Vibration Analysis and Control in Particle Accelerator

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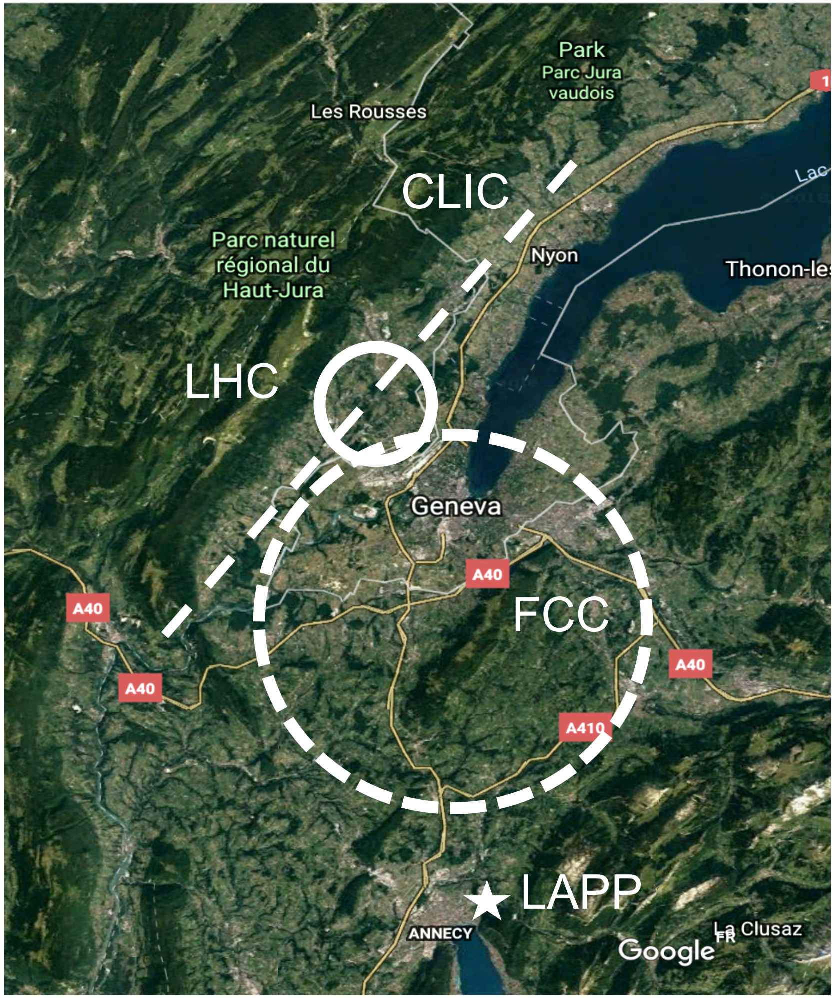
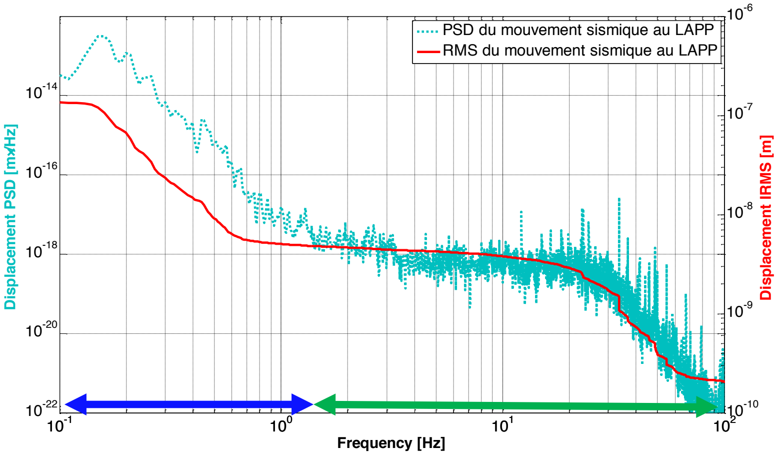
FCC-ee MDI workshop CERN 30 January - 9 February 2018

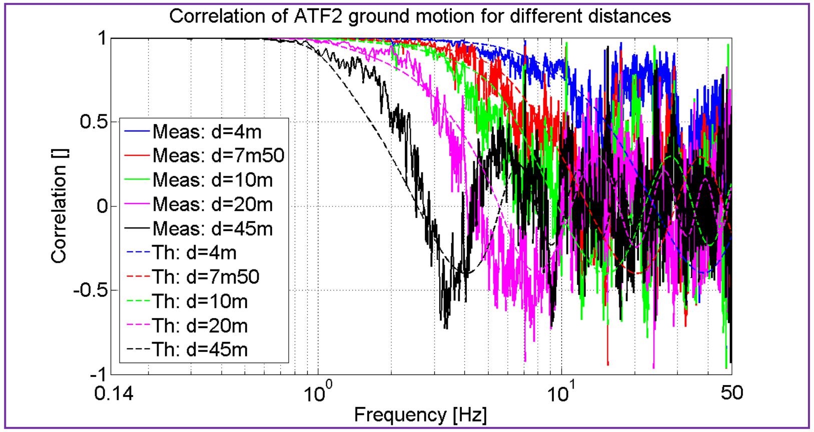
Successful operation of future colliders requires advanced vibration analysis and control.

- **Linear Collider**
  - Need to preserve very low emittance along beamline, collide nanometer beams and measure their position
- **Circular Collider**
  - Need to minimize emittance dilution and stabilize interaction point
- **Vibration effects**
  - Misaligned quadrupoles induce orbit distortion via feed-down effect
  - Orbit distortion generates beam offset at IP and emittance blow-up due to nonlinearities
- **Vibration countermeasures**
  - Feedback and feedforward
  - Active and passive stabilization



- **Vibration description**
  - Power Spectral Density (PSD) [m^2/Hz] is the frequency content of motion due to vibration (natural ground motion, cultural-technical noise)
  - PSD depends on geology of the site and cultural noise can be amplified several times by girders and supports
  - Square root of integrated PSD gives RMS motion induced by vibration as function of lowest *f* of interest
  - Correlation measurements give information about wave velocities and they are used to construct 2D spectrum PSD(ϖ,k)





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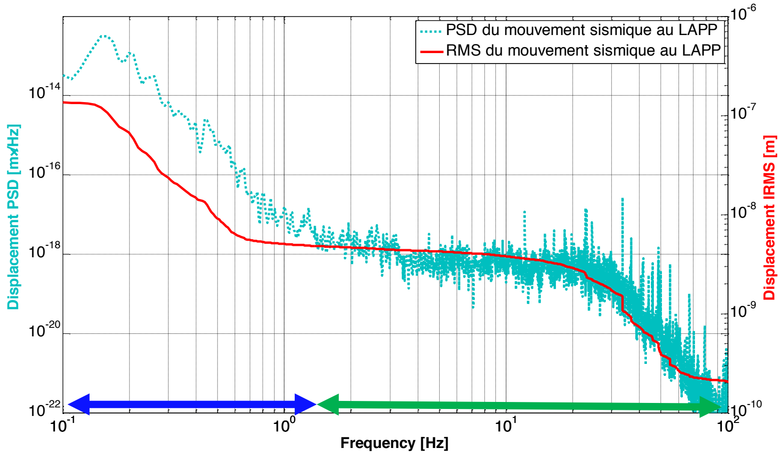
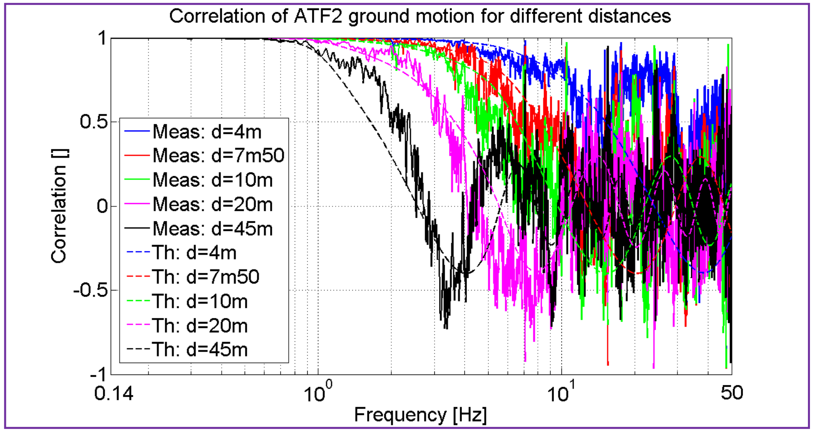
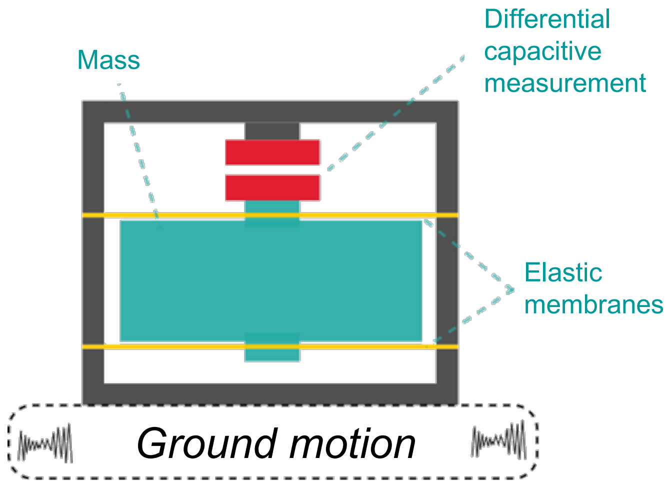


