FCC

STUDIES OF THE GROUND MOTION INDUCED VIBRATIONS IN FCC-EE Z MODE

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F.Poirier on behalf of E.Montbarbon

LAPP, IN2P3, CNRS

2022 International Workshop on the High Energy circular Electron Positron Collider

Thursday, the 27th of October 2022

Summary

- Context of vibrations studies
  - Criticality of vibrations
  - Dynamic misalignments
  - Links to mechanical design

- Impact of vertical misalignments of each quadrupole along the ring

- Vibrations studies in the MDI region of FCC-ee
  - Methodology
  - Study cases

- Frequential studies: Effect of plane ground waves on the closed orbit

- Links to mechanical design

- Conclusions and Perspectives

Criticality of vibrations effects

LHC

FCC-ee

CLIC

Aim: Define vibrations tolerances of the machine

+

- Circular collider:

- High repetition rate of the beams
- Optics symmetry of e^+ and e^- beams

- Coherence around the IPs
- Beam control: orbit correction, post-IP BPM control

-

- Mechanical effects, resonance modes:

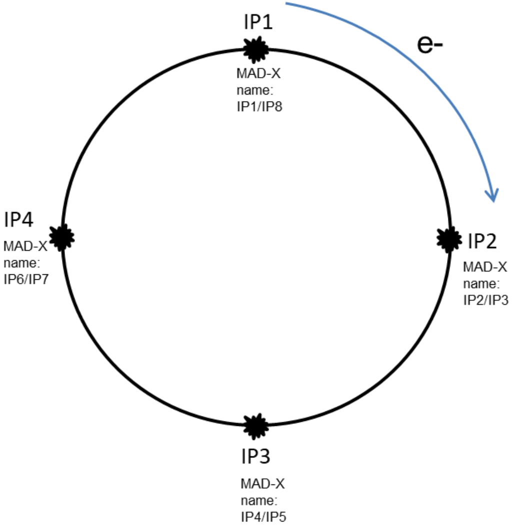
Cryostats in cantilever mode, supports and magnets, positioning system,…

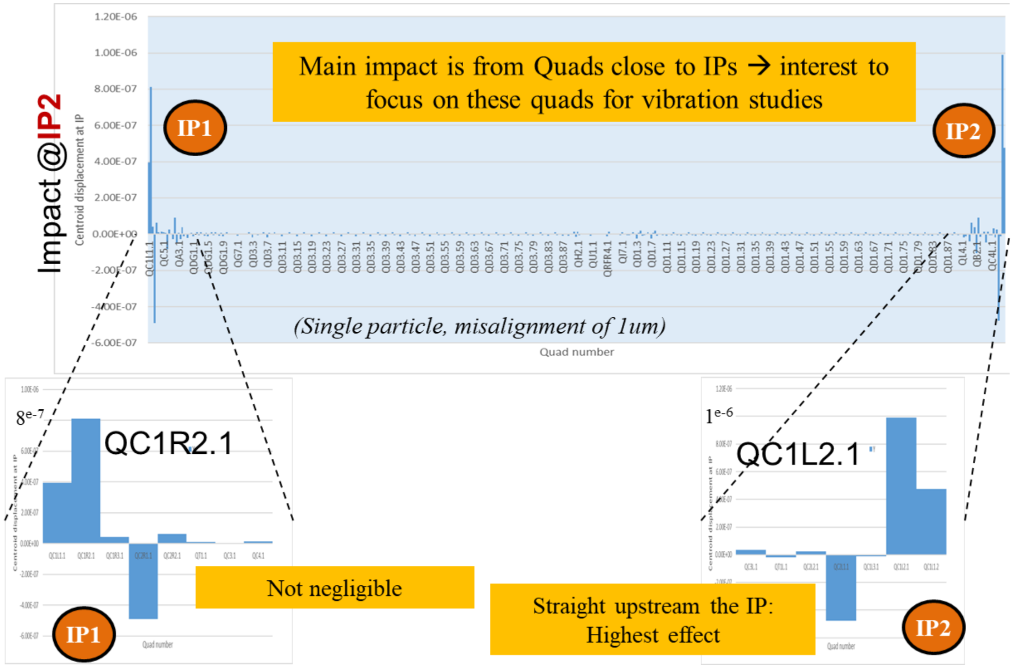
- Nanobeam in the vertical axis
- Weak coherence along the ring, relative to distance and frequency
- 2 different beam pipes
- BPM resolution

Specifically at the Interaction Point:
Small beta* values, meaning strong FFS quadrupoles → very sensitive to vibrations

IMPACT OF VERTICAL MISALIGNMENTS OF INDIVIDUAL QUADRUPOLES AT THE IPS

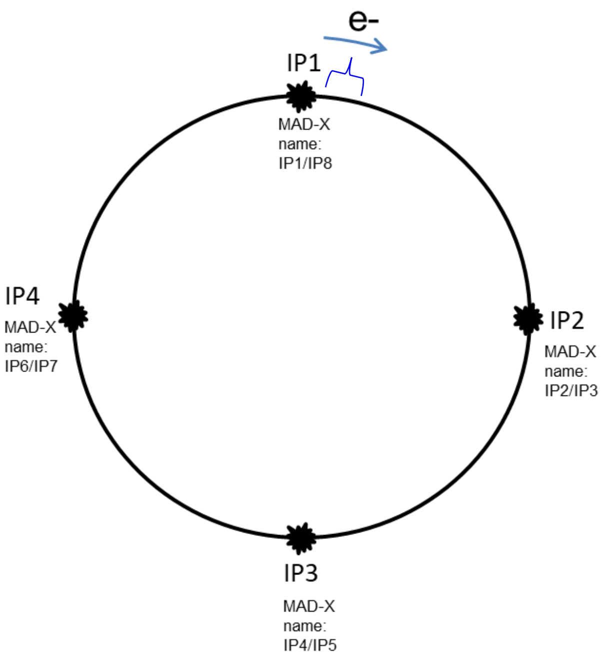
Individual impact of quadrupoles misalignment



