Stabilization and Positioning of CLIC Quadrupole Magnets with sub-Nanometre Resolution

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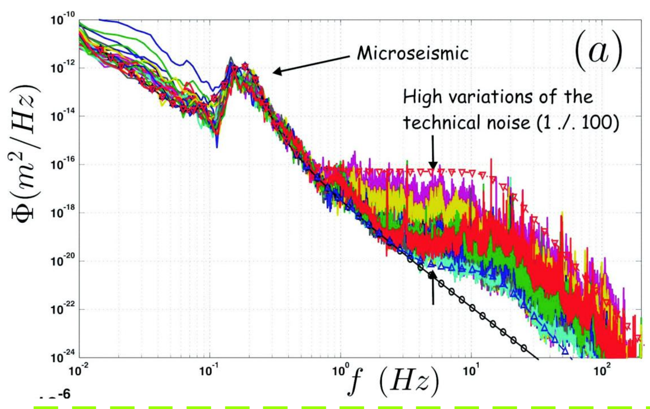
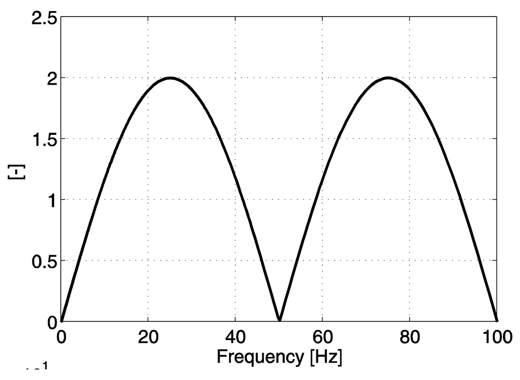
CLIC stabilization

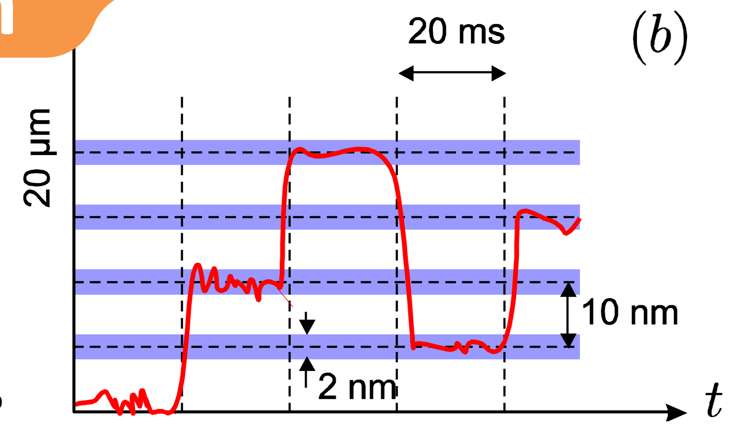
Abstract

To reach the required luminosity at the CLIC interaction point, about 2000 quadrupoles along each linear collider are needed to obtain a vertical beam size of 1 nm at the interaction point. Active mechanical stabilization is required to limit the vibrations of the magnetic axis to the nanometre level in a frequency range from 1 to 100 Hz. The approach of a stiff actuator support was chosen to isolate from ground motion and technical vibrations acting directly on the quadrupoles. The actuators can also reposition the quadrupoles between beam pulses with nanometre resolution. A first conceptual design of the active stabilization and nano positioning based on the stiff support and seismometers was validated in models and experimentally demonstrated on test benches. Lessons learnt from the test benches and information from integrated luminosity simulations using measured stabilization transfer functions lead to improvements of the actuating support, the sensors used and the system controller. The controller electronics were customized to improve performance and to reduce cost size and power consumption. The outcome of this R&D is implemented in the design of the first prototype of a stabilized CLIC quadrupole magnet.

