Update on the vibration studies for FCCee: A naive simulation approach

The intention here is as much to trigger questions/comments as to start to gather information for the vibration simulation activities:

This is here a first exploration based on the work from the LAPP team and ongoing discussions!!!

F.Poirier

Work from: G.Balik, L.Brunetti, I.De Bonis, E.Montbarbon, A.Dominjon, M.Marchand, G. Lamanna, F.Poirier (LAPP)

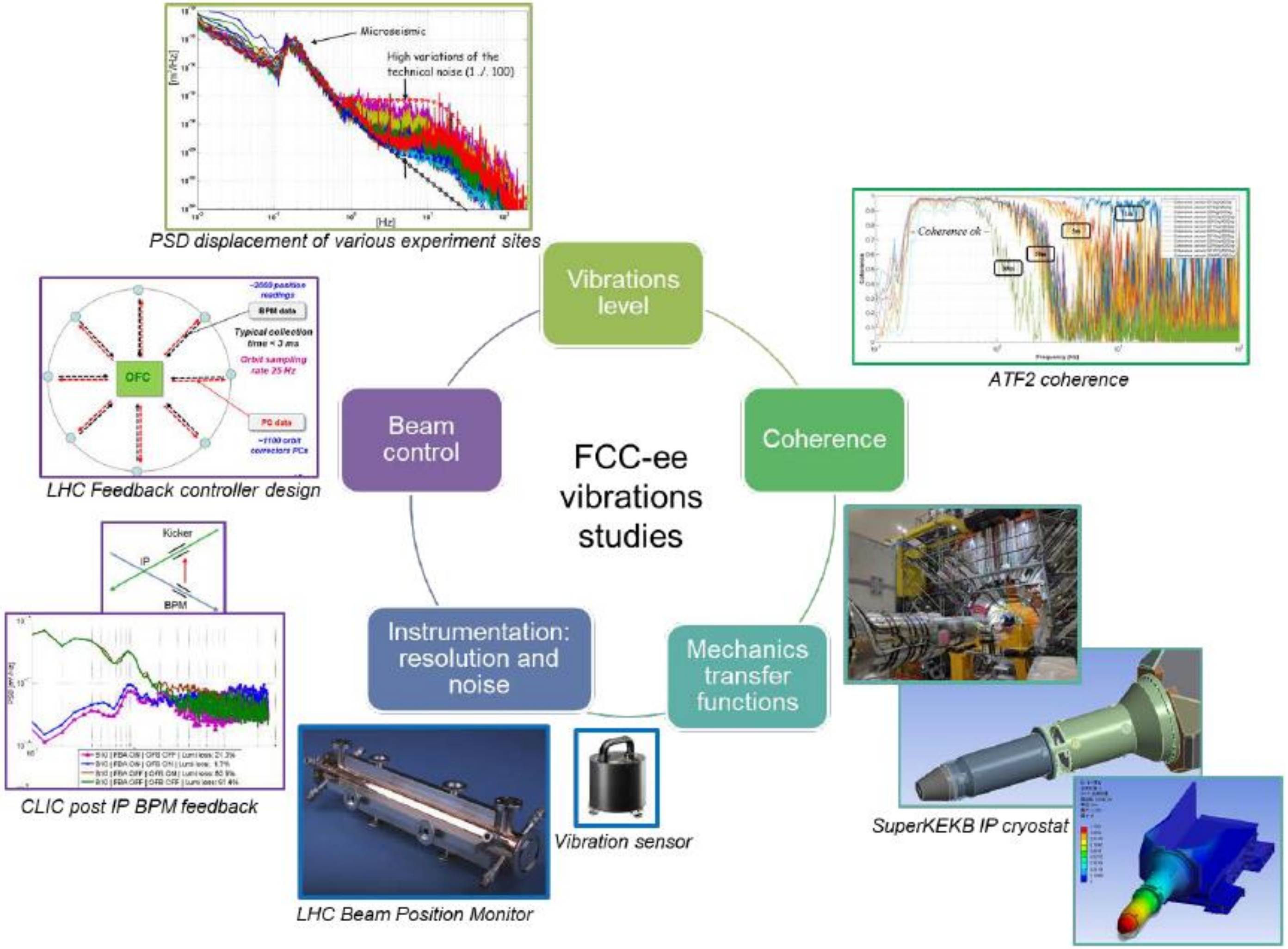
Discussion and exchange with G.Roy and J. Wenninger (CERN) + F.Carra, A.Piccini (CERN)

See also:
L.Brunetti, "LAPP activities: ground motion, vibration models, simulations, SuperKEKB", FCCIS Nov. 2023
E.Montbarbon, "An FCC-ee vibrations study for its MDI", FCC Physics workshop, Fev. 2024

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.'

LAPP Activities in relation to vibrations

- Global scheme of the work on vibrations effects on the beam and the related controls:

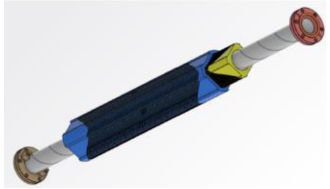


Implication of the LAPP:

- Vibrations (ground motion and mechanics)
- Instrumentation
- Control
- Beam parameters (position, emittance, luminosity)
- Simulations

It also means being (or trying to be) in contact with the experts spread over several international institutes

LAPP is also involved in the design and prototyping of the quadrupole at the IP as well as the beam pipe inside the cryostat (see M.Koratzino's talk)



LAPP: Laboratoire d'Annecy de Physique des particules

47 min south of CERN

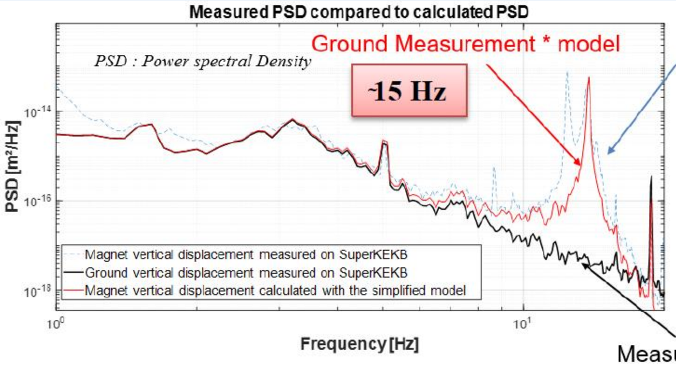
Vibration Measurements at SuperKeKB

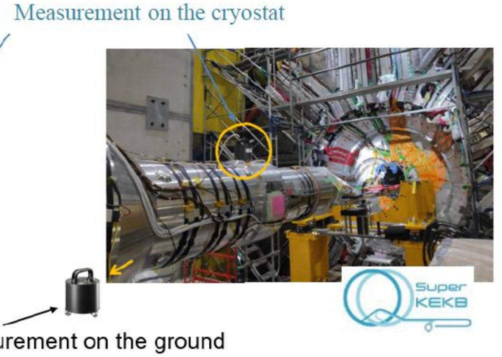
L.Brunetti, G.Balik et al.

- LAPP performs, in collaboration with M.Matsusawa et al (KEK)
- Measurements of Power Spectral Density

- Measurements in the MDI region.
- PSD of ground and cryostat
- Modelling of the local magnet (transfert function)

- Campaign of measurements with cryostat out

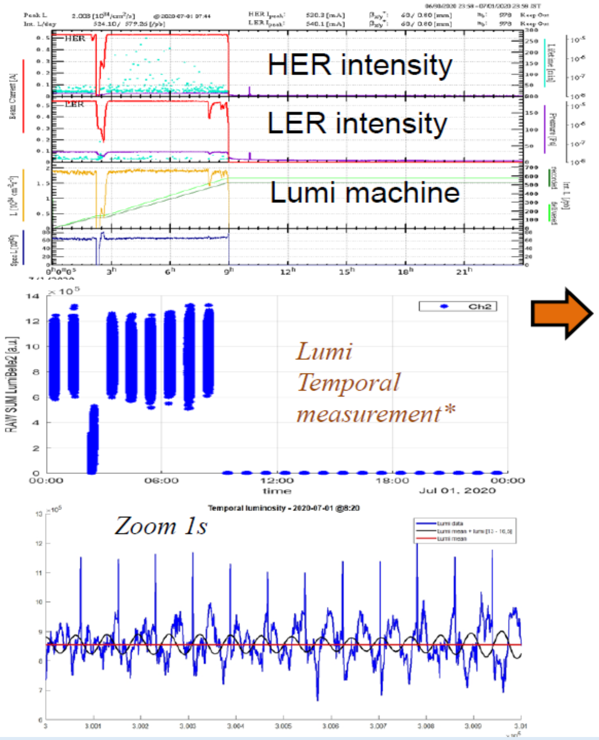




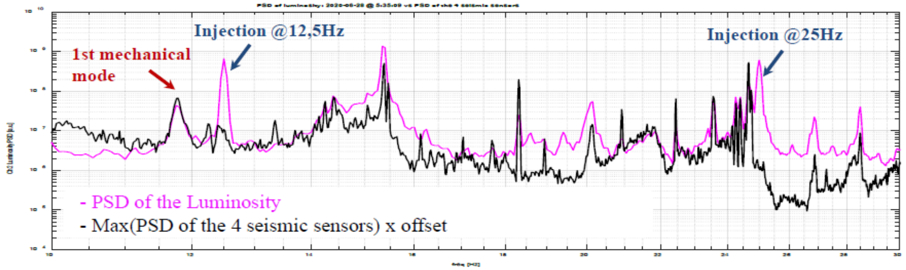
- Permanent vibration measurements (10min every hour)

Track change of vibration & put it in parallel to luminosity meas.

- **Comparison vibrations vs Luminosity monitoring via Bhabha scattering (IJCLab & KEK)**



*: The 4 permanent luminosity measurements are managed by the IJClab team: C. G. Pang et al., *"A fast luminosity monitor based on diamond detectors for the SuperKEKB collider", Nucl. Instrum. Methods Phys. Res., Sect. A, vol. 931, pp. 225–235, Jul. 2019.*



- Except the peaks at 12,5 Hz & 25 Hz dues to the injection, all the luminosity peaks are mainly dues to vibrations amplified by asymmetrical mechanical structures
- **Publication:** ***M. Serluca, G. Balik, L. Brunetti, B. Aimard, A. Dominjon, P. Bambade, S. Wallon, S. Di Carlo, M. Masukawa, S. Uehara, Vibration and luminosity frequency analysis of the SuperKEKB collider, NIMA (2021).***

➢ **This study highlights the effects of the dynamic of the cryostat on the beam**

SuperKeKB (Vib. Meas.)

