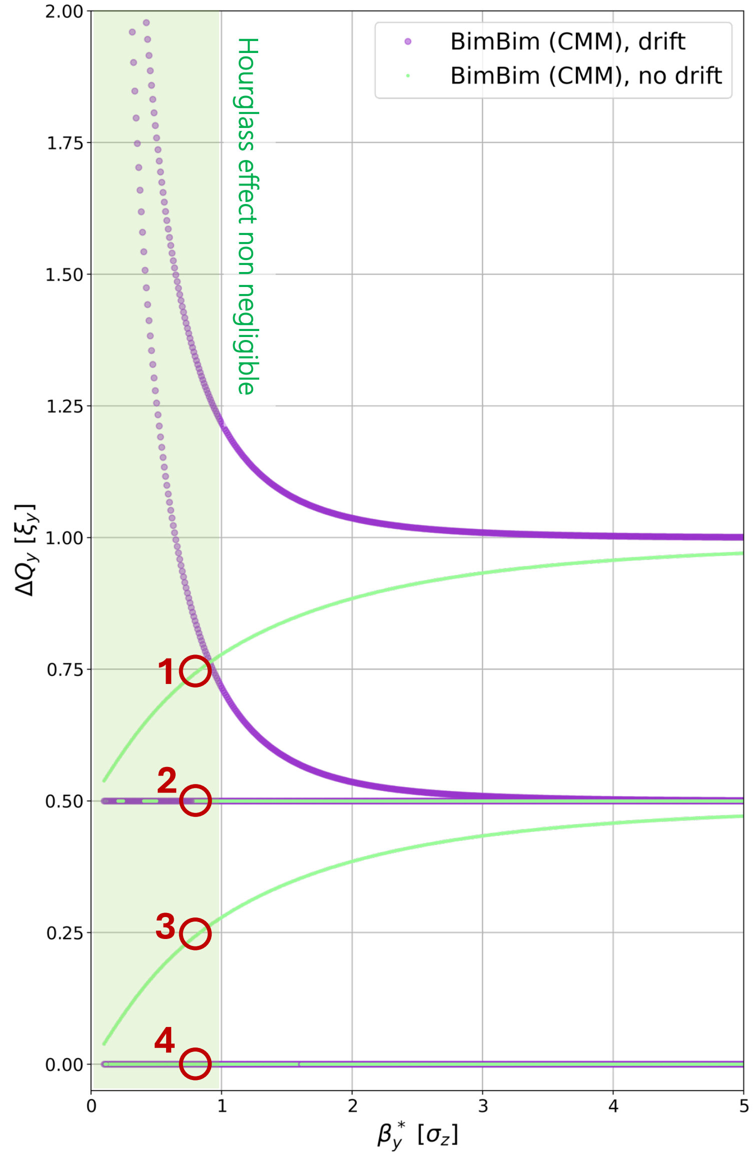
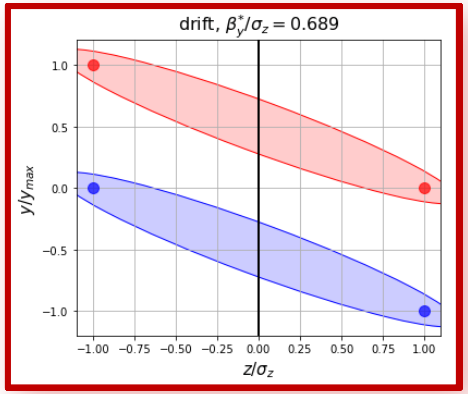


2 particle model for beam-beam effects

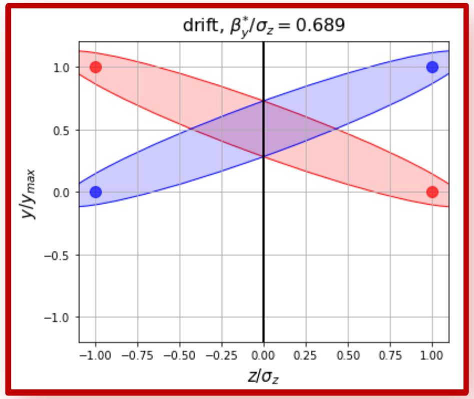
Virtual drift and hourglass effects on fundamental modes