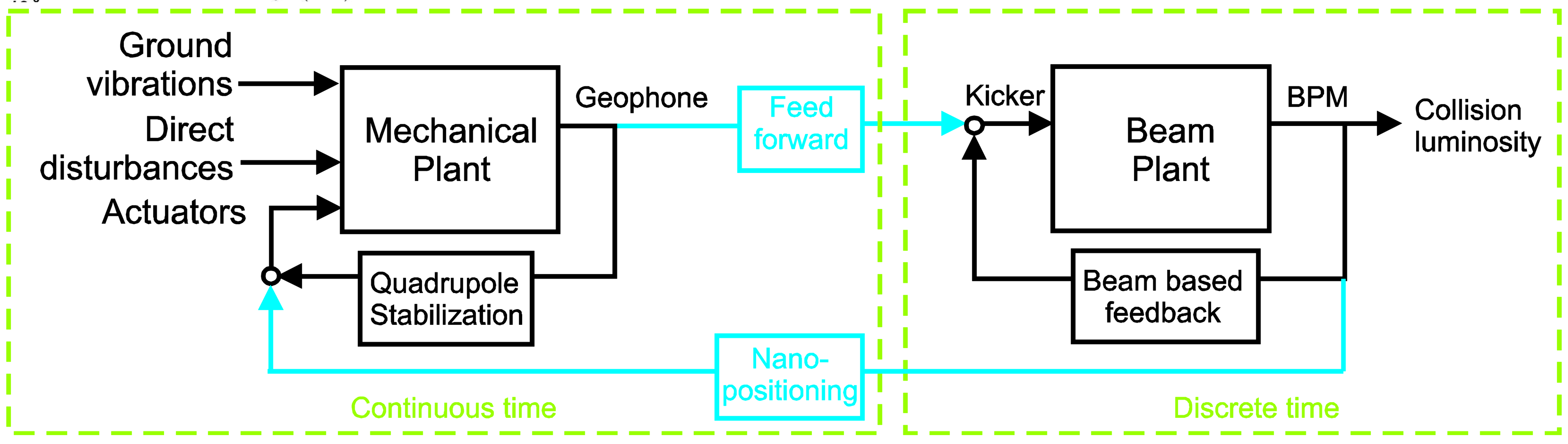


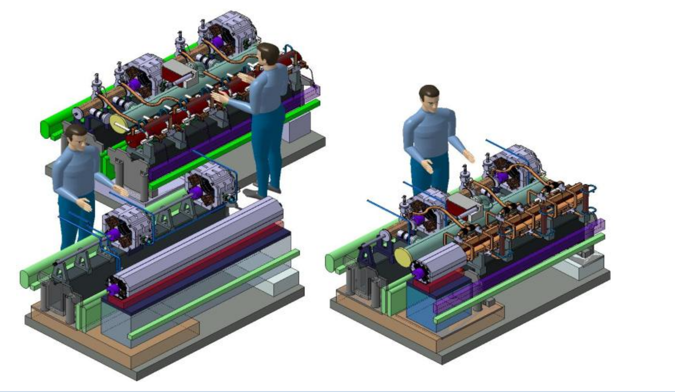


Beam based feedback



Nano positioning



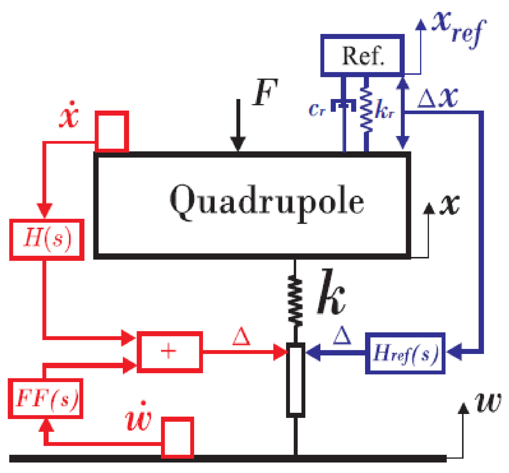


Requirements stabilization:
- Transmissibility reduction >5
- Bandwidth: 1-50 Hz
- No resonances 50-100 Hz

Requirements nano positioning:
- Every 20 ms
- Steps of 20 nm
- Precision +/- 1 nm

Additional requirements:
- Robust against external forces (F)
- Working in accelerator environment
- Fit in the space available in the module
- Cooperate with Beam based orbit feedback

Stabilization strategy



Stiff piezo actuator system
- Robustness against external forces
- Compatible with alignment system
- lockable for transport
- Allows fast nano-positioning

