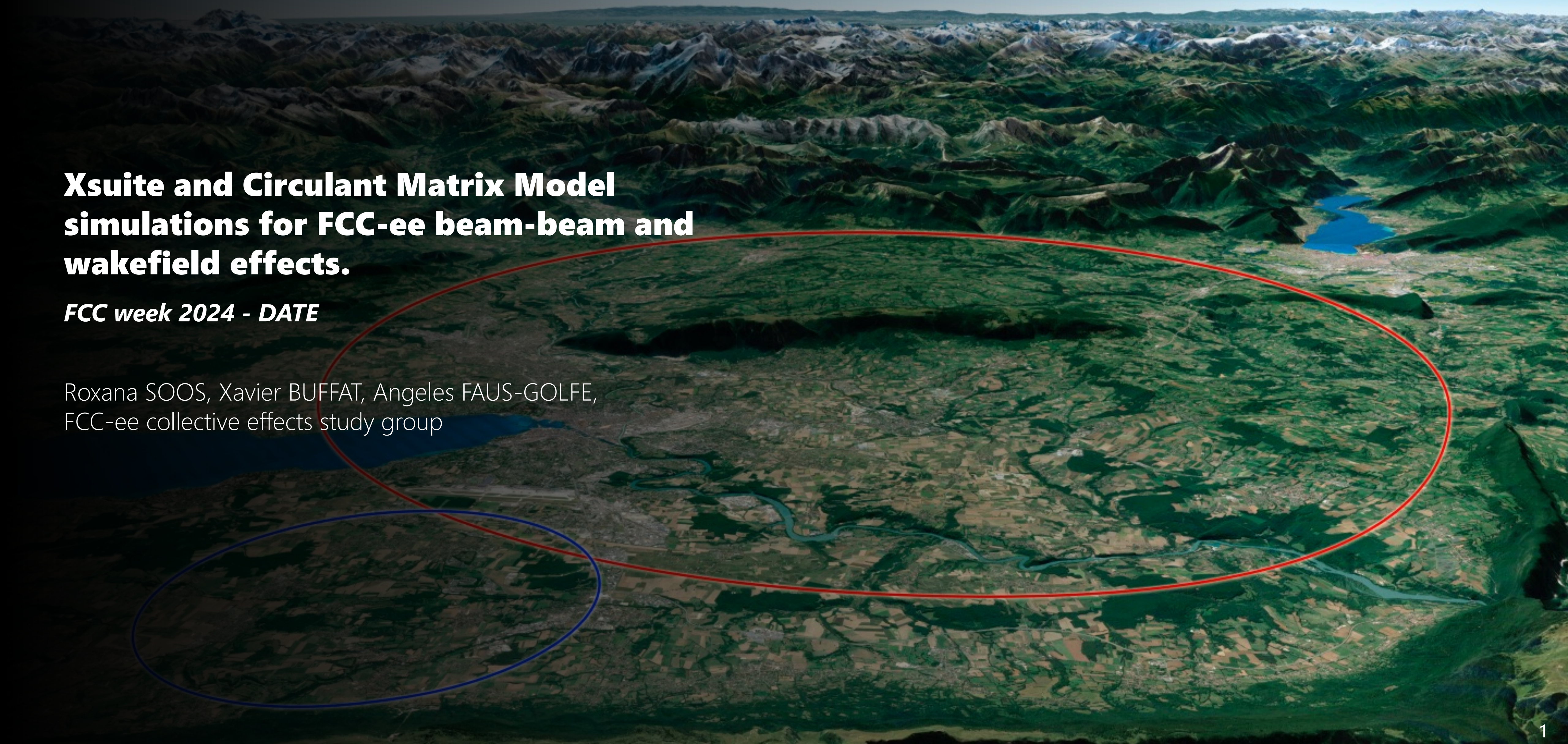
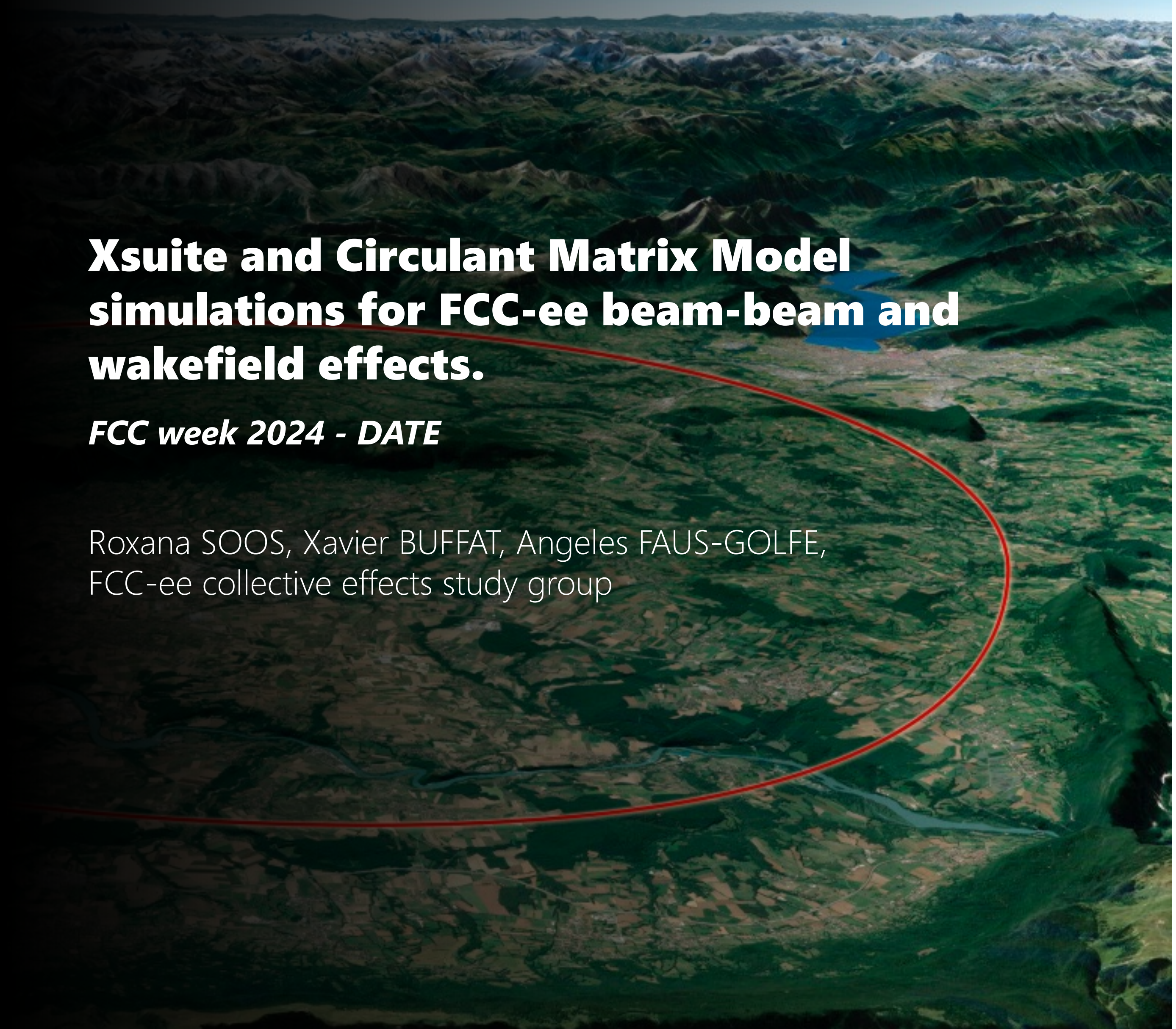
Xsuite and Circulant Matrix Model simulations for FCC-ee beam-beam and wakefield effects.

FCC week 2024 - DATE

Roxana SOOS, Xavier BUFFAT, Angeles FAUS-GOLFE,
FCC-ee collective effects study group



FUTURE CIRCULAR COLLIDER
Innovation Study



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Overview

Introduction

- Study context for FCC-ee
- Xsuite and parameter sets for simulations

Simulation tools

- Circulant matrix model
- Xsuite versus mode analysis algorithm

Simulation of Beam-Beam

- Intensity scans – coherent instability
- Tune scans – study of different characteristics

Simulation of wakefields

- Circulant matrix model for wakefields
- Transverse mode coupling instability simulations

Summary

- Summary and outlook

Introduction

Study context for the FCC-ee

Context:

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 measurements [2], [3]

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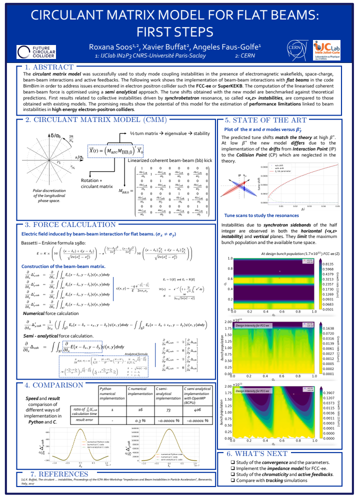

CIRCULANT MATRIX MODEL FOR FLAT BEAMS: FIRST STEPS

Roxana Soos[1,2], Xavier Buffat[2], Angeles Faus-Golfe[1]
1: IJClab IN2P3 CNRS-Université Paris-Saclay 2: CERN

1. ABSTRACT

The ***circulant matrix model*** was successfully used to study mode coupling instabilities in the presence of electromagnetic wakefields, space-charge, beam-beam interactions and active feedbacks. The following work shows the implementation of beam-beam interactions with ***flat beams*** in the code BimBim in order to address issues encountered in electron positron collider such the **FCC-ee** or **SuperKEKB**. The computation of the linearised coherent beam-beam force is optimised using a ***semi analytical*** approach. The tune shifts obtained with the new model are benchmarked against theoretical predictions. First results related to collective instabilities driven by ***synchrobetatron*** resonance, so called ***<x,z> instabilities***, are compared to those obtained with existing models. The promising results show the potential of this model for the estimation of **performance limitations** linked to beam instabilities in **high energy electron-positron colliders**.

2. CIRCULANT MATRIX MODEL (CMM)

$\overrightarrow{X}(t) = \left(M_{\text{arc}} M_{\text{BB},0}\right)^t \overrightarrow{X}_0$

½ turn matrix → eigenvalue → stability

Linearized coherent beam-beam (bb) kick

Rotation + circulant matrix

Polar discretization of the longitudinal phase space.

3. FORCE CALCULATION

Electric field induced by beam-beam interaction for flat beams. $(\sigma_x \neq \sigma_y)$

Bassetti – Erskine formula 1980:

Construction of the beam-beam matrix.

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Semi - analytical force calculation.

Analytical formula

4. COMPARISON

Speed and **result** comparison of different ways of implementation in ***Python*** and ***C***.

	Python numerical implementation	C numerical implementation	C semi-analytical implementation	C semi analytical implementation with OpenMP (8CPU)
ratio of $\frac{\partial}{\partial_x}\Delta'_{x,coh}$ calculation time	1	16	73	406
result error	-	0.3 %	~0.00001 %	~0.00001 %

5. STATE OF THE ART

Plot of the π and σ modes versus β_y^*

The predicted tune shifts ***match the theory*** at high β^*. At low β^* the new model ***differs*** due to the implementation of the ***drifts*** from ***Interaction Point*** (IP) to the ***Collision Point*** (CP) which are neglected in the theory.

Tune scans to study the resonances

Instabilities due to ***synchrotron sidebands*** of the half integer are observed in both the ***horizontal*** (***<x,z> instability***) and ***vertical*** planes. They ***limit*** the maximum bunch population and the available tune space.

At design bunch population (1.7×10^{11}) FCC-ee (Z).

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- ☐ Study of the ***convergence*** and the parameters.
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7. REFERENCES

[1] X. Buffat, The circulant ... instabilities, Proceedings of the ICFA Mini-Workshop "Impedances and Beam Instabilities in Particle Accelerators", Benevento, Italy, 2017

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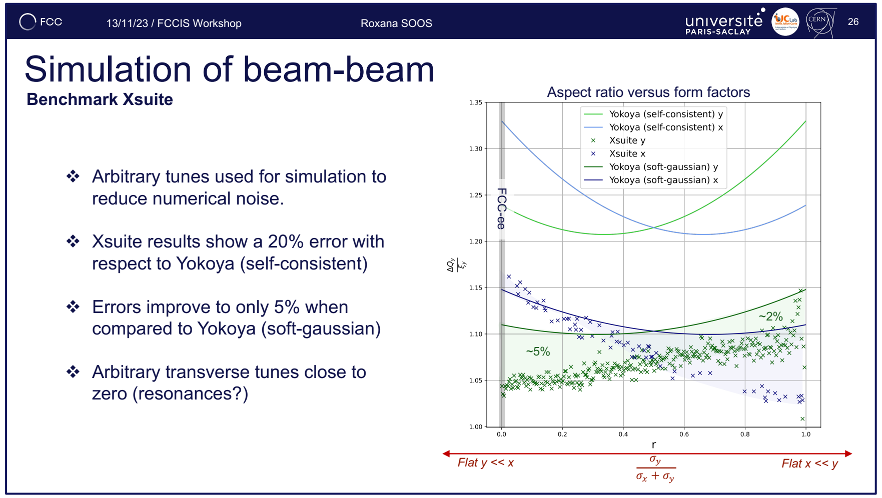

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Simulation of beam-beam

Benchmark Xsuite

- ❖ Arbitrary tunes used for simulation to reduce numerical noise.
- ❖ Xsuite results show a 20% error with respect to Yokoya (self-consistent)
- ❖ Errors improve to only 5% when compared to Yokoya (soft-gaussian)
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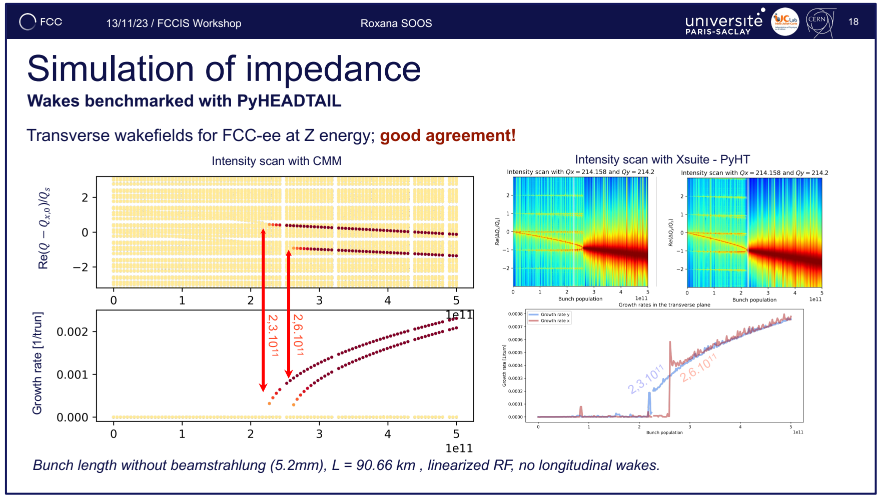

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Wakes benchmarked with PyHEADTAIL

Transverse wakefields for FCC-ee at Z energy; **good agreement!**

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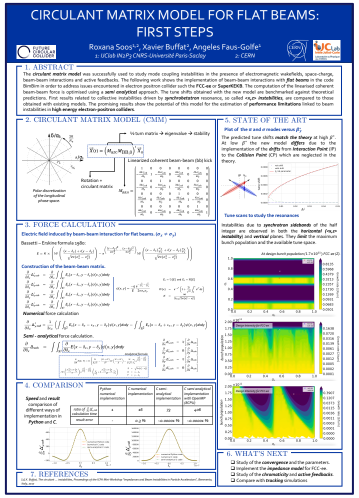

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Design Intensity for FCC-ee

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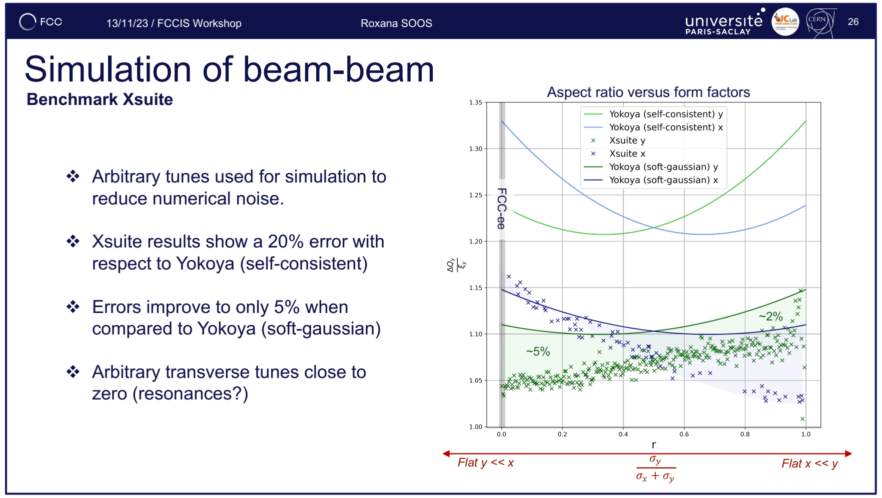

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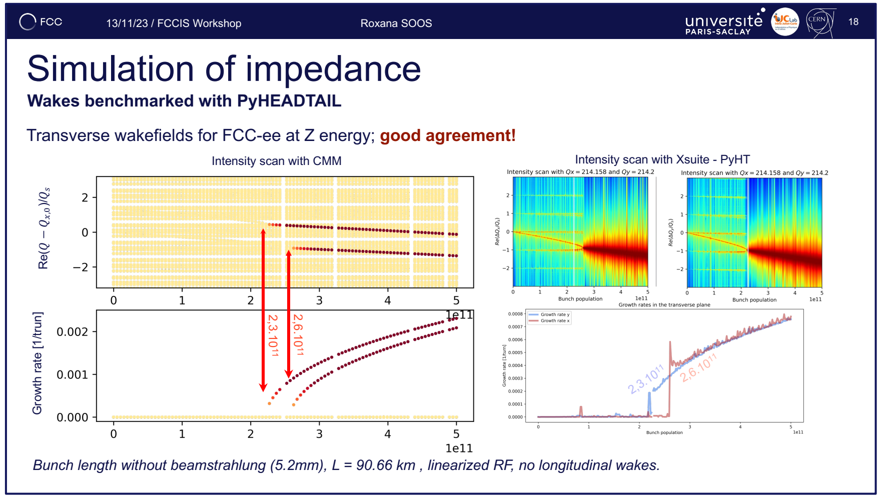

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Bunch length without beamstrahlung (5.2mm), L = 90.66 km , linearized RF, no longitudinal wakes.

