AN FCC-EE VIBRATIONS STUDY FOR ITS MDI

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Outline

Introduction and Context

- Our aims
- Interactions between beam physics and mechanical studies

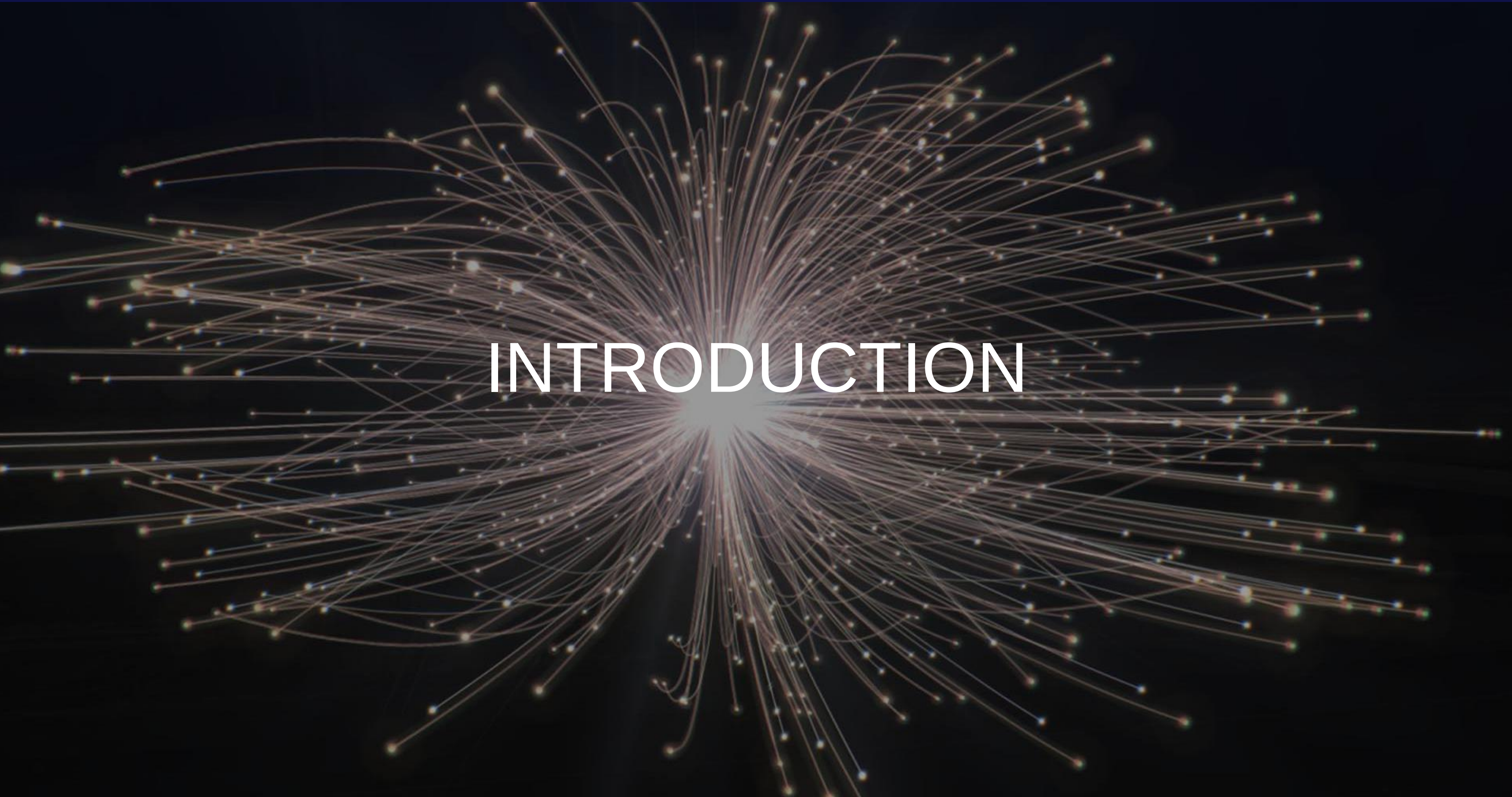
Mechanical studies: amplification of ground motion by the mechanical structure

Physics studies: a study of the ground vibrations

- Simulation strategy
- Comparison with the analytical model
- A focus on the MDI region
- A specific use of the analytical model for the MDI region

Conclusions and Perspectives

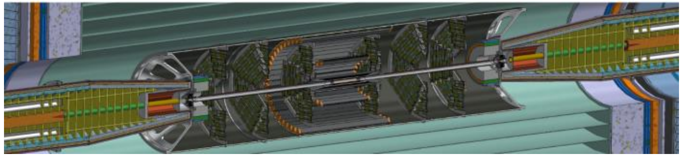
INTRODUCTION



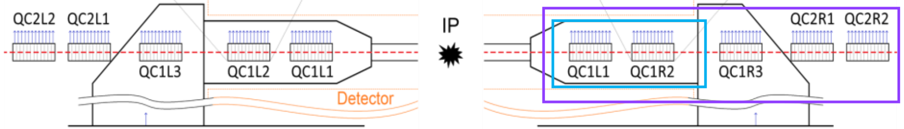
Why studying vibrations in the MDI of FCC-ee?