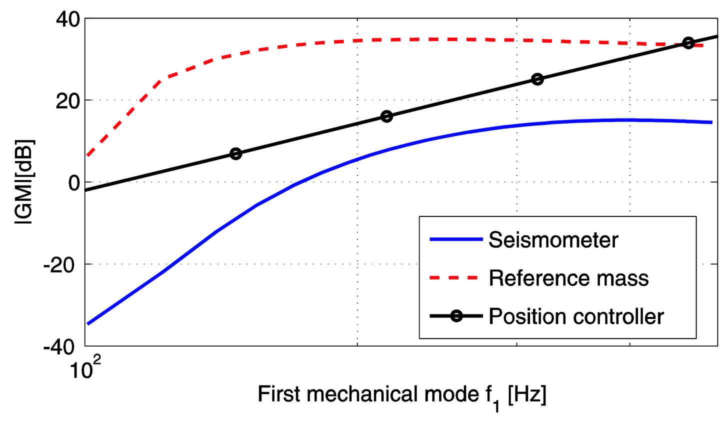
$$X(s) = \frac{k}{ms^2+k}W(s) + \frac{1}{ms^2+k}F(s) + \frac{k}{ms^2+k}\Delta(s)$$

Seismometer

Inertial reference mass

Seismometer	Measures velocity of a magnetic reference mass with a coil. • Bandwidth 33 mHz - 100 Hz • limited by high order filters • Used in FB configuration • Used in FF+FB configuration • Limited by instability in the feedback loop caused by poles in high order low pass filters. Elongation of the actuators *is* given by Δ = *H(s)sX(s) + FF(s)sW(s).*
Inertial reference mass	Measures relative displacement *Δx* between a reference mass *Xref(s)* with a suspension freq of 1 Hz and the quadrupole position *X(s)* • Improved stability as poles high order low-pass filters are removed • Bandwidth 1Hz high-pass filter The elongation of the actuator for this configuration is given by *Δ = -Hr(s)(X(s) - Xr(s)) = -Hr(s)X(s)(1Gr(s))* with *Gr(s)=Xr(s)/X(s) = crs+kr/mrs2+crs+kr*
Nano-position control	Measures the error e(s) between the requested quadrupole position R(s) and the actual relative position *Y (s) = X(s) -W(s)* • limited by the pole of the first mode • In order to increase stability a low pass filter at 40 Hz is added. The actuator elongation is given by *Δ(s) = C(s)e(s).* C(s) is a PI controller.

Stability margins for a vibration isolation system with a seismometer, a reference mass and the positioning controller, all with a fixed gain, in function of the first mode of the system.



Controller architecture

Control center is located kilometers away from the magnets

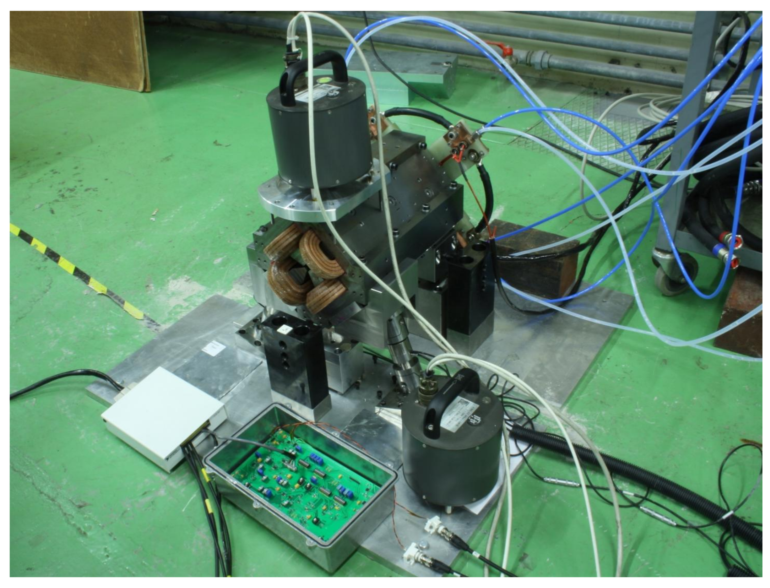
Signals phase shift affects performance of the stabilization

Local hybrid stabilization controller designed to be located next to every magnet