1

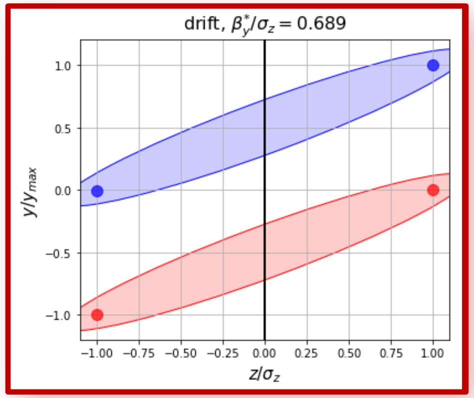


Hybride pi-mode

2



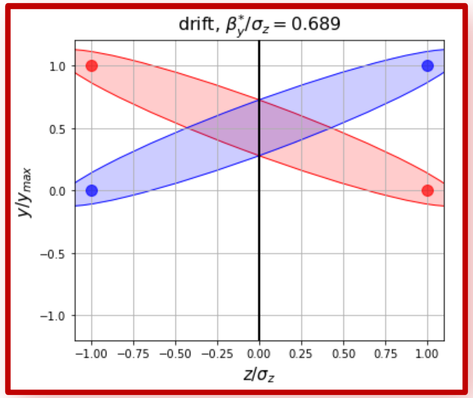
3



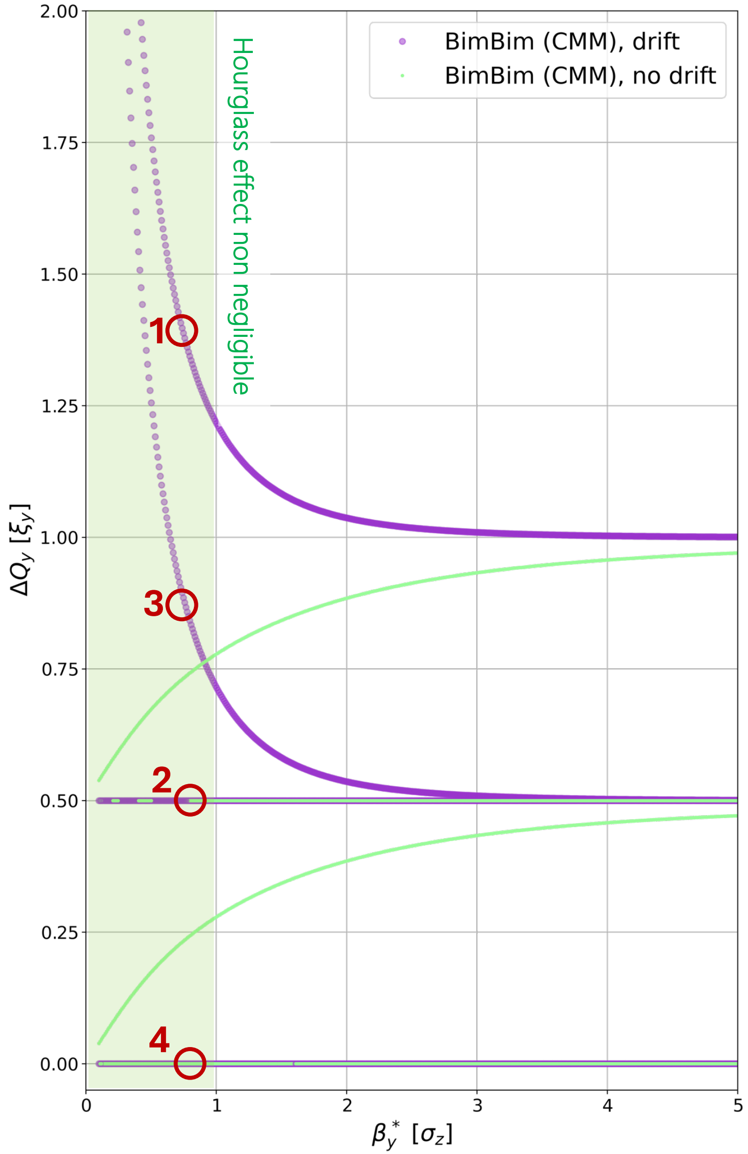
Sidebands

Hybride sigma-mode

4



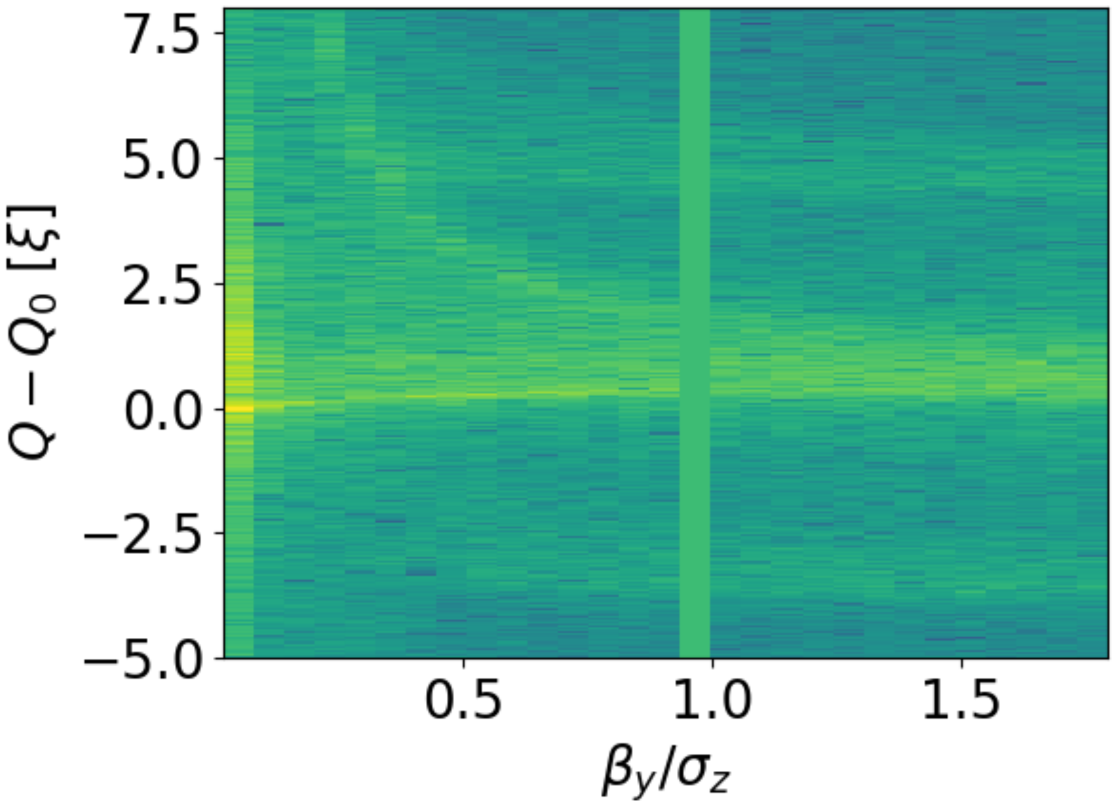
4 modes of the 2-particle case, with, and without virtual drifts. $Q_s = 0$



2 particle model for beam-beam effects

Virtual drift and hourglass effects on fundamental modes

Modes with multiparticle tracking. $Q_s \neq 0$



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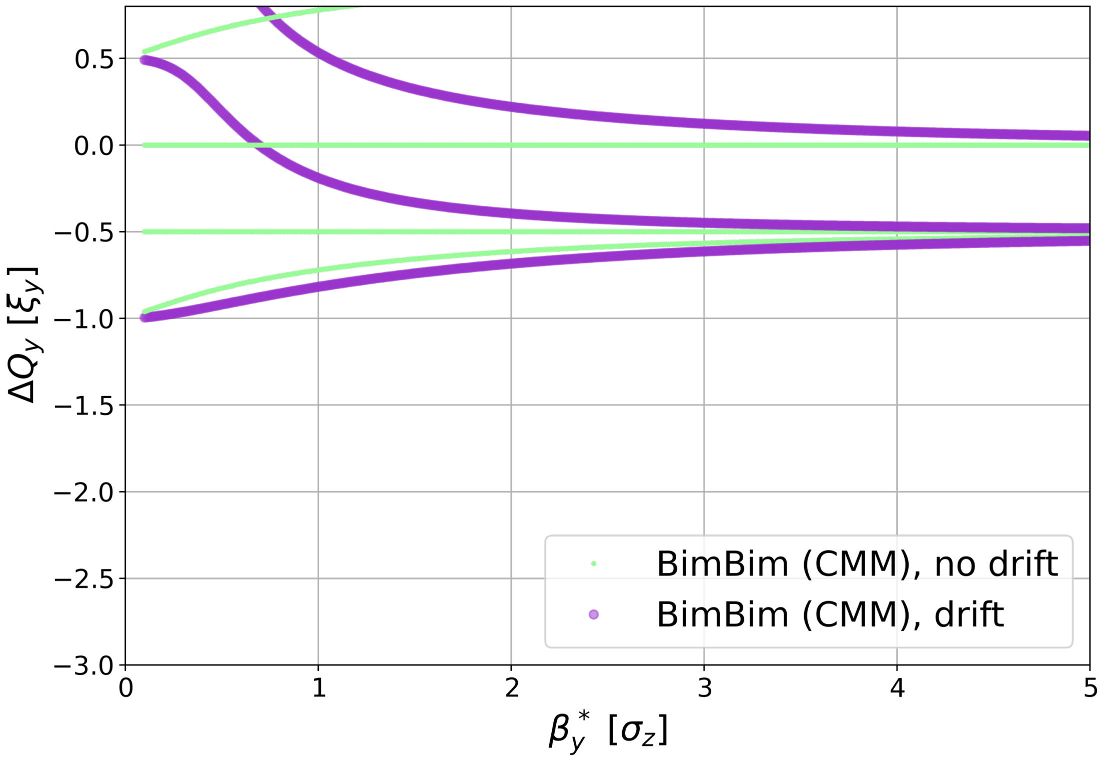


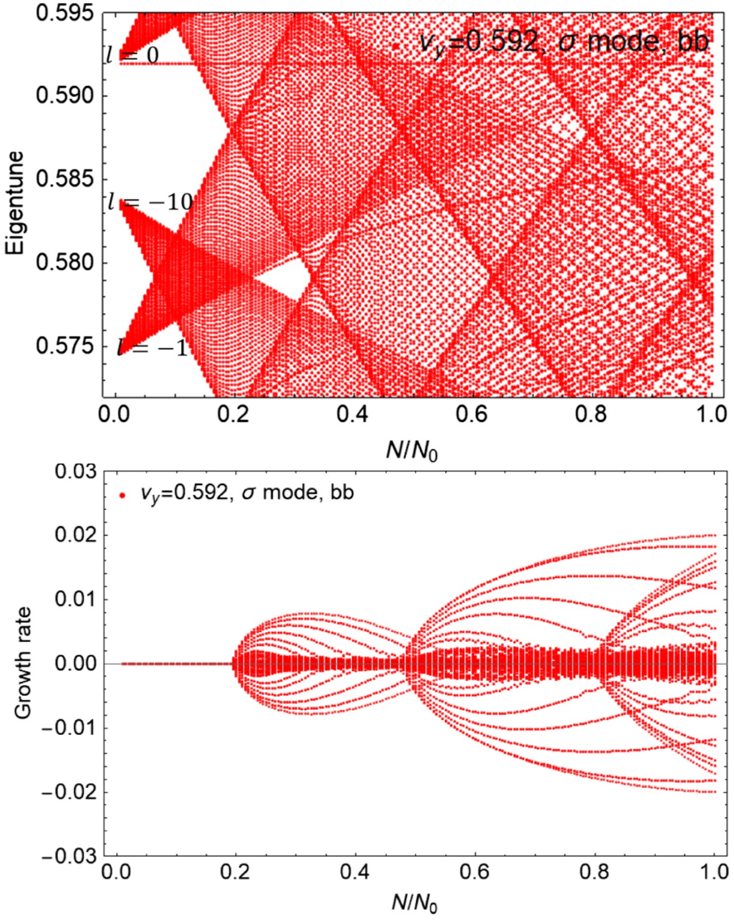
This figure shows the presence of the effect of the phase advance in multiparticle tracking. The observed frequency shifts are different:
- different parameters used
- linearized beam-beam kick and form factor (Yokoya factor) ?

Circulant matrix model simulations

Effects of the virtual drifts on mode couplings

Comparison of CEPC simulation with CMM and another mode analysis method depicted in [1]

CEPC simulation from [1]



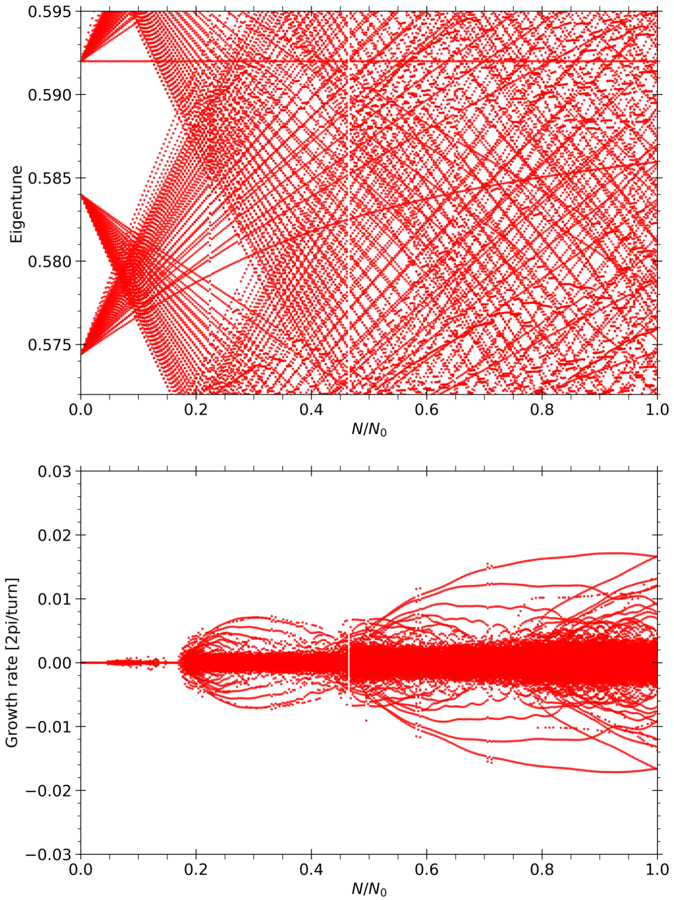
¼ of the CEPC design at Z energy, only beam beam effect considered

Convergence more difficult to obtain with CMM and higher order non-converged modes add numerical artefacts.

