FCC-ee MDI Vibrations mitigation & Positioning technics

G. Balik & L. Brunetti for the LAPP-FCC team

2nd FCC-France Workshop / January 20-21 2021

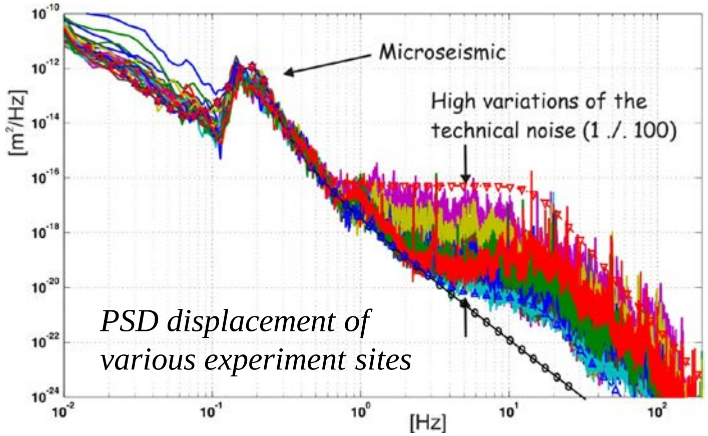
in collaboration with IJClab, KEK & CERN

The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union's Horizon 2020 research and innovation program under grant No 951754.

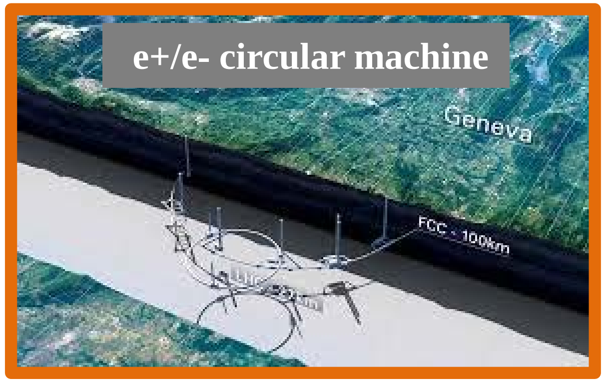
- **Vibrations mitigation tolerances**

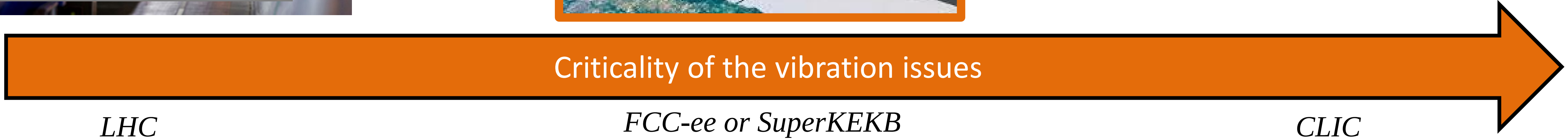
Energy	45.6	80	120	175
σx(IP) (µm)	6.4	13	13	36
σy(IP) (nm)	**28**	**41**	**36**	**66**

FCC-ee beam size in function of the energy



➢ What are the vibrations tolerances of the elements, especially at the IP, given the vertical beam size?





LHC *FCC-ee or SuperKEKB* *CLIC*

- Vibrations mitigation are less critical than for the linear colliders (single pass, nano beam…) but in which limits…
- Strategy of the vibrations mitigation for FCC-ee?

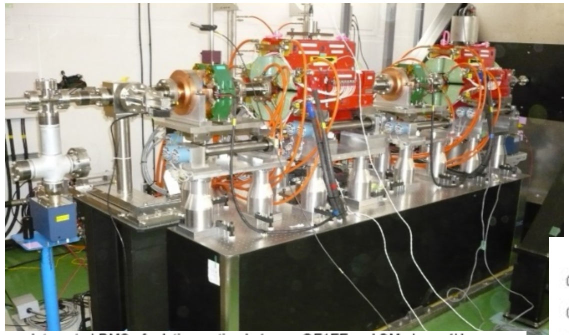
FCC ee mitigation

- **Vibrations mitigation strategy – illustrations with LAPP developments**

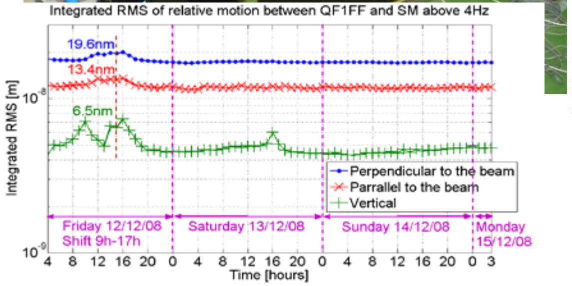
Option "low cost"

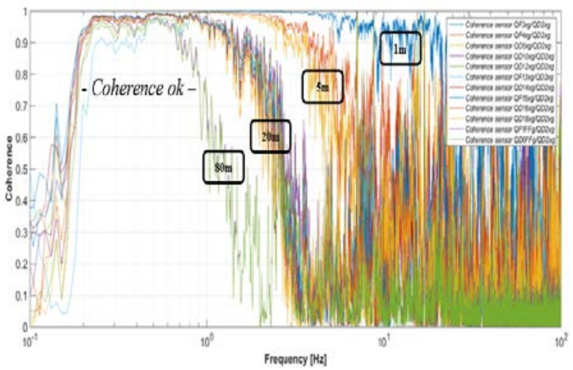
- **Based on the coherence motion, reducing the relative motions between the elements : strategy of the main experiments**

Example of ATF2 (jp) : relative motion between shintake monitor and final doublets of [4 – 6] nm RMS @ 0,1 Hz (vertical axis):



Very stiff in z direction (first eigenfrequency at 70Hz induced by the final doblets supports) - beeswax

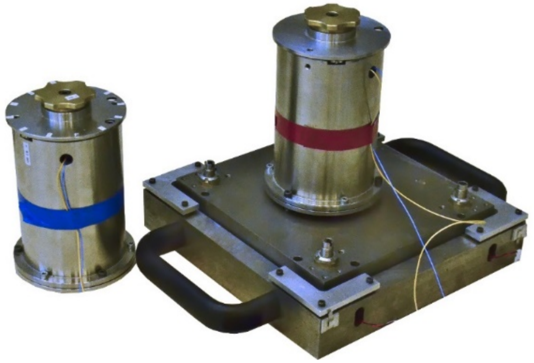




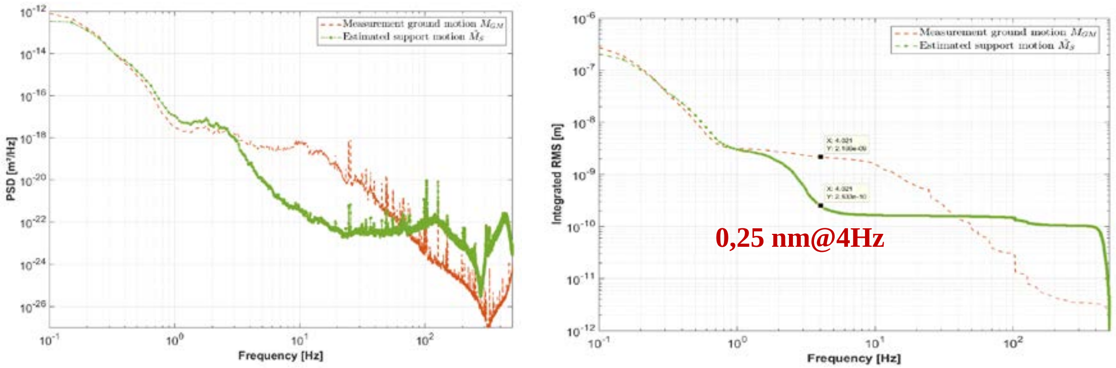
Option "high cost"

- **Active control: reducing the absolute motion**

Example of CLIC : feasibility demonstration of an absolute displacement of 0,25nm RMS@4H with specific actuators and developed sensors



- LAPP active foot + LAPP sensors (one on ground used to monitor ground motion and 1 on top used in feedback) -



*- Displacement **without control** / **with control** at LAPP -*

Coherence

Strategy for FCC-ee?

Active control

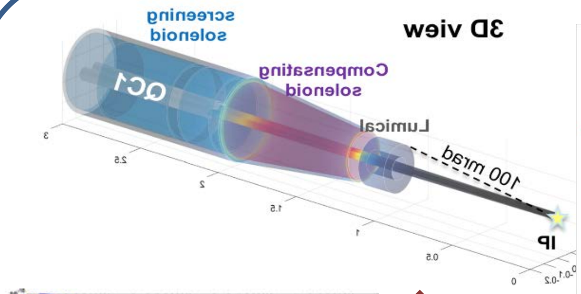
Criticality of the vibration issues

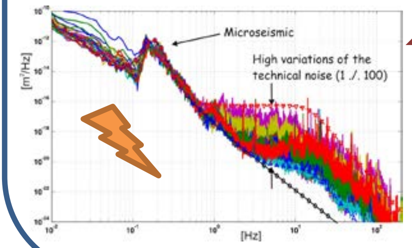
Not very critical | **Has to be defined** | **Extremely critical**

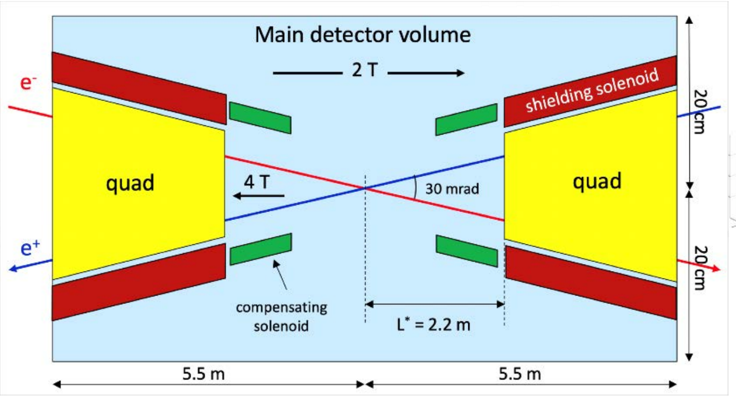
- **First approach: MDI strategy**

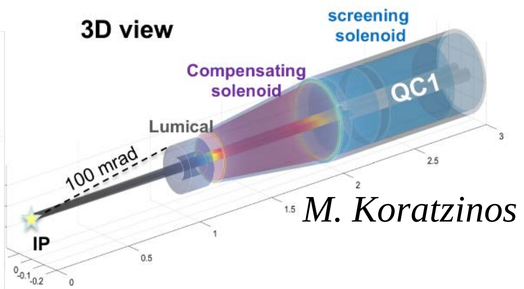
The FF quads for the e+ and e- beams are closed (axes distance of about 100 mm) and the revolution frequency of the machine is about 3 KHz, then we could consider that:

- In principle, any coherent motions of the e+ and e- FF quads per side creates the same orbit deviation for both beams *(except for the main arc quadrupoles where beta functions are different, need to be investigated also in relation to positioning concept)*
- Only the incoherent motions needs to be investigated.