Analog signal path:
- Low latency
- Less sensitive to radiation
- Simplicity

Digital components:
- Remote configurable
- Flexibility

Stabilization on type 1 quadrupole



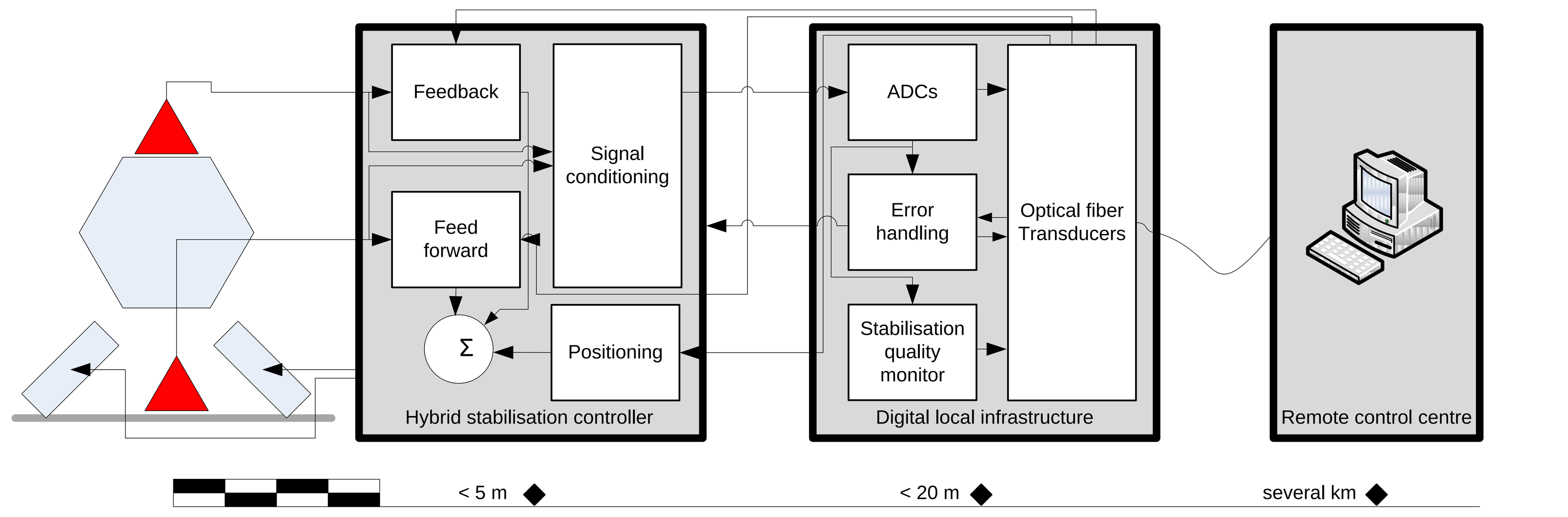
Classification of signals according to sensibility to delay

Critical latency signals
- <80 µs
- All local (sensors, processing, actuators)

