Laboratoire d'Annecy de Physique des Particules

Vibration control and beam stabilization techniques in the sub-nanometer scale range

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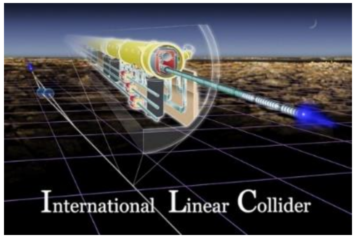
2018-12-11

- ***LAPP**: Laboratory of Annecy in Physics Particles – IN2P3 CNRS University Savoie Mont-Blanc*
- ***SYMME**: laboratory of SYstem and Matériaux for the mecatronics - University Savoie Mont-Blanc*

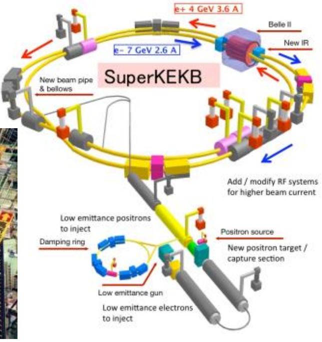
- **Sub-nanometer beam stabilization:**

CLIC: the most stringent specifications

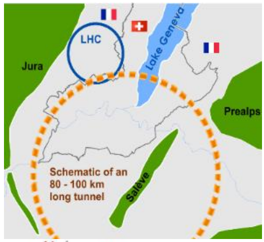


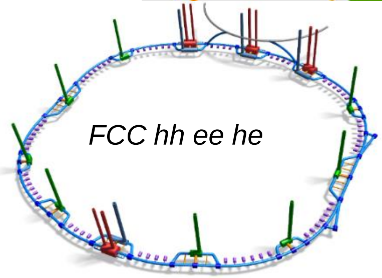
Projet collisionneur ILC au Japon

ATF2 à KEK au Japon Démonstrateur ILC



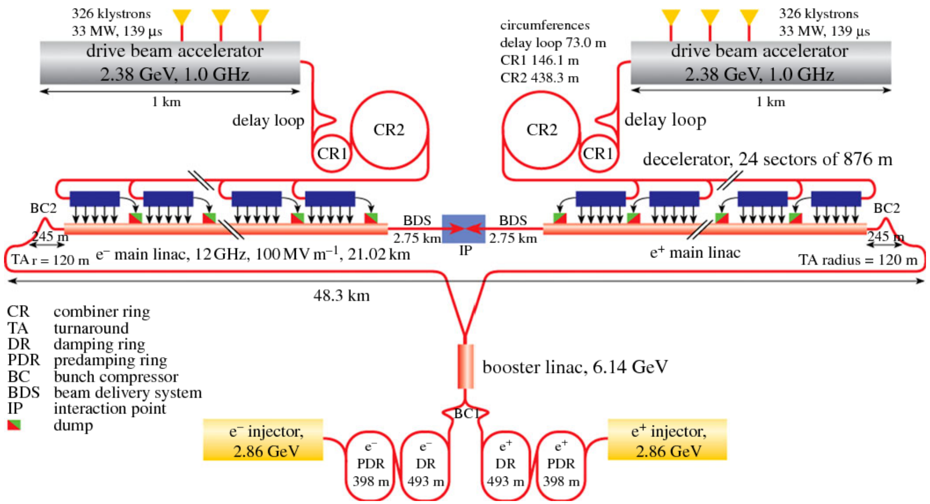
BELLE II SuperKEKB au Japon





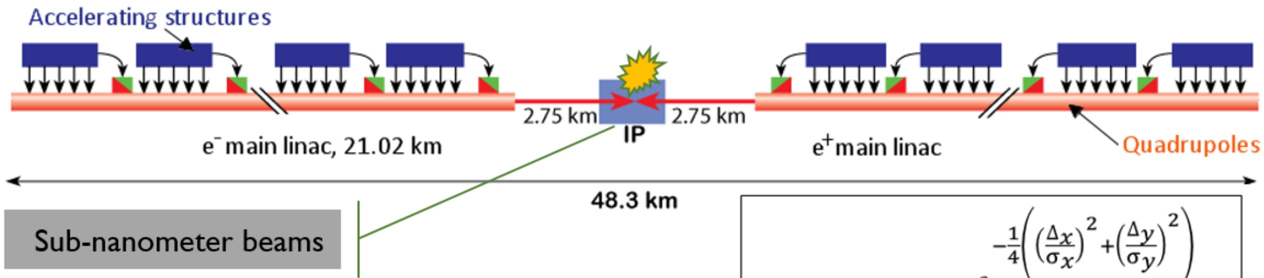
Projet collisionneur FCC au CERN

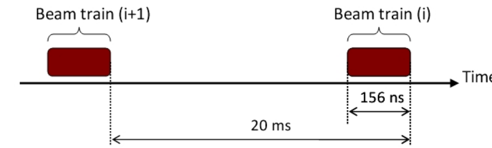
- **CLIC beam stabilization**
  - **Beam trajectory control IPFB**
  - **Active control stabilization**



- **ATF2 : test of others strategies**
  - **Coherence optimization**
  - **Feedforward beam control implementation**

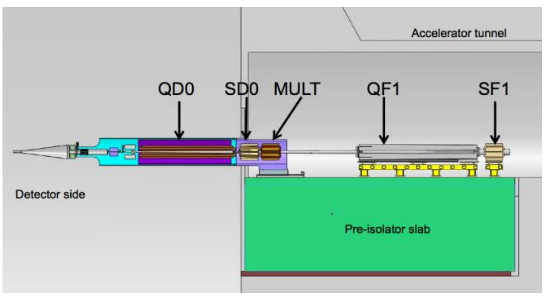
- ***CLIC Final focus R&D:***

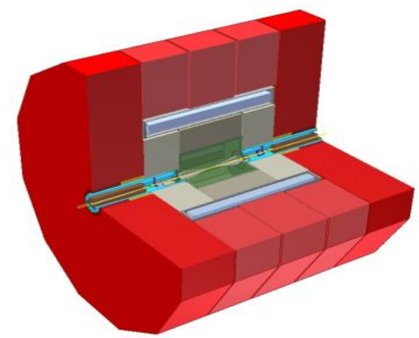




Beam repetition: 50 Hz

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





- **Many controls will be performed all along the collider whose these two critical challenges:**

Main Linac – active control

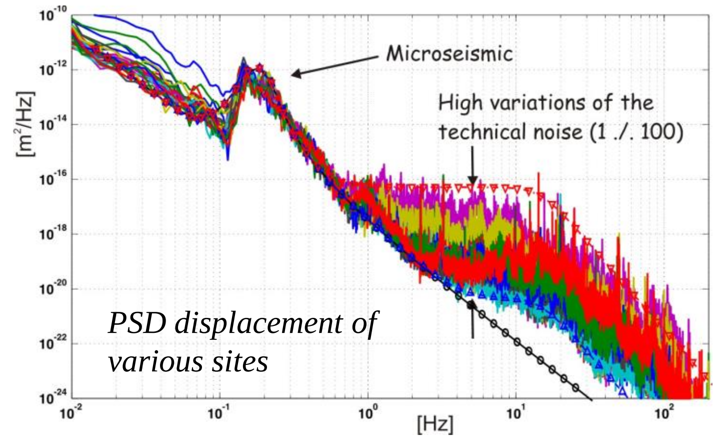
- Keep ultra low emittance by minimizing beam size all along the collider

Interaction point – active control

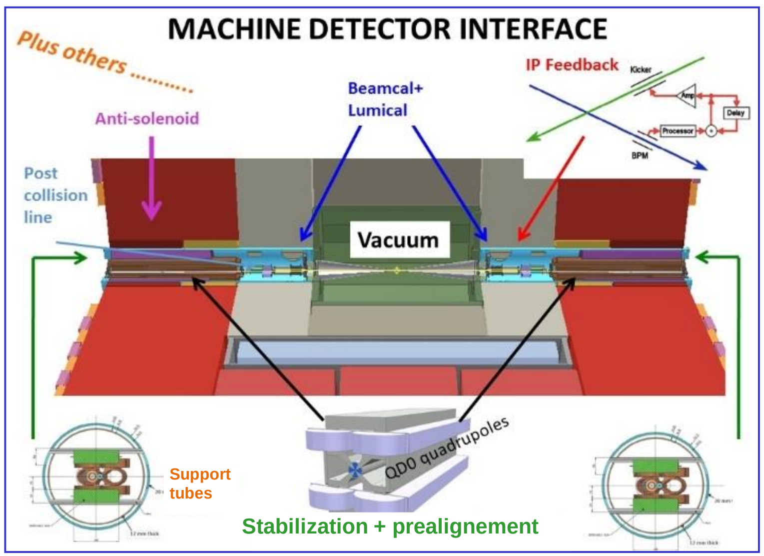
- Maximize the cross section by minimizing the beam-beam offset