Same instability growth rates can be observed.

Sigma and -1 modes can be observed, coupling above the nominal intensity.

CEPC simulation with CMM



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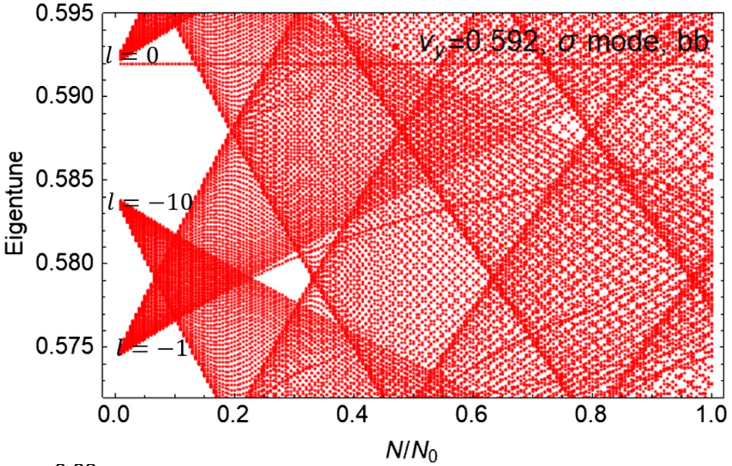

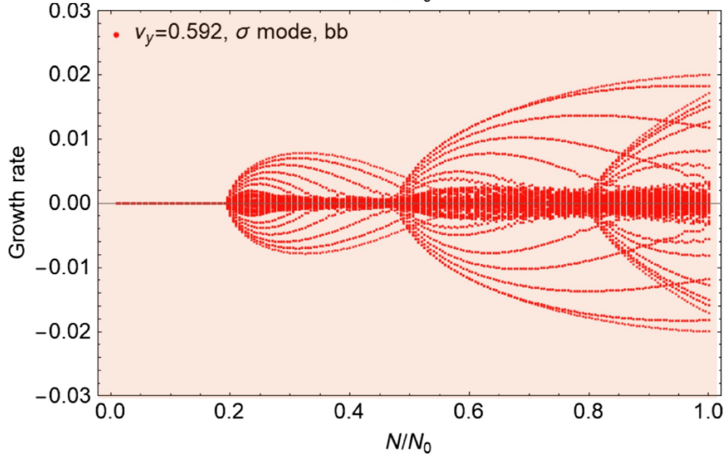

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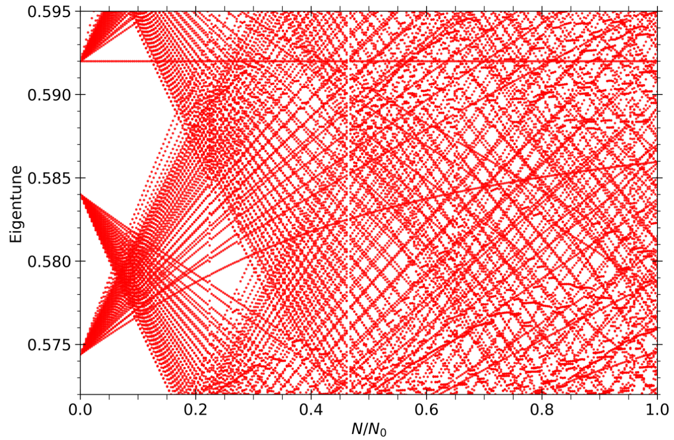

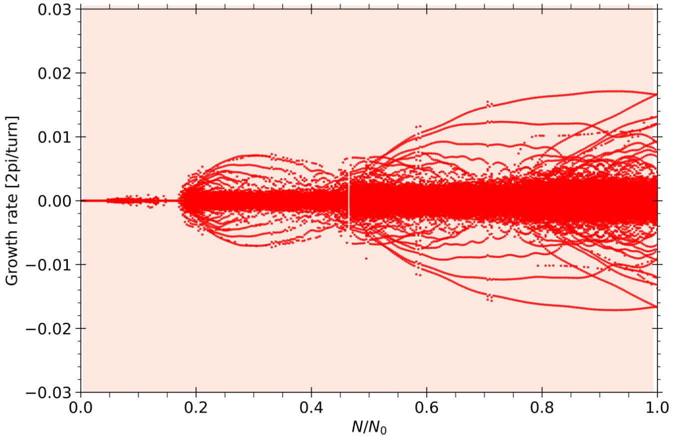

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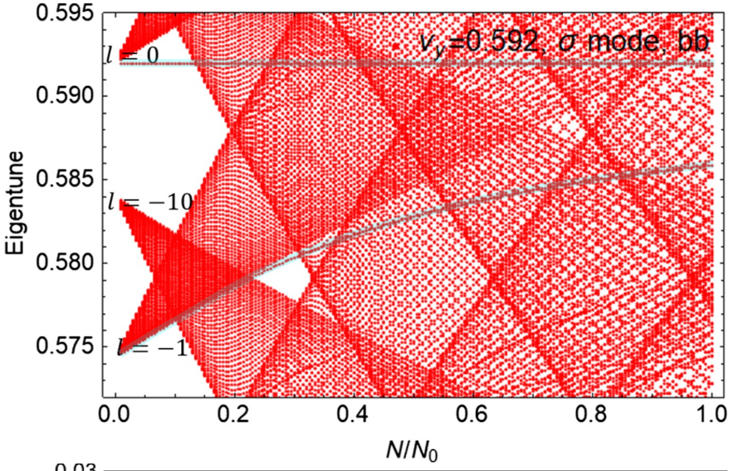

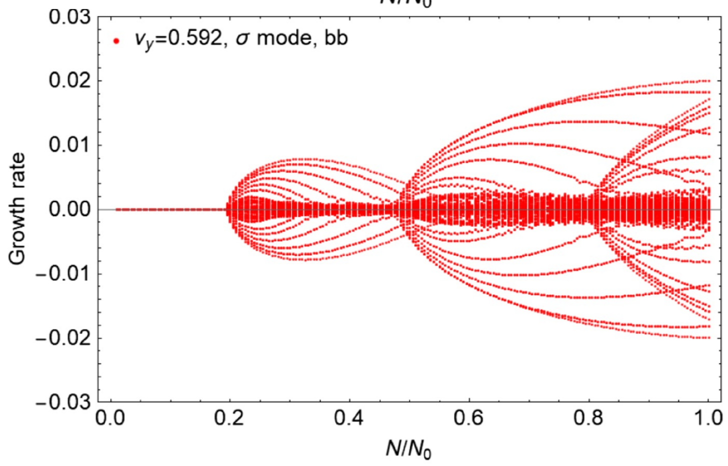

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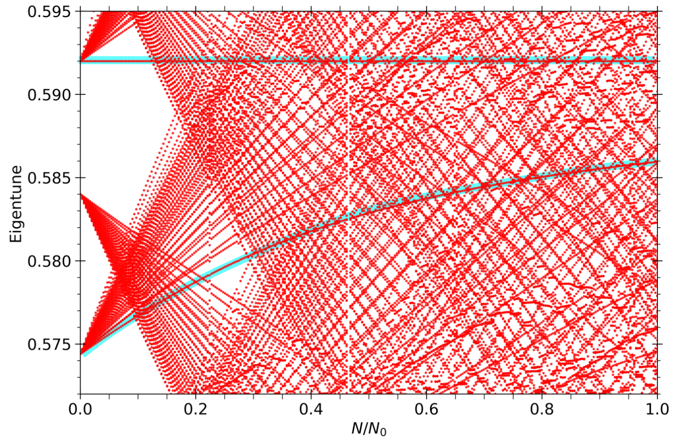
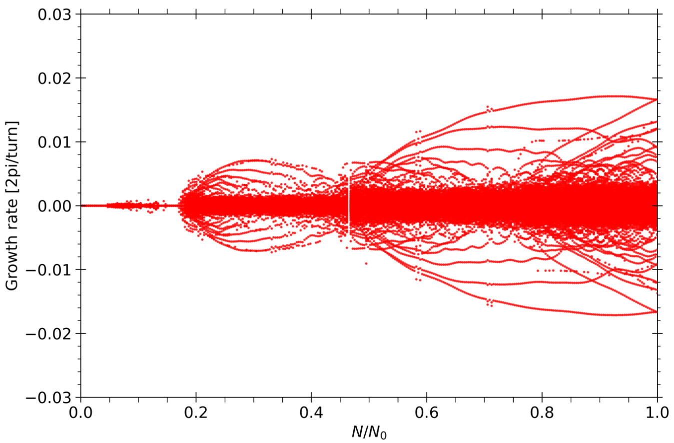