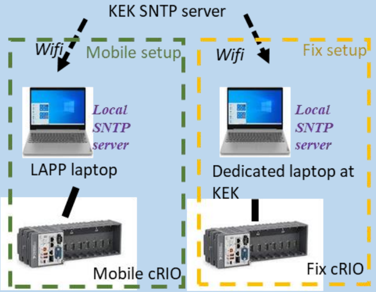
G.Balik, L.Brunetti, F.Poirier et al.

Latest ongoing work (End 2023): Campaign of Measurements of ground and quadrupoles at various location in the ring at SuperKeKB (location according to impact defined from simulation)

Simulation of displacements and impact on beams

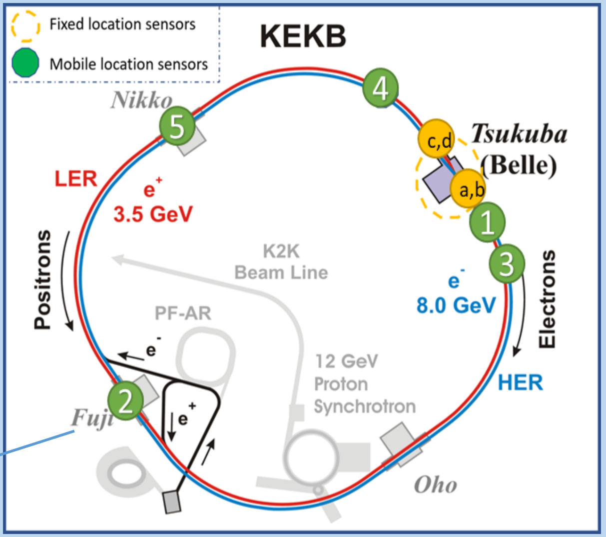
Measurement	Magnet HER	Distance (HER) in m	Magnet LER	Distance (HER) in m
8	QLC7RE	26,4	QLC3RP	26,6
9	QX3RE	1524,3	-	-
10	QLB1RE	55,4	QLB1RP	61,2
11	QLB1LE	2960,4 (55,6)	QLB1LP	2948 (67,2)
12	-	-	QW7NRP	652

1) "fix" setup, measuring vibration close to Belle II detector/ permanent
2) "moving" setup, measuring vibration inside the tunnel / for the campaign



Setup of the synchronization

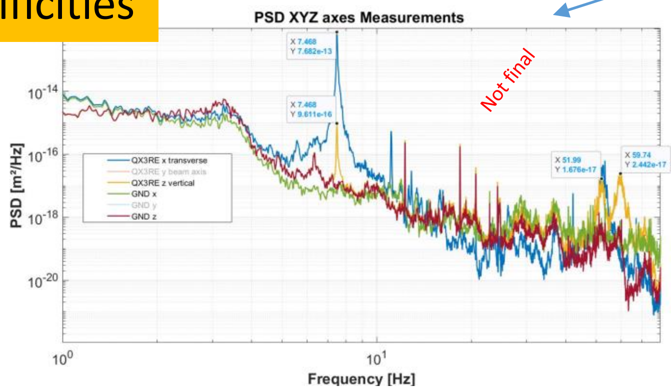
Synchronisation along the ring with a mobile setup



PSD at several locations:
- Local specificities
- Coherence of vibration

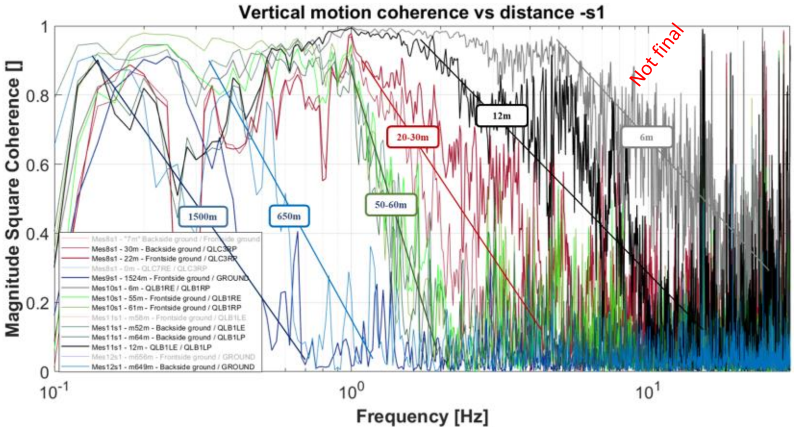
Local specificities

Here horizontal & vertical



On going analysis

Not final



Coherence over frequency for several distances

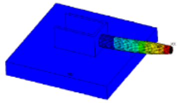
FCC LAPP vib. simulation:

Global view of the present work

Note: a parallel work is being done with SAD on superKeKB. 2 beams

Main Engineering input

Note: similar scheme for Engineering at LAPP



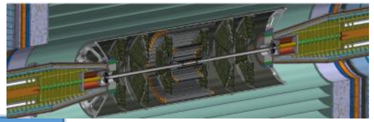
FCC Simulations (1 beam)

specific

global

Trackings

MAD-X



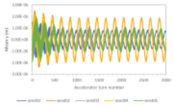
Slicing

Precision (magnet & particles movement)

Aimants simplifies

Statistics (particles)

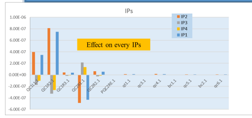
Beam distribution (IP, ε_y)



Displacement (MDI)

Individual Quad

Basic studies of the Quad response (A reference)

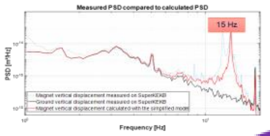


Several Quads (MDI)

Basic response

Sine wave response

Freq Spectrum



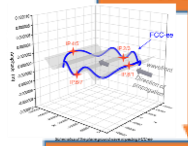
2 quads (vertical, angle)

Models

MAD-X

ground

Uniform wave



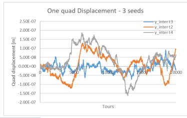
Harmonics studies (FCCee)

Lattice specifics (v22, V23, LCCO)

analytics

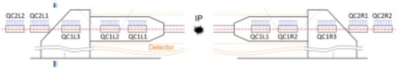
Uniform wave

Vibration spectrum



Simplified model

Vibration scenario



More precise, more time

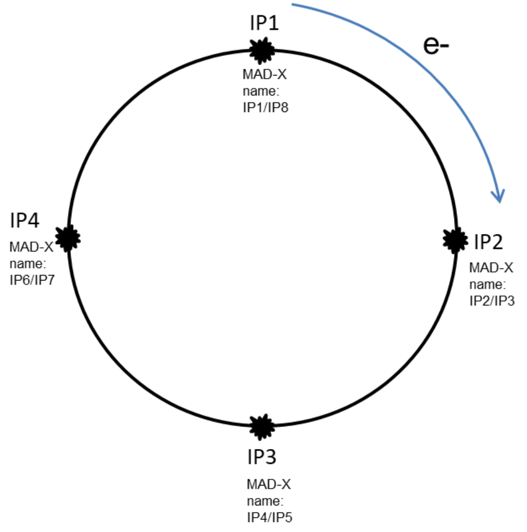
Faster, simplified

Impact of individually misaligned quadrupoles at IPs

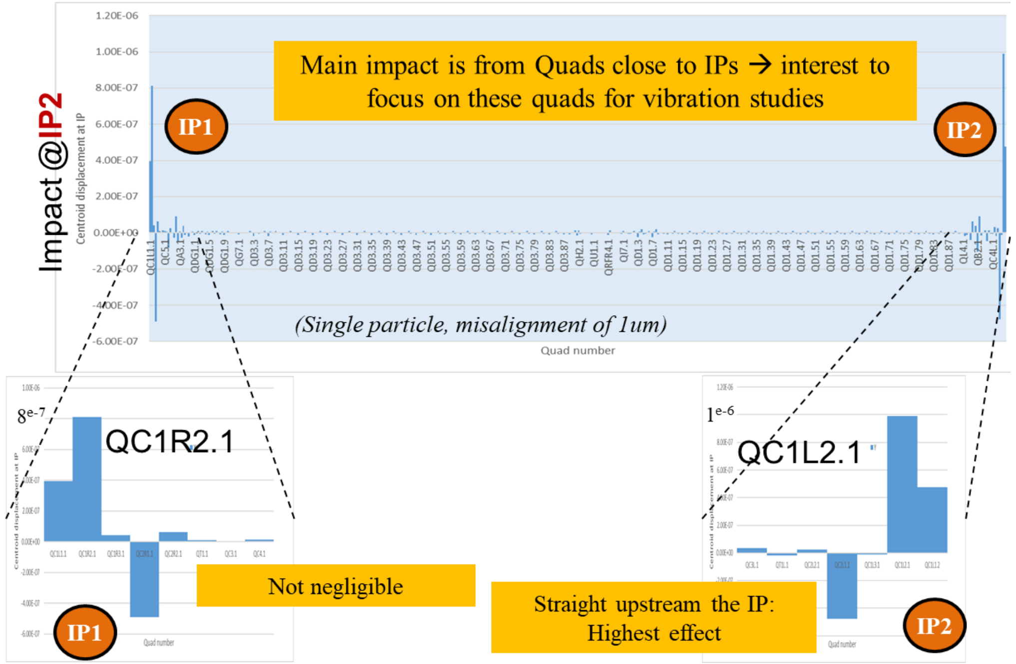
Preparatory work from 2022 indicating the impact of the quad displacement at the local IP and other IPs

Study parameters:

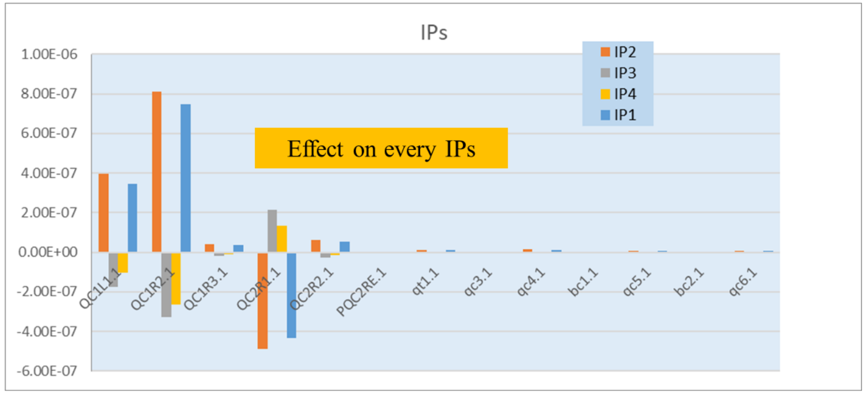
- All quadrupoles individually misaligned by 1 μm in the vertical plane
- Twiss parameters evaluation thanks to MAD-X
- Observable: y offset at IPs



At IP2:



At the other IPs:



Lattice: GHC v22

- The largest vertical offset at IP2 and next IPs comes from the vertical misalignment of the FFS quadrupoles

Quads have a local impact and a distant impact

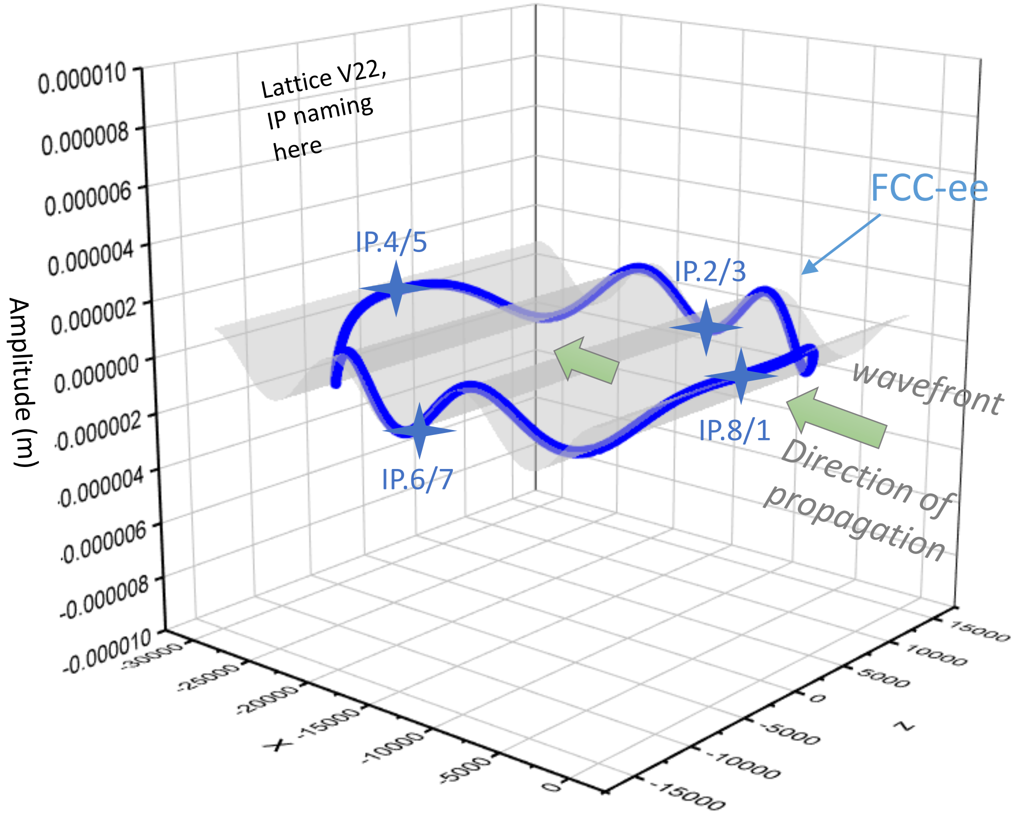
E.Montbarbon et al, « First studies of final focus quadrupoles vibrations of the z lattice of FCC-ee, » doi:10.18429/JACoW-IPAC2023-MOPL077

Plane Ground wave Studies: a corrugated model (E.Montbarbon et al)

- Aims of the study:
  - Compute the response of a potential spatial coherence on the performances of FCC-ee
  - Compare simulation results obtained to the ones of other machines (e.g. LEP, LHC)
- Definition:
  - The coherence length is the maximum distance of two points oscillating on a same ground wave.
- In our study:
  - Vertical misalignement of beam elements according a plane sinusoidal wave
  - Photography of the wave impact on the accelerator

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 (GHC V22), with 4 IPs
- Start of the sequence at IP.1



Schematics of the plane ground wave impacting FCC-ee

Study performed with MAD-X, with the TWISS module & analytical model

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

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

A: amplitude of oscillation

h: harmonic number $h = \frac{Cf}{v_{wave}}$

C: circumference of FCC-ee

α: wavefront tilt angle

φ: phasing advance

Plane Ground wave Studies: Simulation procedure

Process:

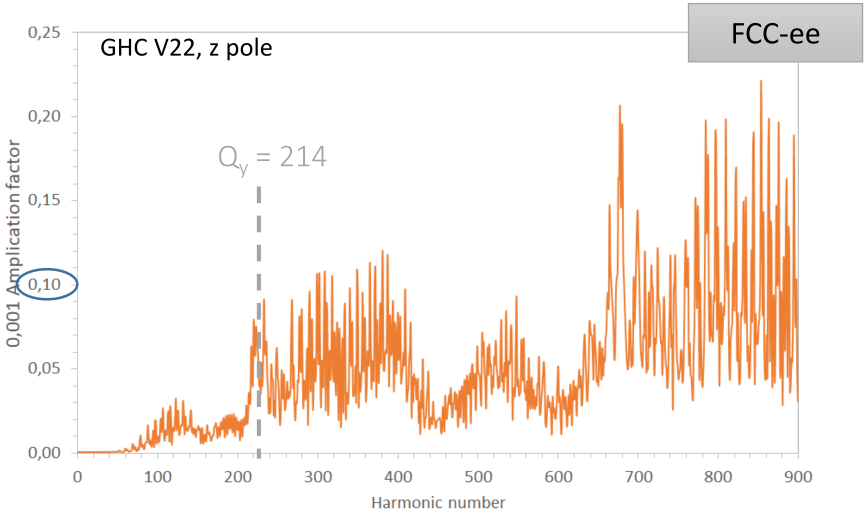
Photography of the accelerator, completely misaligned by the wave → No temporal study

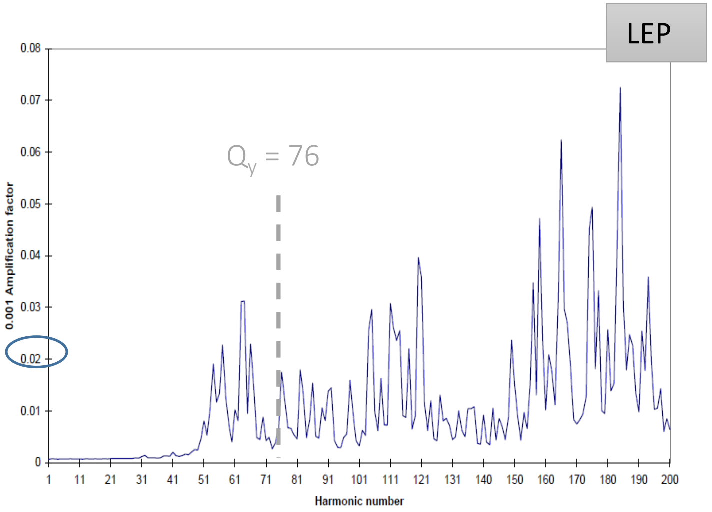
TWISS of the nominal sequence (MAD-X) → Assigning vertical displacements of all quadrupoles relative to plane ground waves (Python program) → TWISS of the "corrugated" sequence (MAD-X) → Storage of relevant outputs → Evaluation of observables (Excel sheet)

- Only one beam considered: no beam-beam effect introduced in the simulations
- Beam made out of only one particle, placed on the ideal closed orbit
- No multi-turn tracking
- No local nor global correction, as starting from a perfectly aligned lattice
- Work performed on the Z lattice (GHC V22) → it is a reference here (see later)
- Sinusoidal plane ground wave

FCC-ee ycorms results: comparison with LEP

- Variables evaluated by MAD-X:
  - yco: vertical position y of the orbit, referred to the ideal orbit, given by the TWISS table (m)
  - ycorms : vertical RMS value of the vertical closed orbit offset over the whole ring, written in the SUMM table (m)
- Calculation of the amplification factor to normalize from the maximum amplitude:
- To refer to literature, this factor is: $\frac{closed\ orbit\ offset}{maximum\ amplitude\ of\ the\ wave} \times C$ C can be 1 or another value (for comparison with previous work)





$$h = \frac{Cf}{v_{wave}}$$

- Similar shape of the vertical RMS value spectra for FCC-ee and LEP
- However, more sensitivity in the case of FCC-ee: at h = Q_y: 4 times bigger amplitude for FCC-ee
- It has to be investigated the induced effects on the machine with further analysis.

- E. Keil, Effect of Plane Ground Waves on the Closed Orbit in Circular Colliders, CERN SL/97-61 (AP), 1997
- R. J. Steinhagen, "LHC Beam Stability and Feedback Control", 2007
- M. Schaumann, "The effect of ground motion on the LHC and HL-LHC beam orbit", 2023

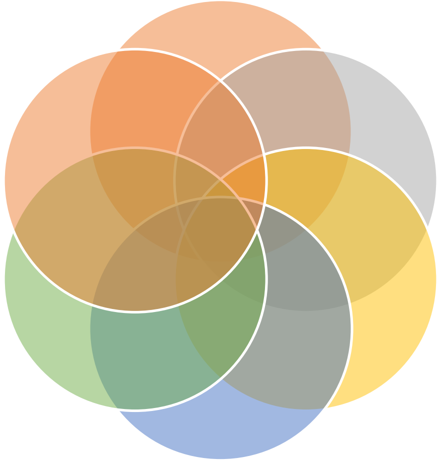
More exhaustive studies (would need much more slides!)

E.Montbarbon + I.Debonis + F.Poirier + J.Tamarzit (MSc Student) et al.