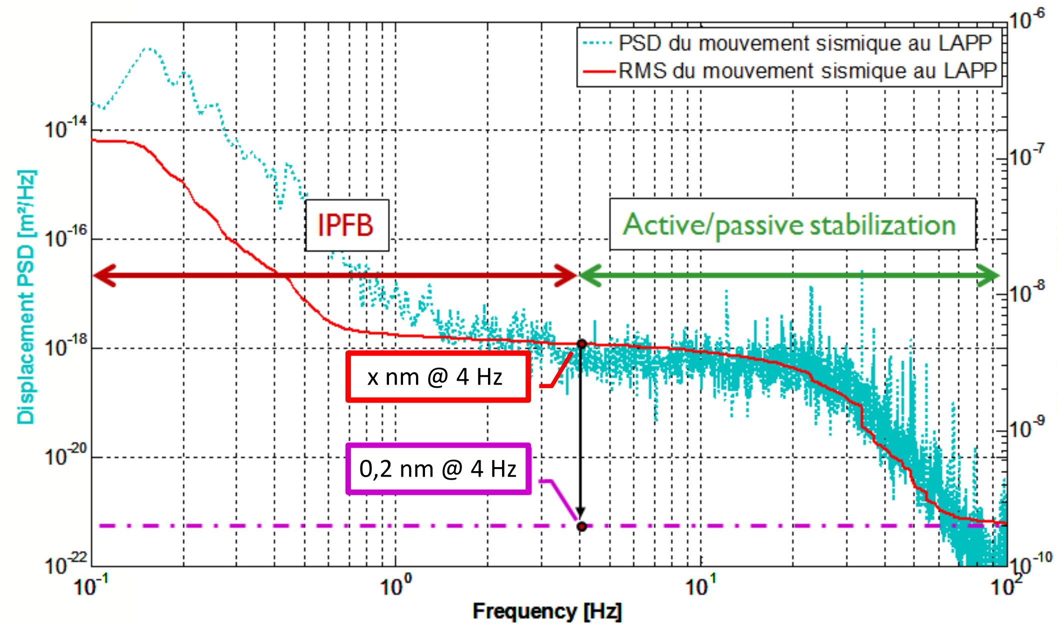
Spec. : Beam offset <= 0,2 nm RMS @ 0,1Hz → **Ground motion mitigation is needed**

- ***Seismic motion:***
    - *Seismic activities (starting in low frequencies)*
    - *Technical noise (human activities, cooling…)*



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

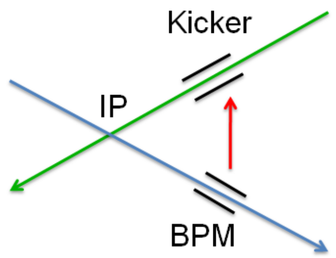


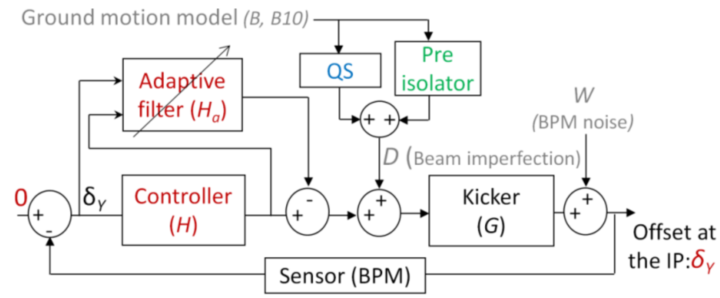


➢ At the Interaction Point (beam feedback: IPFB + mechanical stabilization),

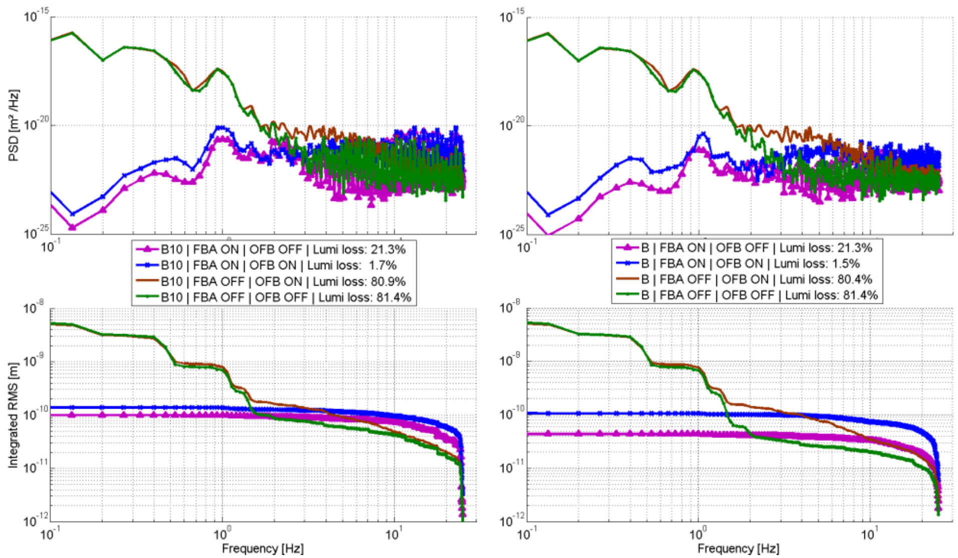
➢ We aim at **0,2 nm RMS at 0,1 Hz**

- ***Beam trajectory control : simulation under Placet***





Feedback and adaptive control scheme



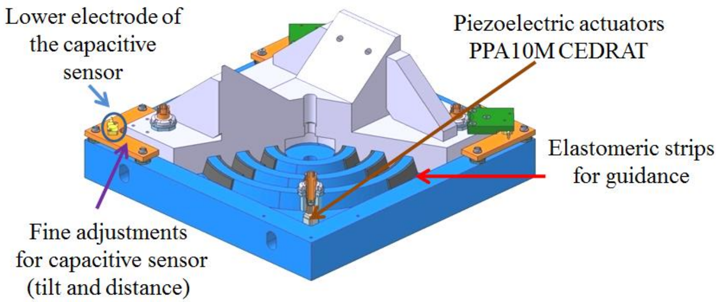
Luminosity vs control ON or OFF and vs model of seismic motion (deal under Placet)

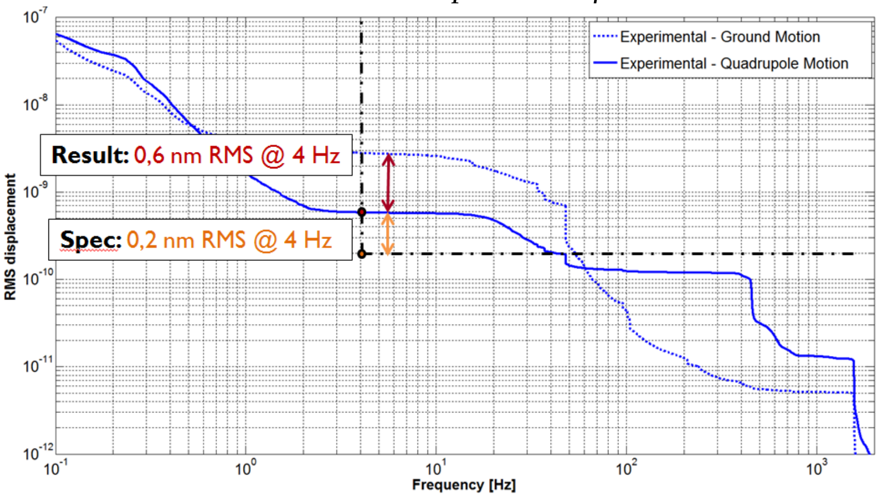
➢ ***Has to be tested on a realistic environment…***

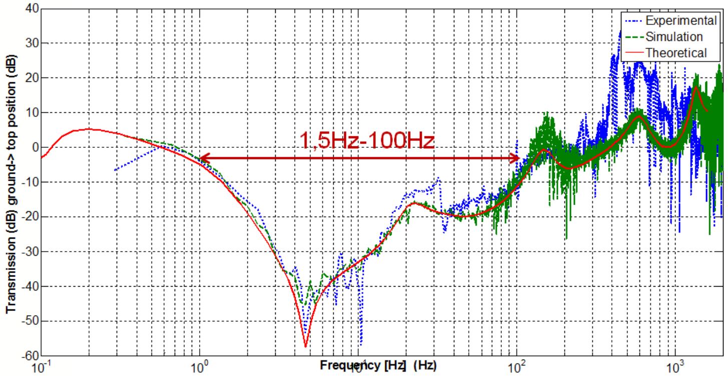
- *Caron B et al, 2012, "Vibration control of the beam of the future linear collider", Control Engineering Practice.*
- *G. Balik et al, 2012, " Integrated simulation of ground motion mitigation, techniques for the future compact linear collider (CLIC) ", Nuclear Instruments and Methods in Physics Research*

- *Prototype of active control system :*

Commercial sensors and a developed active foot







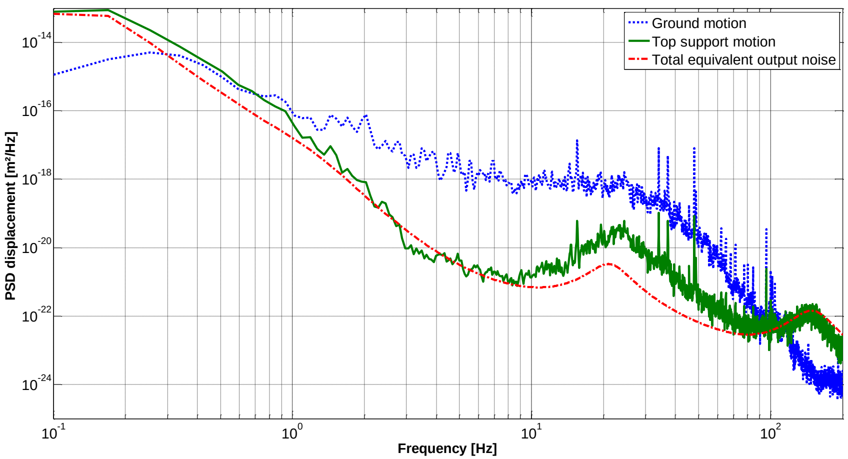
- **Results with commercial sensors : 0,6 nm RMS@4Hz.**