Aims:

- Guarantee a stable collision at the 4 Interaction Points
- Measure the impact of vibrations on luminosity and beam parameters

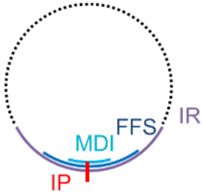


3D plan ongoing (F. Fransesini, M. Boscolo et al.)



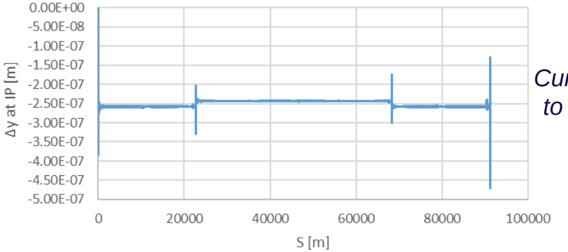
MDI schematics

In a collider:
IR : Interaction Region
FFS : Final Focus System
MDI : Machine-Detector Interface
IP : Interaction Point



Main constraint: nanometer beam size in the vertical plane

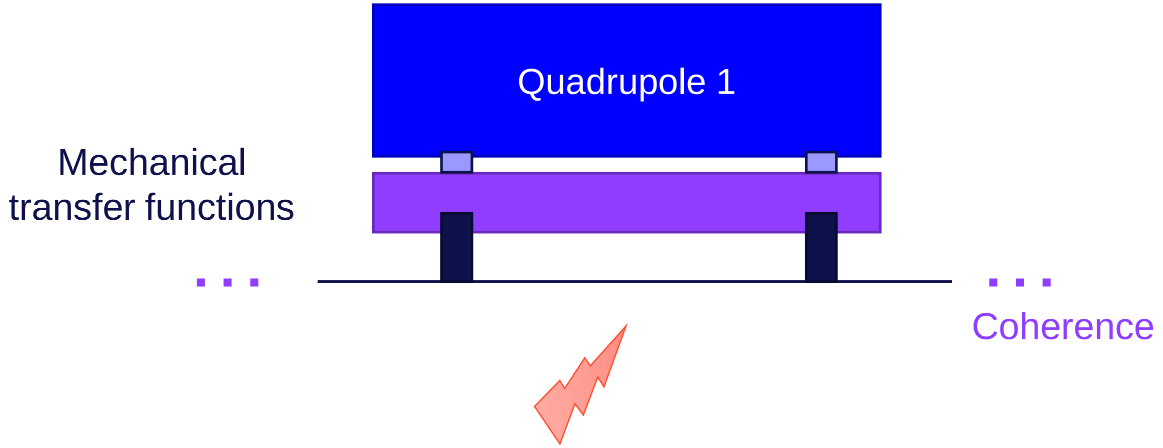
- Quadripoles in the MDI (even IR) with a very high magnetic field gradient



Cumulative vertical contribution to the IP.8 of the quadrupoles along FCC-ee

Some definitions

Vibration:
- ground motion amplified by the mechanical structure
- vary with time

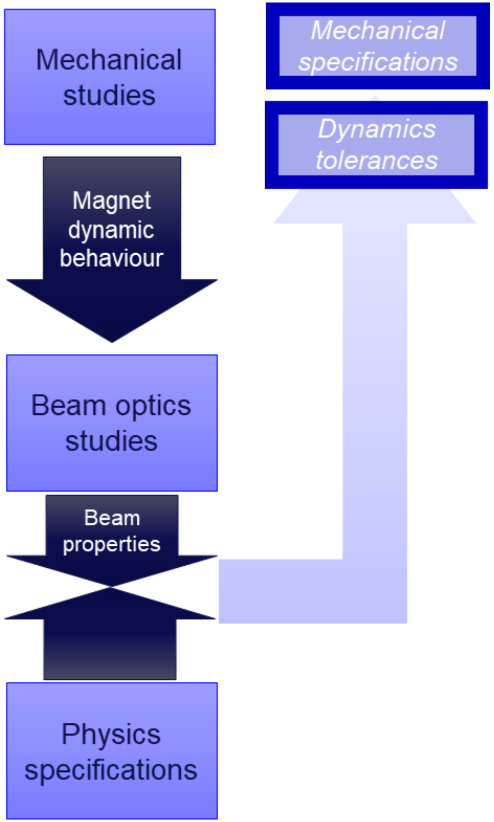


Ground motion excitation, based on Plane Ground Waves
+ cultural noise, environment dependent