Goal:

Understand the different effects due to the contribution of beam-beam and impedance and the dependence on different parameters.
As announced in [1] and other literature, it is difficult to find a stable tune area when the two effects are considered.

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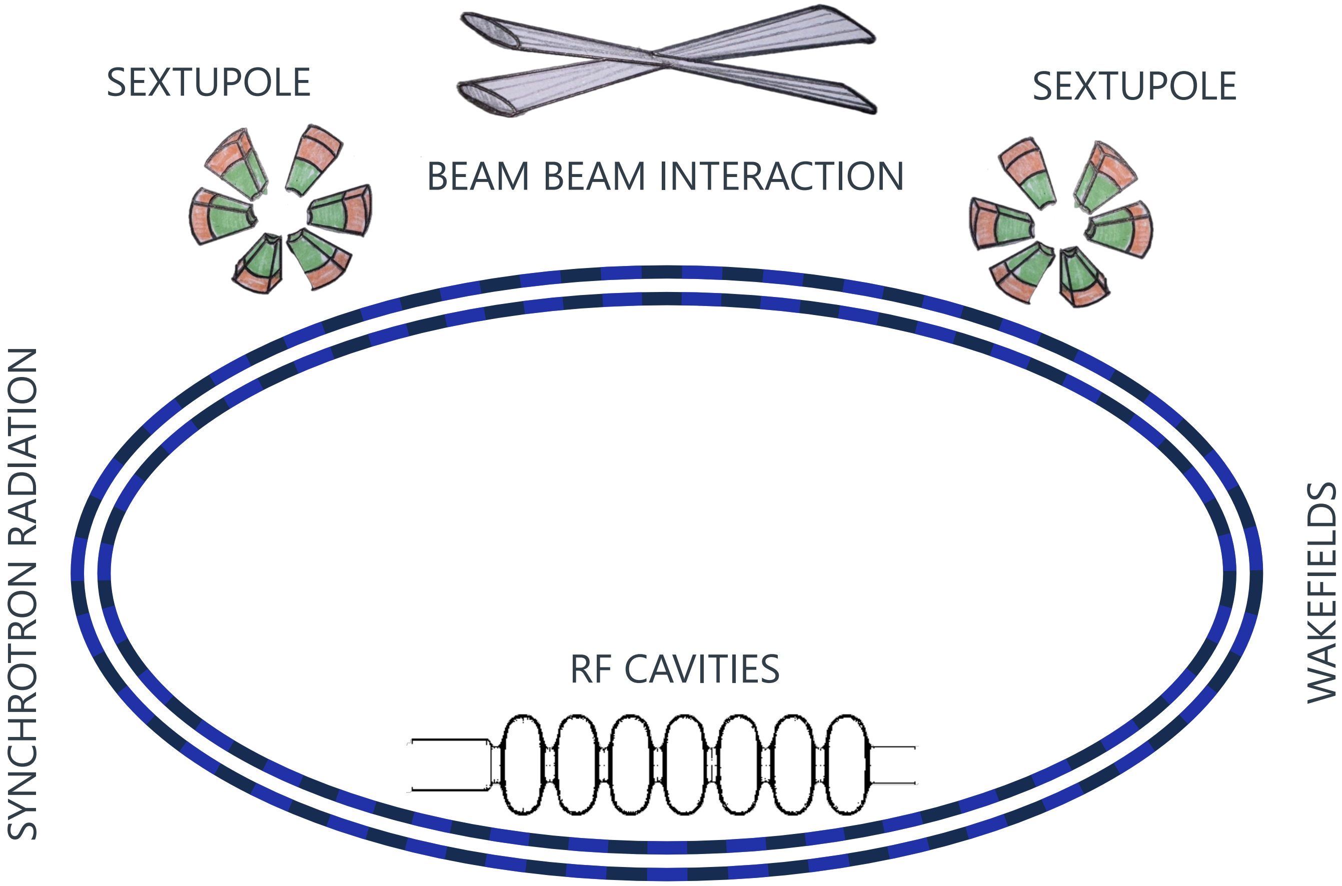
Xsuite and parameter sets for simulation

Turn by turn tracking of particles, calculating nonlinear forces around the specified accelerator components.



FCC-ee (Z) approximated model:

Why:

- Limits the numerous complicated non studied effects.
- Faster simulations.

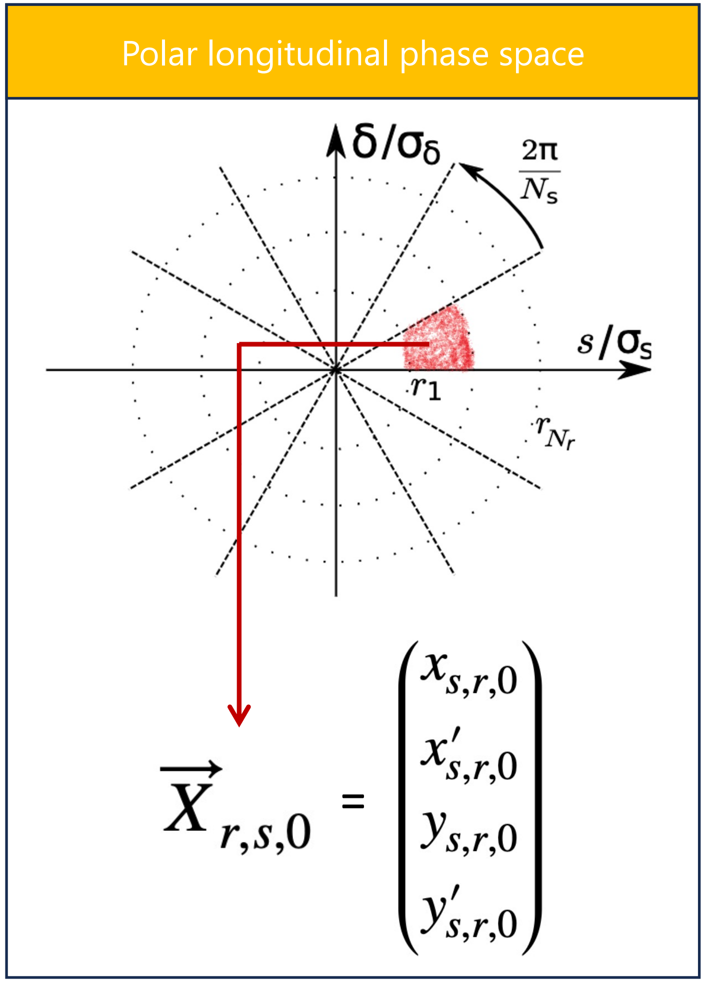
What:

- FCC-ee (Z) parameters table (bunch lengths/sizes, RF power, crossing angle, …)
- Synchrotron radiation (SR) + Radio frequency cavities (RF)
- Single beam-beam interaction point + Beamstrahlung (BS)
- Crab sextupoles (when crossing angle)
- Longitudinal + Transverse wakefields (2023 - M. MIGLIORATI)

Circulant Matrix Model (CMM)

Use linear algebra on a one turn matrix that represents a system, applied on discretized longitudinal phase space

Polar longitudinal phase space



$$\overrightarrow{X}_{r,s,0} = \begin{pmatrix} x_{s,r,0} \\ x'_{s,r,0} \\ y_{s,r,0} \\ y'_{s,r,0} \end{pmatrix}$$

Slicing structure

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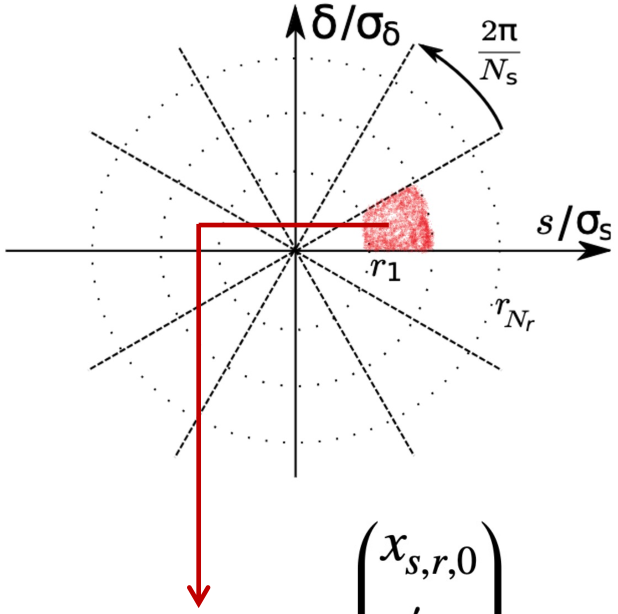

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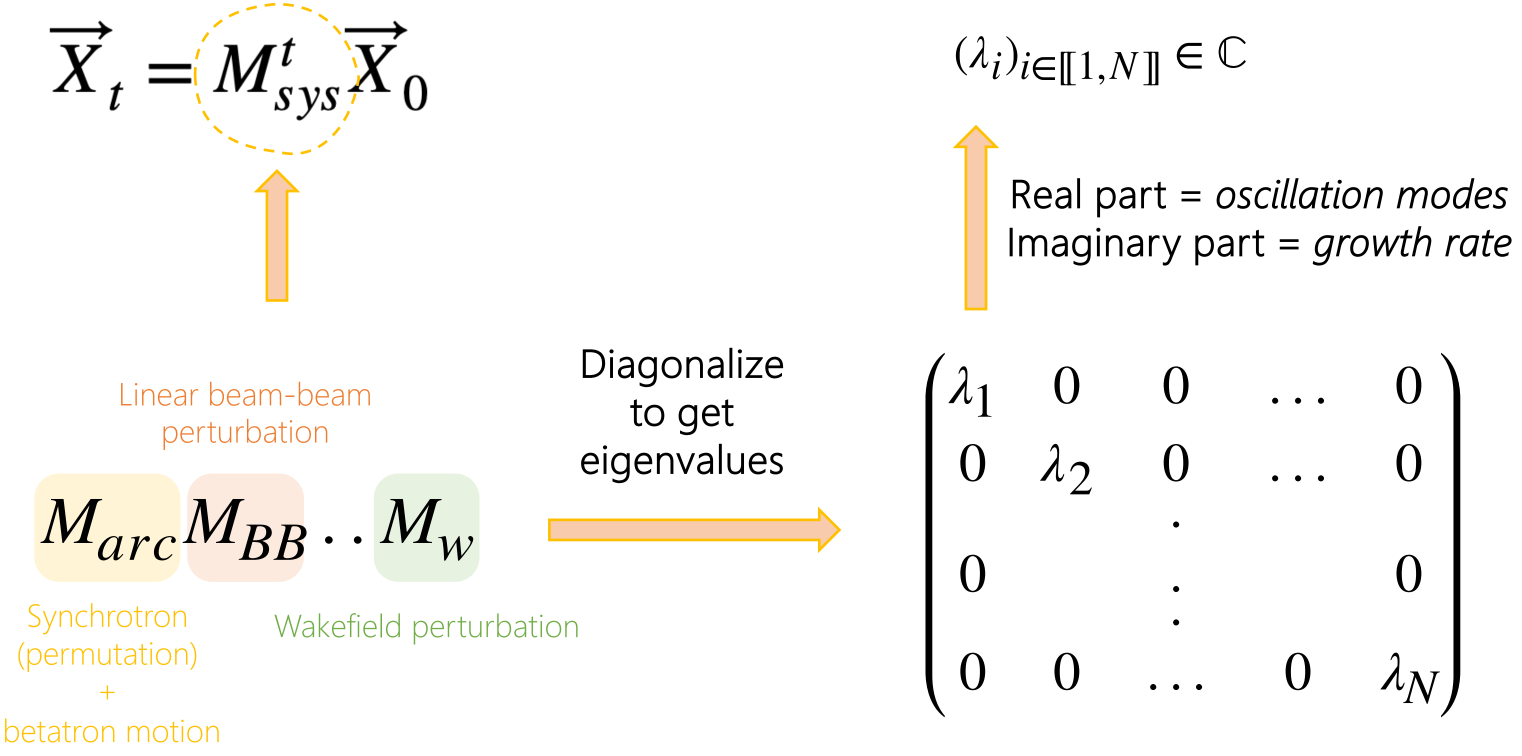
Slicing structure

1 turn system matrix



$$\vec{X}_t = M_{sys}^t \vec{X}_0$$

Linear beam-beam perturbation

$$M_{arc} M_{BB} \,..\, M_w$$

Synchrotron (permutation) + betatron motion

Wakefield perturbation

Diagonalize to get eigenvalues

$$\begin{pmatrix} \lambda_1 & 0 & 0 & \dots & 0 \\ 0 & \lambda_2 & 0 & \dots & 0 \\ 0 & & \vdots & & 0 \\ 0 & 0 & \dots & 0 & \lambda_N \end{pmatrix}$$

Real part = *oscillation modes*
Imaginary part = *growth rate*

$$(\lambda_i)_{i\in[\![1,N]\!]} \in \mathbb{C}$$

Circulant matrix

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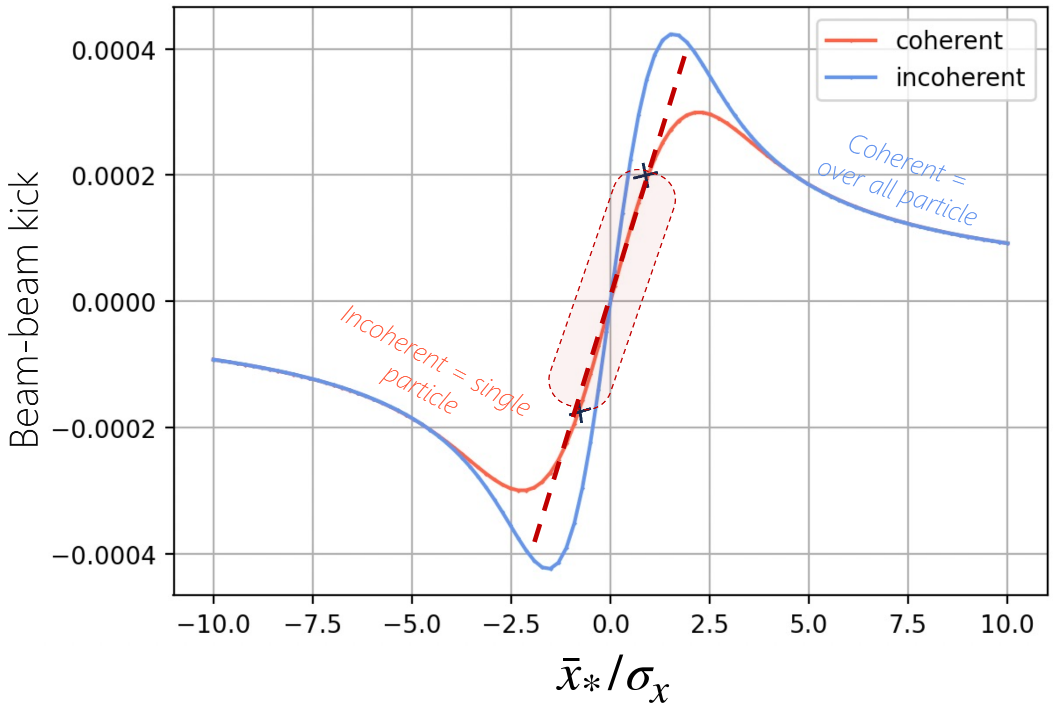
Linearized coherent flat beam-beam kick
(from Bassetti – Erskine formula)

Transverse beam-beam kicks reprensentation
(Given by Bassetti – Erskine formula)



Matrix elements example

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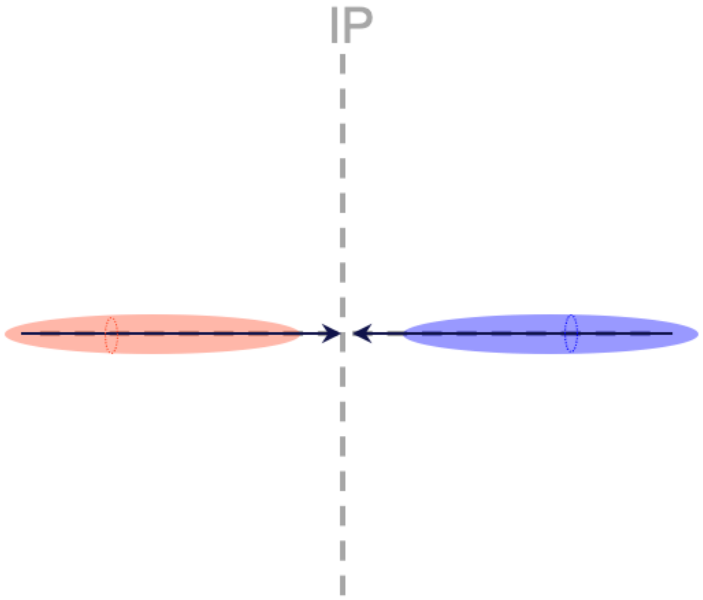

What is in the beam-beam model?

