European Organization for Nuclear Research

LINAC STABILISATION

(INCLUDING FF)

MECHANICAL STABILISATION AND NANO POSITIONING WITH ANGSTROM RESOLUTION

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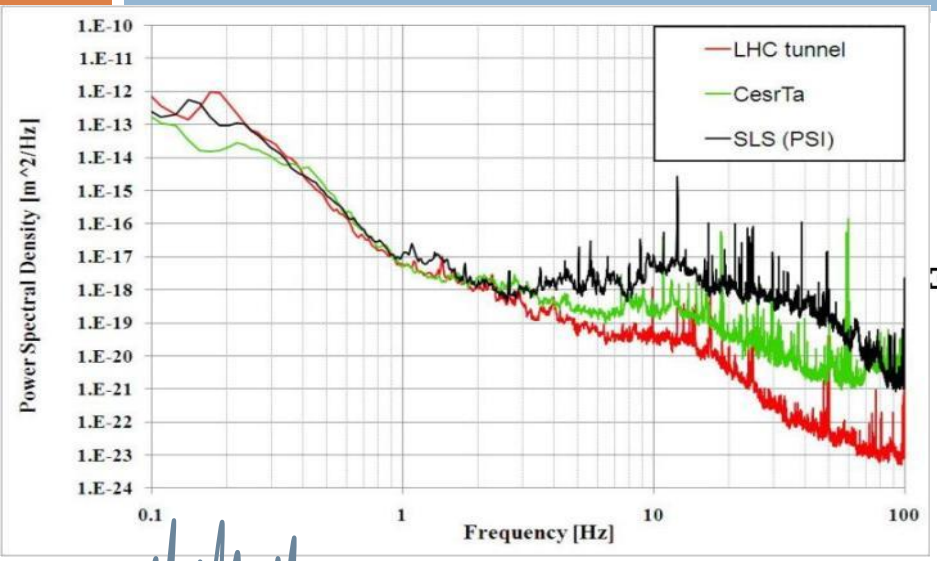
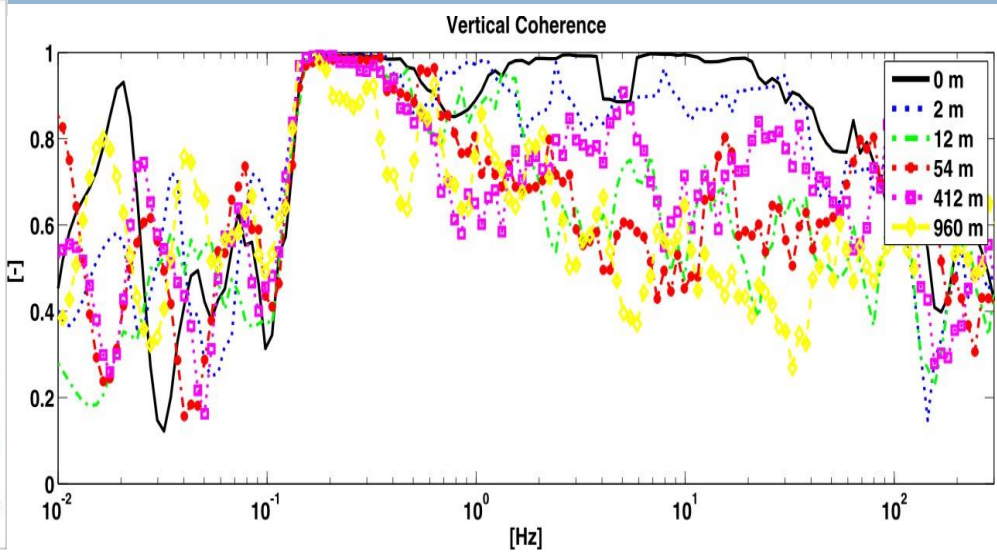
The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD

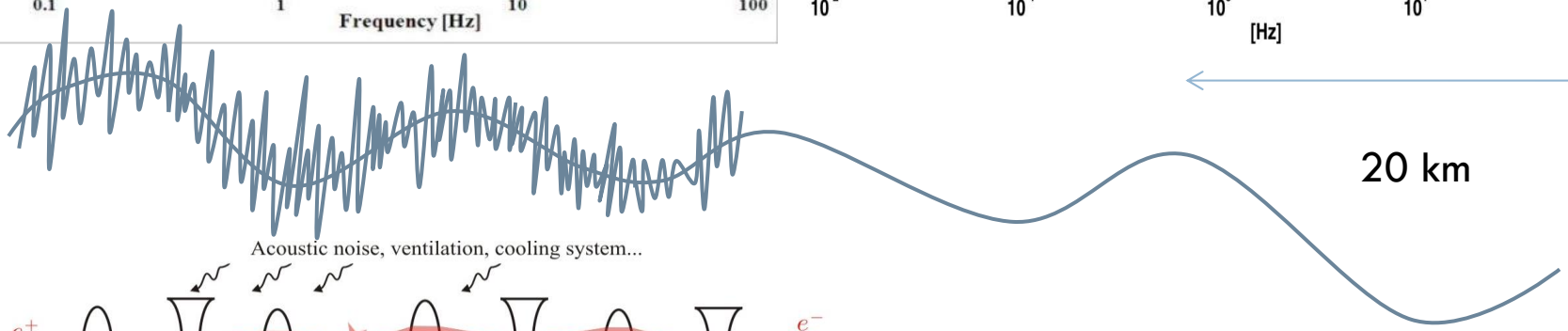
Outline

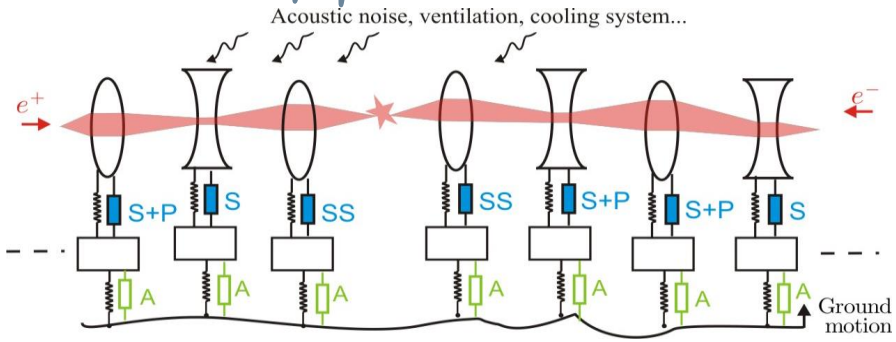
- Ground motion and CLIC Requirements
- Obtained results
- Short view on ultimate performance limitations

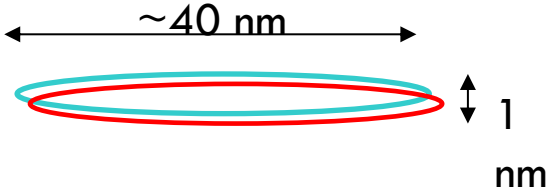
Ground motion





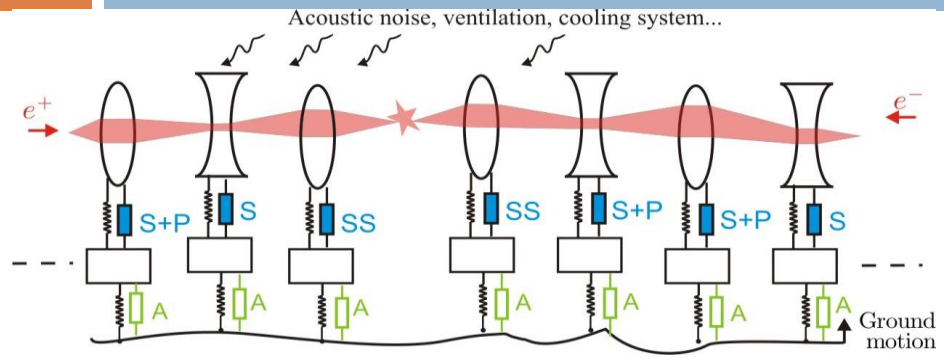






Luminosity, beam size and alignment

$$L = \frac{A}{\sigma_x \sigma_y}$$



Possible mitigation techniques:

f

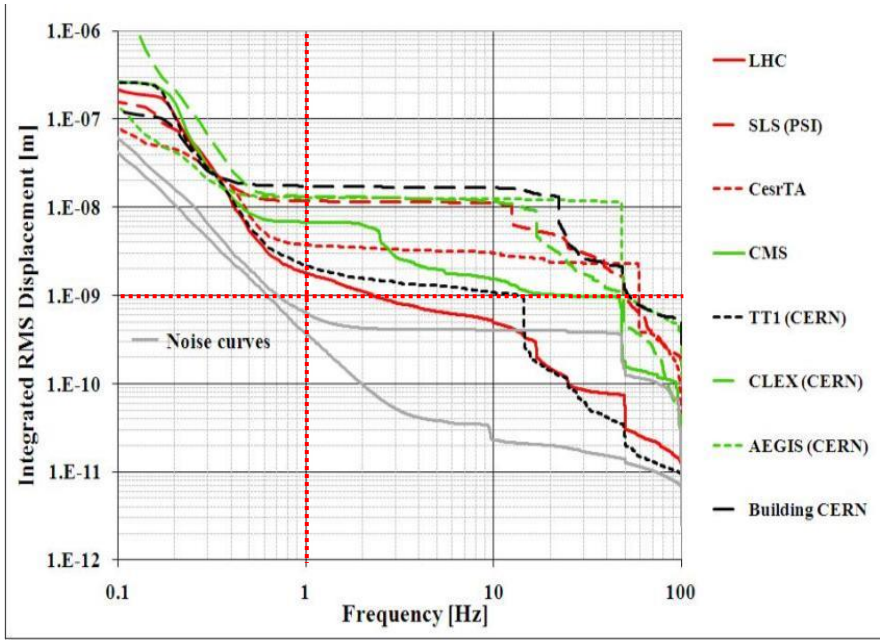
- Alignment
- B.P.M. + dipole correctors
- B.P.M. + Nano positioning
- Seismometers + Dipole correctors
- Mechanical stabilization with seismometers