3 pillars in vibrations studies:

- Alignment
- Vibration
- Coherence

Interactions between mechanics and beam physics



Aims: Define vibrations tolerances of magnets in the MDI

Two major contributions:

- Implementation of a **mechanical model** considering the mechanical behaviour (transfer functions) of each magnet
- **Physics simulations** (beam optics) to evaluate the impact of misalignments of these magnets

Iterative work:

- The result of the mechanical study will give input parameters for the physics study, and vice-versa.

Mechanical studies

Mechanical design of the MDI ongoing

+

Access to SuperKEKB data, as vibrations sensors placed on the cryostat and the ground, near the Interaction Point

↓

Evaluation of the resonance modes of the cryostat

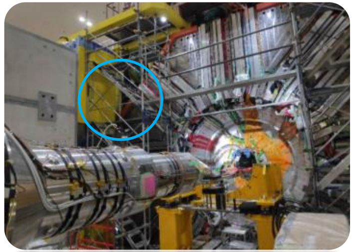
↓

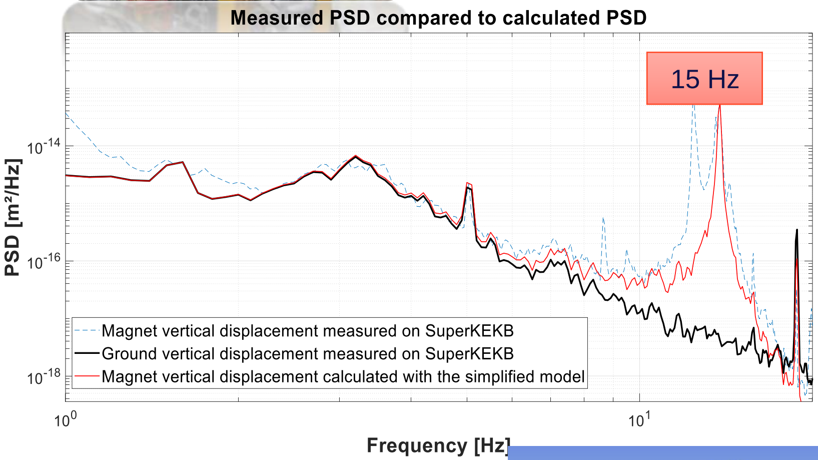
Design of a simplified mechanical model

↓

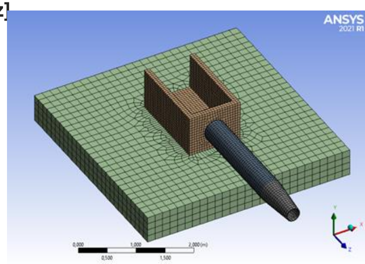
File containing, at MAD-X sampling frequency, the vertical displacements and rotations of the two quadrupoles embedded in the cryostat relative to time (⇔ accelerator turn)

⇨ MAD-X Tracking



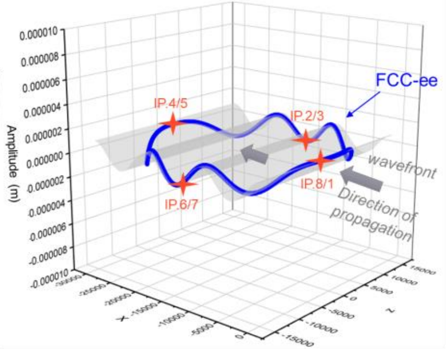


Ground motion **amplified** by the **mechanical structure**



Physics studies

Ground motion excitation **without** amplification of the mechanical structure (transfer functions = 1)



Schematics of the plane ground wave impacting FCC-ee

Plane Ground Wave model:

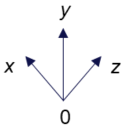
- Vertical misalignment attributed to each beam element *j* along the accelerator ring, in terms of harmonic number, to be fully independent from the wave velocity:

$$\varepsilon(j) = A\sin\left(\frac{2\pi h}{C}(X(j)\times\cos(\alpha) - Z(j)\times\sin(\alpha)) + \varphi\right)$$

A: amplitude of oscillation
h: harmonic number $h = \frac{Cf}{v_{wave}}$
C: circumference of FCC-ee
α: wavefront tilt angle
φ: phasing advance

In the study, f varies and:

$A_0 = 5.10^{-7}$ m
C = 91172 m
$\alpha_0 = 0$ rad
$\varphi_0 = \pi/2$ rad



N.B.: (0, 0, 0) is taken as IP.8/1.