1: All beam elements or only quadrupoles

6: All quadrupoles except IR quadrupoles

2: Only quadrupoles when sextupoles are on or off



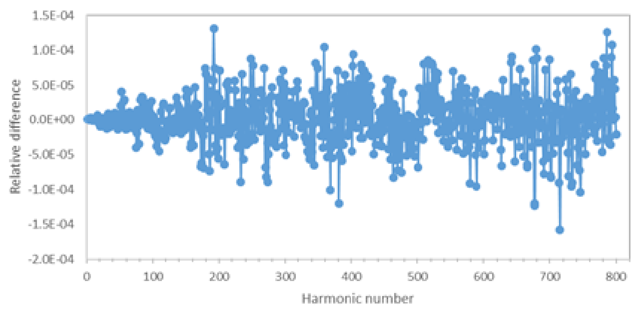
5: Only IR quadrupoles

3: Both quadrupoles and sextupoles or quadrupoles only

4: Only dipoles

1: Misalignment of all beam elements or only quadrupoles relative to the wave:

Relative difference @ IP.8 = $\frac{yco_Q - yco_{SQ}}{yco_Q}$



- *1: Misalignment of all beam elements or only quadrupoles relative to the wave:*
  - Maximum relative difference: 0.016%
  - The impact on the closed orbit is dominated by quadrupoles misalignments: no peculiar characteristic added by other beam elements
  - Consistent with results obtained for the comparison between the analytical model and MAD-X simulations
- *2: Misalignment of only quadrupoles when sextupoles are on/off*
  - Maximum relative difference: 0,3%
  - Peak at h = 677 observed
  - No considerable impact on yco given by the sextupoles
- *3: Misalignment of both quadrupoles and sextupoles*
  - Maximum relative difference: 0,015%
- *4: Only dipoles affected by the plane wave:*
  - Maximum yco = 3 nm
  - No relevant impact on dipoles misalignment because of the plane ground wave
- *5: Only IR quadrupoles affected by the plane ground wave:*
  - Periodic structure of yco at IP.8 relative to h

More ongoing: scan of plane wave parameters + lattices

Definitions of the analytical model

- We put up an analytical model (with rather standard definition) to explore rapidly various parameters (from plane wave to vibration)
- The sequence used to solve analytically the Plane Ground Waves study **only** considers **quadrupoles**.
- 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)

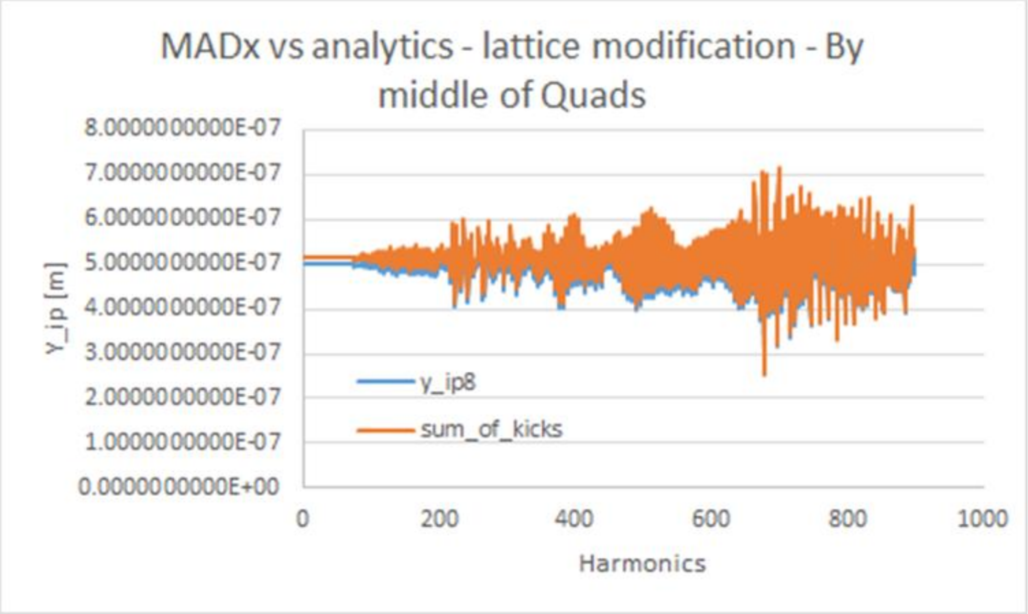
- The i^{th} dipole kick creates a perturbation y_i of the closed orbit:

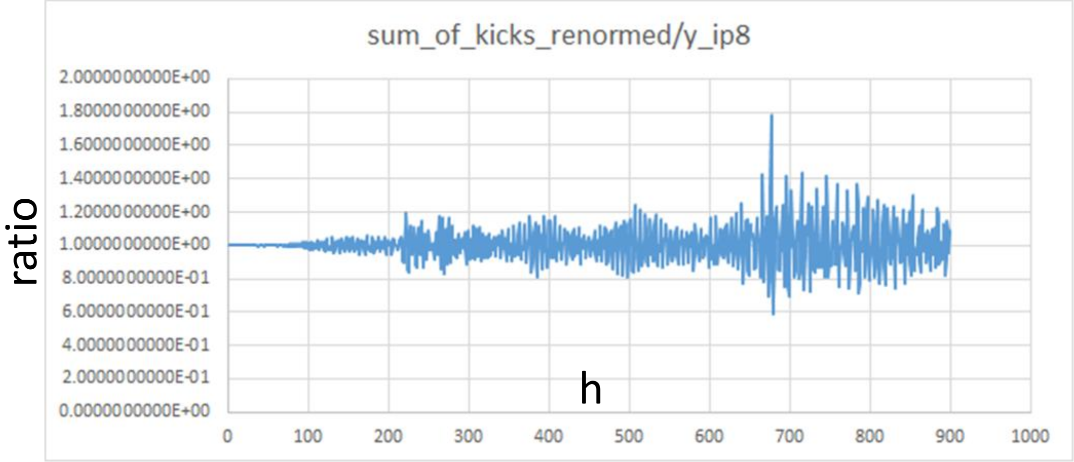
$$y_i = -\sum_{j=0}^{n} \frac{\sqrt{\beta_i \beta_j}}{2sin(\pi Q)} cos(\pi Q - 2\pi\Delta\mu_{ij}) \times \delta_j$$

Comparison between MAD-X and the analytical model

- ***We have access to yco at the IP relative to h***

- The two methods are **very consistent**.
- The first oscillation at h=214 corresponds to the FCC-ee vertical tune (GHC v22).
- The amplitude at IP is significant regarding the amplitude of the wave (0,5 um).
- There is a small offset:
  - At h = 1: 2,8 % of difference
  - Offset not constant relative to h
  - Due to the fact that the β functions defined at the centre of each quadrupole are higher than defined at the exit





Yco: vertical position y of the orbit

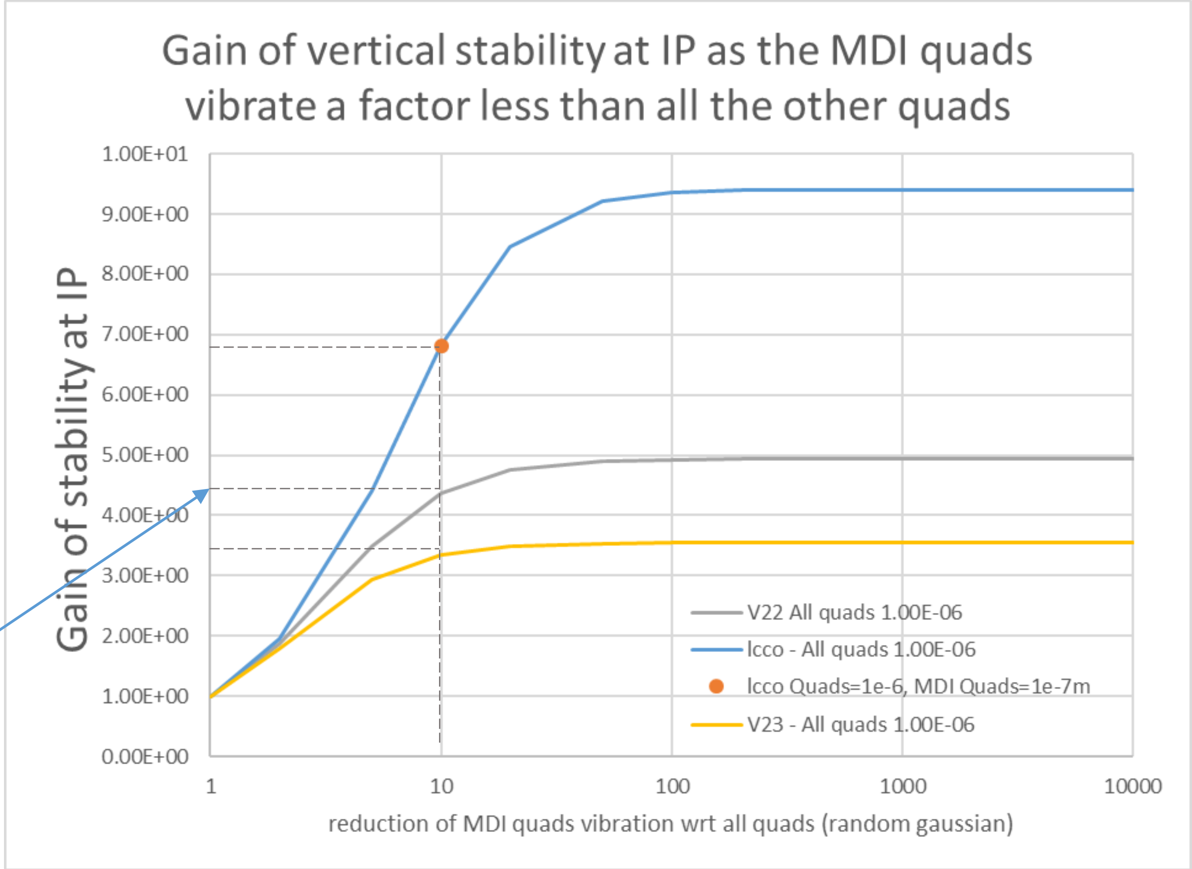
To go beyond the Plane Ground Wave model: random vibration

- No plane wave in this case!
- Analytical method:
- "Vibrations" model:
  - Random vertical displacements of the quadrupoles, following a gaussian distribution
  - 1000 seeds
- **Focus on the MDI region:**
  - 5 quadrupoles for GHC V22/V23
  - 4 quadrupoles for lCCO

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

$\sigma_{y_{0\_mdi}}$ 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)



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 less mouving (& closer** to the nominal orbit).