- Flat beams

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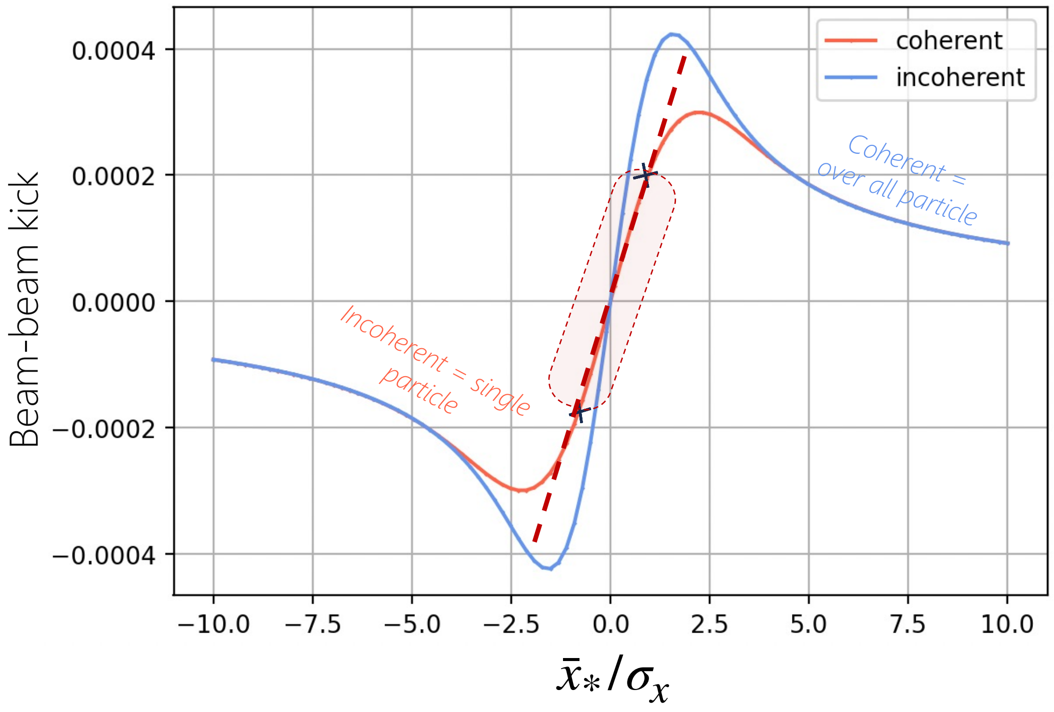

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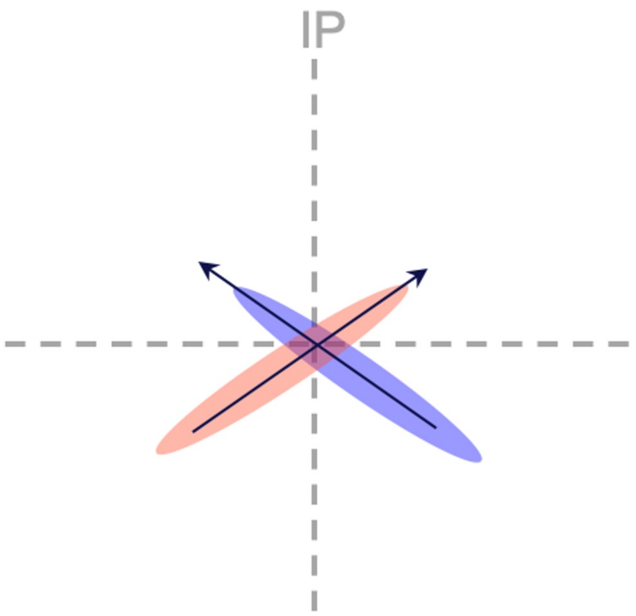

What is in the beam-beam model?

- Flat beams
- Crossing angle

Transverse beam-beam kicks reprensentation

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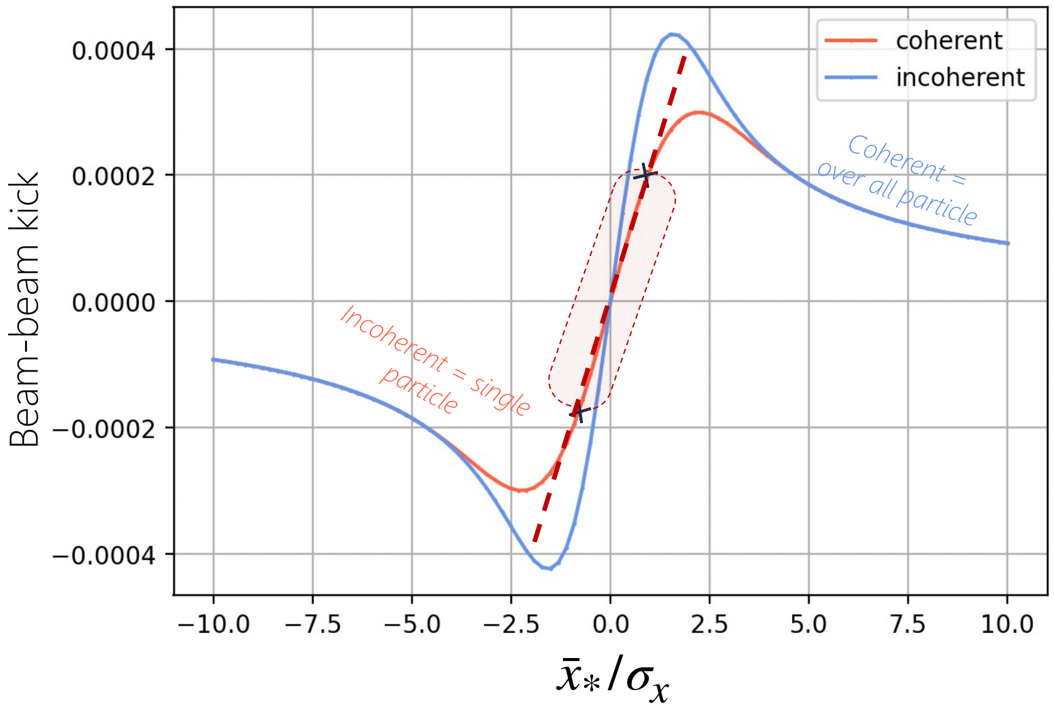

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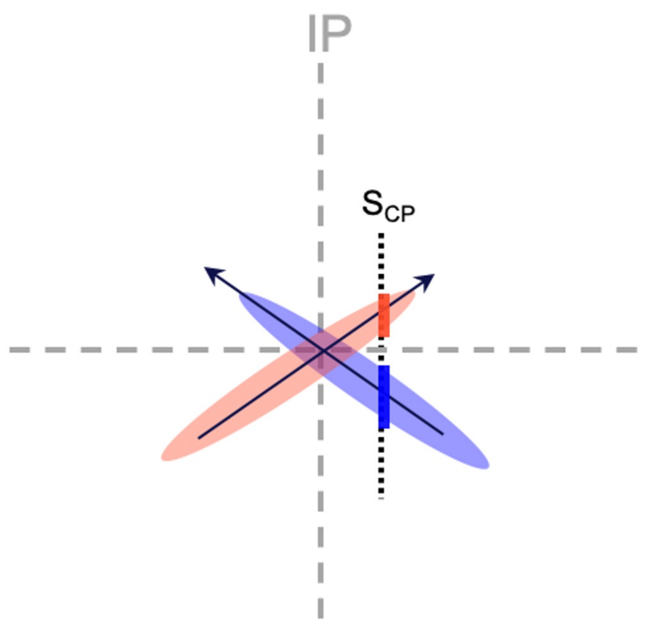

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- Drifts (IP -> CP -> IP)

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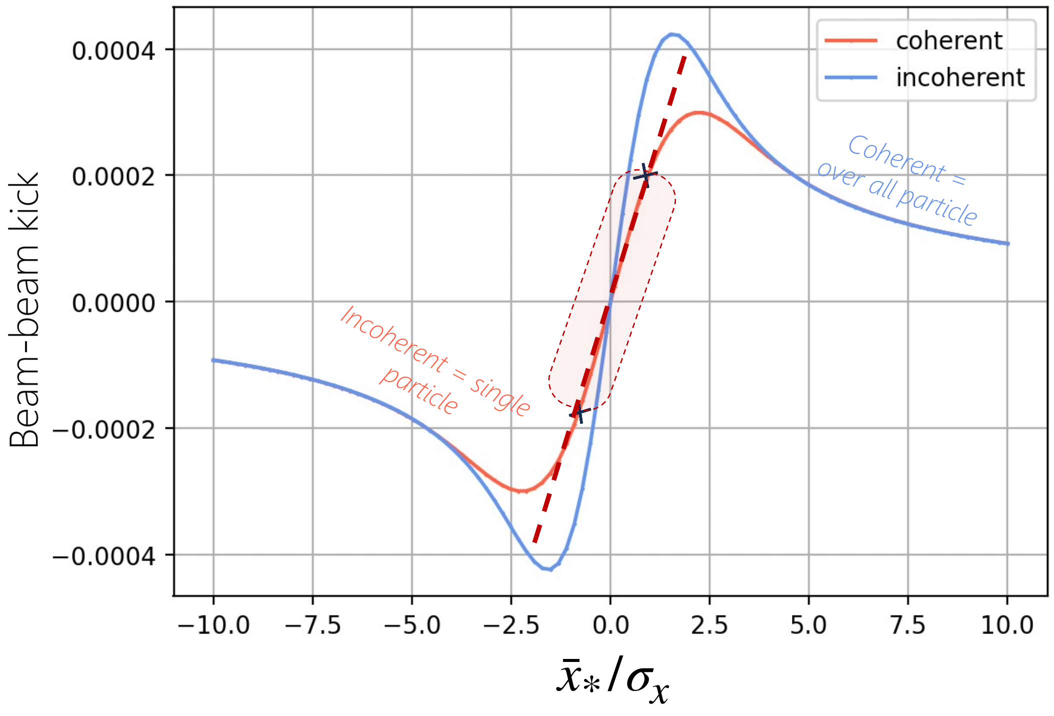

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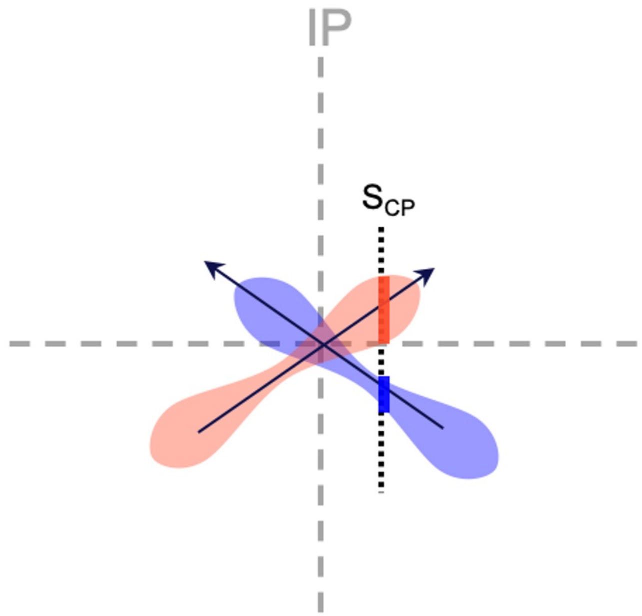

Disclaimer: schematic not 100% accurate representation.

What is in the beam-beam model?

- Flat beams
- Crossing angle
- Drifts (IP -> CP -> IP)
- Hourglass effect

Transverse beam-beam kicks reprensentation

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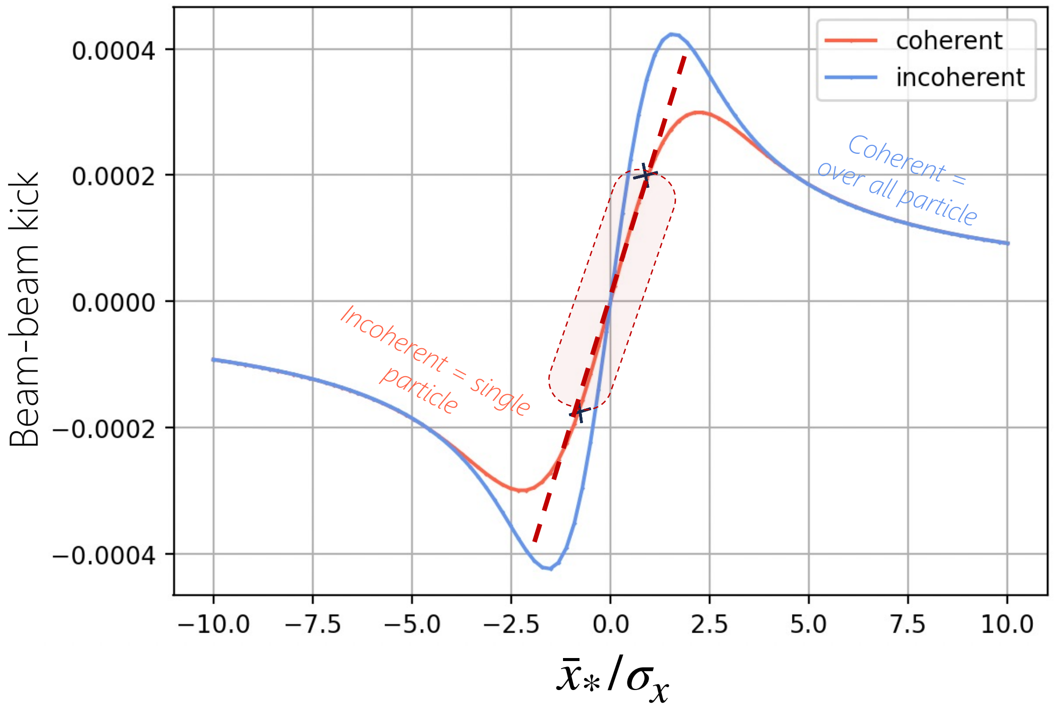

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$$\nabla U\left(x,y\right) = E_{B/E}(x,y)$$

Coherent force

Bassetti – Erskine formula

$$\iint E_{B/E}\left(x-\bar{x}_*, y-\bar{y}_*, \sigma_x, \sigma_y\right)\psi\left(x,y\right)dxdy \overset{[4]}{=} E_{B/E}\left(-\bar{x}_*, -\bar{y}_*, \sqrt{2}\sigma_x, \sqrt{2}\sigma_y\right)$$

Normal forces

$$\frac{\partial}{\partial \bar{x}_*}\Delta x'_{coh}(\bar{x}_*, \bar{y}_*) = \frac{\partial}{\partial \bar{x}_*}E_x\left(\bar{x}_*, \bar{y}_*, \sqrt{2}\sigma_x, \sqrt{2}\sigma_y\right)$$