- *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.*

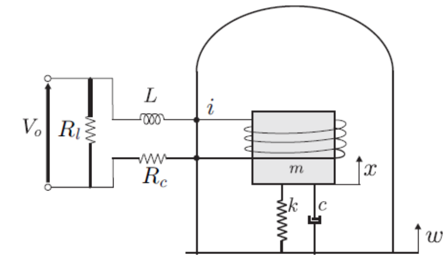
- *Sensors dedicated to measurement but not to control*
- *Two needed technologies for the selected bandwidth (geophones for low frequencies and accelerometers for high frequencies)*
  - ➢ *complexity of the control*

➢ ***Main limitation : SENSORS (Experimental and theoretical demonstration).***

- *Main limits: the use of seismic sensors (geophone, seismoters, acceleromters…) in control*



- ✓ Sensors noise
- ✓ Sensors transfer function



Geophone concept

- ➢ **Commercial investigations**
- ➢ **Internal development**

➢ ***Main limitation : SENSORS (Experimental and theoretical demonstration).***

- *Examples of commercial seismometers and accelerometers to measure nm:*

Streckeisen STS2
x,y,z
2*750Vs/m
120 s -50 Hz
13 kg

Guralp CMG 3T
x,y,z
2*750Vs/m
360s -50 Hz
13.5 kg

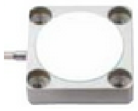
Guralp CMG 40T
x,y,z
2*800Vs/m
30 s -50 Hz
7.5 kg

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

Eentec SP500
z
2000Vs/m
60 s -70 Hz
0.750 kg

PCB 393B31
z
1 Vs²/m
10 s -300 Hz
0.77 kg

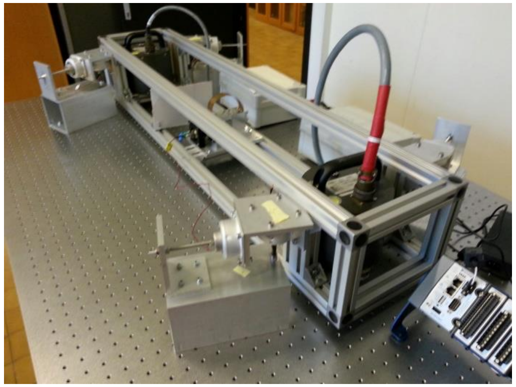
Wilcoxon 731A
z
1 Vs²/m
10 s -300 Hz
0.55 kg



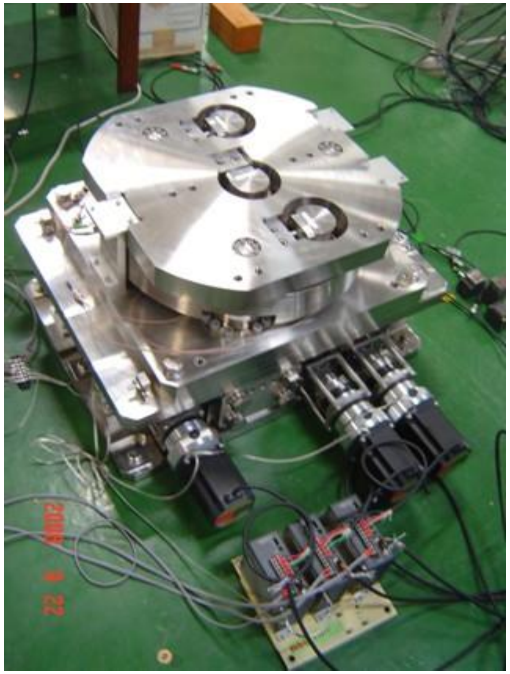
PI D0-015
Δd
0.67 V/µm
10 s -300 Hz
0.635 kg

Active control : worldwide developments

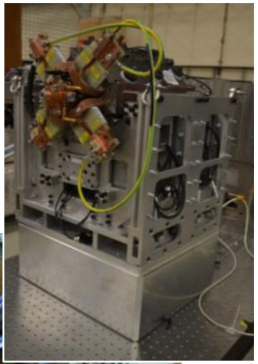
- ***Few examples:***



Active control
ULB



ILC stabilization
KEK

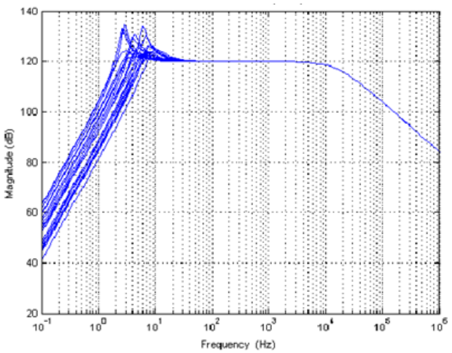


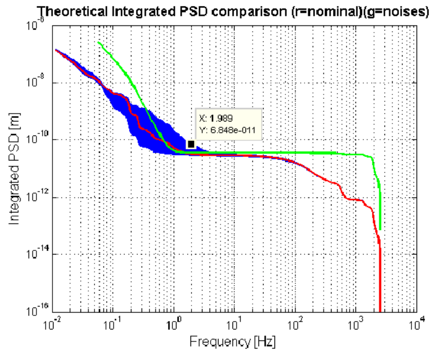
CLIC Main Linac stabilization
CERN

Xband linear collider
SLAC

➢ *And a lot of others experiments like Virgo, ELT, DESY…*

- ***Development of a new vibrations sensor dedicated to control:***

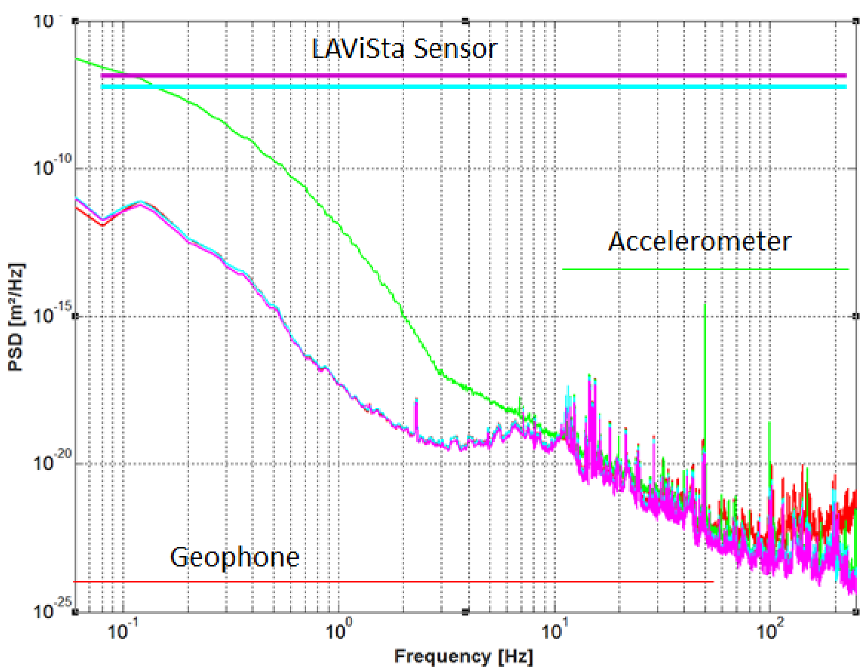




Prototypes developed since 2011

➢ Approach validated → Patent n° FR 13 59336.

- ***Comparison with Güralp and Wilcoxon sensors at CERN (ISR):***



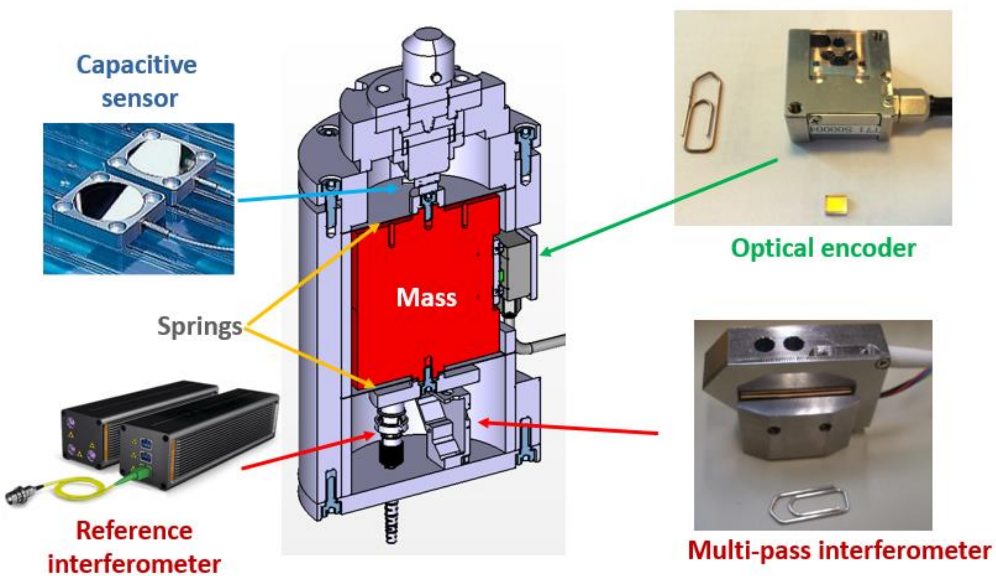
Geophone (Güralp 3-ESP)
Low frequencies

Accelerometer (Wilcoxon 731A)
Mid-High frequencies

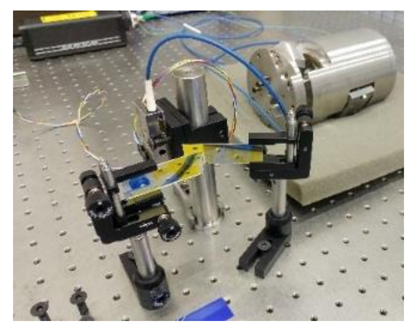
LAViSta sensor (x2)
Large bandwidth

- ***Comparison of different technologies for the embedded sensitive part***

  - PACMAN (-> 2017) : Particle Accelerator Components' Metrology and Alignment to the Nanometre scale (Marie Curie program at CERN)
  - 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))