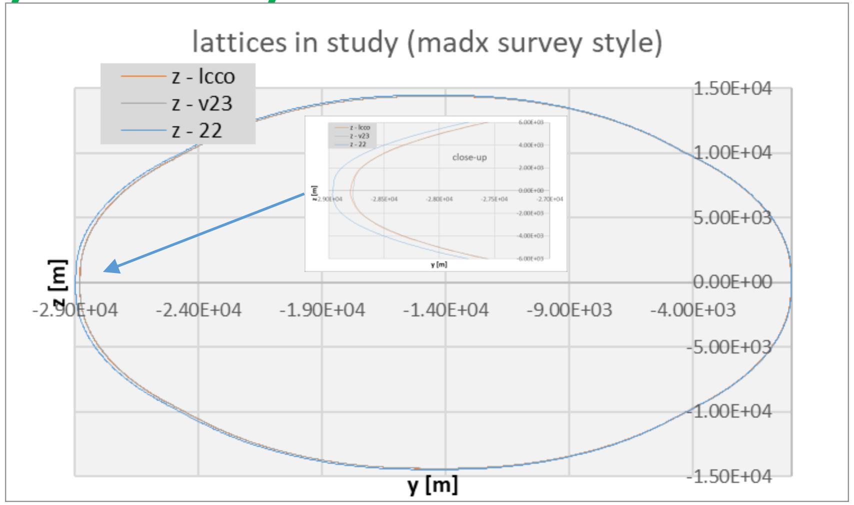
In the case of QC1 vibrations (3 quadrupoles), the maximum gain is equal to 2.

lattice	Gain if factor=10
V22	4.37
V23	3.35
lcco	6.81

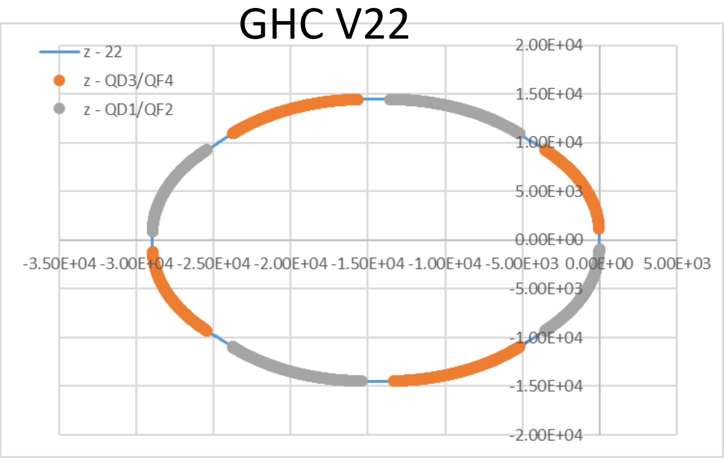
Points at an effort of lowering vibration closest to IP = gain

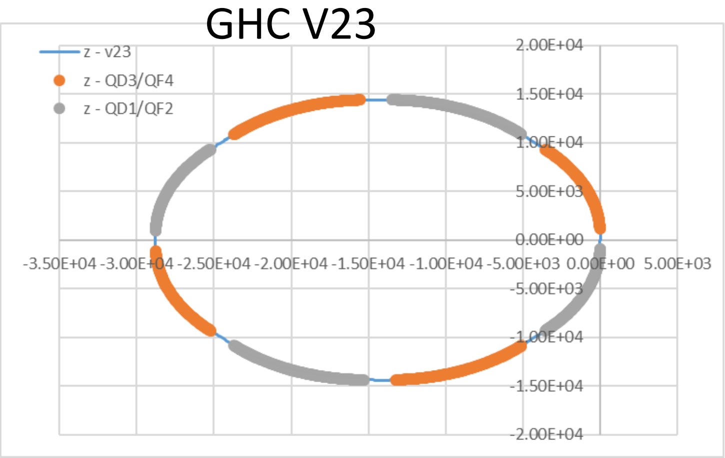
Study could be extended further away from IP

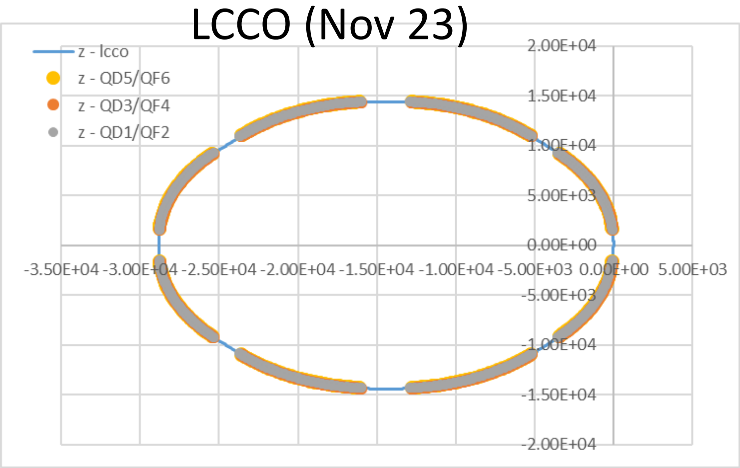
Arc-cell (AC) Quadrupoles – preliminary study



- First Goal:
  - gathering information for later possibly detailed simulation:
  - Study scenario of vibrations:
    - First very crude with random Gaussian distribution
    - Later on : Including acquired knowledge from (modeled or real) vibration spectrum
    - Interact with the Arc-cell prototype being designed (F. Carra, A.Pucini et al – CERN)
- Here for the analytical study, AC defined by the quadrupoles:
  - QD3/QF4 and QD1/QF2 in each GHC v22/v23 lattice
  - LCCO lattice has also some QD5/QF6 in the arcs







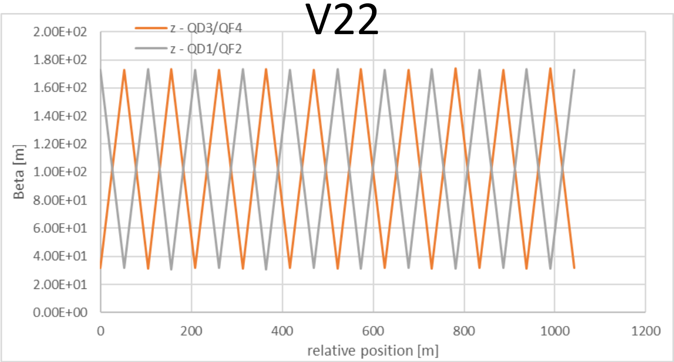
Well separated in names for V22/V23. → might help if we needed to focus on a specific section. No difference in beta function (see next slide)

Lcco: Quad combined within the arc-cell sections

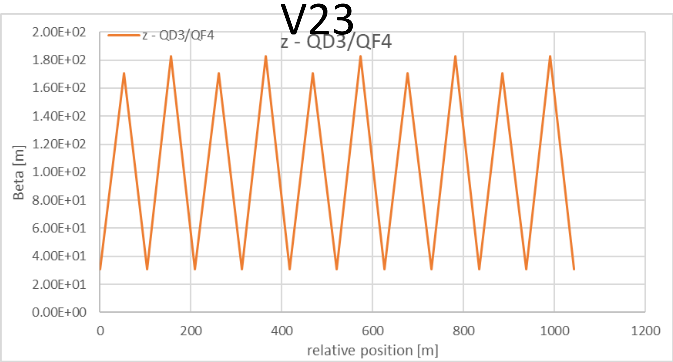
Arc-cell (AC) Quadrupoles random distribution impact at IP

- Beta function in the arcs as seen by the analytical code for each lattice:

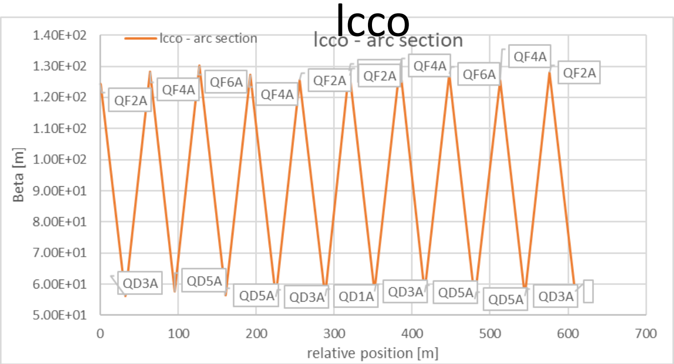
V22



V23



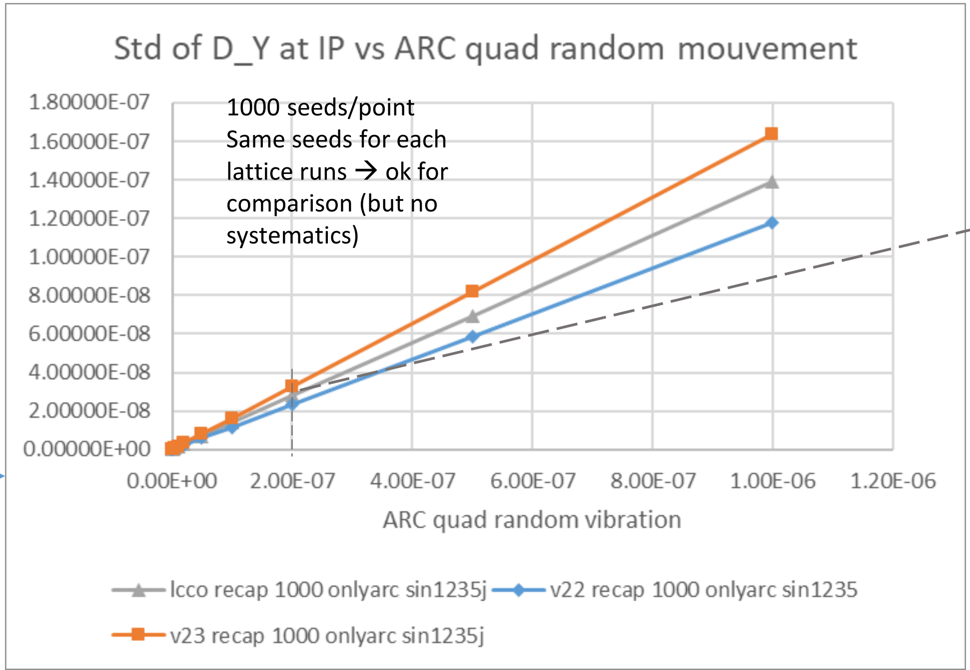
Icco



lattice	v22	v23	Icco
FCC circ [m]	91174.1174	90658.7453	90658.6089
Q_y tune [m]	2.14E+02	2.22E+02	1.74E+02
nb of quads	1856	1876	2960
QD1*	360	360	448
QF2*	360	360	432
QD3*	348	348	432
QF4*	352	352	432
QD5A	0	0	432
QF6A	0	0	216
% arc beta coverage (analyt	18.1613795	15.4965878	32.1978599
beta max (arc QD3/QF4)	174.50465	191.067471	130.280799
beta min (arc QD3/QF4)	31.1029765	29.0008244	55.6523112