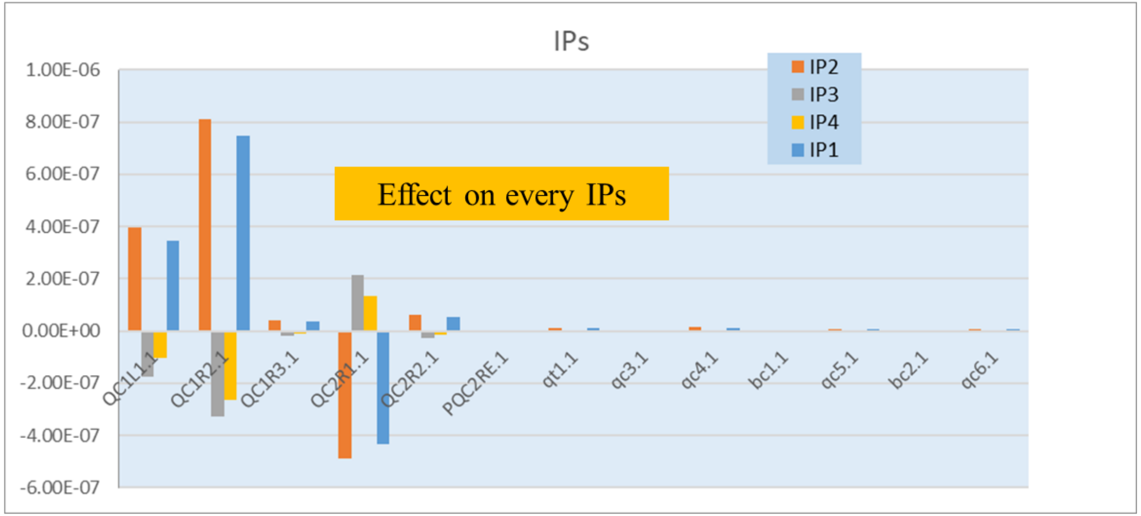


Beam stability is a sum of factors, but the main ones are due to the induced final focusing magnets effects.

Individual impact of quadrupoles misalignment (2)

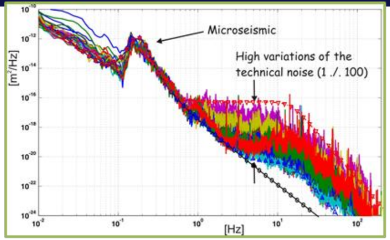


Quadrupole of a specific region impacts other region?
- Here Quads downstream IP1 have effect to all IPs, including at the IP1

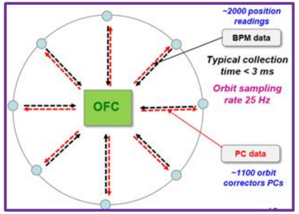


This study gives an input to dynamic vibrations studies.

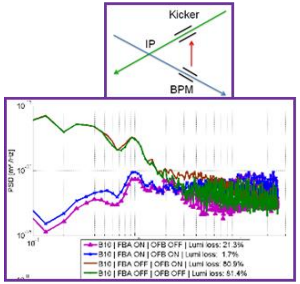
FCC-ee vibrations studies



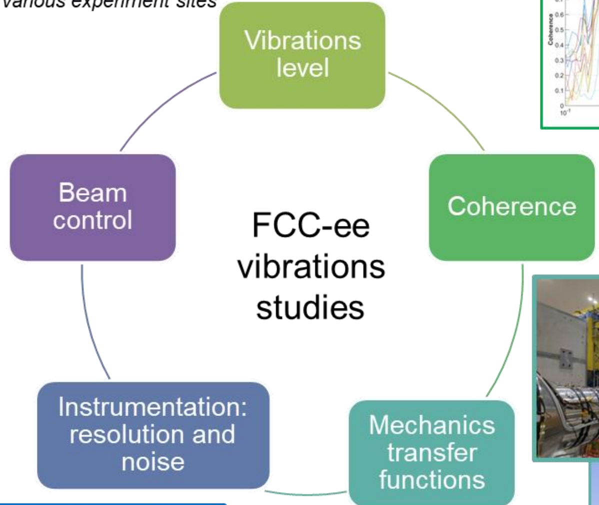
PSD displacement of various experiment sites

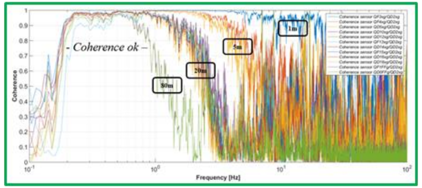


LHC Feedback controller design

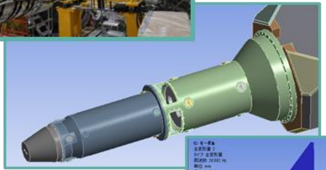


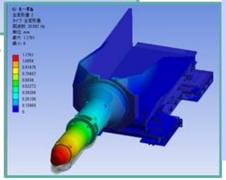
CLIC post IP BPM feedback





ATF2 coherence


SuperKEKB IP cryostat




LHC Beam Position Monitor


Vibration sensor

Work here: two main folds

*1)Simulation of **beam dynamics** due to vibrations*

- Integration of **dynamic effects** of each IP side: **vibrations** localized in the **MDI** region
- Impact of **plane ground waves** on the closed orbit to evaluate global coherence: vertical **displacements** assigned to **all quadrupoles**