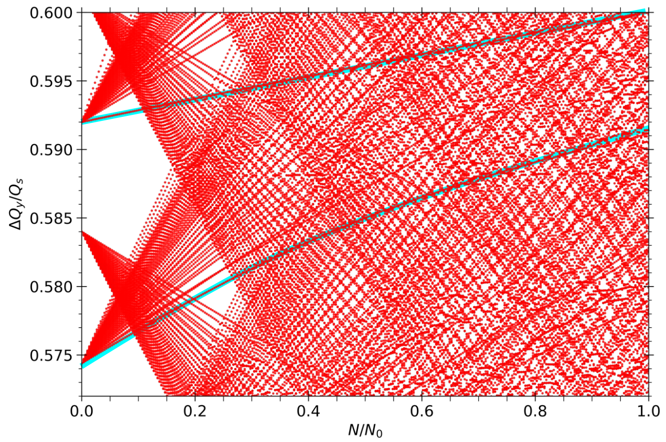


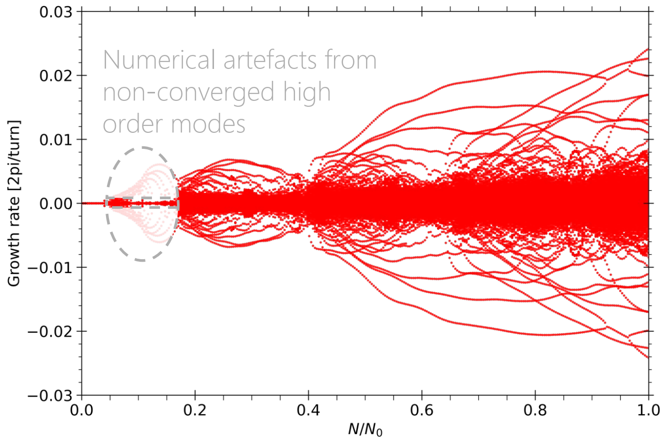
Circulant matrix model simulations

Effects of the virtual drifts on mode couplings

Comparison of CEPC simulation with and without considering the virtual drifts.

CEPC simulation with CMM with virtual drifts



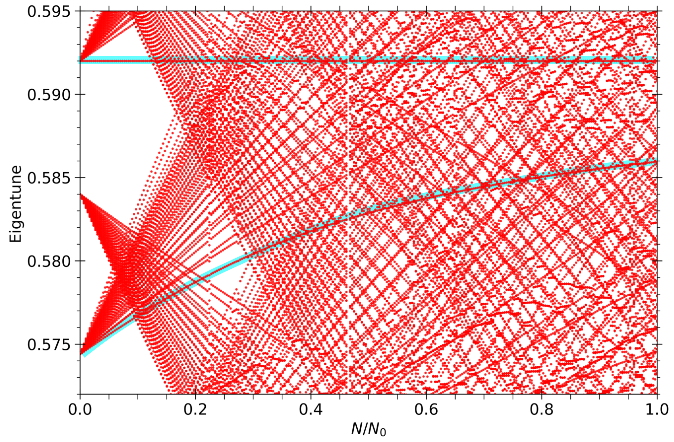


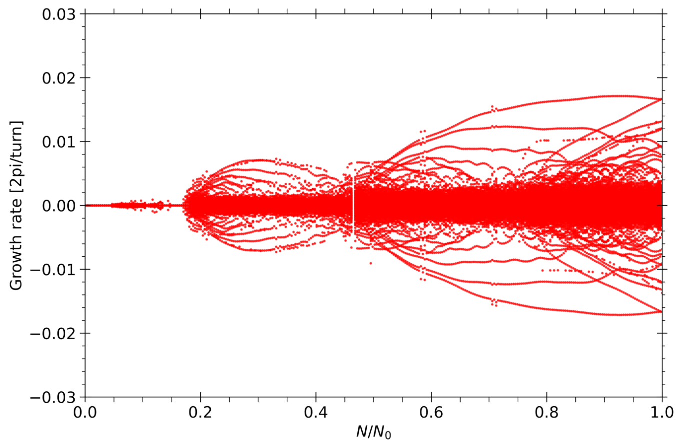
¼ of the CEPC design at Z energy, only beam beam effect considered

Sigma mode causing instabilities is **changed**. Drifting mode may couple at **different intensity**.

Instability growth rates are affected. Most unstable modes are different.

CEPC simulation with CMM without virtual drifts





Circulant matrix model simulations

Effects of the virtual drifts on mode couplings

Comparison of CEPC simulation with and without considering the virtual drifts.

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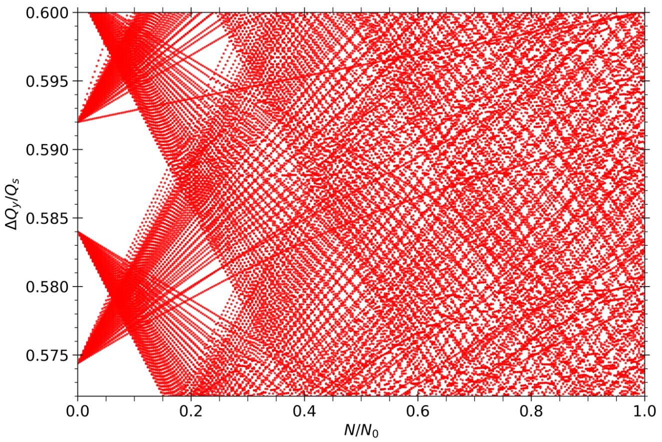

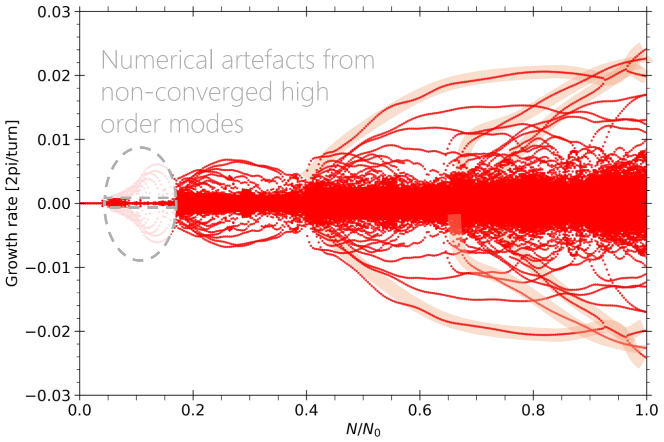

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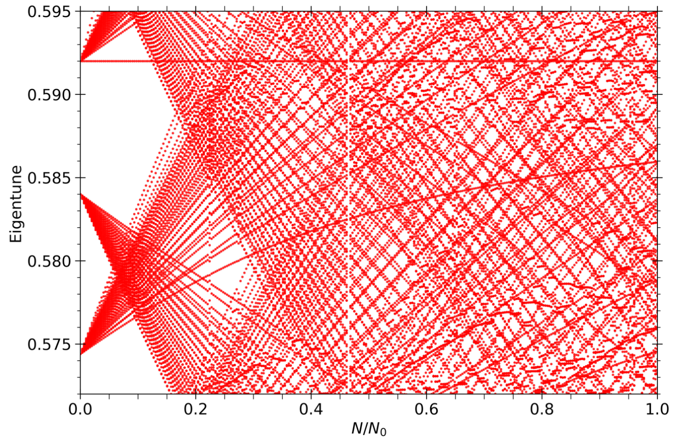
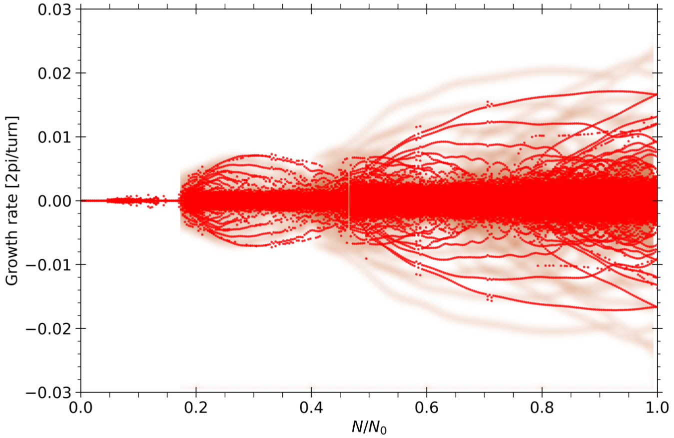