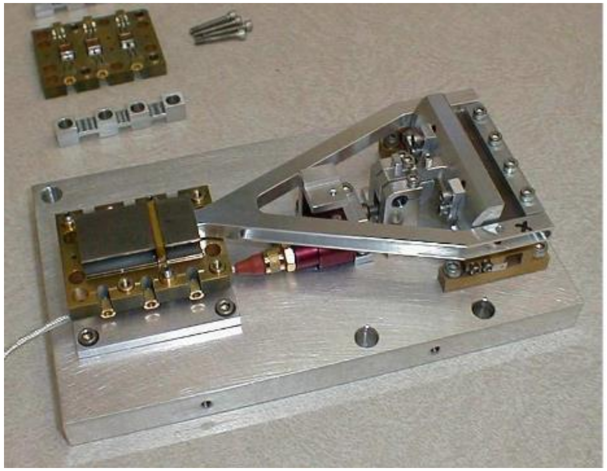


Interféromètre multi-pass

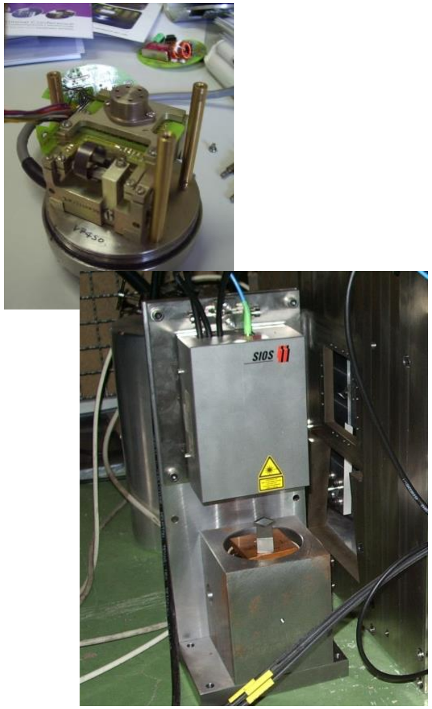
Encodeur optique

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

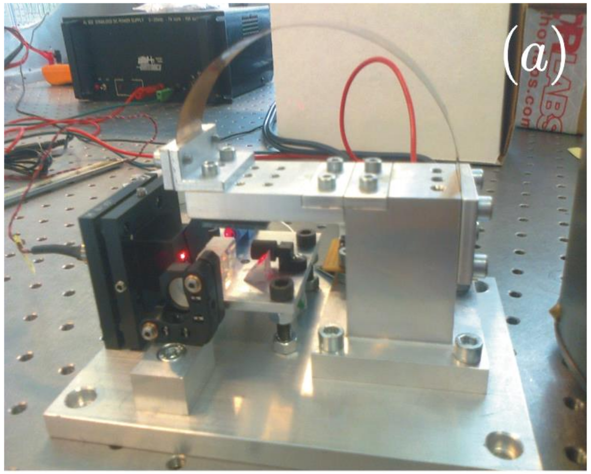
- ***Some examples of vibrations sensors developments:***



Non-magnetic compact vibration sensor developed at SLAC



Vibrations sensors with interferometric measurement at CERN



Vibrations sensors with optical differential measurement at ULB

Objective:

Better signal to noise ratio needed in the bandwidth of interest (1 – 100 Hz)

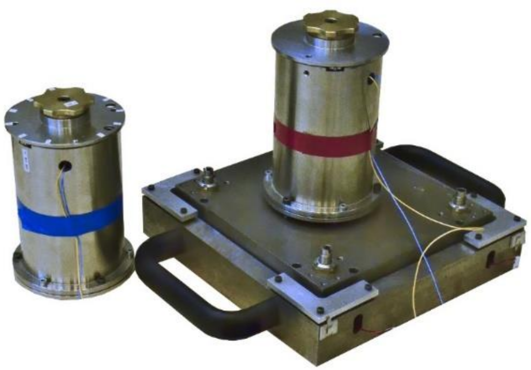
Active control with the developed sensors

- ***CLIC Demonstration of faisability at reduced scale***

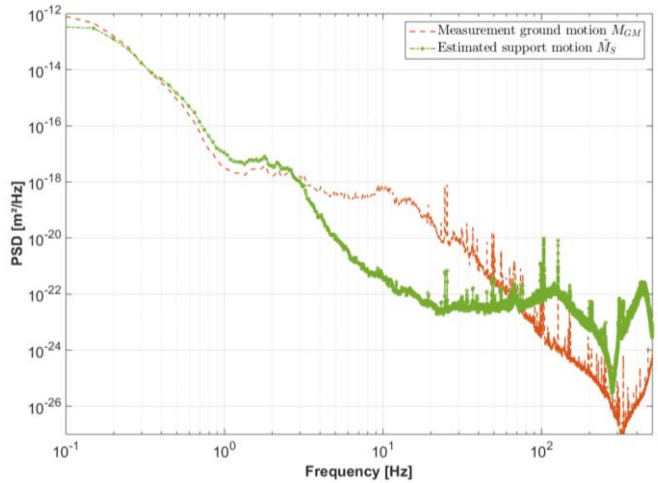
  - CLIC specification (displacement of the QD0 final focus) : 0,20 nm RMS@4Hz
  - Previous results with LAPP active foot + 4 commercial sensors : 0,60 nm RMS@4Hz

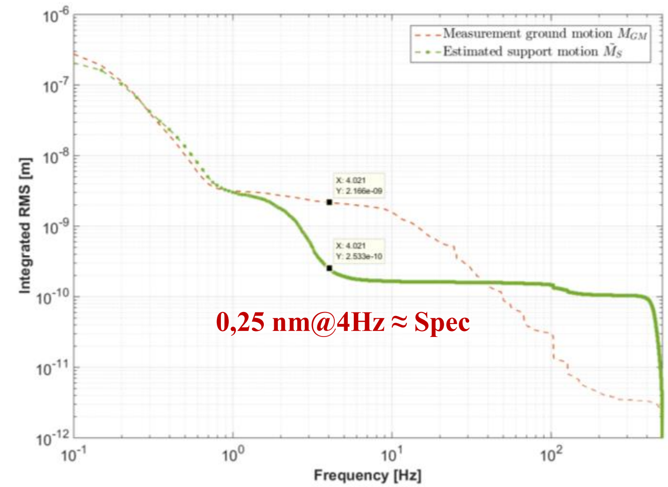
  - ➢ **Results of control (autumn 2016) with LAPP active foot + 1 LAPP vibrations sensor : 0,25 nm RMS@4Hz**

  - *Only 1 sensor in feedback -> control less complex and more efficient*
  - *Journal article submitted in beginning of 2017*



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



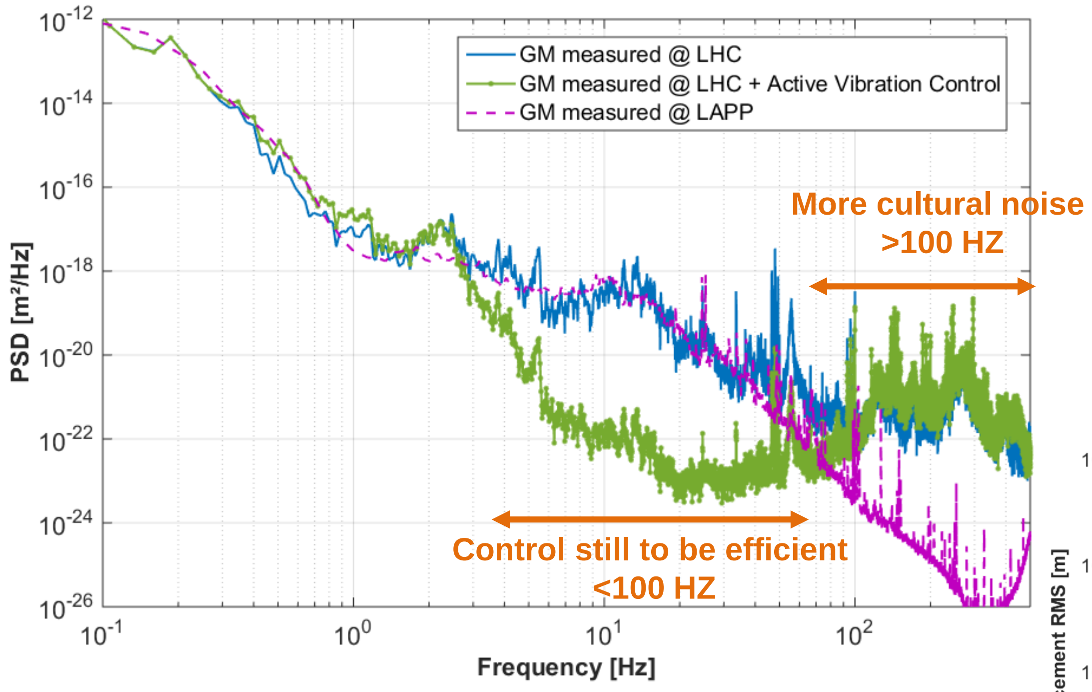


- Displacement ***without control*** */* ***with control*** ***at LAPP*** -

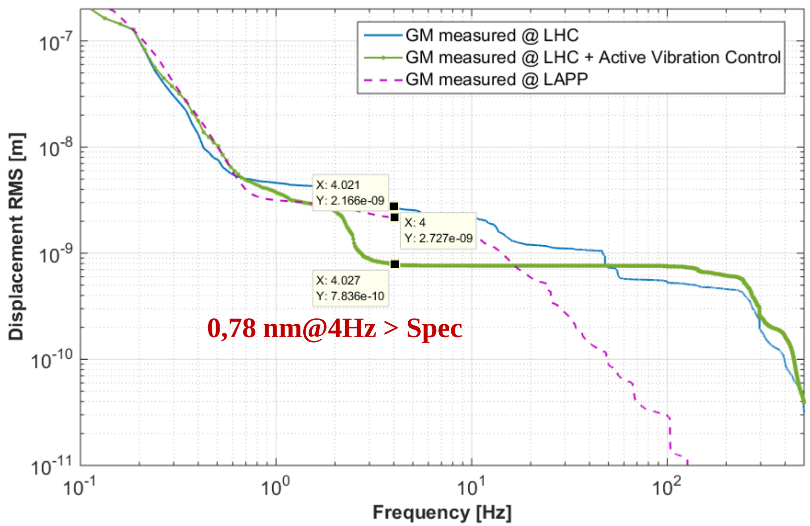
- ➢ *Collider environment*
- ➢ *Large scale*