2) Impact of **Mechanicals** related parameters in the MDI region

Note: On a longer term, integration of instrumentation and feedback control

VIBRATIONS STUDIES IN THE MDI REGION OF FCC-EE

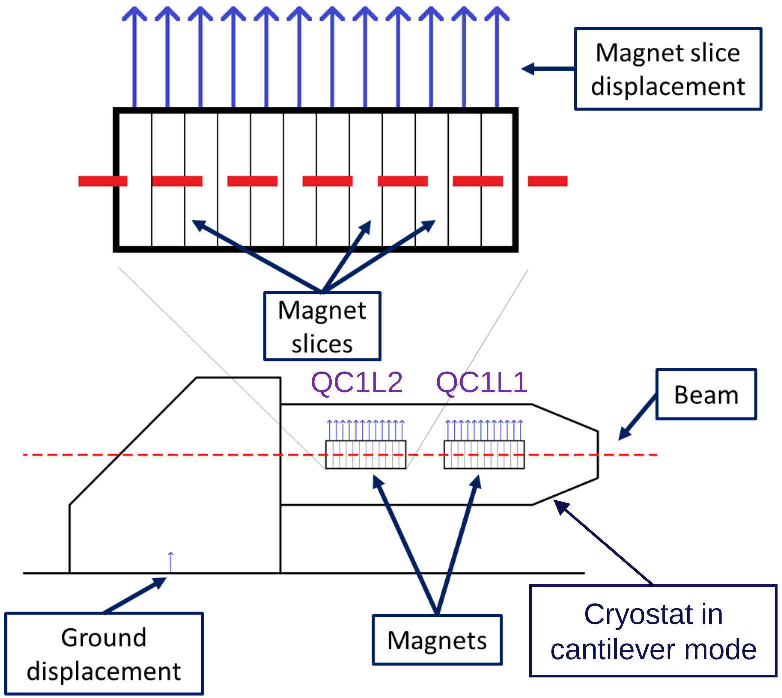
Objectives for beam dynamics

Quantify the impact of vibrating MDI quadrupoles on beam characteristics

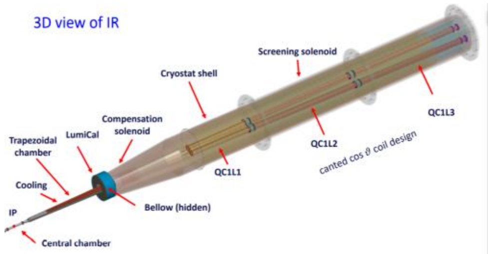
Aims:

- Vibrations study in the MDI region to define vibrations tolerances
  - **Vertical dynamical** displacements
  - Complementary study to the performed misalignments studies as technically the beam trajectory has been already optimized and orbit corrected.
  - Impact on beam characteristics (emittance, size)
- Integration of dynamics beam optics with the mechanical design

For our beam dynamics studies, magnets are sliced such that particle tracking is more precise for long quad. This slicing can represents how magnet field might move, and so, how the magnets are also moving.



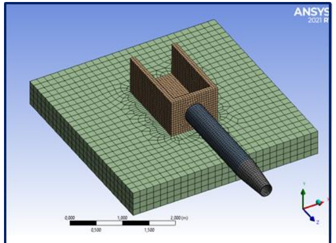
More on the mechanical side…



Courtesy F. Fransesini

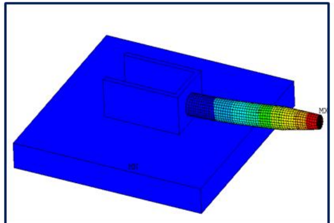
- The mechanical design of the MDI region is still ongoing.
- Development of the process using a simplified 3D model of cryostat (similar to the one of SuperKEKB)

Aim: provide displacements to each sliced magnet relative to the model:



Linear model

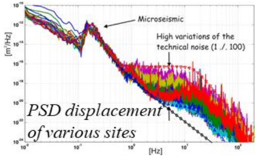
Modal analysis

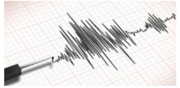


Natural frequencies and mode shapes

Linear model

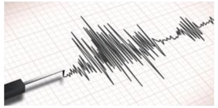
State space matrices





n * Input displacements sequences (in function of the coherence)