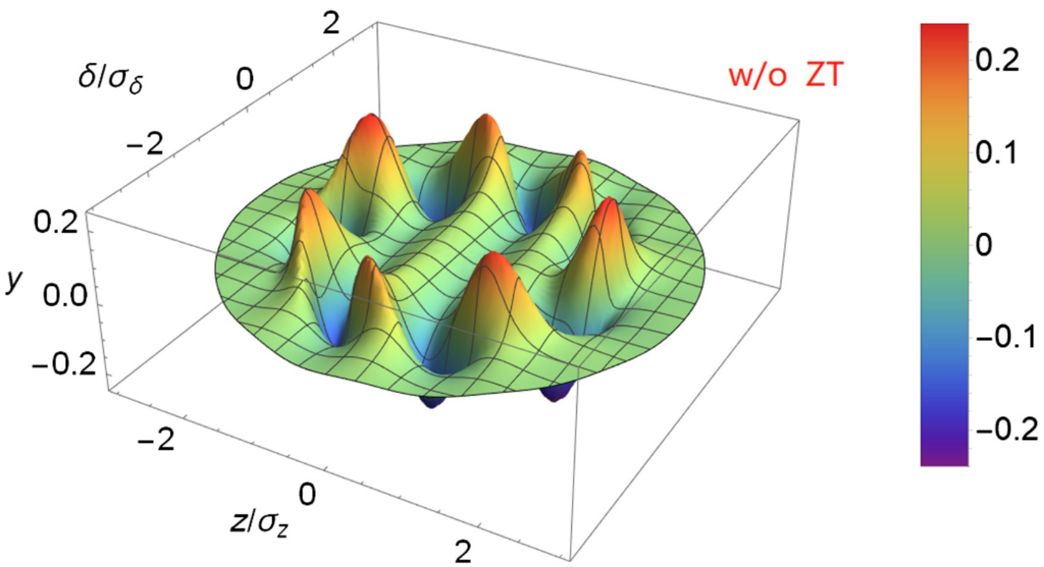


Circulant matrix model simulations

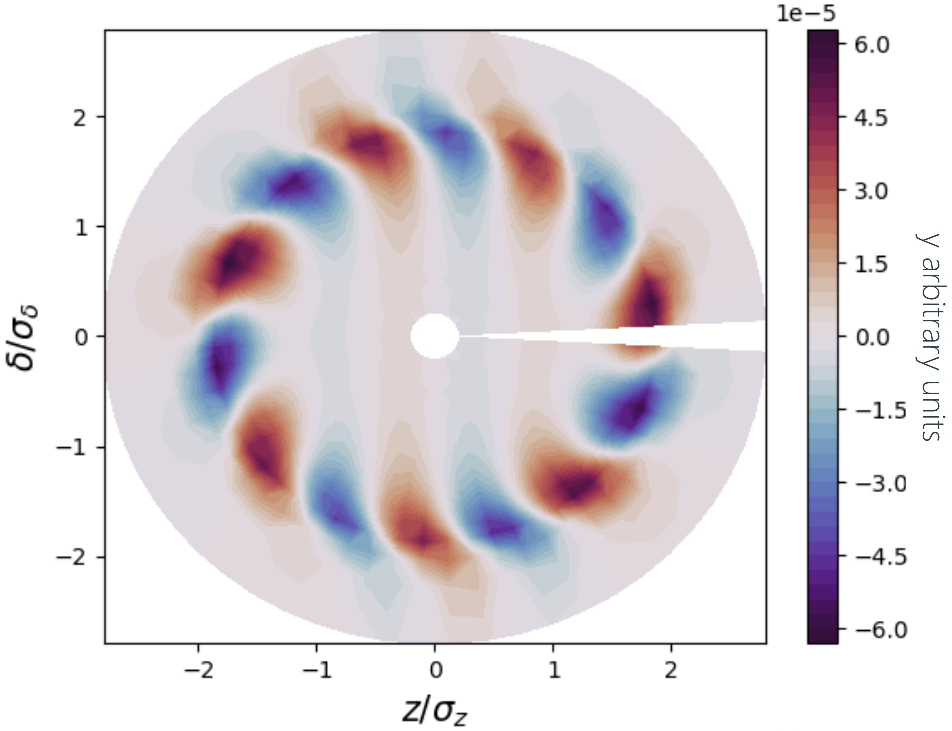
Most unstable modes

Comparison of CEPC most unstable mode eigenvectors with and without considering the virtual drifts.

CEPC simulation from [1]



CEPC simulation with CMM



[2] Y. Zhang, et al., Phys. Rev. Accel. Beams 26, 064401 (2023)

Circulant matrix model simulations

Most unstable modes

Comparison of CEPC most unstable mode eigenvectors with and without considering the virtual drifts.

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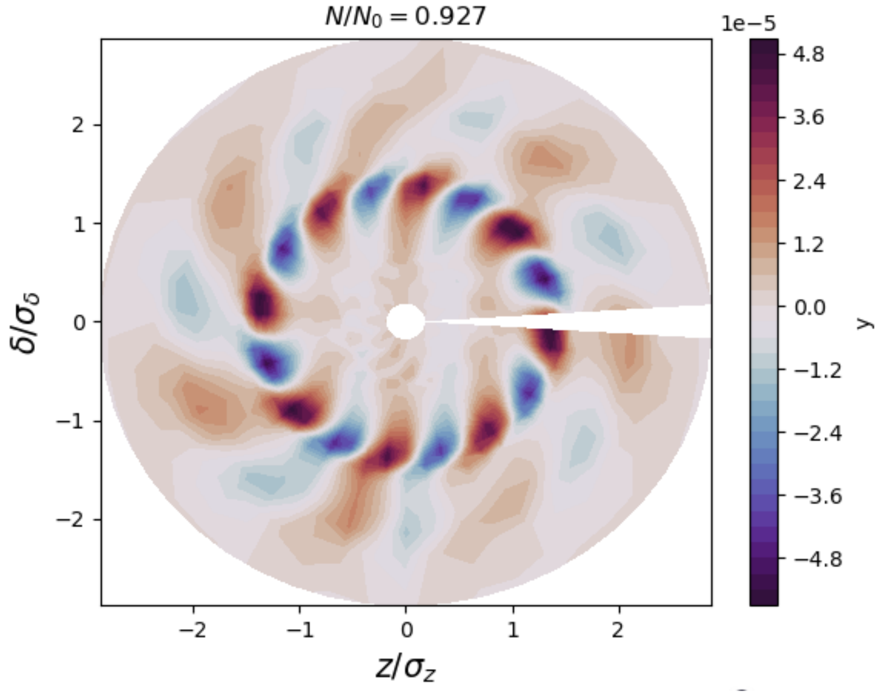
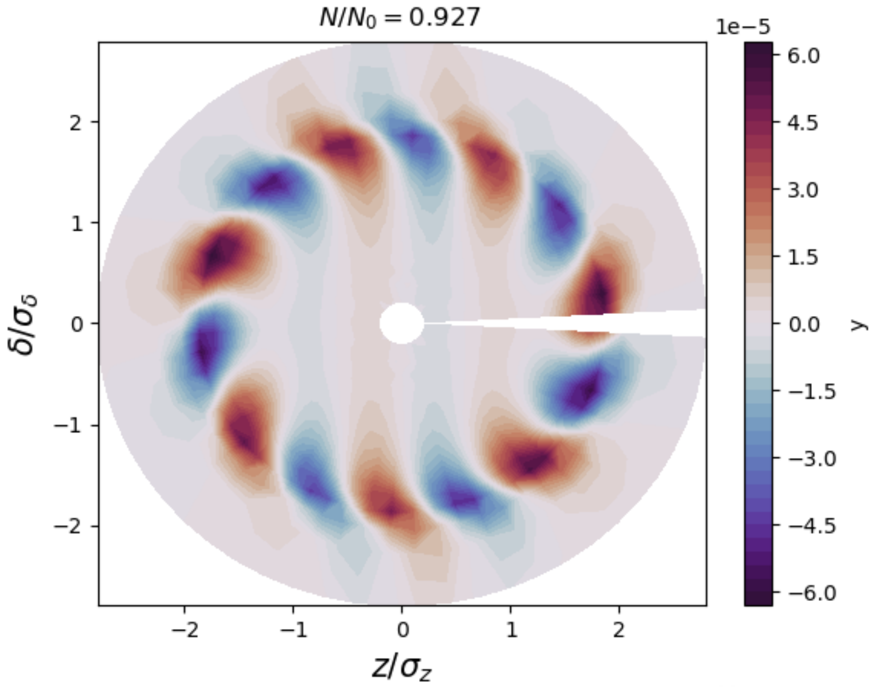


¼ of the CEPC design at Z energy, only beam beam effect considered.

Most unstable modes have changed. Higher order radial modes.

Landau damping could suppress these higher order unstable modes?