Some relevant characteristics

Response at IP to random gaussian (RG) displacement of quads in arcs



i.e. if the arc quads only are moved by a RG of 200nm, the sigma of the centroid is:

ARC quads by RG=200 nm		
lattice	IP centroid sigma [m]	sigma wrt V22
v22	2.35586E-08	1
v23	3.2756E-08	1.39
Icco	2.77775E-08	1.18

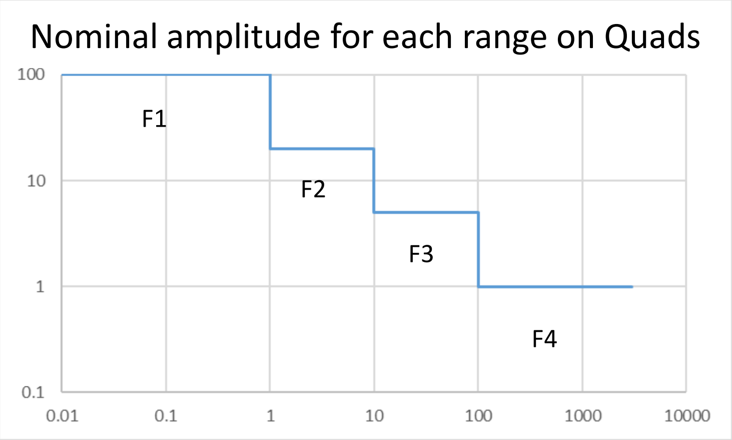
- Not a big difference between the lattices
- Least sensitive → V22
- Sensitivity is global
- Where does come from the difference?

Considering "very naïve" vibrations for simulation

- Goal:
  - To start up on our side!!!!
  - Define what is needed in terms of data, files, … for later more demanding simulation (MAD-X). Lots of quadrupole: Large amount???
  - Use first the previous analytic calculation
- Assumption:
  - Quads vibration taken from a simplified spectrum
  - I have assumed that the table below means each quadrupoles are displaced uncorrelatedly by the amount given here
  - The effect of previous turn is not taken into account (i.e. damping time is long)
  - Machine is perfect (no prior disalignment, no correction, no BBA)

Frequencies	Tolerance	Correlation	
1 > f > 0.01 Hz	100 nm	None	F1
10 > f > 1 Hz	20 nm	None	F2
100 > f > 10 Hz	5 nm	None	F3
f > 100 Hz	1 nm	None	F4
1 > f > 0.01 Hz	1 um	10 km	

Suggestion from T.Raubenheimer [1]

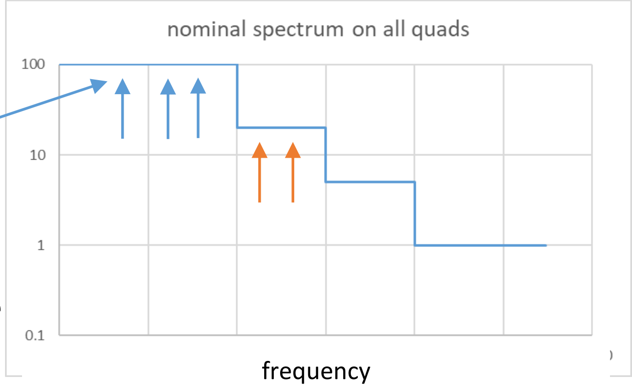


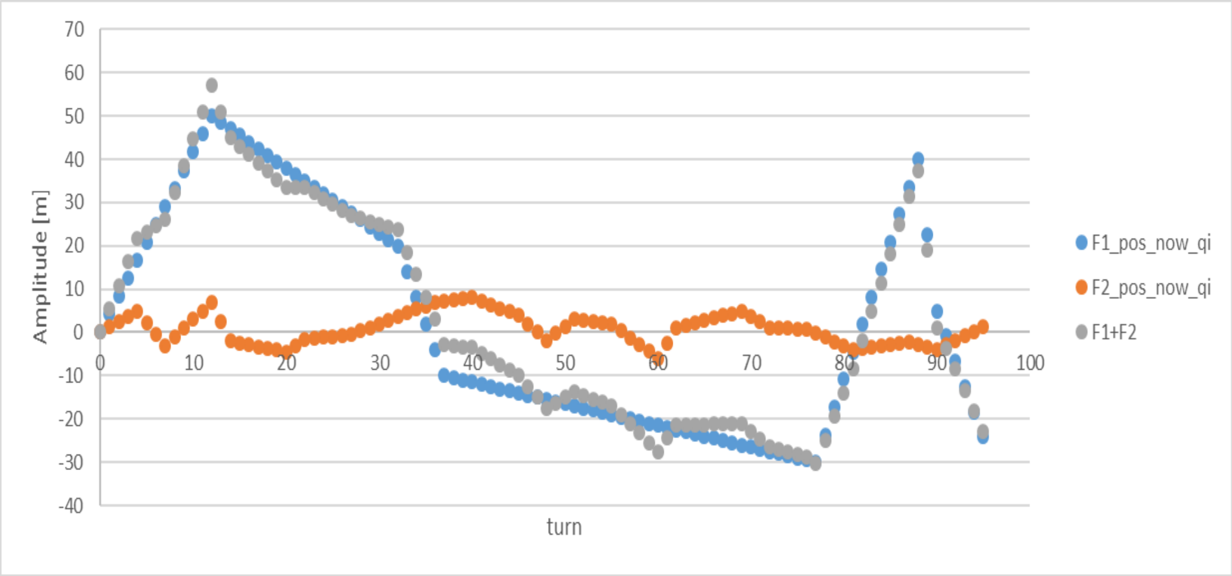
- Various scenarii are studied where only amplitude is modified and the application is also modified (to mdi quads or not), for example:
  - All quads move by a factor 2 less
  - All quads move by a factor 2 less in the range 1 Hz to 3000Hz
  - Mdi quads move by a factor 2 less in the range 100Hz to 3000Hz

[1] T. Raubenheimer, "FCC Arc Alignment Approaches", FCC week 2023

Displacements: dummy model

- The displacements of a quadrupole is fixed according to a uniformly random choice within a first frequency range:
  - For example, say range F1, here (blue points)
    - F1 (low freq) on a single quadrupole, **first a random frequency is chosen** eg. f=230Hz, here it means 13 turns then 142Hz (21 turns more), then 500Hz (6 more turns), and so on. The amplitude of movement is here chosen to be **Gaussian randomly** distributed with a sigma (=amplitude)
    - Each quadripole in between, and at each turn, will move towards the max of the amplitude
  - Additionnally F2 (higher frequency) is applied in the same way (orange points)
  - The addition of the mouvement is then done (grey points)





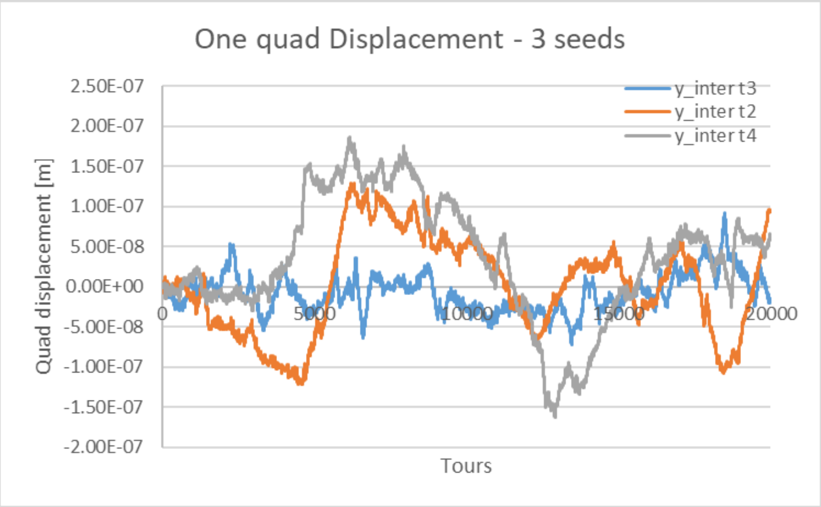
It is somewhat a random walk (but not strictly speaking ATL like)
Only the principle is important here:
- The idea is to easily provide within the developed python codes the amount of data needed as required by the code:
- The spectrum does not have to be necessarily very close to the a true spectrum, but close enough
- Provision of a real spectrum (according to the requirements of the code can come later on)

Application of the displacement model

- The previous scenario can be applied individually to all quadrupoles of the machine other several turns (no memory here!).
- And for statistical studies, this can be over and over again modifying everytime the frequency for each range of choice within F1, F2, F3 and F4