MATLAB®



n * Output displacements sequences *(each magnet is divided in many slices)*

MAD-X

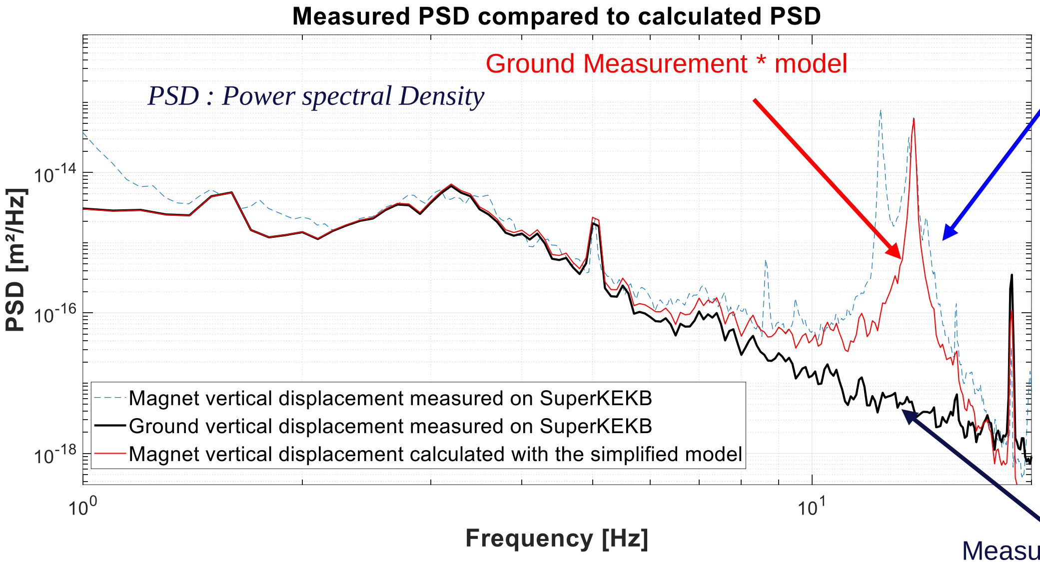
7

S. Grabon *et al.*, Modelling process for vibrations estimations, FCC week 2022

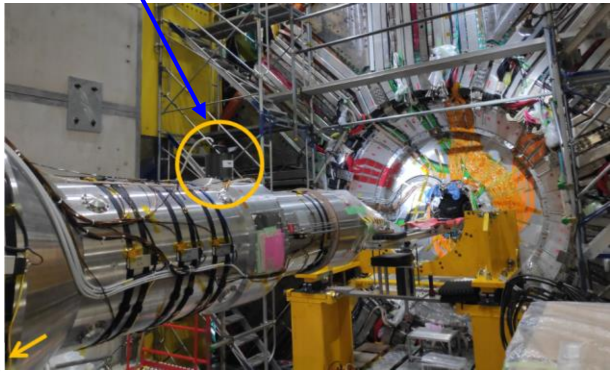
First results

To back-up, the need for the mechanical study, simple vibration model has been applied, here to a the superkekB cantilever, and shows to some extend similar tendency in resulting mode

- **Simulation results:**



Measurement on the cryostat

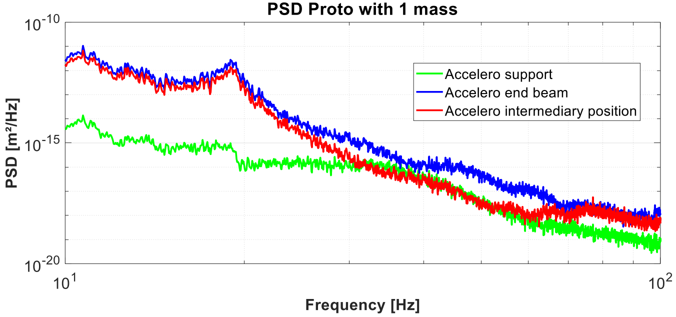


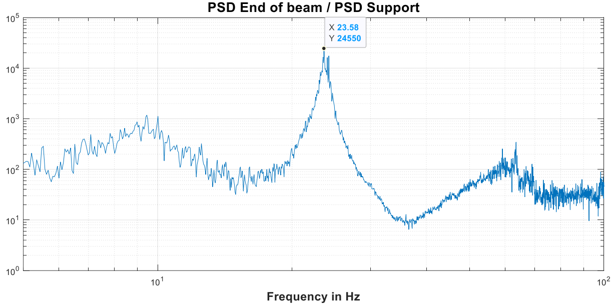
Measurement on the ground

- **Possibility to include designed elements of the MDI**
- **Test of the method on a prototype (work in progress)**

- **Test of the method on a dedicated prototype**

- 3 operation setups (no mass, 1 or 2 masses)

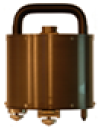




Possibility to add masses

Prototype of a cantilever beam (rod)

Measure of the cantilever part



Guralp CMG 6T
x,y,z
2*1000Vs/m
30s-80Hz
2,6 kg

Wilcoxon 731A
z
1 Vs²/m
10 s -300 Hz
0.55 kg

PCB 393B12
z
10V/g
0,21Kg

B&K 4507B3
z
98mV/g
qq g

B&K 4524
x, y z
98mV/g
qq g

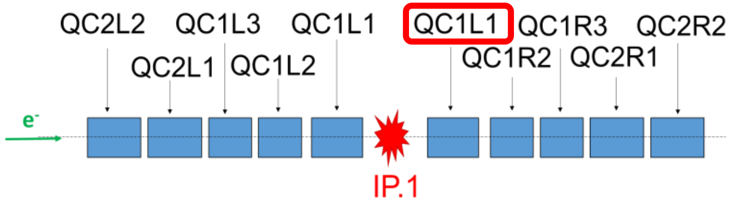
- It will be fixed on the ground to improve the accuracy between the model and the measurements
- Have to implement with our other accelerometers to also analyze the modes at higher frequencies

Methodology for the beam dynamics (1)

Modus operandi:

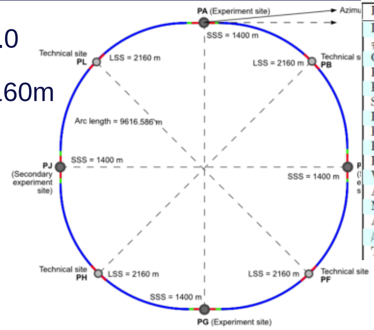
Gradual complexification of the simulations:

- **Magnets**: From only one quadrupole to all quadrupoles of the MDI region
- **Vertical vibration**: From a vertical static misalignment to mechanical related vibrations
- **Spatial coherence**: From no coherence to coherence between quadrupoles



Methodology (2)

PA31-1.0
4 IPs.
LSS=2160m



Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	

Tools:

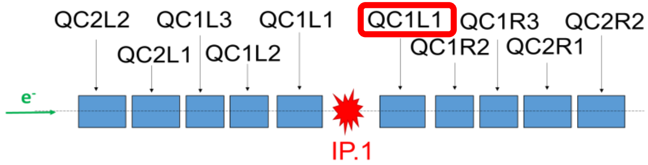
- Latest layout used (PA31-1.0)*, ~91 km long
- Z lattice considered, as smallest beam spot sizes at IP
- Optics simulation with MAD-X:
  Dynamical study → Tracking module used, number of accelerator turn dependent
- **Perfectly aligned accelerator** considered, to highlight vibrations impact on beam characteristics

Observables:

- MAD-X
  - y, py
- Post-treatment
  - Mean and Std deviations of y and py, corresponding to beam centroid and size
- Sensitivity
  - Standard deviation of the y mean

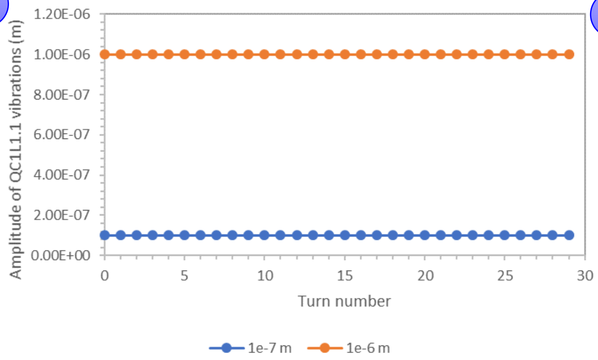
LAPP

First study cases (1)



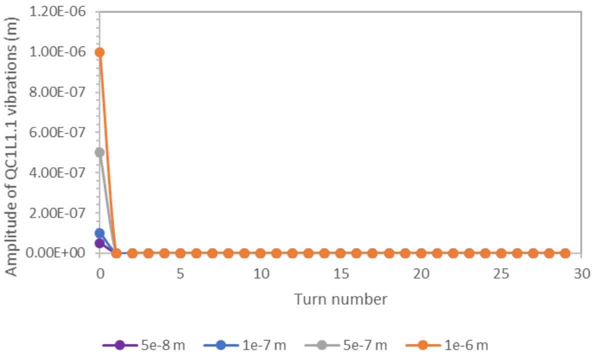
- Only one quadrupole, QC1L1.1, is concerned by vertical displacements/vibrations
- Bunch of 200 electrons are tracked
- 30 turns, i.e. 0.01 s *(not much, only to assess the behaviour of the machine…)*
- Three cases, from static to sinusoidal displacement:

1



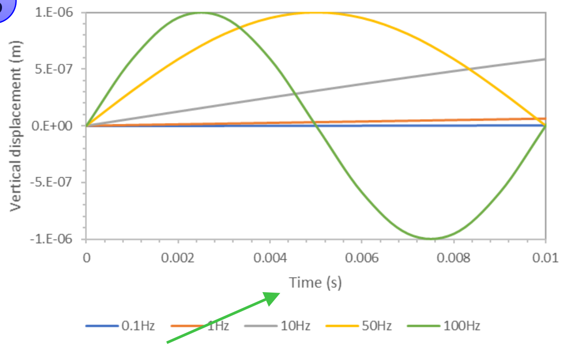
Static vertical displacement

2



“Bump” like vertical displacement

3



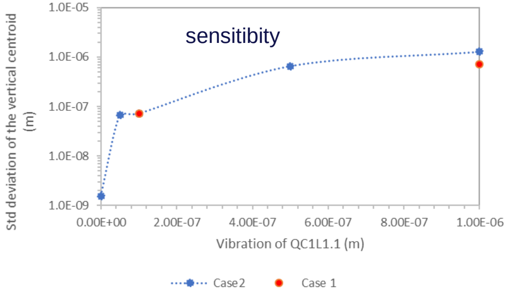
Change of axis scale

Sinusoidal vertical displacement (different frequencies)

IJCLab

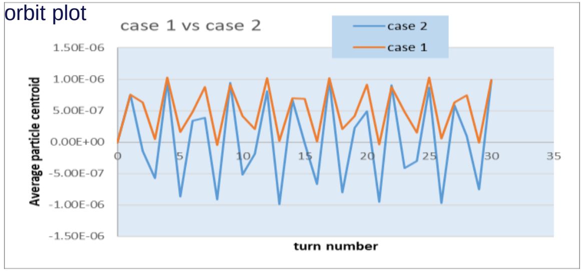
First study cases: sensitivity (2)

1 Case 1: static vertical displacement
2 Case 2: « bump » like displacement



- Variation of the standard deviation of the beam centroid, relative to very local displacement, for **30 turns** (same parameters, quads, turn, seeds)

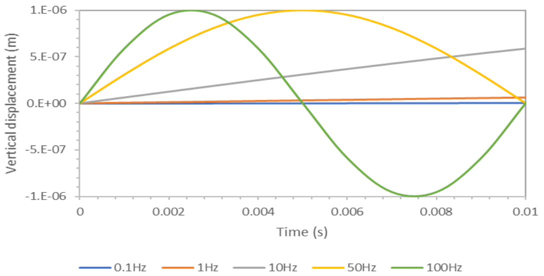
- Two static cases in study here.
  - The sensitibity plot is a tree that « hides the forest » as the centroid oscillates in different manner for both cases.
  - The orbit plot of the two cases indicates that once we hit a potential frequency, the beam will be continuously shifted (expected here)



Towards "real" vibrations (i.e. time-dependent):

- Consideration in terms of time, not in number of turns anymore, as one period of a sinusoidal vibration corresponds to a certain amount of time, different for each frequency.