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Coupled forces

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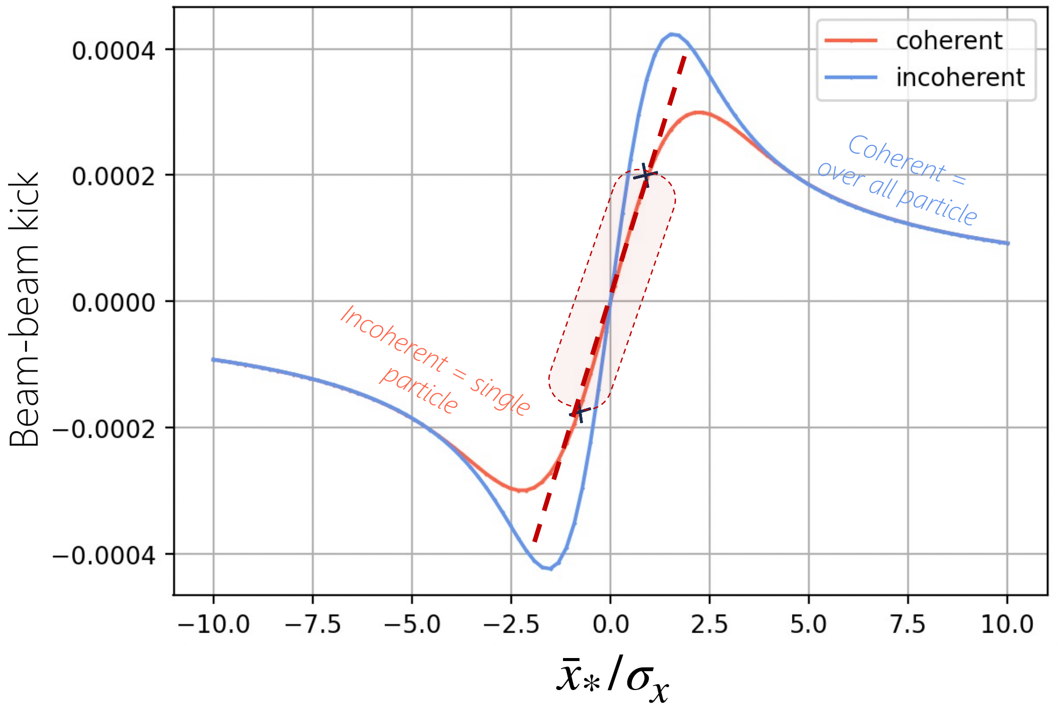

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Coupled forces

$$M_{BB} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\frac{\partial\Delta x'_{coh}}{\partial\bar{x}_*} & 1 & \frac{\partial\Delta x'_{coh}}{\partial\bar{x}_*} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\partial\Delta x'_{coh}}{\partial\bar{x}_*} & 0 & -\frac{\partial\Delta x'_{coh}}{\partial\bar{x}_*} & 1 \end{pmatrix}$$

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Simple case with the beam beam kick only applied to the horizontal space

BEAM 1

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ -\frac{\partial \Delta x'_{coh}}{\partial \bar{x}_*} & 1 & \frac{\partial \Delta x'_{coh}}{\partial \bar{x}_*} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\partial \Delta x'_{coh}}{\partial \bar{x}_*} & 0 & -\frac{\partial \Delta x'_{coh}}{\partial \bar{x}_*} & 1 \end{pmatrix} \begin{pmatrix} x_{B1} \\ x'_{B1} \\ x_{B2} \\ x'_{B2} \end{pmatrix} = \begin{pmatrix} x_{B1} \\ \frac{\partial \Delta x'_{coh}}{\partial \bar{x}_*}\left(x_{B2} - x_{B1}\right) + x'_{B1} \\ x_{B2} \\ \frac{\partial \Delta x'_{coh}}{\partial \bar{x}_*}\left(x_{B1} - x_{B2}\right) + x'_{B2} \end{pmatrix}$$

BEAM 2

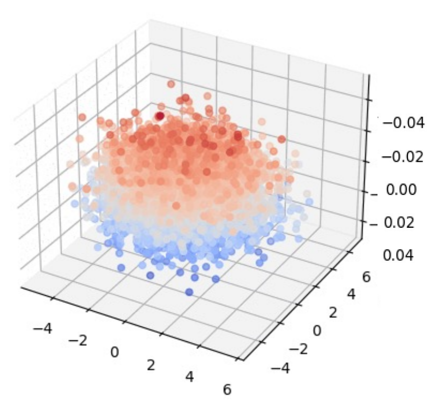
This can be generalized to the vertical space and for N_{slice}x N_{ring} mesh elements.

[4] K. HIRATA, Nuclear Instruments and Methods in Physics Research A269, 7-22 (1988)

XSuite versus mode analysis algorithm

Xsuite

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



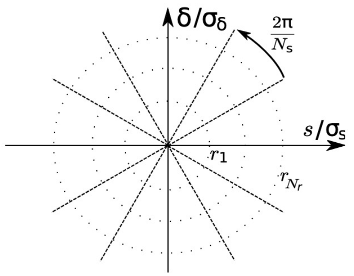
Advantages:
Closer to reality, non-linear models, Landau damping,…

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

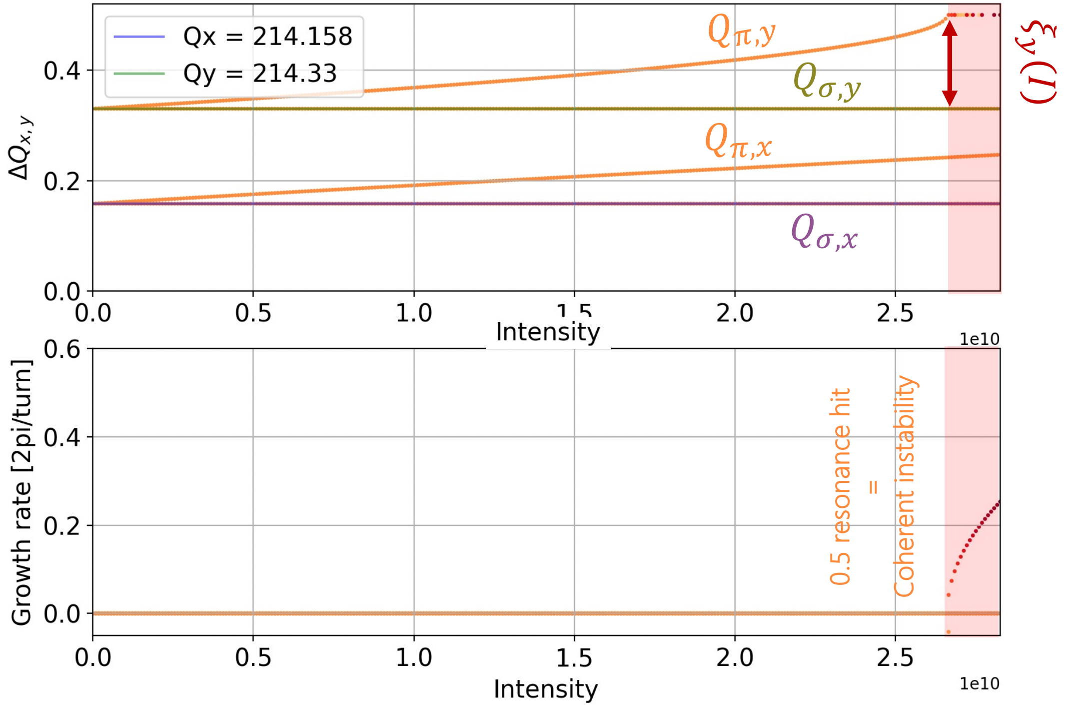
Drawbacks:
Linear model, cannot show non-linear effects

*Circulant Matrix Model

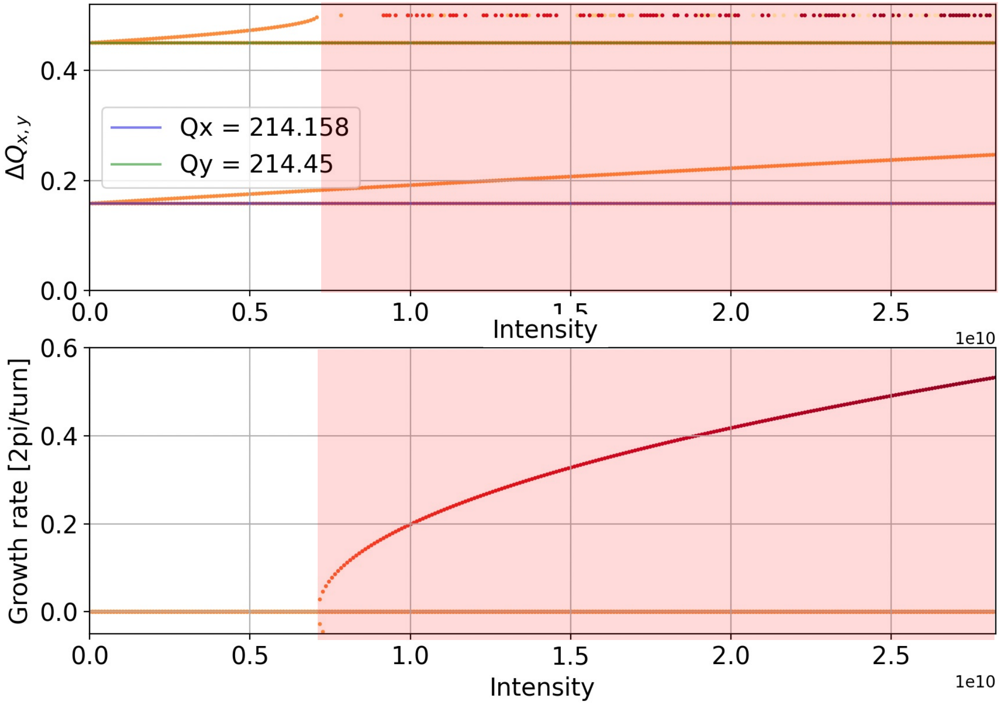
Intensity scans – coherent instability

The intensity scan is a simulation where we study growth rates of the instabilities and modes of oscillation, varying the intensity. The CMM outputs are modes of oscillation and growth rates.

Smaller vertical tune: farther from 0.5 resonance



Higher vertical tune: closer to 0.5 resonance



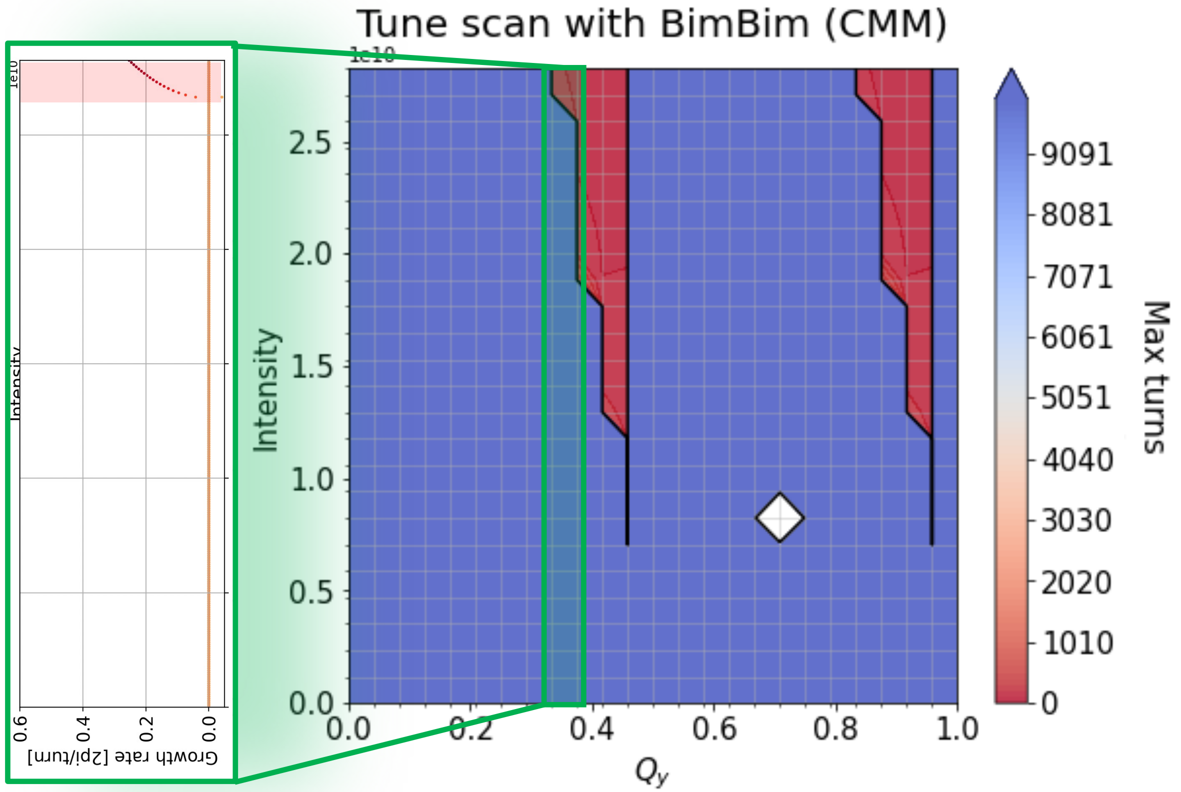
Simple case: Only beam-beam, with circular beam, no hourglass, low intensity, to demonstrate 'simple' intensity scan

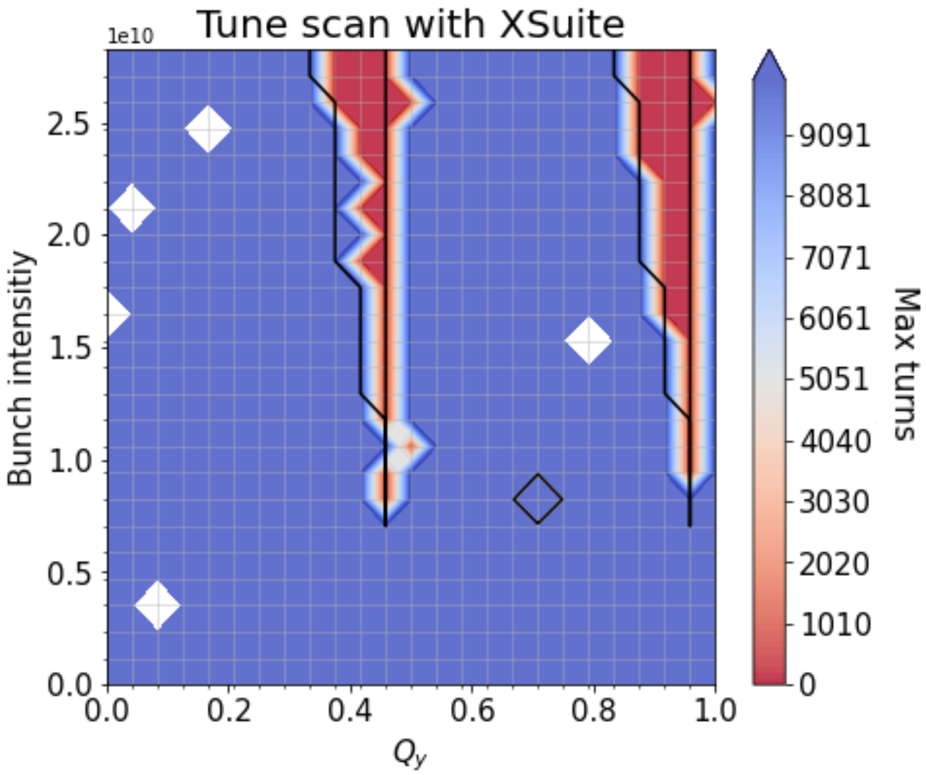
FCC-ee (Z) base parameters with $\beta_x = \beta_y$ *= 0.15 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* θ *= 0 mrad*

[5] A. CHAO, Coherent Beam-Beam Effects (1991)

Tune scans – study of different characteristics

The tune scan is a simulation where we study the growth rate of the instabilities in a bunch, varying the intensity and/or the tune(s).