Pros and cons of this study

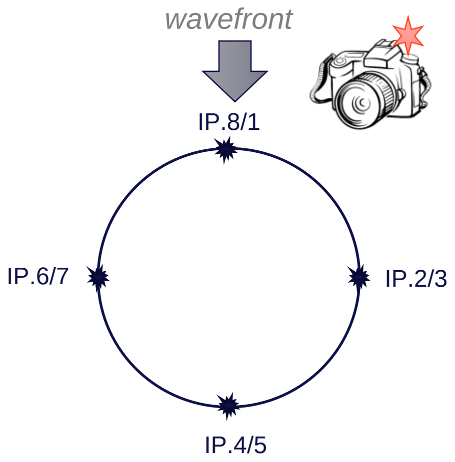
Benefits:

- Study the impact of ground-motion induced vibrations on the whole accelerator
  - With a special highlight put on the MDI area
- Simulate spatial coherence along the ring to quantify the impact on FCC-ee performances
  - So far, impact of these waves never estimated for FCC-ee
- Comparison to SPS, LEP, LHC and HL-LHC possible thanks to previous works
- Help to design building constraints (magnets, supports, hall)

Limitations :

- Beam made out of only one particle, placed on the ideal closed orbit
- Only one beam considered: no beam-beam effect introduced in the simulations
- No multi-turn tracking
- No local nor global correction, as starting from a perfectly aligned lattice
- Sinusoidal plane ground wave

Simulations procedure



Computer tools:

- Optics simulations carried out with MAD-X (5.09.00)
- Post-treatment held with Python, thanks to cpymad module (3.6.9)

Optics-related matters:

- Z lattice (V22)
- Start of the sequence at IP.1

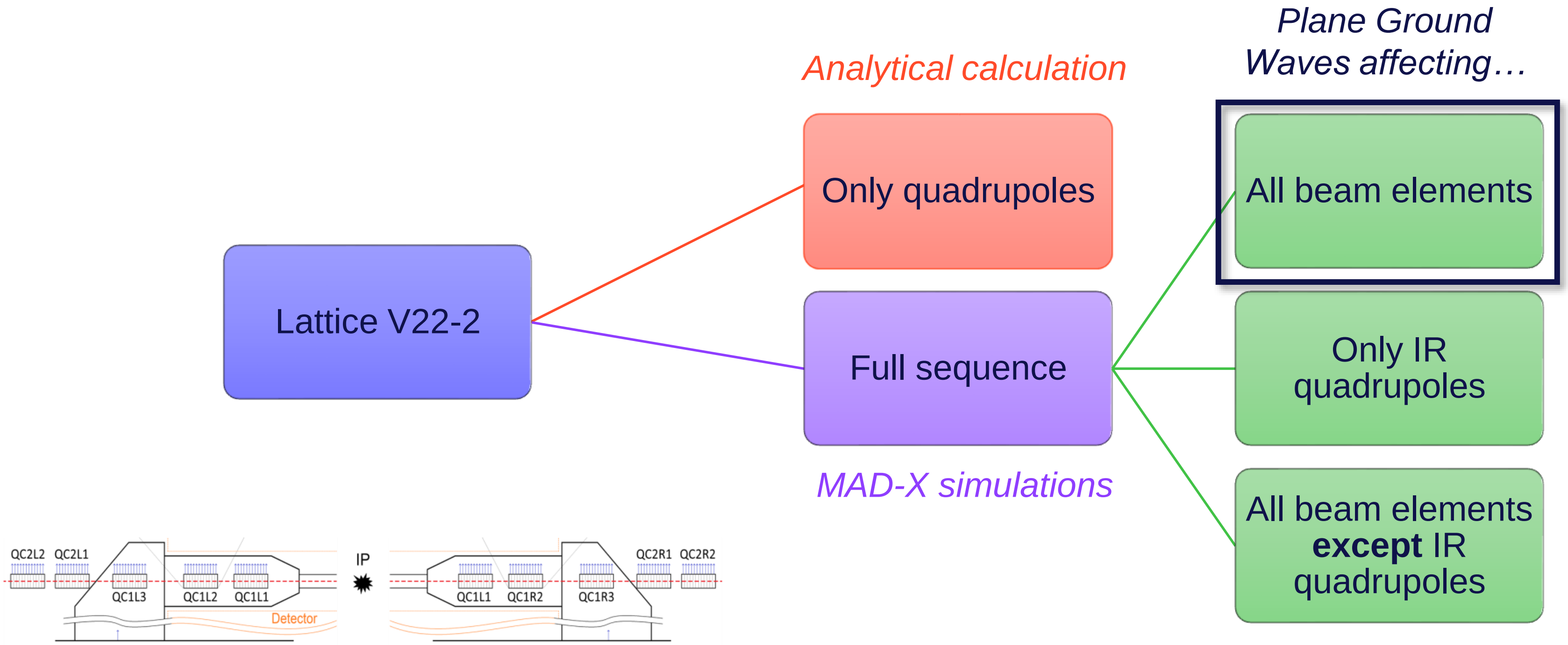
Process:

Photography of the accelerator, completely misaligned by the wave ⇒ No temporal study

TWISS of the nominal sequence → Assigning vertical displacements of all elements relative to plane ground wave → Evaluation of the vertical position of the orbit referred to the ideal orbit: yco

STRATEGY OF THE WORK

Strategy of our work



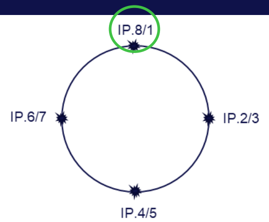
- 5 quadrupoles at each IP side
- 4 IPs

} 40 IR quadrupoles

SIMULATIONS RESULTS

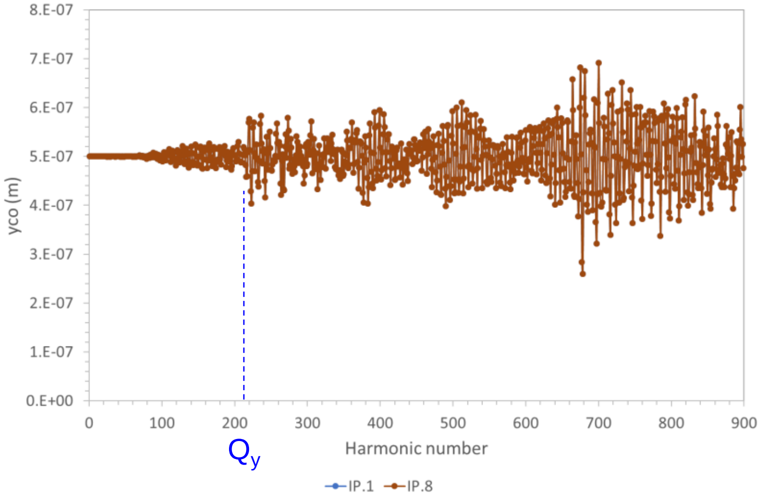
How does yco at the distinct IPs look like relative to the harmonic number?

All beam elements affected by the Plane Ground Wave model



$$\varepsilon(j) = A\sin\left(\frac{2\pi h}{C}(X(j) \times \cos(\alpha) - Z(j) \times \sin(\alpha)) + \varphi\right)$$

- Yco is evaluated at IP.8, equivalent to IP.1 after one accelerator turn.
- Yco at IP.8 is made out of resonance nodes and antinodes with:
  - a baseline at y = A = 0.5 µm
  - a first oscillation at h = $Q_y \approx 214$
  - a maximum amplitude of 0.7 µm



Study **dependent** of the **wavefront** location and inclination angle, as considered in the equation
The work here focuses on yco @ IP.8.

COMPARISON TO THE ANALYTICAL MODEL

Definitions of the analytical model

- The sequence used to solve analytically the Plane Ground Waves study **only** considers **quadrupoles** (1856 in total).

- Each misalignment of quadrupole ε generates a dipole kick δ :

$$\delta = kl\varepsilon$$

k_1: normal quadrupole coefficient (m^{-2})
l: effective length of the quadrupole (m)

- The ith dipole kick creates a vertical perturbation yco_i of the closed orbit:

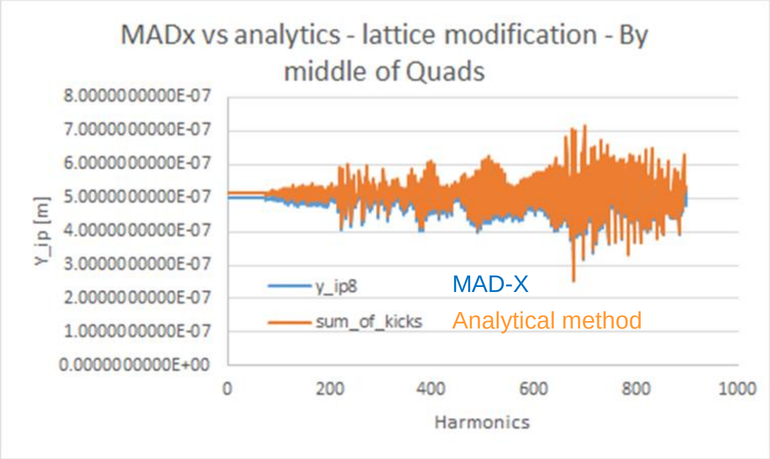
$$yco_i = -\sum_{j=0}^{n} \frac{\sqrt{\beta_i \beta_j}}{2sin(\pi Q_y)} cos(\pi Q_y - 2\pi\Delta\mu_{ij}) \times \delta_j$$