Requirements Mechanical stability:

Vertical MBQ	**1.5 nm at 1 Hz**
Vertical Final Focus	**0.2 nm at 4 Hz**
Lateral MBQ, FF	**5 nm at 1 Hz** **5 nm at 4 Hz**

$$\sigma_x(f) = \sqrt{\int_f^\infty \Phi_x(\nu)d\nu}$$

Integrated r.m.s. displacement



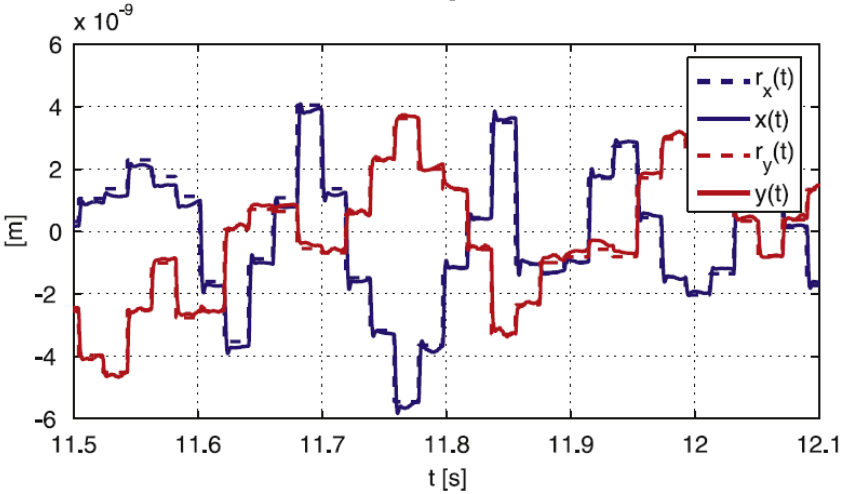
BUT Final requirement is Integrated Luminosity

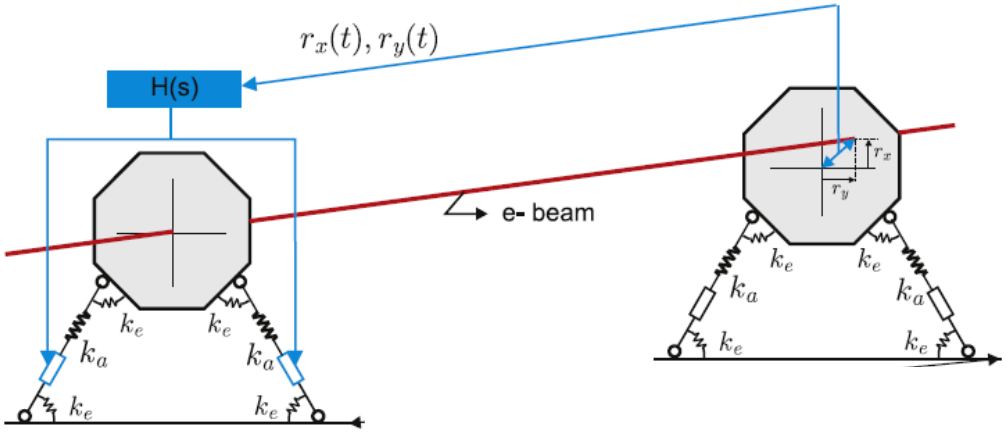
Nano positioning

« Nano-positioning» feasibility study

Modify position quadrupole in between pulses (~ 5 ms)

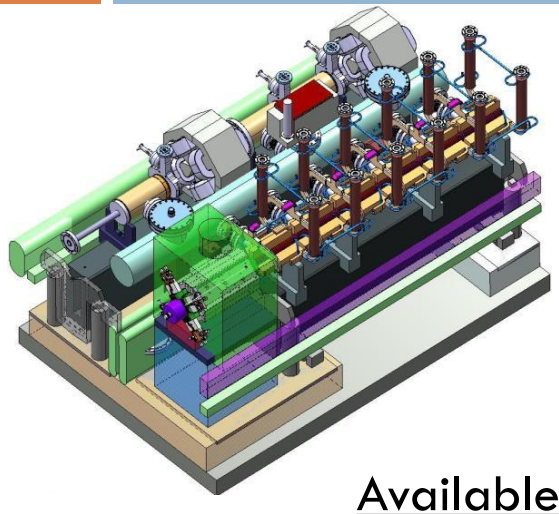
Range ± 5 μm, increments 10 to 50 nm, **precision ± 0.25 nm**





- Lateral and vertical
- In addition/ alternative dipole correctors
- Use to increase time to next realignment with cams

Other requirements stabilisation support



Stiffness-Robustness

Applied forces (water cooling, vacuum, power leads, cabling, interconnects, ventilation, acoustic pressure)

-Compatibility alignment

-Transportability/Installation

Available space

Integration in two beam module

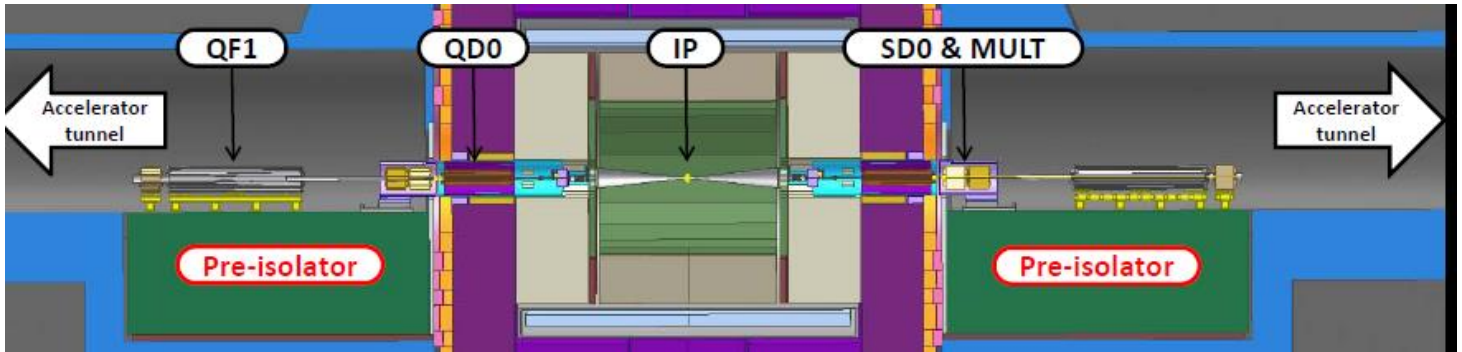
620 mm beam height

Integration in cantilever tube FF

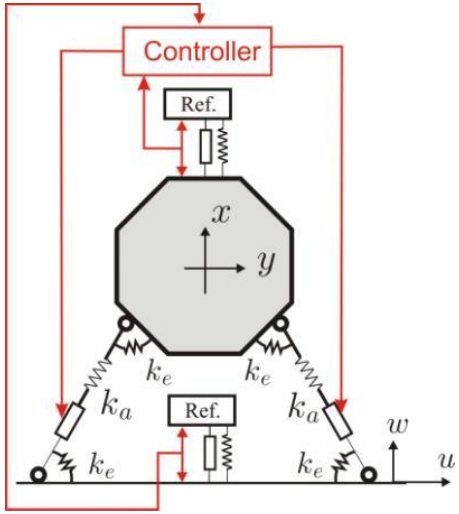
Accelerator environment

High radiation

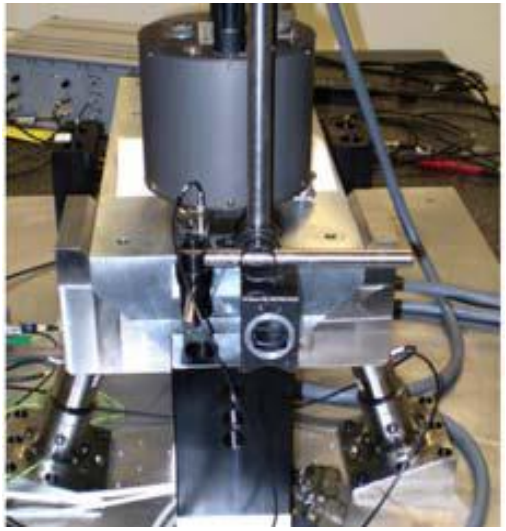
Stray magnetic field

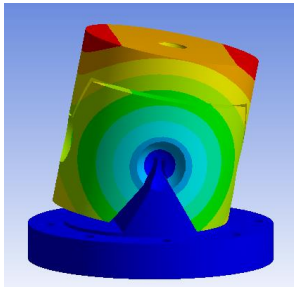


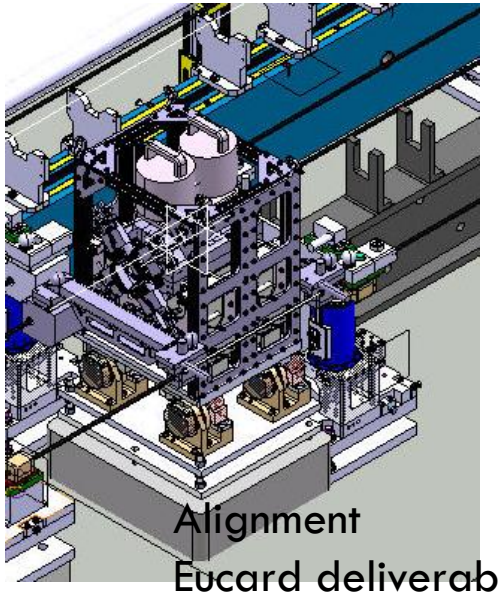
Concept for MBQ



- Inclined stiff piezo actuator pairs with flexural hinges (vertical + lateral motion)
  (four linked bars system)
- X-y flexural guide to block roll + longitudinal d.o.f.+ increased lateral stiffness.
- (Seismometers)/ inertial reference masses for sensors