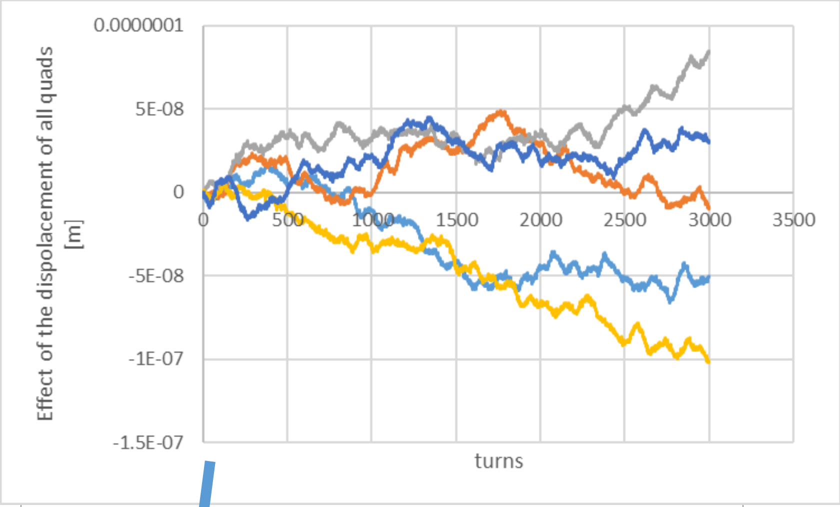
For V22, that it is 1.11 billion data points

Displacement of a single quadrupole over 20000 turns (Dummy model):

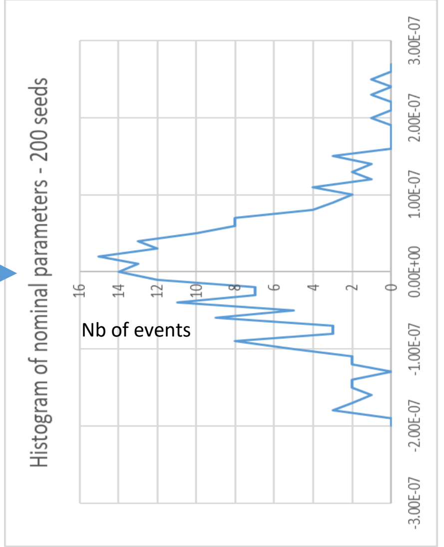


Applied to quads

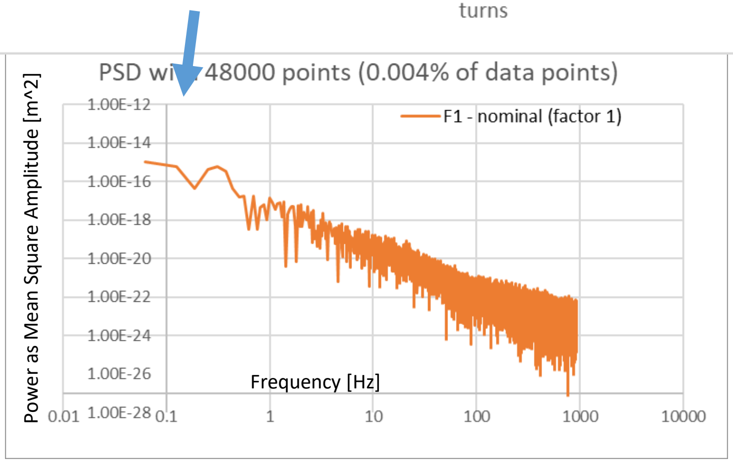
Effect at IP taking into account the nominal model, applied to all quadrupoles (1864 - V22) over 3000 turns:



200 seeds



Sigma=~7.34 10^{-8} m



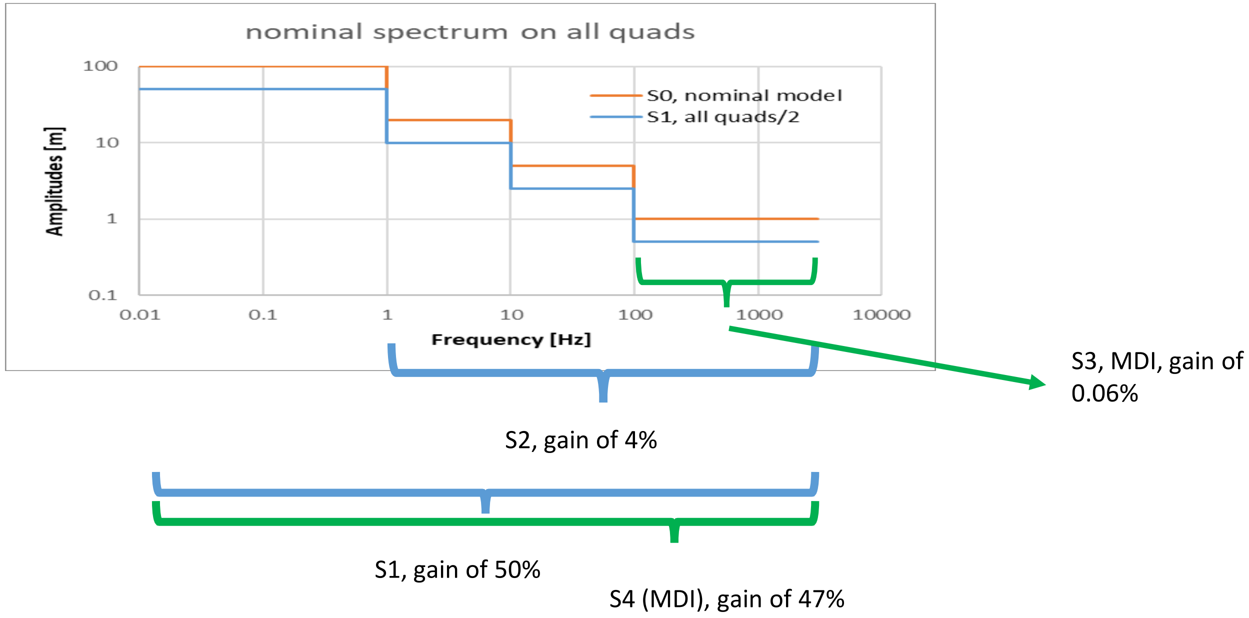
- PSD from a sample of data points with the nominal frequency range and tolerances

This is not a validated model and if needed will have to go through a validation process: only for comparison purposes

Some studied scenario

- At IP, what is the beam displacement (at the 3000th turn)?
- Study with the modification of amplitudes within the model:
  - Scenarii not necessarily wise (i.e. testing the outcome)

Scenario name	Type	Std (centroid) [m]	Gain wrt S0
S0	Nominal	7.34 10-8	
S1	All quads move by a factor 2 less	3.67 10-8	50%
S2	All quads move by a factor 2 less in the range 1Hz to 3000Hz	7.04 10-8	4%
S3	MDI quads move by a factor 2 less in the range 100 Hz to 3000Hz	7.33 10-8	0.06%
S4	MDI quads move by a factor 2 less – all range of frequency	3.86 10-8	47%

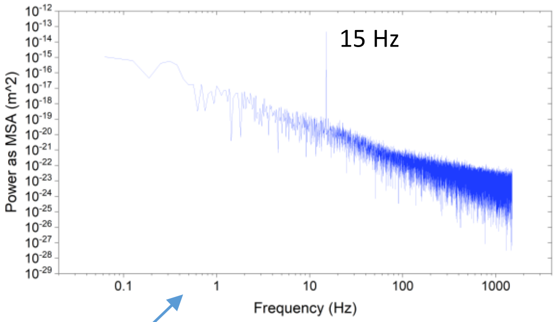


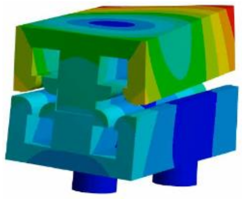
Not realistic scenario but we could easily think of other scenario:
i.e. mitigating the vibration within a range (with a perfect feedback?)

Note if displacement=0, for f<1Hz, factor 4 in gain (i.e. std=20nm) ≠ IP feedback

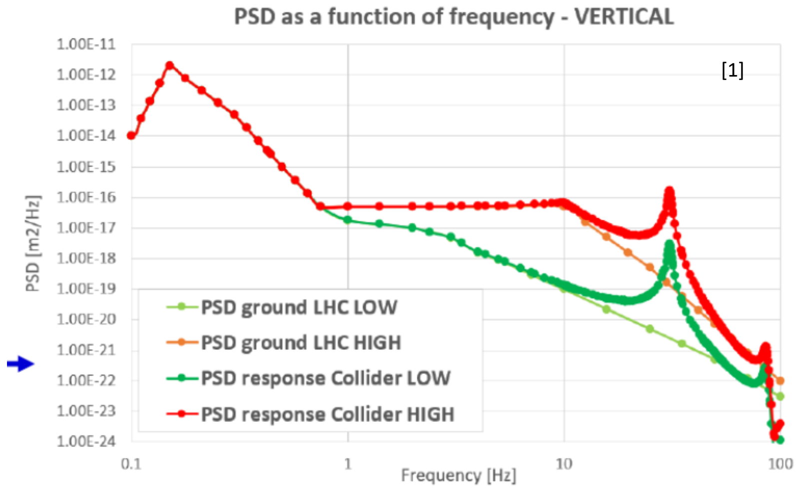
Next?