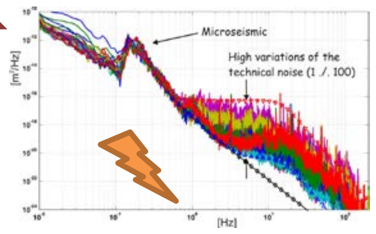




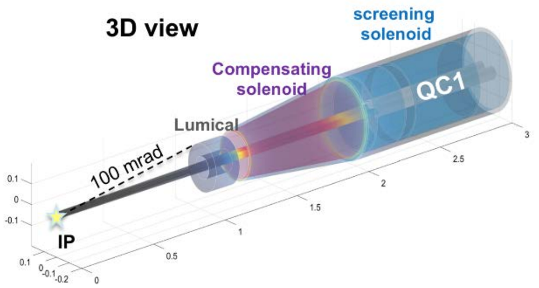




M. Koratzinos



Strategy based on the coherence at the both side?

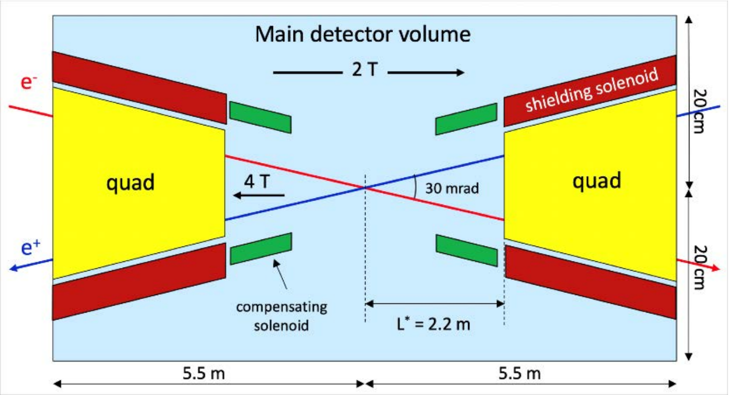


Active (and / or passive) control

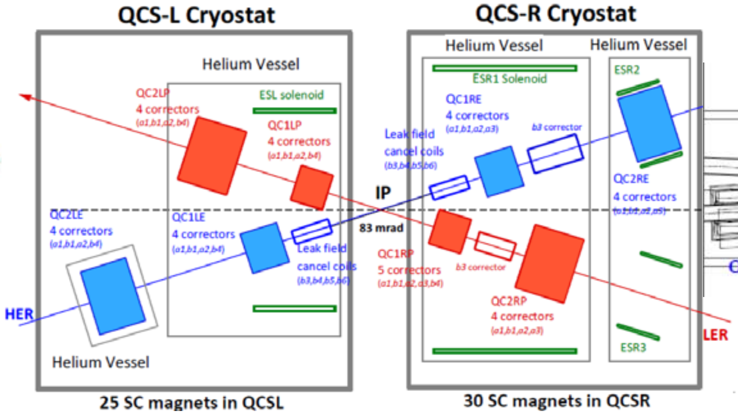
- **Validation of this approach? Within which limits?** *Multiturns vs length & nanobeam*

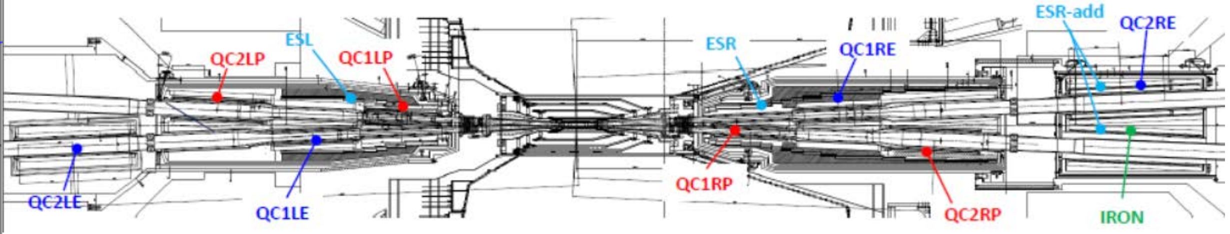
- Note that the orbit feedback (beam-beam deflection) based on IP BPM and kicker will have an action on an estimated bandwidth about [0 to 20-40 Hz] (depending the IP BPM resolution) with an efficiency which will decrease in function of the frequency

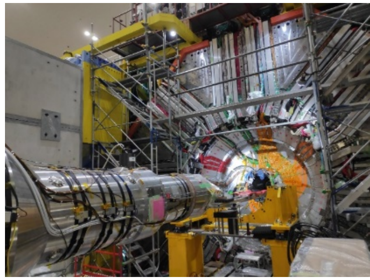
Vibration mitigation : SuperKEKB vs FCC-ee



	SuperKEKB	FCC-ee
Energy(GeV)	7 (e^-) | 4(e^+)	45.6,80,120,175
σx(IP) (μm)	11 | 10	6.4,13,13,36
σy(IP) (nm)	56 | 48	28,41,36,66
Cryostat in cantilever	yes	yes





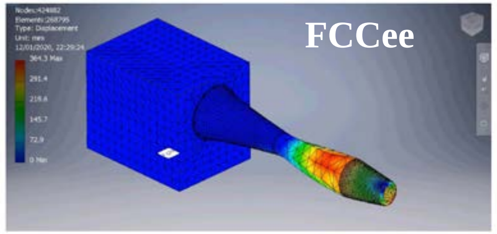


- **Similarities, advantages and opportunities:**

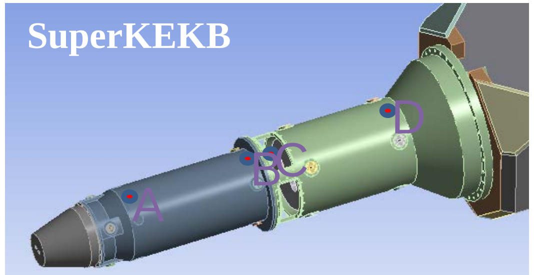
  Collider in operation, similar beam, cryostat in cantilever
  Various common issues : BPM resolution, IP feedback…

- **Difference:**

  The HER and LER final focus magnets are not symmetrical inside the cryostat



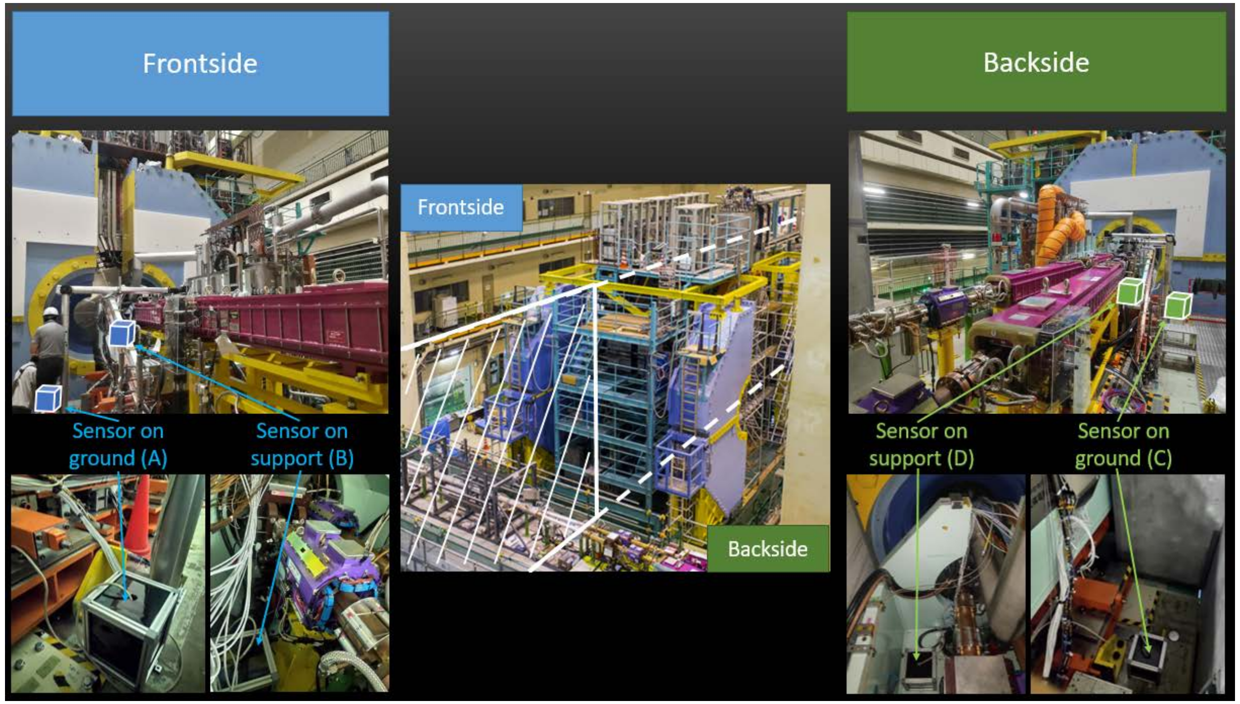
In my "version zero" toy mechanical simulation the twist mode (F9) had a main frequency of 306 Hz.