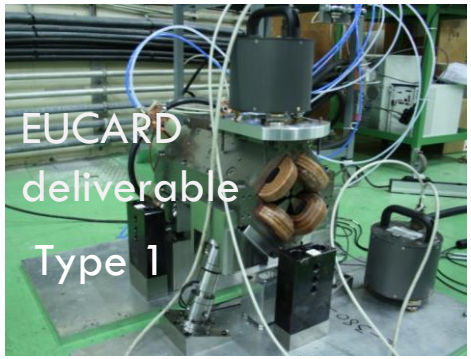


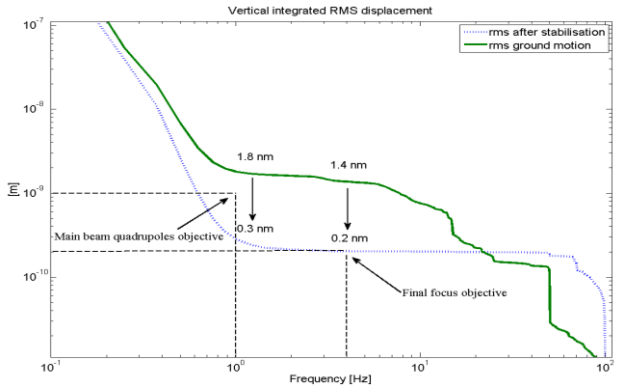


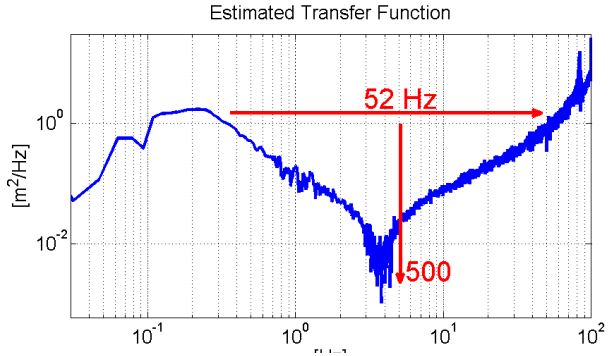


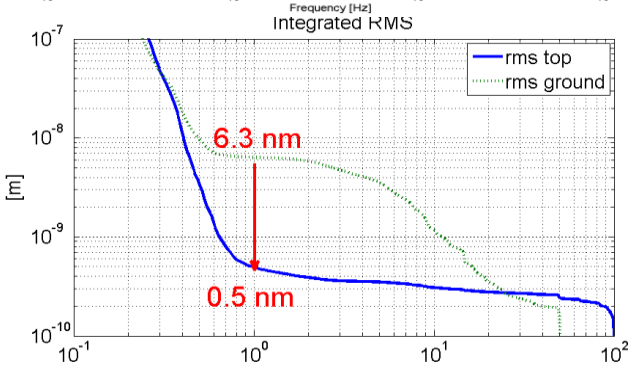
Alignment
Eucard deliverable

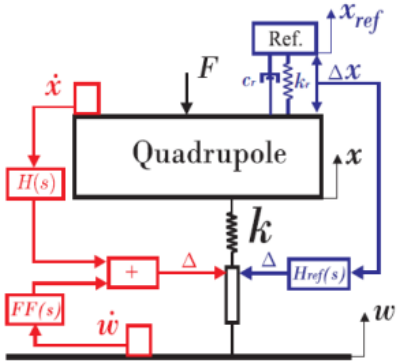
Concept demonstration
actuator support with staged test benches

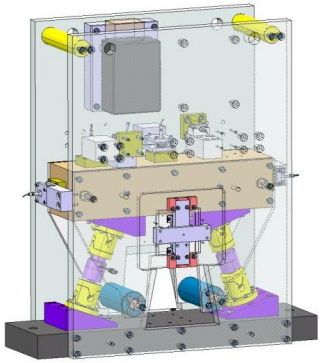




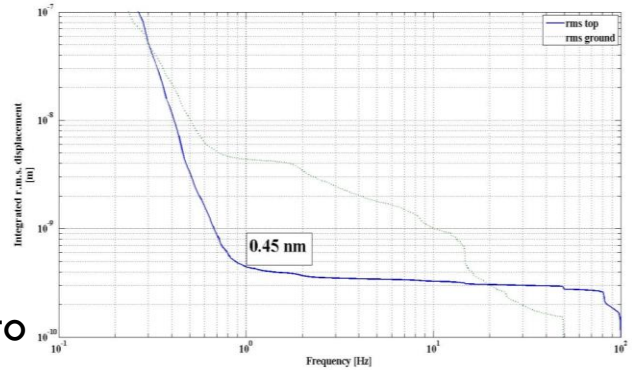








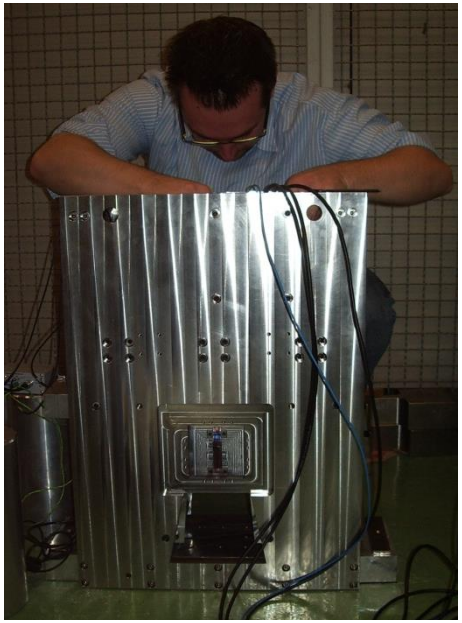
X-y proto

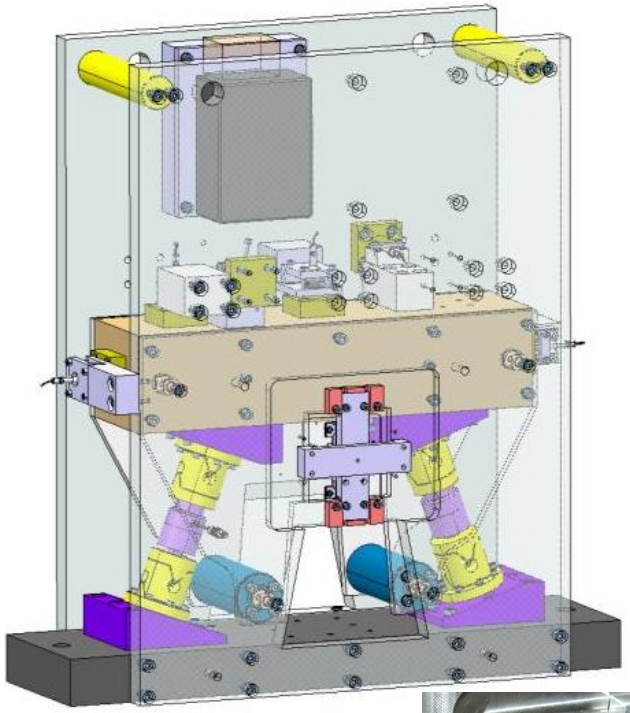


Seismometer FB max. gain +FF (FBFFV1mod): 7 % luminosity loss (no stabilisation 68 % loss)

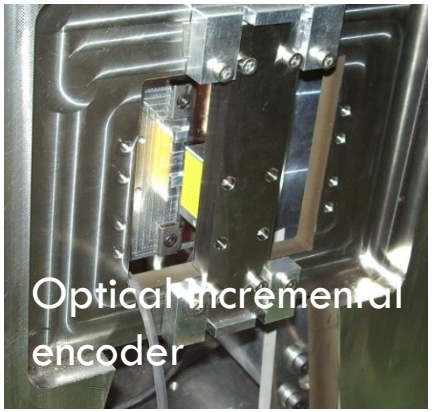
X-y prototype:
Demonstration Nano positioning
Resolution, precision, accuracy