- **Vibration timescale**
  - (minutes-years): **systematic** motion due to ground settlement and seasonal effects, and **diffusive** motion due to water activities (oceans, rivers, dams) and temperature variations
  - (t < seconds): **wave-like** motion mainly due to cultural noise (road and train traffic, and construction work) and technical noise (cooling, cryogenic, air conditioners, pumps, power supplies)

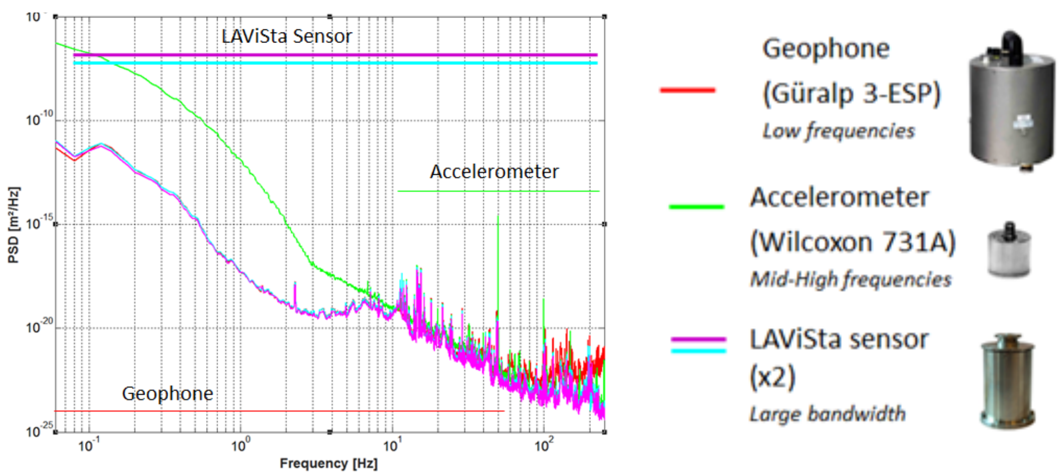


- **Principle**



- Mechanical system: mass - spring
- Capacitive measurement of the differential movement

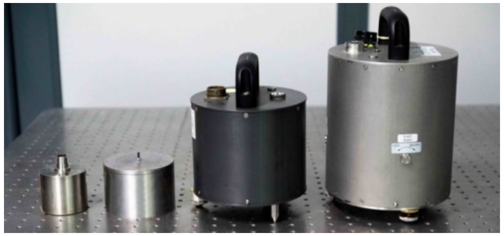
- **Comparison with industrial sensors at CERN (ISR – January 2015):**



To ensure a low noise, no integrated feedback has been design

-> Dedicated to control, not for measurement

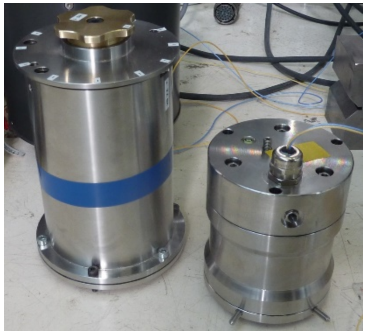
- **Custom vibration sensor**
  - Internal development at LAPP



Industrial sensors

Prototypes developed since 2011

- French patent (FR 13 59336)

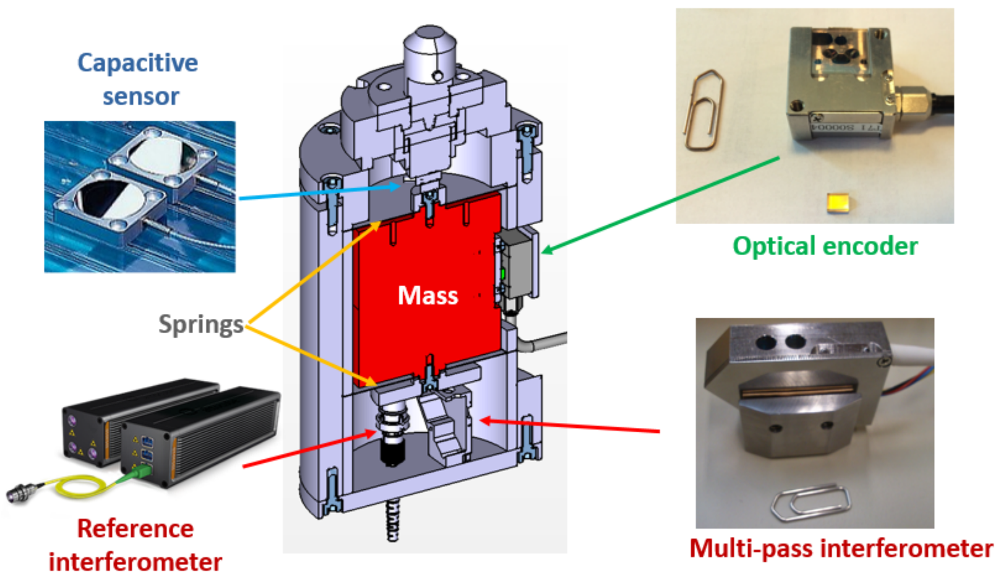


Latest one axis version

Future prospects : vibration sensor improvement

Comparison of different technologies for the embedded sensitive part

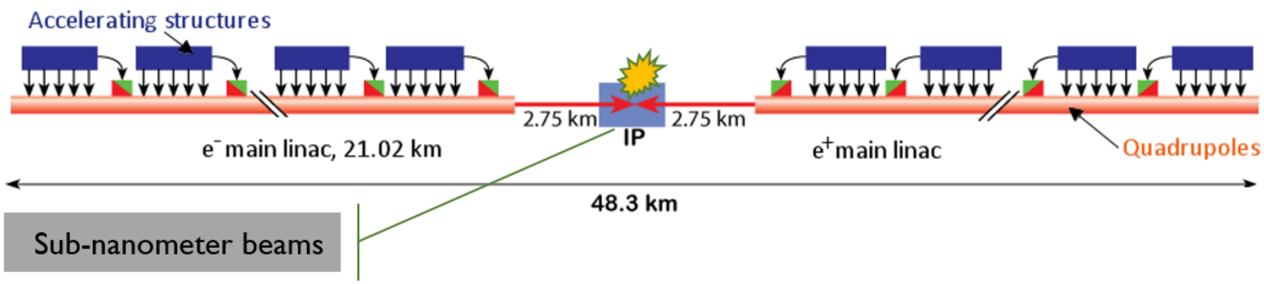
- PACMAN : Particle Accelerator Components' Metrology and Alignment to the Nanometer scale (Marie Curie program at CERN)
- Collaboration with several labs and industries : LAPP academic partner – SYMME co-director of a thesis
- Use of the LAPP sensor with dedicated instrumentations



- Capacitive sensors : PI & Lion Precision
- Optical encoder : Magnescale
- Interferometer : Attocube & a developed one (INRiM (It) and ISI Brno (Cz))

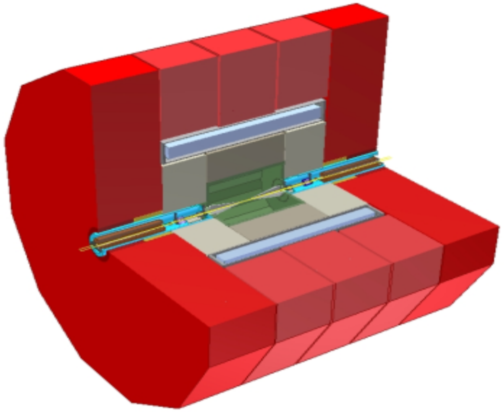
P. Novotny et al, "What is the best displacement transducer for a seismic sensor?", IEEE Inertial Sensors and Systems 2017, Hawai, USA.