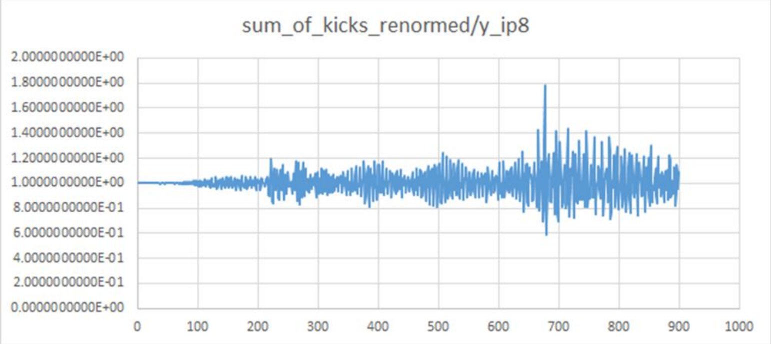
Comparison between MAD-X and the analytical method

- The two methods are **very consistent**.
- The first oscillation at h=214 corresponds to the FCC-ee vertical tune.
- There is a small **offset**:
  - At h = 1: 2,8 % of difference
  - Offset not constant relative to h

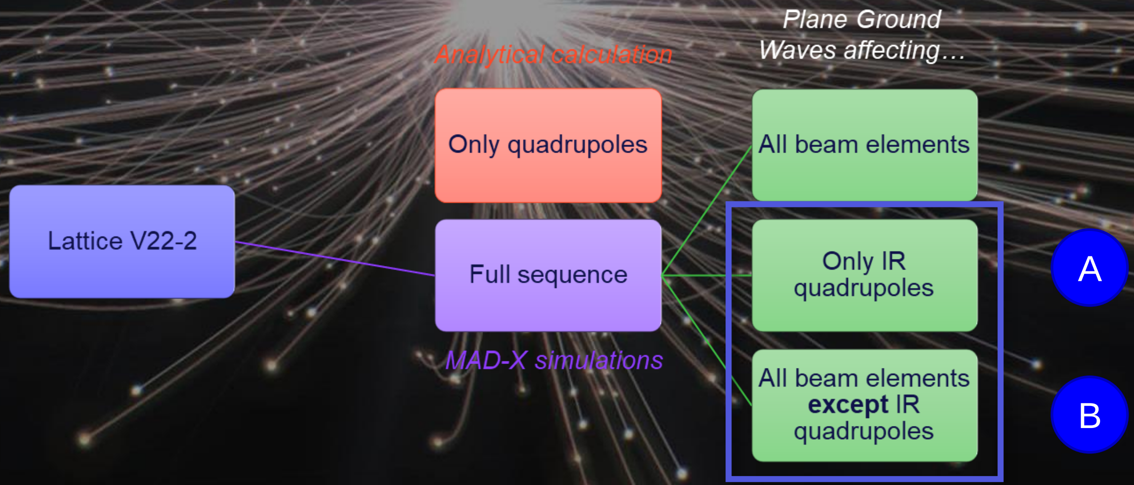
➡ Slight difference of **definitions**

- β functions used in the analytical method are defined at the centre of each quadrupole, and thus are higher than defined at the exit of the beam elements (MAD-X)
- It has been checked that other beam elements than quadrupoles do not contribute to this offset





HIGHLIGHT ON IR QUADRUPOLES



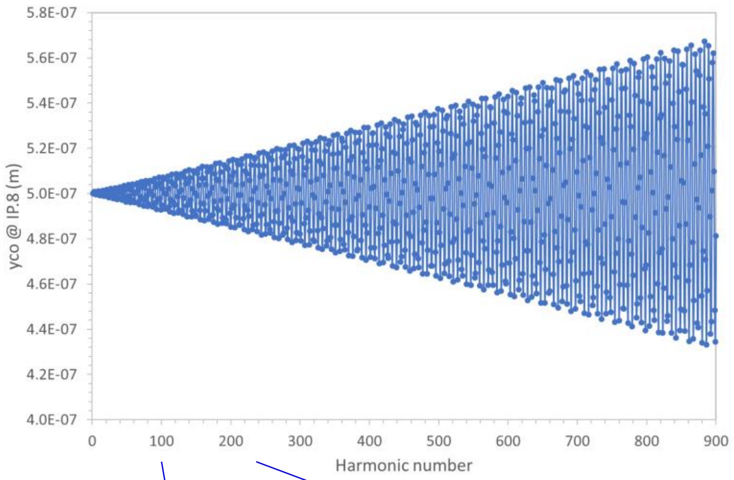
Case A:

If only IR quadrupoles were affected by the wave

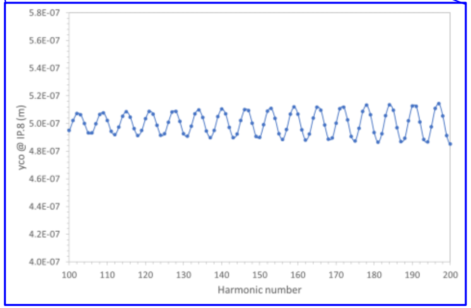
Definition of IR quadrupoles:

- 5 quadrupoles at each IP side
- 4 IPs

} 40 quadrupoles



- Yco at IP.8 has the following parameters:
  - Baseline at y = A = 0.5 µm
  - Periodic structure relative to h: $T_{yco} = 7\ [h]$
  - No specific contribution at h = Q_y



➡ **Linear contribution** of IR quadrupoles

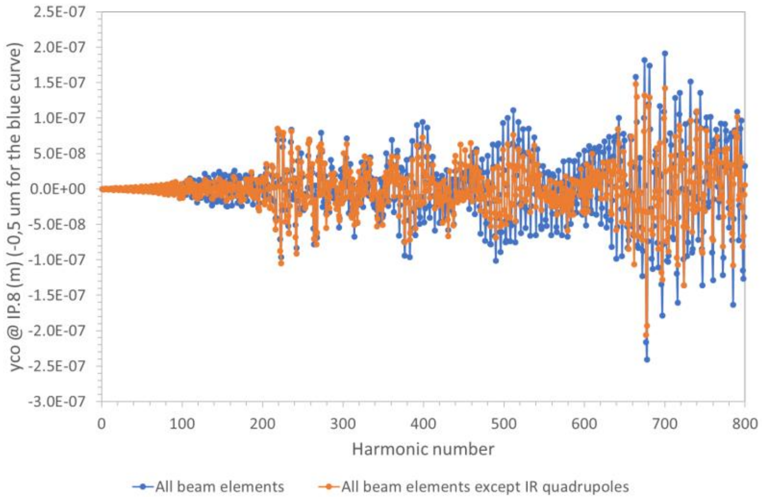
Case B:

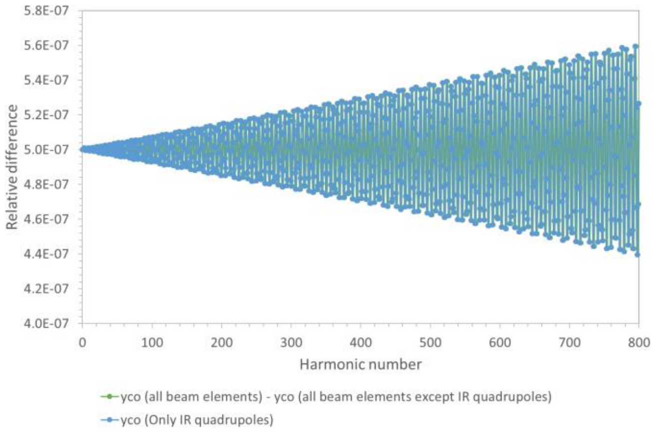
If all beam elements except IR quadrupoles were affected by the wave

- Yco @ IP.8 is similar to the case where all beam elements are impacted by the wave:
  - Correction by the maximum amplitude of the wave
  - Contribution of IR quadrupoles is the difference between the two plots *(green plot)*

- **Exact same values** as in the case where only IR quadrupoles are affected by the wave

➡ Estimate of **spatial coherence** (wavelengths longer than the MDI total length), not a study of vibrations impact





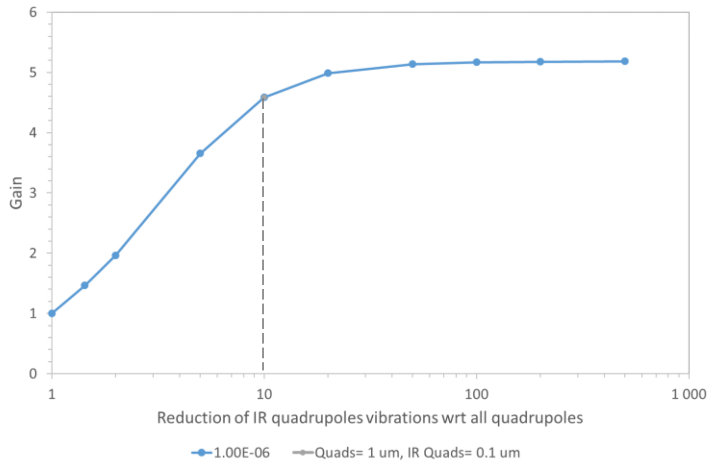
To go beyond the Plane Ground Wave model