- Keep on for this work:
  - More better suited scenario! Suggestion?
  - Comparison between the lattices, comparison with MAD-X
  - Extend Acc. parameters? Extend vib. model (sine wave?)
- Really at some point need a more real vibration model (eg to prepare simulation with MAD-X):
  - Integrate previous studies on sine wave evolution of the beam/turn and tracking – done with MAD-X
  - Use measurements (SuperKeKB at various locations? Other?) and model from LAPP
  - Use model/spectrum from LHC
  - Use other model?
    - SLAC algorithm? Institute of earth science?
    - Add-up coherence
      - Various way to proceed
      - Also see measurements from SuperKeKB





308 Hz [1]



[1]: A.Piccini "FCCee Arc Half Cell: methods to evaluate the systems' stability ", November 2023 / FCCIS WP2 Workshop

A few words to finish

- A naïve approach for the simulation of the vibration:
  - Analytical accelerator model:
    - Fast (1.18 billions data for the spectrum: runs for 4h)
    - Ok for first scenario studies and some comparison studies
    - The model has its limit and limited parameters check (Here centroid, can be extended though)
  - A first vibration model spectrum that needs to be “played with” to check various vibration scenario (spectrum and amplitude)
    - It is versatile and can relatively quickly produce some results
      - point out to the needs and what to do (in terms of simulation)
      - But very naïve approach here (better approach would start-up from a modeled/real PSD and translate that in a temporal displacement)
  - Focus on
    - MDI: tightening there, will help to be less sensitive to vibrations
    - ARCs: some differences between the lattices → Much more detailed work required*. (work with F.Carra group)
- Though this will need:
  - A more refined/thorough and in-depth scrutiny for the accelerator and vibration model:
    - MAD-X (and other codes. We might explore Xsuite if adapted?)
      - Tracking (not yet)? Quadrupole Slicing (not yet) useful when mechanics come into play?
    - Modeled and more real spectrum will be included
      - A suggestion with the ARC-Cell group is to take in PSD for LHC (low and high amplitude model)
      - Use of more real model and/or measurements
        - LAPP is discussing with experts from local branch of earth science Institute
        - Discussed also with the SLAC/Lucretia team on their Algorithm (G.White thanks to T.Raubenheimer)
      - Integration of the spectrum in a MAD-X study?
  - Simulation with MAD-X does take a lot of time so we need to point to what could be done (here is the need for the analytics)
  - The use of a data center: MUST**, at University of Haute Savoie, is being assessed for MAD-X simulation.: last week work has started and been used for further studies of plane ground wave with various lattices

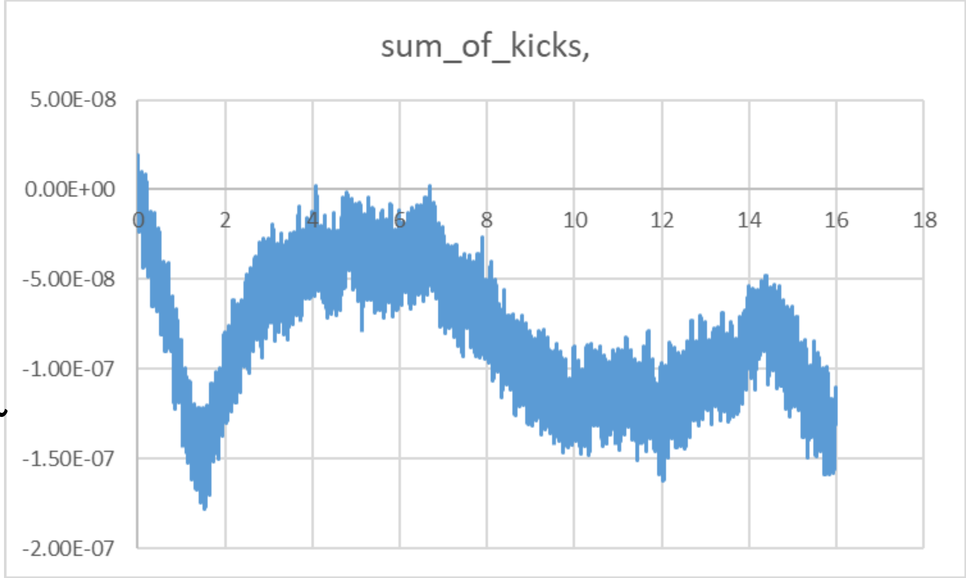
**MUST: Mésocentre de calcul et de stockage de l'Université Savoie Mont Blanc

*Will the amplitude & dispersion of an uncorrelated High Freq over large amount of quadripoles plays a substantial role at IP: to be checked in simulation!

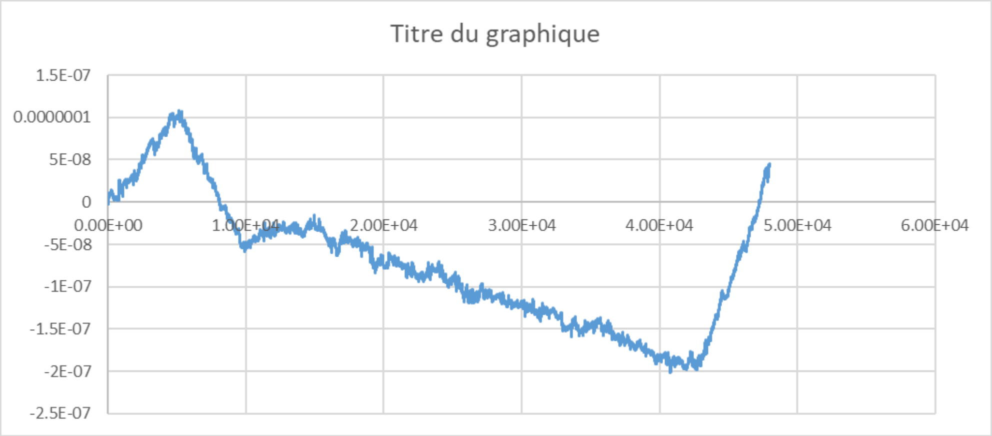
Testing application of the model (1):

Introducing a single sine wave 10 +-0.01Hz,
amplitude=20nm on each quadrupole
F2 (base between 1-10Hz)=5nm (instead of 20 nm)
Single seed

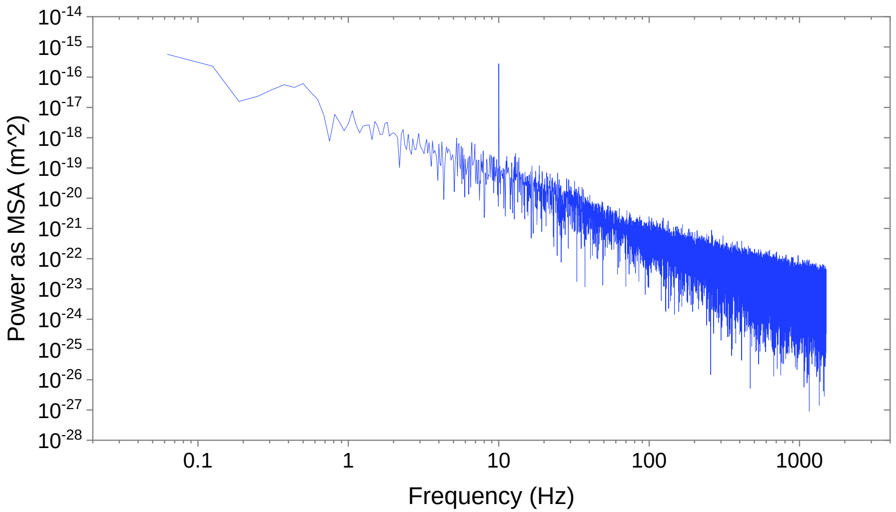
atIPper sec 48000t sin20nm10Hz



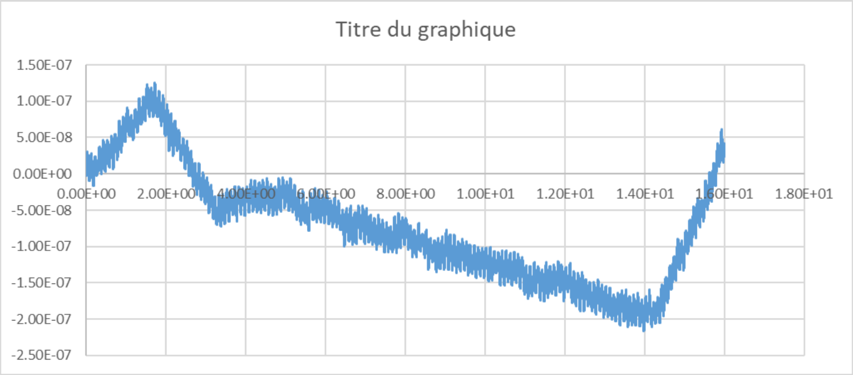
Local: 1quad 48000turns without sine + F1F2F3F4



Gives these effect at the IP



Local: 1quad 48000turns with sine

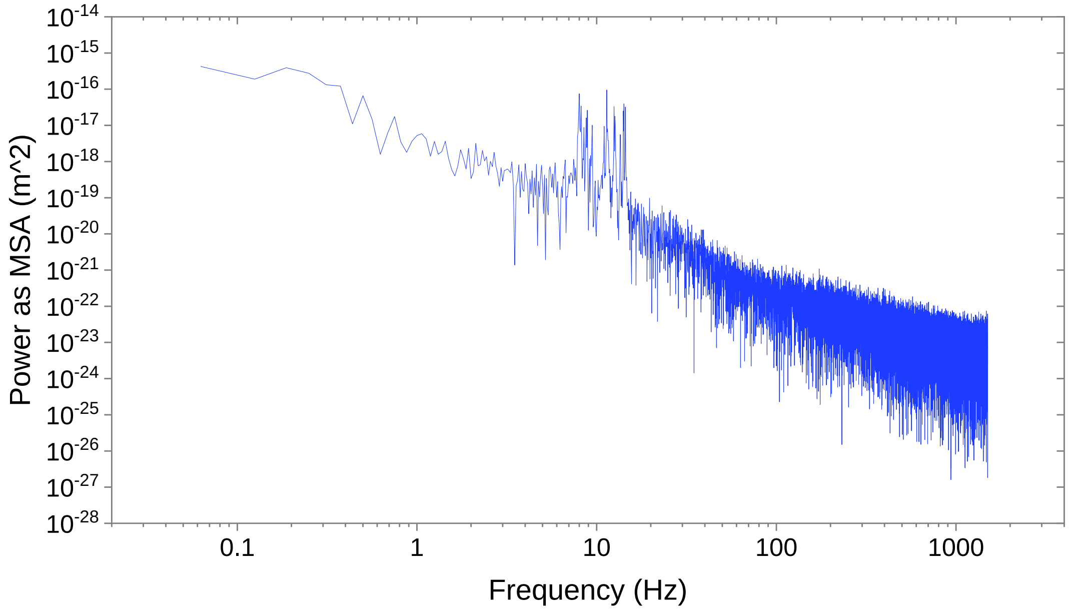


X 1856 quads (v22)
& Random phase
for each quad
10Hz +-0.01Hz

Testing application of the model (2)

- Introducing a single sine wave on each quadrupole but with variation on the sine frequency:
  - All 1816 quads:
    - amplitude=20nm
    - Frequency: 5 to 10 Hz (random) +-0.01 Hz
    - Phase= 0 to 2pi (random)
  - MDI 40 Quads (QC1/QC2) of GHC v22 lattice:
    - Amplitude=30nm
    - Frequency: 7 to 15 Hz (random) +- 0.1 Hz
    - Phase=0 to 2pi (random)

PSD at IP



On the code, everything seems to be ok → more realistic