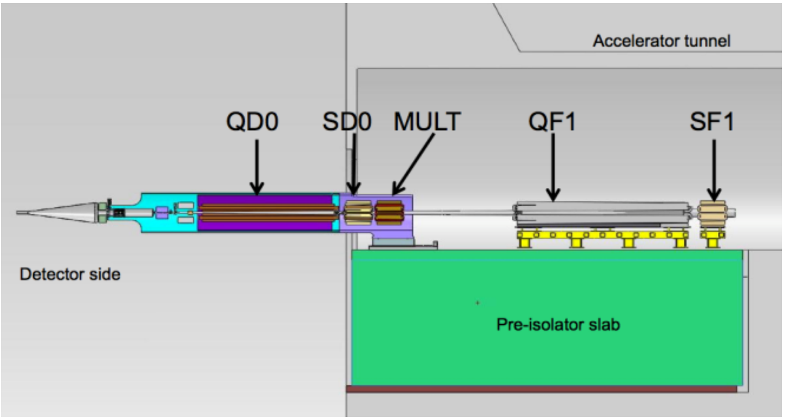
- **Final focus CLIC R&D:**



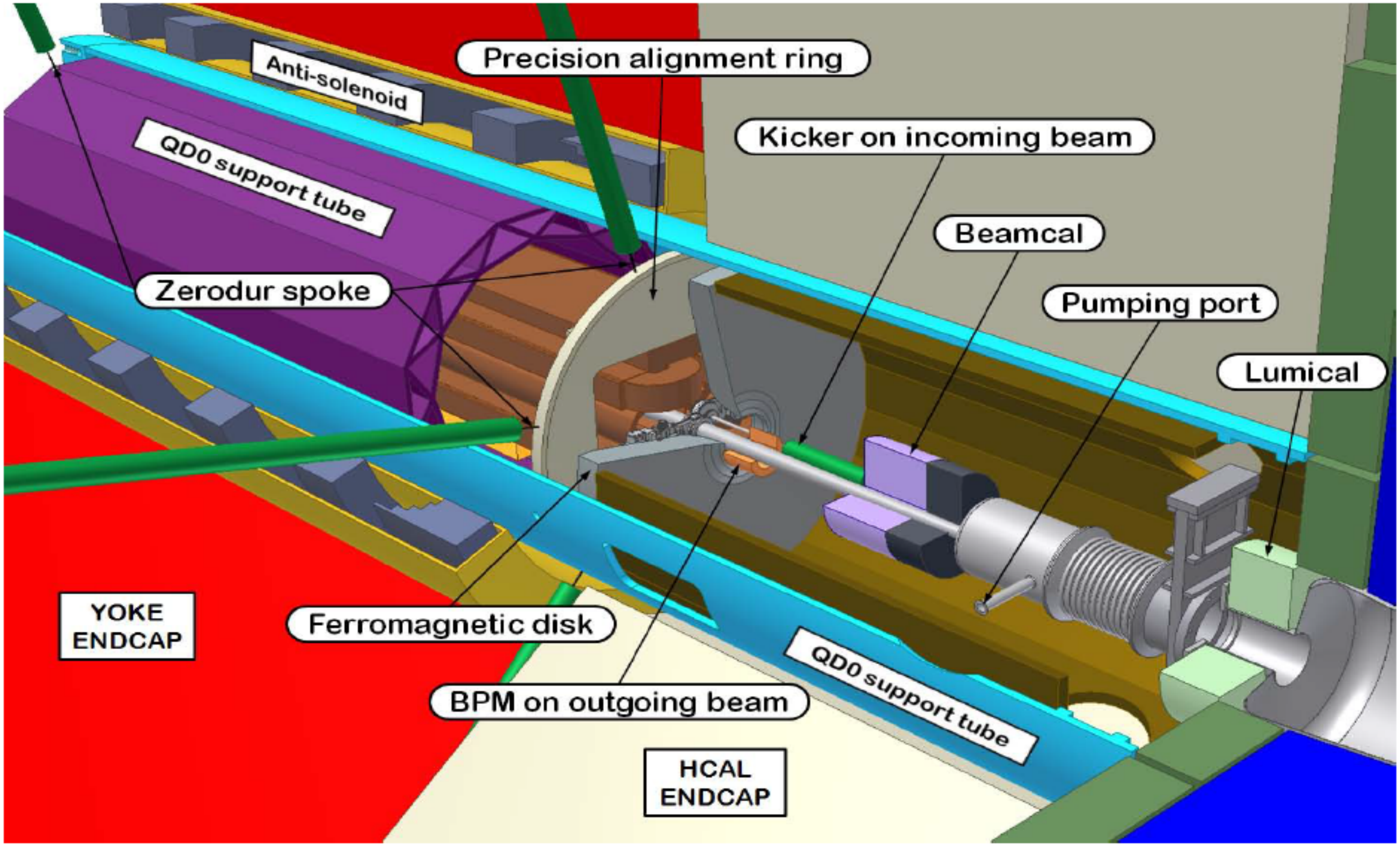
Many controls will be performed all along the collider

- **Most stringent specifications are at the final focus interaction point**



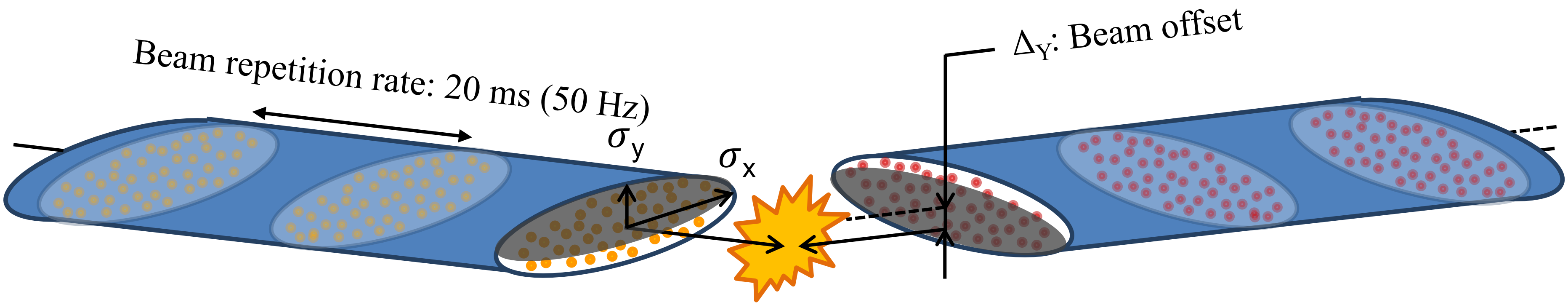


LAPP contributes to the Final Focus vibration stabilization



taken from Lau Gatignon, MDI Status and Plans CLIC Workshop 2017

Final focus CLIC R&D:



$$L(\sigma_{x,y}, \Delta_{x,y}) \sim \frac{e^{-\frac{1}{4}\left(\left(\frac{\Delta x}{\sigma_x}\right)^2+\left(\frac{\Delta y}{\sigma_y}\right)^2\right)}}{\sigma_x \sigma_y}$$

-Beam size $\sigma_{x,y}$
(Nominal: σ_x= 40 nm, σ_y=1 nm)

- Cross section, f($\Delta_{x,y}$)

Two challenges:

Main Linac

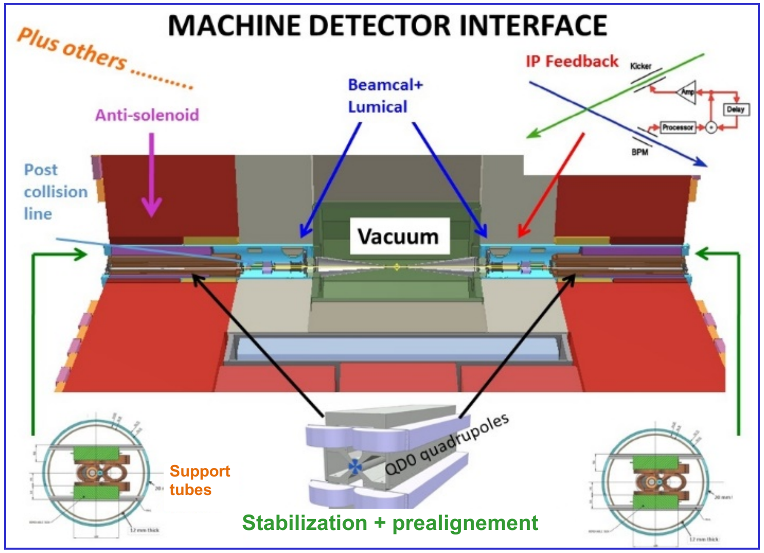
- Keep ultra low emittance all along the collider

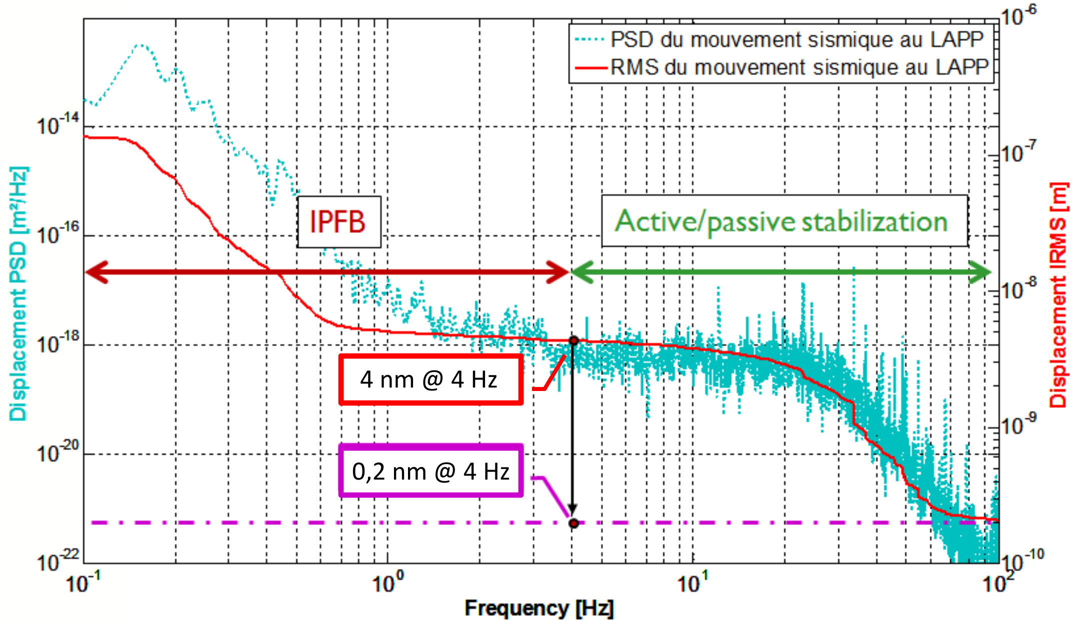
Interaction point

- Maximize cross section by minimizing beam-beam offset

Spec. : Beam offset < 0,2 nm RMS @ 0,1Hz → **Ground motion mitigation measures are needed**

- **Beam trajectory control & mechanical stabilization:**

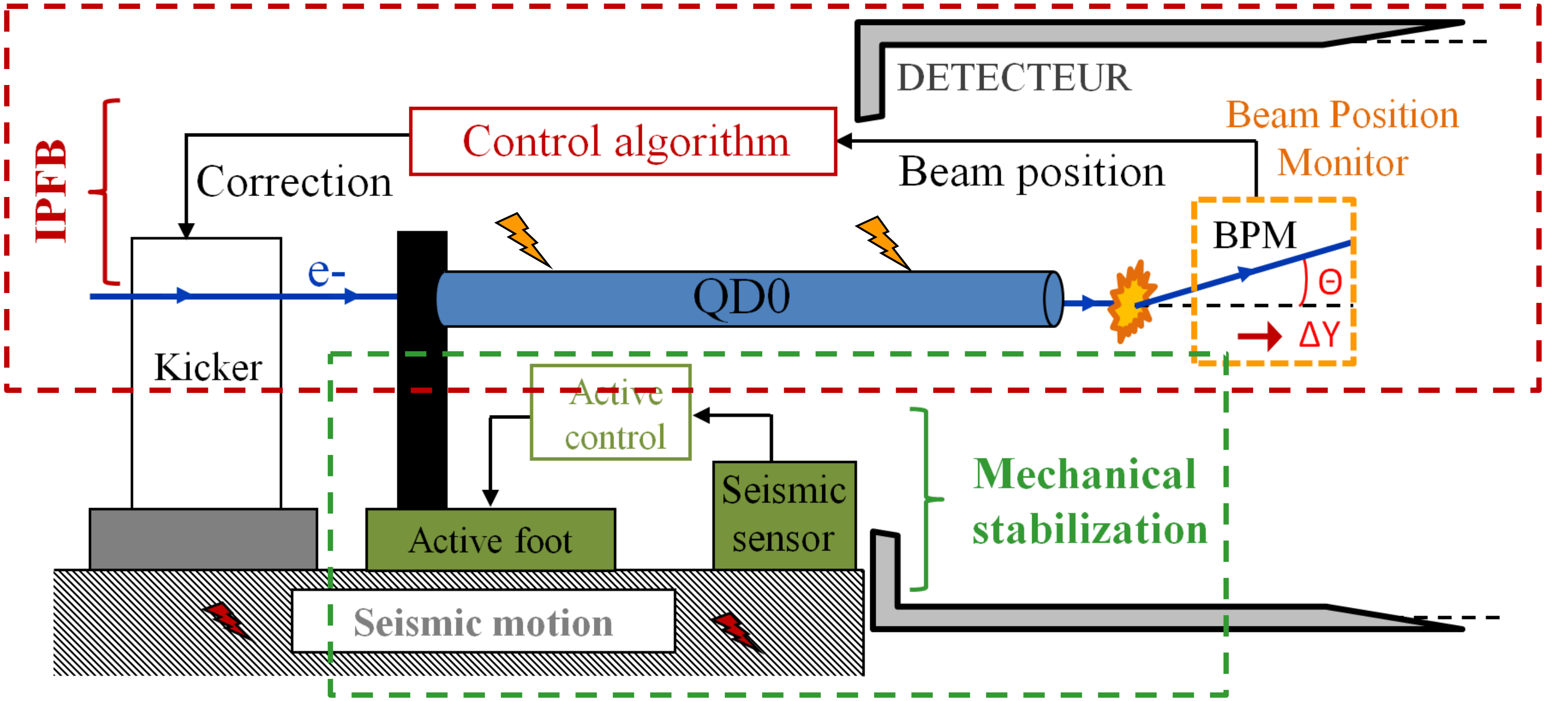




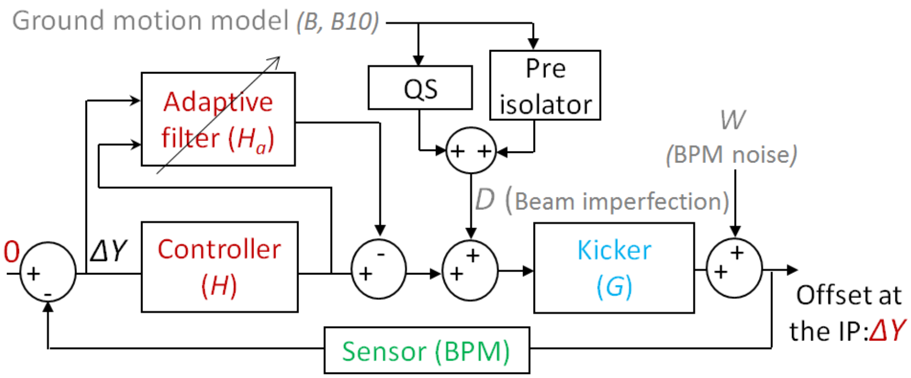
- At the Interaction Point (beam feedback: IPFB + mechanical stabilization),
- We aim at **0,2 nm at 0,1 Hz**