Design of the cryostat (KEK)

SuperKEKB - setup

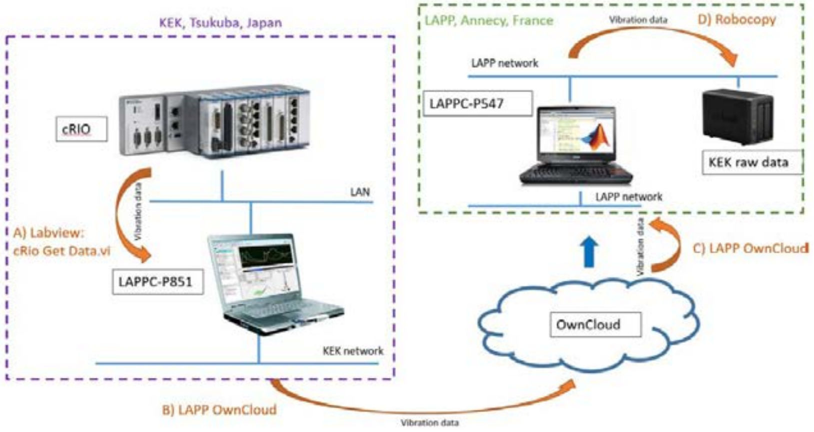
- **SuperKEKB – vibration measurements**



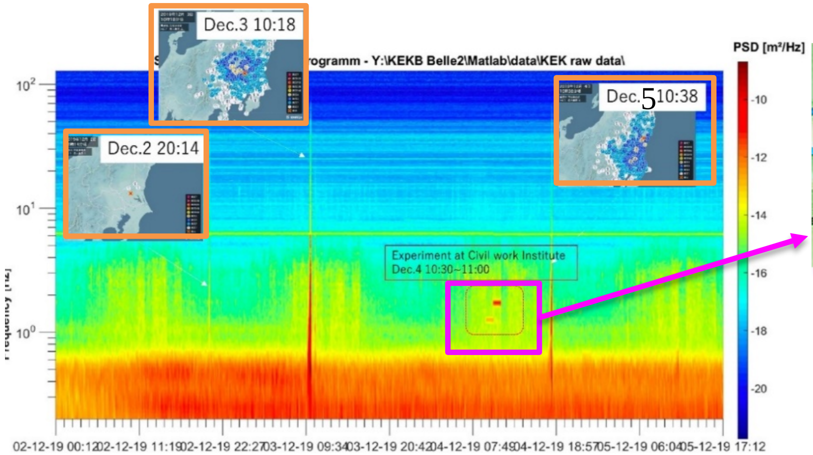
4 seismic sensors - 2 at each side of the BELLE II detector

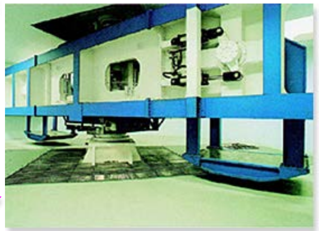
Monitoring 10'/hour to limit the data

Guralp 6T



Architecture of the acquisition





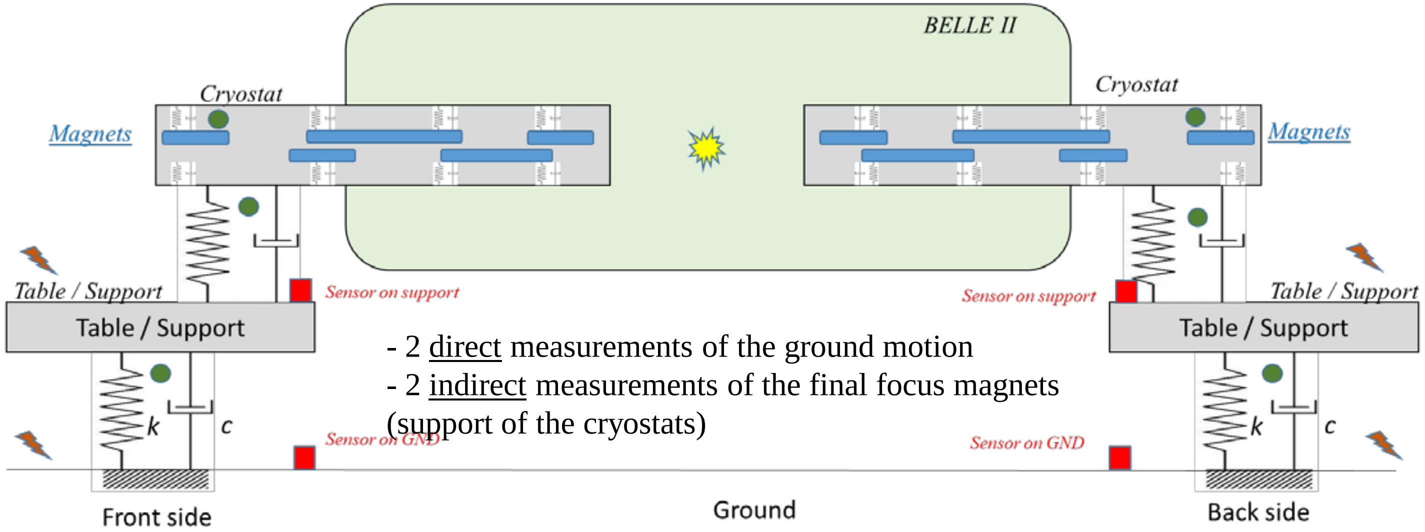
Experiment of accelerate centrifugal force close to KEK

Vibration analysis: earthquake and external perturbations

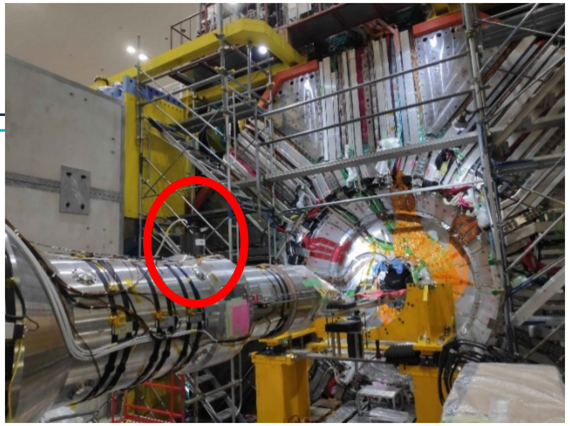
- **Long-term monitoring with continuous available data for the collaboration**
  - Monitoring of the seismic motion and the collider cultural noise
  - Identification of disturbances or specific event (not the topic)
  - Weekly reports are available at : https://lappweb.in2p3.fr/SuperKEKB/

SuperKEKB: current vibration measurements

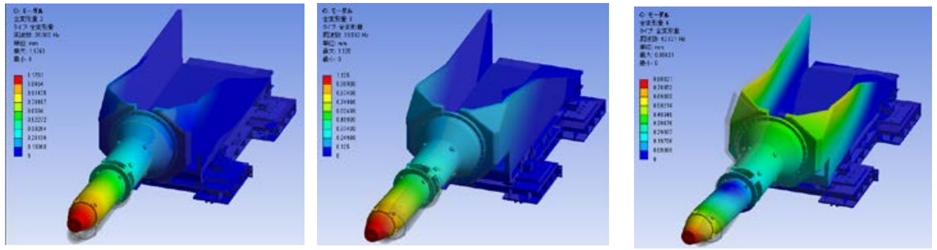
- **Setup:**
  - Disturbances on the ground
  - Disturbances on the support (table) and eigenfrequencies of the support (table)
  - Eigenfrequencies of the cryostat
  - Eigenfrequencies of the magnets



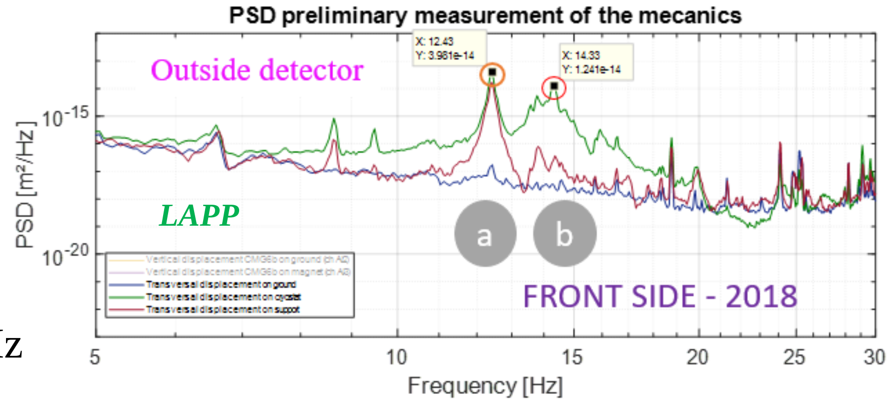
- 2 direct measurements of the ground motion
- 2 indirect measurements of the final focus magnets (support of the cryostats)



Dynamics measurements on the cryostat (LAPP)



Modelling done by KEK



PSD of displacements on the cryostat (vertical direction)

- **FCC-ee cryostat:**
  - SuperKEKB: current first modes at 15 Hz (frontside) & 25 Hz (backside)
  - A ratio of about at least 10 between the first flexion mode and the 1st twist mode seems reasonable
  - FCC-ee : The first simulated twist mode (modelled by M. Koratzinos) is at about 300 Hz

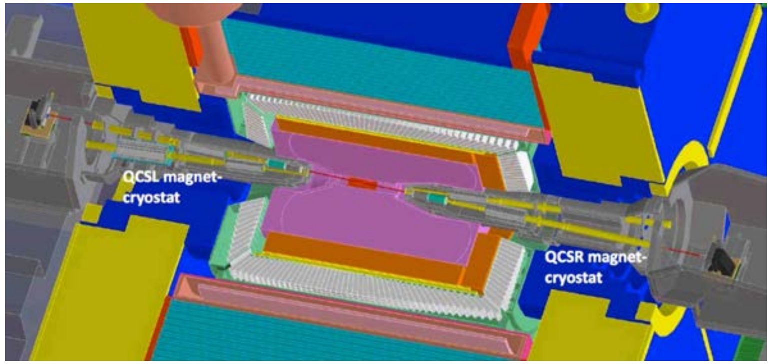
➢ **The limit conditions of the both cryostats are similar**