Capacitive sensor

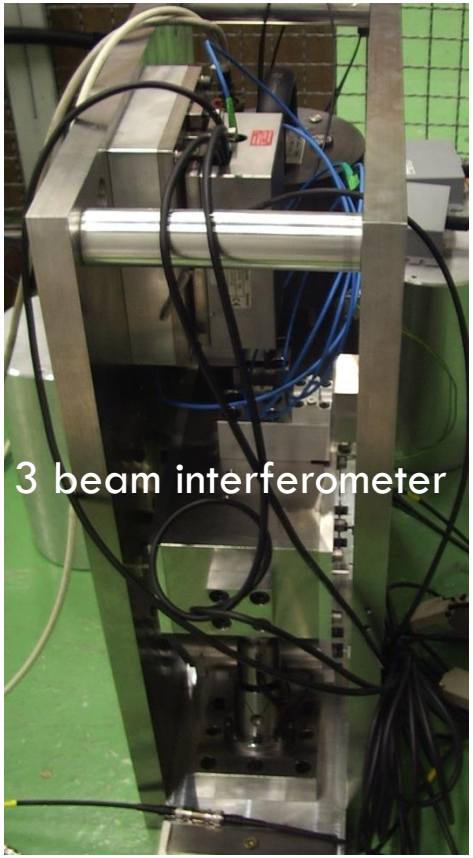




Actuators equipped with strain gauges



Optical incremental encoder

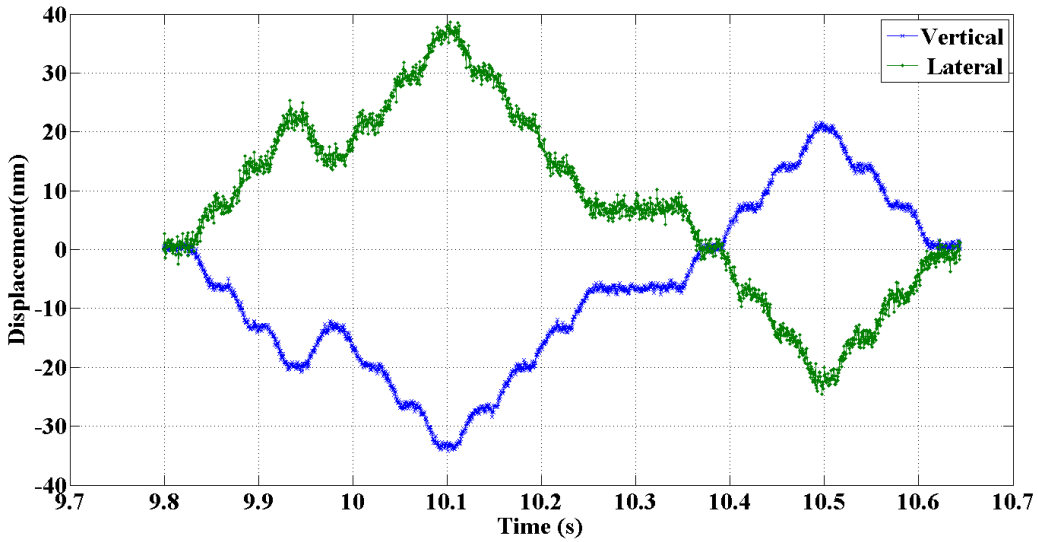


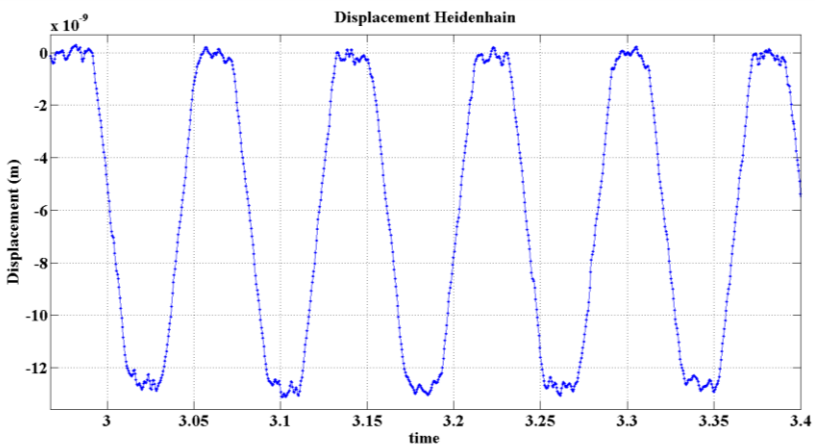
3 beam interferometer

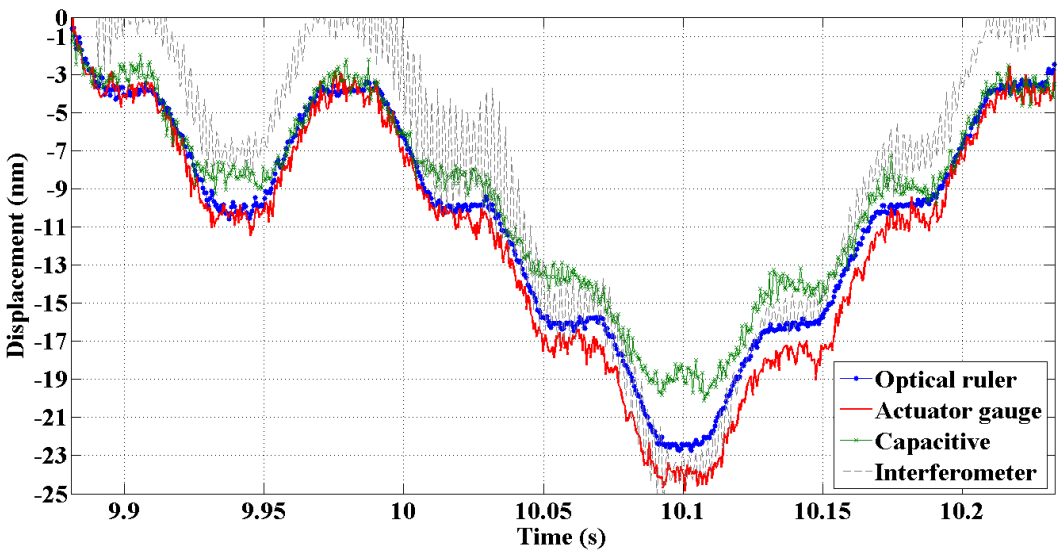
X-y positioning:
Study precision, accuracy and resolution

The precision required (0.25 nm):

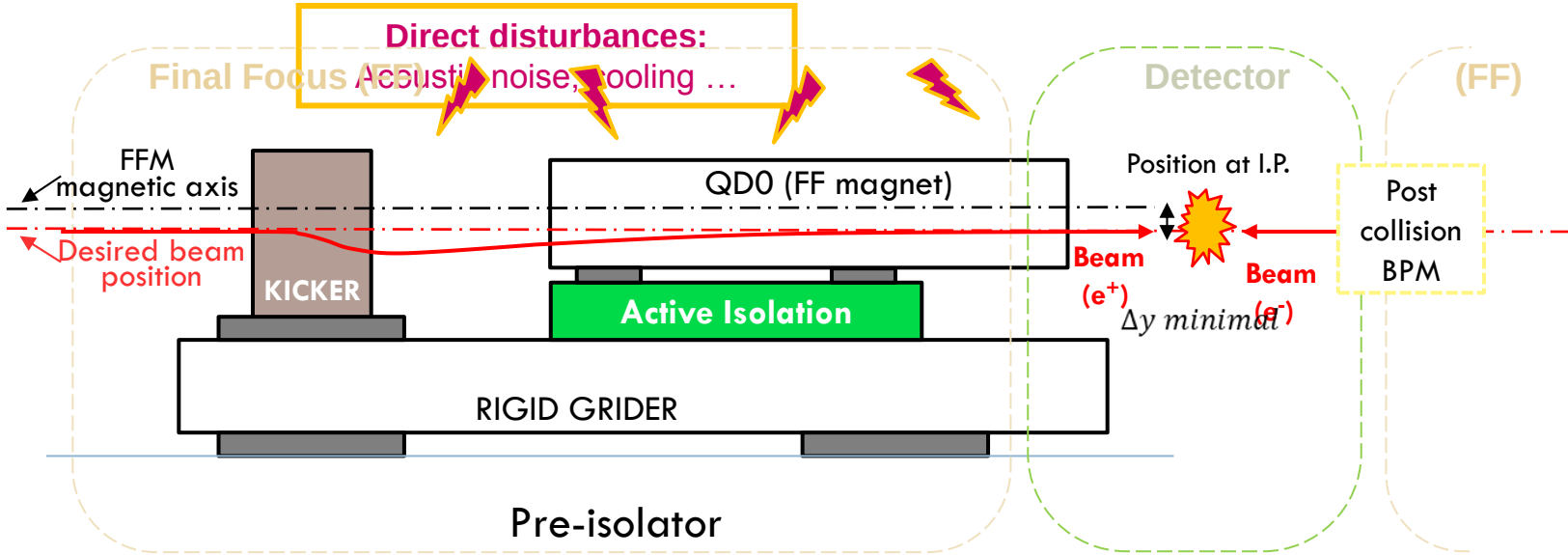
- demonstrated with optical rulers
- in a temperature stable environment , in air
- for simultaneous x and y motion.
- Still increase speed