Simulation of the active control with a collider environment

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

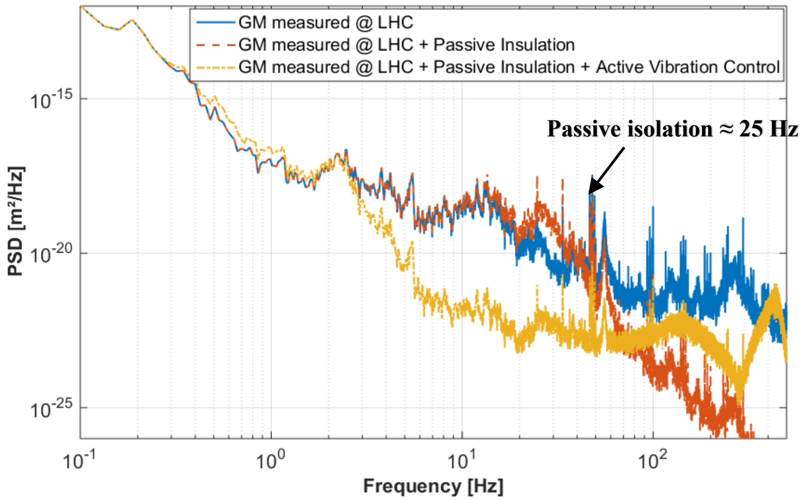


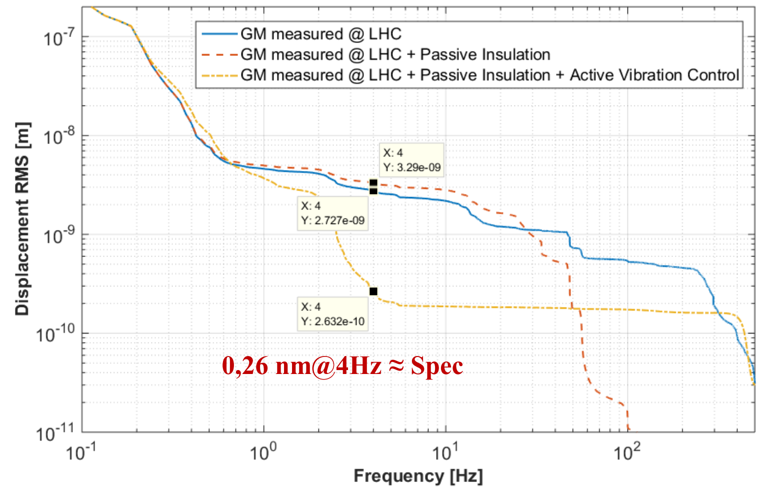
- *Disturbances don't reveal the same distribution (more cultural noise)*



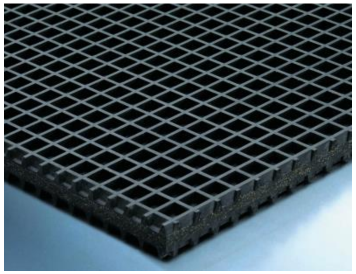
➢ ***Control is not efficient enough in this case (above 100 Hz)***

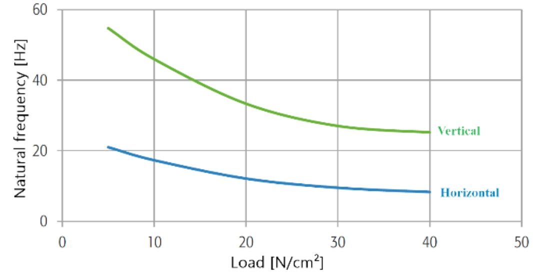
- ***Necessity to have a passive insulation under the concrete or under the last elements***





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

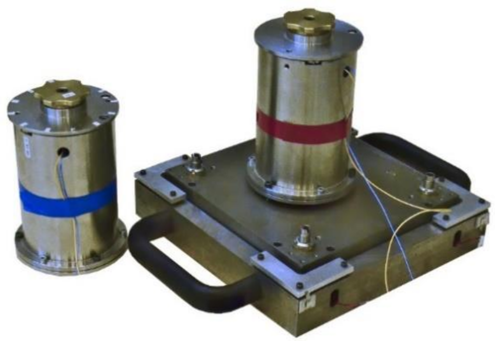


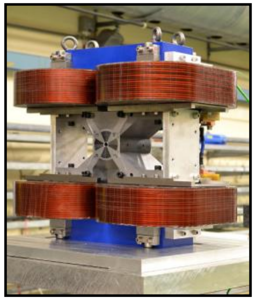


Example of usable PI (Biltz® B13W- vibration isolation rubber pad).

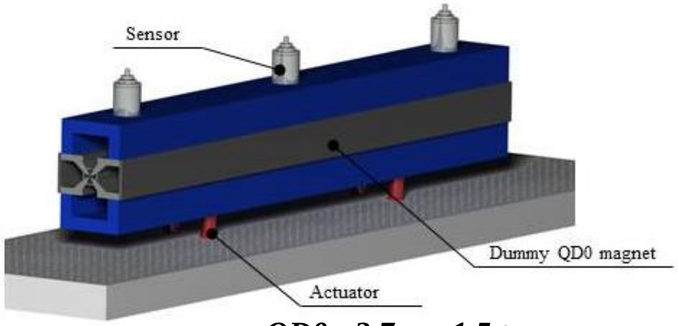
- **Poster session at IPAC17:** G. Balik et al, "Proof of concept of CLIC final focus quadrupoles stabilization", in Proceedings of International Particle Accelerator Conference (IPAC 2017), Copenhagen, Denmark.

From the demonstration to a large scale experiment



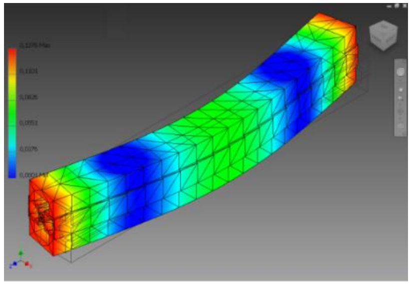


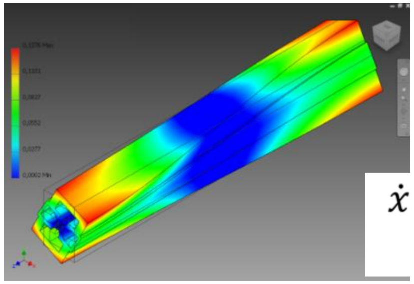
Slide of QD0

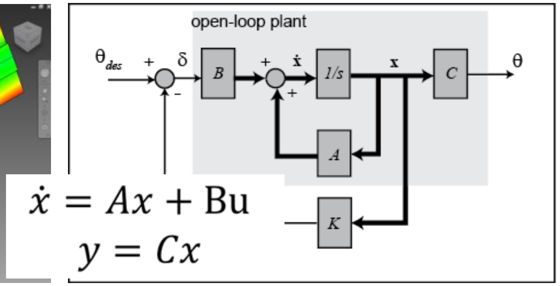


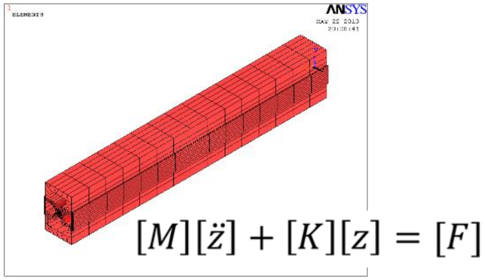
QD0 : 2,7m – 1,5 tons

- ***Simulation***









- FEM : Modal analysis using finite elements - Determination of the most significant modes (frequency response characteristics)
- Expression in the form of a state space model and study of the control stategy
- Integration in a control loop (using Simulink for example) with the whole simulation (sensor, actuactor, ADC, DAC, Data processing…. And seismic motion model and its coherence)
- Control in simulation (location and number of active feet, type of active feet, degrees of freedom, type of control (SISO, MIMO))

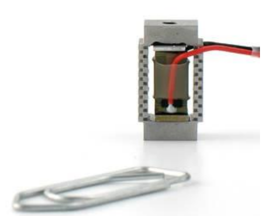
A large actuator

- ***Actuator specifications (results of global simulation)***

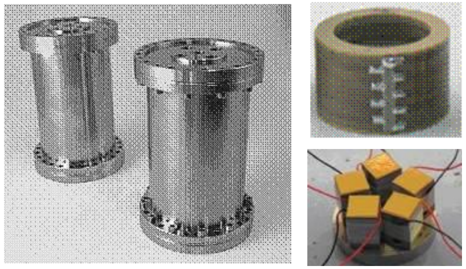
Dynamic	Signal / noise	Bandwidth of freq.	stiffness
6 microns	95 dB	0,3 : 300 Hz	≥ 10 kN/µm