Simple case: Only beam-beam, with circular beam, no hourglass, low intensity, to demonstrate 'simple' tune scan

FCC-ee (Z) base parameters with $\beta_x = \beta_y$ = 0.15 m, $\varepsilon_x = \varepsilon_y$ = 7.1e-10m, θ = 0 mrad

[5] A. CHAO, Coherent Beam-Beam Effects (1991)

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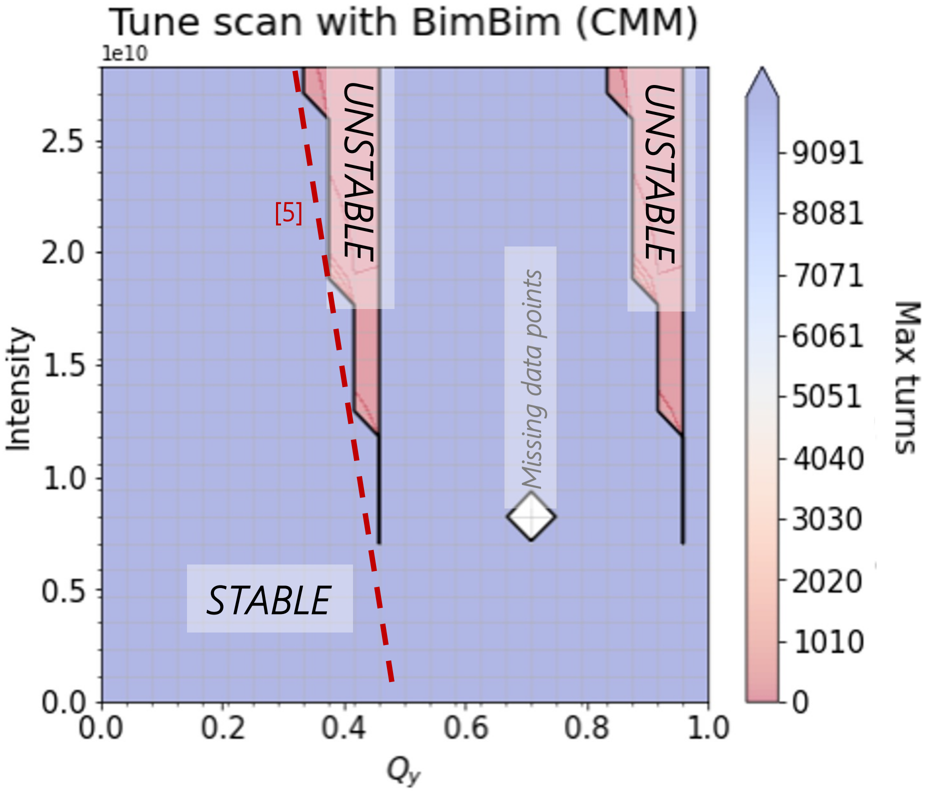
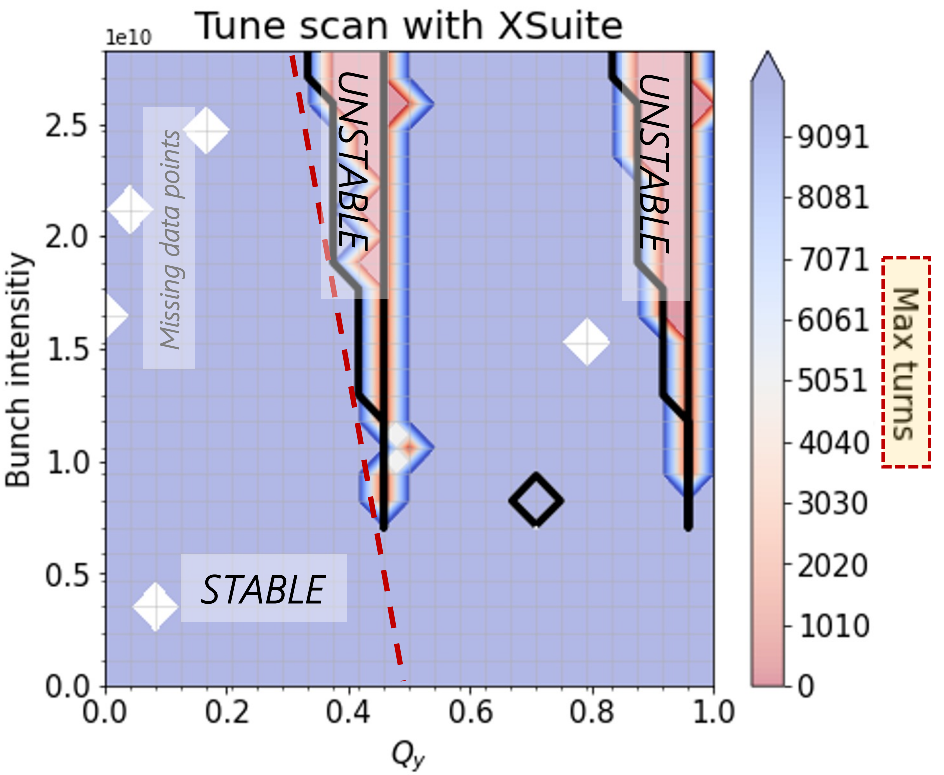

Tune scan with BimBim (CMM)


Tune scan with XSuite

MAX TURNS = 2π/GROWTH RATE

Simple case: Only beam-beam, with circular beam, no hourglass, low intensity, to demonstrate 'simple' tune scan

FCC-ee (Z) base parameters with $\beta_x = \beta_y$ *= 0.15 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* θ *= 0 mrad*

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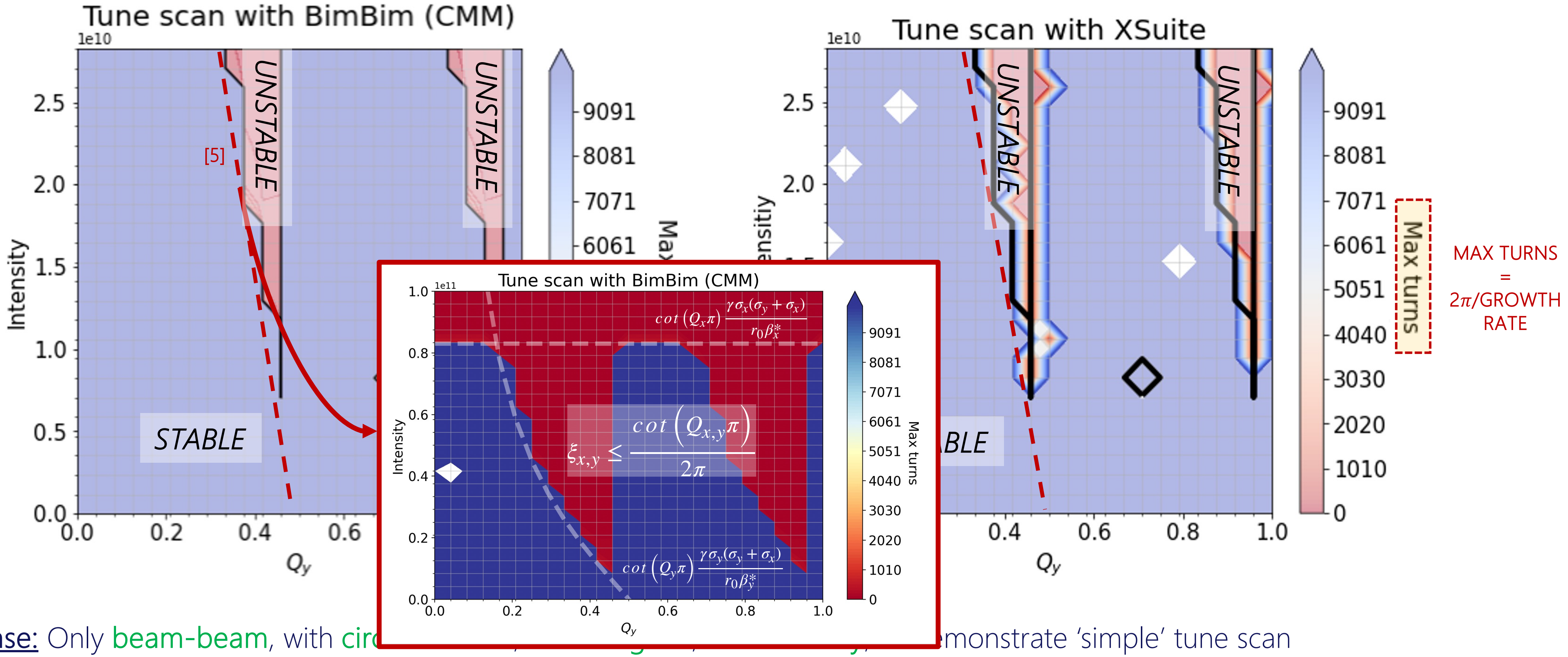

MAX TURNS
=
2π/GROWTH RATE

Simple case: Only beam-beam, with cir … monstrate ‘simple’ tune scan

FCC-ee (Z) base parameters with $\beta_x = \beta_y$ *= 0.15 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* $\boldsymbol{\theta}$ *= 0 mrad*

[5] A. CHAO, Coherent Beam-Beam Effects (1991)

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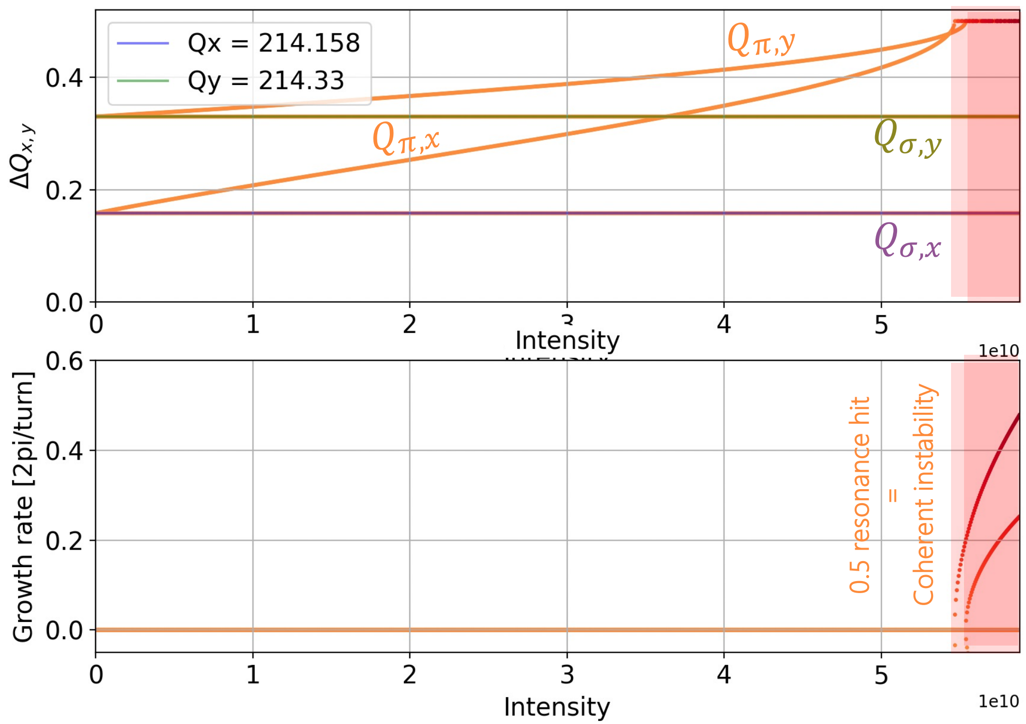
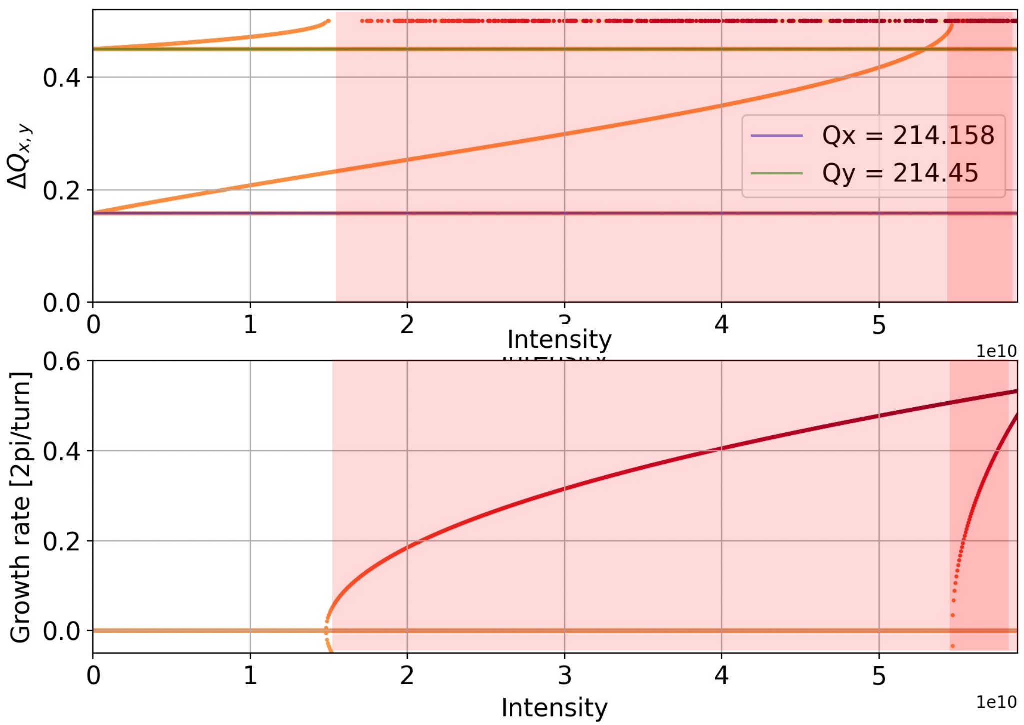


Smaller vertical tune: farther from 0.5 resonance



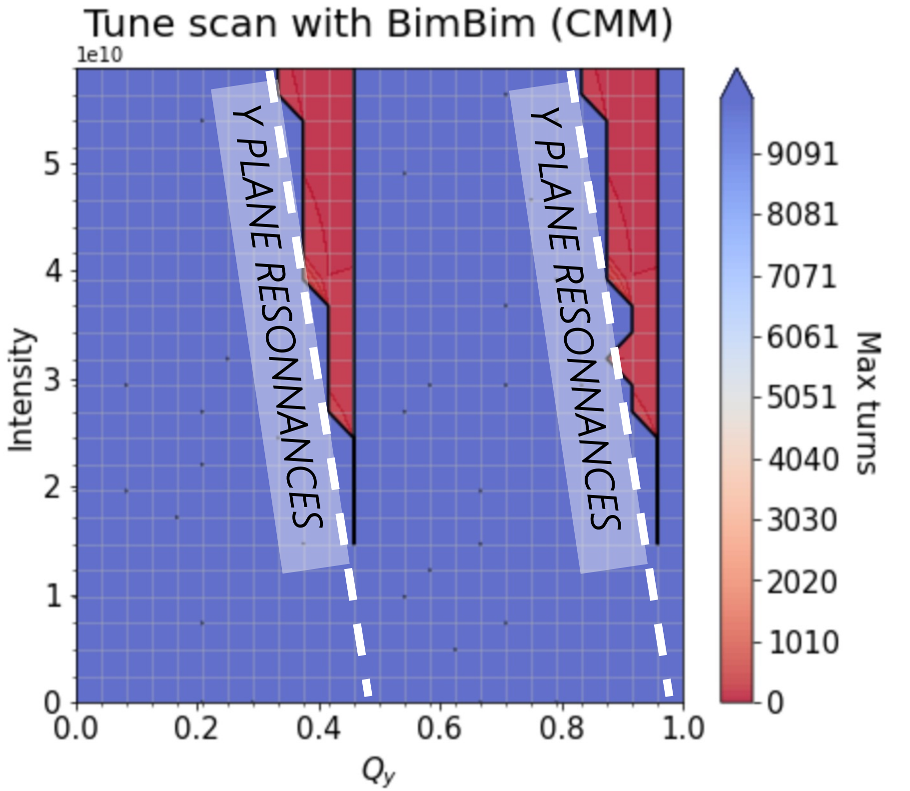
Higher vertical tune: closer to 0.5 resonance

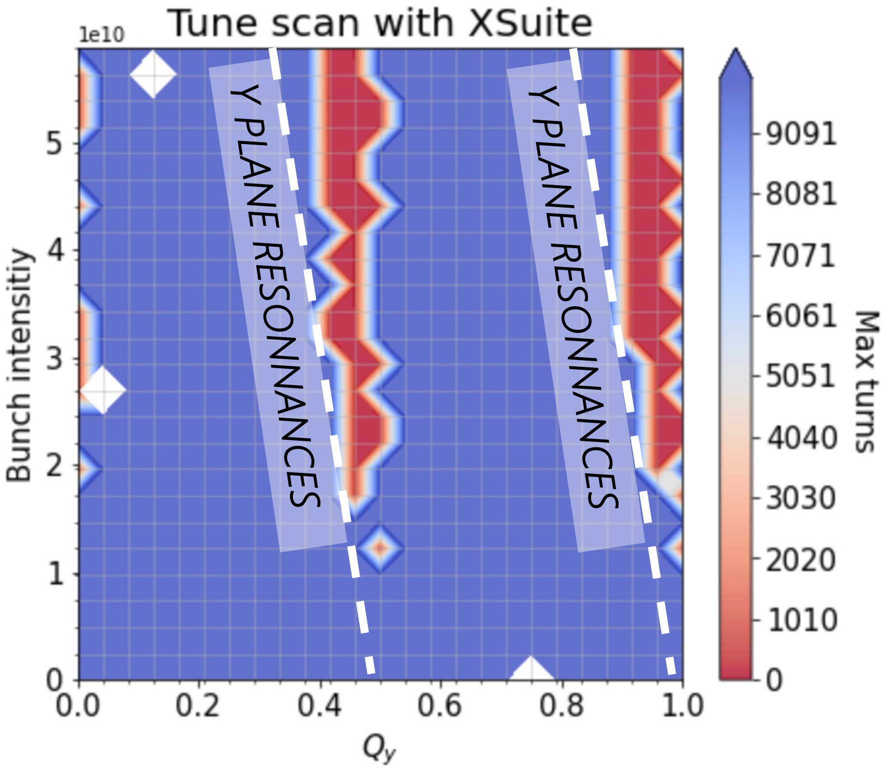
Simple case: Only beam-beam, with flat beam, no hourglass, low intensity, to demonstrate 'simple' intensity scan

FCC-ee (Z) base parameters with β_x *= 1 m,* β_y *= 0.1 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* θ *= 0 mrad*

Tune scans – study of different characteristics

The tune scan is a simulation where we study the growth rate of the instabilities in a bunch, varying the intensity and/or the tune(s).