CEPC simulation with CMM without virtual drifts



Circulant matrix model simulations

Beam beam with transverse wakefields

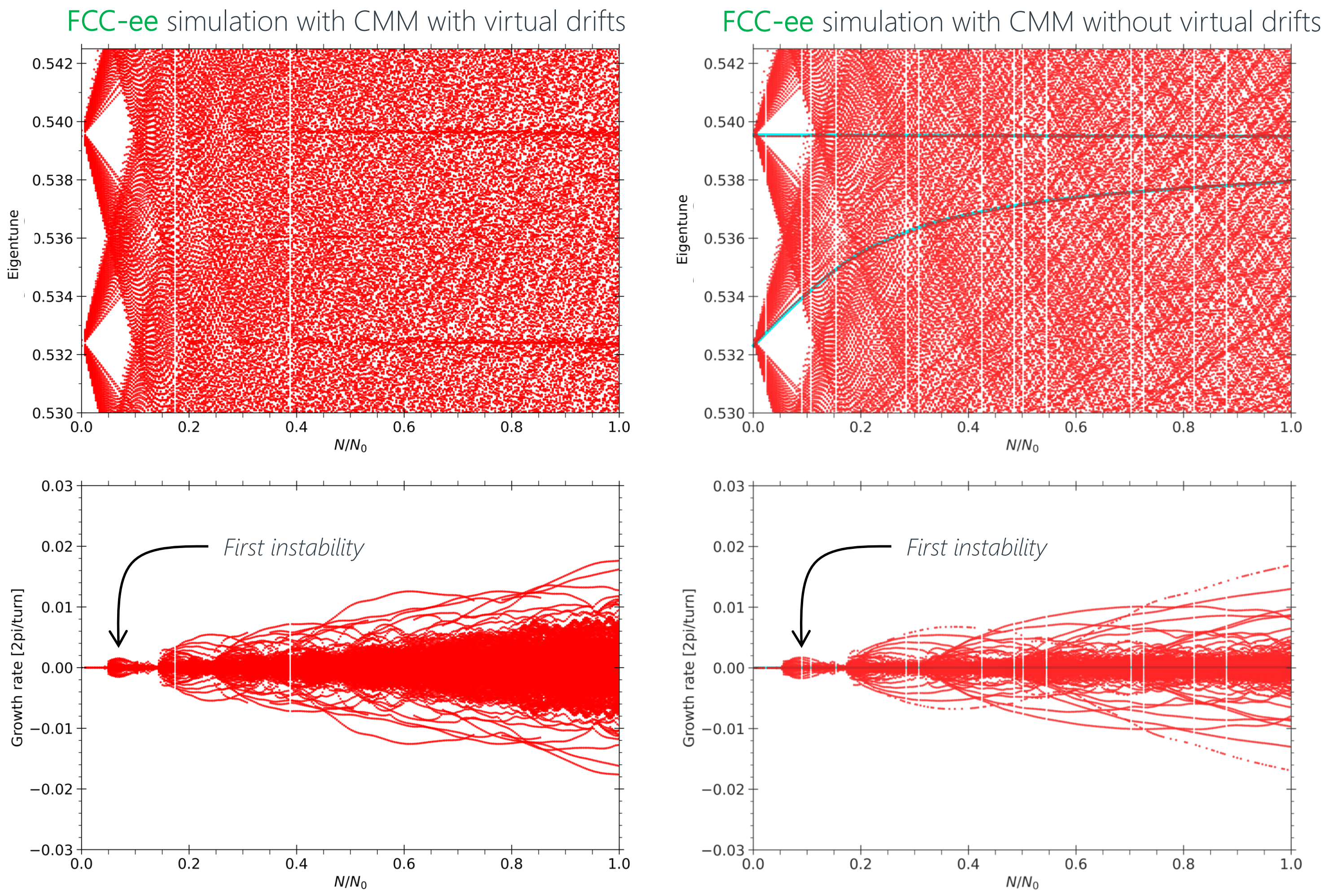
Comparison of FCC-ee (Z) simulations with and without considering the virtual drifts.

¼ of the FCC-ee design at Z energy, only beam beam effect considered

We can see the sigma mode close to coupling to a -1 mode as in CEPC simulations.

Instability growth rates show instabilities below 20% of the nominal intensity, could be caused by:

- *Choice of the vertical tune (wrapped modes)*
- *Higher hourglass in FCC-ee*



Circulant matrix model simulations

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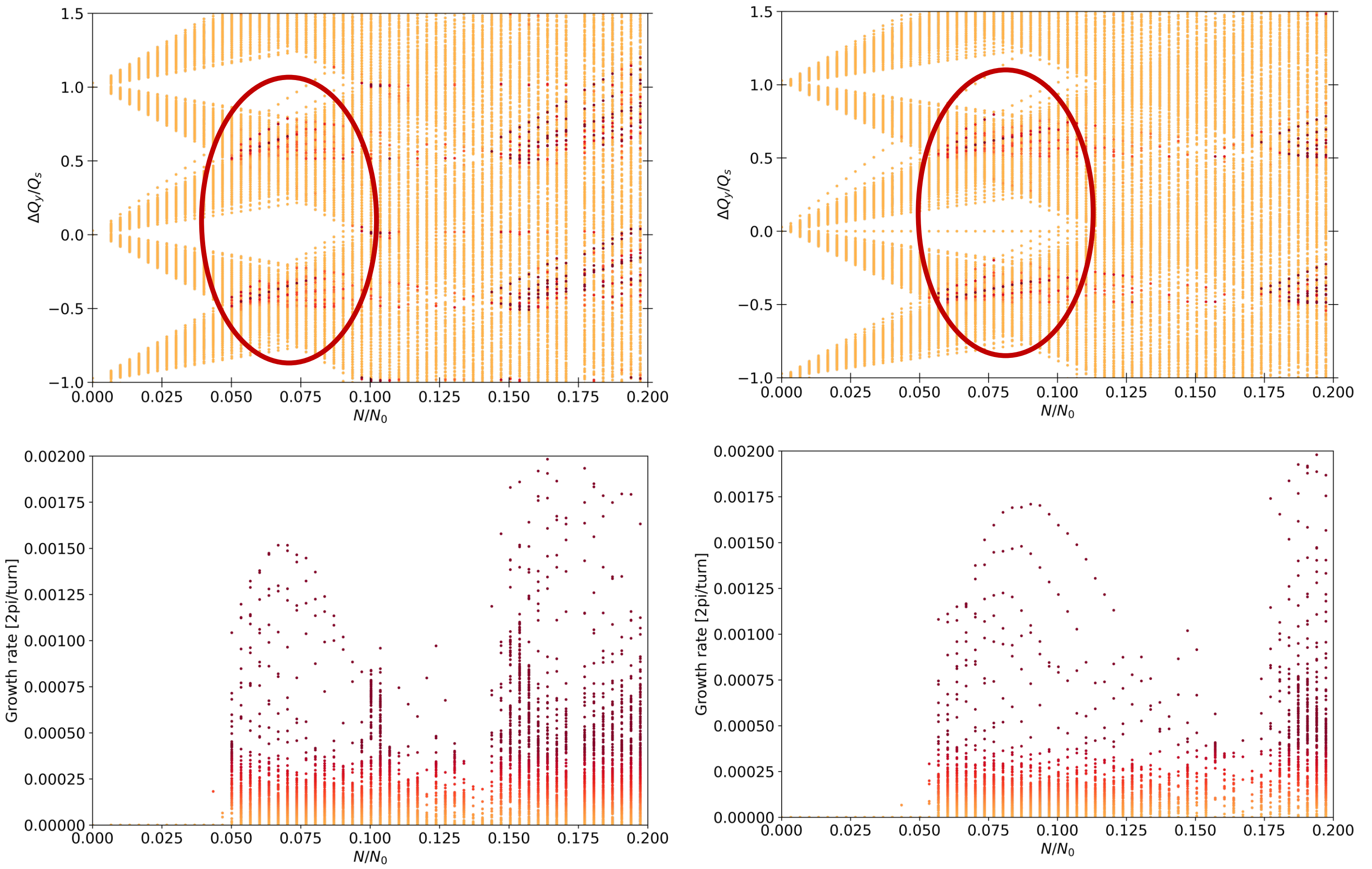
	CEPC (Z)	FCC-ee (Z)
L_i / β_y^* *[6]*	~0.40	~0.84
vertical tune (1/4)	0.592	0.5395

FCC-ee simulation with CMM with virtual drifts

FCC-ee simulation with CMM without virtual drifts



Circulant matrix model simulations

Beam beam with transverse wakefields

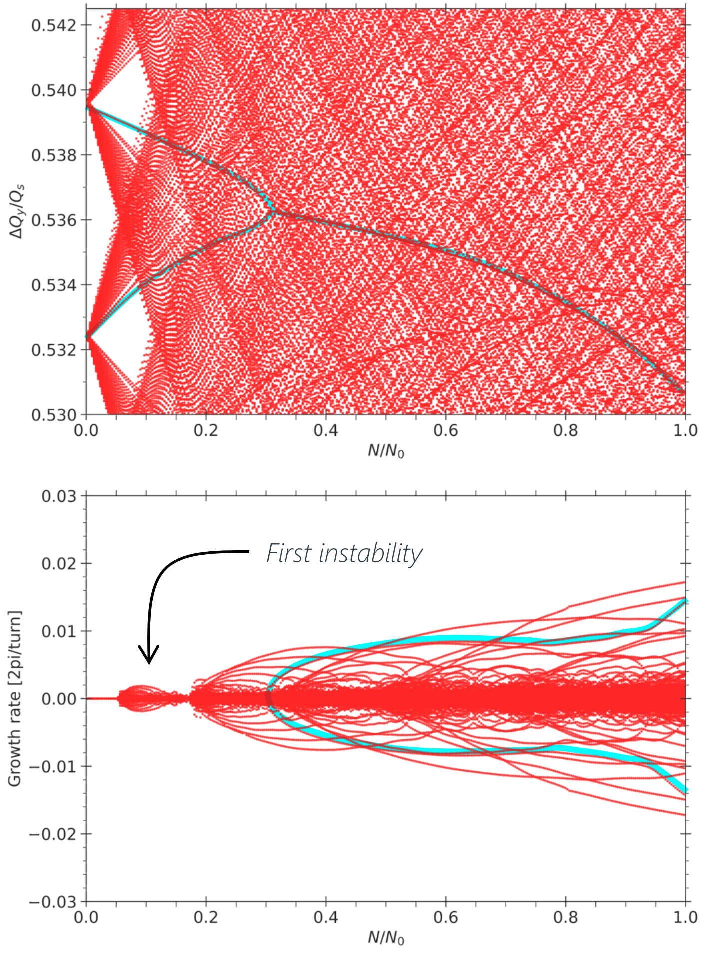
FCC-ee (Z) beam-beam intensity scans with and without transverse wake fields. Without considering the virtual drifts.