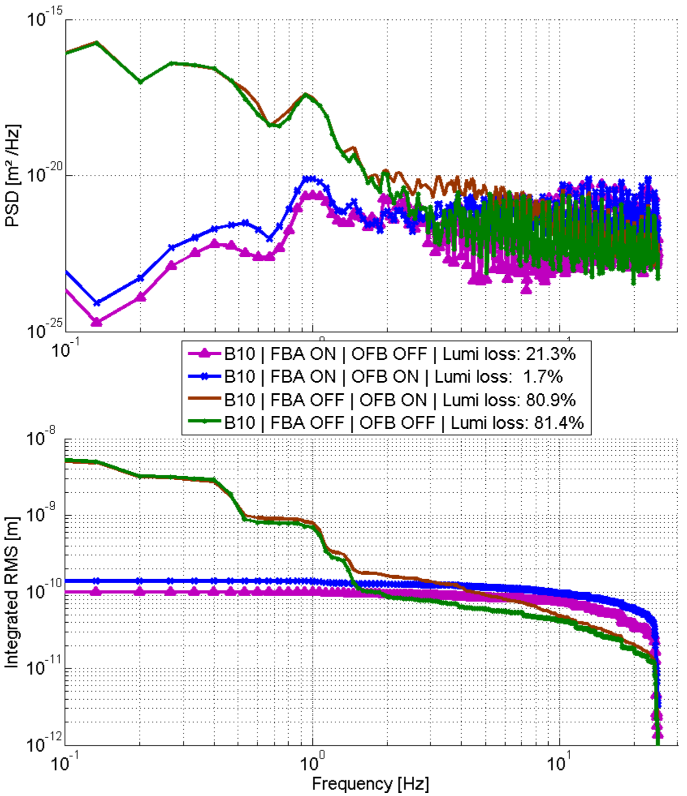
- **How ?**

Frequency < 4 Hz	***Frequency > 4 Hz***
IPFB: Interaction Point FeedBack (Beam dynamic control)	**Mechanical stabilization** Active and passive damping
Efficient for frequency < 4Hz because of the low beam repetition rate of 50 Hz	Active damping developped by LAPP Passive damping developped by CERN



IPFB - Beam trajectory control : simulation under PLACET





Luminosity vs control ON or OFF (simulation under PLACET)

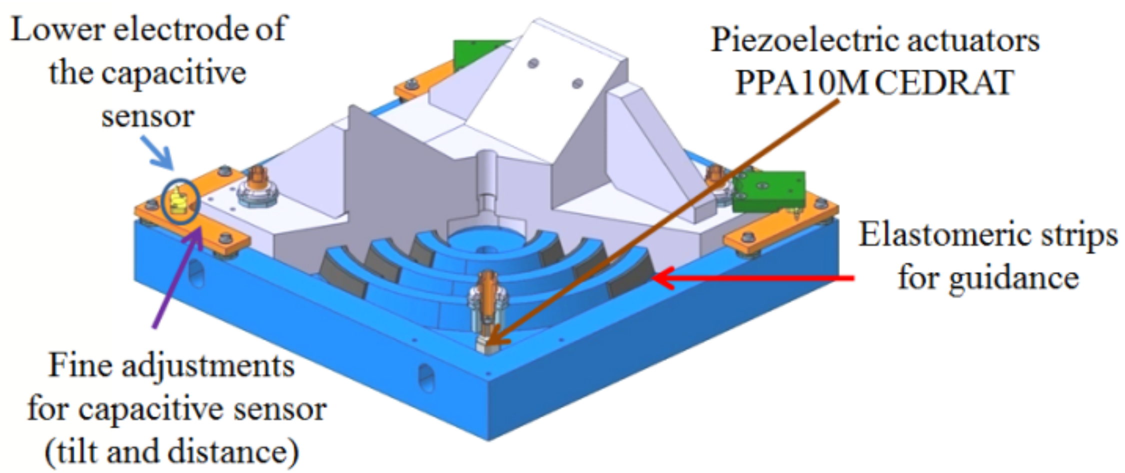
- *Caron B et al, 2012, "Vibration control of the beam of the future linear collider", Control Engineering Practice.*
- *G. Balik et al, 2012, " Integrated simulation of ground motion mitigation, techniques for the future compact linear collider (CLIC) ", Nuclear Instruments and Methods in Physics Research*

Controller performances

		Average luminosity loss (%)					
IPFB		OFF	FB	FBA	PID	PIDA	PID CERN
Ground motion	B	72.54%	1.32%	1.35%	6.40%	1.38%	1.61%
	B10	74.14%	1.57%	1.62%	6.98%	1.63%	1.86%

Mechanical stabilization

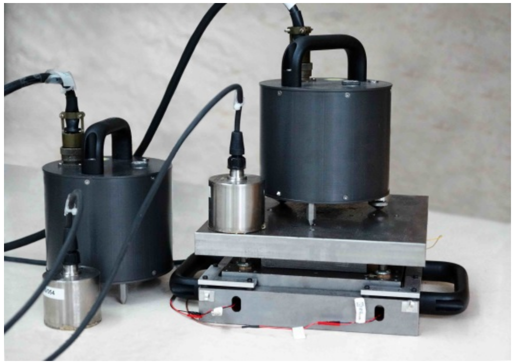
Design of an active stabilization system



- 4 piezoelectric actuators *(PPA10M)*
  - Resolution 0.08 nm
  - Resonance: 65 kHz
  - Response time: 0.01 ms
  - Maximal load: 400 N
  - Maximal stroke: 8 µm

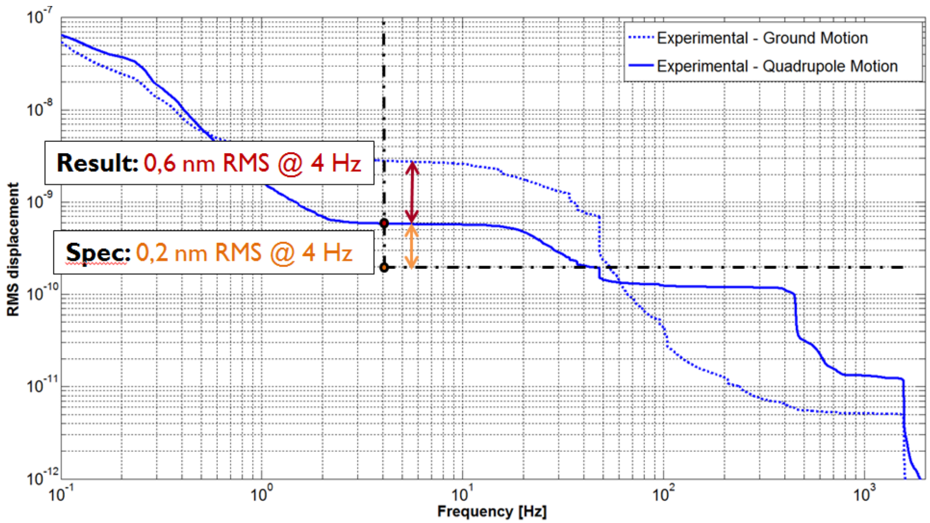
▪ Before 2016 : demonstration at a sub-nanometer scale

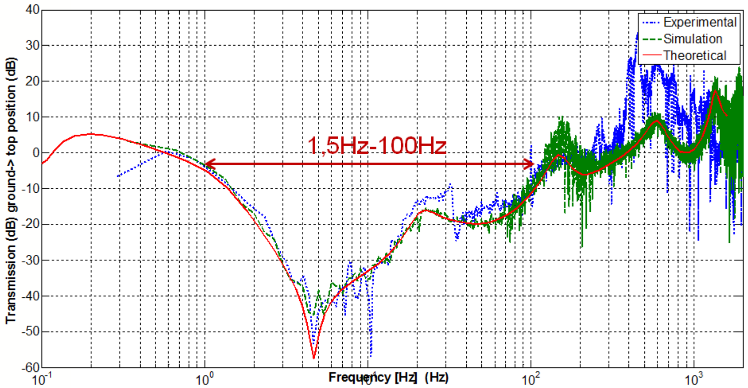
- Developed active foot with commercial sensors (geophones and accelerometers)
- 2 sensors used in feedforward and 2 sensors used in feedback



- Sensors dedicated to measurement but not to control
- Two needed technologies for the selected bandwidth (geophones for low frequencies and accelerometers for high frequencies)
  - ➢ complexity of the control
- Limitation of the internal instrumental noise

Obtained results with commercial sensors : **0,6 nm RMS@4Hz** (vs 0,2 nm RMS @ 4 Hz specification of CLIC)





- *Balik et al, "Active control of a subnanometer isolator", JIMMSS, 2013.*
- *R. Le Breton et al, Nanometer scale active ground motion isolator, Sensors and Actuators A: Physical, 2013.*

Main limitation : SENSORS (Experimental and theoretical demonstration).