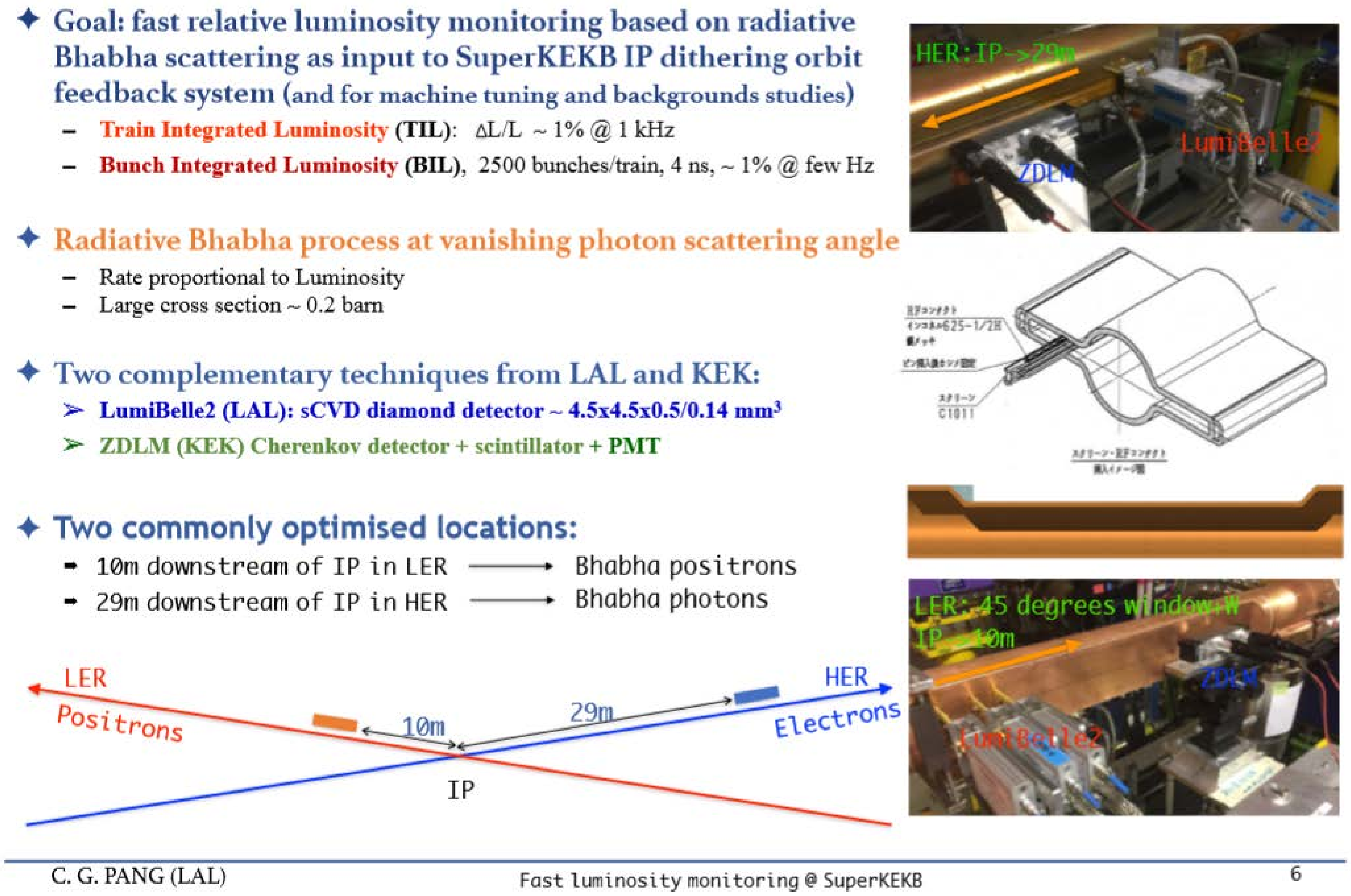
➢ **The indirect cryostat measurements allow to have an interpolation of the resonance modes**

SuperKEKB: luminosity measurements

➢ Correlation between vibrations measurements and luminosity measurements

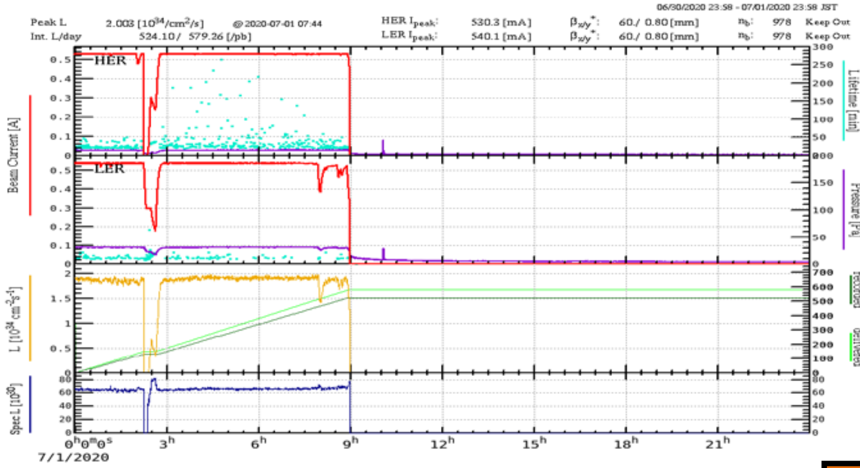
- 4 luminosity measurements (**IJClab**) 2 on the HER(e+) beam, 2 on the LER(e-) beam at 1 KHz
- About the same measurements (ZDLM) are done by **KEK**

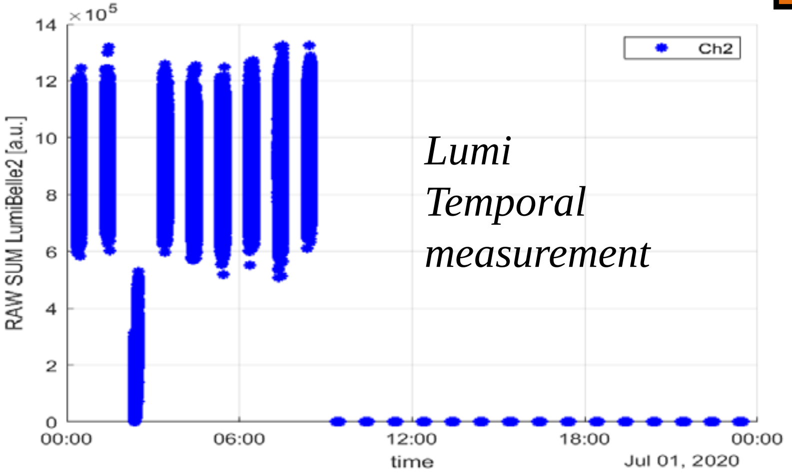


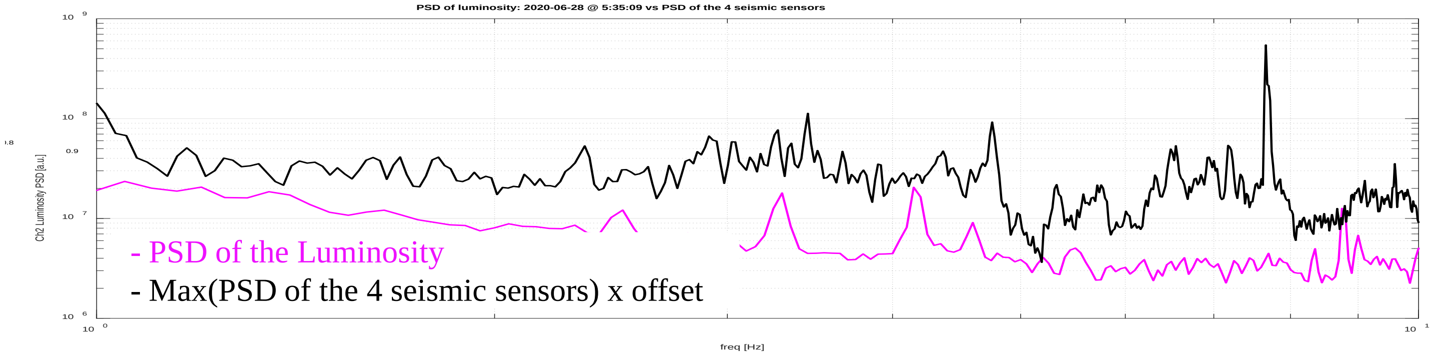


SuperKEKB : corrélation vib - lumi

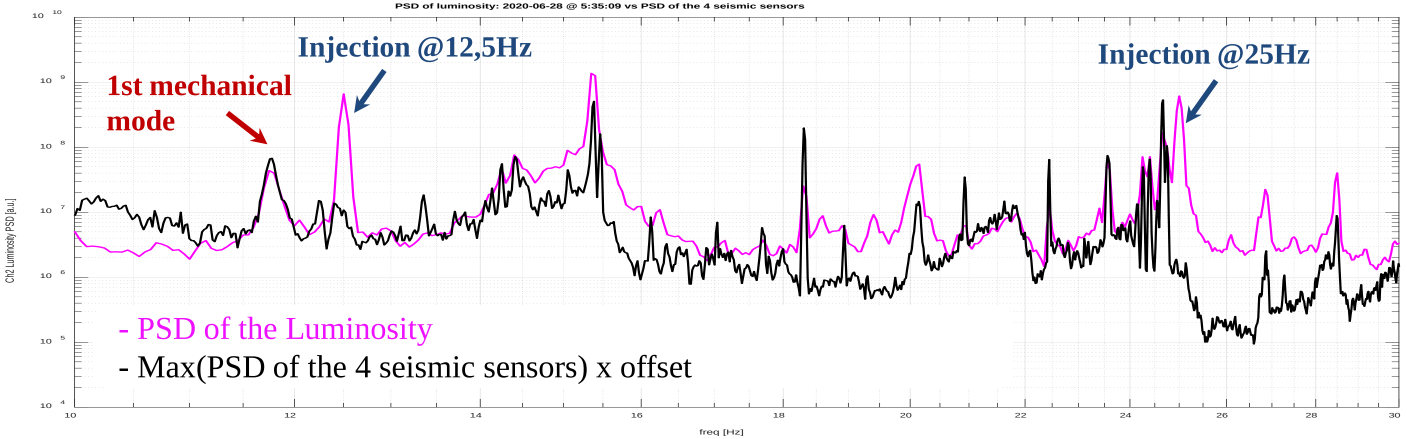
- **Method:**
  - ➢ *To understand the impact of vibrations on the beam with a disturbance that is either coherent on the whole accelerator (ex: seismic motion), or localized (ex: pump) or amplified by mechanics (ex: cryostat resonance mode of the asymmetric final focus)*







o No matching : the disturbances are coherent on the MDI area & efficiency of beam FB