- Studies ongoing



Conclusions on vibrations in MDI

Method:

Tools are set up to simulate more and more realistically the vibrations in the MDI region:

- MAD-X Tracking module adapted to time-dependent vertical displacements of quadrupoles
- Automatization of data processing
- Crosscheck and validate the process with simple study cases *(not realistic yet…)*

Studies ongoing

Perspectives:

Complexify simulations while considering:

- Quadrupoles concerned by vibrations
- Vibrations defined relative to the mechanical design, and add of coherence
- Longer time of machine run, *i.e.* >> 30 turns ⇔ 0.01 s

In parallel:

Provide the same simulations with SuperKEKB cryostat vibrations to compare with real measurements of luminosity

M. Serluca *et al.*, Vibration and luminosity frequency analysis of the SuperKEKB collider, NIMA 1025 (2021) 166123

EFFECT OF PLANE GROUND WAVES ON THE CLOSED ORBIT OF FCC-EE

Simulations of plane ground waves (1)

Aims:

- Compute the response of FCC-ee to coherent plane ground waves
- Compare simulation results obtained to the ones of other machines (*e.g.* LEP, LHC)

Definitions:

- The plane ground wave is described by:
  - its amplitude: 1 μm
  - its oscillation frequency: from 0.1 to 100 Hz
  - its phase advance *(0 for now in the first works)*

- To refer to literature: Amplification factor: $\frac{closed\ orbit\ offset}{ground\ motion\ amplitude\ at\ quad}$; Harmonic number $\mathrm{h} = \frac{C}{\lambda}$

J. Roßbach, Closed-orbit distortions of periodic FODO lattices due to plane ground waves, Particle Accelerators 23 (1988) 121-32
E. Keil, Effect of plane ground waves on the closed orbit in circular colliders, CERN SL/97-61 (1997)
R.J. Steinhagen, LHC Beam Stability and Feedback Control - Orbit and Energy, CERN-THESIS-2007-058 (2007)

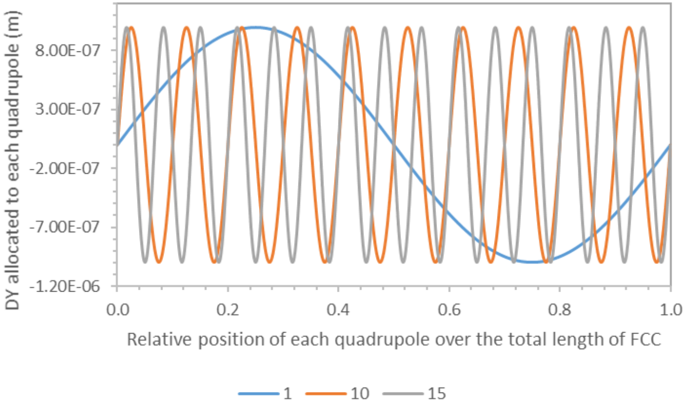
Simulations of plane ground waves (2)

No tracking module used

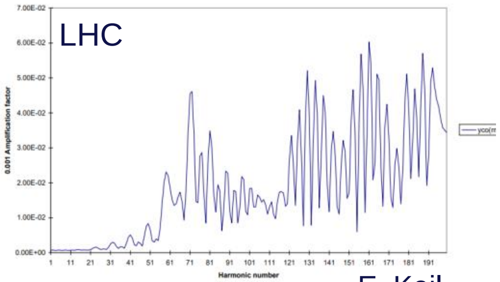
Procedure in MAD-X:

TWISS of the nominal sequence → Assigning vertical displacements of all quadrupoles relative to ground motion → TWISS of the "misaligned"sequence → Extraction of the vertical closed orbit offset

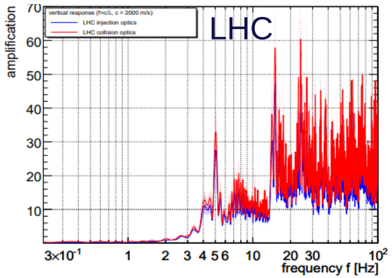
Plot the amplification factor relative to frequency/harmonic number



Number of oscillations or periods relative to FCC total length



E. Keil



R. Steinhagen

Study ongoing

Conclusions and Perspectives

- Setup of a 3D mechanical model, whose aim is to deliver the magnet's displacements relative to ground motion induced vibrations

Two beam optics studies run in parallel:

- Impact of time-dependent vertical vibrations applied in the MDI region on beam characteristics
  - Cumulative perturbation of quadrupoles located in the MDI along time
- Effect of plane ground waves on the closed orbit of FCC-ee
  - No cumulative perturbation, vertical misalignments allocated to all quadrupoles along the ring.

Both studies will require dedicated investigation to provide more realistic results.

At a longer term:

- Define vibrations relative to mechanics design
- Add local and global corrections
- Consideration of both positron and electron beams

Many thanks to: M. Boscolo, T. Charles, M. Hofer, K. Oide, G. Roy, L. Van Riesen-Haupt, F. Zimmermann and the whole FCC-ee collaboration team

Thank you
for your attention!