¼ of the FCC-ee design at Z energy

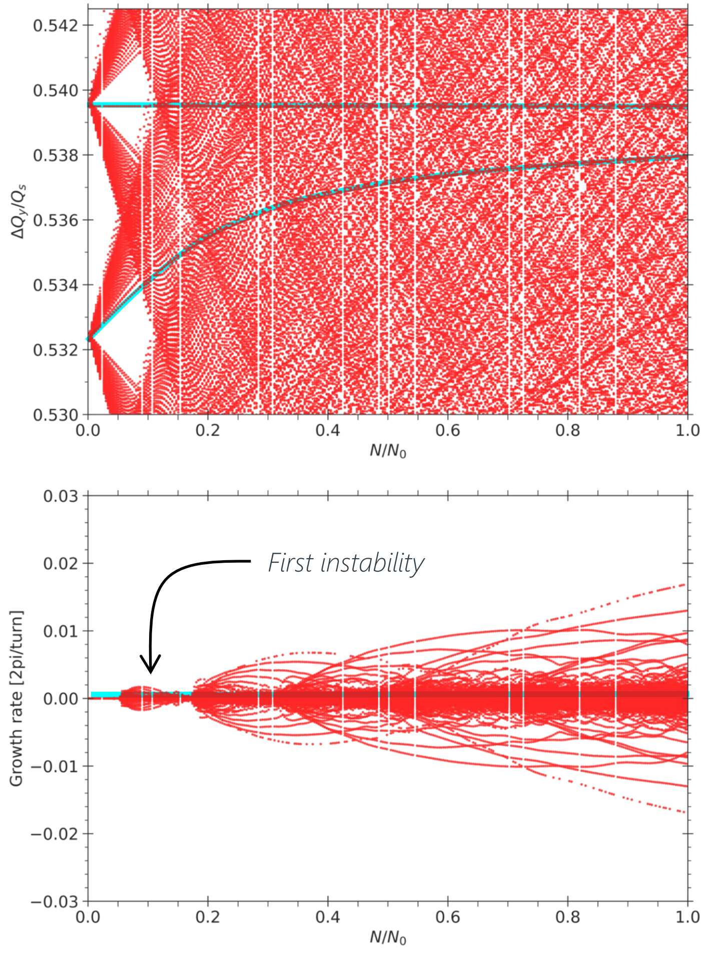
We can see the sigma mode coupling to a -1 mode as in CEPC simulations.

Instability before the mode coupling is still present.

FCC-ee simulation with CMM with wakefields + bb



FCC-ee simulation with CMM without wakefields + bb



Circulant matrix model simulations

Beam beam with transverse wakefields

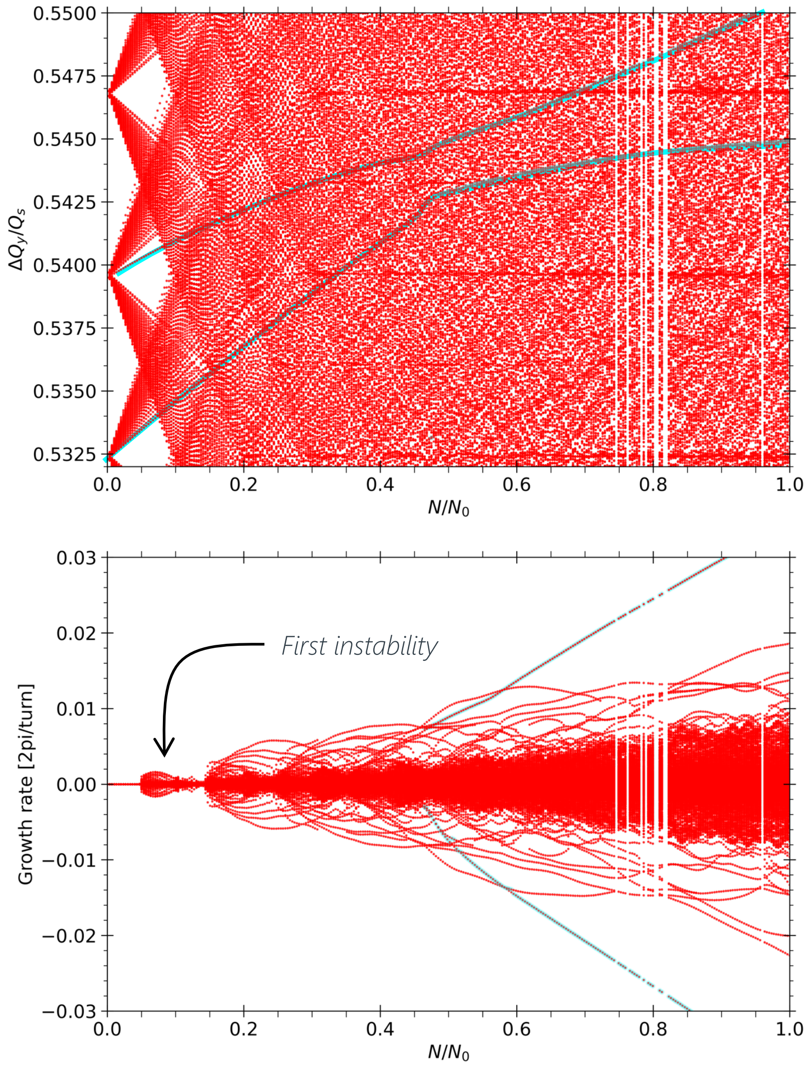
¼ of the FCC-ee design at Z energy

We can see the sigma mode repulsing -1 mode. The resulting modes become unstable very quickly.

Same modes involved as in the simulations without virtual drifts and hourglass considerations.

Instability before the mode coupling is still present.

FCC-ee simulation with CMM with wakefields + bb and virtual drifts



Circulant matrix model simulations

Beam beam with transverse wakefields

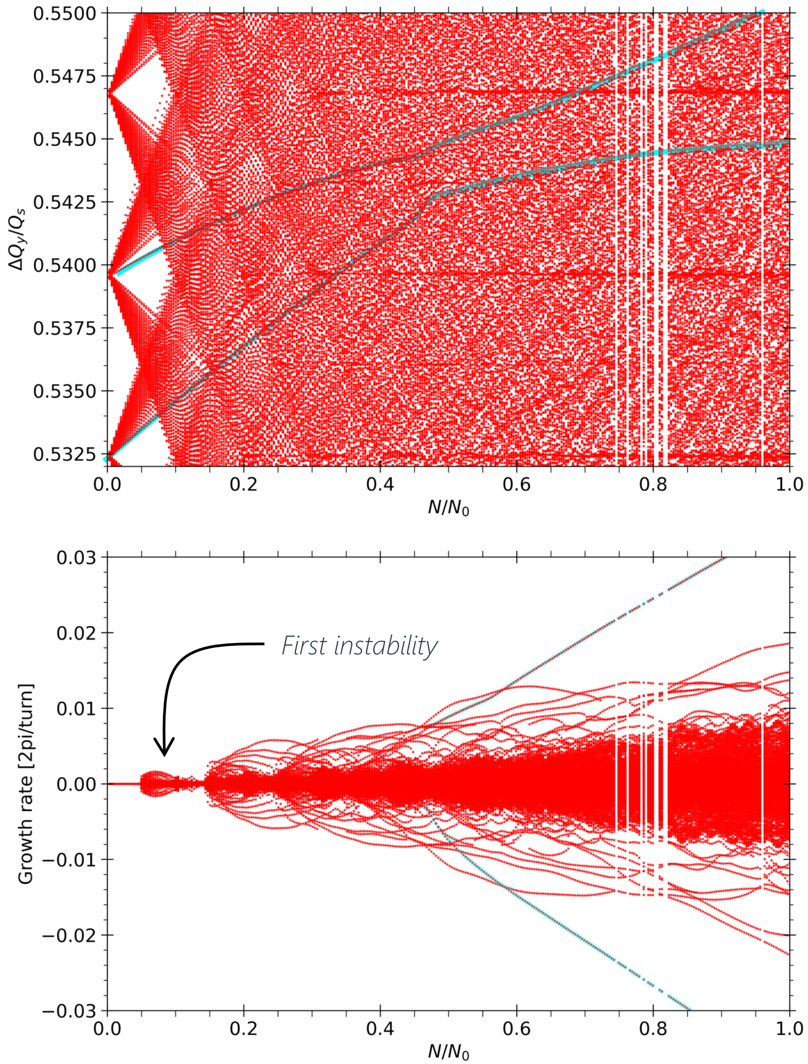
¼ of the FCC-ee design at Z energy

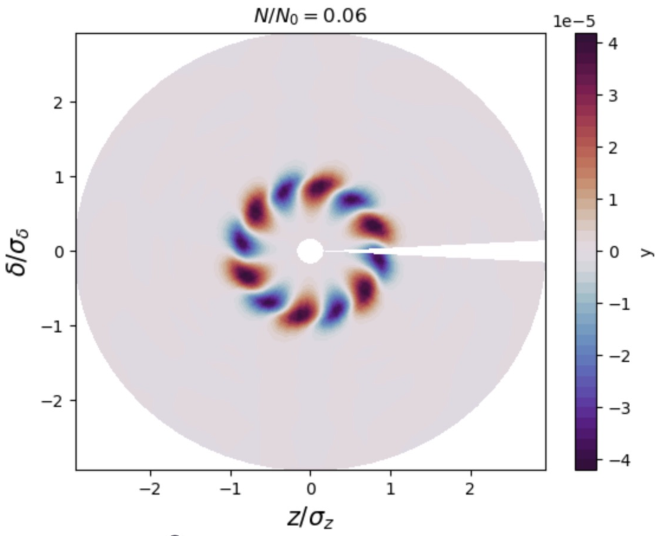
We can see the sigma mode repulsing -1 mode. The resulting modes become unstable very quickly and is of very low order.