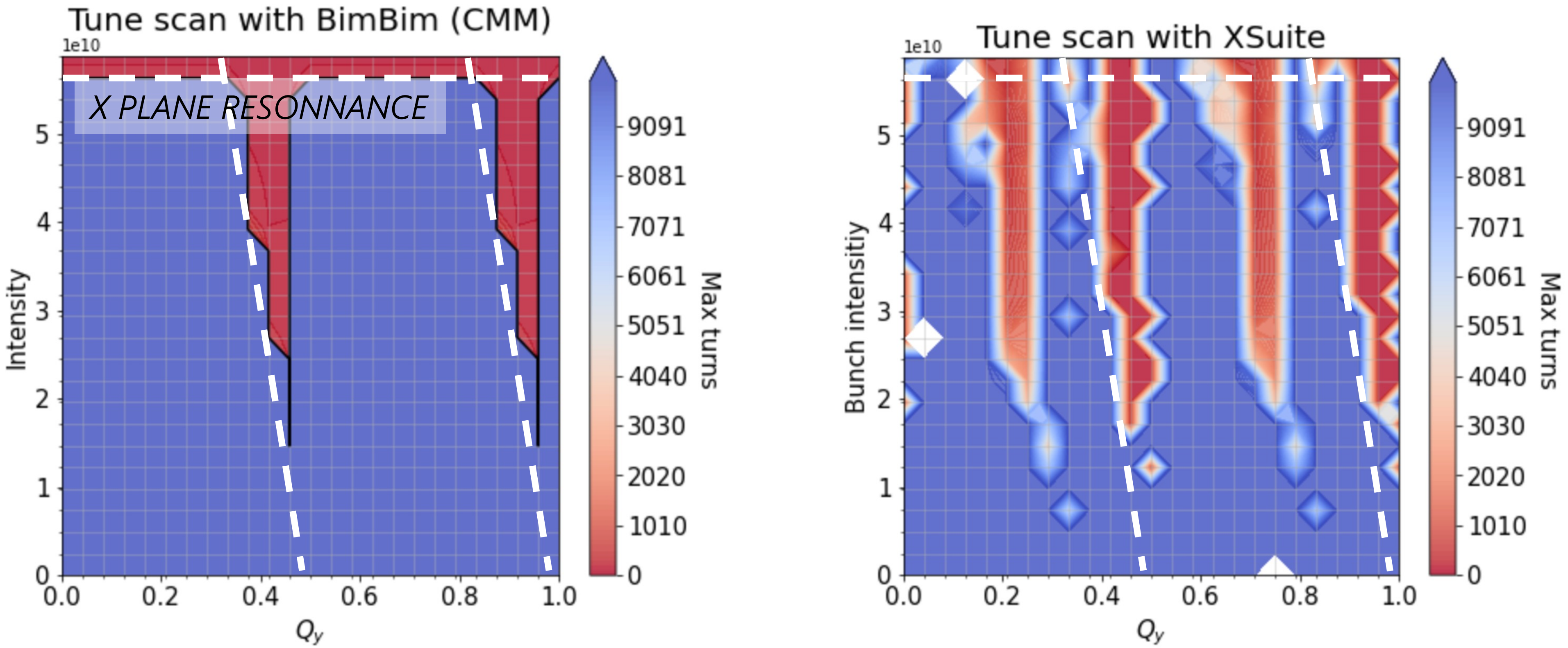


Simple case 2: Only beam-beam, with flat beam, no hourglass, low intensity, ONLY Y PLANE.

FCC-ee (Z) base parameters with β_x *= 1 m,* β_y *= 0.1 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* θ *= 0 mrad*

Tune scans – study of different characteristics

The tune scan is a simulation where we study the growth rate of the instabilities in a bunch, varying the intensity and/or the tune(s).

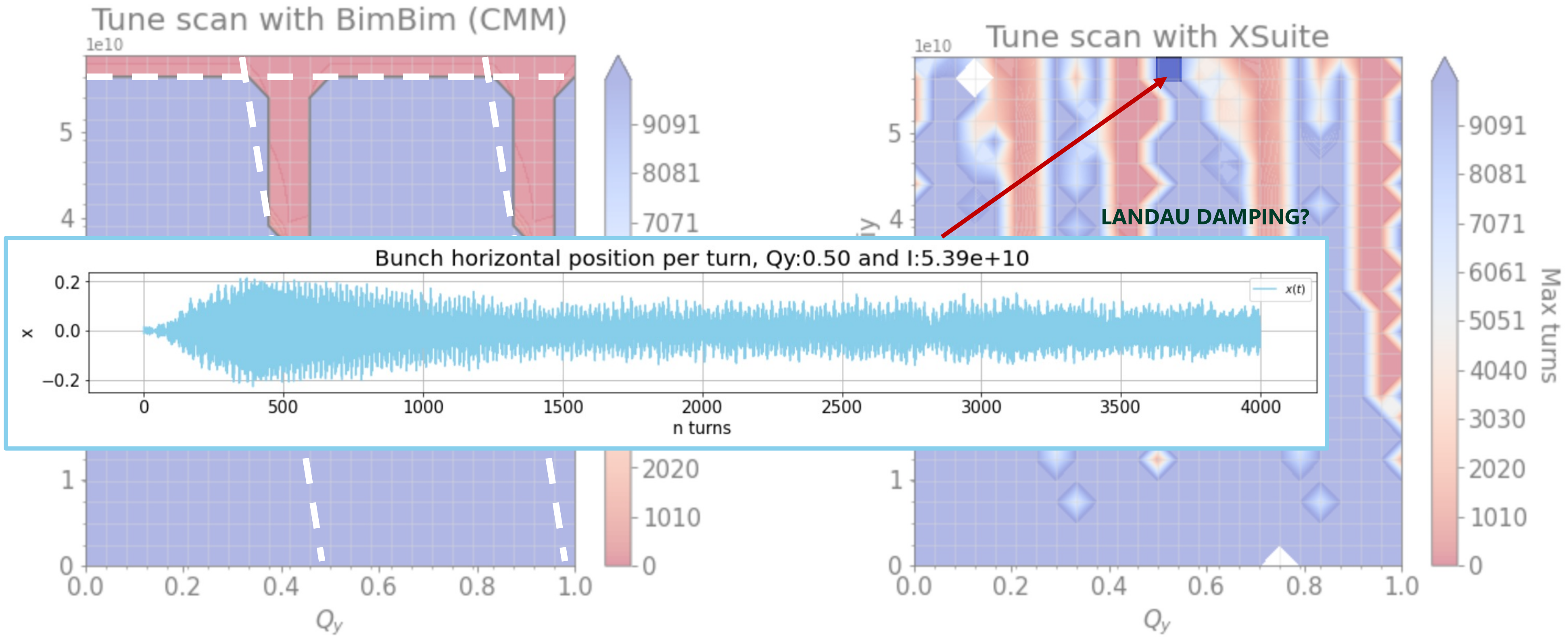


Simple case 2: Only beam-beam, with flat beam, no hourglass, low intensity, Y AND X PLANES.

FCC-ee (Z) base parameters with β_x *= 1 m,* β_y *= 0.1 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* θ *= 0 mrad*

Tune scans – study of different characteristics

The tune scan is a simulation where we study the growth rate of the instabilities in a bunch, varying the intensity and/or the tune(s).



LANDAU DAMPING?

Simple case 2: Only beam-beam, with flat beam, no hourglass, low intensity, Y AND X PLANES.

FCC-ee (Z) base parameters with β_x *= 1 m,* β_y *= 0.1 m,* $\varepsilon_x = \varepsilon_y$ *= 7.1e-10m,* θ *= 0 mrad*

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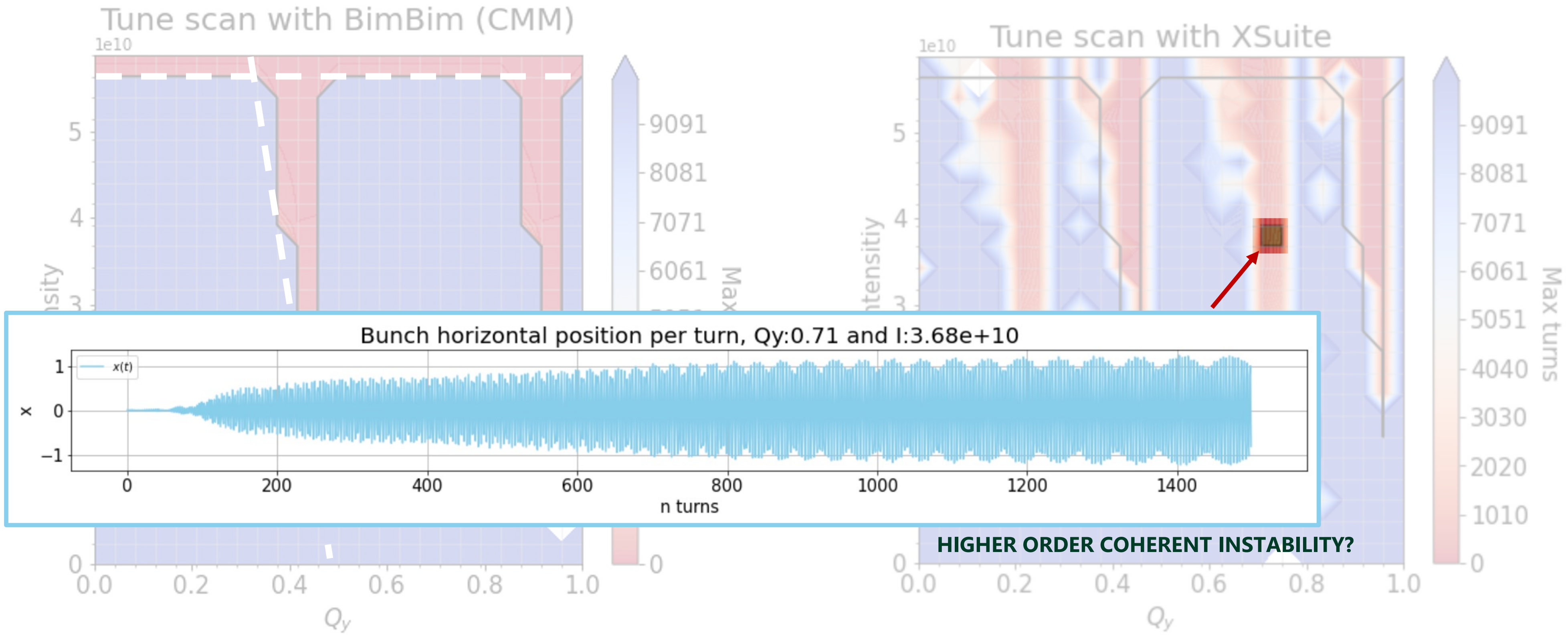


HIGHER ORDER COHERENT INSTABILITY?

Simple case 2: Only beam-beam, with flat beam, no hourglass, low intensity, Y AND X PLANES.

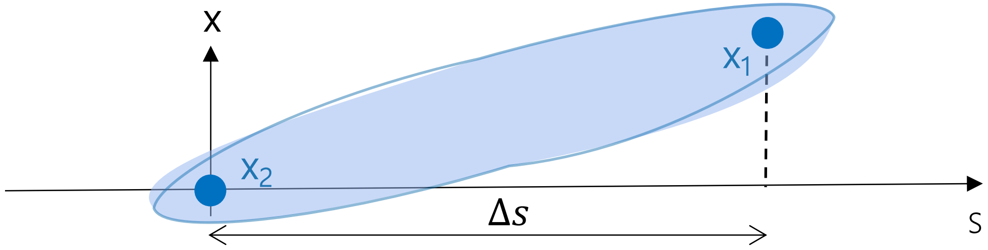
FCC-ee (Z) base parameters with $\beta_x = 1\ m, \beta_y = 0.1\ m, \varepsilon_x = \varepsilon_y = 7.1e\text{-}10m, \theta = 0\ mrad$

Circulant Matrix Model (CMM) for wakefields

Use linear algebra on a one turn matrix that represents a system, applied on discretized longitudinal phase space

Transverse wake kick

$$\begin{cases} \Delta y_2' = \overrightarrow{\mathscr{W}}_{dip,y}(\Delta s)\,\overrightarrow{y_1} + \overrightarrow{\mathscr{W}}_{quad,y}(\Delta s)\,\overrightarrow{y_2} \\ \Delta x_2' = \overrightarrow{\mathscr{W}}_{dip,x}(\Delta s)\,\overrightarrow{x_1} + \overrightarrow{\mathscr{W}}_{quad,x}(\Delta s)\,\overrightarrow{x_2} \end{cases}$$



Matrix elements example

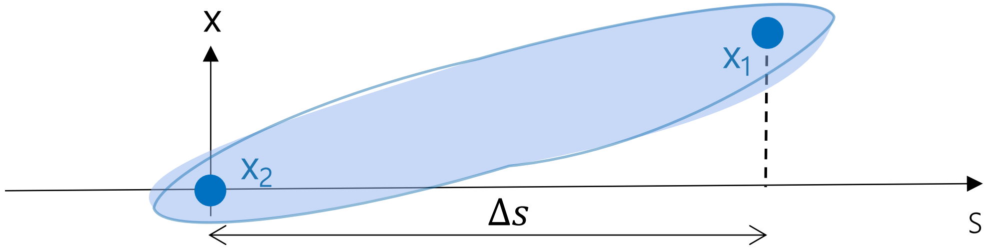
X. BUFFAT CERN– EPFL Thesis 2015

Circulant Matrix Model (CMM) for wakefields

Use linear algebra on a one turn matrix that represents a system, applied on discretized longitudinal phase space

Transverse wake kick

$$\begin{cases} \Delta y_2' = \overrightarrow{\mathscr{W}}_{dip,y}(\Delta s)\,\overrightarrow{y_1} + \overrightarrow{\mathscr{W}}_{quad,y}(\Delta s)\,\overrightarrow{y_2} \\ \Delta x_2' = \overrightarrow{\mathscr{W}}_{dip,x}(\Delta s)\,\overrightarrow{x_1} + \overrightarrow{\mathscr{W}}_{quad,x}(\Delta s)\,\overrightarrow{x_2} \end{cases}$$

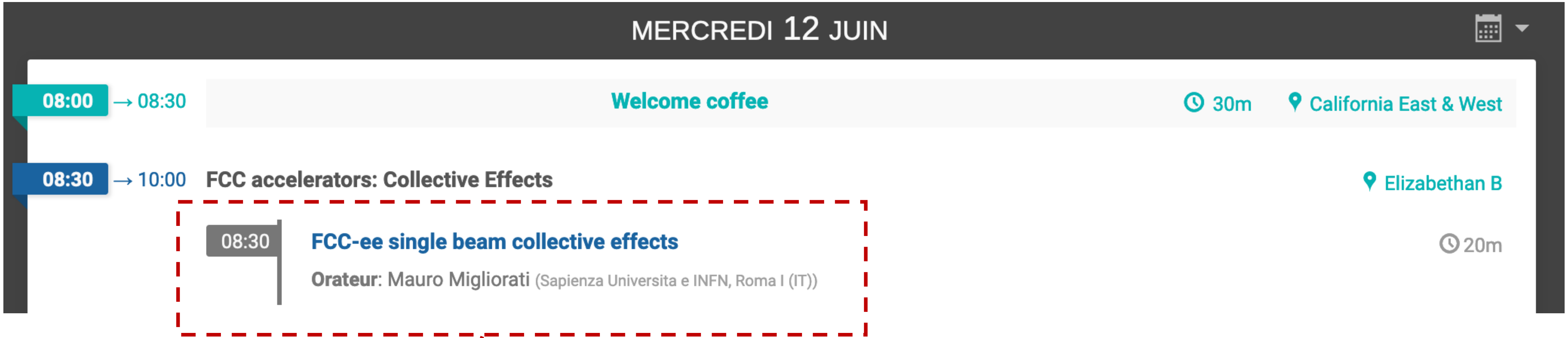


$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \overrightarrow{\mathscr{W}}_{dip,x}(\Delta s) & 0 & \overrightarrow{\mathscr{W}}_{quad,x}(\Delta s) & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \\ x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} x_1 \\ x_1' \\ x_2 \\ \overrightarrow{\mathscr{W}}_{dip,x}(\Delta s)\,\overrightarrow{x_1} + \overrightarrow{\mathscr{W}}_{quad,x}(\Delta s)\,\overrightarrow{x_2} \end{pmatrix}$$

Matrix elements example

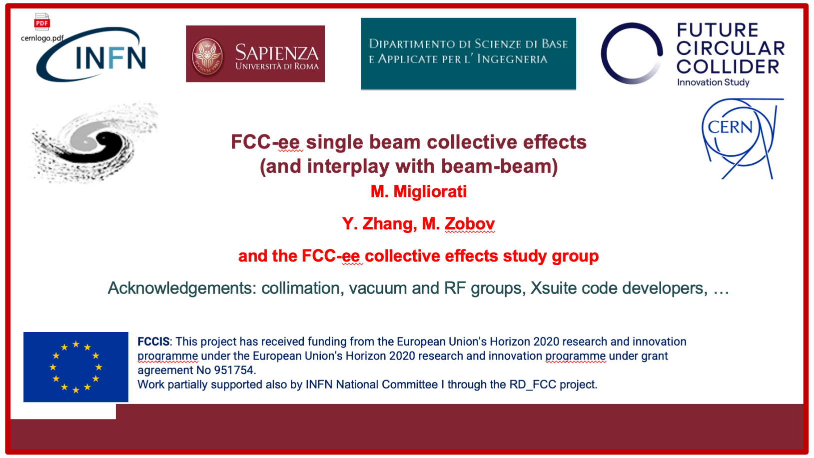
X. BUFFAT CERN– EPFL Thesis 2015

Circulant Matrix Model (CMM) for wakefields



MERCREDI 12 JUIN

08:00 → 08:30	**Welcome coffee**	30m	California East & West
08:30 → 10:00	**FCC accelerators: Collective Effects**		Elizabethan B
08:30	**FCC-ee single beam collective effects** **Orateur:** Mauro Migliorati (Sapienza Universita e INFN, Roma I (IT))	20m	