Vibrations studies

Magnetic field

Magnet positioning

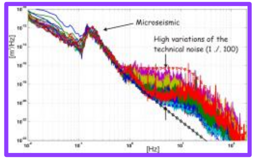
Coupling Cryostat - magnet

Cryostat support

Girder

Positioning system
& alignment

Concrete



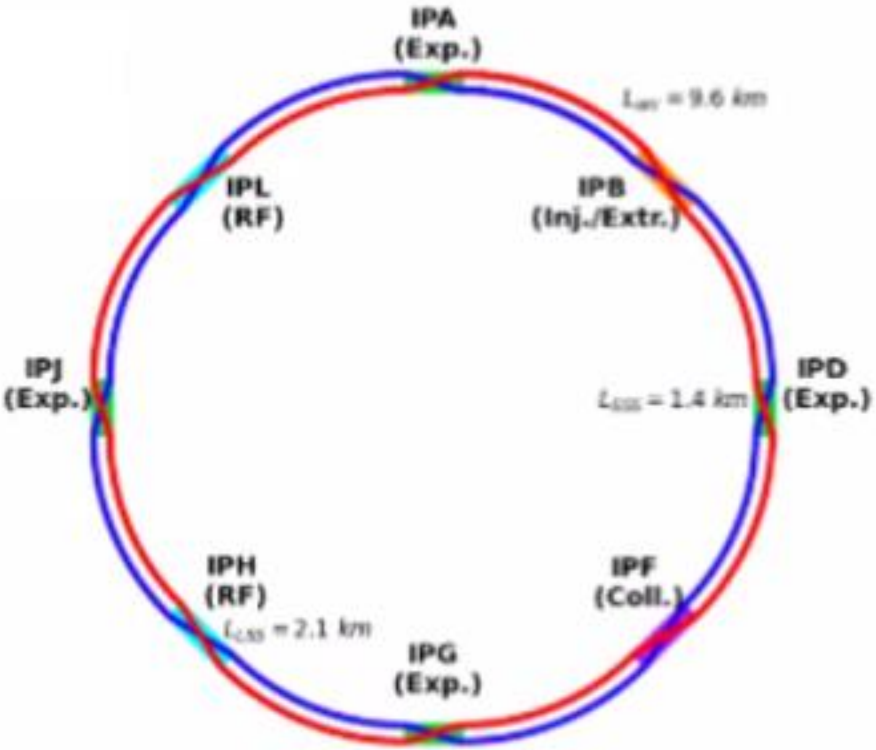
Ground Motion excitation

All defined by mechanical transfer functions
+
Ground coherence

Aims: link beam optics and mechanical design

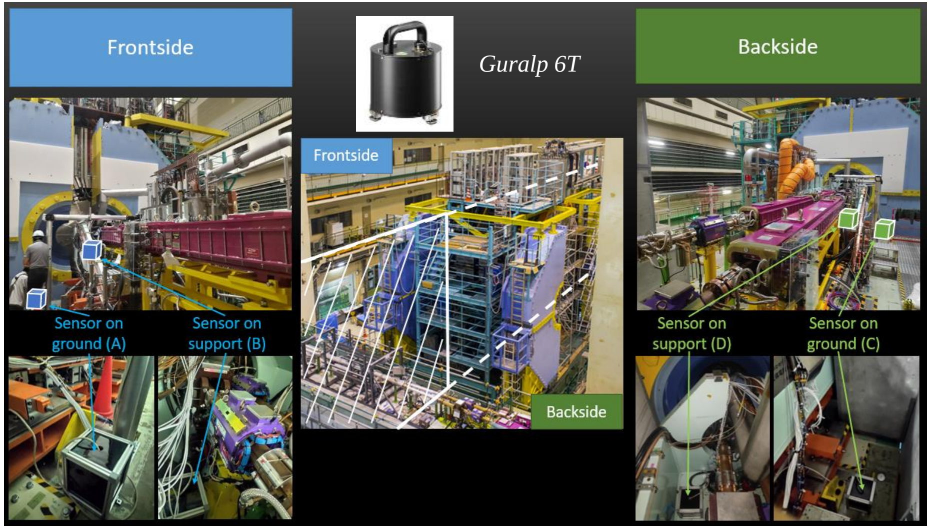
1. Integration of **dynamic effects** of each IP side: **vibrations** localized in the **MDI** region

2. Impact of **plane ground waves** on the closed orbit to evaluate global coherence: vertical **displacements** assigned to **all quadrupoles**


IPA
(Exp.)
$L_{arc} = 9.6$ km
IPL
(RF)
IPB
(Inj./Extr.)
IPJ
(Exp.)
$L_{LSS} = 1.4$ km
IPD
(Exp.)
IPH
(RF)
$L_{LSS} = 2.1$ km
IPF
(Coll.)
IPG
(Exp.)