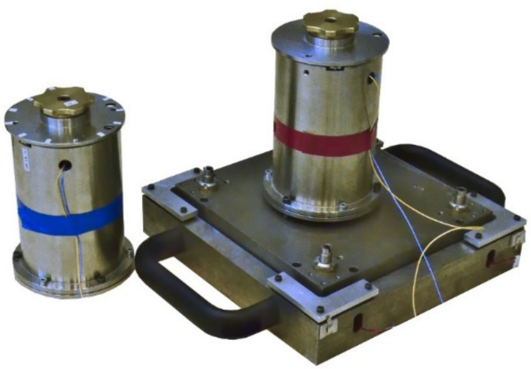
- <u>2016 : CLIC Demonstration of feasibility at reduced scale</u>

Active control with the custom sensor

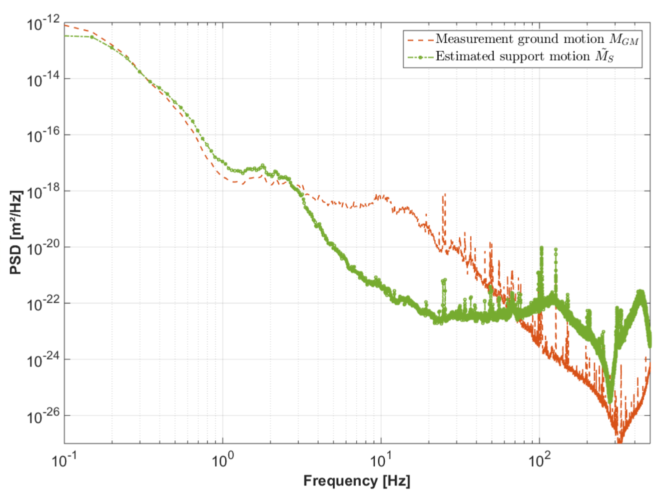
- CLIC specification (displacement of the QD0 final focus) : 0,20 nm RMS@4Hz
- Previous results with LAPP active foot + 4 commercial sensors : 0,60 nm RMS@4Hz

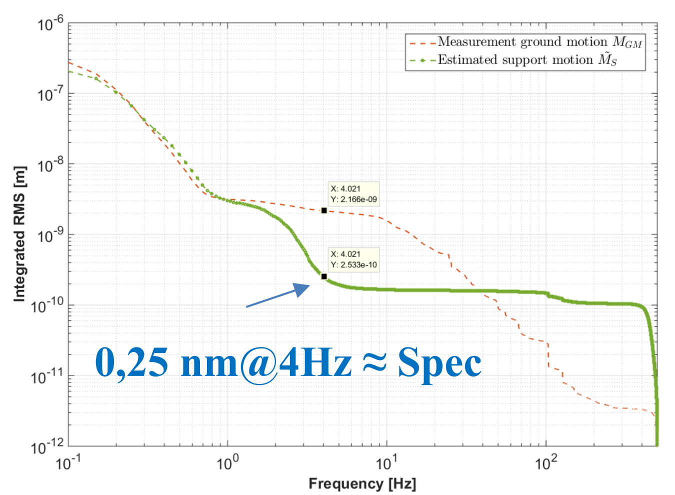
➢ **Results of control (autumn 2016) with LAPP active foot + 1 LAPP vibrations sensor : <u>0,25 nm RMS@4Hz</u>**

- *Only 1 sensor in feedback -> control less complex and more efficient*
- *Submitted in September 2017, in collaboration with SYMME (approval in progress)*



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

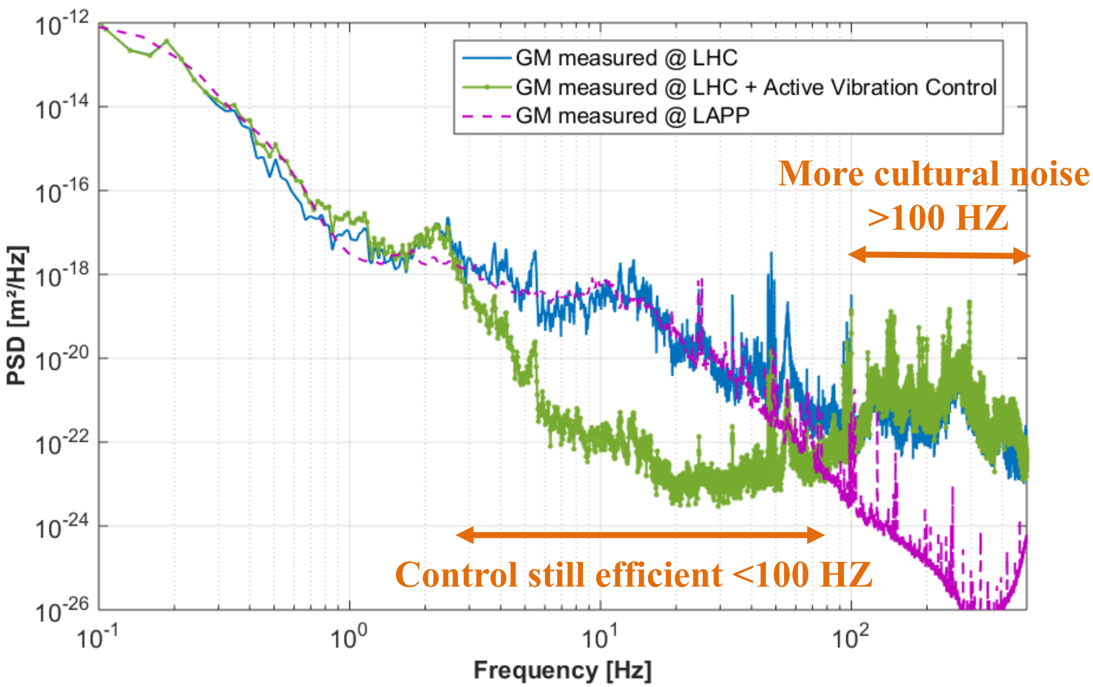


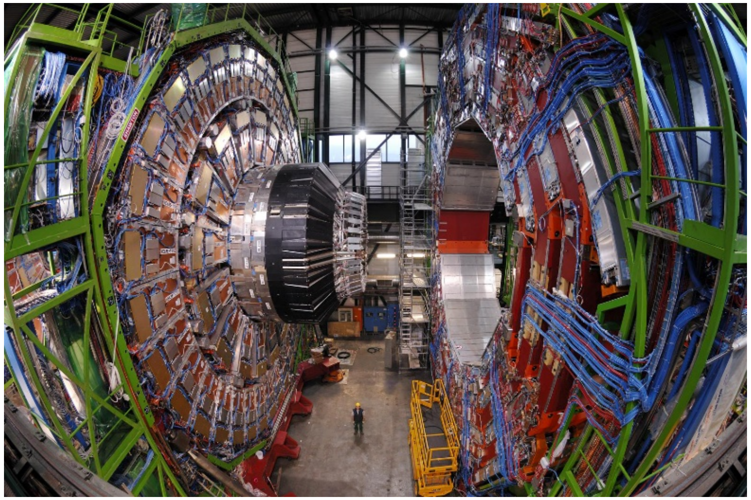


- Displacement without control / with control at LAPP -

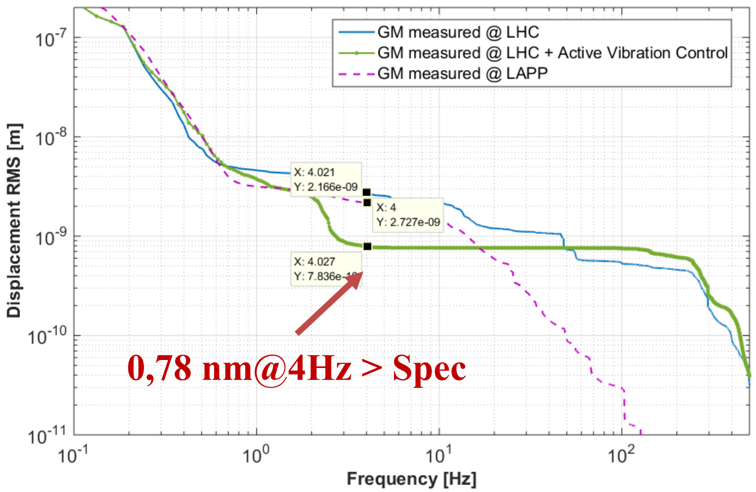
Simulation of the active control with a collider environment