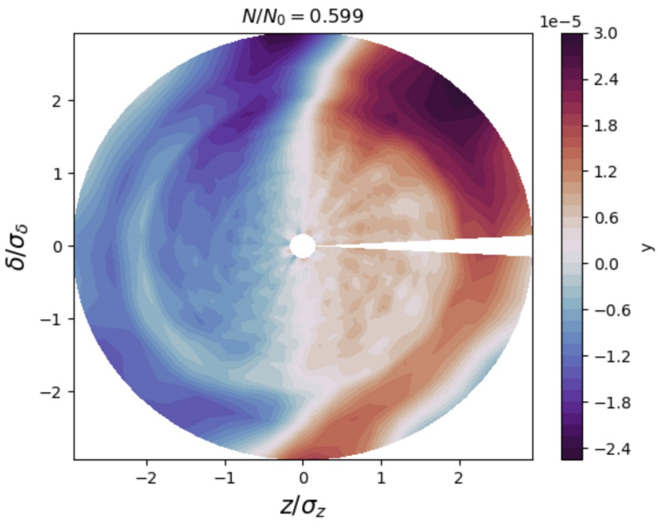
Same modes involved as in the simulations without virtual drifts and hourglass considerations.

Instability before the mode coupling is still present.

FCC-ee simulation with CMM with wakefields + bb and virtual drifts







Conclusions and outlook

A two particles model was used to understand the effects of the phase advance during beam-beam interactions

Virtual drifts and the hourglass have a significant effect on the stability in machines with high hourglass factor such as FCC-ee, CEPC and SuperKEKB (low beta design).

The circulant matrix model was able to reproduce results obtained with different models, showing it can reliably consider beam-beam effects with transverse impedance for FCC-ee.

Potential studies at SuperKEKB?

Multiparticle tracking will be used to confirm the drift and hourglass effects considering a different approach for simulations, observe Landau damping

Parameters such as the beam sizes or the vertical tunes may be rediscussed for FCC-ee at Z energy after extensive studies considering the virtual drifts and the hourglass effect.

Longitudinal wakefields effects will be studied with CMM

Thank you for listening!

References

[1] Y. Zhang, et al., Phys. Rev. Accel. Beams 26, 064401 (2023)

[2] S. White, et al., Phys. Rev. ST Accel. Beams 17, 041002 (2014)

[3] E. A. Perevedentsev and A. A. Valishev, Phys. Rev. ST Accel. Beams 4, 024403 (2001)

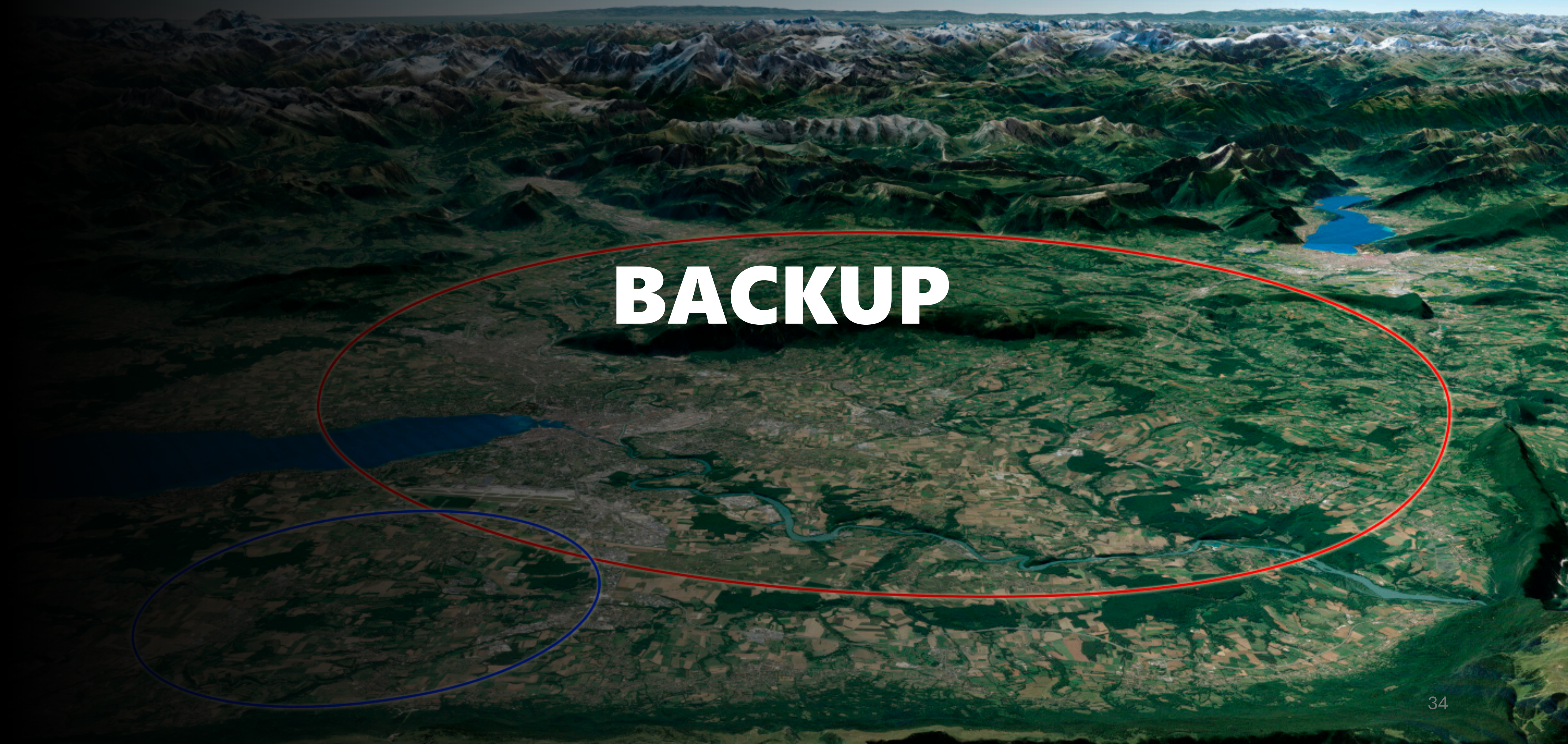
[4] https://indico.cern.ch/event/1202105/

[5] https://indico.cern.ch/event/1326738/

[6] https://inspirehep.net/files/42c81dd79ac5576021ed0d9dfec5bc06

[7] K. HIRATA, et al., Particle Accelerators, 1993, Vol. 40, pp.205-228

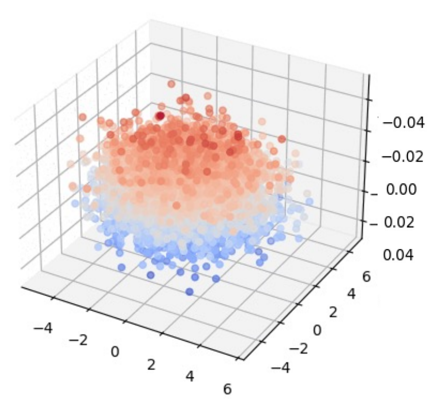
BACKUP



Detailed introduction on the tools done by L. Van Riesen-Haupt and X. Buffat: *INDICO*

Xsuite

Output:
Turn by turn parameters of the particles in the beam

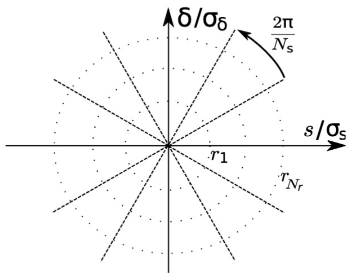


Advantages:
Closer to reality, non-linear models, Landau damping,…

Drawbacks:
Difficult to interpret results, slower

Study of BOTH **wakefields** and **beam-beam** interactions possible

CMM



Output:
Eigenvalues
⇔
tunes and growth rates

Advantages:
We can see all oscillation modes and the growth rates quickly

Drawbacks:
Linear model, cannot show non-linear effects