➢ **No commercial actuator matches with the needs in terms of resolution, dynamic, stiffness…**

- ***Mecatronics challenge***
  - *Structure : QD0 Magnet*
  - *Sensors*
  - *Actuators*
  - *Integration: control, data processing, real time, layout, interfaces…*



Ex of small size PZT actuator



Example of a large actuator

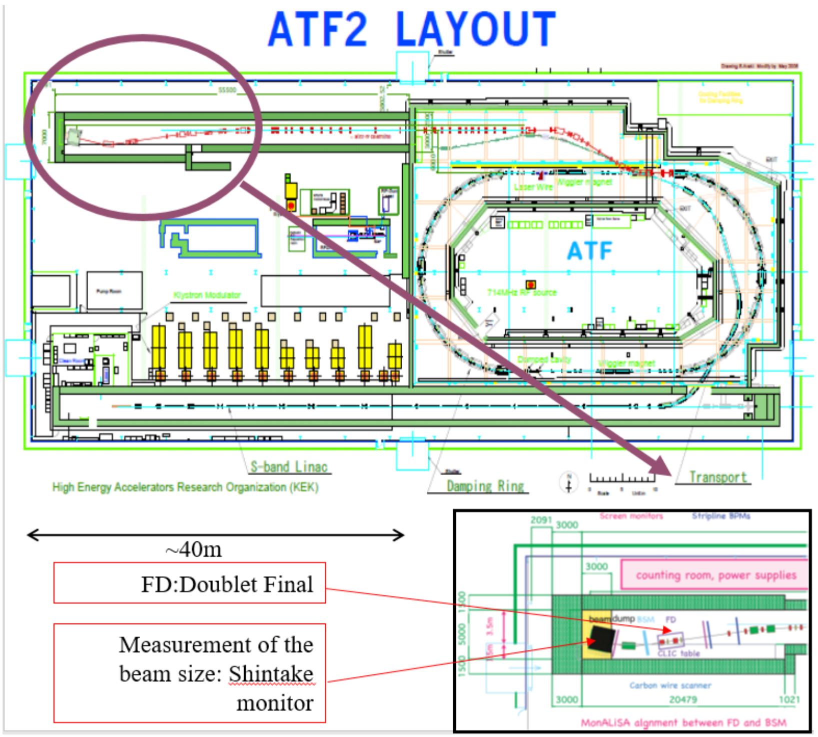
- Actuators have to be developed -

➢ The project of this prototype development in collaboration with manufacturers is already evaluated (still to be expensive)

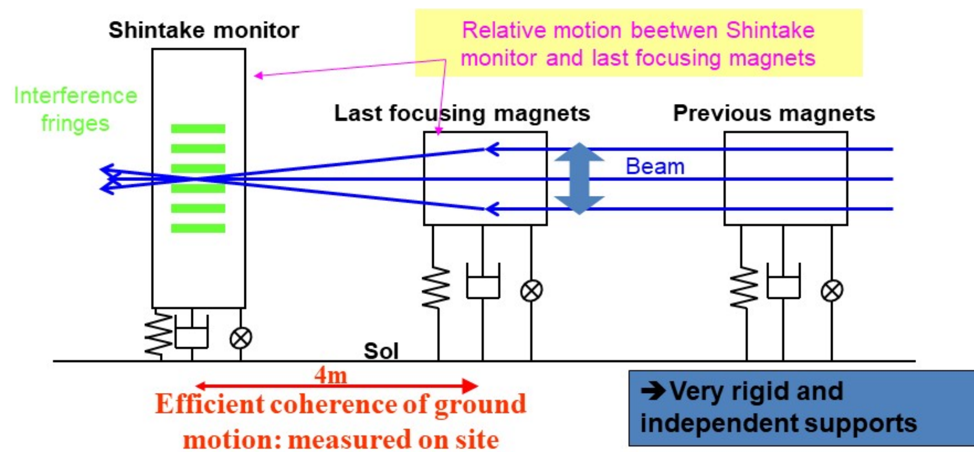
➢ Close to some machining issues

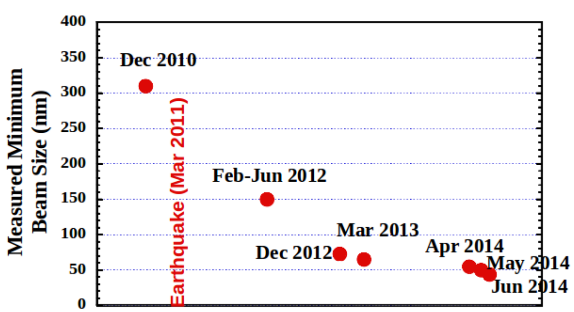
ATF2: strategy of stabilization

- ***Optimization of the coherence***
  - ***ATF2 Objectives :** Steady and repetitive beam with a radius of 37 nm at the focus point.*



- It requires to have a relative motion between the Shintake Monitor and the final focus magnets: **10 nm above 0.1Hz** in the vertical direction
  - Solution 1 : Active isolation of the elements (i.e. CLIC)
  - **Solution 2 : optimization of the motion coherence between the elements**

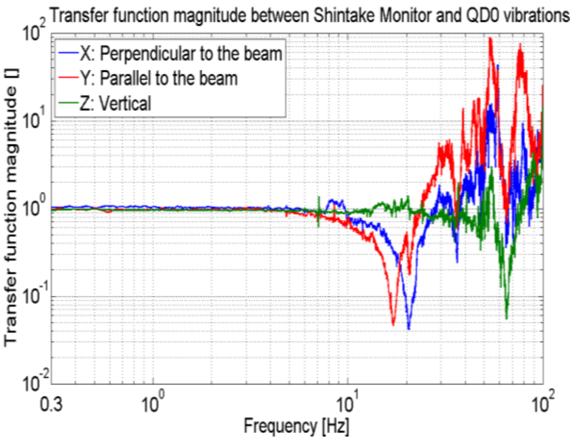


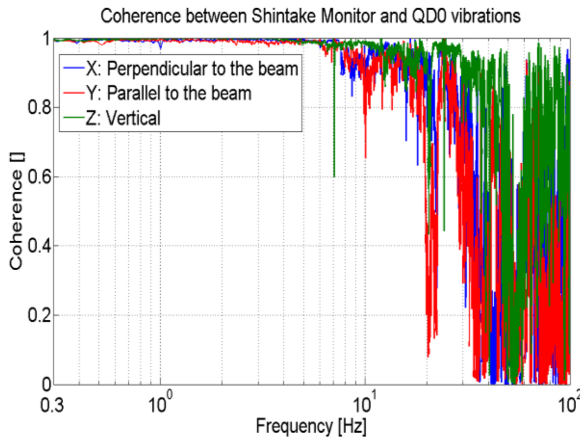


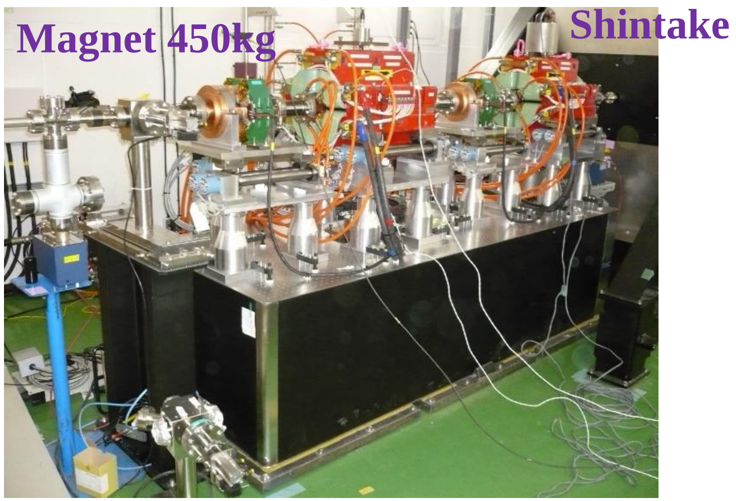
- Transfer funtion between ground and final focus and shintake monitor has to be as close as possible to 1