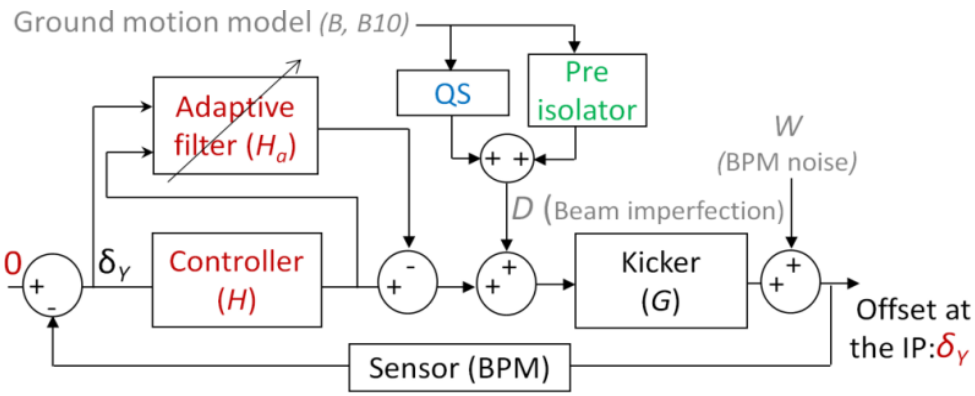


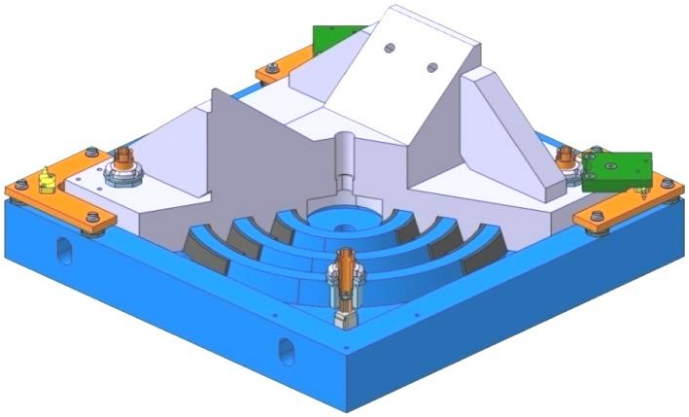




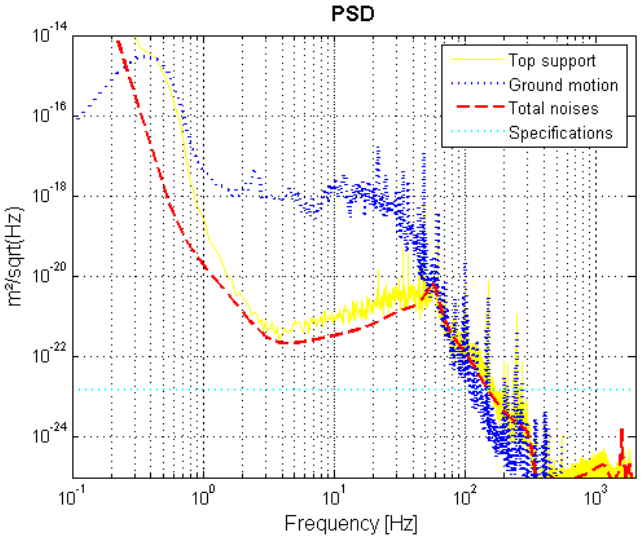
Final focus concept

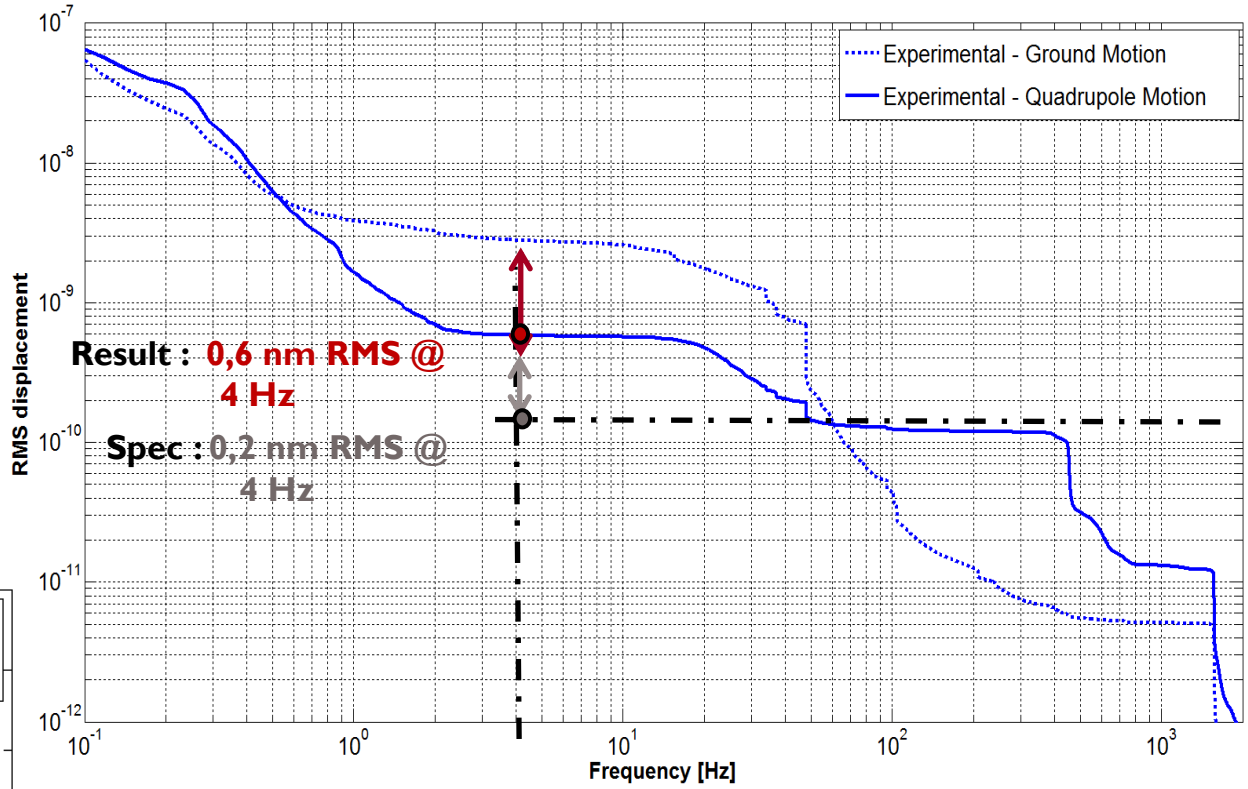






Concept demonstration

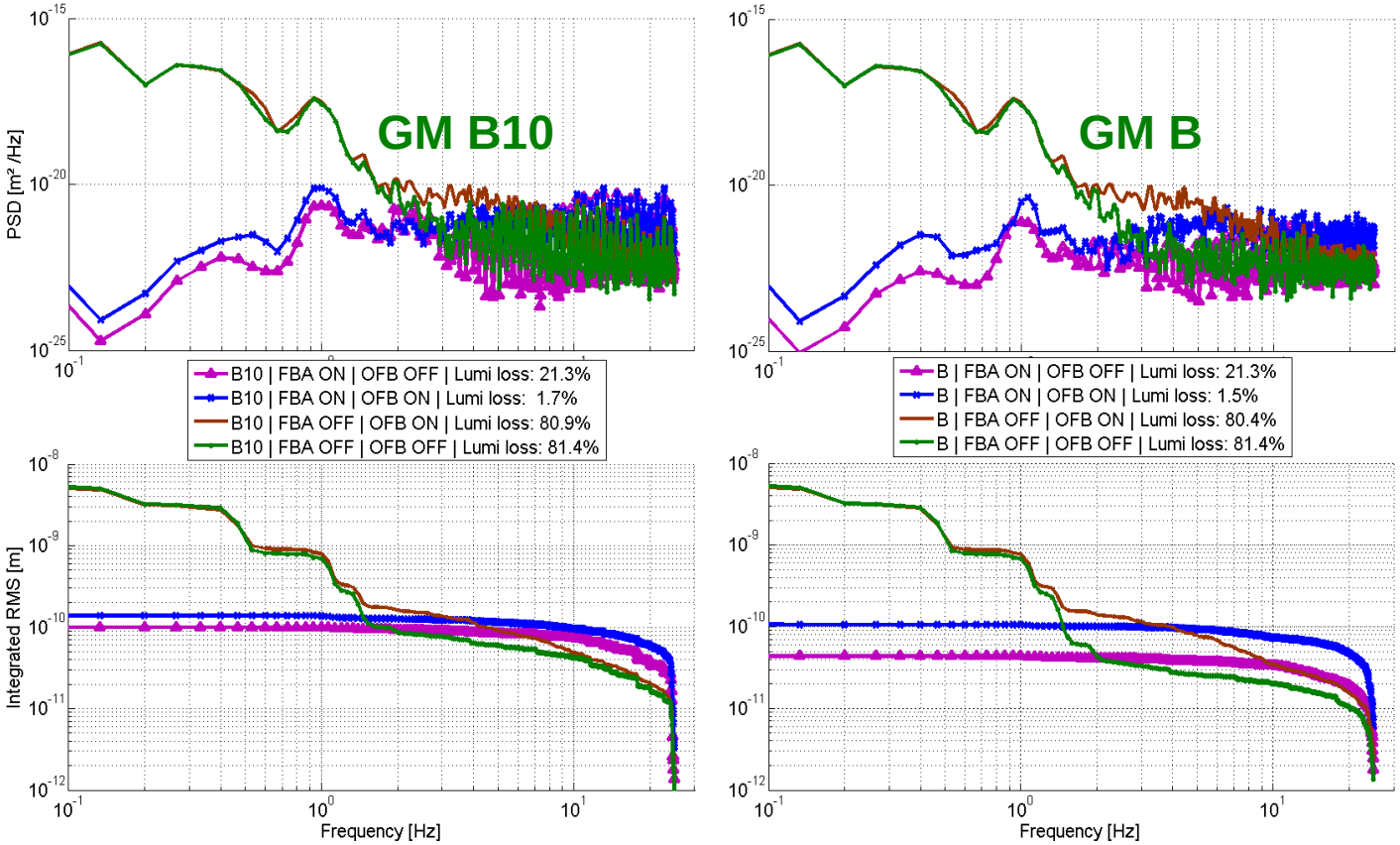




Balik et al, "Active control of a subnanometer isolator", JIMMSS. (accepted)

Indication of sensor limit

Concept demonstration



B. Caron et al, 2012, 236-247, Contr. Eng. Pract. , 20 (3). ; G. Balik et al, 2012, N.I.M.A., 163-170

Reduction of **luminosity losses down to 2%** for different GM models

Demonstration feasability for CLIC MBQ and FF, «*can we do better ?*»

Performance limitations of a mechatronics system

Freely adapted from J. Moerschell

Noise

- Temperature
- Electrical noise (Johnson,…)
- Electromagnetic noise
- SEU
- Digitalisation, quantisation
- Spurious noise, cross talk

Mechanics

- Dimensions, mass, stiffness
- Range
- Degrees of freedom
- Precision guidance
- Modal behaviour