- CMS detector ground motion is taken into account (high level of cultural noise - pessimistic)
- Simulation of the system (foot + sensors) with these disturbances





The Compact Muon Solenoid (CMS)

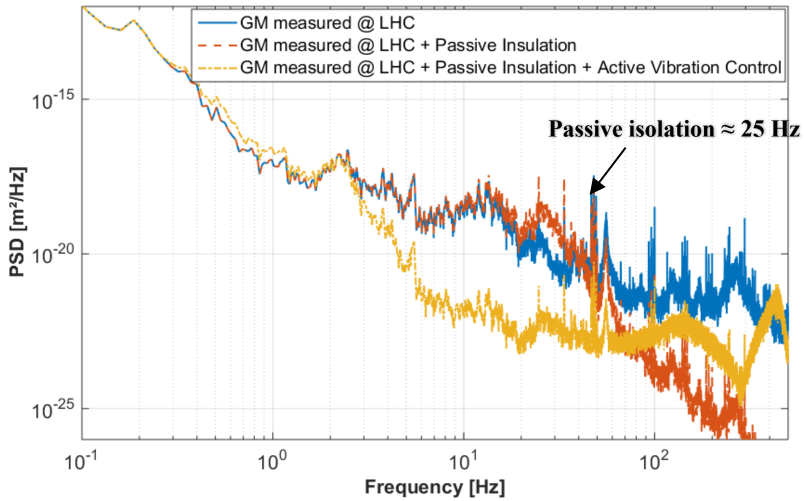


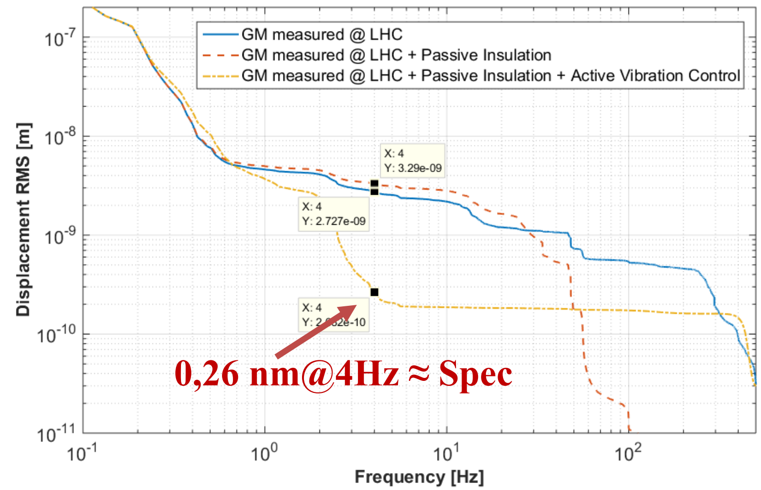
Disturbances don't reveal the same distribution (more cultural noise)

Control is not efficient enough in this case (above 100 Hz)

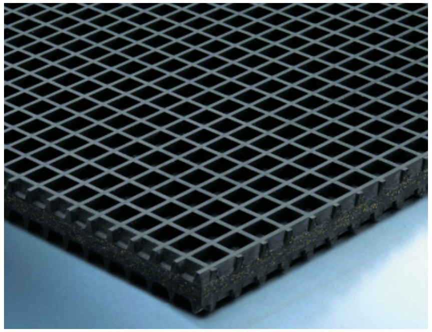
▪ Simulation of the active control with a collider environment

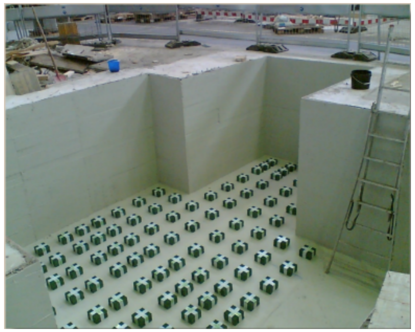
Necessity to have a passive insulation under the concrete or under the last elements

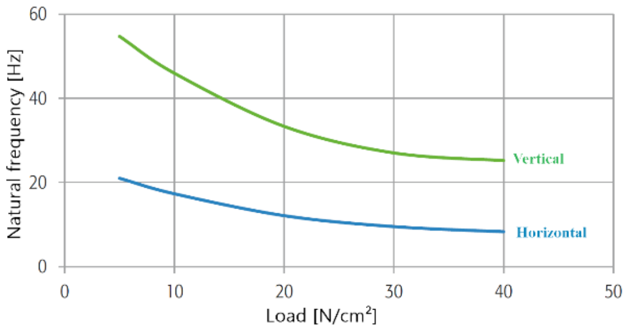




A passive insulation at about 25 Hz is common to the standard industrial solutions







Example of usable PI (Biltz® B13W- vibration isolation rubber pad).

G. Balik et al, "Proof of concept of CLIC final focus quadrupoles stabilization", in Proceedings of IPAC 2017, Copenhagen, Denmark.

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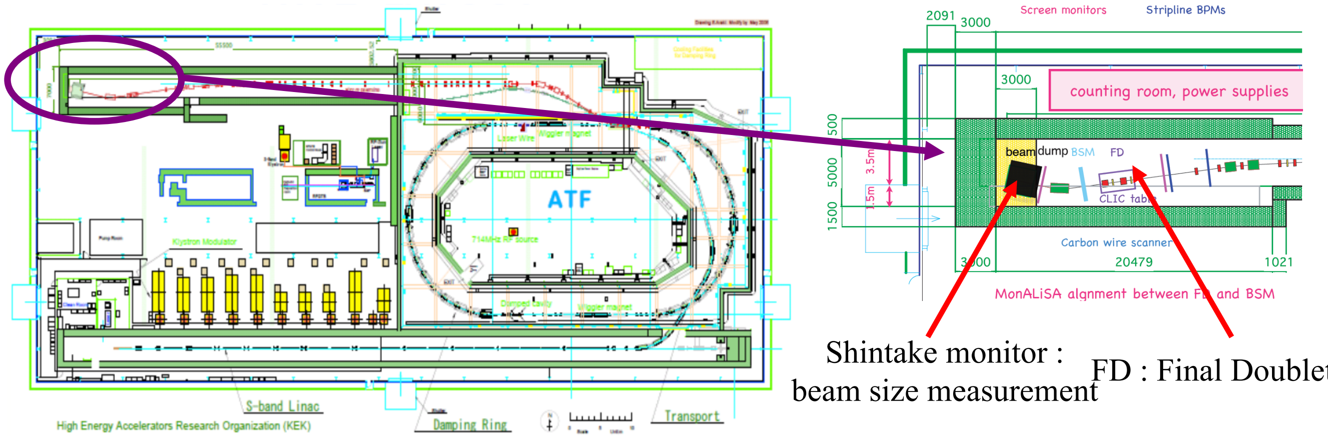
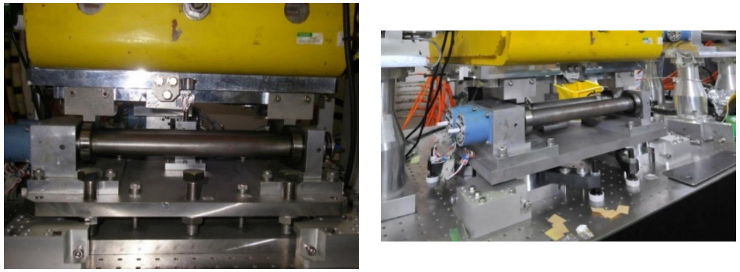
- **Responsible of the final doublet relative displacement**