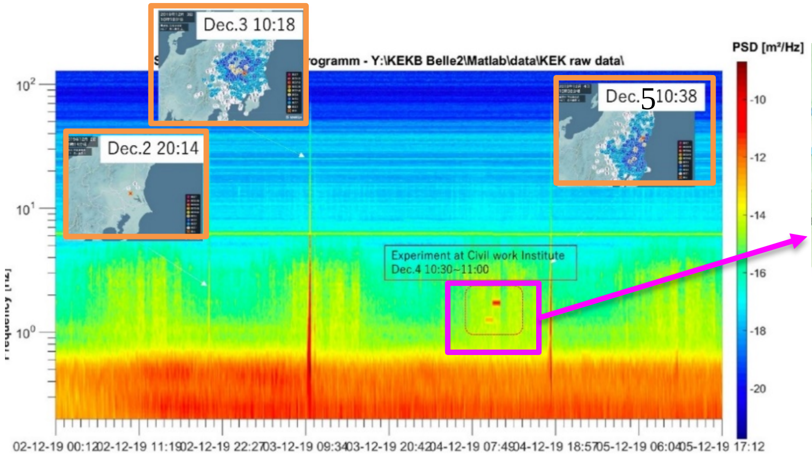
o Except the peaks at 12,5 Hz & 25 Hz dues to the injection, all the luminosity peaks are mainly dues to vibrations amplified by asymmetrical mechanical structures

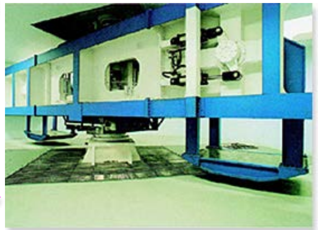
➢ **Study of specific cases (coherence between 0 and 1)**

➢ **Publication in progress & automatic data processing for the next operation beam**

SuperKEKB: correlation vibrations - luminosity

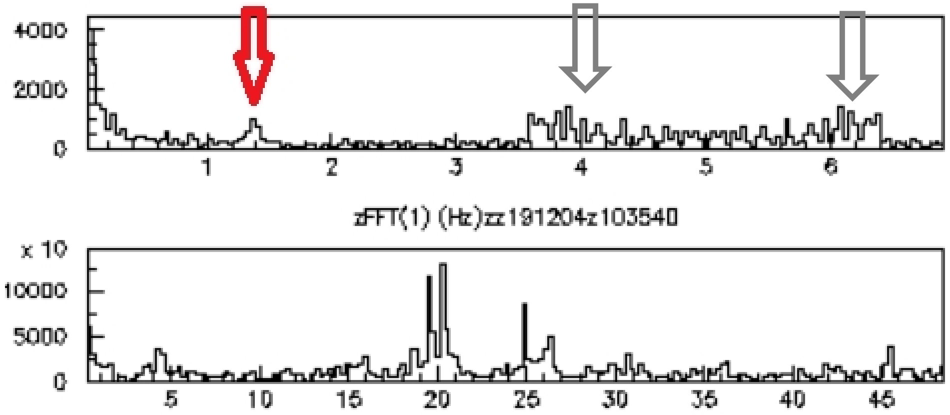
- **The limits (the tolerances…):**



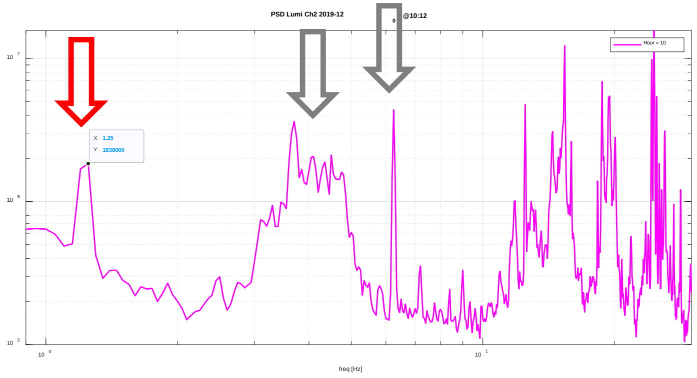


Experiment of accelerate centrifugal force close to KEK

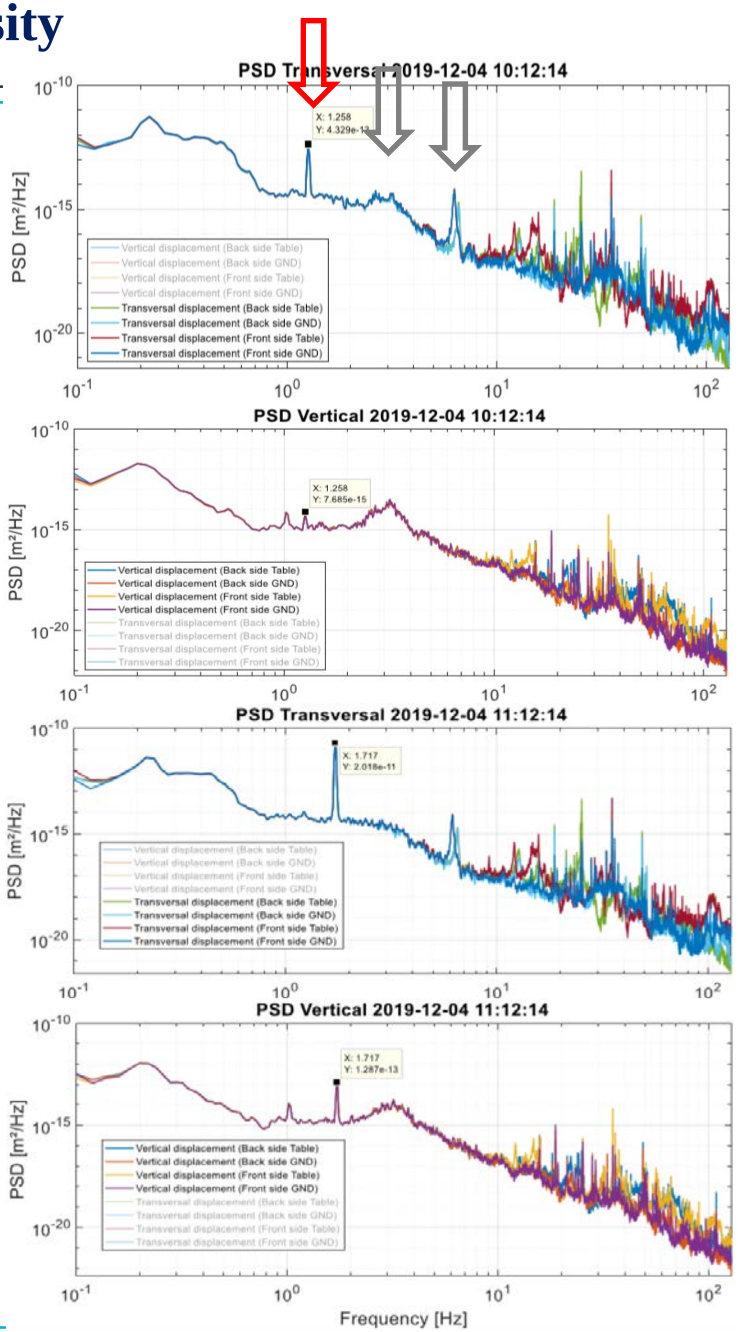
Vibration analysis: earthquake and external perturbations



FFT of the ZDLM luminosity (KEK)



PSD of the luminosity (IJClab) at the beginning of the acceleration phase



- The peak [1,2 – 1,7] Hz is measured (during the acceleration phase) by the luminometers and by the seismic sensors even if the disturbance effects are coherent for the four sensors…

FCC-ee positioning technics

- FCCee: nearly 100 km circumference and around 2900 quadrupole magnets -> dynamic positioning approach by girder seems more adapted
- The alignment requirements for past and future collider are defined for 3 distinct operational.

Pre-alignment – alignment positioning and optimization strategies

- During machine set-up prior to operation for physics production, a good relative alignment of accelerator structures and quadrupoles
- After a probe beam is successfully sent along the whole linac, beam-based methods that involve beam measurements and quadrupole position tuning are used to optimize the machine
- Optimization of the luminosity performance during standard operation

Beam off

And after ?

- Thermal variations
- Seismic activity / slow ground motion
- Slow drifts

Dynamic positioning

- Magnets, … (ATF2, CLIC)
- Girder (ESRF, SLS, CEPC, HEPS-TF…)

Positioning of girder and magnets during operation for the most complex and stringent systems

Beam on

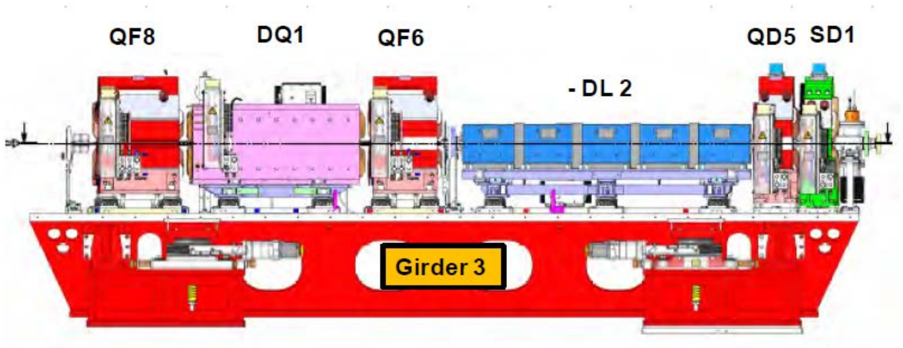
Present technical possibilities have to be compared to future physics requirements, to define which developments need to be undertaken

➢ **State of the art**

STATE OF THE ART - ESRF - EBS STORAGE RING

	Technology							Positioning type		Range	Resolution	Pitch/roll
	Nano system	Jacks	Cam mover	HLS	HPS	LVDT	WPS	Girder	Magnet			
ESRF	☐	☑	☐	☑	☐	☐	☐	☑	☐	5 mm	5 µm	NC
SLS	☐	☐	☑	☑	☑	☐	☐	☑	☐	2,5 mm	2 µm	NC
ATF2	☐	☐	☑	☐	☐	☑	☐	☐	☑	1,5 mm	2 µm	3-5 µrad
CLIC	☑	☐	☑	☐	☐	☐	☑	☐	☑	10mm/10 µm *	0,5 µm/0,45 nm*	1,3 µrad