Material

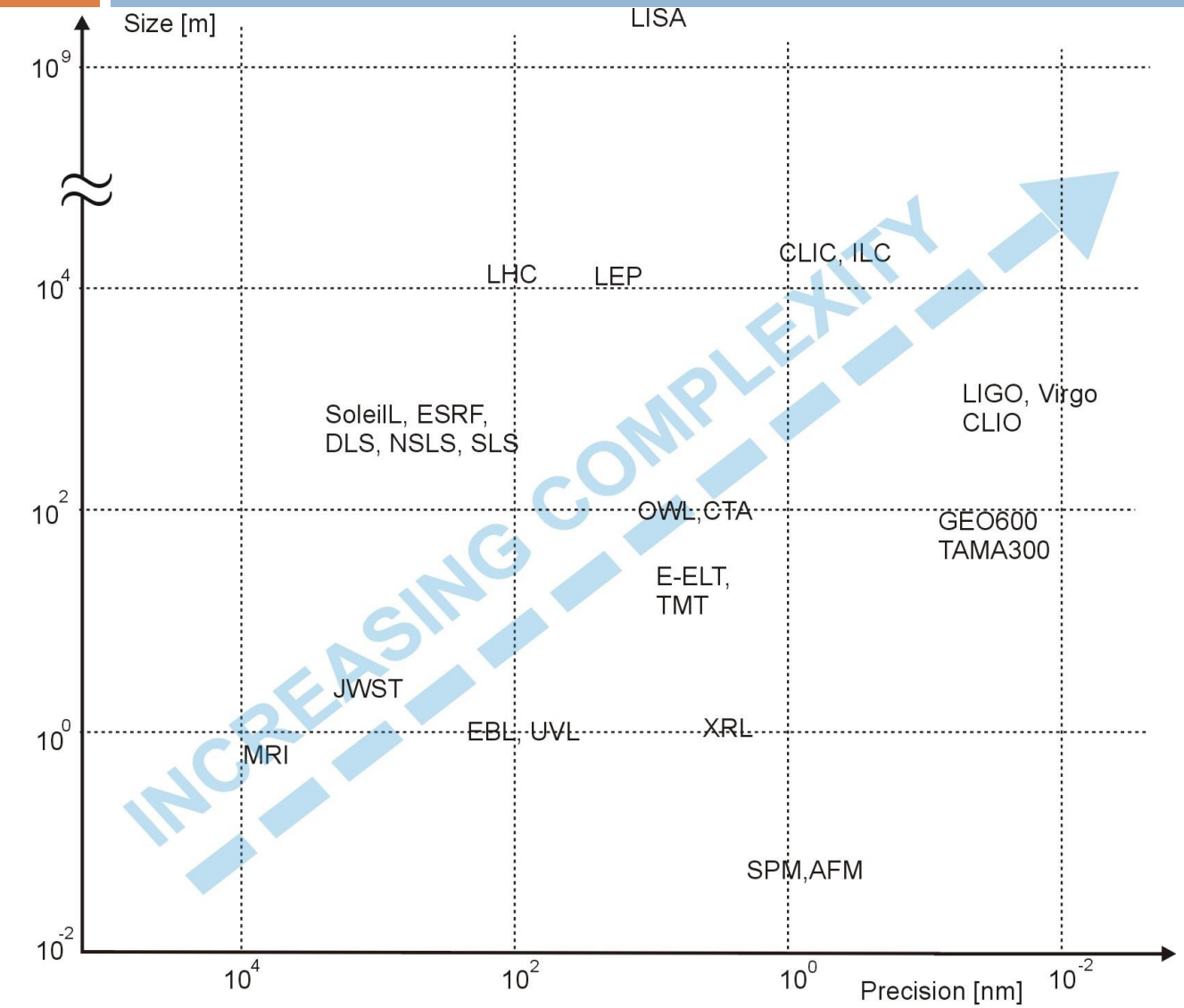
- Elasticity, elastic limit, stress limit
- Damping
- Fatigue
- Ageing (Radiation, Curie-T, humidity)

Control

- Non linearity
- Bandwidth, instabilities
- Control delay
- Parameter uncertainties
- Controller authority, collocation

Machine precision vs size

C. Collette



Particle accelerators:
CLIC: Compact Linear Collider
LHC: Large Hadron Collider
LEP: Large Electron-positron Collider
ILC: Internatinal Linear Collider

Light sources:
ESRF: European Synchrotron Radiation Facility
DLS: Diamond Light Source
NSLS: National Synchrotron Light Source
SLS: Swiss Light Source

Telescopes:
CTA: Cherenkov telescope Array
E-ELT: Eur. Extremely Large Telescope
JWST: James Webb Space Telescope
TMT: Thirty Meter Telescope
OWL: OverWhelmingly Large telescope

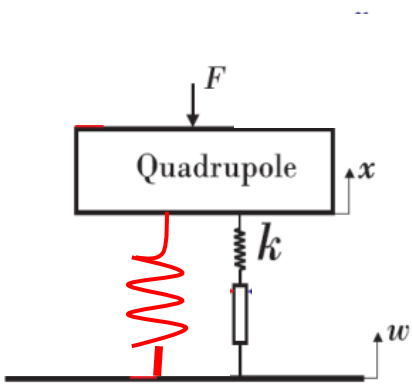
Gravitational Wave Detectors:
LIGO: Laser Interferometer Gravitational wave Observatory
CLIO: Cryogenic Laser Interferometer Observatory
TAMA300: Japanese GWD
GEO600: Germany-UK GWD
LISA: Laser Interferometer Space Antenna

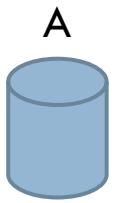
Microscopy:
SPM: Scanning Probe Microscopy
AFM: Atomic Force Microscopy

Imaging:
MRI: Magnetic Resonance Imaging

Manufacturing machines:
XLR: X-ray Lithography
EBL: Electron Beam Lithography
UVL: UV or optical Lithography

Mass/Actuator Resolution/ Range/k/ Bandwidth



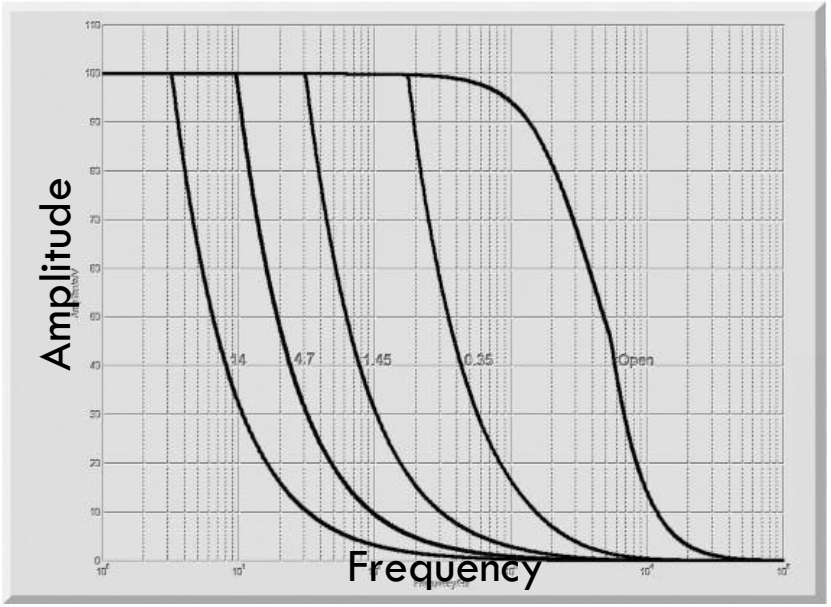


Stress < depolarisation stress

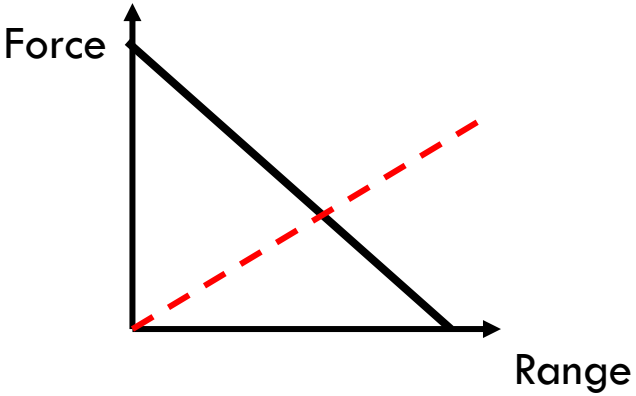
A↑ $Volume \uparrow C_{pzt} \uparrow$ For same Range: P↑ **Resolution ↓**