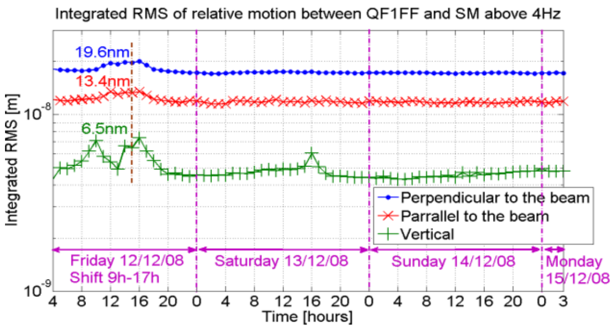
Demonstration of linear colliders - ILC

- ***Final setup of the final focus:***







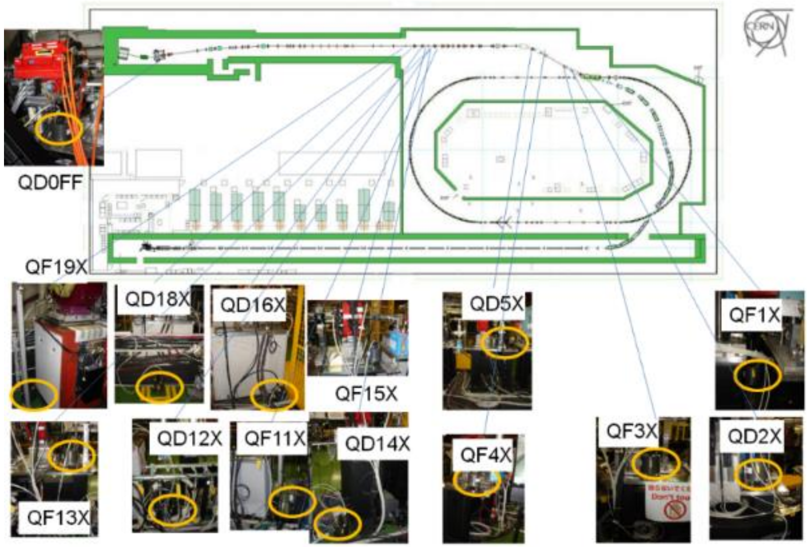


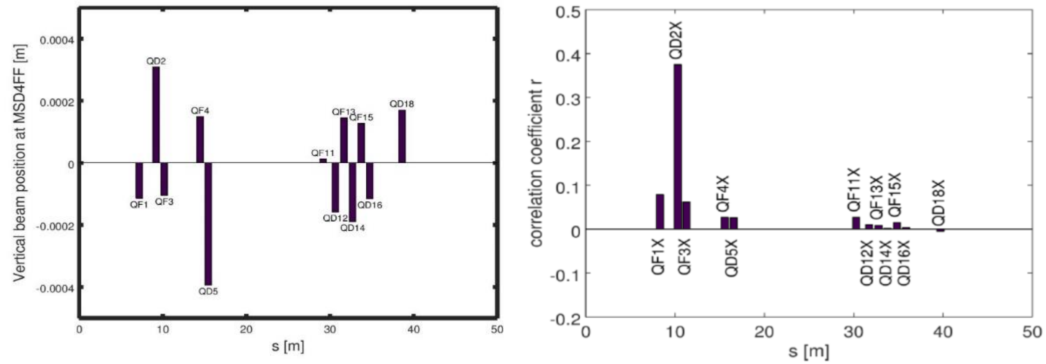
- Very stiff in z direction (first eigenfrequency at 70Hz induced by the final doblets supports) - beeswax

- ***Relative motion between shintake monitor and final doublets of [4 – 6] nm RMS @ 0,1 Hz (vertical axis):***

	Tolerance	Measurement [SM-QD0]	Measurement [SM-QF1]
Vertical	7 nm (for QD0) 20 nm (for QF1)	4.8 nm	6.3 nm
Perpendicular to the beam	~ 500 nm	30.7 nm	30.6 nm
Parallel to the beam	~ 10,000 nm	36.5 nm	27.1 nm

- ***Original approach: test a feedforward control in function of the magnet motions***

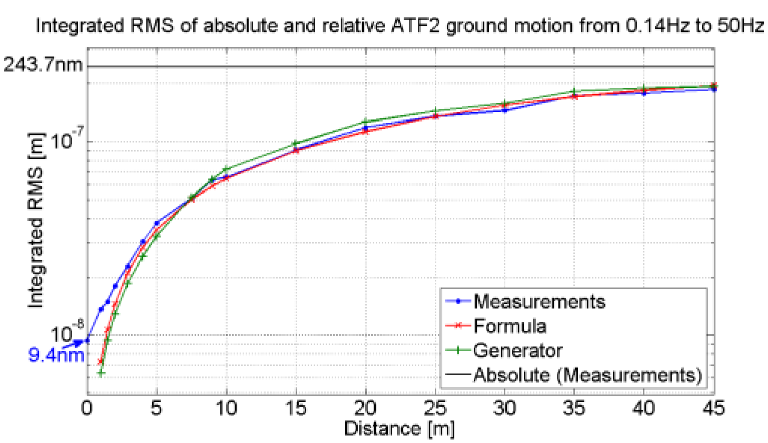




Comparison of the estimated and the correlated perturbations created by the magnets motions at the end of the extraction line

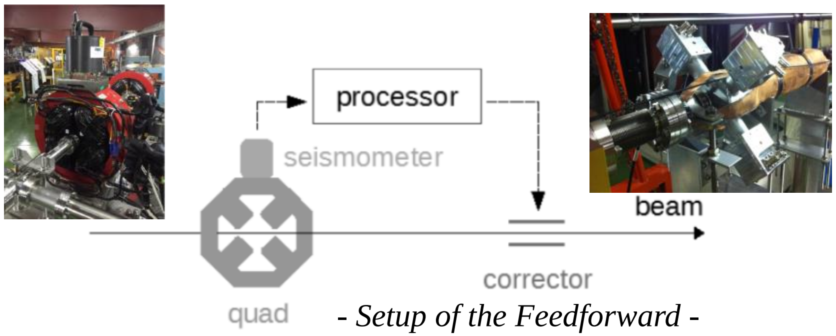
14 capteurs Geophones (Guralp 6T) ***- Collaboration CERN, LAL, Oxford, KEK and LAPP***

- ***Feedforward issues***
  - To extract very accurately the disturbances (coherent vs incoherent motion)
    - *Only the incoherent disturbances / motions along the collider have an influence on the beam (Low frequencies are quite coherent)*
  - **To know very well the system** (the effects of the vibrations and of the magnets on the beam)

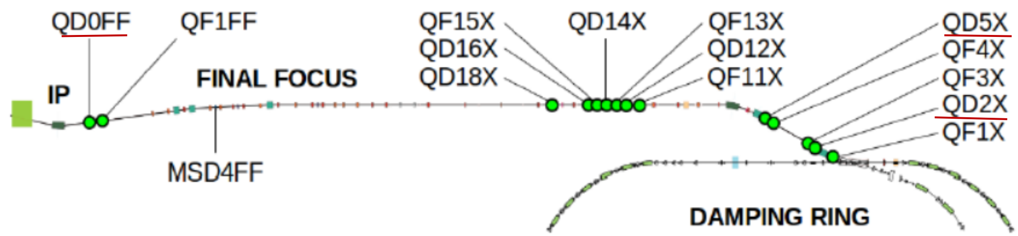


Feedforward setup of the demonstration

- *D. Bett et al, "Compensation of orbit distortion due to quadrupole motion using feed-forward control at KEK ATF", Nuclear Inst. and Methods in Physics Research, A 895 (2018) 10–18*



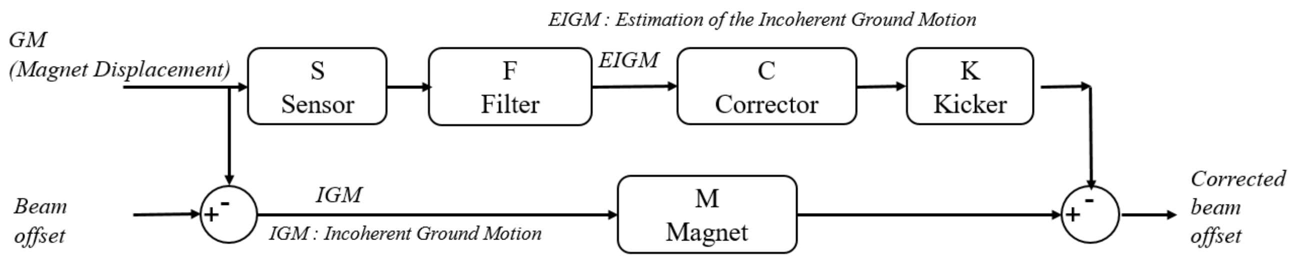
- Setup of the Feedforward -



- Layout of the GM sensors along the collider-

Feedforward concept

- The principle is quite elementary but to implement efficiently this control law, it requires :



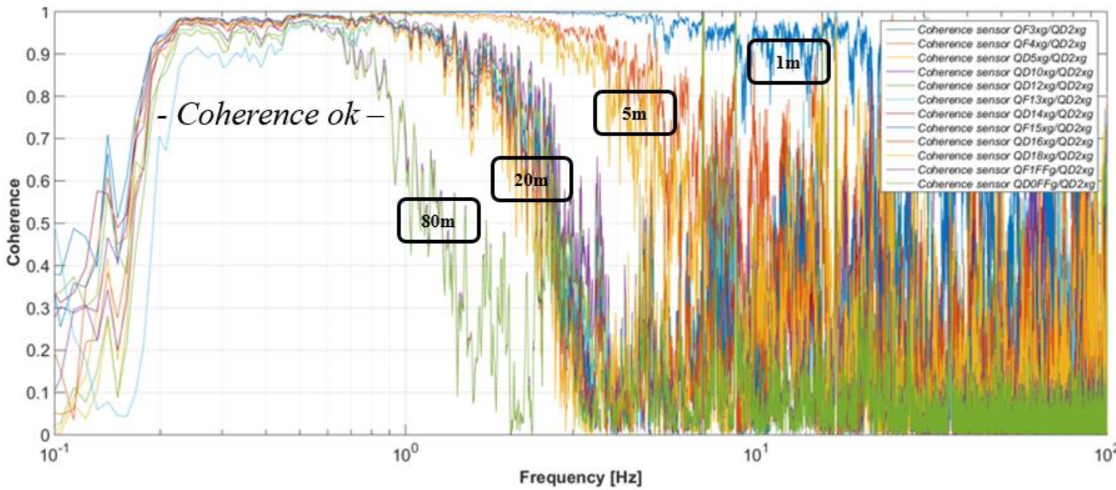
Control law – conceptual scheme

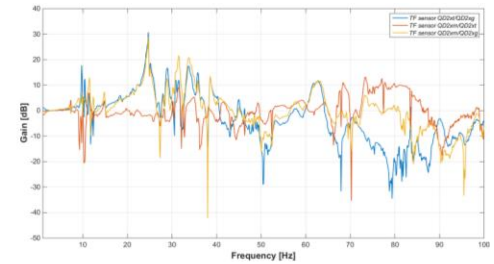
$M= S.F.C.K$ As consequence, the corrector has to satisfy the following condition: $C = \frac{M}{S.F.K}$

Then *C is the constant gain* in the bandwidth of interest.