- No plane wave in this case!
- Analytical method: $yco_i = -\sum_{j=0}^{n} \frac{\sqrt{\beta_i \beta_j}}{2sin(\pi Q)} cos(\pi Q - 2\pi\Delta\mu_{ij}) \times \delta_j$
- “Vibrations” model:
  - Random vertical displacements of the quadrupoles, following a gaussian distribution
  - 1000 seeds

$Gain = \frac{\sigma_{y_{0\_mdi}}}{\sigma_{y_{0\_all}}}$

$\sigma_{y_{0\_mdi}}$ Corresponds to the std of the vertical position of the beam at IP8 when the IR quads vibrate less (by a reduction factor)

$\sigma_{y_{0\_all}}$ Corresponds to the std of the vertical position of the beam at IP8 when the vibration is the same for all quads (here taken as the reference) 1 µm



➡ If the “vibrations” in the IR region are reduced by a factor 10 compared to the rest of FCC-ee, the vertical closed orbit is ≈ **5 times closer** to the nominal one. It **tends** to this numerical value, even though the IR vibrations are lowered. In the case of QC1 vibrations (3 quadrupoles), the maximum gain is equal to 2.

➡ First answers given to a vibrations model regarding the **intrinsic optics** functions of FCC-ee (β functions)

CONCLUSIONS AND PERSPECTIVES

First conclusions and outlook

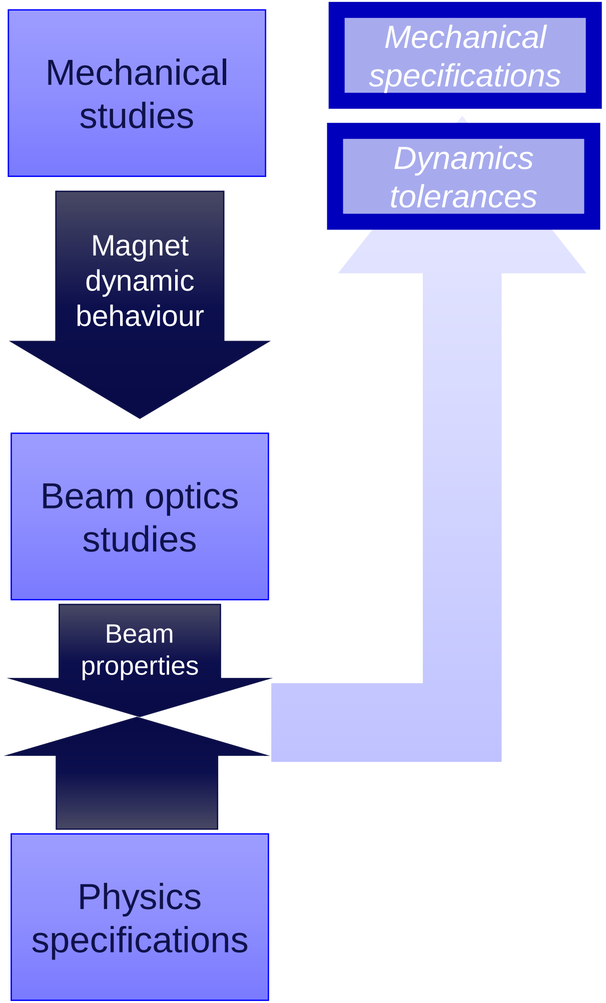
- Investigation of the effect of a plane ground wave on the whole FCC-ee accelerator
  - Photography of the misalignments taken, no tracking yet
- MAD-X simulations and the analytical method are giving the same results
  - Checks done to establish the reliability of the method
- The analytical method can be used as a fast scanner
- Flexible, adaptable and tunable methodology, to highlight:
  - The Machine Detector Interface,
  - But as well, other parts of the accelerator, such as the arc-cells

Perspectives:

- Parametric study to test the influence of all definition parameters (inclination, phase advance)
- Comparison with other FCC-ee lattices (V23, LCCO)
- Towards more realistic waves models:
  - Injection of coherence measurements made at other accelerators (SuperKEKB,…)
  - Wave speed(s) definition

Thank you for your attention!

APPENDICES


Mechanical studies
Mechanical specifications
Dynamics tolerances
Magnet dynamic behaviour
Beam optics studies
Beam properties
Physics specifications