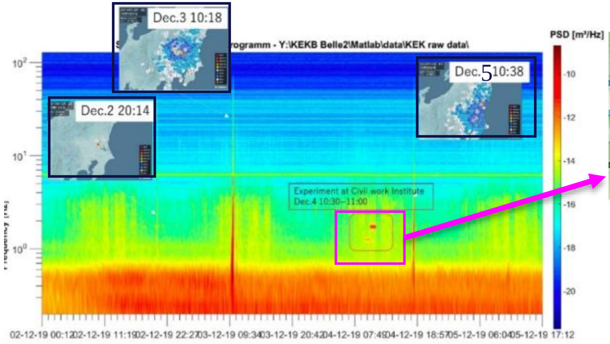
Application on SuperKEKB - setup

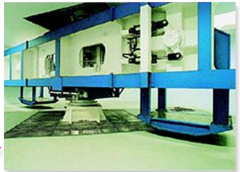
- **SuperKEKB – vibration measurements**



4 seismic sensors - 2 at each side of the BELLE II detector

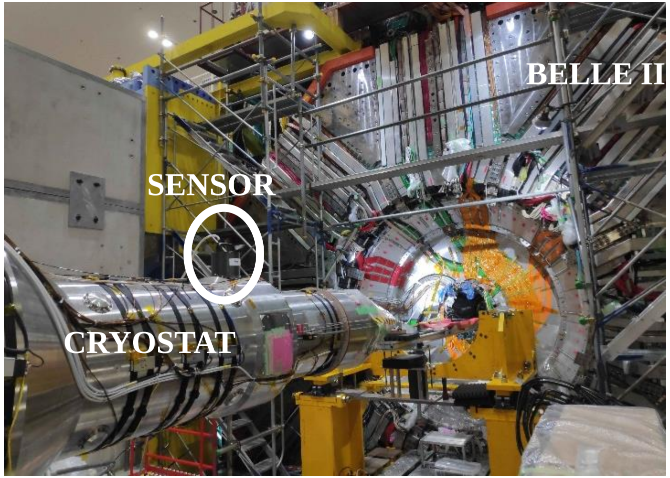
- **Long-term monitoring with continuous available data for the collaboration**
  - Monitoring of the seismic motion and the collider cultural noise
  - Identification of disturbances or specific event (not the topic)
  - Weekly reports are available at : https://lappweb.in2p3.fr/SuperKEKB/





Experiment of accelerate centrifugal force close to KEK

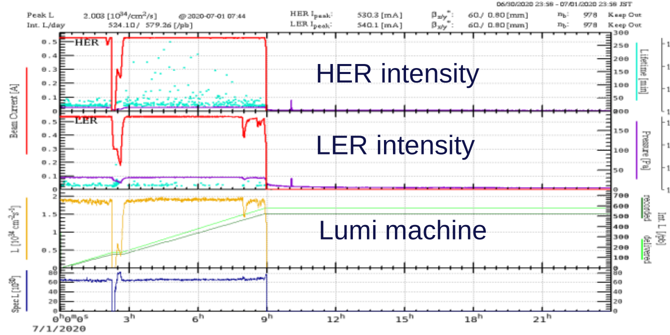
Vibration analysis: earthquake and external perturbations

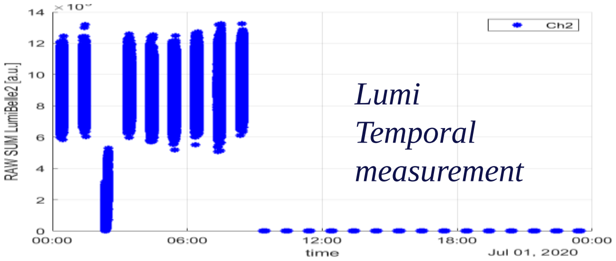


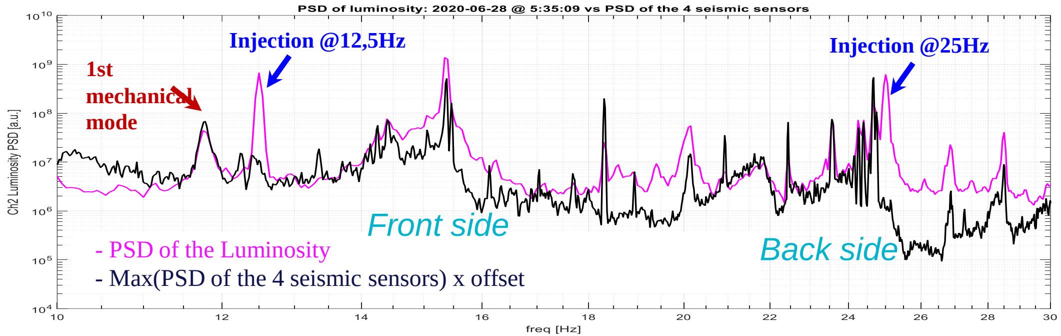
Preliminary measurements
Modelling and measurements done by KEK are also available

SuperKEKB: comparison vibrations – luminosity (1)

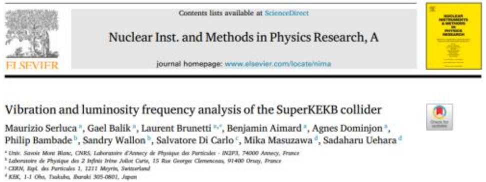
- **Comparison vibrations vs Luminosity monitoring via Bhabha scattering (IJCLab & KEK)**







- 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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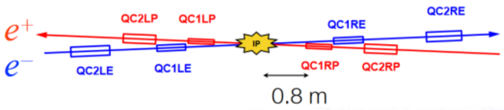
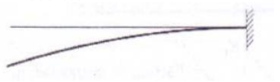
Vibration and luminosity frequency analysis of the SuperKEKB collider

Maurizio Serluca [a], Gael Balik [a], Laurent Brunetti [a], Benjamin Aimard [a], Agnes Dominjon [a], Philip Bambade [b], Sandry Wallon [b], Salvatore Di Carlo [c], Mika Masuzawa [d], Sadaharu Uehara [d]

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





1st cryostat flexion mode shape

- Differential motions between the final magnets

1. **Quantification**
2. **Low frequencies vs coherence**