Best effort delay signals
- Communication with remote centre
- Delay unavoidable

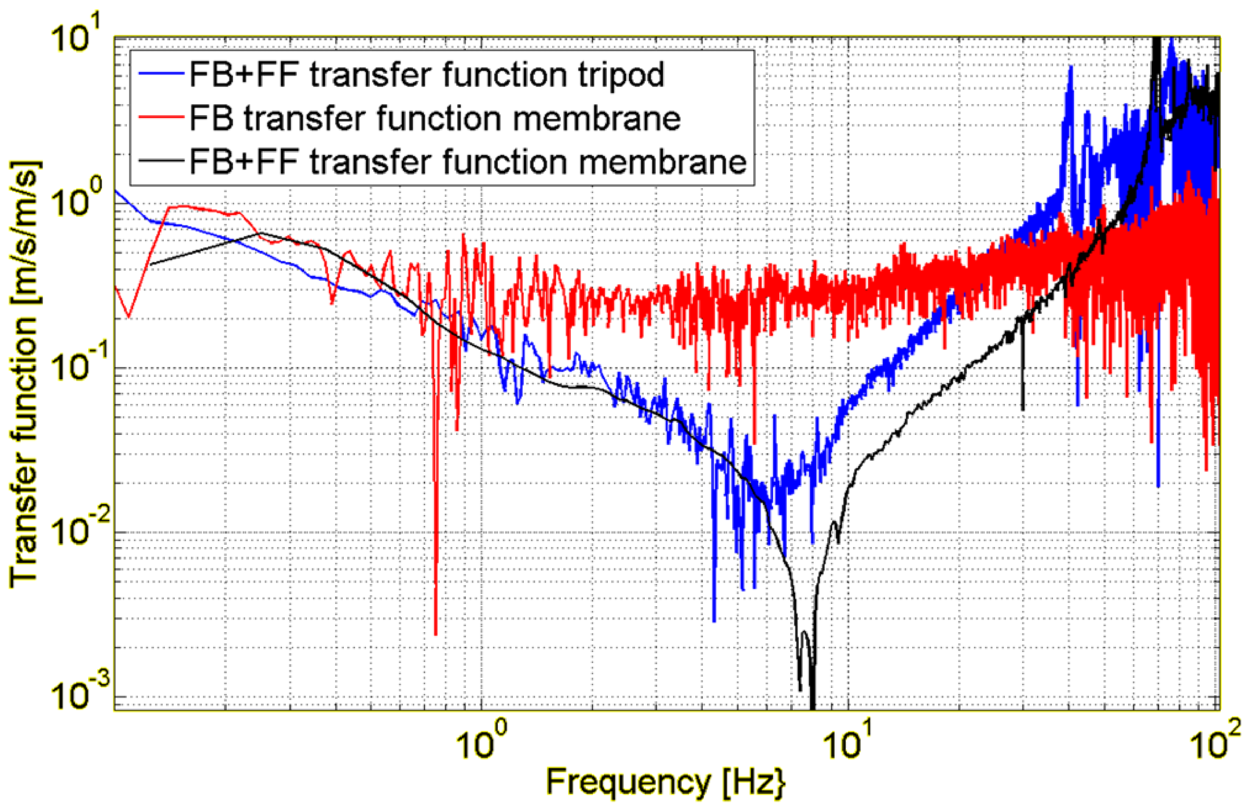
Latency classification of signals

	Critical latency	Best effort delay
Input	x˙ or Δx	Self check
	w˙	Emergency stop
	y	New position R
		Configuration parameters
Output	Δ	x˙
		Error signal
		RMS vibration level of Magnet
		Performance figure