FCC-ee single beam collective effects
(and interplay with beam-beam)
M. Migliorati

Y. Zhang, M. Zobov

and the FCC-ee collective effects study group

Acknowledgements: collimation, vacuum and RF groups, Xsuite code developers, …

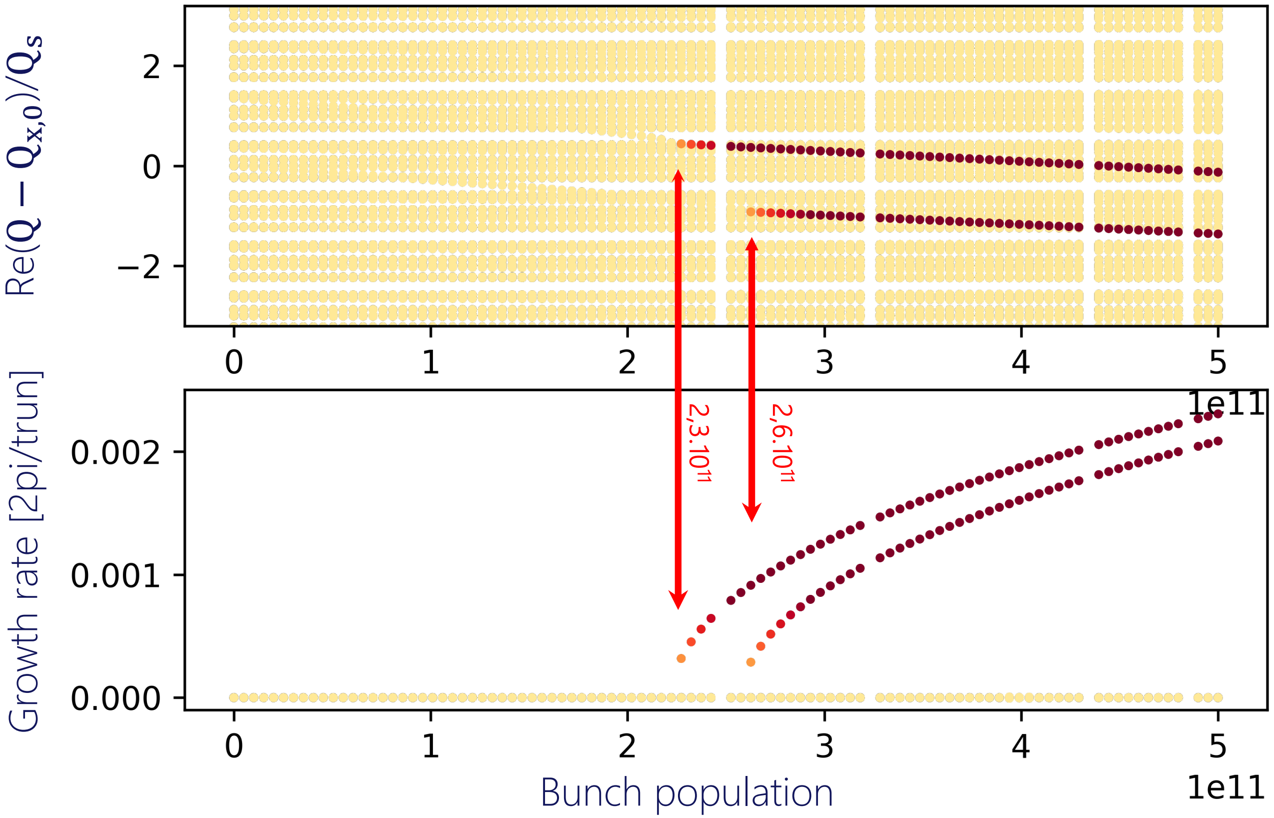
FCCIS: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.
Work partially supported also by INFN National Committee I through the RD_FCC project.

Talk earlier this morning on the effects of wakefields in FCC-ee, and mitigation techniques.

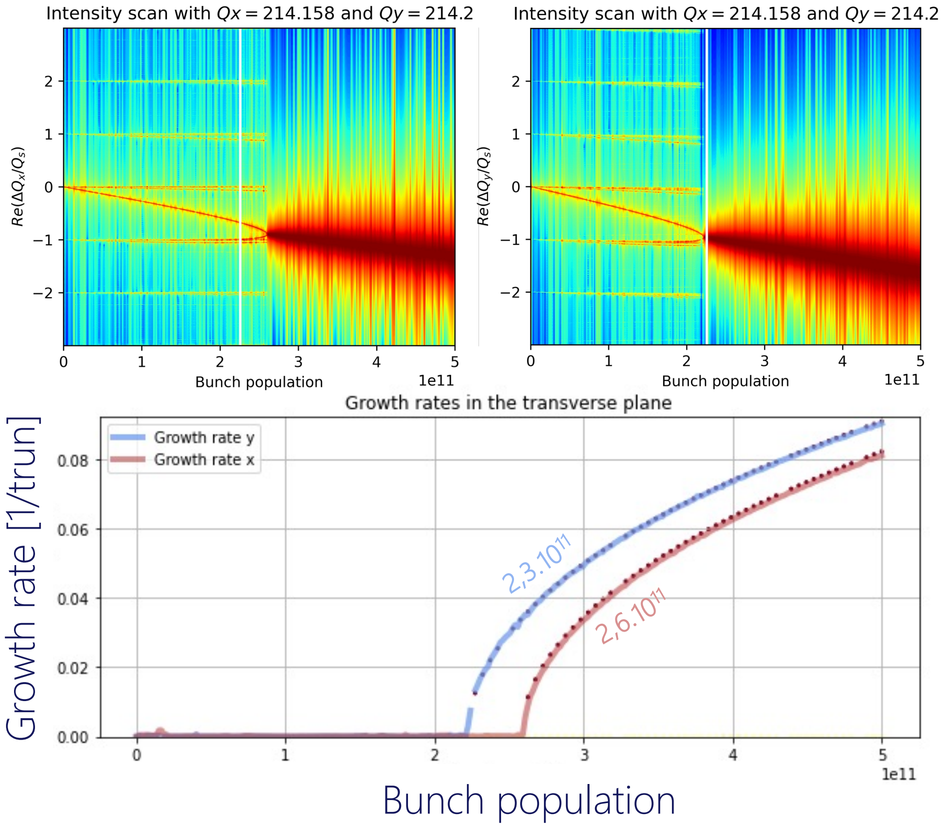
Transverse mode coupling instability simulations

Transverse wakefields for FCC-ee at Z energy; **perfect agreement!**

Intensity scan with CMM



Intensity scan with Xsuite - PyHT



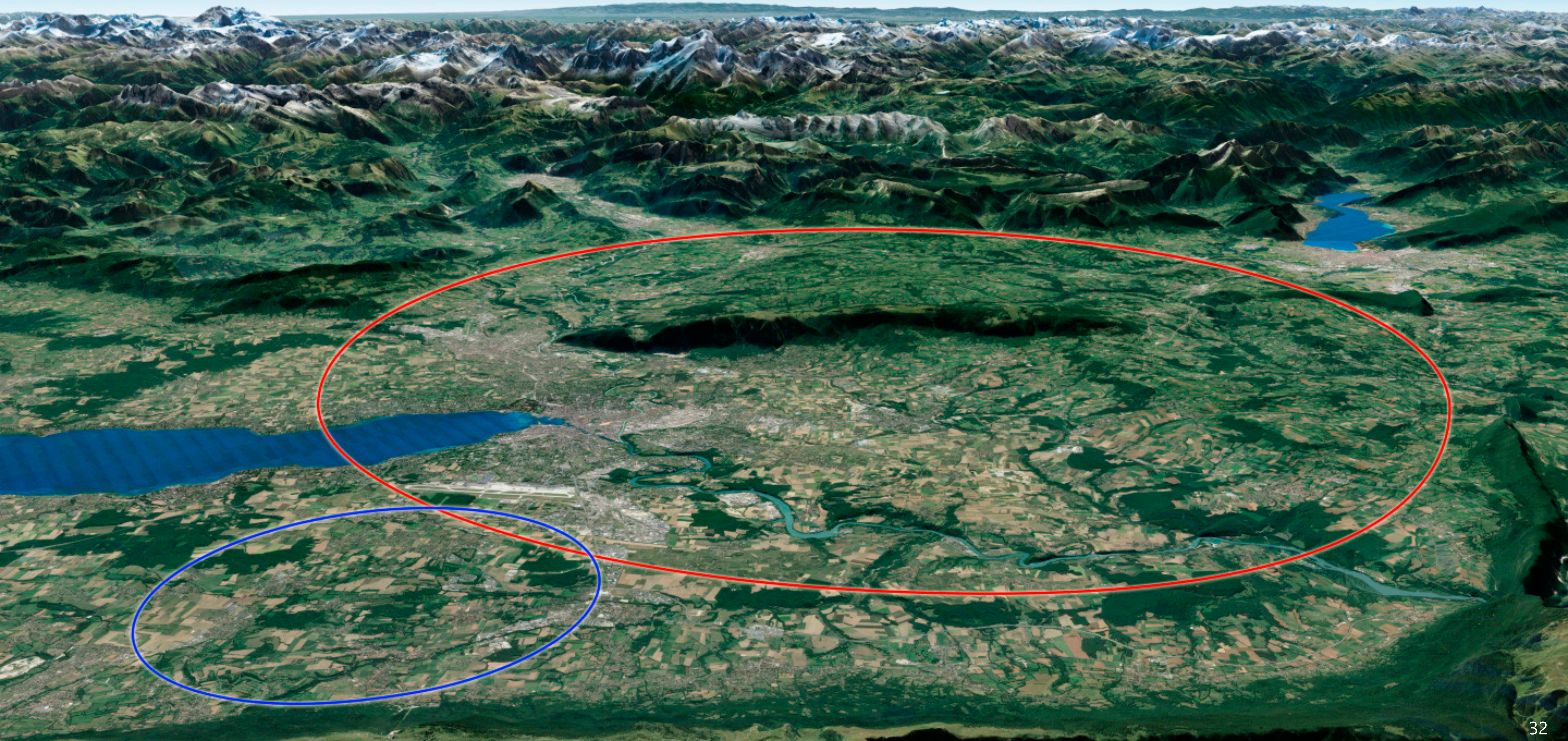
Bunch length without beamstrahlung (5.2mm), L = 90.66 km , linearized RF, no longitudinal wakes.

Summary and outlook

- The circulant matrix model (CMM) has successfully been tested for simple cases of flat beam collisions, x and y planes can be studied separately, but coupled forces can also be calculated.
- Alternative methods shall be considered to assess higher order collective resonances.

- CMM has shown perfect agreement for simulations involving transverse wakefields.
- Synchrotron frequency spread due to longitudinal wakefields could be implemented and studied within the CMM.

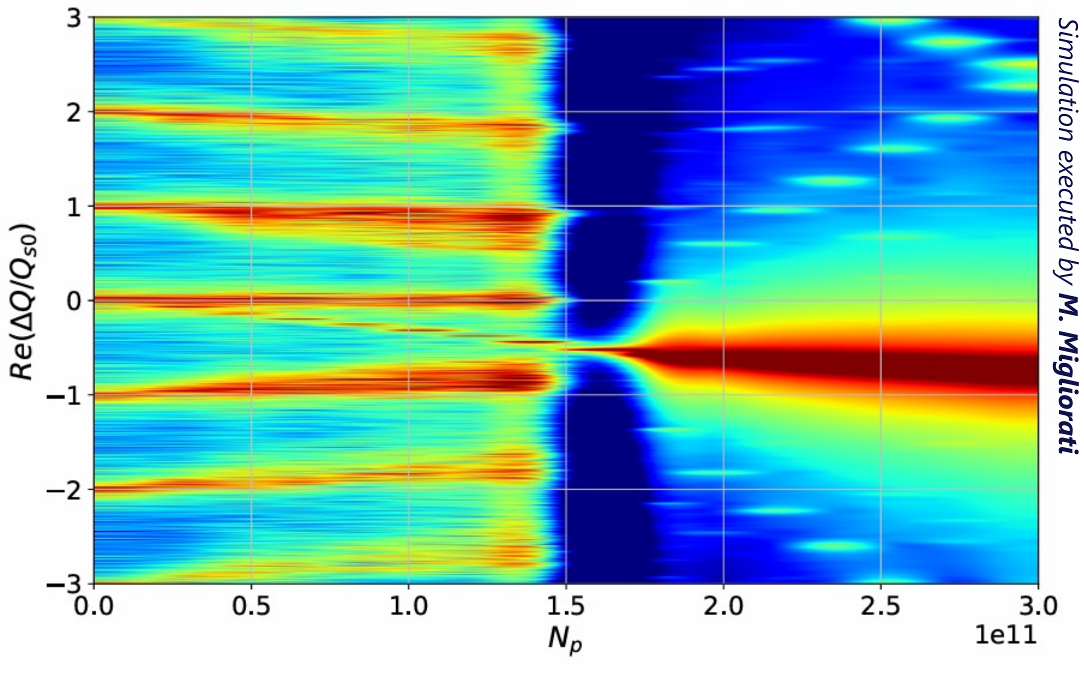
- Studies with a crossing angle and Crab waist are ongoing, with both the CMM and Xsuite, a correct setup is yet to be done with strong-strong simulations.
- Once the setup is totally controlled, reliable simulation with both beam beam and wakefields can be obtained with both Xsuite and CMM. Then can be compared to previous simulations [Y. Zhang, K. Ohmi]



Thank you!

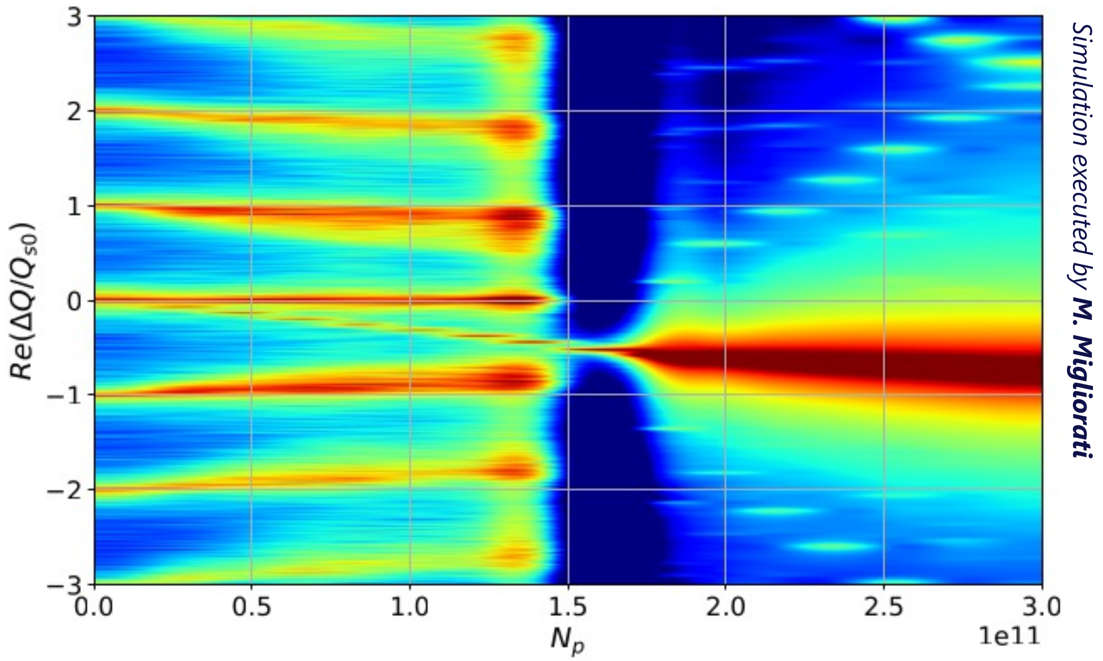
BACKUP

Xsuite - PyHT



Simulation executed by ***M. Migliorati***

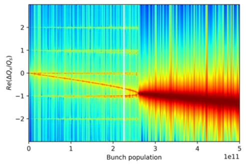
PyHEADTAIL



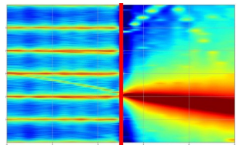
Simulation executed by ***M. Migliorati***

Perfect agreement (Radio frequency cavities and synchrotron radiation + wakes for FCC-ee Z).