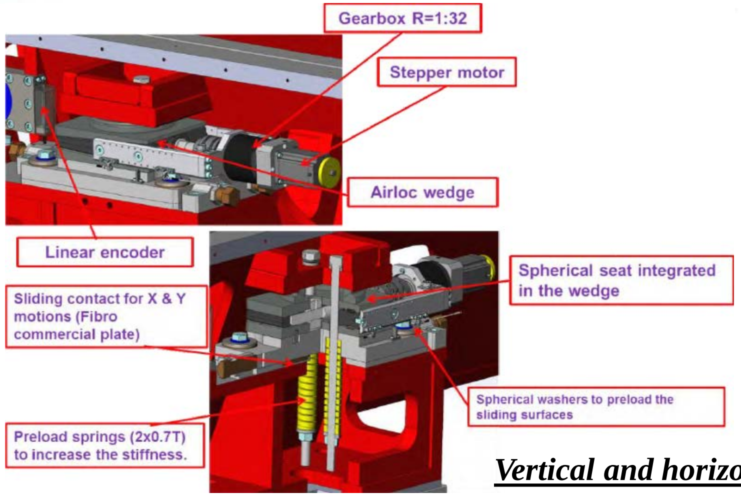
* Static/dynamic

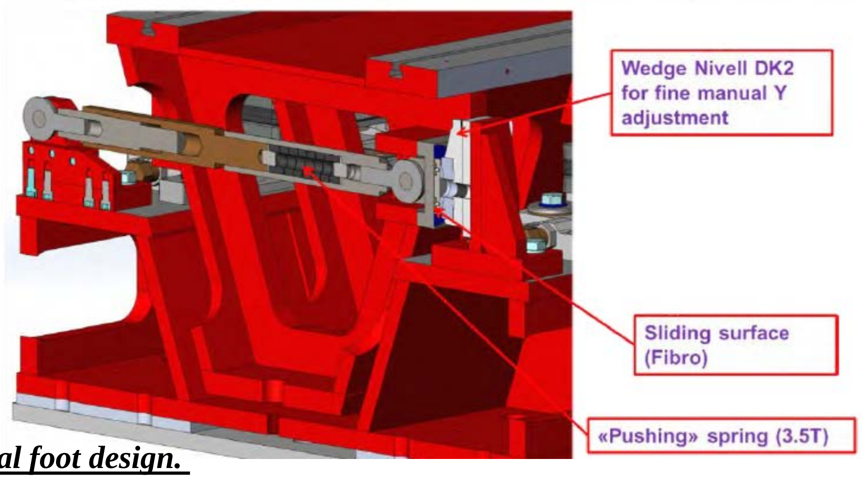


Girder 3 layout

- ESRF storage ring is composed of **129 girders**
- The girders are all identical with a length about 5.1m and 6 tons
- A re-alignment of the girders in the vertical direction will be necessary every six months because of the medium-term displacements of the storage ring floor
- **First natural frequency > 35 Hz**
- Vibrations amplification factor (over 1-100 Hz) < 1.1

- Each girder is equipped with a ± 5 mm motorized vertical adjustment and a ± 5 mm manual transverse adjustment with 5 µm resolution – **Stepper motors and linear encoder**.
- And equipped with three **Hydrostatic Leveling System (HLS)** located immediately above





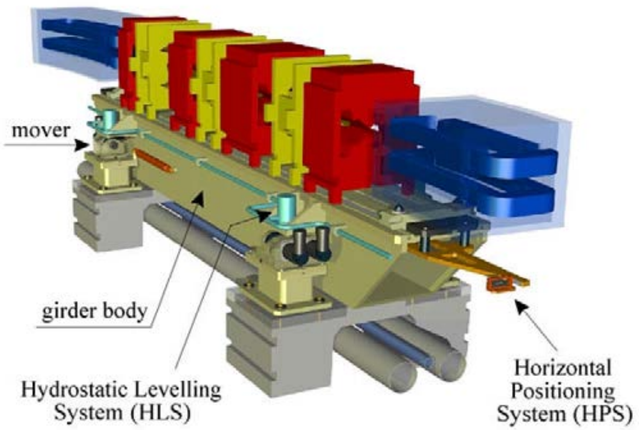
Vertical and horizontal foot design.

- *ESRF – EBS Design Report & F. Cianciosi, the girder system for the new ERF storage ring, MEDSI2016, Barcelona, Spain*

STATE OF THE ART - PSI - SWISS LIGHT SOURCE (SLS)

	Technology							Positioning type		Range	Resolution	Pitch/roll
	Nano system	Jacks	Cam mover	HLS	HPS	LVDT	WPS	Girder	Magnet			
ESRF	☐	☑	☐	☑	☐	☐	☐	☑	☐	5 mm	5 µm	NC
SLS	☐	☐	☑	☑	☑	☐	☐	☑	☐	2,5 mm	2 µm	NC
ATF2	☐	☐	☑	☐	☐	☑	☐	☐	☑	1,5 mm	2 µm	3-5 µrad
CLIC	☑	☐	☑	☐	☐	☐	☑	☐	☑	10mm/10 µm *	0,5 µm/0,45 nm*	1,3 µrad

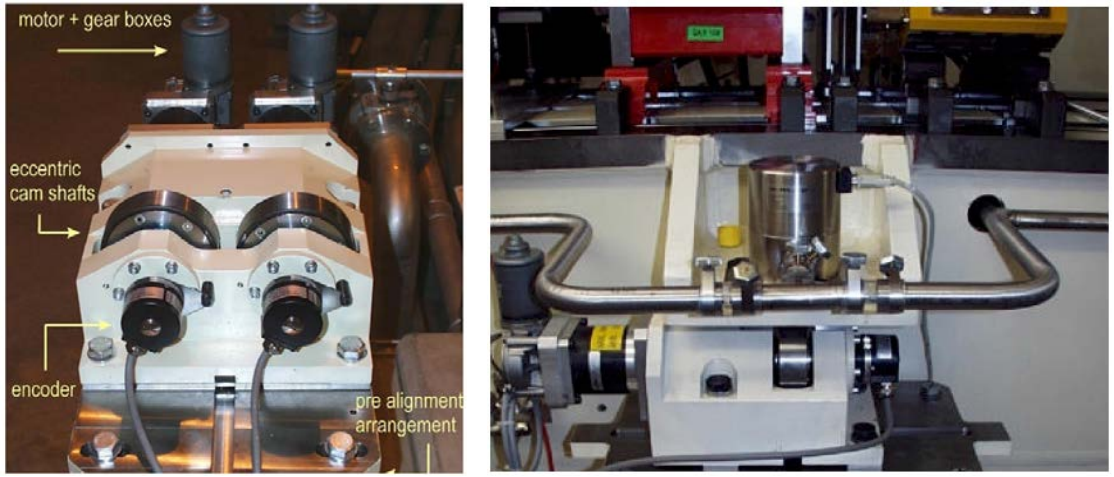
* Static/dynamic



SLS storage ring girder assembly

- **The girder mover system based on five DC motors per girder allows a dynamic realignment of the storage ring**
- The **Hydrostatic Levelling System** (HLS) gives an absolute vertical reference, while the horizontal positioning system (HPS), which employs low cost **linear encoders** with sub-micron resolution, measures relative horizontal movements

The 192 **HLS** sensors are connected by a stainless steel pipe of 25 mm diameter. The system was conceived to monitor any relative and global vertical position change with a resolution of < 2 µm and within a working window of 2.5 mm.



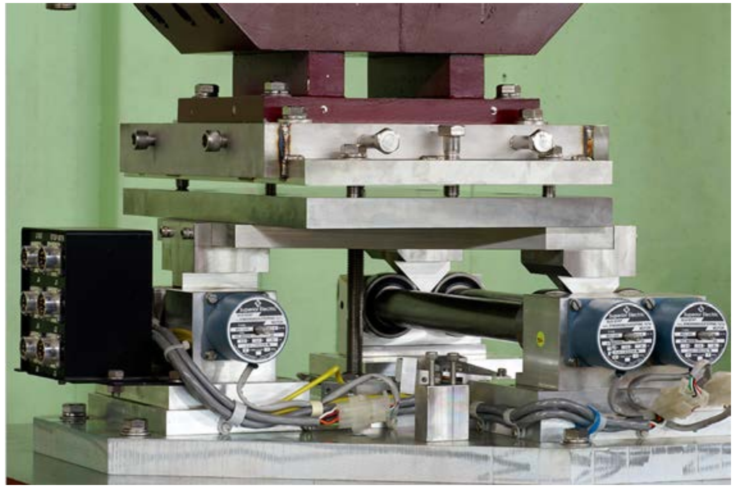
CAM mover and HLS sensor with water pipe connection.

- *DYNAMIC ALIGNMENT AT SLS, V.Schlott et all, SLAC-PUB-9720*

STATE OF THE ART - ACCELERATOR TEST FACILITY (ATF2)

	Technology							Positioning type		Range	Resolution	Pitch/roll
	Nano system	Jacks	Cam mover	HLS	HPS	LVDT	WPS	Girder	Magnet			
ESRF	☐	☑	☐	☑	☐	☐	☐	☑	☐	5 mm	5 µm	NC
SLS	☐	☐	☑	☑	☑	☐	☐	☑	☐	2,5 mm	2 µm	NC
ATF2	☐	☐	☑	☐	☐	☑	☐	☐	☑	1,5 mm	2 µm	3-5 µrad
CLIC	☑	☐	☑	☐	☐	☐	☑	☐	☑	10mm/10 µm *	0,5 µm/0,45 nm*	1,3 µrad

* Static/dynamic



- 20 quadrupole magnets and 3 sextupole magnets in the final focus area were put on remote-controlled 3- axis movers recycled from the FFTB at SLAC.
- Each mover has three camshafts which allow adjustment in horizontal and vertical position (with precision of 1-2 µm and a resolution of about 0.04 µm) as well as rotation angle (tilt, with precision of 3-5 µrad).