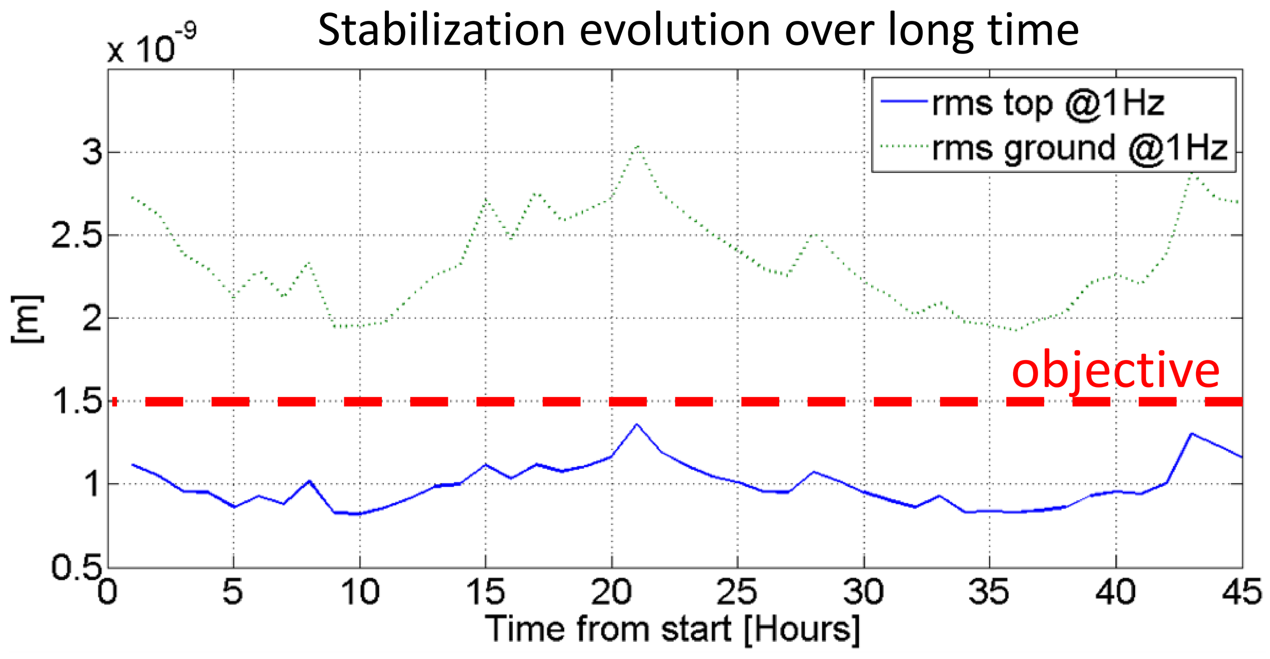


Results achieved

Transmissibility ground to magnet



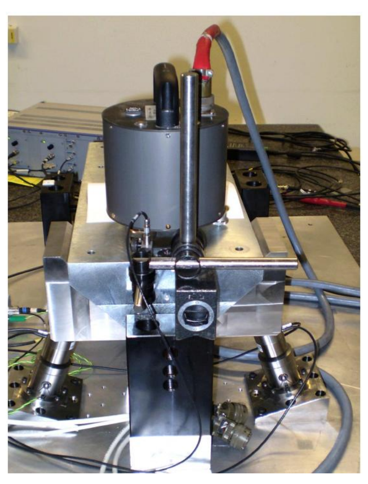
Stabilization evolution over long time



The prototype of the CLIC stabilization system has been tested on two testbenches (see below). Results look promising. Attenuation between ground and magnet can be configured for wider bandwidth or deeper factor according to the machine's needs (see top left). Root Mean Square r.m.s. value of vibrations above 1 Hz for stabilized magnets is below requirements for all testbenches and under different levels of vibrations. 0.3 nm and 0.5 nm vertical values are achieved for small mass on 1 degree of freedom and 100 kg on 2 degrees of freedom testbenches respectively, well below the 1.5 nm originally required (see top right).

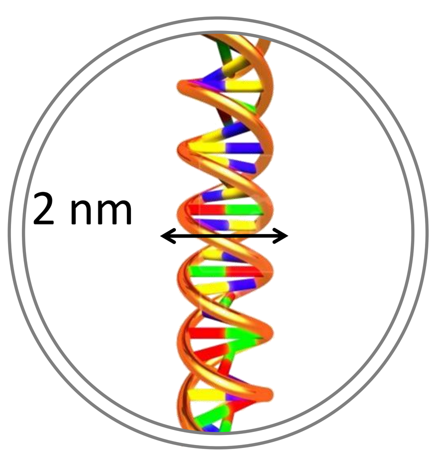
A test with stabilization on 2 d.o.f. testbench has been performed over 2 days, demonstrating feasibility of long term functionality (see bottom left). Preliminary results of nano-positioning system seem promising. Precision of 2 nm is achieved, although work is ongoing to improve speed of the steps (see bottom right).

To conclude a 100 kg mass has been stabilized to 0.5 nm above 1 Hz. For reference a DNA molecule is 2 nm wide.