Bandwidth is limited by

- $f_0(\omega) = \sqrt{\frac{k_{actuator}}{m_{load}}}$
- Actuator slew rate



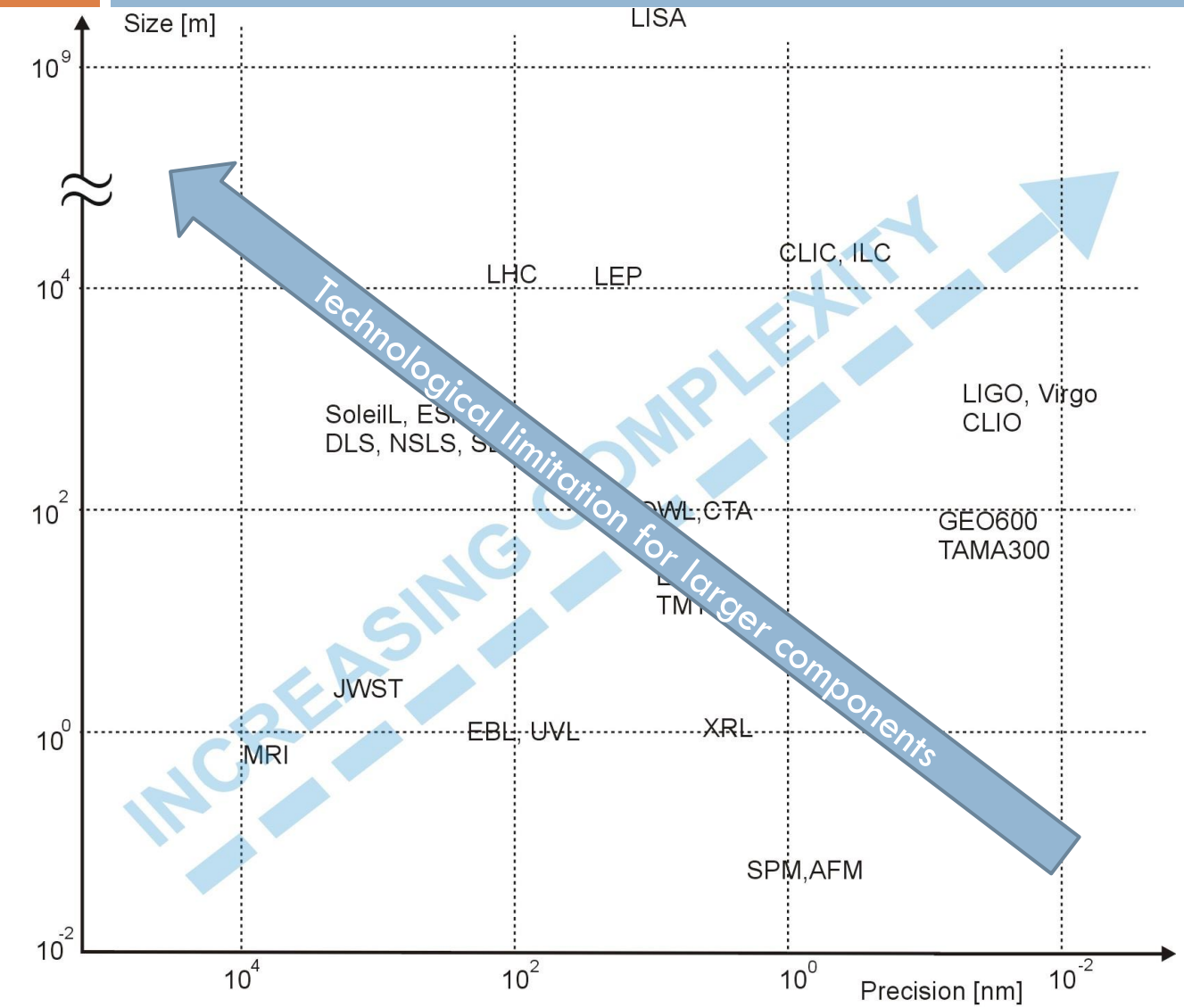
Remark about load compensating springs:



Load compensation reduces range + bandwidth
Improves resolution *

Machine precision vs size

C. Collette



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NSLS: National Synchrotron Light Source
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Telescopes:
CTA: Cherenkov telescope Array
E-ELT: Eur. Extremely Large Telescope
JWST: James Webb Space Telescope
TMT: Thirty Meter Telescope
OWL: OverWhelmingly Large telescope

Gravitational Wave Detectors:
LIGO: Laser Interferometer Gravitational wave Observatory
CLIO: Cryogenic Laser Interferometer Observatory
TAMA300: Japanese GWD
GEO600: Germany-UK GWD
LISA: Laser Interferometer Space Antenna

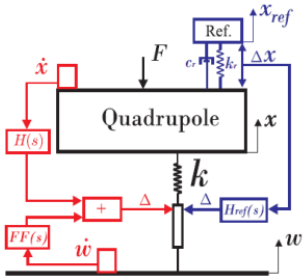
Microscopy:
SPM: Scanning Probe Microscopy
AFM: Atomic Force Microscopy

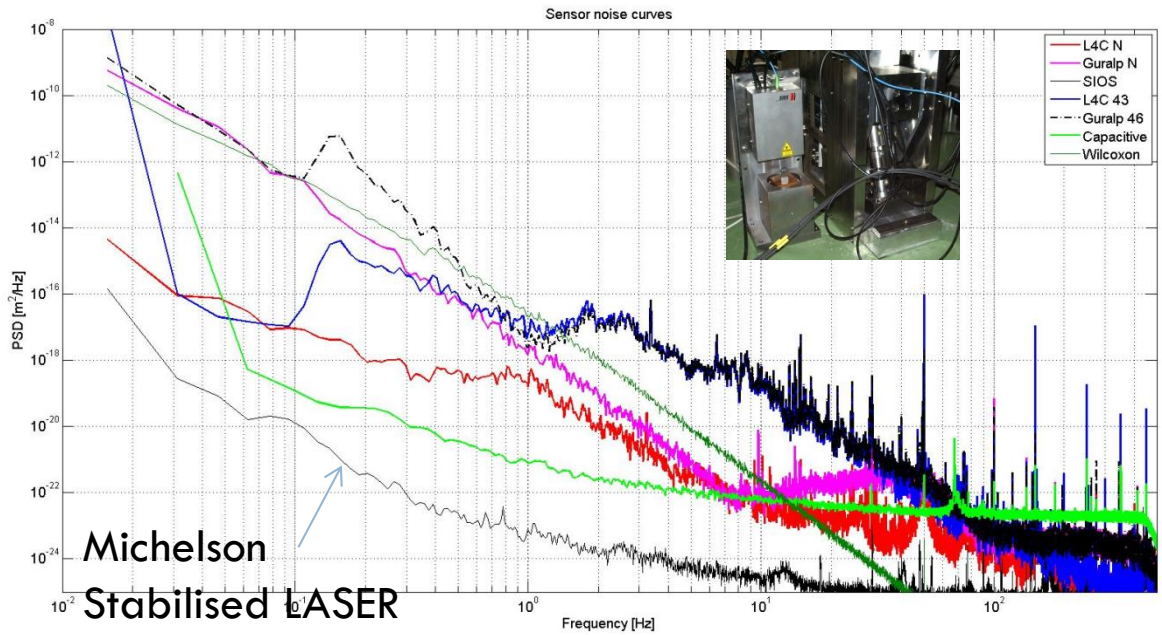
Imaging:
MRI: Magnetic Resonance Imaging

Manufacturing machines:
XLR: X-ray Lithography
EBL: Electron Beam Lithography
UVL: UV or optical Lithography

Resolution limitations
Sensors

Stabilisation

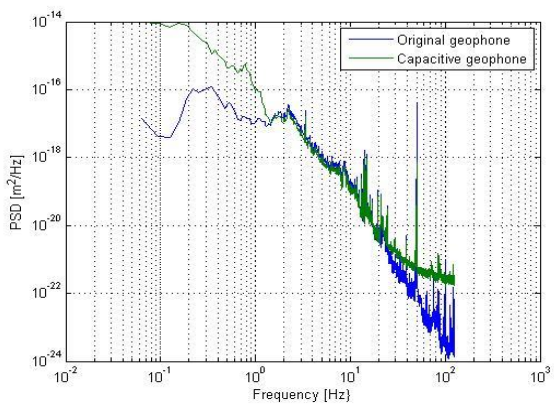


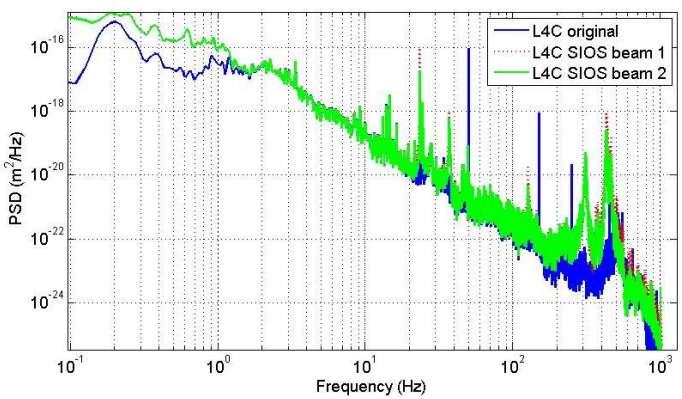


Limitations:

1. Thermal stability (*alignment)
2. EM stray fields
3. Sensor resolution (wavelength light)

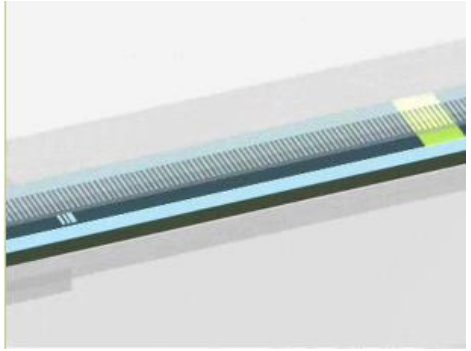
Expected maximum one order of magnitude improvement resolution in next decade (Without major technological innovation)
Low freq. is where you can win the most