- The **camshaft driving motors** are controlled through a CAMAC mover module.
- The potentiometer read backs of the camshaft rotation are read out through an ADC.
- There are also 3 **LVDT** on each mover magnet support plate which are read out via CAMAC modules.
- The interface to these modules is provided by an EPICS control system running in the CAMAC crate controller

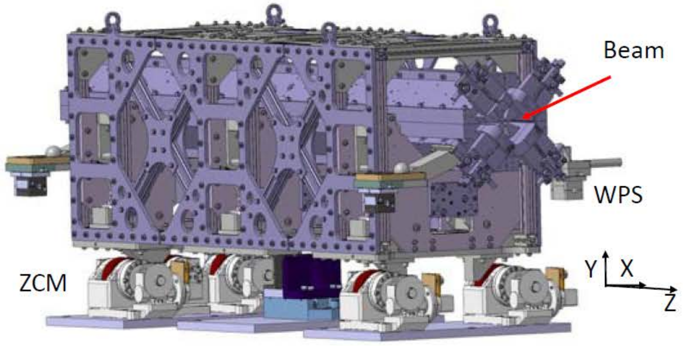
- *ATF2 Commissioning, A. Seryi et al., HAL Id: in2p3-00447323 http://hal.in2p3.fr/in2p3-00447323*

STATE OF THE ART - CERN - THE COMPACT LINEAR COLLIDER (CLIC)

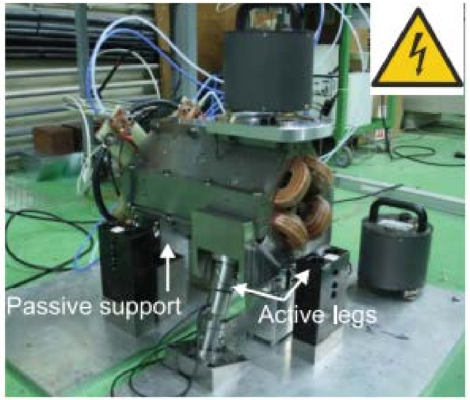
	Technology							Positioning type		Range	Resolution	Pitch/roll
	Nano system	Jacks	Cam mover	HLS	HPS	LVDT	WPS	Girder	Magnet			
ESRF	☐	☑	☐	☑	☐	☐	☐	☑	☐	5 mm	5 µm	NC
SLS	☐	☐	☑	☑	☑	☐	☐	☑	☐	2,5 mm	2 µm	NC
ATF2	☐	☐	☑	☐	☐	☑	☐	☐	☑	1,5 mm	2 µm	3-5 µrad
CLIC	☑	☐	☑	☐	☐	☐	☑	☐	☑	10mm/10 µm *	0,5 µm/0,45 nm*	1,3 µrad

* Static/dynamic

Pre-alignment stage with beam off: cam-mover alignment system positioning with wire position sensor feedback system



- Based on the **cam mover** from Swiss Light Source (SLS)
- The cam mover design was optimized together with the company ZTS VVU Kosice
- Feedback directly from alignment sensors (Wire Position Sensors)



Active-positioning: System Control for the CLIC Main Beam Quadrupole <u>Stabilization and Nano-Positioning</u> with specific actuators

Reduction of the vibration level from 6 nm to 0.45 nm integrated RMS at 1 Hz was achieved for a type 1 magnet, well under the requirements.

- *Stabilisation and precision pointing quadrupole magnets in the Compact Linear Collider (CLIC), Stef Marten Johan Janssens, Thesis*
- *Kemppinen, J; Griffet, S; Leuxe, R; Mainaud Durand, H; Sandomierski, J; Sosin, CLIC main beam quadrupole active pre-alignment based on cammovers, EuCARD-CON-2012-026*

Conclusions & prospects

- **FCCee MDI vibrations mitigation:**
  - A lot of similarities SuperKEKB – FCC-ee
  - Vibrations & luminosity data are available in real time
  - Correlation between vibrations and luminosity are identified
  - Some cases are specific to SuperKEKB & Some peaks analysis in low frequency seem to confirm the theoretical approach with the coherence and the multi –turns experiments specificities but in certain limits which have to be evaluated…
  - Some other more complex situations have to be more investigated…
  - Future prospects: IP feedback and orbit measurements

➢ **SuperKEKB is a great experiment which could be very helpful to study the vibration mitigation aspects of FCC-ee**

- **FCCee Positioning technics:**
  - Given the huge number of magnets and components needing positioning and the stringent alignment requirements, a dynamic positioning approach for girder seems judicious.
  - A more precise and individual positioning of the elements like for CLIC magnet is possible but would need to be refined by optical simulations according to the tolerances.
  - Dynamic positioning system should be considered in the vibration mitigation issues of the MDI working group (ex: HEPS-TF with a locking system - Haijing Wang et al 2018 J. Phys.: Conf. Ser. 1067 082023)
  - No clear dynamic positioning strategy defined yet.

➢ *The next Accelerator Test Facility (ATF3) is under way. This should be considered as an opportunity to solve the current vibration issues of the final focus in testing a girder strategy with a dynamic positioning dedicated to the final focus supports. However, other opportunities should be considered (ex: coupled tests with BNL)*

SPARE

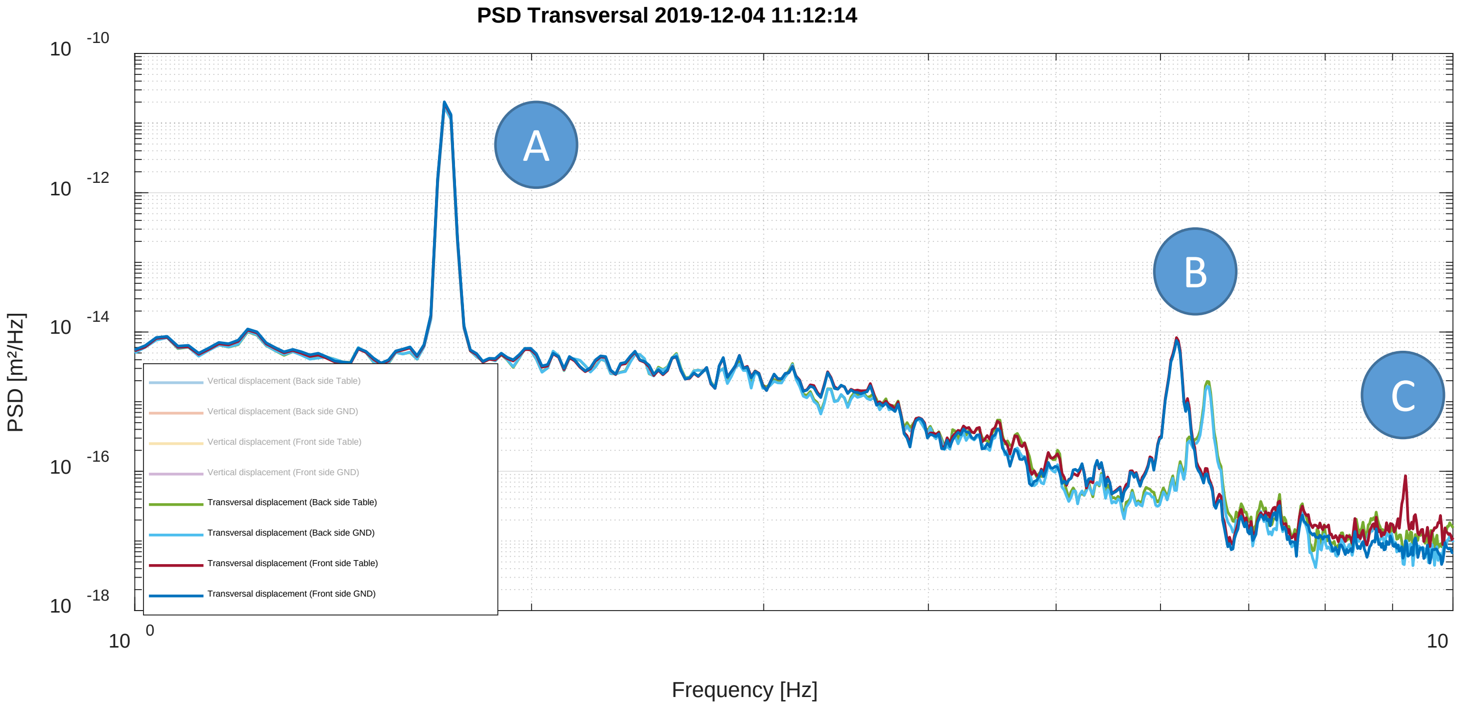
SuperKEKB : target of the correlation study (vibrations vs luminosity)

- The luminosity dynamics part is not present without disturbance: steady luminosity
- The luminosity disturbances come from various sources

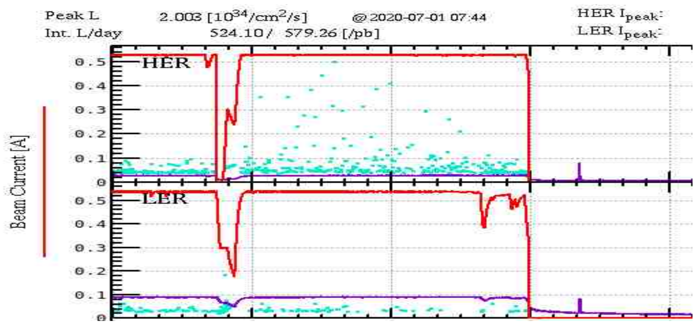
❑ **Variation of the luminosity in function of the disturbances in term of type, frequency, direction, amplitude…**

Types of disturbances:

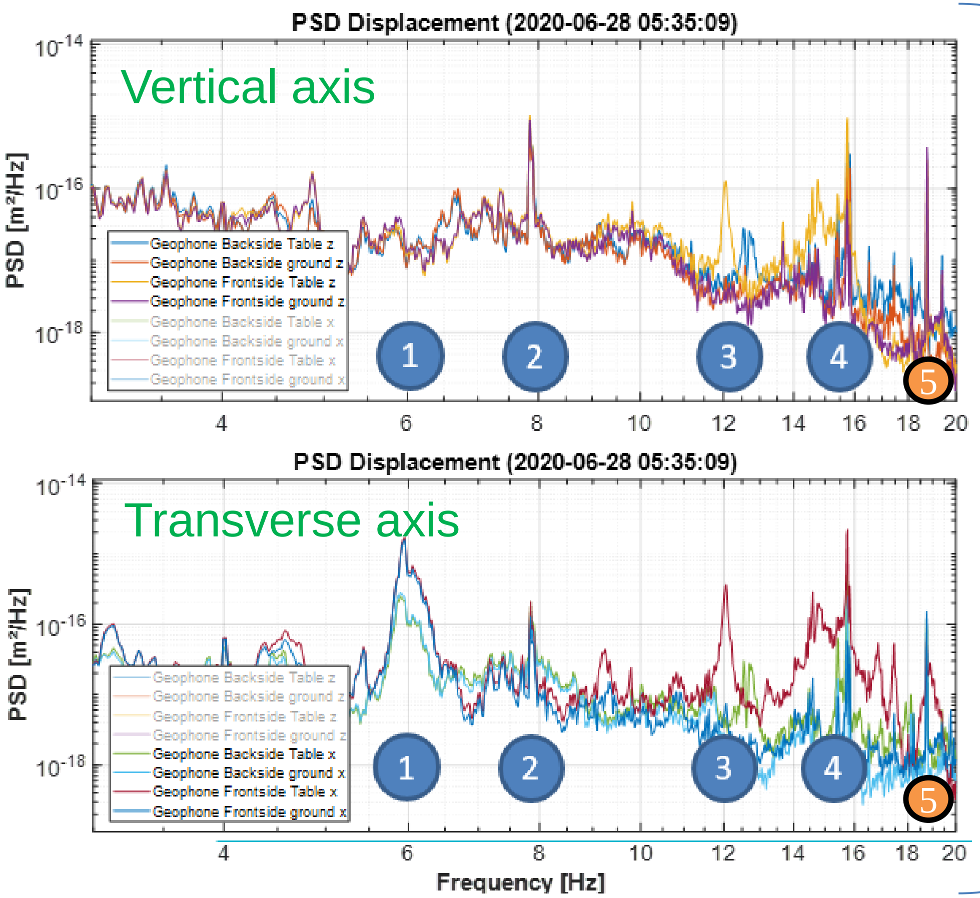
- A: perturbations (external?) **coherent at the both sides** of the detector and **not amplified by the mechanics** (low frequency) – distant source?
- B: perturbations (external?) **not coherent at the both side and not amplified by the mechanics** – local source?
- C: eigenfrequency – **mechanics or a source on the cryostat support** (not measure on the ground)

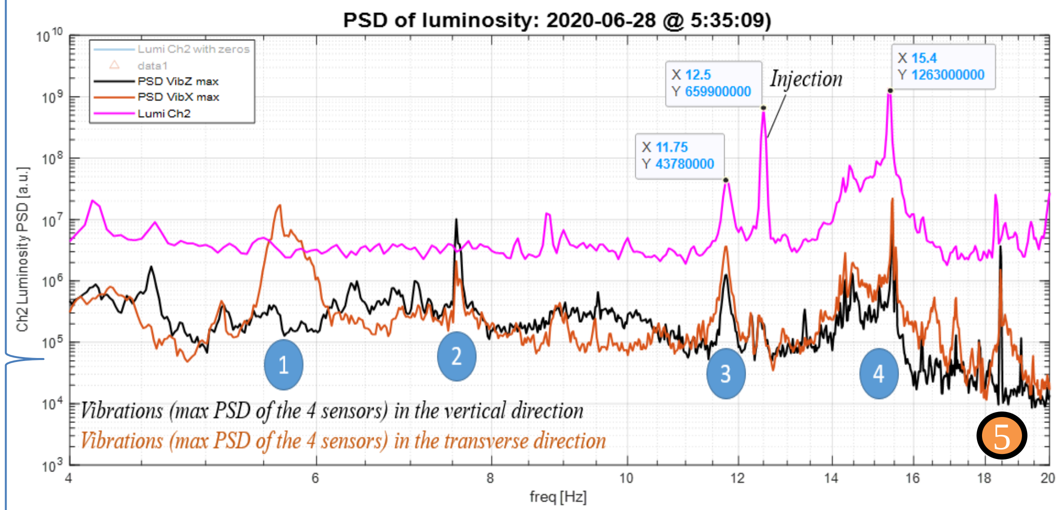


SuperKEKB: correlation vibrations - luminosity



- **Analysis method:**





PSD of displacements on the cryostat (transversal direction)

1.
   - Only transverse direction
   - No transfer function GND Support
   - Partially coherent at the both sides of the detector
     - ➢ *0 correlation*

2.
   - Transverse and vertical direction
   - No transfer function GND Support
   - Coherent at the both sides of the detector
     - ➢ *0 correlation*

3.
   - Transverse and vertical direction
   - Mecanics mode (transfer function GND – support)
   - Only at one side of the detector
     - ➢ *correlation*

4.
   - Transverse and vertical direction
   - Mecanics mode (transfer function GND – support)
   - Only at one side of the detector
     - ➢ *correlation*

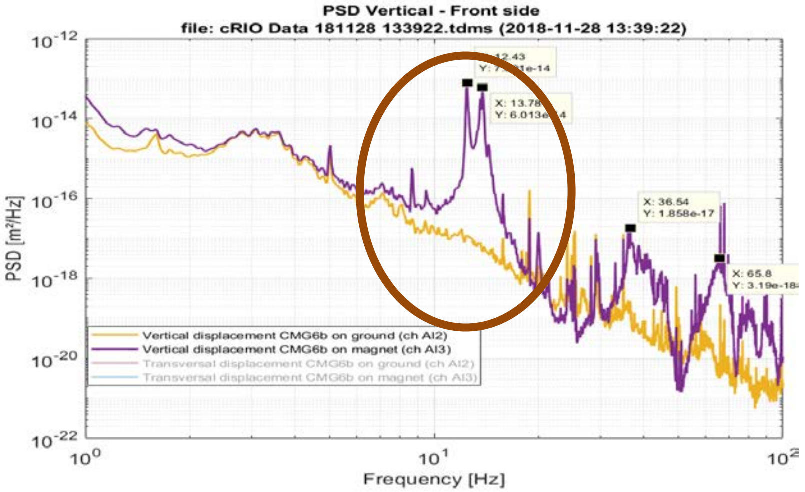
5. More complex case…

- Carry out a systematic analysis (under Matlab) according to the vibrations measurements (direction, max, diff, coherence…), the beam intensity, the measured luminosity, the beam control… in progress!
- Correlation method, criteria ...

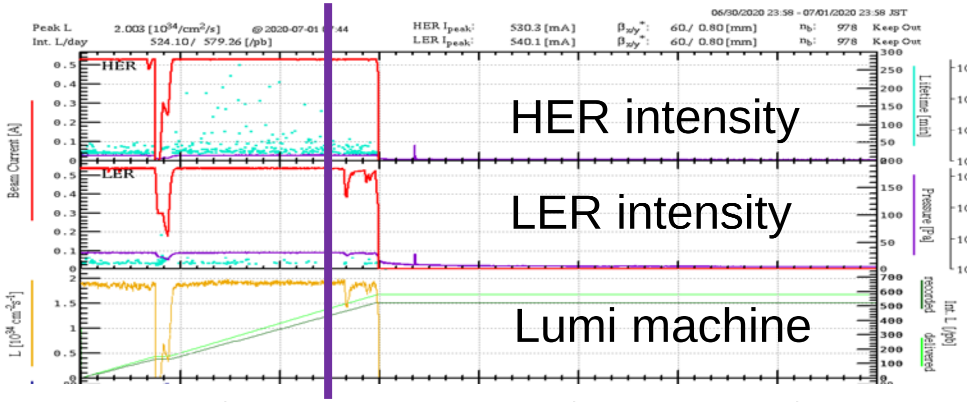
➢ **Objectives :**

- To evaluate the vibrations effects on the beam
- **To identify the common issues with FCC-ee, in particular with the increasing of the beam intensity**

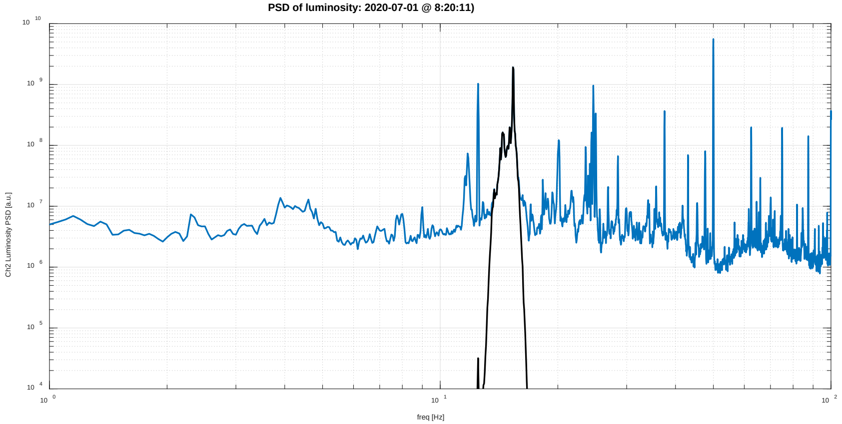
- **A specific aspect: influence of the first flexion mode of the front side cryostat**



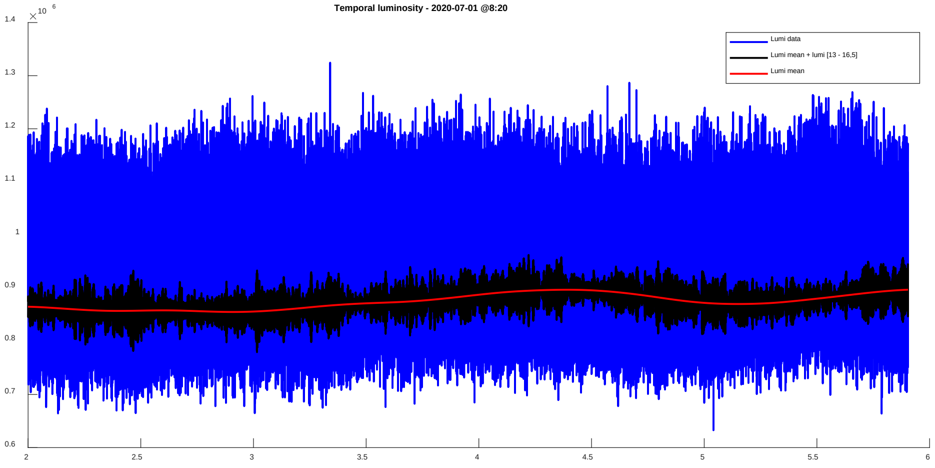
PSD of displacements on the cryostat (vertical direction)



Analysis just before the shunt down (max of intensity) – 1st of July 2020



PSD of luminosity – filtered in black (first flexion mode)



Temporal signal of the luminosity

Luminosity data
Mean of the luminosity
Mean + bandwidth equals to the 1st mode

➢ **Each resonance mode reveals a significant disturbance of the luminosity**