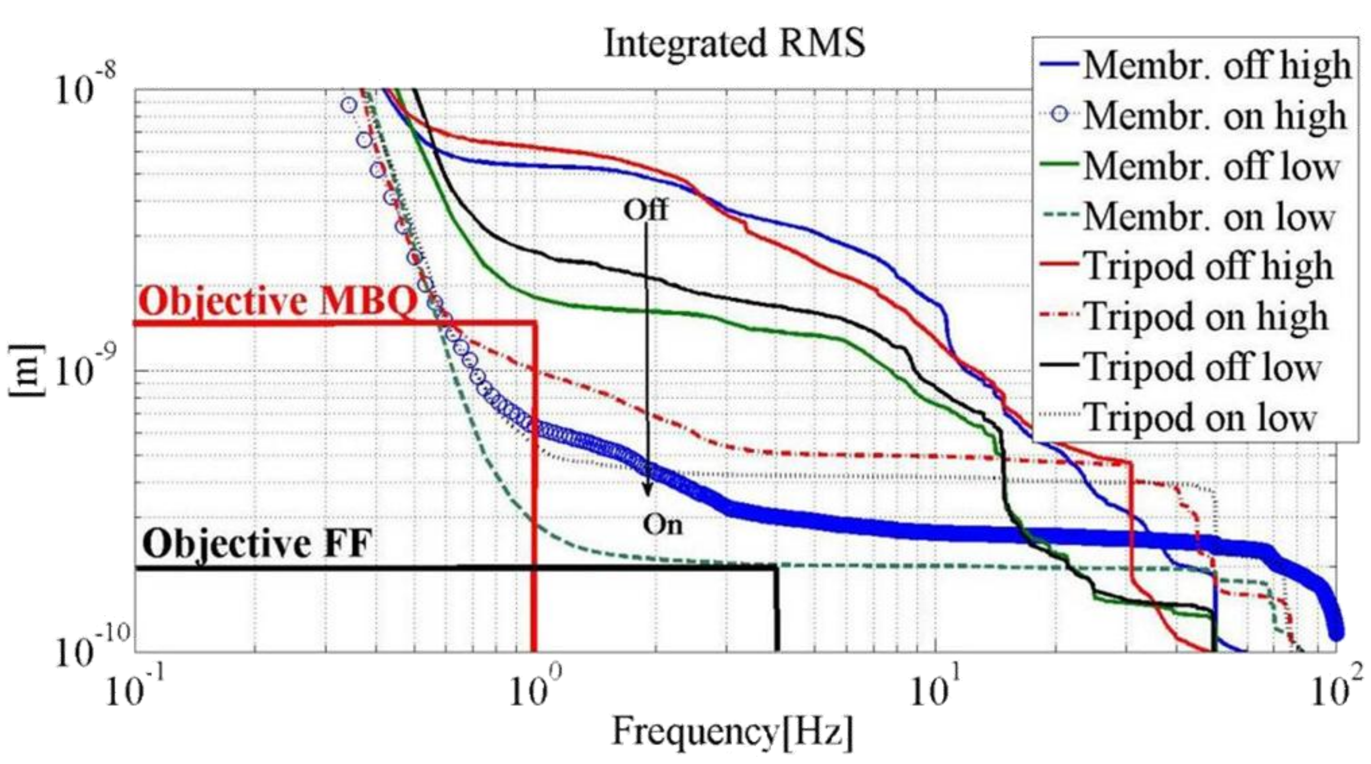


Tripod 2 d.o.f

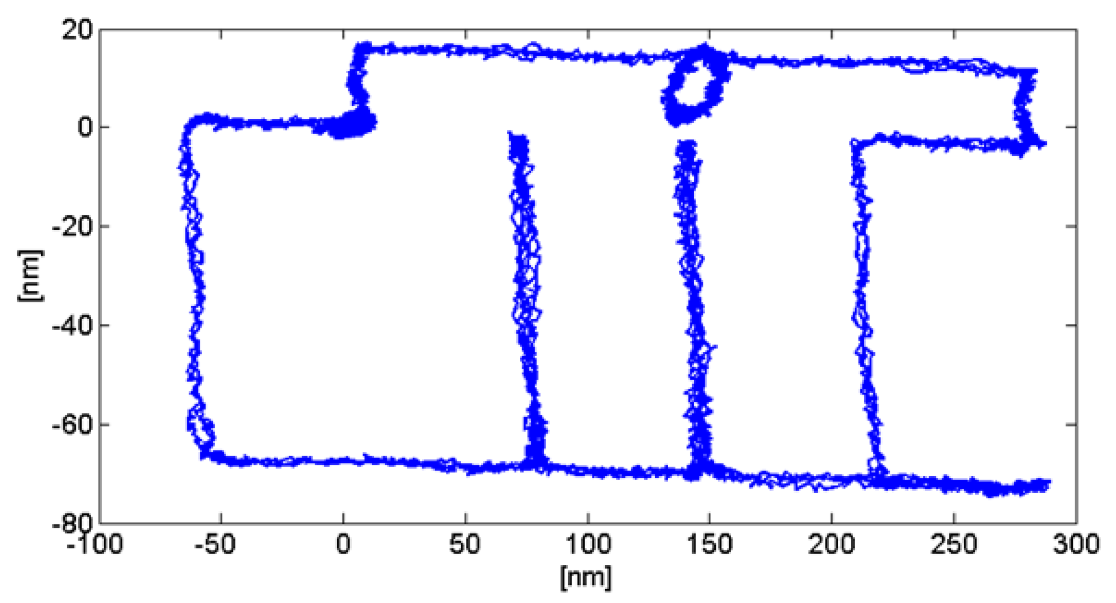
Membrane 1 d.o.f



r.m.s vibration levels for different testbenches and conditions



Nanopositioning demonstration



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http://clic-stability.web.cern.ch/clic-stability