Sum of the Fourier transforms of the higher order momentas.



$$\mathcal{F}\left[m_{0,t}\right] = < x >$$



$$\sum_{j=0}^{10} \mathcal{F}\left[m_{j,t}\right]$$

Momentum of order k at a turn t

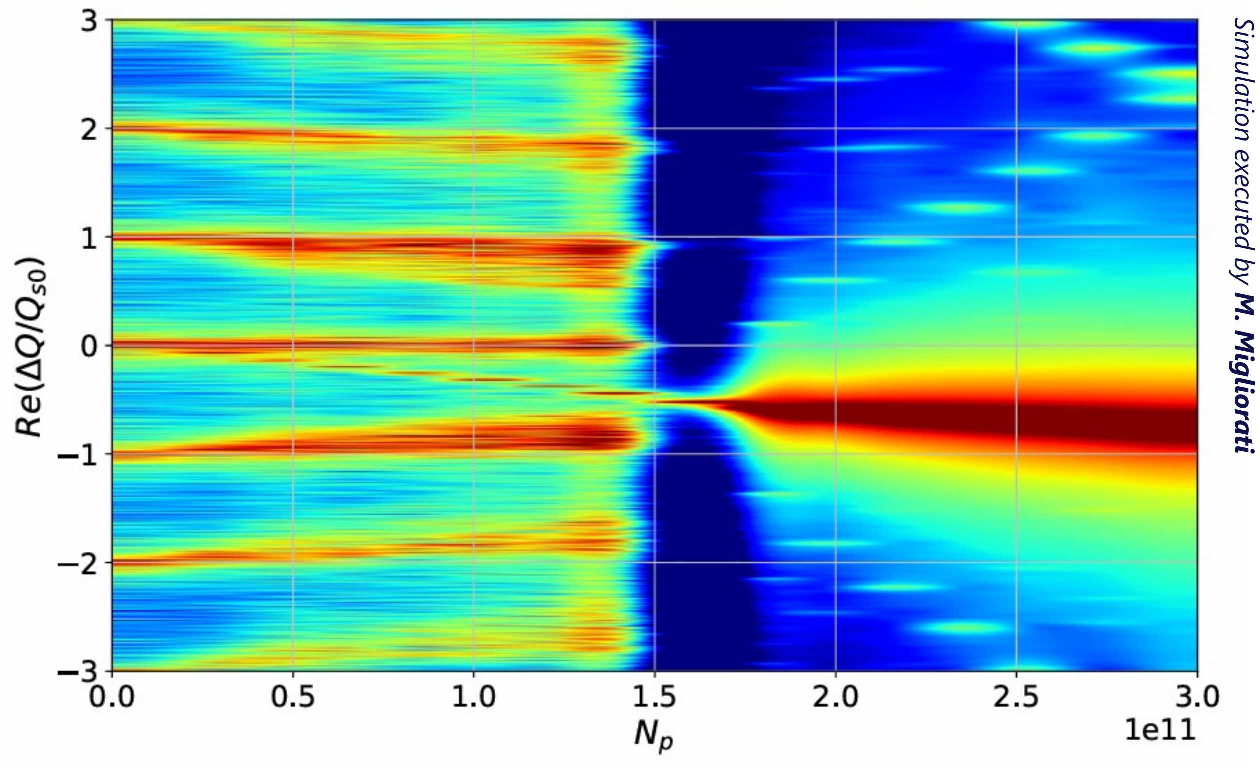
Average on the macroparticles

Horizontal positions

Longitudinal positions relative to the bunch

$$m_{k,t} = \frac{1}{N}\sum_{i=0}^{N-1} x_{i,t} \times \left(z_{i,t} - \bar{z}_{i,t}\right)^k$$

BACKUP



Simulation executed by ***M. Migliorati***

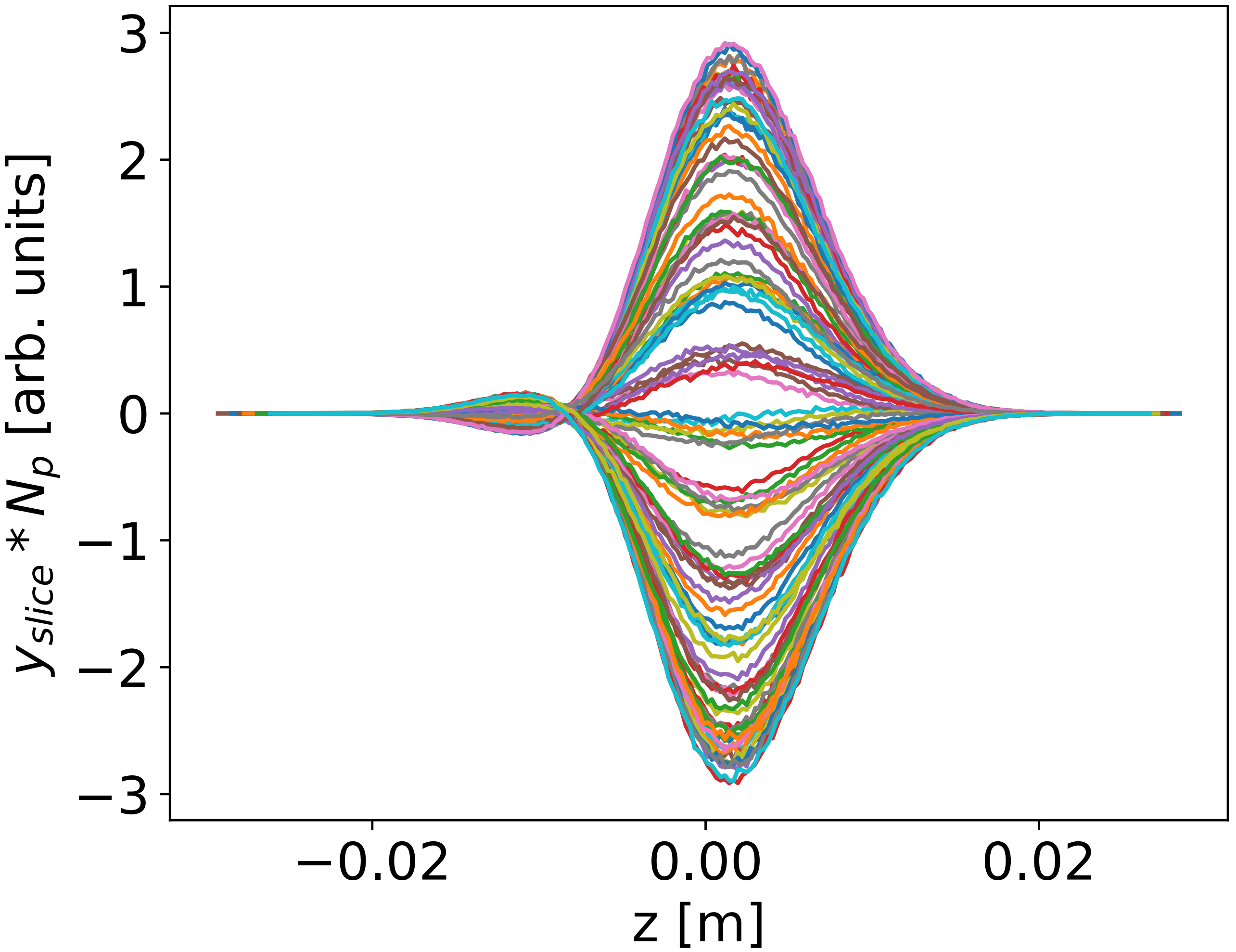
NO geometrical contribution of the collimators

Resisitive wall (Beam pipe + collimator RW)

RF Cavities *Beam Position Monitors (BPM)* *Bellows*

BACKUP

Slice analysis possible with Xsuite.



Simulation executed by ***M. Migliorati***

BACKUP

Computational cost:

Fully numerical method

$\mathcal{O}\left(n^3\right)$ *1000 pts ~6h*

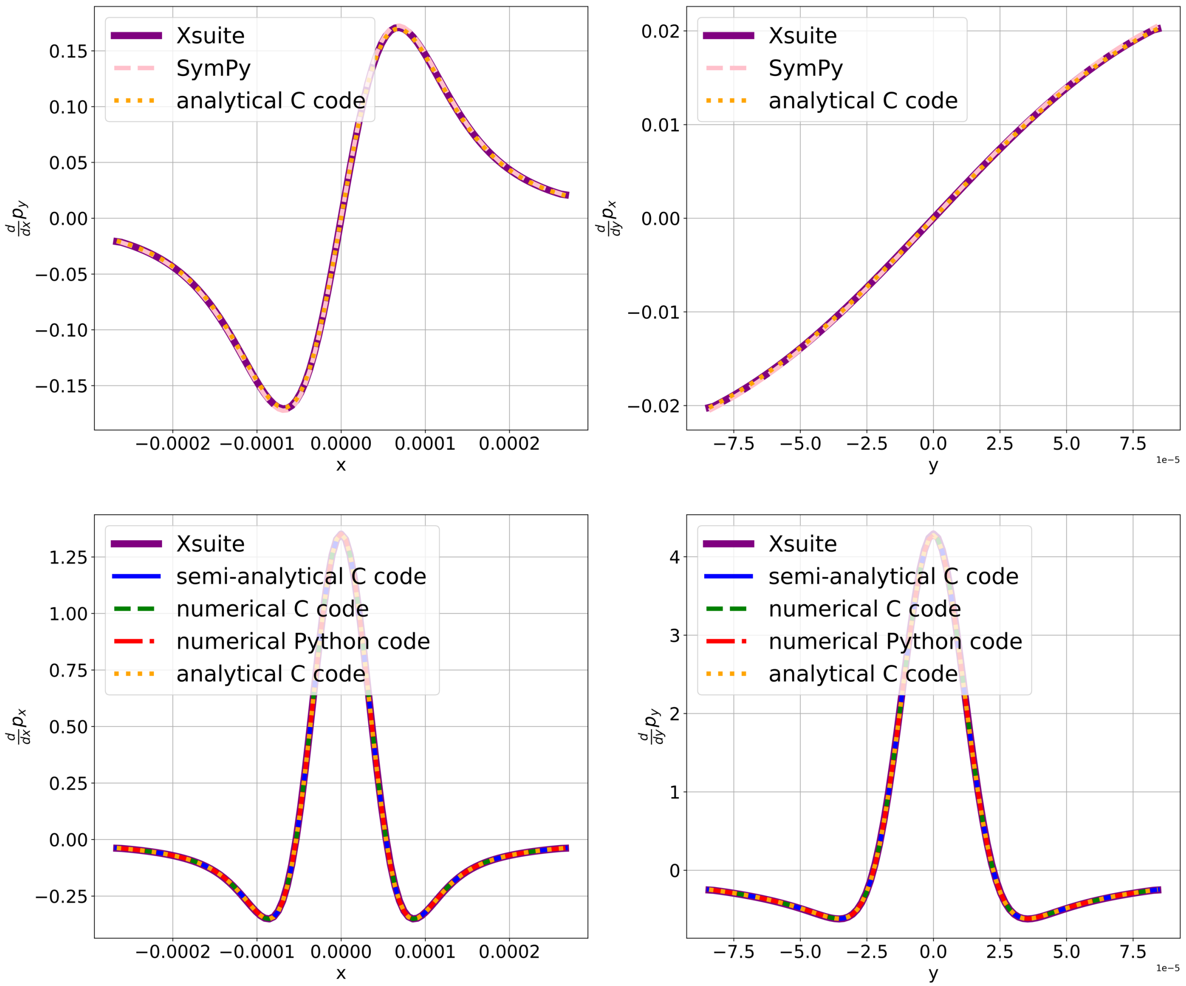
Dependent on numerical values

Fully analytical model

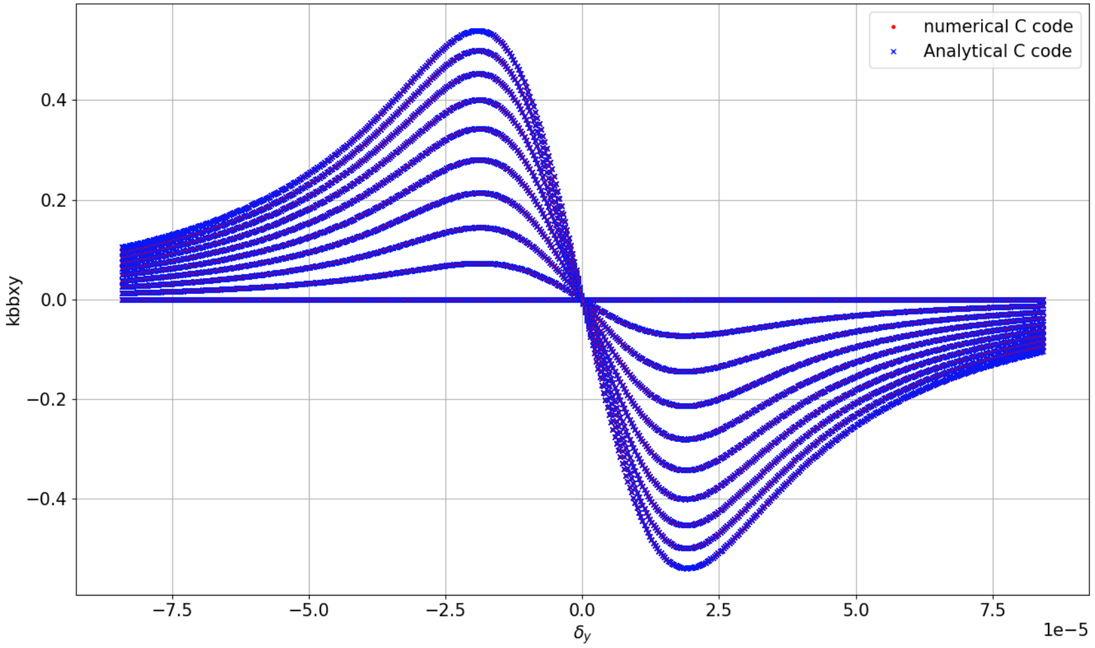
$\mathcal{O}\left(n\right)$ *~ 5µs*

Independent of numerical values

Linearized coherent kick benchmark



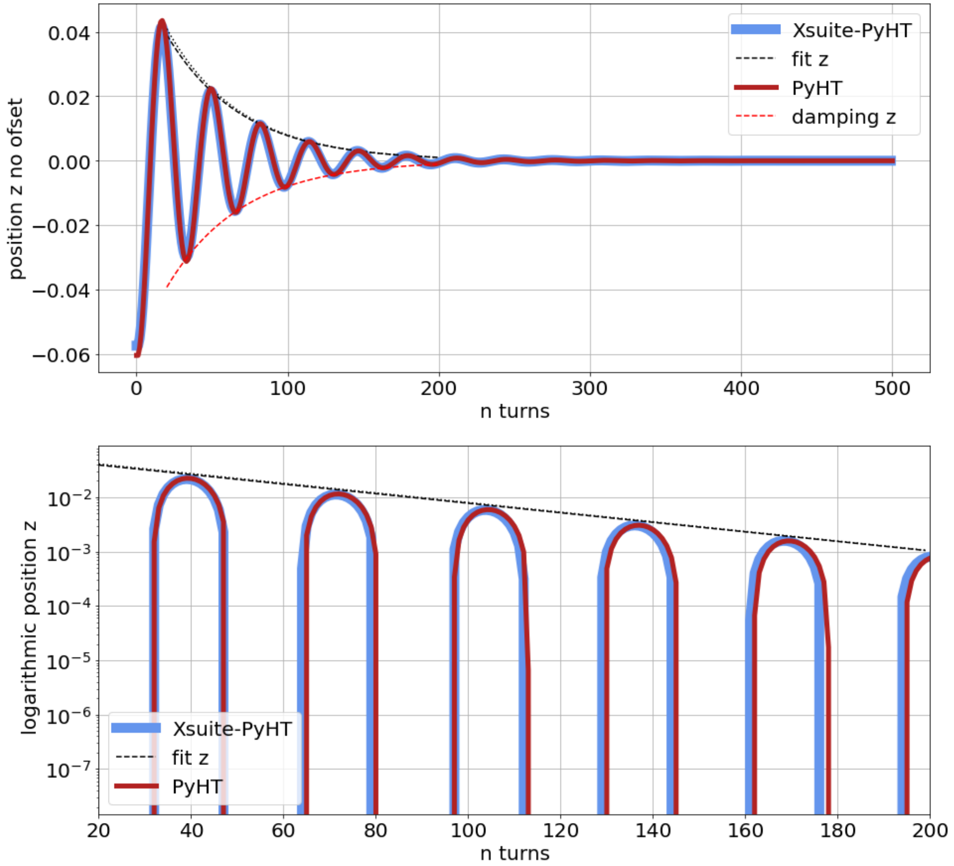
Coupled force at different aspect ratios



BACKUP

Test damping times

Linear map, SR ($E_{loss} = 0$), no wakes, same inital distribution



PERFECT OVERLAP / EXPECTED VALUES

Test equilibrium emittances

Linear map, SR ($E_{loss} = 0$), no wakes, same inital distribution