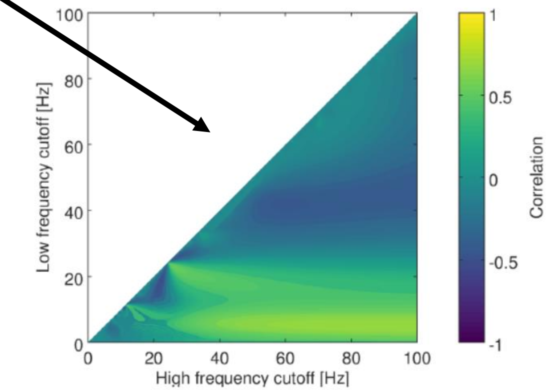
ATF2: feedforward implementation

- ***Filtering of the coherent motion***



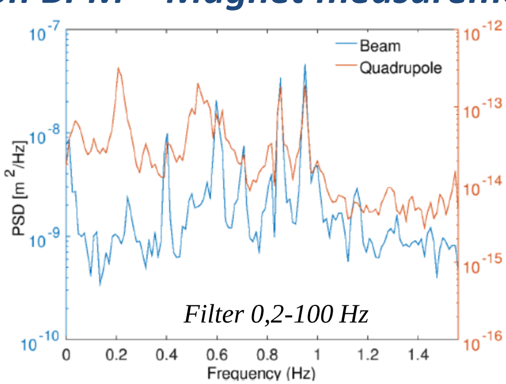


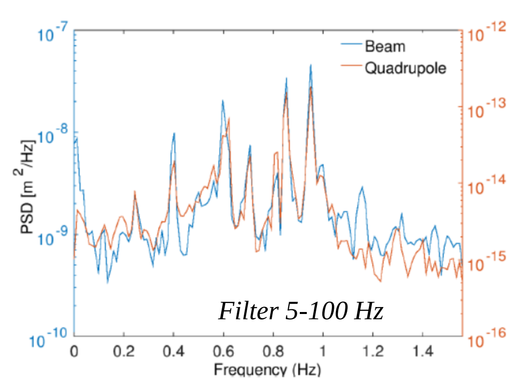
Transfer functions



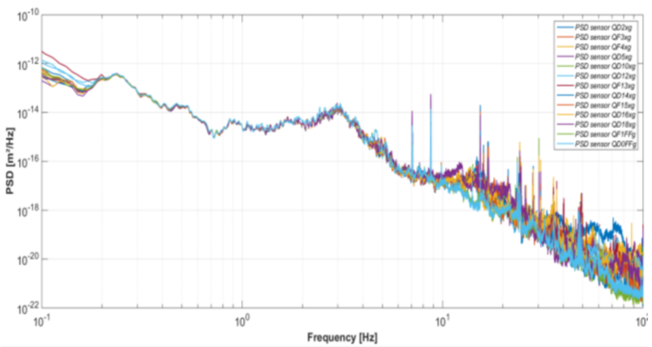
➢ ***The coherence plot could define the pattern of the filters which have to be used as function of the magnet positions (all the data with a coherence of 1 have to be filtered out)***

- ***Correlation BPM – Magnet measurements***

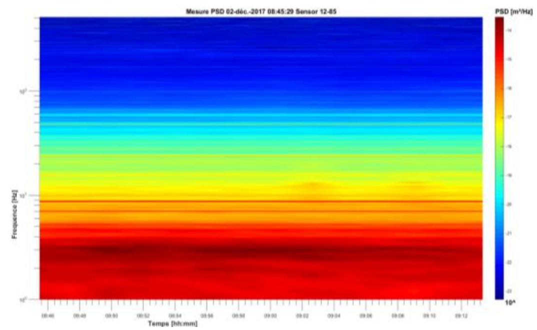




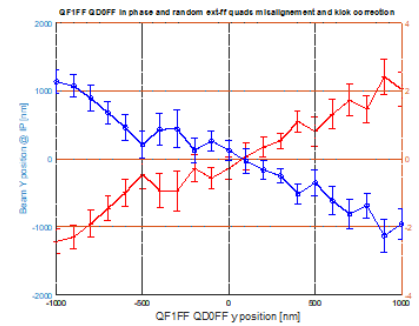
- ***Gain adjustment***



PSD of the magnets displacements

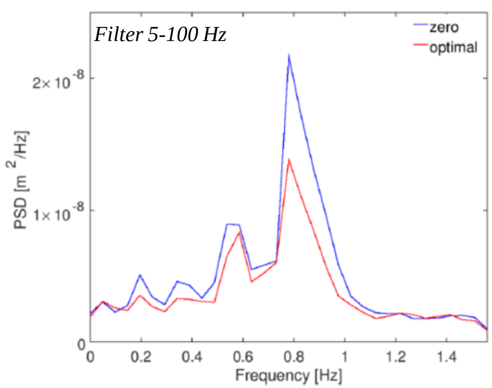


Stability study in time



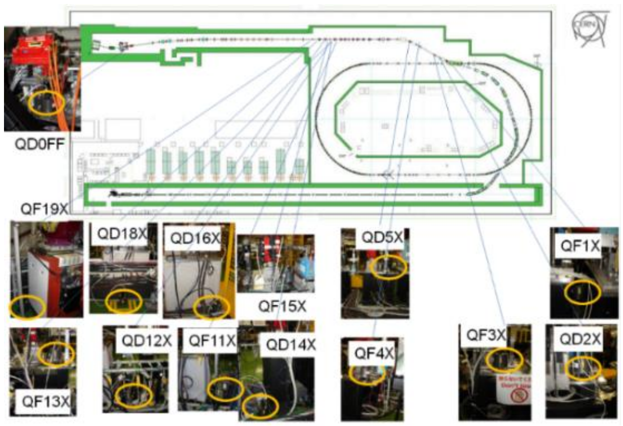
- Optics simulation under MADx -

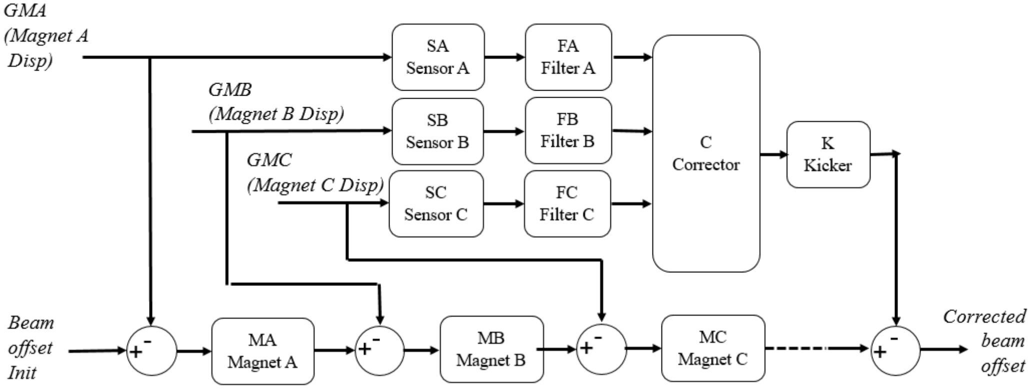
- ***Control the perturbations with the optimized gain & filter at the extraction line***



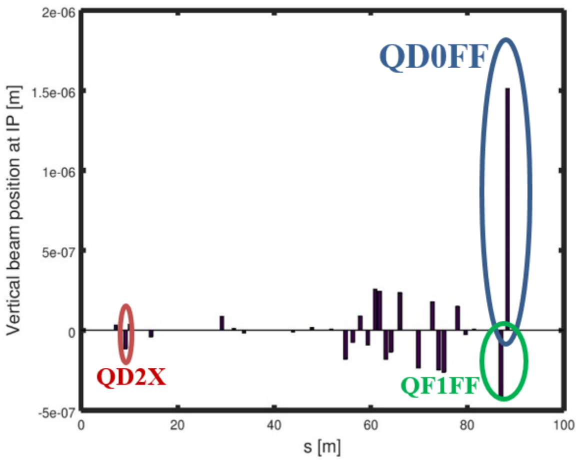
- The obtained experimental results with 1 geophone and 1 kicker -

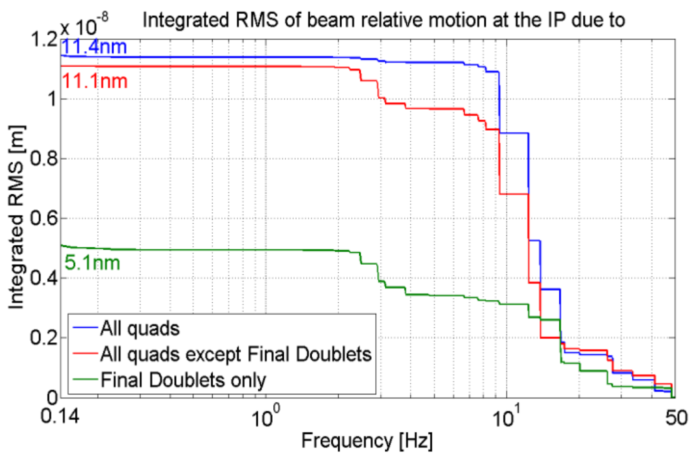
- ***MIMO control and final focus:***





- Foreseen multi-sensors control with 3 geophones and 1 kicker -





- ➢ 3 dedicated runs last November, analysis in progress
- ➢ Main issue is to evaluate the benefits vs the resolution of the BPMs

Conclusions

- ***Sub-nanometer beam (CLIC):***
  - A lot of developments are in progress
  - Great results have been already obtained
  - The main issues still to be the instrumentation

- ***Nanometer beam (ATF2):***
  - An efficient stabilized beam has been achieved
  - An alternative method of beam control has been demonstrated and still to be in progress