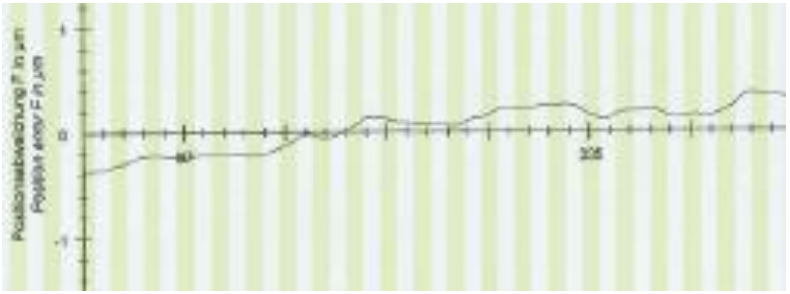


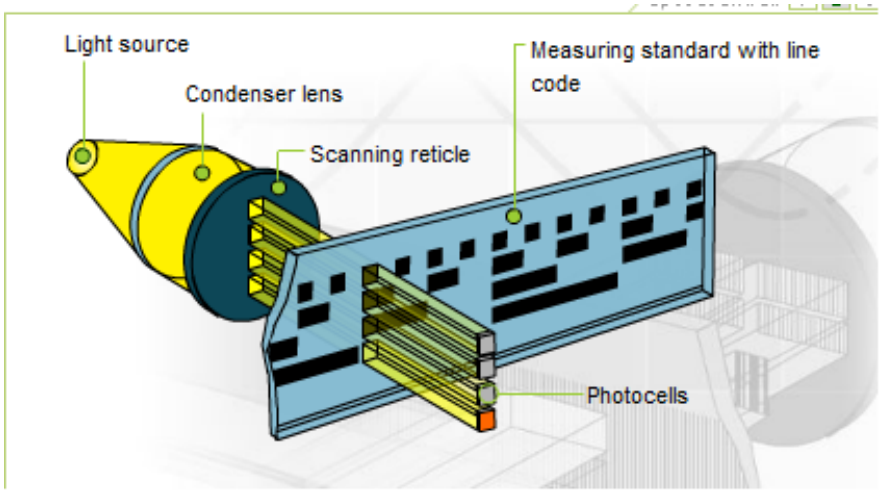


Nano positioning sensors

Technological innovation: digital optical encoders







Heidenhain : 1nm resolution < 1000 CHF
Renishaw: 1 nm resolution < 1000 CHF

Smallest LSB can be used as quadrature …. 0.1 nm resolution is already possible

Conclusion

Noise

- Temperature
- Electrical noise (Johnson,…)
- Electromagnetic noise
- SEU
- Digitalisation
- Spurious noise, cross talk

Mechanics

- Dimensions, mass, stiffness
- Range
- Degrees of freedom
- Precision guidance
- Modal behaviour

Material

- Elasticity, elastic limit, stress limit
- Damping
- Fatigue
- Ageing (Radiation, Curie-T, humidity)

Control

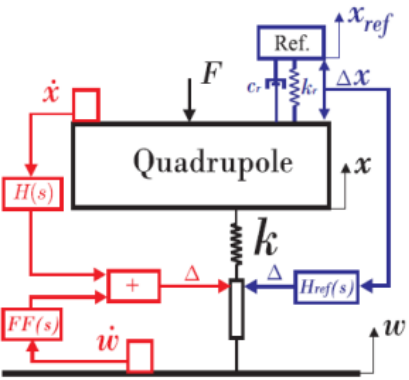
- Non linearity
- Bandwidth, instabilities
- Control delay
- Parameter uncertainties
- Controller authority, collocation

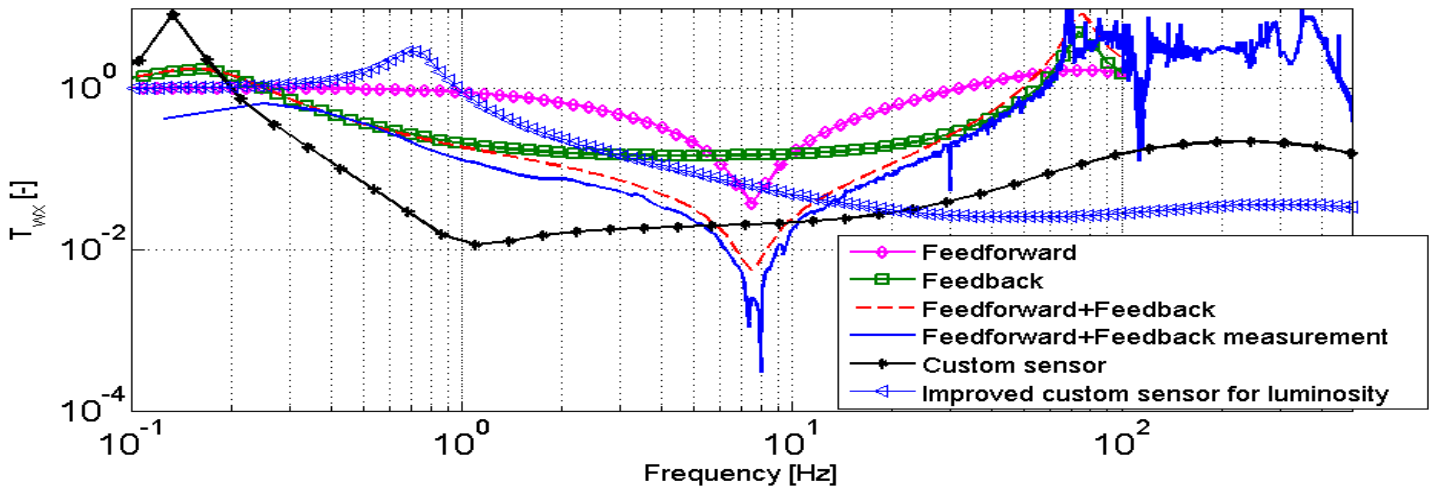
- **In the Eucard grant we demonstrated technical feasibility of the CLIC stability requirements**
- **In a <u>laboratory environment</u> one can expect to go an order better in the next decades, in an <u>accelerator environment</u> it is more complicated**

Synergies between projects: Generic R&D

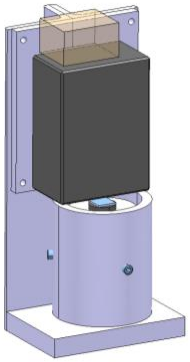
R&D/Projects		Test Facilities	Protons			Ions			Electron-Hadrons			B Factories		Linear Colliders				Muons & Neutrinos		
			HL-LHC	HE-LHC	LHiC	NICA	RHIC II	FAIR	LHeC	eRHIC	ELIC	Super KEKB	SuperB	ILC	CLIC	PFWA LWFA	Dielec-tric Acc	Muon Collider	Neutrin Factory	Project X
	Coordination		CERN	CERN	CERN	DUBNA	BNL	GSI	CERN	BNL	JLAB	KEK	LNF	GDE	CLIC coll	SLAC/LBL	SLAC?	MAP	NF Coll	FNAL
Electron cloud	Cornell?	CESR-TA	X	X		X	X		X	X		X	X	X	X					X
SC magnets (High Field, Fast Cycling, Super-Ferric, Wigglers)	Magnet R&D network?	CERN, FNAL, GSI	HF	HF/FC	HF	SF		FC				HF	HF		W					
Super-Conducting RF	TESLA Tech coll	FLASH, NML, STF, XFEL					X		X	X		X		X				X		X
High field NC Structures	?	CTF3, SLAC, KEK													X				X	
Low emittance generation	CLIC/ILC WG?	ATF1										X	X	X	X	X	X			
Nanometer beam focusing	ATF coll	ATF2	X									X	X	X	X	X	X			
Alignment and stabilisation	?	AlignTF, StabTF					X		X	X	X	X	X		X	X	X			
RF power source high efficiency	?		X	X	X									X	X			X		X
High beam power generation&handling	?	SNS, PSI	X	X								X	X	X	X	X	X	X	X	X
Collimation & targets high power beams	?	HRad,HARP,MERIT	X	X	X							X	X	X	X			X	X	X
Cooling (Electron, Coherent, Stochastic)	?	RHIC				S,E	S		C	C	E									
Ionisation cooling	?	MICE,MTA, MuCool																X	X	
crab cavities	?	KEKB	X						X	X	X			X	X					
Plasmas	LBL, SLAC	BELLA, FACET														X				
Lasers	LBL, Ec. Polyt	BELLA, LULI												X	X	X	X			
Drive beam generation	CTF3 collab	CTF3, FACET													X	X	X			
Beam dynamics simuations	?	Test benches	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Beam Instrumentation	?		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Beam based feedbacks	?					X	X			X	X	X	X	X	X					
Energy recovery linacs	CEBAF?	CEBAF, BNL R&D ERL							X	X	X									
Nanobeam scheme (LPA & Crab waist)	B Fact collab?	DAFNE	X									X	X							
Positron generation	?									X	X	X	X	X	X					
Polarisation	?					X	X		X	X	X		X	X	X					
Dynamic vacuum	?			X	X	X	X			X	X	X	X		X					

Integrated luminosity simulations





Commercial Seismometer



Custom Inertial Reference mass

No stabilization	68% luminosity loss
Seismometer FB maximum gain (V1)	13%
Seismometer FB medium gain (V1mod)	6% (reduced peaks @ 0.1 and 75 Hz)
Seis. FB max. gain +FF (FBFFV1mod)	7%
Inertial ref. mass 1 Hz (V3mod)	11%
Inertial ref. mass 1 Hz + HP filter (V3)	3%

Stef Janssens

Courtesy J. Snuverink, J. Pfingstner *et al.*

Comparison sensors

Sensor	Resolution	Main +	Main -
Actuator sensor	0.15 nm	No separate assembly	Resolution No direct measurement of magnet movement
Capacitive gauge	0.10 nm	Gauge radiation hard	Mounting tolerances Gain change w. α Orthogonal coupling
Interferometer	10 pm	Accuracy at freq.> 10 Hz	Cost Mounting tolerance Sensitive to air flow Orthogonal coupling
Optical ruler	0.5*-1 nm	Cost 1% orthogonal coupling Mounting tolerance Small temperature drift Possible absolute sensor	Rad hardness sensor head not known Limited velocity displacements
Seismometer (after integration)	*< pm at higher frequencies*	*For cross calibration*	