Shintake monitor :
beam size measurement

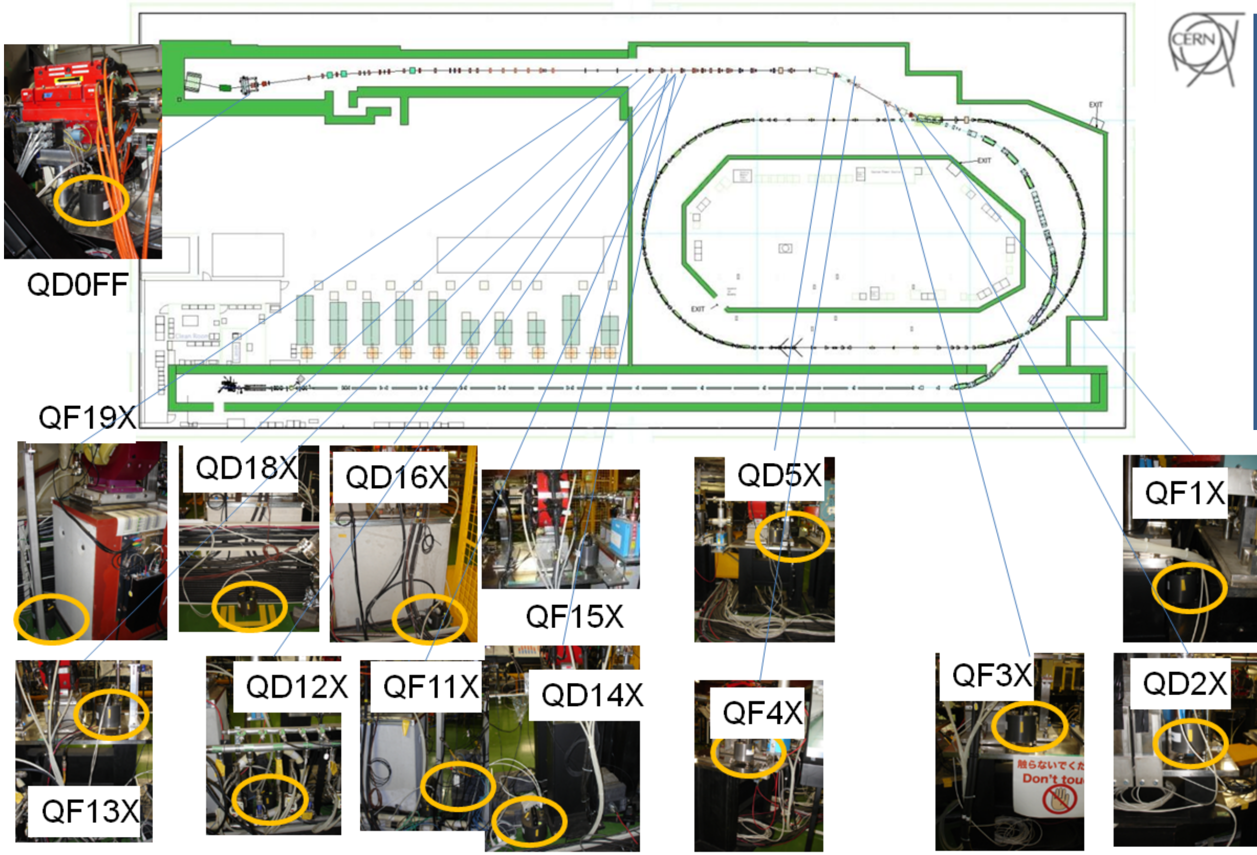
FD : Final Doublet

- Relative motion between shintake monitor and final doublets of 6 nm RMS @ 0,1 Hz in the vertical axis.



LAPP support: feet and T-plate

- **Involved in the assessment of the beam feed-forward control vs ground**



- Vibration sources identification
- Feedforward study: correlation between the ground and the beam motions.

- Processing of 14 Geophones (Guralp 6T sensors)
- Collaboration with CERN, LAL & KEK
- Last campaign of measurements : Nov 2017

D. Bett et al, "Ground motion compensation using feed-forward control at ATF2, in Proceedings of International Particle Accelerator Conference (IPAC 2016), Busan, Korea.

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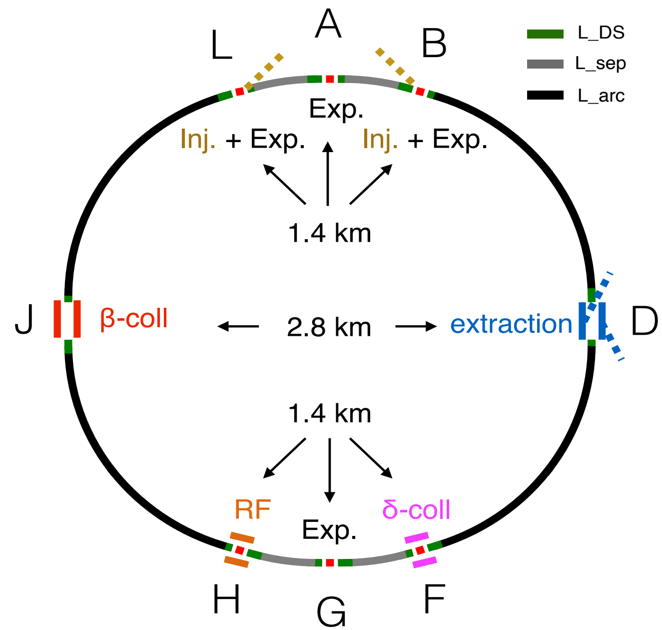
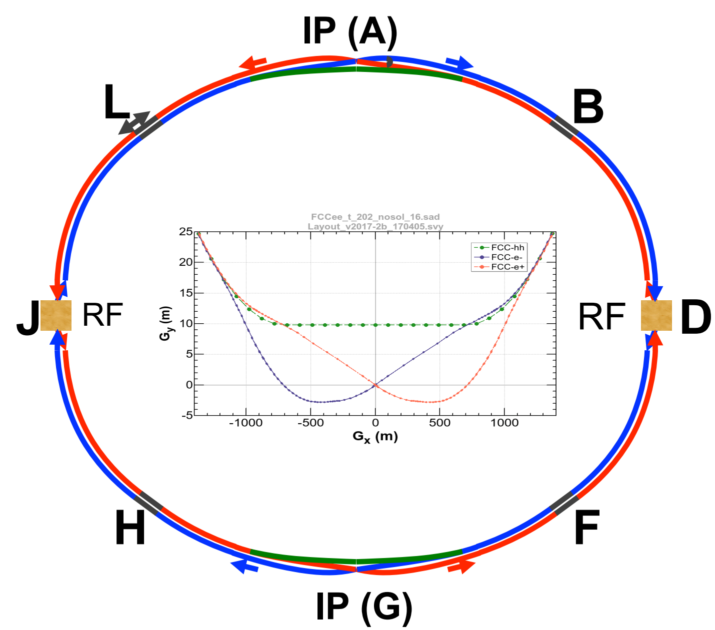
Preliminary considerations about vibration in FCC



- The primary effect of fast ground motion and vibration in large circular machines is to produce emittance growth
- The frequency with the major contribution to emittance dilution is the fractional betatron tune times the revolution frequency (several hundreds Hz)
- Orbit feed-back can reduce emittance dilution
- Stability of beam offset at IP under 10 nm has to be ensured for FCC-ee operation
- Careful technical design of girders and supports including passive damping and, eventually, active stabilization to ensure stability of the focusing systems for FCC-ee
- Steps to study vibration issues and cures for FCC: theoretical estimations of emittance blow-up and orbit instability at IP, simulation setup with vibration from different sources, study the effectiveness of proposed solutions with dedicated simulations including beam-beam



- **R&D ACTIVITIES**

CLIC

- Feasibility demonstration of active control at sub-nanometer scale
- Development of an efficient vibration sensor
- Control of the QD0 magnet in progress

ATF2

- Optimization and analysis of the final doublet relative displacement
- Vibrations analysis of the experiment for the feedforward study
- Team expertise involved in multiple vibration activities

- **Future prospects**
  - Improvements of the developed sensor (Comparison of different technologies for the embedded sensitive part)
  - Test of the whole process at a real scale for ATF2, with a MIMO control
  - ATF2 Beam and ground motions correlation ongoing
  - Start collaboration and studies on FCC vibration issues

Thank you for your attention